Creative Commons Legal Code

Attribution-NonCommercial-NoDerivs 3.0 Unported

CREATIVE COMMONS CORPORATION IS NOT A LAW FIRM AND DOES NOT PROVIDE LEGAL SERVICES. DISTRIBUTION OF THIS LICENSE DOES NOT CREATE AN ATTORNEY-CLIENT RELATIONSHIP. CREATIVE COMMONS PROVIDES THIS INFORMATION ON AN "AS-IS" BASIS. CREATIVE COMMONS MAKES NO WARRANTIES REGARDING THE INFORMATION PROVIDED, AND DISCLAIMS LIABILITY FOR DAMAGES RESULTING FROM ITS USE.

License

THE WORK (AS DEFINED BELOW) IS PROVIDED UNDER THE TERMS OF THIS CREATIVE COMMONS PUBLIC LICENSE ("CCPL" OR "LICENSE"). THE WORK IS PROTECTED BY COPYRIGHT AND/OR OTHER APPLICABLE LAW. ANY USE OF THE WORK OTHER THAN AS AUTHORIZED UNDER THIS LICENSE OR COPYRIGHT LAW IS PROHIBITED.

BY EXERCISING ANY RIGHTS TO THE WORK PROVIDED HERE, YOU ACCEPT AND AGREE TO BE BOUND BY THE TERMS OF THIS LICENSE. TO THE EXTENT THIS LICENSE MAY BE CONSIDERED TO BE A CONTRACT, THE LICENSOR GRANTS YOU THE RIGHTS CONTAINED HERE IN CONSIDERATION OF YOUR ACCEPTANCE OF SUCH TERMS AND CONDITIONS.

1. Definitions

a. "Adaptation" means a work based upon the Work, or upon the Work and other pre-existing works, such as a translation, adaptation, derivative work, arrangement of music or other alterations of a literary or artistic work, or phonogram or performance and includes cinematographic adaptations or any other form in which the Work may be recast, transformed, or adapted including in any form recognizably derived from the original, except that a work that constitutes a Collection will not be considered an Adaptation for the purpose of this License. For the avoidance of doubt, where the Work is a musical work, performance or phonogram, the synchronization of the Work in timed-relation with a moving image ("synching") will be considered an Adaptation for the purpose of this License.

b. "Collection" means a collection of literary or artistic works, such as encyclopedias and anthologies, or performances, phonograms or broadcasts, or other works or subject matter other than works listed
License II

in Section 1(f) below, which, by reason of the selection and arrangement of their contents, constitute intellectual creations, in which the Work is included in its entirety in unmodified form along with one or more other contributions, each constituting separate and independent works in themselves, which together are assembled into a collective whole. A work that constitutes a Collection will not be considered an Adaptation (as defined above) for the purposes of this License.

c. "Distribute" means to make available to the public the original and copies of the Work through sale or other transfer of ownership.
d. "Licensor" means the individual, individuals, entity or entities that offer(s) the Work under the terms of this License.
e. "Original Author" means, in the case of a literary or artistic work, the individual, individuals, entity or entities who created the Work or if no individual or entity can be identified, the publisher; and in addition (i) in the case of a performance the actors, singers, musicians, dancers, and other persons who act, sing, deliver, declaim, play in, interpret or otherwise perform literary or artistic works or expressions of folklore; (ii) in the case of a phonogram the producer being the person or legal entity who first fixes the sounds of a performance or other sounds; and, (iii) in the case of broadcasts, the organization that transmits the broadcast.
f. "Work" means the literary and/or artistic work offered under the terms of this License including without limitation any production in the literary, scientific and artistic domain, whatever may be the mode or form of its expression including digital form, such as a book, pamphlet and other writing; a lecture, address, sermon or other work of the same nature; a dramatic or dramatico-musical work; a choreographic work or entertainment in dumb show; a musical composition with or without words; a cinematographic work to which are assimilated works expressed by a process analogous to cinematography; a work of drawing, painting, architecture, sculpture, engraving or lithography; a photographic work to which are assimilated works expressed by a process analogous to photography; a work of applied art; an illustration, map, plan, sketch or three-dimensional work relative to geography, topography, architecture or science; a performance; a broadcast; a phonogram; a compilation of data to the extent it is protected as a copyrightable work; or a work performed by a variety or circus performer to the extent it is not otherwise considered a literary or artistic work.
g. "You" means an individual or entity exercising rights under this
License who has not previously violated the terms of this License with respect to the Work, or who has received express permission from the Licensor to exercise rights under this License despite a previous violation.

h. "Publicly Perform" means to perform public recitations of the Work and to communicate to the public those public recitations, by any means or process, including by wire or wireless means or public digital performances; to make available to the public Works in such a way that members of the public may access these Works from a place and at a place individually chosen by them; to perform the Work to the public by any means or process and the communication to the public of the performances of the Work, including by public digital performance; to broadcast and rebroadcast the Work by any means including signs, sounds or images.

i. "Reproduce" means to make copies of the Work by any means including without limitation by sound or visual recordings and the right of fixation and reproducing fixations of the Work, including storage of a protected performance or phonogram in digital form or other electronic medium.

2. Fair Dealing Rights. Nothing in this License is intended to reduce, limit, or restrict any uses free from copyright or rights arising from limitations or exceptions that are provided for in connection with the copyright protection under copyright law or other applicable laws.

3. License Grant. Subject to the terms and conditions of this License, Licensor hereby grants You a worldwide, royalty-free, non-exclusive, perpetual (for the duration of the applicable copyright) license to exercise the rights in the Work as stated below:

   a. to Reproduce the Work, to incorporate the Work into one or more Collections, and to Reproduce the Work as incorporated in the Collections; and,

   b. to Distribute and Publicly Perform the Work including as incorporated in Collections.

The above rights may be exercised in all media and formats whether now known or hereafter devised. The above rights include the right to make such modifications as are technically necessary to exercise the rights in other media and formats, but otherwise you have no rights to make Adaptations. Subject to 8(f), all rights not expressly granted by Licensor
License IV

are hereby reserved, including but not limited to the rights set forth in Section 4(d).

4. Restrictions. The license granted in Section 3 above is expressly made subject to and limited by the following restrictions:

a. You may Distribute or Publicly Perform the Work only under the terms of this License. You must include a copy of, or the Uniform Resource Identifier (URI) for, this License with every copy of the Work You Distribute or Publicly Perform. You may not offer or impose any terms on the Work that restrict the terms of this License or the ability of the recipient of the Work to exercise the rights granted to that recipient under the terms of the License. You may not sublicense the Work. You must keep intact all notices that refer to this License and to the disclaimer of warranties with every copy of the Work You Distribute or Publicly Perform. When You Distribute or Publicly Perform the Work, You may not impose any effective technological measures on the Work that restrict the ability of a recipient of the Work from You to exercise the rights granted to that recipient under the terms of the License. This Section 4(a) applies to the Work as incorporated in a Collection, but this does not require the Collection apart from the Work itself to be made subject to the terms of this License. If You create a Collection, upon notice from any Licensor You must, to the extent practicable, remove from the Collection any credit as required by Section 4(c), as requested.

b. You may not exercise any of the rights granted to You in Section 3 above in any manner that is primarily intended for or directed toward commercial advantage or private monetary compensation. The exchange of the Work for other copyrighted works by means of digital file-sharing or otherwise shall not be considered to be intended for or directed toward commercial advantage or private monetary compensation, provided there is no payment of any monetary compensation in connection with the exchange of copyrighted works.

c. If You Distribute, or Publicly Perform the Work or Collections, You must, unless a request has been made pursuant to Section 4(a), keep intact all copyright notices for the Work and provide, reasonable to the medium or means You are utilizing: (i) the name of the Original Author (or pseudonym, if applicable) if supplied, and/or if the Original Author and/or Licensor designate another party or parties (e.g., a sponsor institute, publishing entity, journal) for attribution ("Attribution Parties") in Licensor’s copyright notice,
terms of service or by other reasonable means, the name of such party or parties; (ii) the title of the Work if supplied; (iii) to the extent reasonably practicable, the URI, if any, that Licensor specifies to be associated with the Work, unless such URI does not refer to the copyright notice or licensing information for the Work. The credit required by this Section 4(c) may be implemented in any reasonable manner; provided, however, that in the case of a Collection, at a minimum such credit will appear, if a credit for all contributing authors of Collection appears, then as part of these credits and in a manner at least as prominent as the credits for the other contributing authors. For the avoidance of doubt, You may only use the credit required by this Section for the purpose of attribution in the manner set out above and, by exercising Your rights under this License, You may not implicitly or explicitly assert or imply any connection with, sponsorship or endorsement by the Original Author, Licensor and/or Attribution Parties, as appropriate, of You or Your use of the Work, without the separate, express prior written permission of the Original Author, Licensor and/or Attribution Parties.

d. For the avoidance of doubt:

i. Non-waivable Compulsory License Schemes. In those jurisdictions in which the right to collect royalties through any statutory or compulsory licensing scheme cannot be waived, the Licensor reserves the exclusive right to collect such royalties for any exercise by You of the rights granted under this License;

ii. Waivable Compulsory License Schemes. In those jurisdictions in which the right to collect royalties through any statutory or compulsory licensing scheme can be waived, the Licensor reserves the exclusive right to collect such royalties for any exercise by You of the rights granted under this License if Your exercise of such rights is for a purpose or use which is otherwise than noncommercial as permitted under Section 4(b) and otherwise waives the right to collect royalties through any statutory or compulsory licensing scheme; and,

iii. Voluntary License Schemes. The Licensor reserves the right to collect royalties, whether individually or, in the event that the Licensor is a member of a collecting society that administers voluntary licensing schemes, via that society, from any exercise by You of the rights granted under this License that is for a purpose or use which is otherwise than noncommercial as permitted
under Section 4(b).

e. Except as otherwise agreed in writing by the Licensor or as may be otherwise permitted by applicable law, if You Reproduce, Distribute or Publicly Perform the Work either by itself or as part of any Collections, You must not distort, mutilate, modify or take other derogatory action in relation to the Work which would be prejudicial to the Original Author’s honor or reputation.

5. Representations, Warranties and Disclaimer

UNLESS OTHERWISE MUTUALLY AGreed BY THE PARTIES IN WRITING, LICENSOR OFFERS THE WORK AS-IS AND MAKES NO REPRESENTATIONS OR WARRANTIES OF ANY KIND CONCERNING THE WORK, EXPRESS, IMPLIED, STATUTORY OR OTHERWISE, INCLUDING, WITHOUT LIMITATION, WARRANTIES OF TITLE, MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, NONINFRINGEMENT, OR THE ABSENCE OF LATENT OR OTHER DEFECTS, ACCURACY, OR THE PRESENCE OF ABSENCE OF ERRORS, WHETHER OR NOT DISCOVERABLE. SOME JURISDICTIONS DO NOT ALLOW THE EXCLUSION OF IMPLIED WARRANTIES, SO SUCH EXCLUSION MAY NOT APPLY TO YOU.

6. Limitation on Liability. EXCEPT TO THE EXTENT REQUIRED BY APPLICABLE LAW, IN NO EVENT WILL LICENSOR BE LIABLE TO YOU ON ANY LEGAL THEORY FOR ANY SPECIAL, INCIDENTAL, CONSEQUENTIAL, PUNITIVE OR EXEMPLARY DAMAGES ARISING OUT OF THIS LICENSE OR THE USE OF THE WORK, EVEN IF LICENSOR HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

7. Termination

a. This License and the rights granted hereunder will terminate automatically upon any breach by You of the terms of this License. Individuals or entities who have received Collections from You under this License, however, will not have their licenses terminated provided such individuals or entities remain in full compliance with those licenses. Sections 1, 2, 5, 6, 7, and 8 will survive any termination of this License.

b. Subject to the above terms and conditions, the license granted here is perpetual (for the duration of the applicable copyright in the Work). Notwithstanding the above, Licensor reserves the right to release the Work under different license terms or to stop distributing the Work at any time; provided, however that any such election will not serve to withdraw this License (or any other license that has been, or is required to be, granted under the terms of this License), and this
License will continue in full force and effect unless terminated as stated above.

8. Miscellaneous

a. Each time You Distribute or Publicly Perform the Work or a Collection, the Licensor offers to the recipient a license to the Work on the same terms and conditions as the license granted to You under this License.

b. If any provision of this License is invalid or unenforceable under applicable law, it shall not affect the validity or enforceability of the remainder of the terms of this License, and without further action by the parties to this agreement, such provision shall be reformed to the minimum extent necessary to make such provision valid and enforceable.

c. No term or provision of this License shall be deemed waived and no breach consented to unless such waiver or consent shall be in writing and signed by the party to be charged with such waiver or consent.

d. This License constitutes the entire agreement between the parties with respect to the Work licensed here. There are no understandings, agreements or representations with respect to the Work not specified here. Licensor shall not be bound by any additional provisions that may appear in any communication from You. This License may not be modified without the mutual written agreement of the Licensor and You.

e. The rights granted under, and the subject matter referenced, in this License were drafted utilizing the terminology of the Berne Convention for the Protection of Literary and Artistic Works (as amended on September 28, 1979), the Rome Convention of 1961, the WIPO Copyright Treaty of 1996, the WIPO Performances and Phonograms Treaty of 1996 and the Universal Copyright Convention (as revised on July 24, 1971). These rights and subject matter take effect in the relevant jurisdiction in which the License terms are sought to be enforced according to the corresponding provisions of the implementation of those treaty provisions in the applicable national law. If the standard suite of rights granted under applicable copyright law includes additional rights not granted under this License, such additional rights are deemed to be included in the License; this License is not intended to restrict the license of any rights under applicable law.

Creative Commons Notice
Creative Commons is not a party to this License, and makes no warranty whatsoever in connection with the Work. Creative Commons will not be liable to You or any party on any legal theory for any damages whatsoever, including without limitation any general, special, incidental or consequential damages arising in connection to this license. Notwithstanding the foregoing two (2) sentences, if Creative Commons has expressly identified itself as the Licensor hereunder, it shall have all rights and obligations of Licensor.

Except for the limited purpose of indicating to the public that the Work is licensed under the CCPL, Creative Commons does not authorize the use by either party of the trademark "Creative Commons" or any related trademark or logo of Creative Commons without the prior written consent of Creative Commons. Any permitted use will be in compliance with Creative Commons’ then-current trademark usage guidelines, as may be published on its website or otherwise made available upon request from time to time. For the avoidance of doubt, this trademark restriction does not form part of this License.

Creative Commons may be contacted at http://creativecommons.org/.
http://www.ece.uvic.ca/~mdadams/cppbook.

http://www.ece.uvic.ca/~mdadams/sigsysbook.

Part 0

Preface
This document constitutes a detailed set of lecture slides on the C++ programming language and is current with the C++20 standard. Many aspects of the C++ language are covered from introductory to more advanced. Some aspects of the C++ standard library are also introduced. In addition, various general programming-related topics are considered. These slides are intended to be used in conjunction with the following book:

The author would like to thank Robert Leahy for reviewing various drafts of many of these slides and providing many useful comments that allowed the quality of these materials to be improved significantly.
Many code examples are included throughout these slides.

Often, in order to make an example short enough to fit on a slide, compromises had to be made in terms of good programming style.

These deviations from good style include (but are not limited to) such things as:

1. frequently formatting source code in unusual ways to conserve vertical space in listings;
2. not fully documenting source code with comments;
3. using short meaningless identifier names;
4. omitting include guards from headers; and
5. engaging in various other evil behavior such as: using many global variables and employing constructs like “using namespace std;”.

- In a definition, the term being defined is often typeset *like this*.
- To emphasize particular text, the text is typeset *like this*.
- To show that particular text is associated with a hyperlink to an internal target, the text is typeset *like this*.
- To show that particular text is associated with a hyperlink to an external document, the text is typeset *like this*.
- URLs are typeset like `http://www.ece.uvic.ca/~mdadams`. 
The author of the lecture slides maintains a companion web site for the slides.

The most recent version of the slides can be downloaded from this site.

Additional information related to the slides is also available from this site, including:
- errata for the slides; and
- information on the companion web site, companion Git repository, and companion YouTube channel for the slides.

The URL of this web site is:
- http://www.ece.uvic.ca/~mdadams/cppbook
The author has prepared video lectures for some of the material covered in these slides and the associated book.

All of the videos are hosted by YouTube and available through the author’s YouTube channel:

- https://www.youtube.com/iamcanadian1867

The most up-to-date information about this video-lecture content can be found at:

- https://www.ece.uvic.ca/~mdadams/cppbook/#video_lectures
These lecture slides have a companion Git repository.
Numerous code examples and exercises are available from this repository.
This repository is hosted by GitHub.
The URL of the main repository page on GitHub is:
  - https://github.com/mdadams/cppbook_companion
The URL of the actual repository itself is:
  - https://github.com/mdadams/cppbook_companion.git
The Software Development Environment (SDE) is a collection of tools that can be used to provide a basic up-to-date environment for C++ code development.

The SDE should work with most Linux distributions, provided that the necessary software dependencies are installed.

Amongst other things, the SDE software provides a collection of scripts for installing packages like:

- Boost, Catch2, CGAL, Clang, CMake, GCC, Gcovr, GDB, GSL, Lcov, Libcxx, TeX Live, Vim, Vim LSP, and YCM

The SDE software has a Git repository hosted by GitHub.

The URL of the main repository page on GitHub is:

- https://github.com/mdadams/sde

The URL of the actual repository itself is:

- https://github.com/mdadams/sde.git

For more information about the SDE, refer to the main repository page on GitHub.
The author has prepared a number of virtual-machine (VM) disk images that contain various versions of the Software Development Environment (SDE) mentioned on the previous slide.

These disk images are likely to be helpful to individuals who need a usable software development environment for C++ programming.

The VM disk images are available in several formats and should be usable with most popular VM hypervisor software (such as VirtualBox, VMWare Workstation Player, and GNOME Boxes).

The VM disk images can be obtained from:

- [https://ece.uvic.ca/~mdadams/cppbook/#vm_disk_images](https://ece.uvic.ca/~mdadams/cppbook/#vm_disk_images)
Part 1

Software
Why Is Software Important?

- almost all electronic devices run some software
- automobile engine control system, implantable medical devices, remote controls, office machines (e.g., photocopiers), appliances (e.g., televisions, refrigerators, washers/dryers, dishwashers, air conditioner), power tools, toys, mobile phones, media players, computers, printers, photocopies, disk drives, scanners, webcams, MRI machines
Why Software-Based Solutions?

- more cost effective to implement functionality in software than hardware
- software bugs easy to fix, give customer new software upgrade
- hardware bugs extremely costly to repair, customer sends in old device and manufacturer sends replacement
- systems increasingly complex, bugs unavoidable
- allows new features to be added later
- implement only absolute minimal functionality in hardware, do the rest in software
many more software jobs than hardware jobs
relatively small team of hardware designers produce platform like iPhone
thousands of companies develop applications for platform
only implement directly in hardware when absolutely necessary (e.g., for performance reasons)
created by Dennis Ritchie, AT&T Bell Labs in 1970s
international standard ISO/IEC 9899
available on wide range of platforms, from microcontrollers to supercomputers; very few platforms for which C compiler not available
procedural, provides language constructs that map efficiently to machine instructions
does not directly support object-oriented or generic programming
application domains: system software, device drivers, embedded applications, application software
greatly influenced development of C++
when something lasts in computer industry for more than 40 years (outliving its creator), must be good
C++

- created by Bjarne Stroustrup, Bell Labs
- originally C with Classes, renamed as C++ in 1983
- international standard ISO/IEC 14882
- procedural
- loosely speaking is superset of C
- directly supports object-oriented and generic programming
- maintains efficiency of C
- application domains: systems software, application software, device drivers, embedded software, high-performance server and client applications, entertainment software such as video games, native code for Android applications
- greatly influenced development of C# and Java
- developed in 1990s by James Gosling at Sun Microsystems (later bought by Oracle Corporation)
- de facto standard but not international standard
- usually less efficient than C and C++
- simplified memory management (with garbage collection)
- direct support for object-oriented programming
- application domains: web applications, Android applications
- designed by John Backus, IBM, in 1950s
- international standard ISO/IEC 1539-1
- application domain: scientific and engineering applications, intensive supercomputing tasks such as weather and climate modelling, finite element analysis, computational fluid dynamics, computational physics, computational chemistry
C#

- developed by Microsoft, team led by Anders Hejlsberg
- ECMA-334 and ISO/IEC 23270
- most recent language specifications not standardized by ECMA or ISO/IEC
- intellectual property concerns over Microsoft patents
- object oriented
Objective C

- developed by Tom Love and Brad Cox of Stepstone (later bought by NeXT and subsequently Apple)
- used primarily on Apple Mac OS X and iOS
- strict superset of C
- no official standard that describes Objective C
- authoritative manual on Objective-C 2.0 available from Apple
- proprietary language, developed by The MathWorks
- not general-purpose programming language
- application domain: numerical computing
- used to design and simulate systems
- not used to implement real-world systems
Why Learn C++?

- vendor neutral
- international standard
- general purpose
- powerful yet efficient
- loosely speaking, includes C as subset; so can learn two languages (C++ and C) for price of one
- easy to move from C++ to other languages but often not in other direction
- many other popular languages inspired by C++
- popular language
- consistently ranks amongst top languages in TIOBE Software Programming Community Index
  (https://www.tiobe.com/tiobe-index/)
Part 2

C++
Section 2.1

History of C++
developed by Bjarne Stroustrup starting in 1979 at Computing Science Research Center of Bell Laboratories, Murray Hill, NJ, USA

doctoral work in Computing Laboratory of University of Cambridge, Cambridge, UK

study alternatives for organization of system software for distributed systems

required development of relatively large and detailed simulator

dissertation:


in 1979, joined Bell Laboratories after having finished doctorate

work started with attempt to analyze UNIX kernel to determine to what extent it could be distributed over network of computers connected by LAN

needed way to model module structure of system and pattern of communication between modules

no suitable tools available
Objectives

- had bad experiences writing simulator during Ph.D. studies; originally used Simula for simulator; later forced to rewrite in BCPL for speed; more low level than C; BCPL was horrible to use
- notion of what properties good tool would have motivated by these experiences
- suitable tool for projects like simulator, operating system, other systems programming tasks should:
  - support for effective program organization (like in Simula) (i.e., classes, some form of class hierarchies, some form of support for concurrency, strong checking of type system based on classes)
  - produce programs that run fast (like with BCPL)
  - be able to easily combine separately compilable units into program (like with BCPL)
  - have simple linkage convention, essential for combining units written in languages such as C, Algol68, Fortran, BCPL, assembler into single program
  - allow highly portable implementations (only very limited ties to operating system)
Timeline for C with Classes (1979–1983) I

May 1979  work on C with Classes starts

Oct 1979  initial version of Cpre, preprocessor that added Simula-like classes to C; language accepted by preprocessor later started being referred to as C with Classes

Mar 1980  Cpre supported one real project and several experiments (used on about 16 systems)

Apr 1980  first internal Bell Labs paper on C with Classes published (later to appear in ACM SIGPLAN Notices in Jan. 1982)

Timeline for C with Classes (1979–1983) II

1980  initial 1980 implementation had following features:

- classes
- derived classes
- public/private access control
- constructors and destructors
- call and return functions (call function implicitly called before every call of every member function; return function implicitly called after every return from every member function; can be used for synchronization)
- friend classes
- type checking and conversion of function arguments

1981  in 1981, added:

- inline functions
- default arguments
- overloading of assignment operator

Jan 1982  first external paper on C with Classes published

Feb 1983  more detailed paper on C with Classes published


- C with Classes proved very successful; generated considerable interest
- first real application of C with Classes was network simulators
started to work on cleaned up and extended successor to C with Classes, initially called C84 and later renamed C++

Spring 1982  
started work on Cfront compiler front-end for C84;  
initially written in C with Classes and then transcribed to C84;  
traditional compiler front-end performing complete check of syntax and semantics of language, building internal representation of input, analyzing and rearranging representation, and finally producing output for some code generator;  
generated C code as output;  
difficult to bootstrap on machine without C84 compiler; Cfront software included special “half-processed” version of C code resulting from compiling Cfront, which could be compiled with native C compiler and resulting executable then used to compile Cfront
Dec 1983  C84 (C with Classes) renamed C++; name used in following paper prepared in Dec. 1983


(name C++ suggested by Rick Mascitti)

1983  virtual functions added

Note: going from C with Classes to C84 added: virtual functions, function name and operator overloading, references, constants (*const*), user-controlled free-store memory control, improved type checking

Jan 1984  first C++ manual


Sep 1984  paper describing operator overloading published

1984 stream I/O library first implemented and later presented in

Feb 1985 Cfront Release E (first external release); “E” for “Educational”; available to universities

Oct 1985 Cfront Release 1.0 (first commercial release)

Oct 1985 first edition of C++PL written


(Cfront Release 1.0 corresponded to language as defined in this book)
Oct 1985  tutorial paper on C++  

Jun 1986  Cfront Release 1.1; mainly bug fix release

Aug 1986  first exposition of set of techniques for which C++ was aiming to provide support (rather than what features are already implemented and in use)  

Sep 1986  first Object-Oriented Programming, Systems, Languages, and Applications (OOPSLA) conference (start of OO hype centered on Smalltalk)
Nov 1986  first commercial Cfront PC port (Cfront 1.1, Glockenspiel [in Ireland])
Feb 1987  Cfront Release 1.2; primarily bug fixes but also added:
  ▪ pointers to members
  ▪ protected members
Nov 1987  first conference devoted to C++:
  USENIX C++ conference (Santa Fe, NM, USA)
Dec 1987  first GNU C++ release (1.13)
Jan 1988  first Oregon Software (a.k.a. TauMetric) C++ release
Jun 1988  first Zortech C++ release
Oct 1988  first presented templates at USENIX C++ conference (Denver, CO, USA) in paper:
Timeline for C84 to C++98 (1982–1998) VI

Oct 1988  first USENIX C++ implementers workshop (Estes Park, CO, USA)

Jan 1989  first C++ journal “The C++ Report” (from SIGS publications) started publishing

Jun 1989  Cfront Release 2.0 major cleanup; new features included:

- multiple inheritance
- type-safe linkage
- better resolution of overloaded functions
- recursive definition of assignment and initialization
- better facilities for user-defined memory management
- abstract classes
- static member functions
- const member functions
- protected member functions (first provided in release 1.2)
- overloading of operator →
- pointers to members (first provided in release 1.2)

1989  main features of Cfront 2.0 summarized in
Timeline for C84 to C++98 (1982–1998) VII


first presented in


Nov 1989 paper describing exceptions published


followed up by


Dec 1989 ANSI X3J16 organizational meeting (Washington, DC, USA)

Mar 1990 first ANSI X3J16 technical meeting (Somerset, NJ, USA)
Apr 1990  Cfront Release 2.1; bug fix release to bring Cfront mostly into line with ARM

May 1990  annotated reference manual (ARM) published

May 1990  first Borland C++ release

Jul 1990  templates accepted (Seattle, WA, USA)

Nov 1990  exceptions accepted (Palo Alto, CA, USA)

Jun 1991  second edition of C++PL published

Jun 1991  first ISO WG21 meeting (Lund, Sweden)

Sep 1991  Cfront Release 3.0; added templates (as specified in ARM)
Oct 1991  estimated number of C++ users 400,000
Feb 1992  first DEC C++ release (including templates and exceptions)
Mar 1992  run-time type identification (RTTI) described in
           B. Stroustrup and D. Lenkov. Run-time type identification for
           (RTTI in C++ based on this paper)
Mar 1992  first Microsoft C++ release (did not support templates or
           exceptions)
May 1992  first IBM C++ release (including templates and exceptions)
Mar 1993  RTTI accepted (Portland, OR, USA)
Jul 1993  namespaces accepted (Munich, Germany)
1993      further work on Cfront Release 4.0 abandoned after failed
          attempt to add exception support
Aug 1994  ANSI/ISO Committee Draft registered
Aug 1994  Standard Template Library (STL) accepted (Waterloo, ON, CA); described in

Aug 1996  export accepted (Stockholm, Sweden)

1997  third edition of C++PL published

Nov 1997  final committee vote on complete standard (Morristown, NJ, USA)

Jul 1998  Microsoft releases VC++ 6.0, first Microsoft compiler to provide close-to-complete set of ISO C++

1998  Beman Dawes starts Boost (provides peer-reviewed portable C++ source libraries)

Feb 2000  special edition of C++PL published

Timeline After C++98 (1998–Present) I

Apr 2001  motion passed to request new work item: technical report on libraries (Copenhagen, Denmark); later to become ISO/IEC TR 19768:2007

Oct 2003  ISO/IEC 14882:2003 (informally known as C++03) published; essentially bug fix release; no changes to language from programmer’s point of view


2003  work on C++0x (now known as C++11) starts

Oct 2004  estimated number of C++ users 3,270,000

Apr 2005  first votes on features for C++0x (Lillehammer, Norway)

2005  auto, static_assert, and rvalue references accepted in principle

Apr 2006  first full committee (official) votes on features for C++0x (Berlin, Germany)
Sep 2006  performance technical report (TR 18015) published:


   work spurred by earlier proposal to standardize subset of C++ for embedded systems called Embedded C++ (or just EC++); EC++ motivated by performance concerns

Apr 2006  decision to move special mathematical functions to separate ISO standard (Berlin, Germany); deemed too specialized for most programmers

Nov 2007  ISO/IEC TR 19768:2007 (informally known as C++TR1) published;

specifies series of library extensions to be considered for adoption later in C++

2009 another particularly notable book on C++ published


Aug 2011 ISO/IEC 14882:2011 (informally known as C++11) ratified


2013 fourth edition of C++PL published


2014 ISO/IEC 14882:2014 (informally known as C++14) ratified

2017 ISO/IEC 14882:2017 (informally known as C++17) ratified

2020 ISO/IEC 14882:2020 (informally known as C++20) ratified
reasons for using C as starting point:
- flexibility (can be used for most application areas)
- efficiency
- availability (C compilers available for most platforms)
- portability (source code relatively portable from one platform to another)

main sources for ideas for C++ (aside from C) were Simula, Algol68, BCPL, Ada, Clu, ML; in particular:
- Simula gave classes
- Algol68 gave operator overloading, references, ability to declare variables anywhere in block
- BCPL gave // comments
- exceptions influenced by ML
- templates influenced by generics in Ada and parameterized modules in Clu
<table>
<thead>
<tr>
<th>Time</th>
<th>Estimated Number of Users</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct 1979</td>
<td>1</td>
</tr>
<tr>
<td>Oct 1980</td>
<td>16</td>
</tr>
<tr>
<td>Oct 1981</td>
<td>38</td>
</tr>
<tr>
<td>Oct 1982</td>
<td>85</td>
</tr>
<tr>
<td>Oct 1983</td>
<td>??+2 (no Cpre count)</td>
</tr>
<tr>
<td>Oct 1984</td>
<td>??+50 (no Cpre count)</td>
</tr>
<tr>
<td>Oct 1985</td>
<td>500</td>
</tr>
<tr>
<td>Oct 1986</td>
<td>2,000</td>
</tr>
<tr>
<td>Oct 1987</td>
<td>4,000</td>
</tr>
<tr>
<td>Oct 1988</td>
<td>15,000</td>
</tr>
<tr>
<td>Oct 1989</td>
<td>50,000</td>
</tr>
<tr>
<td>Oct 1990</td>
<td>150,000</td>
</tr>
<tr>
<td>Oct 1991</td>
<td>400,000</td>
</tr>
<tr>
<td>Oct 2004</td>
<td>over 3,270,000</td>
</tr>
</tbody>
</table>

- above numbers are conservative
- 1979 to 1991: C++ user population doubled approximately every 7.5 months
- stable growth thereafter
Success of C++

- C++ very successful programming language
- not luck or solely because based on C
- efficient, provides low-level access to hardware, but also supports abstraction
- non-proprietary: in 1989, all rights to language transferred to standards bodies (first ANSI and later ISO) from AT&T
- multi-paradigm language, supporting procedural, object-oriented, generic, and functional (e.g., lambda functions) programming
- does not force particular programming style
- reasonably portable
- has continued to evolve, incorporating new ideas (e.g., templates, exceptions, STL)
- stable: high degree of compatibility with earlier versions of language
- very strong bias towards providing general-purpose facilities rather than more application-specific ones
Application Areas

- banking and financial (funds transfer, financial modelling, teller machines)
- classical systems programming (compilers, operating systems, device drivers, network layers, editors, database systems)
- small business applications (inventory systems)
- desktop publishing (document viewers/editors, image editing)
- embedded systems (cameras, cell phones, airplanes, medical systems, appliances, space technologies)
- entertainment (games)
- graphics programming
- hardware design and verification
- scientific and numeric computation (physics, engineering, simulations, data analysis, geometry processing)
- servers (web servers, billing systems)
- telecommunication systems (phones, networking, monitoring, billing, operations systems)
- middleware
Section 2.1.1

References


- ISO/IEC 29124:2010 — information technology — programming languages, their environments and system software interfaces — extensions to the C++ library to support mathematical special functions, Sept. 2010.


- ISO JTC1/SC22/WG21 web site.  
Section 2.2

Getting Started
```cpp
#include <iostream>

int main() {
    std::cout << "Hello, world!\n";
    return std::cout.flush() ? 0 : 1;
}
```

- Program prints message “Hello, world!” and then exits.
- Starting point for execution of C++ program is function called `main`; every C++ program must define function called `main`.
- `#include` preprocessor directive to include complete contents of file.
- `iostream` standard header file that defines various types and variables related to I/O.
- `std::cout` is standard output stream (defaults to user’s terminal).
- `operator <<` is used for output.
Software Build Process (Without Modules)

- start with C++ source code files (.cpp, .hpp)
- compile: convert source code to object code
- object code stored in object file (.o)
- link: combine contents of one or more object files (and possibly some libraries) to produce executable program
- executable program can then be run directly
g++ command provides both compiling and linking functionality
command-line usage:

```bash
g++ [options] input_file ...
```
many command-line options are supported
some particularly useful command-line options listed on next slide
compile C++ source file `file.cpp` to produce object code file `file.o`:

```bash
g++ -c file.cpp
```
link object files `file_1.o`, `file_2.o`, ... to produce executable file `executable`:

```bash
g++ -o executable file_1.o file_2.o ...
```
web site:

```
http://www.gnu.org/software/gcc
```
C++ standards support in GCC:

```
```
Common g++ Command-Line Options

- **-c**
  - compile only (i.e., do not link)

- **-o file**
  - use file file for output

- **-g**
  - include debugging information

- **-O n**
  - set optimization level to n (0 almost none; 3 full)

- **-std=c++20**
  - conform to C++20 standard

- **-I dir**
  - specify additional directory dir to search for include files

- **-L dir**
  - specify additional directory dir to search for libraries

- **-l lib**
  - link with library lib
-pthread
  - enable concurrency support (via pthreads library)

-pedantic-errors
  - strictly enforce compliance with standard

-Wall
  - enable most warning messages

-Wextra
  - enable some extra warning messages not enabled by -Wall

-Wpedantic
  - warn about deviations from strict standard compliance

-Werror
  - treat all warnings as errors

-fno-elide-constructors
  - in contexts where standard allows (but does not require) optimization that omits creation of temporary, do not attempt to perform this optimization
-fconstexpr-loop-limit=n
  - set maximum number of iterations for loop in constexpr functions to n

-fconstexpr-depth=n
  - set maximum nested evaluation depth for constexpr functions to n
- **clang++** command provides both compiling and linking functionality
- command-line usage:
  ```
  clang++ [options] input_file ...
  ```
- many command-line options are supported
- command-line interface is largely compatible with that of GCC *g++* command
- web site:
  ```
  http://clang.llvm.org
  ```
- C++ standards support in Clang:
  ```
  http://clang.llvm.org/cxx_status.html
  ```
many of more frequently used command-line options for `clang++` identical to those for `g++`

consequently, only small number of `clang++` options given below

- `-fconstexpr-steps=n`
  - sets maximum number of computation steps in constexpr functions to $n$

- `-fconstexpr-depth=n`
  - sets maximum nested evaluation depth for constexpr functions to $n$
Manually Building *hello* Program

- numerous ways in which *hello* program could be built
- often advantageous to compile each source file separately
- can compile and link as follows:
  1. compile source code file *hello.cpp* to produce object file *hello.o*:
     ```
g++ -c hello.cpp
     ```
  2. link object file *hello.o* to produce executable program *hello*:
     ```
g++ -o hello hello.o
     ```
- generally, manual building of program is quite tedious, especially when program consists of multiple source files and additional compiler options need to be specified
- in practice, we use tools to automate build process (e.g., CMake and Make)
Section 2.3
The C++ Programming Language

- created by Bjarne Stroustrup of Bell Labs
- originally known as C with Classes; renamed as C++ in 1983
- most recent specification of language in ISO/IEC 14882:2020 (informally known as “C++20”)
- next version of standard expected in approximately 2023 (informally known as “C++23”)
- procedural
- loosely speaking is superset of C
- directly supports object-oriented and generic programming
- maintains efficiency of C
- application domains: systems software, application software, device drivers, embedded software, high-performance server and client applications, entertainment software such as video games, native code for Android applications
- greatly influenced development of C# and Java
Comments

- two styles of comments provided
- comment starts with // and proceeds to end of line
- comment starts with /* and proceeds to first */

```cpp
// This is an example of a comment.
/* This is another example of a comment. */
/* This is an example of a comment that spans multiple lines. */
```

- comments of /* ··· */ style do not nest

```cpp
/*
 /* This sentence is part of a comment. */
This sentence is not part of any comment and will probably cause a compile error.
*/
```
Identifiers

- Identifiers used to name entities such as: types, objects (i.e., variables), and functions.

- Valid identifier is sequence of one or more letters, digits, and underscore characters that does not begin with a digit. \[\text{[C++17 §5.10/1]}\]

- Identifiers that begin with underscore (in many cases) or contain double underscores are reserved for use by C++ implementation and should be avoided. \[\text{[C++17 §5.10/3]}\]

- Examples of valid identifiers:
  - `event_counter`
  - `eventCounter`
  - `sqrt_2`
  - `f_o_o_b_a_r_4_2`

- Identifiers are case sensitive (e.g., `counter` and `cOuNtEr` are distinct identifiers).

- Identifiers cannot be any of reserved keywords (see next slide).

- Scope of identifier is context in which identifier is valid (e.g., block, function, global).
Reserved Keywords

alignas  constexpr  mutable  switch
alignof  constinit  namespace  template
class   co_await  new  this
and     co_return  noexcept  throw
and_eq  continue  not  try
asm     do          or   try
auto    dynamic_cast  or_eq  typedef
default  else        private  typeid
declaytype  enum      protected  typename
char    explicit  public  virtual
char8_t  export     register  void
char16_t  extern     reinterpret_cast  volatile
char32_t  false      requires  wchar_t
class    float       return  while
class   for          short
co_await  friend     signed
co_return goto       sizeof
co_yield int         static
compl    if          static_assert
concept  inline      static_cast
const    int          struct
consteval long

*Note: context sensitive
Section 2.3.1

Preprocessor
The Preprocessor

- prior to compilation, source code transformed by preprocessor
- preprocessor output then passed to compiler for compilation
- preprocessor behavior can be controlled by preprocessor directives
- preprocessor directive occupies single line and consists of:
  1. hash character (i.e., “#”)
  2. preprocessor instruction (i.e., define, undef, include, if, ifdef, ifndef, else, elif, endif, line, error, and pragma)
  3. arguments (depending on instruction)
  4. line break

- preprocessor can be used to:
  - conditionally compile parts of source file
  - define macros and perform macro expansion
  - include other files
  - force error to be generated
Source-File Inclusion

- can include contents of another file in source using preprocessor `#include` directive
- syntax:
  - `#include <path_specifier>`
  - or
  - `#include "path_specifier"
- `path_specifier` is pathname (which may include directory) identifying file whose content is to be substituted in place of include directive
- typically, angle brackets used for system header files and double quotes used otherwise
- example:
  - `#include <iostream>
  - `#include <boost/tokenizer.hpp>
  - `#include "my_header_file.hpp"
  - `#include "some_directory/my_header_file.hpp"`
can define macros using `#define` directive

**Syntax:**

```c
#define name value
```

- `name` is the name of the macro and `value` is the value of the macro.

**Example:**

```c
#define DEBUG_LEVEL 10
```

Macros can also take arguments.

Generally, macros should be avoided when possible (i.e., when other better mechanisms are available to achieve desired effect).

For example, although macros can be used as a way to accomplish inlining of functions, such usage should be avoided since language mechanisms exist for specifying inline functions.
can conditionally include code through use of if-elif-else construct

conditional preprocessing block consists of following (in order)

1. `#if`, `#ifdef`, or `#ifndef` directive
2. optionally any number of `#elif` directives
3. at most one `#else` directive
4. `#endif` directive

code in taken branch of if-elif-else construct passed to compiler, while code in other branches discarded

example:

```c
#if DEBUG_LEVEL == 1
// ...
#elif DEBUG_LEVEL == 2
// ...
#else
// ...
#endif
```
preprocessor predicate __has_include can be used in expressions for preprocessor to test for existence of header files

example:

```c
#ifdef __has_include
#else
#endif
```
Section 2.3.2

Objects, Types, and Values
Fundamental Types

- boolean type: `bool`

- character types:
  - `char` (may be signed or unsigned)
  - `signed char`
  - `unsigned char`
  - `char8_t, char16_t, char32_t`
  - `wchar_t`

- `char` is distinct type from `signed char` and `unsigned char`

- standard signed integer types: [C++17 §6.9.1/2]
  - `signed char`
  - `signed short int`
  - `signed int`
  - `signed long int`
  - `signed long long int`

- standard unsigned integer types:
  - `unsigned char`
  - `unsigned short int`
  - `unsigned int`
  - `unsigned long int`
  - `unsigned long long int`
“int” may be omitted from names of (non-character) integer types (e.g., “unsigned” equivalent to “unsigned int” and “signed” equivalent to “signed int”)

“signed” may be omitted from names of signed integer types, excluding signed char (e.g., “int” equivalent to “signed int”)

boolean, character, and (signed and unsigned) integer types collectively called integral types

Integral types must use binary positional representation; two’s complement, one’s complement, and sign magnitude representations permitted [C++17 §6.9.1/7]

Floating-point types:
- float
- double
- long double

Void (i.e., incomplete/valueless) type: void

Null pointer type: std::nullptr_t (defined in header file cstddef)
- **literal** (a.k.a. literal constant) is value written exactly as it is meant to be interpreted

- examples of literals:

  "Hello, world"
  "Bjarne"
  'a'
  'A'
  123
  123U
  1'000'000'000
  3.1415
  1.0L
  1.23456789e-10
Character Literals

- Character literal consists of optional prefix followed by one or more characters enclosed in single quotes.
- Type of character literal determined by prefix (or lack thereof) as follows:

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Literal</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>ordinary</td>
<td>normally <code>char</code> (in special cases <code>int</code>)</td>
</tr>
<tr>
<td>u8</td>
<td>UTF-8</td>
<td><code>char8_t</code></td>
</tr>
<tr>
<td>u</td>
<td>UCS-2</td>
<td><code>char16_t</code></td>
</tr>
<tr>
<td>U</td>
<td>UCS-4</td>
<td><code>char32_t</code></td>
</tr>
<tr>
<td>L</td>
<td>wide</td>
<td><code>wchar_t</code></td>
</tr>
</tbody>
</table>

- Special characters can be represented by escape sequence:

<table>
<thead>
<tr>
<th>Character</th>
<th>Escape Sequence</th>
<th>Character</th>
<th>Escape Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>newline (LF)</td>
<td>\n</td>
<td>question mark (?)</td>
<td>?</td>
</tr>
<tr>
<td>horizontal tab (HT)</td>
<td>\t</td>
<td>single quote (’)</td>
<td>‘</td>
</tr>
<tr>
<td>vertical tab (VT)</td>
<td>\v</td>
<td>double quote (&quot;)</td>
<td>&quot;</td>
</tr>
<tr>
<td>backspace (BS)</td>
<td>\b</td>
<td>octal number ooo</td>
<td>\ooo</td>
</tr>
<tr>
<td>carriage return (CR)</td>
<td>\r</td>
<td>hex number hhh</td>
<td>\xh</td>
</tr>
<tr>
<td>form feed (FF)</td>
<td>\f</td>
<td>code point nnn</td>
<td>\unn</td>
</tr>
<tr>
<td>alert (BEL)</td>
<td>\a</td>
<td>code point nnnnnnn</td>
<td>\Unnnnnnnnn</td>
</tr>
<tr>
<td>backslash ()</td>
<td>\</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Examples of character literals:

```
'a'  'l'  '!'  '
'  u'a'  U'a'  L'a'  u8'a'
```
- decimal digit characters guaranteed to be consecutive in value (e.g., ‘1’ must equal ‘0’ + 1) \[C++17 \S5.3/3\]

- in case of ordinary character literals, alphabetic characters are not guaranteed to be consecutive in value (e.g., ‘b’ is not necessarily ‘a’ + 1)
String Literals

- (non-raw) string literal consists of optional prefix followed by zero or more characters enclosed in double quotes
- string literal has character array type
- type of string literal determined by prefix (or lack thereof) as follows:

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Literal</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>narrow</td>
<td>const char[]</td>
</tr>
<tr>
<td>u8</td>
<td>UTF-8</td>
<td>const char8_t[]</td>
</tr>
<tr>
<td>u</td>
<td>UTF-16</td>
<td>const char16_t[]</td>
</tr>
<tr>
<td>U</td>
<td>UTF-32</td>
<td>const char32_t[]</td>
</tr>
<tr>
<td>L</td>
<td>wide</td>
<td>const wchar_t[]</td>
</tr>
</tbody>
</table>

- examples of string literals:
  "Hello, World!\n"
  "123"
  "ABCDEFG"

- adjacent string literals are concatenated (e.g., "Hel" "lo" equivalent to "Hello")
- string literals implicitly terminated by null character (i.e., ‘\0’)
- so, for example, "Hi" means ‘H’ followed by ‘i’ followed by ‘\0’
Raw String Literals

- interpretation of escape sequences (e.g., “\n”) inside string literal can be avoided by using raw literal
- raw literal has form:
  - prefix \texttt{R"delimiter (raw_characters) delimiter"}
- optional \textit{prefix} is string-literal prefix (e.g., \texttt{u8})
- optional \textit{delimiter} is sequence of characters used to assist in delimiting string
- \textit{raw_characters} is sequence of characters comprising string
- escape sequences not processed inside raw literal
- raw literal can also contain newline characters
- examples of raw string literals:
  - \texttt{R"(He said, "No.")"}
  - \texttt{u8R"(He said, "No.")"}
  - \texttt{R"foo(The answer is 42.)foo"}
  - \texttt{R"((+-)?[[:digit:]]+)"}
Integer Literals

- can be specified in decimal, binary, hexadecimal, and octal
- number base indicated by prefix (or lack thereof) as follows:

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Number Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>decimal</td>
</tr>
<tr>
<td>Leading 0</td>
<td>octal</td>
</tr>
<tr>
<td>0b or 0B</td>
<td>binary</td>
</tr>
<tr>
<td>0x or 0X</td>
<td>hexadecimal</td>
</tr>
</tbody>
</table>

- various suffixes can be specified to control type of literal:
  - u or U
  - l or L
  - both u or U and l or L
  - ll or LL
  - both u or U and ll or LL

- can use single quote as digit separator (e.g., `1'000'000`)

- examples of integer literals:
  - 42
  - 1'000'000'000'000ULL
  - 0xdeadU

- integer literal always nonnegative; so, for example, \(-1\) is integer literal \(1\) with negation operation applied

[C++17 §5.13.2] [C++17 §5.13.4]
## Integer Literals (Continued)

<table>
<thead>
<tr>
<th>Suffix</th>
<th>Decimal Literal</th>
<th>Non-Decimal Literal</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>int</td>
<td>int</td>
</tr>
<tr>
<td></td>
<td>long int</td>
<td>unsigned int</td>
</tr>
<tr>
<td></td>
<td>long long int</td>
<td>long int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>unsigned long int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>long long int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>unsigned long long int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>long long int</td>
</tr>
<tr>
<td>u or U</td>
<td>unsigned int</td>
<td>unsigned int</td>
</tr>
<tr>
<td></td>
<td>unsigned long int</td>
<td>unsigned long int</td>
</tr>
<tr>
<td></td>
<td>unsigned long long int</td>
<td>unsigned long long int</td>
</tr>
<tr>
<td>l or L</td>
<td>long int</td>
<td>long int</td>
</tr>
<tr>
<td></td>
<td>long long int</td>
<td>unsigned long int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>long long int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>unsigned long long int</td>
</tr>
<tr>
<td>Both u or U</td>
<td>unsigned long int</td>
<td>unsigned long int</td>
</tr>
<tr>
<td>and l or L</td>
<td></td>
<td>unsigned long long int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>long long int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>unsigned long long int</td>
</tr>
<tr>
<td>ll or LL</td>
<td>long long int</td>
<td>long long int</td>
</tr>
<tr>
<td></td>
<td></td>
<td>unsigned long long int</td>
</tr>
<tr>
<td>Both u or U</td>
<td>unsigned long long int</td>
<td>unsigned long long int</td>
</tr>
<tr>
<td>and ll or LL</td>
<td></td>
<td>unsigned long long int</td>
</tr>
</tbody>
</table>

Floating-Point Literals

- type of literal indicated by suffix (or lack thereof) as follows:

<table>
<thead>
<tr>
<th>Suffix</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>double</td>
</tr>
<tr>
<td>f or F</td>
<td>float</td>
</tr>
<tr>
<td>l or L</td>
<td>long double</td>
</tr>
</tbody>
</table>

- examples of **double** literals:
  1. 1.414
  2. 1.25e-8

- examples of **float** literals:
  1. 1.414f
  2. 1.25e-8f

- examples of **long double** literals:
  1. 1.5L
  2. 1.25e-20L

- floating-point literals always nonnegative; so, for example, \(-1.0\) is literal 1.0 with negation operator applied.
Hexadecimal Floating-Point Literals

- hexadecimal floating-point literal has general form:
  1. prefix 0x or 0X
  2. hexadecimal digits for integer part of number (optional if at least one digit after radix point)
  3. period character (i.e., radix point)
  4. hexadecimal digits for fractional part of number (optional if at least one digit before radix point)
  5. p character (which designates exponent to follow)
  6. one or more decimal digits for base-16 exponent
  7. optional floating-point literal suffix (e.g., f or l)

- examples of hexadecimal floating-point literals:

<table>
<thead>
<tr>
<th>Literal</th>
<th>Type</th>
<th>Value (Decimal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x.8p0</td>
<td>double</td>
<td>0.5</td>
</tr>
<tr>
<td>0x10.cp0</td>
<td>double</td>
<td>16.75</td>
</tr>
<tr>
<td>0x.8p0f</td>
<td>float</td>
<td>0.5</td>
</tr>
<tr>
<td>0xf.fp0f</td>
<td>float</td>
<td>15.9375</td>
</tr>
<tr>
<td>0x1p10L</td>
<td>long double</td>
<td>1024</td>
</tr>
</tbody>
</table>
Boolean and Pointer Literals

- boolean literals:
  - `true`
  - `false`

- pointer literal:
  - `nullptr`
• **declaration** introduces identifier for type, object (i.e., variable), or function (without necessarily providing full information about identifier)
  - in case of object, specifies type (of object)
  - in case of function, specifies number of parameters, type of each parameter, and type of return value (if not automatically deduced)

• each identifier must be declared before it can be used (i.e., referenced)

• **definition** provides full information about identifier and causes entity associated with identifier (if any) to be created
  - in case of type, provides full details about type
  - in case of object, causes storage to be allocated for object and object to be created
  - in case of function, provides code for function body

• in case of objects, in most (but not all) contexts, declaring object also defines it

• can declare identifier multiple times but can define only once

• above terminology often abused, with “declaration” and “definition” being used interchangeably
Examples of Declarations and Definitions

```c
int count; // declare and define count
extern double alpha; // (only) declare alpha

void func() { // declare and define func
    int n; // declare and define n
    double x = 1.0; // declare and define x
    // ...
}

bool isOdd(int); // declare isOdd
bool isOdd(int x); // declare isOdd (x ignored)

bool isOdd(int x) { // declare and define isOdd
    return x % 2;
}

struct Thing; // declare Thing

struct Vector2 { // declare and define Vector2
    double x;
    double y;
};
```
variable declaration (a.k.a. object declaration) introduces identifier that names object and specifies type of object.

variable definition (a.k.a. object definition) provides all information included in variable declaration and also causes object to be created (e.g., storage allocated for object).

Example:

```cpp
int count;
    // declare and define count
double alpha;
    // declare and define alpha
extern double gamma;
    // declare (but do not define) gamma
```
**Arrays**

- **array** is collection of one or more objects of **same** type that are stored **contiguously** in memory.
- Each element in array identified by (unique) integer index, with indices starting from **zero**.
- Array denoted by `[]`.
- Example:
  ```
  double x[10]; // array of 10 doubles
  int data[512][512]; // 512 by 512 array of ints
  ```
- Elements of array accessed using subscripting operator `[]`.
- Example:
  ```
  int x[10];
  // elements of arrays are x[0], x[1], ..., x[9]
  ```
- Often preferable to use user-defined type for representing array instead of array type.
- For example, `std::array` and `std::vector` types (to be discussed later) have numerous practical advantages over array types.
Array Example

- **code:**

  ```
  int a[4] = {1, 2, 3, 4};
  ```

- **assumptions (for some completely fictitious C++ language implementation):**
  - `sizeof(int)` is 4
  - array `a` starts at address 1000

- **memory layout:**

<table>
<thead>
<tr>
<th>Address</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>1</td>
</tr>
<tr>
<td>1004</td>
<td>2</td>
</tr>
<tr>
<td>1008</td>
<td>3</td>
</tr>
<tr>
<td>1012</td>
<td>4</td>
</tr>
</tbody>
</table>
**Pointers**

- **pointer** is object whose value is address in memory where another object is stored
- Pointer to object of type $T$ denoted by $T^*$
- **null pointer** is special pointer value that does not refer to any valid memory location
- Null pointer value provided by `nullptr` keyword
- Accessing object to which pointer refers called **dereferencing**
- Dereferencing pointer performed by *indirection operator* (i.e., “*”)
- If $p$ is pointer, $*p$ is object to which pointer refers
- If $x$ is object of type $T$, $&x$ is (normally) address of object, which has type $T^*$
- Example:

```cpp
char c;
char* cp = nullptr; // cp is pointer to char
char* cp2 = &c; // cp2 is pointer to char
```
code:

```c
int i = 42;
int* p = &i;
assert(*p == 42);
```

assumptions (for some completely fictitious C++ language implementation):

- `sizeof(int)` is 4
- `sizeof(int*)` is 4
- `&i` is `((int*)1000)`
- `&p` is `((int*)1004)`

memory layout:

<table>
<thead>
<tr>
<th>Address</th>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>i</td>
<td>42</td>
</tr>
<tr>
<td>1004</td>
<td>p</td>
<td>1000</td>
</tr>
</tbody>
</table>
- **reference** is alias (i.e., nickname) for *already existing* object
- two kinds of references:
  1. lvalue reference
  2. rvalue reference
- lvalue reference to object of type \( T \) denoted by \( T\& \)
- rvalue reference to object of type \( T \) denoted by \( T&& \)
- initializing reference called **reference binding**
- lvalue and rvalue references differ in their binding properties (i.e., to what kinds of objects reference can be bound)
- in most contexts, lvalue references usually needed
- rvalue references used in context of move constructors and move assignment operators (to be discussed later)
- example:

```cpp
int x;
int& y = x; // y is lvalue reference to int
int&& tmp = 3; // tmp is rvalue reference to int
```
References Example

- code:

```c
int i = 42;
int& j = i;
assert(j == 42);
```

- assumptions (for some completely fictitious C++ language implementation):
  - `sizeof(int)` is 4
  - `&i` is `((int*)1000)`

- memory layout:

<table>
<thead>
<tr>
<th>Address</th>
<th>Name</th>
<th>Address</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>42</td>
<td>i, j</td>
<td></td>
</tr>
</tbody>
</table>
References Versus Pointers

- references and pointers similar in that both can be used to refer to some other entity (e.g., object or function)

- two key differences between references and pointers:
  1. reference must refer to something, while pointer can have null value (`nullptr`)
  2. references cannot be rebound, while pointers can be changed to point to different entity

- references have cleaner syntax than pointers, since pointers must be dereferenced upon each use (and dereference operations tend to clutter code)

- use of pointers often implies need for memory management (i.e., memory allocation, deallocation, etc.), and memory management can introduce numerous kinds of bugs when done incorrectly

- often faced with decision of using pointer or reference in code

- generally advisable to prefer use of references over use of pointers unless compelling reason to do otherwise, such as:
  - must be able to handle case of referring to nothing
  - must be able to change entity being referenced
Unscoped Enumerations

- **enumerated type** provides way to describe range of values that are represented by named constants called **enumerators**
- object of enumerated type can take any one of enumerators as value
- enumerator values represented by some **integral type**
- enumerator can be assigned specific value (which may be negative)
- if enumerator not assigned specific value, value defaults to zero if first enumerator in enumeration and one greater than value for previous enumerator otherwise

**example:**

```cpp
enum Suit {
    Clubs, Diamonds, Hearts, Spades
};

Suit suit = Clubs;
```

**example:**

```cpp
enum Suit {
    Clubs = 1, Diamonds = 2, Hearts = 4, Spades = 8
};
```
Scoped Enumerations

- scoped enumeration similar to unscoped enumeration, except:
  - all enumerators are placed in scope of enumeration itself
  - integral type used to hold enumerator values can be explicitly specified
  - conversions involving scoped enumerations are stricter (i.e., more type safe)

- **class** or **struct** added after **enum** keyword to make enumeration scoped

- scope resolution operator (i.e., “::”) used to access enumerators

- scoped enumerations should probably be preferred to unscoped ones

- example:

  ```
  enum struct Season {
    spring, summer, fall, winter
  };

  enum struct Suit : unsigned char {
    clubs, diamonds, hearts, spades
  };

  Season season = Season::summer;
  Suit suit = Suit::spades;
  ```
**typedef** keyword used to create alias for existing type

example:

```cpp
typedef long long BigInt;
BigInt i; // i has type long long

typedef char* CharPtr;
CharPtr p; // p has type char*
```
**Type Aliases with using Statement**

- `using` statement can be used to create alias for existing type
- probably preferable to use `using` statement over `typedef`
- example:

  ```cpp
  using BigInt = long long;
  BigInt i; // i has type long long

  using CharPtr = char*;
  CharPtr p; // p has type char*
  ```
**The `extern` Keyword**

- **translation unit**: basic unit of compilation in C++ (i.e., single source code file plus all of its directly and indirectly included header files)
- **extern** keyword used to declare object/function in separate translation unit
- example:

  ```
  extern int evil_global_variable;
  // declaration only
  // actual definition in another file
  ```
The `const` Qualifier

- `const` qualifier specifies that object has value that is *constant* (i.e., cannot be changed)
- qualifier that applies to object itself said to be *top level*
- following defines `x` as `int` with value 42 that cannot be modified:
  ```
  const int x = 42;
  ```
- example:
  ```
  const int x = 42;
  x = 13; // ERROR: x is const
  const int& x1 = x; // OK
  const int* p1 = &x; // OK
  int& x2 = x; // ERROR: x const, x2 not const
  int* p2 = &x; // ERROR: x const, *p2 not const
  ```
- example:
  ```
  int x = 0;
  const int& y = x;
  x = 42; // OK
  // y also changed to 42 since y refers to x
  // y cannot be used to change x, however
  // i.e., the following would cause compile error:
  // y = 24; // ERROR: y is const
with types that are not pointer or reference types, `const` can only be applied to object itself (i.e., top level)

that is, object itself may be const or non-const

e.g.,

```cpp
int i = 0; // object i is modifiable
i = 42; // OK: i can be modified
const int ci = 0; // object ci is not modifiable
ci = 42; // ERROR: ci cannot be modified
```
Example: `const` Qualifier and Non-Pointer/Non-Reference Types

```cpp
// with types that are not pointer or reference types, const
// can only be applied to object itself (i.e., top level)
// object itself may be const or non-const

int i = 0; // non-const int object
const int ci = 0; // const int object

i = 42; // OK: can modify non-const object
ci = 42; // ERROR: cannot modify const object

i = ci; // OK: can modify non-const object
ci = i; // ERROR: cannot modify const object
```
The `const` Qualifier and Pointer Types

- every pointer is associated with two objects: pointer itself and pointee (i.e., object to which pointer points)
- `const` qualifier can be applied to each of pointer (i.e., top-level qualifier) and pointee

```c
int i = 42; // pointee

// p is pointer to int i
// for example:
// int* p = &i;
// const int* p = &i;
// int* const p = &i;
// const int* const p = &i;
```

Address

```
1000 (&p)  
    .     
    .     

2000 (&i)  
    .     
    .     
```

Example: `const` Qualifier and Pointer Types

```c
// with pointer types, const can be applied to each of:
//    pointer and pointee
// pointer itself may be const or non-const (top-level)
// pointee may be const or non-const

int i = 0;
int j = 0;

int* pi = &i; // non-const pointer to a non-const int
pi = &j; // OK: can modify non-const pointer
*pi = 42; // OK: can modify non-const pointee

const int* pci = &i; // non-const pointer to a const int
// equivalently: int const* pci = &i;
pci = &j; // OK: can modify non-const pointer
*pcci = 42; // ERROR: cannot modify const pointee

int* const cpi = &i; // const pointer to a non-const int
cpi = &j; // ERROR: cannot modify const pointer
*cpi = 42; // OK: can modify non-const pointee

const int* const cpci = &i; // const pointer to a const int
// equivalently: int const* const cpci = &i;
cpci = &j; // ERROR: cannot modify const pointer
*cpci = 42; // ERROR: cannot modify const pointee

pci = pi; // OK: adds const to pointee
pi = pci; // ERROR: discards const from pointee
```
The `const` Qualifier and Reference Types

- reference is name that refers to object (i.e., referee)
- in principle, `const` qualifier can be applied to reference itself (i.e., top-level qualifier) or referee
- since reference cannot be rebound, reference itself is effectively always constant
- for this reason, does not make sense to explicitly apply `const` as top-level qualifier for reference type and language disallows this
- `const` qualifier can only be applied to referee
- example:

```cpp
int j = 0;
int k = 42;
int& i = j;
// i is reference; j is referee
// referee is modifiable
const int& ci = j;
// ci is reference; j is referee
// referee is not modifiable
const int& ci = k; // ERROR: cannot redefine/rebind
int& const r = j;
// ERROR: reference itself cannot be specified as const
```
Example: `const` Qualifier and Reference Types

```c++
// with reference types, const can only be applied to referee
// reference itself cannot be rebound (i.e., is constant)
// referee may be const or non-const

int i = 0; const int ci = 0;
int i1 = 0; const int ci1 = 0;

// reference to non-const int
int& ri = i;
ri = ci; // OK: can modify non-const referee
int& ri = i1; // ERROR: cannot redefine/rebind reference

// reference to const int
const int& rci = ci;
rci = i; // ERROR: cannot modify const referee
const int& rci = ci1;
    // ERROR: cannot redefine/rebind reference

    // ERROR: reference itself cannot be const qualified
int& const cri = i; // ERROR: invalid const qualifier

    // ERROR: reference itself cannot be const qualified
const int& const crci = ci; // ERROR: invalid const qualifier
    // also: int const& const crci = ci; // ERROR

const int& r1 = ci; // OK: adds const to referee
int& r2 = ci; // ERROR: discards const from referee
```
The \texttt{const} Qualifier and Pointer-to-Pointer Types

- for given type $T$, cannot implicitly convert $T**$ to \texttt{const} $T**$
- although such conversion looks okay at first glance, actually would create backdoor for changing const objects
- can, however, implicitly convert $T**$ to \texttt{const} $T* \texttt{const}*$
- for example, code like that shown below could be used to change const objects if $T**$ to \texttt{const} $T**$ were valid conversion:

```c
const int i = 42;
int* p;
const int** q = &p;
    // Fortunately, this line is not valid code.
    // ERROR: cannot convert int** to const int**
*q = &i;
    // Change p (to which q points) to point to i.
    // OK: *q is not const (only **q is const)
*p = 0;
    // Set i (to which p points) to 0.
    // OK: *p is not const
    // This line would change i, which is const.
```
The `volatile` Qualifier

- **volatile** qualifier used to indicate that object can change due to agent external to program (e.g., memory-mapped device, signal handler)
- Compiler cannot optimize away read and write operations on **volatile** objects (e.g., repeated reads without intervening writes cannot be optimized away)
- **volatile** qualifier typically used when object:
  - corresponds to register of memory-mapped device
  - may be modified by signal handler (namely, object of type `volatile std::sig_atomic_t`)
- Example:
  ```cpp
  volatile int x;
  volatile unsigned char* deviceStatus;
  ```
in various contexts, `auto` keyword can be used as placeholder for type

in such contexts, implication is that compiler must deduce type

example:

```cpp
auto i = 3; // i has type int
auto j = i; // j has type int
auto& k = i; // k has type int&
const auto& n = i; // n has type const int&
auto x = 3.14; // x has type double
```

very useful in generic programming (covered later) when types not always easy to determine

- can potentially save typing long type names
- can lead to more readable code (if well used)
- if overused, can lead to bugs (sometimes very subtle ones) and difficult to read code
**Inline Variables**

- **inline variable**: variable that may be defined in multiple translation units as long as all definitions are identical.
- Potential for multiple definitions avoided by having linker simply choose one of identical definitions and discard others (if more than one exists).
- Can request that variable be made inline by including `inline` qualifier in variable declaration.
- Inline variable must have static storage duration (e.g., static class member or namespace-scope variable).
- Inline variable typically used to allow definition of variable to be placed in header file without danger of multiple definitions.
- Inline variable has same address in all translation units.
inline_variable_1_1.hpp

```cpp
inline int magic = 42;
```

main.cpp

```cpp
#include <iostream>

#include "inline_variable_1_1.hpp"

int main() {
    std::cout << magic << "\n";
}
```

other.cpp

```cpp
#include "inline_variable_1_1.hpp"

void func() {/* ... */}
```
Section 2.3.3

Operators and Expressions
### Arithmetic Operators

<table>
<thead>
<tr>
<th>Operator Name</th>
<th>Syntax</th>
</tr>
</thead>
<tbody>
<tr>
<td>addition</td>
<td>a + b</td>
</tr>
<tr>
<td>subtraction</td>
<td>a - b</td>
</tr>
<tr>
<td>unary plus</td>
<td>+a</td>
</tr>
<tr>
<td>unary minus</td>
<td>-a</td>
</tr>
<tr>
<td>multiplication</td>
<td>a * b</td>
</tr>
<tr>
<td>division</td>
<td>a / b</td>
</tr>
<tr>
<td>modulo (i.e., remainder)</td>
<td>a % b</td>
</tr>
<tr>
<td>pre-increment</td>
<td>++a</td>
</tr>
<tr>
<td>post-increment</td>
<td>a++</td>
</tr>
<tr>
<td>pre-decrement</td>
<td>--a</td>
</tr>
<tr>
<td>post-decrement</td>
<td>a--</td>
</tr>
</tbody>
</table>

### Bitwise Operators

<table>
<thead>
<tr>
<th>Operator Name</th>
<th>Syntax</th>
</tr>
</thead>
<tbody>
<tr>
<td>bitwise NOT</td>
<td>~a</td>
</tr>
<tr>
<td>bitwise AND</td>
<td>a &amp; b</td>
</tr>
<tr>
<td>bitwise OR</td>
<td>a</td>
</tr>
<tr>
<td>bitwise XOR</td>
<td>a ^ b</td>
</tr>
<tr>
<td>arithmetic left shift</td>
<td>a &lt;&lt; b</td>
</tr>
<tr>
<td>arithmetic right shift</td>
<td>a &gt;&gt; b</td>
</tr>
</tbody>
</table>
### Assignment and Compound-Assignment Operators

<table>
<thead>
<tr>
<th>Operator Name</th>
<th>Syntax</th>
</tr>
</thead>
<tbody>
<tr>
<td>assignment</td>
<td><code>a = b</code></td>
</tr>
<tr>
<td>addition assignment</td>
<td><code>a += b</code></td>
</tr>
<tr>
<td>subtraction assignment</td>
<td><code>a -= b</code></td>
</tr>
<tr>
<td>multiplication assignment</td>
<td><code>a *= b</code></td>
</tr>
<tr>
<td>division assignment</td>
<td><code>a /= b</code></td>
</tr>
<tr>
<td>modulo assignment</td>
<td><code>a %= b</code></td>
</tr>
<tr>
<td>bitwise AND assignment</td>
<td><code>a &amp; b</code></td>
</tr>
<tr>
<td>bitwise OR assignment</td>
<td>`a</td>
</tr>
<tr>
<td>bitwise XOR assignment</td>
<td><code>a ^= b</code></td>
</tr>
<tr>
<td>arithmetic left shift assignment</td>
<td><code>a &lt;&lt;= b</code></td>
</tr>
<tr>
<td>arithmetic right shift assignment</td>
<td><code>a &gt;&gt;= b</code></td>
</tr>
</tbody>
</table>
## Logical/Relational Operators

<table>
<thead>
<tr>
<th>Operator Name</th>
<th>Syntax</th>
</tr>
</thead>
<tbody>
<tr>
<td>three-way comparison</td>
<td>a &lt;=&gt; b</td>
</tr>
<tr>
<td>equal</td>
<td>a == b</td>
</tr>
<tr>
<td>not equal</td>
<td>a != b</td>
</tr>
<tr>
<td>greater than</td>
<td>a &gt; b</td>
</tr>
<tr>
<td>less than</td>
<td>a &lt; b</td>
</tr>
<tr>
<td>greater than or equal</td>
<td>a &gt;= b</td>
</tr>
<tr>
<td>less than or equal</td>
<td>a &lt;= b</td>
</tr>
<tr>
<td>logical negation</td>
<td>!a</td>
</tr>
<tr>
<td>logical AND</td>
<td>a &amp;&amp; b</td>
</tr>
<tr>
<td>logical OR</td>
<td>a</td>
</tr>
</tbody>
</table>

## Member and Pointer Operators

<table>
<thead>
<tr>
<th>Operator Name</th>
<th>Syntax</th>
</tr>
</thead>
<tbody>
<tr>
<td>array subscript</td>
<td>a[b]</td>
</tr>
<tr>
<td>indirection</td>
<td>*a</td>
</tr>
<tr>
<td>address of</td>
<td>&amp;a</td>
</tr>
<tr>
<td>member selection</td>
<td>a.b</td>
</tr>
<tr>
<td>member selection</td>
<td>a-*b</td>
</tr>
<tr>
<td>member selection</td>
<td>a-&gt;b</td>
</tr>
<tr>
<td>member selection</td>
<td>a-&gt;*b</td>
</tr>
</tbody>
</table>
### Other Operators

<table>
<thead>
<tr>
<th>Operator Name</th>
<th>Syntax</th>
</tr>
</thead>
<tbody>
<tr>
<td>function call</td>
<td>a(...)</td>
</tr>
<tr>
<td>comma</td>
<td>a, b</td>
</tr>
<tr>
<td>ternary conditional</td>
<td>a ? b : c</td>
</tr>
<tr>
<td>scope resolution</td>
<td>a::b</td>
</tr>
<tr>
<td>sizeof</td>
<td>sizeof(a)</td>
</tr>
<tr>
<td>parameter-pack sizeof</td>
<td>sizeof...(a)</td>
</tr>
<tr>
<td>alignof</td>
<td>alignof(T)</td>
</tr>
<tr>
<td>allocate storage</td>
<td>new T</td>
</tr>
<tr>
<td>allocate storage (array)</td>
<td>new T[a]</td>
</tr>
<tr>
<td>deallocate storage</td>
<td>delete a</td>
</tr>
<tr>
<td>deallocate storage (array)</td>
<td>delete[] a</td>
</tr>
</tbody>
</table>
Other Operators (Continued)

<table>
<thead>
<tr>
<th>Operator Name</th>
<th>Syntax</th>
</tr>
</thead>
<tbody>
<tr>
<td>type ID</td>
<td><code>typeid(a)</code></td>
</tr>
<tr>
<td>type cast</td>
<td><code>(T) a</code></td>
</tr>
<tr>
<td>const cast</td>
<td><code>const_cast&lt;T&gt;(a)</code></td>
</tr>
<tr>
<td>static cast</td>
<td><code>static_cast&lt;T&gt;(a)</code></td>
</tr>
<tr>
<td>dynamic cast</td>
<td><code>dynamic_cast&lt;T&gt;(a)</code></td>
</tr>
<tr>
<td>reinterpret cast</td>
<td><code>reinterpret_cast&lt;T&gt;(a)</code></td>
</tr>
<tr>
<td>throw</td>
<td><code>throw a</code></td>
</tr>
<tr>
<td>noexcept</td>
<td><code>noexcept(e)</code></td>
</tr>
<tr>
<td>await</td>
<td><code>co_await e</code></td>
</tr>
<tr>
<td>yield</td>
<td><code>co_yield e</code></td>
</tr>
</tbody>
</table>
## Operator Precedence

<table>
<thead>
<tr>
<th>Precedence</th>
<th>Operator</th>
<th>Name</th>
<th>Associativity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>::</td>
<td>scope resolution</td>
<td>none</td>
</tr>
<tr>
<td>2</td>
<td>.</td>
<td>member selection (object)</td>
<td>left to right</td>
</tr>
<tr>
<td></td>
<td>-&gt;</td>
<td>member selection (pointer)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[]</td>
<td>subscripting</td>
<td></td>
</tr>
<tr>
<td></td>
<td>()</td>
<td>function call</td>
<td></td>
</tr>
<tr>
<td></td>
<td>++</td>
<td>post-increment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>--</td>
<td>post-decrement</td>
<td></td>
</tr>
<tr>
<td>Precedence</td>
<td>Operator</td>
<td>Name</td>
<td>Associativity</td>
</tr>
<tr>
<td>------------</td>
<td>----------</td>
<td>-------------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>3</td>
<td><code>sizeof</code></td>
<td>size of object/type</td>
<td>right to left</td>
</tr>
<tr>
<td></td>
<td><code>++</code></td>
<td>pre-increment</td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>--</code></td>
<td>pre-decrement</td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>~</code></td>
<td>bitwise NOT</td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>!</code></td>
<td>logical NOT</td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>-</code></td>
<td>unary minus</td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>+</code></td>
<td>unary plus</td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>&amp;</code></td>
<td>address of</td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>*</code></td>
<td>indirection</td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>co_await</code></td>
<td>await</td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>new</code></td>
<td>allocate storage</td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>new[]</code></td>
<td>allocate storage (array)</td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>delete</code></td>
<td>deallocate storage</td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>delete[]</code></td>
<td>deallocate storage (array)</td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>()</code></td>
<td>cast</td>
<td></td>
</tr>
<tr>
<td>Precedence</td>
<td>Operator</td>
<td>Name</td>
<td>Associativity</td>
</tr>
<tr>
<td>------------</td>
<td>----------</td>
<td>-------------------------------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>4</td>
<td>.*</td>
<td>member selection (objects)</td>
<td>left to right</td>
</tr>
<tr>
<td></td>
<td></td>
<td>member selection (pointers)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>*</td>
<td>multiplication</td>
<td>left to right</td>
</tr>
<tr>
<td></td>
<td>/</td>
<td>division</td>
<td></td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>modulus</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>+</td>
<td>addition</td>
<td>left to right</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>subtraction</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>&lt;&lt;</td>
<td>left shift</td>
<td>left to right</td>
</tr>
<tr>
<td></td>
<td>&gt;&gt;</td>
<td>right shift</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>&lt;=&gt;</td>
<td>three-way comparison</td>
<td>left to right</td>
</tr>
<tr>
<td>9</td>
<td>&lt;</td>
<td>less than</td>
<td>left to right</td>
</tr>
<tr>
<td></td>
<td>&lt;=</td>
<td>less than or equal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;</td>
<td>greater than</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;=</td>
<td>greater than or equal</td>
<td></td>
</tr>
<tr>
<td>Precedence</td>
<td>Operator</td>
<td>Name</td>
<td>Associativity</td>
</tr>
<tr>
<td>------------</td>
<td>----------</td>
<td>---------------</td>
<td>---------------</td>
</tr>
<tr>
<td>10</td>
<td>==</td>
<td>equality</td>
<td>left to right</td>
</tr>
<tr>
<td></td>
<td>!=</td>
<td>inequality</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>&amp;</td>
<td>bitwise AND</td>
<td>left to right</td>
</tr>
<tr>
<td>12</td>
<td>^</td>
<td>bitwise XOR</td>
<td>left to right</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
<td>bitwise OR</td>
</tr>
<tr>
<td>14</td>
<td>&amp;&amp;</td>
<td>logical AND</td>
<td>left to right</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precedence</td>
<td>Operator</td>
<td>Name</td>
<td>Associativity</td>
</tr>
<tr>
<td>------------</td>
<td>----------</td>
<td>-----------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>16</td>
<td>? :</td>
<td>ternary conditional</td>
<td>right to left</td>
</tr>
<tr>
<td></td>
<td>throw</td>
<td>throw</td>
<td></td>
</tr>
<tr>
<td></td>
<td>co_yield</td>
<td>yield</td>
<td></td>
</tr>
<tr>
<td></td>
<td>=</td>
<td>assignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>*=</td>
<td>multiplication assignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>/=</td>
<td>division assignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>%=</td>
<td>modulus assignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+=</td>
<td>addition assignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-=</td>
<td>subtraction assignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;&lt;=</td>
<td>left shift assignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;&gt;=</td>
<td>right shift assignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&amp;=</td>
<td>bitwise AND assignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>=</td>
<td>bitwise OR assignment</td>
</tr>
<tr>
<td></td>
<td>^=</td>
<td>bitwise XOR assignment</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>,</td>
<td>comma</td>
<td>left to right</td>
</tr>
</tbody>
</table>
Alternative Tokens

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Primary</th>
</tr>
</thead>
<tbody>
<tr>
<td>and</td>
<td>&amp;&amp;</td>
</tr>
<tr>
<td>bitor</td>
<td></td>
</tr>
<tr>
<td>or</td>
<td></td>
</tr>
<tr>
<td>xor</td>
<td>^</td>
</tr>
<tr>
<td>compl</td>
<td>~</td>
</tr>
<tr>
<td>bitand</td>
<td>&amp;</td>
</tr>
<tr>
<td>and_eq</td>
<td>&amp;=</td>
</tr>
<tr>
<td>or_eq</td>
<td></td>
</tr>
<tr>
<td>xor_eq</td>
<td>^=</td>
</tr>
<tr>
<td>not</td>
<td>!</td>
</tr>
<tr>
<td>not_eq</td>
<td>!=</td>
</tr>
</tbody>
</table>

Alternative tokens above probably best avoided as they lead to more verbose code.
Expressions

- An **expression** is a sequence of operators and operands that specifies a computation. [C++17 §8/1]
- An expression has a type and, if the type is not **void**, a value. [C++17 §6.9.1/9]
- A **constant expression** is an expression that can be evaluated at compile time (e.g., 1 + 1).
- Example:

```c++
int x = 0;
int y = 0;
int* p = &x;
double d = 0.0;
// Evaluate some
// expressions here.
```

<table>
<thead>
<tr>
<th>Expression</th>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>int</td>
<td>0</td>
</tr>
<tr>
<td>y = x</td>
<td>int</td>
<td>reference to y</td>
</tr>
<tr>
<td>x + 1</td>
<td>int</td>
<td>1</td>
</tr>
<tr>
<td>x * x + 2 * x</td>
<td>int</td>
<td>0</td>
</tr>
<tr>
<td>y = x * x</td>
<td>int&amp;</td>
<td>reference to y</td>
</tr>
<tr>
<td>x == 42</td>
<td>bool</td>
<td>false</td>
</tr>
<tr>
<td>*p</td>
<td>int&amp;</td>
<td>reference to x</td>
</tr>
<tr>
<td>p == &amp;x</td>
<td>bool</td>
<td>true</td>
</tr>
<tr>
<td>x &gt; 2 * y</td>
<td>bool</td>
<td>false</td>
</tr>
<tr>
<td>std::sin(d)</td>
<td>double</td>
<td>0.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Expression</th>
<th>Fully-Parenthesized Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>a + b + c</td>
<td>((a + b) + c)</td>
</tr>
<tr>
<td>a = b = c</td>
<td>(a = (b = c))</td>
</tr>
<tr>
<td>c = a + b</td>
<td>(c = (a + b))</td>
</tr>
<tr>
<td>d = a &amp;&amp; !b</td>
<td></td>
</tr>
<tr>
<td>++*p++</td>
<td>(++(*(p++)))</td>
</tr>
<tr>
<td>a</td>
<td>~b &amp; c ^ d</td>
</tr>
<tr>
<td>a[0]++ + a[1]++</td>
<td>(((a[0])++) + ((a[1])++))</td>
</tr>
<tr>
<td>a + b * c / d % - g</td>
<td>(a + (((b * c) / d) % (-g)))</td>
</tr>
<tr>
<td>++p[i]</td>
<td>(++(p[i]))</td>
</tr>
<tr>
<td>--*++p</td>
<td>(--(*(++p)))</td>
</tr>
<tr>
<td>a += b += c += d</td>
<td>(a += (b += (c += d)))</td>
</tr>
<tr>
<td>z = a == b ? ++c : --d</td>
<td>(z = (((a == b) ? (++c) : (--d)))</td>
</tr>
<tr>
<td>a + b &lt;=&gt; c + d &gt; 0</td>
<td>(((a + b) &lt;=&gt; (c + d)) &gt; 0</td>
</tr>
</tbody>
</table>
for integral operands, division operator yields algebraic quotient with any fractional part discarded (i.e., round towards zero)

if quotient $a \div b$ is representable in type of result, 
$(a \div b) \times b + a \% b$ is equal to $a$

so, assuming $b$ is not zero and no overflow, $a \% b$ equals $a - (a \div b) \times b$

result of modulus operator not necessarily nonnegative

element:

```cpp
1 static_assert(5 % 3 == 2);
2 static_assert(5 % (-3) == 2);
3 static_assert((-5) % 3 == -2);
4 static_assert((-5) % (-3) == -2);
```
Short-Circuit Evaluation

- **logical-and operator (i.e., &&):**
  - groups left-to-right
  - result true if both operands are true, and false otherwise
  - second operand is *not evaluated* if first operand is false (in case of built-in logical-and operator)

- **logical-or operator (i.e., ||):**
  - groups left-to-right
  - result is true if either operand is true, and false otherwise
  - second operand is *not evaluated* if first operand is true (in case of built-in logical-or operator)

- **example:**
  ```cpp
  int x = 0;
  bool b = (x == 0 || ++x == 1);
  // b equals true; x equals 0
  b = (x != 0 && ++x == 1);
  // b equals false; x equals 0
  ```

- above behavior referred to as short circuit evaluation
for three values \(a, b, c\) of type \texttt{bool}, consider evaluation of expression \(a \text{ || } b \text{ || } c\)

code showing short-circuit evaluation and associated control-flow graph given below

```cpp
bool _result;
if (a)
    goto _true;
if (b)
    goto _true;
if (c)
    goto _true;
_result = \texttt{false};
goto done;
_true:
_result = \texttt{true};
done:
```

```
\begin{itemize}
    
   \item[\texttt{True}] \hspace{2cm} \texttt{F} \\
   \item[\texttt{False}] \hspace{2cm} \texttt{T} \\
\end{itemize}
```
for three values $a$, $b$, $c$ of type `bool`, consider evaluation of expression $a \land b \land c$

code showing short-circuit evaluation and associated control-flow graph given below

```cpp
bool _result;
if (!a)
    goto _false;
if (!b)
    goto _false;
if (!c)
    goto _false;
_result = true;
goto done;

_false:
_result = false;
done:
```

![Control-Flow Graph](image-url)
for three values $a$, $b$, $c$ of type `bool`, consider evaluation of expression

$$(a \lor b) \land c$$

code showing short-circuit evaluation and associated control-flow graph
given below (example of compiler-generated assembly code)

```c
bool _result;
if (a)
    goto _second;
if (!b)
    goto _false;
_second:
if (!c)
    goto _false;
_result = true;
goto done;
_false:
_result = false;
done:
```
**static_assert** allows testing of boolean condition at compile time

- used to test sanity of code or test validity of assumptions made by code

**static_assert** has two arguments:

1. boolean constant expression (condition to test)
2. string literal for error message to print if boolean expression not true

- second argument is optional

- failed static assertion results in compile error

- example:

```cpp
static_assert(sizeof(int) >= 4, "int is too small");
static_assert(1 + 1 == 2, "compiler is buggy");
```
The `sizeof` Operator

- `sizeof` operator is used to query size of object or object type (i.e., amount of storage required)
- for object type `T`, `sizeof(T)` yields size of `T` in bytes (e.g., `sizeof(int), sizeof(int[10])`)
- for expression `e`, `sizeof e` yields size of object required to hold result of `e` in bytes (e.g., `sizeof(&x)` where `x` is some object)
- `sizeof(char), sizeof(signed char), and sizeof(unsigned char)` guaranteed to be 1
- byte is at least 8 bits (usually exactly 8 bits except on more exotic platforms)
**The constexpr Qualifier for Variables**

- **constexpr** qualifier indicates object has value that is *constant expression* (i.e., can be evaluated at compile time)
- **constexpr** implies **const** (but converse not necessarily true)
- following defines `x` as constant expression with type **const int** and value 42:

  ```cpp
  constexpr int x = 42;
  ```
- example:

  ```cpp
  constexpr int x = 42;
  int y = 1;
  x = 0; // ERROR: x is const
  const int& x1 = x; // OK
  const int* p1 = &x; // OK
  int& x2 = x; // ERROR: x const, x2 not const
  int* p2 = &x; // ERROR: x const, *p2 not const
  int a1[x]; // OK: x is constexpr
  int a2[y]; // ERROR: y is not constexpr
  ```
The `constinit` Specifier

- `constinit` specifier can be added to variable declaration to assert that variable must be statically initialized.
- Can be used for variable with static or thread-local storage duration.
- If `constinit` used for variable that is not statically initialized, compiler error will result.
- `constinit` variable not implicitly `const`.
- Cannot use `constexpr` qualifier with `constinit` (as `constexpr` makes `constinit` redundant).
- Can be used in non-initializing declaration to indicate that variable is statically initialized.
- Example:
  ```cpp
  constexpr double func(double);
  constinit double x = func(42.0);
  // error if x not statically initialized
  ```
- Example:
  ```cpp
  extern thread_local constinit int x;
  int f() {
    return x;
    // no check of guard variable needed
  }
  ```
Section 2.3.4

Control-Flow Constructs: Selection and Looping
The if Statement

- allows conditional execution of code
- syntax has form:
  ```
  if (expression)
  statement_1
  else
  statement_2
  ```
- if expression `expression` is true, execute statement `statement_1`; otherwise, execute statement `statement_2`
- `else` clause can be omitted leading to simpler form:
  ```
  if (expression)
  statement_1
  ```
- conditional execution based on more than one condition can be achieved using construct like:
  ```
  if (expression_1)
  statement_1
  else if (expression_2)
  statement_2
  ...
  else
  statement_n
  ```
to include multiple statements in branch of *if*, *must group statements* into single statement using brace brackets

```c++
if (expression) {
    statement1,1
    statement1,2
    statement1,3
    ...
} else {
    statement2,1
    statement2,2
    statement2,3
    ...
}
```

advisable to *always include brace brackets* even when not necessary, as this avoids potential bugs caused by forgetting to include brackets later when more statements added to branch of *if*
■ if statement may include initializer:

```cpp
if (initializer; expression)
    statement_1;
else
    statement_2;
```

■ above construct equivalent to:

```cpp
{
    initializer;
    if (expression)
        statement_1;
    else
        statement_2;
}
```

■ if condition in if statement is constant expression, `constexpr` keyword can be added after `if` keyword to yield what is called constexpr-if statement

■ constexpr-if statement is evaluated at compile time and branch of if statement that is not taken is discarded
The if Statement: Example

- **example with else clause:**
  ```cpp
  int x = someValue;
  if (x % 2 == 0) {
    std::cout << "x is even\n";
  } else {
    std::cout << "x is odd\n";
  }
  ```

- **example without else clause:**
  ```cpp
  int x = someValue;
  if (x % 2 == 0) {
    std::cout << "x is divisible by 2\n";
  }
  ```

- **example that tests for more than one condition:**
  ```cpp
  int x = someValue;
  if (x > 0) {
    std::cout << "x is positive\n";
  } else if (x < 0) {
    std::cout << "x is negative\n";
  } else {
    std::cout << "x is zero\n";
  }
  ```
example with initializer:

```cpp
int execute_command();
if (int ret = execute_command(); ret == 0) {
    std::cout << "command successful\n";
} else {
    std::cout << "command failed with status " << ret << "\n";
}
```

example constexpr-if statement:

```cpp
constexpr int x = 10;
if constexpr (x < 0) {
    std::cout << "negative\n";
} else if constexpr (x > 0) {
    std::cout << "positive\n";
} else {
    std::cout << "zero\n";
}
```
The `switch` Statement

- allows conditional execution of code based on integral/enumeration value
- syntax has form:

  ```
  switch (expression) {
    case const_expr1:
      statements1
    case const_expr2:
      statements2
    ...
    case const_exprn:
      statementsn
    default:
      statements
  }
  ```

- `expression` is expression of integral or enumeration type or implicitly convertible to such type; `const_expr_i` is constant expression of same type as `expression` after conversions/promotions

- if expression `expression` equals `const_expr_i`, jump to beginning of statements `statements_i`; if expression `expr` does not equal `const_expr_i` for any `i`, jump to beginning of statements `statements`

- then, continue executing statements until `break` statement is encountered
The `switch` Statement (Continued)

- switch statement can also include initializer:

  ```
  switch (initializer; expression)
  statement
  ```

- above construct equivalent to:

  ```
  {
    initializer;
    switch (expression)
    statement
  }
  ```

- remember that, in absence of break statement, execution in switch statement falls through from one case to next; if fall through not considered, bugs will result, such as in following code:

  ```
  unsigned int x = 0;
  switch (x & 1) {
    case 0:
      std::cout << "x is even\n";
      // BUG: missing break statement
    case 1:
      std::cout << "x is odd\n";
      break;
  }
  ```
example without initializer:

```cpp
int x = someValue;
switch (x) {
    case 0:
        // Note that there is no break here.
        case 1:
            std::cout << "x is 0 or 1\n";
            break;
    case 2:
        std::cout << "x is 2\n";
        break;
    default:
        std::cout << "x is not 0, 1, or 2\n";
        break;
}
```
example with initializer:

```cpp
int get_value();
switch (int x = get_value(); x) {
    case 0:
    case 1:
        std::cout << "x is 0 or 1\n";
        break;
    case 2:
        std::cout << "x is 2\n";
        break;
    default:
        std::cout << "x is not 0, 1, or 2\n";
        break;
}
```
The **while** Statement

- looping construct
- syntax has form:
  
  ```
  while (expression) 
  statement
  ```

- if expression *expression* is true, statement *statement* is executed; this process repeats until expression *expression* becomes false

- to allow multiple statements to be executed in loop body, *must group multiple statements* into single statement with brace brackets

  ```
  while (expression) {
    statement_1
    statement_2
    statement_3
    . . .
  }
  ```

- advisable to *always use brace brackets*, even when loop body consists of only one statement
// print hello 10 times
int n = 10;
while (n > 0) {
    std::cout << "hello\n";
    --n;
}

// loop forever, printing hello
while (true) {
    std::cout << "hello\n";
}
The `for` Statement

- looping construct
- has following syntax:
  
  ```
  for (statement_1; expression; statement_2) 
  statement_3
  ```

- first, execute statement `statement_1`; then, while expression `expression` is true, execute statement `statement_3` followed by statement `statement_2`

- `statement_1` and `statement_2` may be omitted; `expression` treated as `true` if omitted

- to include multiple statements in loop body, *must group multiple statements* into single statement using brace brackets; advisable to *always use brace brackets*, even when loop body consists of only one statement:
  
  ```
  for (statement_1; expression; statement_2) {
  statement_3,1
  statement_3,2
  ...
  }
  ```

- any objects declared in `statement_1` go out of scope as soon as `for` loop ends
consider **for** loop:

```
for (statement\_1; expression; statement\_2)
statement\_3
```

above **for** loop can be equivalently expressed in terms of **while** loop as follows (except for behavior of **continue** statement, yet to be discussed):

```
{
    statement\_1;
    while (expression) {
        statement\_3
        statement\_2;
    }
}
```
The \texttt{for} Statement: Example

- example with single statement in loop body:

  // Print the integers from 0 to 9 inclusive.
  \textbf{for} (\texttt{int} i = 0; i < 10; ++i)
  \texttt{std::cout \textless \textless i \textless \textless 'n';}

- example with multiple statements in loop body:

  \texttt{int} values[10];
  // ...
  \texttt{int} sum = 0;
  \textbf{for} (\texttt{int} i = 0; i < 10; ++i) {
    // Stop if value is negative.
    \textbf{if} (\texttt{values[i] < 0}) {
      \texttt{break;}
    }
    \texttt{sum += values[i];}
  }

- example with error in assumption about scoping rules:

  \textbf{for} (\texttt{int} i = 0; i < 10; ++i) {
    \texttt{std::cout \textless \textless i \textless \textless 'n';}
  }
  \texttt{++i; // ERROR: i no longer exists}
Range-Based **for** Statement

- variant of for loop for iterating over elements in range
- example:

  ```
  int array[4] = {1, 2, 3, 4};
  // Triple the value of each element in the array.
  for (auto&& x : array) {
    x *= 3;
  }
  ```

- range-based for loop nice in that it clearly expresses programmer intent (i.e., iterate over each element of collection)
consider range-based for statement:

\[
\text{attr}(optional) \quad \text{for} \ (\text{init-statement}(optional) \ \text{range-declaration} : \ \text{range-expression}) \ \\
\text{loop-statement}
\]

above statement equivalent to:

\[
\{ \ \\
\text{init-statement} \ \\
\text{auto} \ \&\& \ \_\_range = \ \text{range-expression}; \ \\
\text{auto} \ \_\_begin = \ \text{begin-expr}; \ \\
\text{auto} \ \_\_end = \ \text{end-expr}; \ \\
\text{for} \ (\_\_begin != \_\_end; ++\_\_begin) \ { \ \\
\text{range-declaration} = *\_\_begin; \ \\
\text{loop-statement} \ \\
\}
\} \]
The **do** Statement

- looping construct
- has following general syntax:
  ```
  do
  statement
  while (expression);
  ```
  - statement *statement* executed;
  - then, expression *expression* evaluated;
  - if expression *expression* is true, entire process repeats from beginning

- to execute multiple statements in body of loop, must group multiple statements into single statement using brace brackets
  ```
  do {
  statement1
  statement2
  ...
  } while (expression);
  ```
  - advisable to **always use brace brackets**, even when loop body consists of only one statement
The `do` Statement: Example

- example with single statement in loop body:
  ```c++
  // delay by looping 10000 times
  int n = 0;
  do
      ++n;
  while (n < 10000);
  ```

- example with multiple statements in loop body:
  ```c++
  // print integers from 0 to 9 inclusive
  int n = 0;
  do {
      std::cout << n << '\n';
      ++n;
  } while (n < 10);
  ```
**break** statement causes enclosing loop or switch to be terminated immediately

**example:**

```cpp
// Read integers from standard input until an
// error or end-of-file is encountered or a
// negative integer is read.
int x;
while (std::cin >> x) {
    if (x < 0) {
        break;
    }
    std::cout << x << '\n';
}
```
The `continue` Statement

- `continue` statement causes next iteration of enclosing loop to be started immediately

- example:

```c++
int values[10];
...
// Print the nonzero elements of the array.
for (int i = 0; i < 10; ++i) {
    if (values[i] == 0) {
        // Skip over zero elements.
        continue;
    }
    // Print the (nonzero) element.
    std::cout << values[i] << '\n';
}
```
The `goto` Statement

- `goto` statement transfers control to another statement specified by label
- should generally try to *avoid use of `goto` statement*
- well written code rarely has legitimate use for `goto` statement
- example:

```cpp
int i = 0;
loop: // label for goto statement
do {
    if (i == 3) {
        ++i;
        goto loop;
    }
    std::cout << i << '\n';
    ++i;
} while (i < 10);
```

- some restrictions on use of `goto` (e.g., cannot jump over initialization in same block as `goto`)

```cpp
goto skip; // ERROR
int i = 0;
skip:
++i;
```
Section 2.3.5

Functions
Function Parameters, Arguments, and Return Values

- **argument** (a.k.a. **actual parameter**): argument is value supplied to function by caller; appears in parentheses of function-call operator \[C++17 \S 3.2\]

- **parameter** (a.k.a. **formal parameter**): parameter is object/reference declared as part of function that acquires value on entry to function; appears in function definition/declaration \[C++17 \S 3.16\]

- although abuse of terminology, parameter and argument often used interchangeably

- **return value**: result passed from function back to caller

- example:

  ```c++
  int square(int i) { // i is parameter
      return i * i; // return value is i * i
  }

  void compute() {
      int i = 3;
      int j = square(i); // i is argument
  }
  ```
**function declaration** introduces identifier that names function and specifies following properties of function:

- number of parameters
- type of each parameter
- type of return value (if not automatically deduced)

**example:**

```cpp
bool isOdd(int); // declare isOdd
bool isOdd(int x); // declare isOdd (x ignored)
```

**function definition** provides all information included in function declaration as well as code for body of function

**example:**

```cpp
bool isOdd(int x) { // declare and define isOdd
    return x % 2;
}
```
Basic Syntax (Leading Return Type)

- most basic syntax for function declarations and definitions places return type at start (i.e., leading return-type syntax)

- basic syntax for function declaration:
  
  ```
  return_type function_name (parameter_declarations) ;
  ```

- examples of function declarations:
  
  ```
  int min(int, int);
  double square(double);
  ```

- basic syntax for function definition:
  
  ```
  return_type function_name (parameter_declarations)
  {
      statements
  }
  ```

- examples of function definitions:
  
  ```
  int min(int x, int y) {return x < y ? x : y;}
  double square(double x) {return x * x;}
  ```
with trailing return-type syntax, return type comes after parameter declarations and `auto` used as placeholder for where return type would normally be placed

trailing return-type syntax for function declaration:

```
auto  function_name (parameter_declarations)  ->  return_type;
```

eamples of function declarations:

```
auto  min(int, int)  ->  int;
auto  square(double)  ->  double;
```

trailing return-type syntax for function definition:

```
auto  function_name (parameter_declarations)  ->  return_type
{
  statements
}
```

eamples of function definitions:

```
auto  min(int  x, int  y)  ->  int
  {return  x < y ? x : y;}
auto  square(double  x)  ->  double  {return  x * x;}
```
The **return** Statement

- **return** statement used to exit function, passing specified return value (if any) back to caller
- code in function executes until **return** statement is reached or execution falls off end of function
- if function return type is not **void**, **return** statement takes single parameter indicating value to be returned
- if function return type is **void**, function does not return any value and **return** statement takes either no parameter or expression of type **void**
- falling off end of function equivalent to executing **return** statement with no value
- example:

```cpp
double unit_step(double x) {
    if (x >= 0.0) {
        return 1.0; // exit with return value 1.0
    }
    return 0.0; // exit with return value 0.0
}
```
with both leading and trailing return-type syntax, can specify return type as `auto`

- in this case, return type of function will be automatically deduced
- if function definition has no `return` statement, return type deduced to be `void`
- otherwise, return type deduced to match type in expression of `return` statement or, if `return` statement has no expression, as `void`
- if multiple return statements, must use same type for all `return` expressions

when return-type deduction used, function definition must be visible in order to call function (since return type cannot be determined otherwise)

example:

```cpp
auto square(double x) {
    return x * x;
    // x * x has type double
    // deduced return type is double
}
```
The main Function

- entry point to program is always function called `main`
- has return type of `int`
- can be declared to take either no arguments or two arguments as follows (although other possibilities may also be supported by implementation):
  
  ```cpp
  [C++17 §6.6.1/2]
  int main();
  int main(int argc, char* argv[]);
  ```
- two-argument variant allows arbitrary number of C-style strings to be passed to program from environment in which program run
- `argc`: number of C-style strings provided to program
- `argv`: array of pointers to C-style strings
- `argv[0]` is name by which program invoked
- `argv[argc]` is guaranteed to be 0 (i.e., null pointer)
- `argv[1], argv[2], ..., argv[argc - 1]` typically correspond to command line options

suppose that following command line given to shell:

```c
program one two three
```

**main function would be invoked as follows:**

```c
int argc = 4;
char* argv[] = {
    "program", "one", "two", "three", 0
};
main(argc, argv);
```

**return value of main typically passed back to operating system**

**can also use function void exit(int) to terminate program, passing integer return value back to operating system**

**return statement in main is optional**

**if control reaches end of main without encountering return statement, effect is that of executing "return 0;"**
- **lifetime** of object is period of time in which object exists (e.g., block, function, global)

```c
int x;

void wasteTime()
{
    int j = 10000;
    while (j > 0) {
        --j;
    }
    for (int i = 0; i < 10000; ++i) {
    }
}
```

- in above example: `x` global scope and lifetime; `j` function scope and lifetime; `i` block scope and lifetime
function parameter can be passed by value or by reference

**pass by value**: function given copy of object from caller

**pass by reference**: function given reference to object from caller

to pass parameter by reference, use *reference type* for parameter

example:

```c++
void increment(int& x)
    // x is passed by reference
{
    ++x;
}

double square(double x)
    // x is passed by value
{
    return x * x;
}
```
if function needs to *change value of object in caller*, must pass by reference

for example:

```cpp
void increment(int& x)
    // x refers to object in caller
{
    ++x;
}
```

if object being passed to function is *expensive to copy* (e.g., a very large data type), always faster to pass by reference

for example:

```cpp
double compute(const std::vector<double>& x)
    // x refers to object in caller
    // object is not copied
{
    double result;
    // ... (initialize result with value computed from x)
    return result;
}
```
Increment Example: Incorrectly Using Pass By Value

consider code:
```cpp
1  void increment(int x) {
2      ++x;
3  }
4
5  void func() {
6      int i = 0;
7      increment(i); // i is not modified
8      // i is still 0
9  }
```

when `func` calls `increment`, parameter passing copies value of `i` in `func` to local variable `x` in `increment`:

```
<table>
<thead>
<tr>
<th>i in func</th>
<th>Copy Value</th>
<th>x in increment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>
```

when code in `increment` executes, local variable `x` is incremented (not `i` in `func`):

```
<table>
<thead>
<tr>
<th>i in func</th>
<th>x in increment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
```
consider code:

```c++
void increment(int& x) {
    ++x;
}

void func() {
    int i = 0;
    increment(i); // i is incremented
    // i is now 1
}
```

when func calls increment, reference x in increment is bound to object i in func (i.e., x becomes alias for i):

```
i in func
and
x in increment
```

when code in increment executes, x is incremented, which is alias for i in func:

```
i in func
and
x in increment
```

```c++
0
1
```
The \texttt{const} Qualifier and Functions

- \texttt{const} qualifier can be used in function declaration to make promises about what non-local objects will not be modified by function.
- for function parameter of pointer type, const-ness of pointed-to object (i.e., pointee) extremely important
- if pointee is const, function promises not to change pointee; for example:
  \begin{verbatim}
  int strlen(const char*); // get string length
  \end{verbatim}
- for function parameter of reference type, const-ness of referred-to object (i.e., referee) extremely important
- if referee is const, function promises not to change referee; for example:
  \begin{verbatim}
  std::complex<double>
  square(const std::complex<double>&); // compute square of number
  \end{verbatim}
- not making appropriate choice of const-ness for pointed-to or referred-to object will result in \textit{fundamentally incorrect} code
- if function will never modify pointee/referee associated with function parameter, parameter type should be made pointer/reference to const object
String Length Example: Not Const Correct

```c

int string_length(char* s) {
    int n = 0;
    while (*s++ != '\0') {++n;}
    return n;
}

int main() {
    char buf[] = "Goodbye";
    const char* const m1 = "Hello";
    char* const m2 = &buf[0];
    int n1 = string_length(m1);
    // must copy argument m1 to parameter s:
    //    char* s = m1;
    // convert from const char* const to char*
    // ERROR: must discard const from pointee
    int n2 = string_length(m2);
    // must copy argument m2 to parameter s:
    //    char* s = m2;
    // convert from char* const to char*
    // OK: constness of pointee unchanged
}
```

Copyright © 2015–2021 Michael D. Adams
Programming in C++  Version 2021-04-01
// OK: pointee is const
int string_length(const char* s) {
    int n = 0;
    while (*s++ != '\0') {++n;}
    return n;
}

int main() {
    char buf[] = "Goodbye";
    const char* const m1 = "Hello";
    char* const m2 = &buf[0];
    int n1 = string_length(m1);
    // must copy argument m1 to parameter s:
    //    const char* s = m1;
    // convert from const char* const to const char*
    //    OK: constness of pointee unchanged
    int n2 = string_length(m2);
    // must copy argument m2 to parameter s:
    //    const char* s = m2;
    // convert from char* const to const char*
    //    OK: can add const to pointee
    }
#include <complex>

using Complex = std::complex<long double>;

// ERROR: parameter type should be reference to const
Complex square(Complex& z) {
    return z * z;
}

int main() {
    const Complex c1(1.0, 2.0);
    Complex c2(1.0, 2.0);
    Complex r1 = square(c1);
    // must bind parameter z to argument c1
    //    Complex& z = c1;
    // convert from const Complex to Complex&
    // ERROR: must discard const from referee
    Complex r2 = square(c2);
    // must bind parameter z to argument c2
    //    Complex& z = c2;
    // convert from Complex to Complex&
    // OK: constness of referee unchanged
}


```cpp
#include <complex>

using Complex = std::complex<long double>;

// OK: parameter type is reference to const
Complex square(const Complex& z) {
    return z * z;
}

int main() {
    const Complex c1(1.0, 2.0);
    Complex c2(1.0, 2.0);
    Complex r1 = square(c1);
    // must bind parameter z to argument c1
    //    const Complex& z = c1;
    // convert from const Complex to const Complex&
    // OK: constness of referee not discarded
    Complex r2 = square(c2);
    // must bind parameter z to argument c2
    //    const Complex& z = c2;
    // convert from Complex to const Complex&
    // OK: can add const to referee
}
```
// top-level qualifiers of parameter types are not part of function type and should be omitted
// from function declaration

// BAD: const not part of function type
// (nothing here to which const can refer)
bool is_even(const unsigned int);

// OK
bool is_odd(unsigned int);

// OK: parameter with top-level const qualifier
// is ok in function definition
bool is_even(const unsigned int x) {
    // cannot change x in function
    return x % 2 == 0;
}

// OK
bool is_odd(unsigned int x) {
    // x can be changed if desired
    return x % 2 != 0;
}
in general programming sense, **inline function** is function for which compiler copies code from function definition directly into code of calling function rather than creating separate set of instructions in memory.

since code copied directly into calling function, no need to transfer control to separate piece of code and back again to caller, **eliminating performance overhead** of function call.

inline typically used for **very short functions** (where overhead of calling function is large relative to cost of executing code within function itself).

can request function be made inline by including **inline** qualifier along with function return type (but **compiler may ignore request**).

inline function must be defined in each translation unit in which function is used and all definitions must be identical; this is exception to one-definition rule.  

example:

```cpp
inline bool isEven(int x) {
    return x % 2 == 0;
}
```
Inlining of a Function

- **Inlining of \texttt{isEven} function transforms code fragment 1 into code fragment 2**

**Code fragment 1:**

```c++
inline bool isEven(int x) {
    return x % 2 == 0;
}

void myFunction() {
    int i = 3;
    bool result = isEven(i);
}
```

**Code fragment 2:**

```c++
void myFunction() {
    int i = 3;
    bool result = (i % 2 == 0);
}
```
**The constexpr Qualifier for Functions**

- **constexpr** qualifier indicates return value of function is constant expression (i.e., can be evaluated at compile time) **provided that all arguments to function are constant expressions**

- constexpr function required to be evaluated at compile time if all arguments are constant expressions and return value **used in constant expression**

- constexpr functions are implicitly inline [C++17 §10.1.5/1]

- constexpr function very restricted in what it can do (e.g., no external state, can only call constexpr functions)

- example:

  ```cpp
class constexpr int factorial(int n)  
  {return n >= 2 ? (n * factorial(n - 1)) : 1;}
  
  int u[factorial(5)];  
  // OK: factorial(5) is constant expression

  int x = 5;
  int v[factorial(x)];  
  // ERROR: factorial(x) is not constant
  // expression
  ```
```cpp
constexpr int square(int i) {
    return i * i;
}

constexpr int func(int n) {
    int sum = 0;
    for (int i = 1; i <= n; ++i) {
        sum += square(i);
    }
    return sum;
}

int main() {
    // at compile time, compute sum of the squares of
    // 1, 2, 3 (i.e., 14)
    constexpr int result = func(3);
    static_assert(result == 14);
}
```
```cpp
#include <iostream>

constexpr double square(double x) {
    return x * x;
}

int main() {
    constexpr double a = square(2.0);
    // must be computed at compile time

    double b = square(0.5);
    // might be computed at compile time

    double t;
    if (!(std::cin >> t)) {
        return 1;
    }
    const double c = square(t);
    // must be computed at run time

    std::cout << a << ' ' << b << ' ' << c << '\n';
}
```cpp
#include <iostream>

constexpr double power_int_helper(double x, int n) {
    return (n > 0) ? x * power_int_helper(x, n - 1) : 1;
}

constexpr double power_int(double x, int n) {
    return (n < 0) ? power_int_helper(1.0 / x, -n) : power_int_helper(x, n);
}

int main() {
    constexpr double a = power_int(0.5, 8);
    // must be computed at compile time

    double b = power_int(0.5, 8);
    // might be computed at compile time

    double x;
    if (!(std::cin >> x)) { return 1; }
    const double c = power_int(x, 2);
    // must be computed at run time

    std::cout << a << ' ' << b << ' ' << c << '
';
}
```
```cpp
#include <iostream>

constexpr double power_int(double x, int n) {
    double result = 1.0;
    if (n < 0) {
        x = 1.0 / x;
        n = -n;
    }
    while (--n >= 0) {
        result *= x;
    }
    return result;
}

int main() {
    constexpr double a = power_int(0.5, 8);
    // must be computed at compile time

    double b = power_int(0.5, 8);
    // might be computed at compile time

    double x;
    if (!(std::cin >> x)) { return 1; }
    constexpr double c = power_int(x, 2);
    // must be computed at run time

    std::cout << a << ' ' << b << ' ' << c << '\n';
}
```

Constexpr Function Example: power_int (Iterative)
The `constexpr` Specifier

- **Immediate function** is a function that must always yield a constant expression.
- In other words, the immediate function must execute at compile time.
- `constexpr` qualifier can be added to the declaration of a function to assert that the function is an immediate function.
- `constexpr` function must satisfy all requirements of `constexpr` function.
- `constexpr` implies `inline`.
- `constexpr` implies `constexpr` and `constinit`.

---

Copyright © 2015–2021 Michael D. Adams

Programming in C++

Version 2021-04-01

178
constexpr double square(double x) { return x * x; }

consteval double func(double x) {
    return 2.0 * square(x);
}

int main() {
    constexpr double cx = func(2.0);
    // OK: func evaluated at compile time
    double x = func(2.0);
    // OK: func evaluated at compile-time
    double y1 = func(cx);
    // OK: func evaluated at compile-time
    // double y2 = func(x);
    // ERROR: x not constexpr
    double y3 = square(x);
    // OK: square can be evaluated at run-time
}
The `std::is_constant_evaluated` Function

- `std::is_constant_evaluated` is (constexpr) function that returns boolean value indicating if called from within constant-evaluated context (i.e., code executing at compile time)
- being able to detect whether code running at compile-time can be very useful
- for example, can have constexpr function use different algorithm depending on whether invoked at compile-time or run-time
- note that `is_constant_evaluated` always returns true in condition for constexpr if (since constexpr-if always evaluated at compile time)
```cpp
#include <cassert>
#include <cmath>
#include <type_traits>

constexpr double square_root(double x) {
    if (std::is_constant_evaluated() && x >= 0.0) {
        double cur = 0.5 * x;
        double old = 0.0;
        while (cur != old) {
            old = cur;
            cur = 0.5 * (old + x / old);
        }
        return cur;
    } else {
        return std::sqrt(x);
    }
}

int main() {
    constexpr double x = 1.414213562373095;
    constexpr double cy = x * x;
    double y = cy;
    constexpr double z1 = square_root(cy);
    // uses compile-time square-root algorithm
    double z2 = square_root(cy); // may use std::sqrt
    double z3 = square_root(y); // uses std::sqrt
    static_assert(std::abs(z1 - x) < 1e-6);
    assert(std::abs(z2 - x) < 1e-6);
    assert(std::abs(z3 - x) < 1e-6);
}
```
Example: Misuse of `is_constant_evaluated`

```cpp
#include <type_traits>
#include <cassert>

constexpr int func1(int i) {
    // LIKELY ERROR:
    // following line of code same as "if (true) {return 42;}
    // due to constexpr-if, std::is_constant_evaluated() always true
    if constexpr (std::is_constant_evaluated()) {return 42;}
    else {return i;}
}

constexpr int func2(int i) {
    if (std::is_constant_evaluated()) {return 42;}
    else {return i;}
}

int main(){
    constexpr int x = 0;
    int y = x;
    static_assert(func1(x) == 42);
    static_assert(func2(x) == 42);
    assert(func1(y) == 42);  // OK, BUT LIKELY NOT INTENDED
    assert(func2(y) == 0);
}
```
in some very special cases (for largely historical reasons), const variables usable in constant expressions

const variable of integral or enumerated type usable in constant expression if initializer is constant expression \([\text{C++20}\ §7.7/3–4]\)

eample:

```cpp
1 constexpr int forty_two() { return 42; }
2 constexpr bool is_even(int x) { return !(x % 2); }
3 constexpr double cube(double x) { return x * x * x; }

4 int main() {
5     const int i = forty_two();
6     /* i is const, has integral type, and is initialized with constant expression; so i usable in constant expression */
7     float x[i]; // OK
8     constexpr bool b = is_even(i); // OK
9     constexpr double d = 42.0;
10     // d not usable in constant expression
11     // double d2 = cube(d); // ERROR: d not constexpr
12     }
```
// f returns i at compile time and -i at run time
constexpr int f(int i) {
    const int si = std::is_constant_evaluated() ? 1 : -1;
    static_assert(si == 1);
    int s = std::is_constant_evaluated() ? 1 : -1;
    return s * i;
}

int main() {
    const int i1 = std::is_constant_evaluated() ? 1 : -1;
    static_assert(i1 == 1); // i1 evaluated at compile time
    const int i5 = f(i1);
    static_assert(i5 == 1); // i5 evaluated at compile time
    int i2 = std::is_constant_evaluated() ? 1 : -1;
    assert(i2 == -1); // i2 evaluated at run time
    const double d1 = std::is_constant_evaluated() ? 1.0 : -1.0;
    assert(d1 == -1.0); // d1 evaluated at run time
    constexpr double d2 = std::is_constant_evaluated() ? 1.0 : -1.0;
    static_assert(d2 == 1.0); // d2 evaluated at compile time
    constexpr int i3 = f(42); // f evaluated at compile time
    static_assert(i3 == 42);
    int i = 42;
    int i4 = f(i); // f evaluated at run time
    assert(i4 == -42);
}
constexpr variables and constexpr functions provide mechanism for moving computation from run time to compile time

benefits of compile-time computation include:

1. no execution-time cost at run-time
2. can facilitate compiler optimization (e.g., eliminate conditional branch if condition always true/false)
3. can reduce code size since code used only for compile-time computation does not need to be included in executable
4. can find errors at compile-time and link-time instead of at run time
5. no concerns about order of initialization (which is not necessarily true for const objects)
6. no synchronization concerns (e.g., multiple threads trying to initialize object)

when floating point is involved, compile-time and run-time computations can yield different results, due to differences in such things as
- rounding mode in effect
- processor architecture used for computation (when cross compiling)
**Function Overloading**

- **function overloading**: multiple functions can have same name as long as they differ in number/type of their arguments

- **example:**

```
void print(int x) {
    std::cout << "int has value " << x << '\n';
}

void print(double x) {
    std::cout << "double has value " << x << '\n';
}

void demo() {
    int i = 5;
    double d = 1.414;
    print(i); // calls print(int)
    print(d); // calls print(double)
    print(42); // calls print(int)
    print(3.14); // calls print(double)
}
```
can specify default values for arguments to functions

example:

```
// Compute log base b of x.
double logarithm(double x, double b) {
    return std::log(x) / std::log(b);
}

// Declaration of logarithm with a default argument.
double logarithm(double, double = 10.0);

void demo() {
    double x =
        logarithm(100.0); // calls logarithm(100.0, 10.0)
    double y =
        logarithm(4.0, 2.0); // calls logarithm(4.0, 2.0)
}
Argument Matching

- call of given function name chooses function that best matches actual arguments
- consider all functions in scope for which set of conversions exists so function could possibly be called
- best match is intersection of sets of functions that best match on each argument
- matches attempted in following order:  
  1. exact match with zero or more trivial conversions (e.g., $T$ to $T\&$, $T\&$ to $T$, adding `const` and/or `volatile`); of these, those that do not add `const` and/or `volatile` to pointer/reference better than those that do
  2. match with promotions (e.g., `int` to `long`, `float` to `double`)
  3. match with standard conversions (e.g., `float` to `int`, `double` to `int`)
  4. match with user-defined conversions
  5. match with ellipsis
- if set of best matches contains exactly one element, this element chosen as function to call
- if set of best matches is either empty or contains more than one element, function call is invalid (since either no matches found or multiple equally-good matches found)
## Argument Matching: Example

```cpp
int max(int, int);
double max(double, double);

int main() {
    int i, j, k;
    double a, b, c;
    // ...
    k = max(i, j);
    // viable functions: max(int, int), max(double, double)
    // best match on first argument: max(int, int)
    // best match on second argument: max(int, int)
    // best viable function: max(int, int)
    // OK: calls max(int, int)
    c = max(a, b);
    // viable functions: max(int, int), max(double, double)
    // best match on first argument: max(double, double)
    // best match on second argument: max(double, double)
    // best viable function: max(double, double)
    // OK: calls max(double, double)
    c = max(i, b);
    // viable functions: max(int, int), max(double, double)
    // best match on first argument: max(int, int)
    // best match on second argument: max(double, double)
    // no best viable function
    // ERROR: ambiguous function call
}
```
The `assert` Macro

- **assert** macro allows testing of boolean condition at run time
- typically used to test sanity of code (e.g., test preconditions, postconditions, or other invariants) or test validity of assumptions made by code
- defined in header file `cassert`
- macro takes single argument: boolean expression
- if assertion fails, program is terminated by calling `std::abort`
- if `NDEBUG` preprocessor symbol is defined at time `cassert` header file included, all assertions are disabled (i.e., not checked)
- `assert(expr)` is constant expression if `expr` is constant expression that evaluates to `true` or `NDEBUG` is defined \[C++17 §22.3.2/1\]
- example:

```cpp
#include <cassert>

double sqrt(double x) {
  assert(x >= 0);
  // ...
}
```
Section 2.3.6

Input/Output (I/O)
relevant declarations and such in header file `iostream`

`std::istream`: stream from which characters/data can be read (i.e., input stream)

`std::ostream`: stream to which characters/data can be written (i.e., output stream)

`std::istream std::cin` standard input stream

`std::ostream std::cout` standard output stream

`std::ostream std::cerr` standard error stream

in most environments, above three streams refer to user’s terminal by default

output operator (inserter) `<<`

input operator (extractor) `>>`

stream can be used as `bool` expression; converts to `true` if stream has not encountered any errors and `false` otherwise (e.g., if invalid data read or I/O error occurred)
```cpp
#include <iostream>

int main() {
    std::cout << "Enter an integer: ";
    int x;
    std::cin >> x;
    if (std::cin) {
        std::cout << "The integer entered was ";
        << x << ".\n";
    } else {
        std::cerr << "End-of-file reached or I/O error.\n";
    }
}
```
I/O Manipulators

- Manipulators provide a way to control the formatting of data values written to streams as well as parsing of data values read from streams.
- Declarations related information for manipulators can be found in header files: `ios`, `iomanip`, `istream`, and `ostream`.
- Most manipulators are used to control output formatting.
- Focus here on manipulators as they pertain to output.
- Manipulator may have immediate effect (e.g., `endl`), only affect next data value output (e.g., `setw`), or affect all subsequent data values output (e.g., `setprecision`).
<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>setw</td>
<td>set field width</td>
</tr>
<tr>
<td>setfill</td>
<td>set fill character</td>
</tr>
<tr>
<td>endl</td>
<td>insert newline and flush</td>
</tr>
<tr>
<td>flush</td>
<td>flush stream</td>
</tr>
<tr>
<td>dec</td>
<td>use decimal</td>
</tr>
<tr>
<td>hex</td>
<td>use hexadecimal</td>
</tr>
<tr>
<td>oct</td>
<td>use octal</td>
</tr>
<tr>
<td>showpos</td>
<td>show positive sign</td>
</tr>
<tr>
<td>noshowpos</td>
<td>do not show positive sign</td>
</tr>
<tr>
<td>left</td>
<td>left align</td>
</tr>
<tr>
<td>right</td>
<td>right align</td>
</tr>
<tr>
<td>fixed</td>
<td>write floating-point values in fixed-point notation</td>
</tr>
<tr>
<td>scientific</td>
<td>write floating-point values in scientific notation</td>
</tr>
<tr>
<td>setprecision</td>
<td>for default notation, specify maximum number of meaningful digits to display before and after decimal point; for fixed and scientific notations, specify exactly how many digits to display after decimal point (padding with trailing zeros if necessary)</td>
</tr>
</tbody>
</table>
```cpp
#include <iostream>
#include <ios>
#include <iomanip>

int main() {
    constexpr double pi = 3.1415926535;
    constexpr double big = 123456789.0;
    // default notation
    std::cout << pi << ' ' << big << '
';
    // fixed-point notation
    std::cout << std::fixed << pi << ' ' << big << '
';
    // scientific notation
    std::cout << std::scientific << pi << ' ' << big << '
';
    // fixed-point notation with 7 digits after decimal point
    std::cout << std::fixed << std::setprecision(7) << pi << ' ' << big << '
';
    // fixed-point notation with precision and width specified
    std::cout << std::setw(8) << std::fixed << std::setprecision(2) << pi << ' ' << std::setw(20) << big << '
';
    // fixed-point notation with precision, width, and fill specified
    std::cout << std::setw(8) << std::setfill('x') << std::fixed << std::setprecision(2) << pi << ' ' << std::setw(20) << big << '
';
}
```

/* This program produces the following output:
3.14159 1.23457e+08
3.141593 123456789.000000
3.141593e+00 1.234568e+08
3.1415927 123456789.0000000
3.14 123456789.00
xxxx3.14 xxxxxxxx123456789.00
*/
Use of `std::istream::eof`

- **do not use** `std::istream::eof` **to determine if earlier input operation has failed**, as this will not always work.
- `eof` simply returns end-of-file (EOF) flag for stream.
- EOF flag for stream can be set during *successful* input operation (when input operation takes places just before end of file).
- when stream extractors (i.e., `operator>>`) used, fields normally delimited by whitespace.
- to read all data in whitespace-delimited field, must read *one character beyond* field in order to know that end of field has been reached.
- if field followed immediately by EOF without any intervening whitespace characters, reading one character beyond field will cause EOF to be encountered and EOF bit for stream to be set.
- in preceding case, however, EOF being set does not mean that input operation failed, only that stream data ended immediately after field that was read.
Example: Incorrect Use of `eof`

- example of *incorrect* use of `eof`:

```cpp
#include <iostream>

int main() {
    while (true) {
        int x;
        std::cin >> x;
        // std::cin may not be in a failed state.
        if (std::cin.eof()) {
            // Above input operation may have succeeded.
            std::cout << "EOF encountered\n";
            break;
        }
        std::cout << x << ' \n';
    }
}
```

- code incorrectly assumes that `eof` will only return `true` if preceding input operation has failed
- last field in stream will be incorrectly ignored if not followed by at least one whitespace character; for example, if input stream consists of three character sequence ’1’, space, ’2’, program will output:

```
EOF encountered
```
Example: Correct Use of `eof`

- to determine if input operation failed, simply check if stream in failed state
- if stream already known to be in failed state and need to determine specifically if failure due to EOF being encountered, then use `eof`

example of correct use of `eof`:

```cpp
#include <iostream>

int main() {
    int x;
    // Loop while std::cin not in a failed state.
    while (std::cin >> x) {
        std::cout << x << '
';
    }
    // Now std::cin must be in a failed state.
    // Use eof to determine the specific reason for failure.
    if (std::cin.eof()) {
        std::cout << "EOF encountered\n";
    } else {
        std::cout << "input error (excluding EOF)\n";
    }
}
```
- `std::endl` is not some kind of string constant
- `std::endl` is stream manipulator and declared as
  `std::ostream& std::endl(std::ostream&)`
- inserting `endl` to stream always (regardless of operating system)
  equivalent to outputting single newline character `'
'` followed by flushing stream
- flushing of stream can incur very substantial overhead; so only flush when strictly necessary
- some operating systems terminate lines with single linefeed character (i.e., '\n'), while other operating systems use carriage-return and linefeed pair (i.e., '\r' plus '\n')
- existence of `endl` has nothing to do with dealing with handling new lines in operating-system independent manner
- when stream opened in text mode, translation between newline characters and whatever character(s) operating system uses to terminate lines is performed automatically (both for input and output)
- above translation done for all characters input and output and has nothing to do with `endl`
for built-in types, if stream extraction fails, value of target for stream extraction depends on reason for failure. 

[C++17 §25.4.2.1.2/3 (Stage 3)]

in following example, what is value of \texttt{x} if stream extraction fails:

```
int x;
std::cin >> x;
if (!std::cin) {
  // what is value of \texttt{x}?
}
```

in above example, \texttt{x} may be \textit{uninitialized} upon stream extraction failure

if failure due to I/O error or EOF, target of extraction is \textit{not modified}

if failure due to badly formatted data, target of extraction is zero

if failure due to overflow, target of extraction is closest machine-representable value

\textbf{common error:} incorrectly assume that target of extraction will always be initialized if extraction fails

for class types, also dangerous to assume target of extraction always written upon failure
```cpp
#include <iostream>
#include <sstream>
#include <limits>
#include <cassert>

int main() {
    int x;

    std::stringstream s0(" ");
    x = -1;
    s0 >> x;
    // No data; x is not set by extraction.
    assert(s0.fail() && x == -1);

    std::stringstream s1("A");
    x = -1;
    s1 >> x;
    // Badly formatted data; x is zeroed.
    assert(s1.fail() && x == 0);

    std::stringstream s2("99999999999999999999999999999999");
    x = -1;
    s2 >> x;
    // Overflow; x set to closest machine-representable value.
    assert(s2.fail() && x == std::numeric_limits<int>::max());
}
```
- consider `istream` or `ostream` object `s`
- `!s` is equivalent to `s.fail()`
- `bool(s)` is not equivalent to `s.good()` [C++17 §30.5.5.4/1] [C++17 §30.5.5.4/7]
- `s.good()` is not the same as `!s.fail()`
- do not use `good` as opposite of `fail` since this is wrong
Section 2.3.7

Miscellany
**Namespaces**

- **namespace** is region that provides scope for identifiers declared inside.
- namespace provides mechanism for reducing likelihood of naming conflicts.
- syntax for namespace has general form:
  ```
  namespace name {
    body
  }
  ```
  
  - **name**: identifier that names namespace
  - **body**: body of namespace (i.e., code)
  - all identifiers (e.g., names of variables, functions, and types) declared in **body** made to belong to scope associated with namespace **name**
  - same identifier can be re-used in different namespaces, since each namespace is separate scope
  - scope-resolution operator (i.e., ::) can be used to explicitly specify namespace to which particular identifier belongs
  - **using** statement can be used to bring identifiers from other namespaces into current scope
```cpp
#include <iostream>

using std::cout; // bring std::cout into current scope

namespace mike {
    int someValue;
    void initialize() {
        cout << "mike::initialize called\n";
        someValue = 0;
    }
}

namespace fred {
    double someValue;
    void initialize() {
        cout << "fred::initialize called\n";
        someValue = 1.0;
    }
}

void func() {
    mike::initialize(); // call initialize in namespace mike
    fred::initialize(); // call initialize in namespace fred
    using mike::initialize;
    // bring mike::initialize into current scope
    initialize(); // call mike::initialize
}```
name given in namespace declaration can be qualified name in order to succinctly specify nested namespace

consider following namespace declaration:

```cpp
namespace foo {
    namespace bar {
        namespace impl {
            // ...
        }
    }
}
```

preceding declaration can be written more succinctly as:

```cpp
namespace foo::bar::impl {
    // ...
}
```
Namespace Aliases

- identifier can be introduced as alias for namespace
- syntax has following form:
  
  namespace alias_name = ns_name;

- identifier alias_name is alias for namespace ns_name
- namespace aliases particularly useful for creating short names for deeply-nested namespaces or namespaces with long names
- example:

```cpp
#include <iostream>

namespace foobar {
    namespace miscellany {
        namespace experimental {
            int get_meaning_of_life() {return 42;}
            void greet() {std::cout << "hello\n";};
        }
    }
}

int main() {
    namespace n = foobar::miscellany::experimental;
    n::greet();
    std::cout << n::get_meaning_of_life() << '\n';
}
```
namespace can be made inline, in which case all identifiers in namespace also visible in enclosing namespace

inline namespaces useful, for example, for library versioning

example:

```cpp
#include <cassert>

// some awesome library
namespace awesome {
    // version 1
    namespace v1 {
        int meaning_of_life() { return 41; }
    }
    // new and improved version 2
    // which should be default for library users
    inline namespace v2 {
        int meaning_of_life() { return 42; }
    }

    int main() {
        assert(awesome::v1::meaning_of_life() == 41);
        assert(awesome::v2::meaning_of_life() == 42);
        assert(awesome::meaning_of_life() == 42);
    }
}
```
can create unnamed namespace (i.e., namespace without name)
unnamed namespace often referred to as anonymous namespace
each translation unit may contain its own unique unnamed namespace
entities defined in unnamed namespace only visible in its associated translation unit (i.e., has internal linkage)

example:

```cpp
#include <iostream>

namespace {
  const int forty_two = 42;
  int x;
}

int main() {
  x = forty_two;
  std::cout << x << '\n';
}
```
Memory Allocation: **new** and **delete**

- to allocate memory, use **new** statement
- to deallocate memory allocated with **new** statement, use **delete** statement
- similar to **malloc** and **free** in C
- two forms of allocation: 1) single object (i.e., nonarray case) and 2) array of objects
- array version of **new**/**delete** distinguished by [[]]
- example:
  ```cpp
  char* buffer = new char[64]; // allocate
  // array of 64 chars
  delete [] buffer; // deallocate array
  double* x = new double; // allocate single double
  delete x; // deallocate single object
  ```

- important to match nonarray and array versions of **new** and **delete**:
  ```cpp
  char* buffer = new char[64]; // allocate
  delete buffer; // ERROR: nonarray delete to
  // delete array
  // may compile fine, but crash
  ```

C++ has several categories of literals (e.g., character, integer, floating-point, string, boolean, and pointer)

- can define additional literals based on these categories
- identifier used as suffix for user-defined literal must begin with underscore
- suffixes that do not begin with underscore are reserved for use by standard library

example:

```cpp
t #include <iostream>
#include <complex>

std::complex<long double> operator "_i(long double d) {
    return std::complex<long double>(0.0, d);
}

int main() {
    auto z = 3.14_i;
    std::cout << z << ' \n';
}

// Program output:
// (0, 3.14)
```
Attributes

- attributes provide unified syntax for implementation-defined language extensions
- attribute can be used almost anywhere in source code and can be applied to almost anything (e.g., types, variables, functions, names, code blocks, and translation units)
- specific types of entities to which attribute can be applied depends on particular attribute in question
- attribute specifiers start with two consecutive left brackets and continue to two consecutive right brackets
- example:

```c
[[deprecated]]
void some_very_old_function() {/* ... */};
```
## Some Standard Attributes

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>noreturn</td>
<td>function does not return</td>
</tr>
<tr>
<td>deprecated</td>
<td>use of entity is deprecated (i.e., allowed but discouraged)</td>
</tr>
<tr>
<td>fallthrough</td>
<td>fall through in switch statement is deliberate</td>
</tr>
<tr>
<td>maybe_unused</td>
<td>entity (e.g., variable) may be unused</td>
</tr>
<tr>
<td>nodiscard</td>
<td>used to indicate that return value of function should not be ignored</td>
</tr>
</tbody>
</table>
Some GCC and Clang Attributes

### GCC C++ Compiler

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>gnu::noinline</td>
<td>do not inline function</td>
</tr>
<tr>
<td>gnu::no_sanitize_address</td>
<td>do not instrument function for address sanitizer</td>
</tr>
<tr>
<td>gnu::no_sanitize_undefined</td>
<td>do not instrument function for undefined-behavior sanitizer</td>
</tr>
</tbody>
</table>

### Clang C++ Compiler

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>gnu::noinline</td>
<td>do not inline function</td>
</tr>
<tr>
<td>clang::no_sanitize</td>
<td>do not instrument function for sanitizer</td>
</tr>
</tbody>
</table>


Section 2.4

Classes
since fundamental types provided by language are quite limiting, language provides mechanism for defining new (i.e., user-defined) types

- **class** is user-defined type

- class specifies:
  1. how objects of class are *represented*
  2. *operations* that can be performed on objects of class

- not all parts of class are directly accessible to all code

- **interface** is part of class that is directly accessible to its users

- **implementation** is part of class that its users access only indirectly through interface
Section 2.4.1

Members and Access Specifiers
class consists of *zero or more members*

three basic kinds of members (excluding enumerators):

1. data member
2. function member
3. type member

*data members* define representation of class object

*function members* (also called member functions) provide operations on such objects

*type members* specify any types associated with class
can control *level of access* that users of class have to its members

three levels of access:

1. **public**: member can be accessed by any code
2. **protected**: member can only be accessed by other members of class and friends of class (to be discussed shortly)
3. **private**: relates to inheritance (discussion deferred until later)

**public**: member can be accessed by any code

**private**: member can only be accessed by other members of class and friends of class (to be discussed shortly)

**protected**: relates to inheritance (discussion deferred until later)

public members constitute class interface

private members constitute class implementation
class typically has form:

```cpp
class Widget // The class is named Widget.
{
    public:
        // public members
        // (i.e., the interface to users)
        // usually functions and types (but not data)
    private:
        // private members
        // (i.e., the implementation details only
        // accessible by members of class)
        // usually functions, types, and data
};
```
Default Member Access

- class members are private by default
- two code examples below are exactly equivalent:

```cpp
class Widget {
    // ...
};
```

```cpp
class Widget {
private:
    // ...
};
```
- **struct** is class where members public by default
- two code examples below are exactly equivalent:

```cpp
struct Widget {
    // ...
};

class Widget {
public:
    // ...
};
```
class example:

```cpp
class Vector_2 { // Two-dimensional vector class.
public:
    double x; // The x component of the vector.
    double y; // The y component of the vector.
};

void func() {
    Vector_2 v;
    v.x = 1.0; // Set data member x to 1.0
    v.y = 2.0; // Set data member y to 2.0
}
```

- above class has data members `x` and `y`
- members accessed by `member-selection operator` (i.e., “.”)
Function Members

- **class example:**

  ```cpp
  class Vector_2 { // Two-dimensional vector class.
  public:
      void initialize(double newX, double newY);
      double x; // The x component of the vector.
      double y; // The y component of the vector.
  };
  
  void Vector_2::initialize(double newX, double newY) {
      x = newX; // "x" means "this->x"
      y = newY; // "y" means "this->y"
  }
  
  void func() {
      Vector_2 v; // Create Vector_2 called v.
      v.initialize(1.0, 2.0); // Initialize v to (1.0, 2.0).
  }
  ```

- **above class has member function** `initialize`
- **to refer to member of class outside of class body must use** `scope-resolution operator` (i.e., `::`)
- **for example, in case of** `initialize` **function, we use** `Vector_2::initialize`
- **member function always has** `implicit parameter` **referring to class object**
The **this** Keyword

- member function always has *implicit parameter* referring to class object
- implicit parameter accessible inside member function via **this** keyword
- **this** is pointer to object for which member function is being invoked
- data members can be accessed through **this** pointer
- since data members can also be referred to directly by their names, explicit use of **this** often not needed and normally avoided
- example:

```cpp
class Widget {
public:
    int updateValue(int newValue) {
        int oldValue = value; // "value" means "this->value"
        value = newValue; // "value" means "this->value"
        return oldValue;
    }
private:
    int value;
};

void func() {
    Widget x;
    x.updateValue(5);
    // in Widget::updateValue, variable this equals &x
}
```
Member Functions

- Member function has reference to object of class as implicit parameter (i.e., object pointed to by \texttt{this})
- Need way to indicate if member function can change value of object
- \texttt{const} member function cannot change value of object

```cpp
class Counter {
public:
    int getCount() const
    { return count; } // count means this->count
    void setCount(int newCount)
    { count = newCount; } // count means this->count
    void incrementCount()
    { ++count; } // count means this->count
private:
    int count; // counter value
};

void func() {
    Counter ctr;
    ctr.setCount(0);
    int count = ctr.getCount();
    const Counter& ctr2 = ctr;
    count = ctr2.getCount(); // getCount better be const!
}
```
Definition of Function Members in Class Body

- member function whose definition is provided in body of class is implicitly **inline** (except when in module purview)
- two code examples below are exactly equivalent:

```cpp
class MyInteger {
public:
    // Set the value of the integer and return the old value.
    int setValue(int newValue) {
        int oldValue = value;
        value = newValue;
        return oldValue;
    }
private:
    int value;
};
```

```cpp
class MyInteger {
public:
    // Set the value of the integer and return the old value.
    int setValue(int newValue);
private:
    int value;
};
```

```cpp
inline int MyInteger::setValue(int newValue) {
    int oldValue = value;
    value = newValue;
    return oldValue;
}
```
example:

```cpp
class Point_2 { // Two-dimensional point class.
public:
    using Coordinate = double; // Coordinate type.
    Coordinate x; // The x coordinate of the point.
    Coordinate y; // The y coordinate of the point.
};

void func() {
    Point_2 p;
    // ...
    Point_2::Coordinate x = p.x;
    // Point_2::Coordinate same as double
}
```

above class has type member `Coordinate`

to refer to type member outside of class body, we must use

`scope-resolution operator` (i.e., `::`)

Friends

- normally, only class has access to its private members
- sometimes, necessary to allow another class or function to have access to private members of class
- friend of class is function/class that is allowed to access private members of class
- to make function or class friend of another class, use `friend` statement
- example:

```cpp
class Gadget; // forward declaration of Gadget

class Widget { // ...
    friend void myFunc();
    // function myFunc is friend of Widget
    friend class Gadget;
    // class Gadget is friend of Widget
    // ...
};
```

- generally, use of friends should be avoided except when absolutely necessary
```cpp
class Widget {
public:
    int setValue(int newValue) { // member function
        int oldValue = value; // save old value
        value = newValue; // change value to new value
        return oldValue; // return old value
    }

private:
    friend void wasteTime();
    void doNothing() {}
    int value; // data member
};

void wasteTime() {
    Widget x;
    x.doNothing(); // OK: friend
    x.value = 5; // OK: friend
}

void func() {
    Widget x; // x is object of type Widget
    x.setValue(5); // call Widget's setValue member
    // sets x.value to 5
    x.value = 5; // ERROR: value is private
    x.doNothing(); // ERROR: doNothing is private
}
```
Section 2.4.2

Constructors and Destructors
Suppose that we have two objects of the same type and we want to propagate the value of one object (i.e., the source) to the other object (i.e., the destination).

This can be accomplished in one of two ways: 1) copying or 2) moving.

**Copying** propagates the value of the source object to the destination object *without modifying the source object*.

**Moving** propagates the value of the source object to the destination object and is *permitted to modify the source object*.

Moving is always at least as efficient as copying, and for many types, moving is *more efficient* than copying.

For some types, *copying does not make sense*, while moving does (e.g., `std::ostream`, `std::istream`).
Copy operation. Propagating the value of the source object \texttt{source} to the destination object \texttt{destination} by copying.

A copy operation \textit{does not modify} the value of the source object.

Move operation. Propagating the value of the source object \texttt{source} to the destination object \texttt{destination} by moving.

A move operation is \textit{not guaranteed to preserve} the value of the source object. After the move operation, the source object has a value that is \textit{valid} but \textit{typically unspecified}. 
Constructors

- when new object created usually desirable to immediately initialize it to some known state
- prevents object from accidentally being used before it is initialized
- **constructor** is member function that is *called automatically* when object created in order to *initialize* its value
- constructor has *same name as class* (i.e., constructor for class \( T \) is function \( T::T \))
- constructor has *no return type* (not even `void`)
- constructor *cannot be called directly* (although placement new provides mechanism for achieving similar effect, in rare cases when needed)
- constructor *can be overloaded*
- before constructor body is entered, all data members of class type are first constructed in order of declaration in class definition
- in certain circumstances, constructors may be automatically provided
- sometimes, automatically provided constructors *will not* have correct behavior
constructor that can be called with no arguments known as **default constructor** \[\text{C++17 §15.1/4}\]

example:

```cpp
class Vector { // Two-dimensional vector class.
public:
    Vector() // Default constructor.
    { x_ = 0.0; y_ = 0.0; }
    // ...
private:
    double x_; // The x component of the vector.
    double y_; // The y component of the vector.
};

Vector v; // calls Vector::Vector(); v set to (0,0)
Vector x(); // declares function x that returns Vector
```
- **defaulted default constructor** for class \( T \) performs similar initialization as constructor defined as \[ \text{C++17 §15.1/7} \]
  \[
  T::T() {}
  \]

- if class has no default member initializers, this corresponds to default constructing each data member of class type and leaving data members of built-in type uninitialized

- defaulted default constructor automatically provided (i.e., implicitly declared) as public member if no user-declared constructors \[ \text{C++17 §15.1/4} \]

- example:

  ```cpp
  #include <string>

  // class has implicitly-defined defaulted default constructor
  struct Widget {
    void foo() {}
    std::string s;
  };
  ```
for class $T$, constructor taking lvalue reference to $T$ as first parameter that can be called with one argument known as **copy constructor** [C++17 §15.8.1/1]

used to *create* object by *copying* from already-existing object

**copy constructor** for class $T$ typically is of form $T(const\ T&)$

**example:**

```cpp
class Vector { // Two-dimensional vector class.
public:
    Vector() {x_ = 0.0; y_ = 0.0;} // Default constructor
    Vector(const Vector& v) // Copy constructor.
        {x_ = v.x_; y_ = v.y_;}
    // ... 
private:
    double x_; // The x component of the vector.
    double y_; // The y component of the vector.
};

Vector v;
Vector w(v); // calls Vector::Vector(const Vector&)
Vector u = v; // calls Vector::Vector(const Vector&)
```

■ **defaulted copy constructor** performs memberwise copy of its data members (and bases), where copy performed using: [C++17 §15.8.1/14]
  
  - copy constructor for class types
  - bitwise copy for built-in types

■ defaulted copy constructor automatically provided (i.e., implicitly defined) as public member if none of following user declared: [C++17 §15.8.1/6]
  
  - move constructor
  - move assignment operator
  - copy assignment operator (if not relying on deprecated behavior)
  - destructor (if not relying on deprecated behavior)

■ example:

```cpp
// class has defaulted copy constructor
class Widget {
public:
    Widget(int i) {i_ = i;}
    int get() const {return i_;}
private:
    int i_; // default member
};
```
for class \( T \), constructor taking rvalue reference to \( T \) as first parameter that can be called with one argument known as **move constructor** \([\text{C++17 §15.8.1/2}]\)

- used to *create* object by *moving* from already-existing object
- move constructor for class \( T \) typically is of form \( T(T&&) \)

**example:**

```cpp
class Vector { // Two-dimensional vector class.
public:
    Vector() {x_ = 0.0; y_ = 0.0;} // Default constructor
    Vector(Vector&& v) {x_ = v.x_; y_ = v.y_;} // Move constructor.
    // ...
private:
    double x_; // The x component of the vector.
    double y_; // The y component of the vector.
};

#include <utility>
Vector v;
Vector w(std::move(v)); // calls Vector::Vector(Vector&&)
Vector x = std::move(w); // calls Vector::Vector(Vector&&)
```
**Defaulted Move Constructor**

- **defaulted move constructor** performs memberwise move of its data members (and bases) using: [C++17 §15.8.1/14]
  - move constructor if available and copy constructor otherwise in case of class type
  - bitwise copy in case of built-in type

- defaulted move constructor automatically provided (i.e., implicitly defined) as public member if none of following user declared: [C++17 §15.8.1/8]
  - copy constructor
  - copy assignment operator
  - move assignment operator
  - destructor

- **example:**
  ```cpp
  // class has defaulted move constructor
  struct Widget {
      Widget();
      void foo();
  };
  ```
class Vector { // Two-dimensional vector class.

public:
  // Default constructor.
  Vector() {x_ = 0.0; y_ = 0.0;}

  // Copy constructor.
  Vector(const Vector& v) {x_ = v.x_; y_ = v.y_;}

  // Move constructor.
  Vector(Vector&& v) {x_ = v.x_; y_ = v.y_;}

  // Another constructor.
  Vector(double x, double y) {x_ = x; y_ = y;}

private:
  double x_; // The x component of the vector.
  double y_; // The y component of the vector.
};
// include definition of Vector class here

int main() {
    Vector u;
    // calls default constructor
    Vector v(1.0, 2.0);
    // calls Vector::Vector(double, double)
    Vector w(v);
    // calls copy constructor
    Vector x = u;
    // calls copy constructor
    Vector y = Vector(1.0, 0.0);
    // guaranteed copy/move elision
    // calls Vector::Vector(double, double), directly
    // constructing new object in y
    // does not call move constructor
    Vector z{Vector()};
    // guaranteed copy/move elision
    // calls default constructor, directly constructing
    // new object in z
    // does not call move constructor
    Vector f();
    // declares function f that returns Vector
}
#include <utility>
#include <cstdlib>

// include definition of Vector class here

// named RVO not possible
Vector func1() {
    Vector a(1.0, 0.0);
    Vector b(0.0, 1.0);
    if (std::rand() % 2) return a;
    else return b;
}

// RVO required
Vector func2() {return Vector(1.0, 1.0);}

int main() {
    Vector u(1.0, 1.0);
    Vector v(std::move(u));
    // move constructor invoked to propagate value from u
    // to v
    Vector w = func1();
    // move constructor invoked to propagate value of object
    // in return statement of func1 to object w in main
    // (named RVO not possible)
    Vector x = func2();
    // move constructor not invoked, due to guaranteed
    // copy/move elision (return value of func2 directly
    // constructed in object x in main)
}
in constructor of class, often we want to control which constructor is used to initialize each data member

since all data members are constructed before body of constructor is entered, this cannot be controlled inside body of constructor

to allow control over which constructors are used to initialize individual data members, mechanism called initializer lists provided

initializer list forces specific constructors to be used to initialize individual data members before body of constructor is entered

data members always initialized in order of declaration, regardless of order in initializer list
class ArrayDouble { // array of doubles class
    public:
        ArrayDouble(); // create empty array
        ArrayDouble(int size); // create array of specified size
    
    private:
        // ...
};

class Vector { // n-dimensional real vector class
    public:
        Vector(int size) : data_(size) {}
        // force data_ to be constructed with
        // ArrayDouble::ArrayDouble(int)
        // ...
    
    private:
        ArrayDouble data_; // elements of vector
};
can provide default values with which to initialize data members

if initializer for data member not given in constructor initializer list, default member initializer used if specified

example:

```cpp
#include <string>

struct Widget {
    Widget() {}
    // constructor behaves as if it had initializer list:
    // answer(42), message("hello")
    int answer = 42;
    std::string message = "hello";
};
```
Member Initialization Order

- recall that data members initialized in order of declaration in class definition
- failing to consider this fact can easily lead to bugs in code
- for example, consider the following code:

```cpp
#include <cassert>

class Widget {
public:
    Widget() : y_(42), x_(y_ + 1) {assert(x_ == 43);}
    int x_;  // x_ initialized before y_, which results in use of y_ before its initialization
    int y_;
};

int main() {
    Widget w;
}
```

- in Widget's default constructor, x_ initialized before y_, which results in use of y_ before its initialization
- therefore, above code has undefined behavior
- in practice, likely x_ will simply have garbage value when body of constructor executes and assertion will fail
Destructors

- when object reaches end of lifetime, typically some cleanup required before object passes out of existence
- destructor is member function that is automatically called when object reaches end of lifetime in order to perform any necessary cleanup
- often object may have allocated resources associated with it (e.g., memory, files, devices, network connections, processes/threads)
- when object destroyed, must ensure that any resources associated with object are released
- destructors often serve to release resources associated with object
- destructor for class \( \text{T} \) always has name \( \text{T}::\text{~T} \)
- destructor has no return type (not even \text{void})
- destructor cannot be overloaded
- destructor always takes no parameters
Defaulted Destructor

- **defaulted destructor** performs no clean-up action, except to destroy each of its data members (and bases)
- defaulted destructor automatically provided (i.e., implicitly defined) if no user-declared destructor \[\text{C++17 §15.4/4}\]
- for classes that require additional clean-up, defaulted destructor will not yield correct behavior
example:

```cpp
class Widget {
public:
    Widget(int bufferSize) { // Constructor.
        // allocate some memory for buffer
        bufferPtr_ = new char[bufferSize];
    }
    ~Widget() { // Destructor.
        // free memory previously allocated
        delete[] bufferPtr_;
    }
    // copy constructor, assignment operator, ...
private:
    char* bufferPtr_; // pointer to start of buffer
};
```

if defaulted destructor were used, memory associated with `bufferPtr_` would not be freed
Section 2.4.3

Operator Overloading
**Operator Overloading**

- can specify meaning of operator whose operands are one or more user-defined types through process known as **operator overloading**

- operators that can be overloaded:

<table>
<thead>
<tr>
<th>Category</th>
<th>Operators</th>
</tr>
</thead>
<tbody>
<tr>
<td>arithmetic</td>
<td>+, -, *, /, %</td>
</tr>
<tr>
<td>bitwise</td>
<td>^, &amp;,</td>
</tr>
<tr>
<td>logical</td>
<td>!, &amp;&amp;,</td>
</tr>
<tr>
<td>relational</td>
<td>==, !=, &lt;=, &gt;=, &lt;, &gt;</td>
</tr>
<tr>
<td>assignment</td>
<td>=</td>
</tr>
<tr>
<td>compound assignment</td>
<td>+=, -=, *=, /=, %=, ^=, &amp;=,</td>
</tr>
<tr>
<td>increment/decrement</td>
<td>++, --</td>
</tr>
<tr>
<td>subscript</td>
<td>[ ]</td>
</tr>
<tr>
<td>function call</td>
<td>()</td>
</tr>
<tr>
<td>address, indirection</td>
<td>&amp; <em>, -&gt;, -&gt;</em></td>
</tr>
<tr>
<td>others</td>
<td>new, delete</td>
</tr>
</tbody>
</table>

- not possible to change precedence/associativity or syntax of operators

- meaning of operator specified by specially named function
Operator Overloading (Continued 1)

- `operator @` overloaded via special function named `operator@`
- with some exceptions, operator can be overloaded as member function or nonmember function
- if operator overloaded as member function, first operand provided as `*this` and remaining operands, if any, provided as function parameters
- if operator overloaded as nonmember function, all operands provided as function parameters
- postfix unary (increment/decrement) operators take additional dummy parameter of type `int` in order to distinguish from prefix case
- expressions involving overloaded operators interpreted as follows:

<table>
<thead>
<tr>
<th>Type</th>
<th>Expression</th>
<th>Interpretation As</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary</td>
<td><code>a@b</code></td>
<td>Member Function: <code>a.operator@(b)</code></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nonmember Function: <code>operator@(a, b)</code></td>
</tr>
<tr>
<td>Prefix unary</td>
<td><code>@a</code></td>
<td>Member Function: <code>a.operator@()</code></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nonmember Function: <code>operator@(a)</code></td>
</tr>
<tr>
<td>Postfix unary</td>
<td><code>a@</code></td>
<td>Member Function: <code>a.operator@(i)</code></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nonmember Function: <code>operator@(a, i)</code></td>
</tr>
</tbody>
</table>

`i` is dummy parameter of type `int`
assignment, function-call, subscript, and member-selection operators must be overloaded as member functions

- if member and nonmember functions both defined, argument matching rules determine which is called
- if first operand of overloaded operator not object of class type, must use nonmember function
- for most part, operators can be defined quite arbitrarily for user-defined types
- for example, no requirement that "++x", "x += 1", and "x = x + 1" be equivalent
- of course, probably not advisable to define operators in very counterintuitive ways, as will inevitably lead to bugs in code
Some examples showing how expressions translated into function calls are as follows:

<table>
<thead>
<tr>
<th>Expression</th>
<th>Member Function</th>
<th>Nonmember Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>y = x</td>
<td>y.operator=(x)</td>
<td>—</td>
</tr>
<tr>
<td>y += x</td>
<td>y.operator+==(x)</td>
<td>operator+=(y, x)</td>
</tr>
<tr>
<td>x + y</td>
<td>x.operator+=(y)</td>
<td>operator+(x, y)</td>
</tr>
<tr>
<td>++x</td>
<td>x.operator++()</td>
<td>operator++(x)</td>
</tr>
<tr>
<td>x++</td>
<td>x.operator++(int)</td>
<td>operator++(x, int)</td>
</tr>
<tr>
<td>x == y</td>
<td>x.operator===(y)</td>
<td>operator==(x, y)</td>
</tr>
<tr>
<td>x &lt; y</td>
<td>x.operator&lt;(y)</td>
<td>operator&lt;(x, y)</td>
</tr>
</tbody>
</table>
Operator Overloading Example: Vector

class Vector { // Two-dimensional vector class
    public:
        Vector() : x_(0.0), y_(0.0) {}
        Vector(double x, double y) : x_(x), y_(y) {}
        double x() const { return x_; }
        double y() const { return y_; }
    private:
        double x_; // The x component
        double y_; // The y component
};

// Vector addition
Vector operator+(const Vector& u, const Vector& v)
    { return Vector(u.x() + v.x(), u.y() + v.y()); }

// Dot product
double operator*(const Vector& u, const Vector& v)
    { return u.x() * v.x() + u.y() * v.y(); }

void func() {
    Vector u(1.0, 2.0);
    Vector v(u);
    Vector w;
    w = u + v; // w.operator=(operator+(u, v))
    double c = u * v; // calls operator*(u, v)
    // since c is built-in type, assignment operator
    // does not require function call
}
class Array10 { // Ten-element real array class

public:
    Array10() {
        for (int i = 0; i < 10; ++i) { // Zero array
            data_[i] = 0;
        }
    }

    const double & operator[](int index) const {
        return data_[index];
    }

    double & operator[](int index) {
        return data_[index];
    }

private:
    double data_[10]; // array data
};

void func() {
    Array10 v;
    v[1] = 3.5; // calls Array10::operator[](int)
    double c = v[1]; // calls Array10::operator[](int)
    const Array10 u;
    u[1] = 2.5; // ERROR: u[1] is const
    double d = u[1]; // calls Array10::operator[](int) const
}

in most cases, operator can be overloaded as either member or nonmember function

some considerations that factor into decision of whether to use member or nonmember function given below

if access to private members is required, using member function may be preferable to having nonmember friend function

if first operand of operator is of non-class type, must use nonmember function; otherwise, either member or nonmember could be used

if conversions for first argument to operator are desired, must use nonmember function; if such conversions not desired, must use member function
class Complex { // Complex number type.
public:
    Complex(double x, double y) : x_(x), y_(y) {}
    double real() const { return x_; }
    double imag() const { return y_; }
    // Alternatively, overload operator+ as a member function.
    // Complex operator+(double b) const
    // {return Complex(real() + b, imag());}
private:
    double x_; // The real part.
    double y_; // The imaginary part.
};

// Overload as a nonmember function.
// (A member function could instead be used. See above.)
Complex operator+(const Complex& a, double b)
{ return Complex(a.real() + b, a.imag());}

// This can only be accomplished with a nonmember function.
Complex operator+(double b, const Complex& a)
{ return Complex(b + a.real(), a.imag());}

void myFunc() {
    Complex a(1.0, 2.0);
    Complex b(1.0, -2.0);
    double r = 2.0;
    Complex c = a + r; /* could use nonmember or member function
    operator+(a, r) or a.operator+(r) */
    Complex d = r + a; /* must use nonmember function
    operator+(r, a), since r.operator+(a) will not work */
}
```cpp
#include <string_view>

class Widget {
public:
    Widget();
    Widget(std::string_view); // converting constructor
    operator std::string_view() const; // conversion operator
    // ...
};

// overload as nonmember function
Widget operator+(Widget, std::string_view);

int main() {
    Widget w;
    std::string_view sv("hello");
    Widget a = w + sv;
    /* OK: operator+(Widget, std::string_view) called
       with no conversions necessary */
    Widget b = sv + w;
    /* OK: operator+(Widget, std::string_view) called, where
       first argument implicitly converted to Widget by
       Widget’s converting constructor and second argument
       implicitly converted to std::string_view by
       Widget’s conversion operator; if operator+ were
       overloaded as member of Widget class, compiler error
       would result as overload resolution would fail to
       yield any viable function to call */
}
for class T, \texttt{T::operator=} having exactly one parameter that is lvalue reference to T known as \textit{copy assignment operator} [C++17 §15.8.2/1]

used to assign, to already-existing object, value of another object by \textit{copying}

copy assignment operator for class \texttt{T} typically is of form
\texttt{T& operator=(const T&) (returning reference to \texttt{*this})}

copy assignment operator returns (nonconstant) reference in order to allow for statements like following to be valid (where \texttt{x}, \texttt{y}, and \texttt{z} are of type \texttt{T} and \texttt{T::modify} is a non-const member function):
\begin{verbatim}
  x = y = z; // x.operator=(y.operator=(z))
  (x = y) = z; // (x.operator=(y)).operator=(z)
  (x = y).modify(); // (x.operator=(y)).modify()
\end{verbatim}

must be careful to correctly consider case of self-assignment
**Defaulted Copy Assignment Operator**

- **defaulted copy assignment operator** performs memberwise copy of its data members (and bases), where copy performed using: [C++17 §15.8.2/12]
  - copy assignment operator for class types
  - bitwise copy for built-in types

- defaulted copy assignment operator automatically provided (i.e., implicitly defined) as public member if none of following user declared: [C++17 §15.8.2/2]
  - move constructor
  - move assignment operator
  - copy constructor (if not relying on deprecated behavior)
  - destructor (if not relying on deprecated behavior)

- **example:**

```cpp
// class has implicitly-defined defaulted copy-assignment operator
class Widget {
public:
  Widget(int i) {i_ = i;}
  int get() const {return i_;}
private:
  int i_;}
```

Copyright © 2015–2021 Michael D. Adams
in practice, self assignment typically occurs when references (or pointers) are involved

example:

```cpp
void doSomething(SomeType& x, SomeType& y) {
    x = y; // self assignment if &x == &y
    // ...
}

void myFunc() {
    SomeType z;
    // ...
    doSomething(z, z); // results in self assignment
    // ...
}
```
for class \( T \), \( T :: \text{operator=} \) having exactly one parameter that is rvalue reference to \( T \) known as move assignment operator \(^{[\text{C++17 §15.8.2/3}]}\)

used to assign, to already-existing object, value of another object by moving

move assignment operator for class \( T \) typically is of form
\( T & \text{operator=} (T &&) \) (returning reference to \(*\text{this}\))

move assignment operator returns (nonconstant) reference for same reason as in case of copy assignment operator

in case of move, self-assignment should probably not occur, but might be prudent to test for this with assertion in order to protect against “insane” code

standard library effectively forbids self-assignment for move \(^{[\text{C++17 §20.5.4.9/(1,3)}]}\)
**defaulted move assignment operator** performs memberwise move of its data members (and bases) where move performed using: [C++17 §15.8.2/12]

- if class type: move assignment operator if available and copy assignment operator otherwise
- if built-in type: bitwise copy

**defaulted move assignment operator automatically provided** (i.e., implicitly defined) as public member if none of following user declared: [C++17 §15.8.2/4]

- copy constructor
- move constructor
- copy assignment operator
- destructor

**example:**

```cpp
#include <vector>

// class has implicitly-defined defaulted move-assignment operator
struct Widget {
    Widget();
    std::vector<int> v;
};
```
class Complex {
    public:
        Complex(double x = 0.0, double y = 0.0) :
            x_(x), y_(y) {}
        Complex(const Complex& a) : x_(a.x_), y_(a.y_) {}
        Complex(Complex&& a) : x_(a.x_), y_(a.y_) {}
        Complex& operator=(const Complex& a) { // Copy assign
            if (this != &a) {
                x_ = a.x_; y_ = a.y_;}
        return *this;
        }
    } Complex& operator=(Complex&& a) { // Move assign
        x_ = a.x_; y_ = a.y_;
        return *this;
    }
    private:
        double x_; // The real part.
        double y_; // The imaginary part.
    };

int main() {
    Complex z(1.0, 2.0);
    Complex v(1.5, 2.5);
    v = z; // v.operator=(z)
    v = Complex(0.0, 1.0); // v.operator=(Complex(0.0, 1.0))
Assignment Operator Example: Buffer

```cpp
class Buffer { // Character buffer class.
    public:
        Buffer(int bufferSize) { // Constructor.
            bufSize_ = bufferSize;
            bufPtr_ = new char[bufferSize];
        }
        Buffer(const Buffer& buffer) { // Copy constructor.
            bufSize_ = buffer.bufSize_;  
            bufPtr_ = new char[bufSize_];
            for (int i = 0; i < bufSize_; ++i)
                bufPtr_[i] = buffer.bufPtr_[i];
        } 
        ~Buffer() { // Destructor.
            delete [] bufPtr_;        
        }
        Buffer& operator=(const Buffer& buffer) { // Copy assignment operator.
            if (this != &buffer) {
                delete [] bufPtr_;  
                bufSize_ = buffer.bufSize_;  
                bufPtr_ = new char[bufSize_];
                for (int i = 0; i < bufSize_; ++i)
                    bufPtr_[i] = buffer.bufPtr_[i];
            }
            return *this;
        }
    private:
        int bufSize_; // buffer size
        char* bufPtr_; // pointer to start of buffer
};
```

- without explicitly-provided assignment operator (i.e., with defaulted assignment operator), memory leaks and memory corruption would result
Section 2.4.4

Miscellany
class template std::initializer_list provides lightweight list type

in order to use initializer_list, need to include header file initializer_list

declaration:
  template <class T> initializer_list;

T is type of elements in list

initializer_list is very lightweight

can query number of elements in list and obtain iterators to access these elements

initializer_list often useful as parameter type for constructor
#include <iostream>
#include <vector>

class Sequence {
public:
    Sequence(std::initializer_list<int> list) {
        for (std::initializer_list<int>::const_iterator i = list.begin(); i != list.end(); ++i)
            elements_.push_back(*i);
    }

    void print() const {
        for (std::vector<int>::const_iterator i = elements_.begin(); i != elements_.end(); ++i)
            std::cout << *i << '
';
    }

private:
    std::vector<int> elements_;}

int main() {
    Sequence seq = {1, 2, 3, 4, 5, 6};
    seq.print();
}
Converting Constructors

- constructor that is not declared with `explicit` specifier is called **converting constructor**
- converting constructor can be used for *implicit* conversions
- example:

```cpp
#include <string>
using namespace std::literals;

class Widget {
public:
    Widget(const std::string&); // converting constructor
    Widget(const char*, int); // converting constructor
    // ...
};

int main() {
    Widget v = "hello"s; // invokes Widget::Widget(const std::string&)
    Widget w = {"goodbye", 4}; // invokes Widget::Widget(const char*, int)
    v = "bonjour"s; // invokes Widget::Widget(const std::string&)
    w = {"au revoir", 2}; // invokes Widget::Widget(const char*, int)
}
```
**Explicit Constructors**

- converting constructor can be used for implicit conversions (e.g., when attempting to obtain matching type for function parameter in function call) and copy initialization
- often, desirable to prevent constructor from being used in these contexts
- to accommodate this, constructor can be marked as explicit
- **explicit constructor** is constructor that cannot be used for performing implicit conversions or **copy initialization**
- prefixing constructor declaration with **explicit** keyword makes constructor explicit
- to conditionally make constructor explicit, **explicit** keyword can be followed by parenthesized constant expression of type **bool**, in which case constructor is explicit if expression evaluates to **true**
- example:
  ```cpp
  class Widget {
  public:
    explicit Widget(int); // explicit constructor
    // ...
  }
  ```
# Example Without Explicit Constructor

```c++
#include <cstdlib>

// one-dimensional integer array class
class IntArray {
public:
    // create array of int with size elements
    IntArray(std::size_t size) { /* ... */ };  
    // ...
};

void processArray(const IntArray& x) {
    // ...
}

int main() {
    // following lines of code almost certain to be incorrect, but valid due to implicit type conversion provided by
    // IntArray::IntArray(std::size_t)
    IntArray a = 42;
    // probably incorrect
    // implicit conversion effectively yields code:
    // IntArray a = IntArray(42);
    processArray(42);
    // probably incorrect
    // implicit conversion effectively yields code:
    // processArray(IntArray(42));
}
```
```cpp
#include <cstdlib>

// one-dimensional integer array class
class IntArray {
public:
  // create array of int with size elements
  explicit IntArray(std::size_t size) { /* ... */ }; // ...

};

void processArray(const IntArray& x) {
  // ...
}

int main() {
  IntArray a = 42; // ERROR: cannot convert
  processArray(42); // ERROR: cannot convert
}
```
```cpp
#include <type_traits>
#include <utility>
#include <concepts>

struct im {
    im(int) {} // not explicit
};

struct ex {
    explicit ex(int) {} // explicit
};

template<class T>
class wrapper {
    public:
        template<class U> requires std::constructible_from<T, U>
        explicit(!std::is_convertible_v<U, T>) // conditionally explicit
            wrapper(U&& u) : t_(std::forward<U>(u)) {}
        // ...
    private:
        T t_;
    }

    int main() {
        wrapper<im> i = 42; // OK: wrapper constructor not explicit
        // wrapper<ex> e = 42; // ERROR: wrapper constructor explicit
    }
```
Conversion Operators

- conversion operator enables conversion from class type to another type
- conversion operator to convert from class $T$ to another type must be provided as (nonstatic) member function of $T$
- member function takes no parameters (except implicit `this` parameter) and has no explicit return type
- requiring conversion operator to be member function likely motivated by desire to allow code for performing conversions to be more easily identified (i.e., only need to examine conversion operators and converting constructors for at most two classes)

example:

```cpp
class Widget {
public:
    operator bool(); // conversion operator
    // ...
};
```
Explicit Conversion Operators

- by default, conversion operator can be used for implicit conversions
- sometimes, desirable to prevent conversion operator from being used in such contexts
- to accommodate this, conversion operator can be marked as explicit
- prefixing conversion operator declaration with `explicit` keyword makes conversion operator explicit
- to conditionally make conversion operator explicit, `explicit` keyword can be followed by parenthesized constant expression of type `bool`, in which case conversion operator is explicit if expression evaluates to `true`
- example:

```cpp
class Widget {
public:
    explicit operator int(); // explicit conversion operator
    // note: "explicit" is equivalent to "explicit(true)"
    // ...
};
```
Conversion Operator Example

```cpp
#include <iostream>
#include <string>
#include <cassert>
using namespace std::literals;

class Widget {
public:
    explicit operator int() const { return 42; }
    operator std::string() const { return "Widget"s; }
    // ...
};

int main() {
    Widget w;
    int i(w);
    // direct initialization can use explicit conversion operator;
    // uses conversion operator to convert Widget to int
    assert(i == 42);
    // int j = w;
    // ERROR: copy initialization requires implicit conversion and
    // conversion operator that converts Widget to int is explicit
    int j = static_cast<int>(w);
    // uses (explicit) conversion operator to convert Widget to int
    std::string s(w);
    // uses conversion operator to convert Widget to std::string
    assert(s == "Widget"s);
    std::string t = w;
    // uses conversion operator to convert Widget to std::string
    assert(t == "Widget"s);
}
```
can explicitly default or delete special member functions (i.e., default constructor, copy constructor, move constructor, destructor, copy assignment operator, and move assignment operator)

can also delete non-special member functions

element:

```cpp
class Thing {
public:
    Thing() = delete;
    // Prevent copying.
    Thing(const Thing&) = delete;
    Thing& operator=(const Thing&) = delete;
    Thing(Thing&&) = default;
    Thing& operator=(Thing&&) = default;
    ~Thing() = default;
    // ...
};
// Thing is movable but not copyable.
```
Delegating Constructors

- sometimes, one constructor of class needs to perform all work of another constructor followed by some additional work
- rather than duplicate common code in both constructors, one constructor can use its initializer list to invoke other constructor (which must be only one in initializer list)
- constructor that invokes another constructor via initializer list called **delegating constructor**

example:

```cpp
class Widget {
  public:
    Widget(char c, int i) : c_(c), i_(i) {} // delegating constructor
    Widget(int i) : Widget('a', i) {} // ... 
  private:
    char c_; // ... 
    int i_; // ... 
};

int main() {
  Widget w('A', 42);
  Widget v(42); 
  return 0;  
}
```
sometimes want to have object that is shared by all objects of class

data member that is shared by all objects of class is called **static data member**

to make data member static, declare using **static** qualifier

static data member must (in most cases) be defined outside body of class

example:

```cpp
class Widget {
  public:
    Widget() {++count_;}
    Widget(const Widget&) {++count_;}
    Widget(Widget&&) {++count_;}
    ~Widget() {--count_;}
    // ...
  private:
    static int count_;  
    // total number of Widget objects in existence
};

// Define (and initialize) count member.
int Widget::count_ = 0;
```
sometimes want to have member function that does not operate on objects of class

member function of class that does not operate on object of class (i.e., has no `this` variable) called **static member function**

to make member function static, declare using `static` qualifier

example:

```cpp
1  class Widget {
2     public:
3         // ...
4         // convert degrees to radians
5             static double degToRad(double deg)  
6             { return (M_PI / 180.0) * deg; }
7     private:
8         // ...
9     }
10
11    void func() {
12        Widget x; double rad;
13        rad = Widget::degToRad(45.0);
14        rad = x.degToRad(45.0); // x is ignored
15    }
```
- Like non-member functions, member functions can also be qualified as constexpr to indicate function can be computed \textit{at compile time} provided that all arguments to function are constant expressions.
- Some additional restrictions on constexpr member functions relative to nonmember case.
- constexpr member function \textit{implicitly inline}.
- constexpr member function \textit{not implicitly const} (as of C++14).
constructors and destructors can also be qualified as `constexpr`

`constexpr` constructors and `constexpr` destructors must meet all requirements of `constexpr` functions

some restrictions on what types can have `constexpr` constructors and `constexpr` destructors and what such constructors and destructors can do (e.g., no virtual base classes)

these restrictions discussed in some detail later

`constexpr` constructors and `constexpr` destructors are `implicitly inline`
```cpp
#include <iostream>

// Two-dimensional vector class.
class Vector {
  public:
    constexpr Vector() : x_(0), y_(0) {}
    constexpr Vector(double x, double y) : x_(x), y_(y) {}
    constexpr Vector(const Vector& v) : x_(v.x_), y_(v.y_) {}
    constexpr Vector& operator=(const Vector& v) {
      x_ = v.x_; y_ = v.y_; return *this;}
    constexpr double x() const {return x_;
    constexpr double y() const {return y_;}
    constexpr double squared_norm() const
      {return x_ * x_ + y_ * y_;}
    // ...
  private:
    double x_; // The x component of the vector.
    double y_; // The y component of the vector.
};

int main() {
  constexpr Vector v(3.0, 4.0);
  static_assert(v.x() == 3.0 && v.y() == 4.0);
  constexpr double d = v.squared_norm();
  std::cout << d << '\n';
}
```
Why Constexpr Member Functions Are Not Implicitly Const

class Widget {
  public:
    constexpr Widget() : i_(42) {}
    constexpr const int& get() const { return i_; }
    constexpr int& get() /* what if implicitly const? */
    { return i_; }
    // ...
  private:
    int i_; 
};

constexpr Widget w;
static_assert(w.get() == 42);
// invokes const member function
constexpr int i = ++Widget().get();
// invokes non-const member function
static_assert(i == 43);

- in above code example, we want to have const and non-const overloads of `get` member function that can each be used in constant expressions
- so both overloads of `get` need to be constexpr
- if constexpr member functions were implicitly const, it would be impossible to overload on const in manner we wish to do here, since second overload of `get` would automatically become const member function (resulting in multiple conflicting definitions of const member function `get`)
The `mutable` Qualifier

- Type for nonstatic data member can be qualified as `mutable` meaning that member does not affect externally visible state of class object.
- `mutable` data member can be modified in `const` member function.
- `mutable` qualifier often used for mutexes, condition variables, cached values, statistical information for performance analysis or debugging.
#include <iostream>
#include <string>

class Employee {
    public:
        Employee(int id, std::string& name, double salary) :
            id_(id), name_(name), salary_(salary), accessCount_(0) {}

        int getId() const {
            ++accessCount_; return id_;}
        std::string getName() const {
            ++accessCount_; return name_;}
        double getSalary() const {
            ++accessCount_; return salary_;}
        
        // ...
        // for debugging
        void outputDebugInfo(std::ostream& out) const {
            out << accessCount_ << '
';}

    private:
        int id_; // employee ID
        std::string name_; // employee name
        double salary_; // employee salary
        mutable unsigned long accessCount_; // for debugging
};
pointers to members provide means to reference particular nonstatic member of class, independent of any class object instance

pointers to member can only be formed for nonstatic (data or function) member of class

can obtain pointer to member that references nonstatic member $m$ in class $T$ by applying address-of operator to $T::m$ (i.e., using expression $&T::m$)
special value nullptr can be given to pointer to member to indicate that pointer to member does not refer to any member

pointer to member of class $T$ written as $T::*$
type of pointer to member embodies type of class and type of member within class

example:

- `int Widget::*` is pointer to member of `Widget` class having type `int`
- `const int Widget::*` is pointer to member of `Widget` class having type `const int`
- `float (Gadget::*)(int) const` is pointer to const member function of `Gadget` class that takes single `int` parameter and has return type of `float`
since pointer to member is not associated with any class object instance, dereferencing pointer to member requires object (or pointer to object) to be specified

given object \( x \) of type \( T \), can access member through pointer to member \( \text{ptm} \) by applying member-selection operator \( .\ast \) to \( x \) using expression \( x.\ast\text{ptm} \)

given pointer \( p \) to object of type \( T \), can access member through pointer to member \( \text{ptm} \) by applying member-selection operator \( \rightarrow\ast \) to \( p \) using expression \( p\rightarrow\ast\text{ptm} \)
Pointers to Members for Data Members

- conceptually, pointer to member for (nonstatic) data member can be thought of as offset (in memory) from start of class object to start of data member (i.e., location of data member *relative to start of class object*)

- since pointer to member does not identify particular object instance (i.e., value for `this`), pointer to member alone not sufficient to specify *particular instance* of member in object

- consequently, when dereferencing pointer to member, must always specify object (or pointer to object)

- example:

```
struct Widget {
  int i;
  inline static int j;
};

int main(){
  Widget w, v;
  int Widget::* ptm = &Widget::i; // pointer to member
  int* jp = &Widget::j;
  // address of static member is ordinary pointer
  w.*ptm = 42; // w.*ptm references w.i
  v.*ptm = 42; // v.*ptm references v.i
  *jp = 42; // references Widget::j
}
```
```cpp
#include <type_traits>

template <class T1, class T2, class T3>
struct triplet {
    triplet(T1 first_, T2 second_, T3 third_) :
        first(first_), second(second_), third(third_) {}
    T1 first;
    T2 second;
    T3 third;
};

int main() {
    using widget = triplet<const int, int, double>;
    widget w(1, 1, 1.0);
    static_assert(std::is_same_v<decltype(&widget::first),
        const int widget::*>);
    static_assert(std::is_same_v<decltype(&widget::second),
        int widget::*>);
    static_assert(std::is_same_v<decltype(&widget::third),
        double widget::*>);
    const int widget::* cp = nullptr;
    int widget::* p = nullptr;
    cp = &widget::first; // OK: constness of pointee same
    cp = &widget::second; // OK: adds const to pointee
    // p = &widget::first; // ERROR: discards const from pointee
    p = &widget::second; // OK: constness of pointee same
}
```
pointer to member for (nonstatic) member function simply identifies particular member function of class (independent of any object instance)

since pointer to member does not identify particular object instance (i.e., value for `this`), pointer to member alone not sufficient to invoke member function

consequently, when dereferencing pointer to member, must always specify object (or pointer to object) so that `this` parameter can be set appropriately

example:

```cpp
struct Widget {
    void func() {/* ... */}
    static void set_verbosity(int level) {/* ... */}
};

int main() {
    Widget w, v;
    void (Widget::* ptm)() = &Widget::func; // pointer to member
    void (*pf)(int) = &Widget::set_verbosity;
    // address of static member is ordinary pointer
    (w.*ptm)(); // calls w.func()
    (v.*ptm)(); // calls v.func()
    (*pf)(42); // calls Widget::set_verbosity()
}
```
#include <string>
#include <cassert>

struct Widget {
    std::string s;
    int i = 0;
    void clear() {i = 0; s = "";}
};

int main() {
    Widget w;
    Widget* wp = &w;

    // pointer to member of Widget of type int
    int Widget::* iptm = nullptr;
    // w.*iptm = 42; // ERROR: null pointer to member
    iptm = &Widget::i; // iptm references i member of Widget
    w.*iptm = 42; // w.*iptm references w.i
    assert(w.i == 42);

    // pointer to member of Widget of type std::string
    std::string Widget::* sptm = &Widget::s;
    wp->*sptm = "hello"; // wp->*sptm references w.s
    assert(w.s == "hello");

    // pointer to member of Widget that is function that takes
    // no parameters and returns void
    void (Widget::* fptm)() = &Widget::clear;
    (w.*fptm)(); // w.*fptm references w.clear
    assert(w.i == 0 && w.s == "");
}
#include <iostream>

class Widget {

public:

    Widget(bool flag) {
        op_ = flag ? &Widget::op_2 : &Widget::op_1;
    }

    void modify() {
        // ...
        (this->*op_)(); // invoke member function
        // ...
    }

private:

    void op_1() {std::cout << "op_1 called\n";}
    void op_2() {std::cout << "op_2 called\n";}
    void (Widget::*op_)(
        // pointer to member function of Widget class that
        // takes no parameters and returns no value
        // ...
    );

int main() {
    Widget u(false);
    Widget v(true);
    u.modify(); // modify invokes op_1
    v.modify(); // modify invokes op_2
}
#include <iostream>
#include <iterator>

struct Point {double x; double y;};
struct Thing {int i; float f;};

template <auto P, class Iter, class T>
T accumulate(Iter first, Iter last, T init_sum) {
    for (auto i = first; i != last; ++i)
    {
        init_sum += i->*P;
    }
    return init_sum;
}

int main() {
    constexpr Point p[]{{1.0, 21.0}, {0.5, 21.0}, {0.5, 0.0}};
    constexpr Thing t[]{{1, 0.1f}, {2, 0.1f}, {3, 0.1f}};
    std::cout
        << accumulate<&Point::x>(std::begin(p), std::end(p), 0.0) << ' '
        << accumulate<&Point::y>(std::begin(p), std::end(p), 0.0) << '

    std::cout
        << accumulate<&Thing::i>(std::begin(t), std::end(t), 0) << ' '
        << accumulate<&Thing::f>(std::begin(t), std::end(t), 0.0f) << '
    }
}
#include <iostream>

template <auto Count, auto Sum, class T, class Value>
void update_statistics(T& stats, Value value) {
    ++(stats.*Count); // adjust count of values
    stats.*Sum += value; // adjust sum of values
}

struct Widget {
    int count = 0; // count
    double sum = 0; // sum
    short int si;
};

struct Gadget {
    int n = 0; // count
    double d;
    double sigma = 0; // sum
};

int main() {
    Widget w;
    Gadget g;
    for (auto&& x : {0.5, 1.5, 2.5}) {
        update_statistics<&Widget::count, &Widget::sum>(w, x);
        update_statistics<&Gadget::n, &Gadget::sigma>(g, x);
    }
    std::cout << w.sum / static_cast<double>(w.count) << '\n';
    std::cout << g.sigma / static_cast<double>(g.n) << '\n';
}
Stream Inserters

- Stream inserters write data to output stream
- Overload `operator<<`
- Have general form
  \[
  \text{std::ostream& } \text{operator}<<(\text{std::ostream&}, \ \text{T}) \text{ where type T is typically const lvalue reference type}
  \]
- Example:
  ```cpp
  \text{std::ostream& } \text{operator}<<(\text{std::ostream& outStream, const Complex& a})
  \{
    \text{outStream } \text{<< a.real()} \text{ } \text{<< ' ' } \text{<< a.imag();
    return } \text{outStream;}
  \}
  ```

- Inserter and extractor should use compatible formats (i.e., what is written by inserter should be readable by extractor)
Stream Extractors

- stream extractors read data from input stream
- overload `operator>>`
- have general form
  ```cpp
  std::istream& operator>>(std::istream&, T) where type T is typically non-const lvalue reference type
  ```
- example:
  ```cpp
  std::istream& operator>>(std::istream& inStream, Complex& a)
  {
    double real = 0.0;
    double imag = 0.0;
    inStream >> real >> imag;
    a = Complex(real, imag);
    return inStream;
  }
  ```
Structured bindings allow, with single statement, multiple variables to be declared and initialized with values from pair, tuple, array, or struct.

- declaration uses auto keyword
- variables enclosed in brackets
- multiple variables separated by commas
```cpp
#include <tuple>
#include <array>
#include <cassert>

int main() {
    int a[3] = {1, 2, 3};
    auto [a0, a1, a2] = a;
    assert(a0 == a[0] && a1 == a[1] && a2 == a[2]);

    int b[3] = {0, 2, 3};
    auto& [b0, b1, b2] = b;
    ++b0;
    assert(b[0] == 1);

    std::array<int, 3> c = {1, 2, 3};
    auto [c0, c1, c2] = c;
    assert(c0 == c[0] && c1 == c[1] && c2 == c[2]);

    auto t = std::tuple(true, 42, 'A');
    auto [tb, ti, tc] = t;
    assert(tb == true && ti == 42 && tc == 'A');
}
```
```cpp
#include <map>
#include <string>
#include <iostream>

int main() {
    std::map<std::string, int> m = {
    {"apple", 1},
    {"banana", 2},
    {"orange", 3},
    };
    for (auto&& [key, value] : m) {
        std::cout << key << ' ' << value << '
';
    }
}
```
**Literal Types**

- each of following types said to be **literal type**: \[C++20 \S6.8/10\]
  - `void`
  - scalar type (e.g., integral, floating point, pointer, enumeration, pointer to member)
  - reference type
  - array of literal type
  - class type that has all of following properties:
    - *has constexpr destructor*
    - is either closure type or aggregate type or has at least one constexpr constructor or constructor template (possibly inherited) that is not copy or move constructor
    - if is union, at least one nonstatic data member is of nonvolatile literal type
    - if is not union, all nonstatic data members and base classes are of nonvolatile literal types

- examples of literal types:
  - `int`, `double`, `std::vector<int>`, `std::string`

- examples of types that are not literal types:
  - `std::list` and `std::set`

- literal types important in context of constexpr variables, functions, and constructors
Example: Literal Types

```cpp
// literal type
class Widget {
    public:
        constexpr Widget(int i = 0) : i_(i) {}
        ~Widget() = default; // constexpr destructor
    private:
        int i_;  
    };

// not literal type
class Gadget {
    public:
        constexpr Gadget() {}
        ~Gadget() {} // non-constexpr destructor
    };

// not literal type
// no constexpr constructor, excluding copy/move constructor
class Foo {
    public:
        Foo() {};
        ~Foo() = default; // constexpr destructor
    };
```
constexpr Variable Requirements

- constexpr variable must satisfy following requirements: \[\text{[C++20 §9.2.5/10]}\]
  - its type must be literal type
  - it must be immediately initialized
  - full expression of its initialization must be constant expression (including all implicit conversions and constructor calls)
  - it must have constant destruction \[\text{[C++20 §7.7/7]}\]
Example: Constexpr Variable Requirement Violations

```cpp
#include <set>
#include <vector>

constexpr std::set s{1, 2, 3};
// ERROR: not literal type

constexpr int i;
// ERROR: not initialized

float func();
constexpr float f = func();
// ERROR: initializer is not constant expression since func is not
// constexpr function

constexpr std::vector<int> v{1, 2, 3};
// ERROR: construction result is not constant expression since
// constructor of std::vector<int> allocates memory via new
```
constexpr function must satisfy following requirements: \[\text{[C++20 §9.2.5/3]}\]

- must not be a coroutine
- its return type (if any) must be literal type
- each of its parameters must be of literal type
- there exists at least one set of argument values such that invocation of function could be evaluated expression of core constant expression
- function body must be either deleted or defaulted or contain any statements except:
  - goto statement
  - statement with label other than `case` and `default`
  - definition of variable of non-literal type
  - definition of variable of static or thread storage duration
Example: Constexpr Function Requirement Violations

```cpp
#include <set>
#include <iostream>

// ERROR: return type not literal type
ccstring std::set<int> get_values()
    { return std::set<int>{1, 2, 3}; }

// ERROR: parameter type not literal type
ccstring void foo(std::set<int> s) { /* ... */ } 

// ERROR: no argument exists such that function can be used
// in constant expression
ccstring void output(int i) {std::cout << i << '\n';}

ccstring void func()
    { std::set<int> v{1, 2, 3};
        // ERROR: definition of variable of non-literal type
        // ...
    }

ccstring int count()
    { static unsigned int i = 0;
        // ERROR: definition of variable with static storage
        // duration
        return i++;
    }
```
- constexpr constructor must satisfy all requirements of constexpr function and constructor’s class must not have any virtual base classes \([\text{C++20 \S 9.2.5/3}]\)

- definition of constexpr constructor whose function body is not \(=\) \texttt{delete} must additionally satisfy following requirements: \([\text{C++20 \S 9.2.5/4}]\)
  - for non-delegating constructor, every constructor selected to initialize nonstatic data members and base class subobjects must be constexpr constructor
  - for delegating constructor, target constructor must be constexpr constructor

- constexpr destructor must satisfy all requirements of constexpr function and destructor’s class must not have any virtual base classes \([\text{C++20 \S 9.2.5/3}]\)

- definition of constexpr destructor whose function body is not \(=\) \texttt{delete} must additionally satisfying following requirements: \([\text{C++20 \S 9.2.5/5}]\)
  - for every subobject of class type or (possibly multidimensional array thereof) that class type must have constexpr destructor

- constructors may be constinit, while destructors cannot be \([\text{C++20 \S 9.2.5/2}]\)
```cpp
#include <set>

class Widget {
public:
    constexpr Widget(std::set<int> s) : i_(s.size()) {} // ERROR: type of constructor parameter not literal type
    // ...
private:
    // only one data member
    int i_;  
};

// OK
class Base {
public:
    Base(int i) : i_(i) {}  
private:
    int i_;  
};

class Derived : public Base {
public:
    constexpr Derived() : Base(42) {} // ERROR: Base constructor not constexpr
    // ...
};
```

Example: Constexpr Constructor Requirement Violations
```cpp
#include <utility>

class widget {
  public:
    constexpr widget(int i = 0) : ip_(new int(i)) {}
    constexpr ~widget() {delete ip_;} 
    constexpr widget(widget&& other) : ip_(nullptr) 
      {std::swap(ip_, other.ip_);} 
    constexpr widget& operator=(widget&& other) {
      std::swap(ip_, other.ip_); 
      return *this;
    }
    constexpr int get() const {return *ip_;}

  private:
    int *ip_; 
};

constexpr int func() {
  widget w(42);
  widget u(std::move(w));
  w = std::move(u);
  return w.get();
}

static_assert(func() == 42);
```
```cpp
#include <cassert>

constexpr void func_1() {
    char c = 'A';
    // c has automatic storage (i.e., on stack)
    const char* p = &c;
    // OK: address of c is well defined
    assert(*p == 'A'); // OK
    // constexpr const char* q = &c;
    /* ERROR: &c not constant expression;
       address of automatic object can be different
       for each invocation of func_1 */
    // above results also same if c is const or constexpr
}

static char sc = 'A';
// sc has static storage (i.e., in program image)
constexpr void func_2() {
    const char* p = &sc;
    // OK: address of sc is fixed and known at compile time
    constexpr const char* q = &sc;
    /* OK: address of static object sc is fixed and known
       at compile time */
    // above results also same if sc is const or constexpr
}
```
Example: Pointers/References to Constexpr Objects

```cpp
class Buffer {
public:
    constexpr Buffer() : data_() {}
    constexpr const char& operator[](unsigned int i) const
    { return data_[i]; }
    constexpr char& operator[](unsigned int i)
    { return data_[i]; }
    constexpr const char* data() const { return data_; }
    // ...
private:
    char data_[256];
};

int main() {
    constexpr Buffer b; // OK
    constexpr Buffer a = b; // OK
    constexpr char c = b[0]; // OK
    // constexpr const Buffer& br = b;
    // ERROR: reference to b is not a constant expression
    // constexpr const char& cr = b[0];
    // ERROR: reference to subobject of b is not constant
    // expression
    // constexpr const char* cp = b.data();
    // ERROR: pointer to subobject of b is not constant
    // expression
    // constexpr const Buffer* bp = &b;
    // ERROR: pointer to b is not constant expression
} 
```
// ERROR: static object not allowed in constexpr function
// (since function would have state that persists across
// invocations)
constexpr unsigned int get_count() {
    static int count = 0;
    return count++;
}

int global_count = 0;
// ERROR: constexpr function cannot modify state outside
// that function that might be used at run time
constexpr int get_global_count() { return global_count++; }

double alpha = 2.0;
// ERROR: constexpr function cannot access state outside
// that function that can be modified at run time.
constexpr double foo(double x) { return alpha * x + 3.0; }
debugging constexpr code can often be somewhat tricky

cannot generate output to assist in debugging (e.g., by writing to standard output/error stream) since cannot perform I/O at compile time

use of source-level debugger not practical, since compiler would need to be run in debugger

could first debug code without constexpr qualifier and then add constexpr qualifier after code is working, but this may not be practical if code must fundamentally execute at compile time (e.g., due to return value of function being assigned to constexpr variable)

can use assert to test for conditions indicative of bugs (since assert(expr) is constant expression if expr is true)

can throw exception if condition indicative of bug is detected (since still constant expression as long as throw statement not executed)
```cpp
#include <stdexcept>
#include <cassert>

constexpr double sqrt(double x) {
    // if assertion fails, sqrt function will not yield
    // constant expression
    assert(x >= 0.0);
    double result = 0.0;
    // ... (correctly initialize result)
    return result;
}

constexpr int foo(unsigned x) {
    unsigned i = 0;
    // ... (code that changes i)
    // assume odd i indicative of bug
    // if i is odd (which would result in exception
    // being thrown), foo function will not yield
    // constant expression
    if (i & 1) {throw std::logic_error("i is odd");}
    return 0;
}
```
- proxy class provides modified interface to another class
- classic example of proxy class is type returned by nonconst overload of subscript operator in `std::vector<bool>` class
- in this case, proxy type serves as stand-in for single `bool` element in vector
in this example, we consider simple container class called `BoolVector` that provides dynamically-sized array of boolean values, where booleans are *packed* into bytes

want to provide only very basic functionality for class:
- member function for querying size of container
- subscript operator for accessing elements in container

return type of nonconst overload of subscript operator is proxy type (called `Proxy`) in order to handle fact that bits are packed into bytes

`BoolVector` is essentially greatly simplified version of `std::vector<bool>`
Proxy Class Example: BoolVector.hpp

```cpp
#include <stddef>
#include <utility>

class BoolVector;

class Proxy {
  public:
    ~Proxy() = default;
    Proxy& operator=(const Proxy&);
    Proxy& operator=(bool b);
    operator bool() const;
  private:
    friend class BoolVector;
    Proxy(const Proxy&) = default;
    Proxy(BoolVector* v, std::size_t i) : v_(v), i_(i) {}
    BoolVector* v_; 
    std::size_t i_; 
  
  inline Proxy& Proxy::operator=(const Proxy& other) {v_->setElem(i_, other); return *this;}
  inline Proxy& Proxy::operator=(bool b) {v_->setElem(i_, b); return *this;}
  inline Proxy::operator bool() const {return v_->getElem(i_);}
};

class BoolVector {
  public:
    BoolVector(std::size_t n) : n_(n), d_(new unsigned char[(n + 7) / 8]) {std::fill_n(d_, (n + 7) / 8, 0);}
    ~BoolVector() {delete [] d_;
    std::size_t size() const {return n_;}
    bool operator[](std::size_t i) const {return getElem(i);}
    Proxy operator[](std::size_t i) {return Proxy(this, i);
  private:
    friend class Proxy;
    bool getElem(std::size_t i) const {return (d_[i / 8] >> (i % 8)) & 1;}
    void setElem(std::size_t i, bool b) { (d_[i / 8] &= ~((1 << (i % 8))) |= (b << (i % 8));
    std::size_t n_; 
    unsigned char* d_; 
};
```
Proxy Class Example: `BoolVector.cpp`

```cpp
#include <cassert>
#include <iostream>
#include "BoolVector.hpp"

int main() {
    constexpr int bits[] = {0, 0, 1, 1, 0, 1, 0, 1};
    constexpr int n = sizeof(bits) / sizeof(int);
    BoolVector v(n);
    BoolVector w(n);
    assert(v.size() == n && w.size() == n);
    for (int i = 0; i < n; ++i) {
        w[i] = v[i] = bits[i];
    }
    const BoolVector& cv = v;
    for (int i = 0; i < n; ++i) {
        assert(v[i] == bits[i]);
        assert(w[i] == bits[i]);
        assert(cv[i] == bits[i]);
        std::cout << (v[i] ? '1' : '0');
    }
    std::cout << '
';
}
```
Implementing Postfix Increment/Decrement Operator

- often, good idea to implement postfix increment/decrement operator in terms of prefix increment/decrement operator
- ensures that prefix and postfix versions of operator always consistent
- example:

```cpp
class Counter {
    public:
        Counter(int count = 0) : count_(count) {} 
        Counter& operator++() {
            ++count_; 
            return *this; 
        }
        Counter operator++(int) {
            Counter old(*this); 
            ++(*this); 
            return old; 
        }
        // similarly for prefix/postfix decrement
    private:
        int count_; 
};
```
pointer to implementation (pimpl) idiom splits interface and implementation across two classes, namely, handle class and implementation class

- all implementation details placed in implementation class
- handle class provides only interface functions which simply forward calls through to implementation class
- handle object has pointer that owns implementation object
- only handle class is exposed to client
- consequently, changes to implementation class do not require client code to be recompiled (since interface has not changed)
- thus, pimpl idiom useful for reducing compile-time dependencies (which can facilitate faster compiles) and maintaining stable class ABIs
```cpp
#include <experimental/propagate_const>
#include <memory>
#include <iostream>

class WidgetImpl {
public:
    void foo() {std::cout << "WidgetImpl::foo()\n";}  
    void foo() const {std::cout << "WidgetImpl::foo() const\n";}
};

class Widget {
public:
    void foo() {p_->foo();}
    void foo() const {p_->foo();}
private:
    std::experimental::propagate_const<std::unique_ptr<WidgetImpl>> p_;  
    /* const or non-const member functions of WidgetImpl invoked
     * as appropriate based on constness of *this; using
     * std::unique_ptr<const WidgetImpl> would cause only const member
     * functions of WidgetImpl to be invoked; using
     * std::unique_ptr<WidgetImpl> would cause only non-const member
     * functions of WidgetImpl to be invoked */
};

int main() {
    Widget w;
    const Widget cw;
    w.foo(); // calls WidgetImpl::foo()
    cw.foo(); // calls WidgetImpl::foo() const
}
```
Section 2.4.5

Functors
- **function object** (also known as **functor**) is object that can be invoked or called as if it were ordinary function
- class that provides member function that overloads `operator()` is called **functor class** and object of that class is **functor**
- functors more flexible than functions as functors are objects and can therefore carry arbitrary state information
- when ordinary function used, function often invoked through pointer whose value cannot be determined at compile time, which makes inlining impossible
- when functor used, function to be called is fixed and always known at compile time (namely, function-call operator for functor class)
- moreover, definition of function-call operator very likely to be visible at point of use, especially if functor created from lambda expression
- consequently, functors often more amenable to inlining
- functors are extremely useful, especially in generic programming
- as we will see later, standard library makes heavy use of functors
```cpp
struct LessThan { // Functor class
    bool operator()(double x, double y) const {
        return x < y;
    }
};

void myFunc() {
    double a = 1.0;
    double b = 2.0;
    LessThan lessThan; // Functor
    bool result = lessThan(a, b);
    // calls LessThan::operator()(double, double)
    // lessThan is functor, not function
    // result == true
}
```
class IsGreater { // Functor class
public:
    IsGreater(int threshold) : threshold_(threshold) {}
    bool operator()(int x) const {
        return x > threshold_;}
private:
    // state information for functor
    int threshold_; // threshold for comparison
};

void myFunc() {
    IsGreater isGreater(5); // functor
    int x = 3;
    bool result = isGreater(x);
    // calls IsGreater::operator()(int)
    // result == false
}
Ordering Relations

- often, need arises to impose some ordering on data
- for example, ordering relation needed for any sorting algorithm or ordered container (such as ordered set, multiset, map, or multimap)
- to define ordering relation, sufficient to specify either less-than (i.e., “precedes”) relation or greater-than (i.e., “follows”) relation
- typically, in C++ (such as in standard library) less-than relation is used to define all other relational operators
- \( \text{less}(x, y) \) is true if \( x \) precedes \( y \) in sorted order and false otherwise
- can synthesize all other relational operators from less as follows:
  - \( \text{greater}(x, y) = \text{less}(y, x) \)
  - \( \text{equal}(x, y) = \neg \text{less}(x, y) \land \neg \text{less}(y, x) \)
  - \( \text{notEqual}(x, y) = \text{less}(x, y) \lor \text{less}(y, x) \)
  - \( \text{lessEqual}(x, y) = \neg \text{less}(y, x) \)
  - \( \text{greaterEqual}(x, y) = \neg \text{less}(x, y) \)
- note: “\( \neg \)” denotes logical NOT, “\( \land \)” denotes logical AND, and “\( \lor \)” denotes logical OR
Selection Sort Example

```cpp
#include <algorithm>
#include <cassert>
#include <forward_list>
#include <functional>
#include <iterator>

// reverse digits in decimal representation of integer
constexpr unsigned int reverse(unsigned int x) {
    unsigned int y = 0;
    for (; x; x /= 10) {auto d = x % 10; x -= d; y = 10 * y + d;}
    return y;
}

custom bool rev_less(unsigned int x, unsigned int y)
    {return reverse(x) < reverse(y);}

template <std::forward_iterator I, class Compare>
void selection_sort(I first, I last, Compare less) {
    for (auto i = first; i != last; ++i)
    {std::iter_swap(i, std::min_element(i, last, less));}
}

int main() {
    std::forward_list<unsigned int> values{12, 21, 123, 321, 1234, 4321};
    selection_sort(values.begin(), values.end(), std::greater<unsigned int>());
    assert((values == std::forward_list<unsigned int>{
        4321, 1234, 321, 123, 21, 12}));
    selection_sort(values.begin(), values.end(), rev_less);
    assert((values == std::forward_list<unsigned int>{
        21, 12, 321, 123, 4321, 1234}));
}
```

Bubble Sort Example

```cpp
#include <algorithm>
#include <cassert>
#include <forward_list>
#include <functional>
#include <iterator>

template <std::forward_iterator I, class Compare>
void bubble_sort(I first, I last, Compare less) {
    for (auto sorted = first; first != last; last = sorted) {
        sorted = first;
        for (auto cur = first, prev = first; ++cur != last; ++prev) {
            if (less(*cur, *prev)) {
                std::iter_swap(cur, prev);
                sorted = cur;
            }
        }
    }
}

int main() {
    std::forward_list<int> values{7, 0, 6, 1, 5, 2, 4, 3};
    bubble_sort(values.begin(), values.end(), std::less<int>());
    assert((values == std::forward_list<int>{0, 1, 2, 3, 4, 5, 6, 7}));
    bubble_sort(values.begin(), values.end(), std::greater<int>());
    assert((values == std::forward_list<int>{7, 6, 5, 4, 3, 2, 1, 0}));
}```
#include <cassert>
#include <algorithm>
#include <set>

template <class T> class compare {
public:
    constexpr compare(bool less = true) : less_(less) {}
    constexpr bool operator()(const T& x, const T& y) const
    { return less_ ? (x < y) : (x > y); }

private:
    bool less_;
};

constexpr bool even_then_odd(int x, int y)
    { if ((x % 2) != (y % 2)) { return !(x % 2); } else { return x < y; } }

int main() {
    constexpr int values[] = {0, 7, 6, 1, 2, 5, 3, 4};
    std::set<int, compare<int>> s1(std::begin(values), std::end(values));
    constexpr int d1[] = {0, 1, 2, 3, 4, 5, 6, 7};
    assert(std::equal(s1.begin(), s1.end(), std::begin(d1)));
    std::set<int, compare<int>> s2(std::begin(values), std::end(values),
    compare<int>(false));
    constexpr int d2[] = {7, 6, 5, 4, 3, 2, 1, 0};
    assert(std::equal(s2.begin(), s2.end(), std::begin(d2)));
    std::set<int, bool (*)(int, int)> s3(std::begin(values), std::end(values),
    even_then_odd);
    constexpr int d3[] = {0, 2, 4, 6, 1, 3, 5, 7};
    assert(std::equal(s3.begin(), s3.end(), std::begin(d3)));
}
Comparison Object Propagation

- invariant of ordered container: elements of container always sorted with respect to ordering relation defined by comparison object

- thus, state for ordered container (ignoring possible allocator) consists of:
  1. elements in container; and
  2. comparison object that determines order of those elements

- consider propagating value of one container to another (via copy or move)

- when propagating value of container, two choices possible:
  1. propagate comparison object
  2. do not propagate comparison object

- if comparison object not propagated and source and destination comparison objects differ, must re-sort elements (to be consistent with destination comparison object) to avoid violating container invariant

- if no equality/inequality operator provided by comparison-object type, must assume worst (i.e., not equal) and always re-sort

- if comparison object propagated, never any need to re-sort elements

- for efficiency, prefer solution of always propagating comparison object
#include <algorithm>
#include <cassert>
#include <set>
#include <utility>

// Comparison Object Propagation Example

template <class T> class compare {
public:
    compare(bool less = true) : less_(less) {}
    bool operator()(const T& x, const T& y) const
    { return less_ ? (x < y) : (x > y); }
    bool less() const { return less_; }
private:
    bool less_;  
};

int main() {
    constexpr int values[] = {0, 7, 6, 1, 2, 5, 3, 4};
    std::set<int, compare<int>> s3(values, std::end(values));
    std::set<int, compare<int>> s1(std::move(s3)); // move construct
    assert(s1.key_comp().less()); // comparison object was moved
    std::set<int, compare<int>> s2(s1); // copy construct
    assert(s2.key_comp().less()); // comparison object was copied
    s3 = std::set<int, compare<int>>(values, std::end(values),
      compare<int>(false));
    assert(s1.key_comp().less() && !s3.key_comp().less());
    s1 = std::move(s3); // move assign
    assert(!s1.key_comp().less()); // comparison object was moved
    assert(s2.key_comp().less() && !s1.key_comp().less());
    s2 = s1; // copy assign
    assert(!s2.key_comp().less()); // comparison object was copied
}
Section 2.4.6

References


Section 2.5

Templates
**generic programming**: algorithms written in terms of types to be specified later (i.e., algorithms are generic in sense of being applicable to any type that meets only some very basic constraints)

- templates facilitate generic programming
- extremely important language feature
- avoids code duplication
- leads to highly efficient and customizable code
- promotes code reuse
- C++ standard library makes very heavy use of templates (actually, most of standard library consists of templates)
- many other libraries make heavy use of templates (e.g., CGAL, Boost)
Section 2.5.1

Function Templates
Motivation for Function Templates

consider following functions:

```c
int max(int x, int y)
{ return x > y ? x : y; }
```

```c
double max(double x, double y)
{ return x > y ? x : y; }
```

// more similar-looking max functions...

each of above functions has same general form; that is, for some type T, we have:

```c
T max(T x, T y)
{ return x > y ? x : y; }
```

would be nice if we did not have to repeatedly type, debug, test, and maintain nearly identical code

in effect, would like code to be parameterized on type T
function template is family of functions parameterized by one or more parameters

each template parameter can be: non-type (e.g., integral constant), type, template, or parameter pack (in case of variadic template)

syntax for template function has general form:

```
template <parameter_list> function_declaration
```

parameter_list: parameters on which template function depends

function_declaration: function declaration or definition

type parameter designated by class or typename keyword

template parameter designated by template keyword

non-type parameter designed by its type (e.g., bool, int)

example:

```cpp
// declaration of function template
template <class T> T max(T x, T y);

// definition of function template
template <class T> T max(T x, T y)
{return x > y ? x : y;}
```
to explicitly identify particular instance of template, use syntax:

\[ f(\text{parameters}) \]

e.g., for function template declaration:

\[
\text{template } <\text{class } T> \ T \ \text{max}(T \ x, \ T \ y);
\]

\[
\text{max<\text{int}> refers to int max(int, int)}
\]

\[
\text{max<\text{double}> refers to double max(double, double)}
\]

compiler only creates code for function template when it is instantiated (i.e., used)

therefore, definition of function template must be visible in place where it is instantiated

consequently, function template definitions usually appear in header file

template code only needs to pass basic syntax checks, unless actually instantiated
// compute minimum of two values

```cpp
template <typename T>
T min(T x, T y) {
    return x < y ? x : y;
}
```

// compute square of value

```cpp
template <typename T>
T sqr(T x) {
    return x * x;
}
```

// swap two values

```cpp
template <typename T>
void swap(T& x, T& y) {
    T tmp = x;
    x = y;
    y = tmp;
}
```

// invoke function/functor multiple times

```cpp
template <int N = 1, typename F, typename T>
void invoke(F func, const T& value) {
    for (int i = 0; i < N; ++i) {
        func(value);
    }
}
```
Template Function Overload Resolution

- overload resolution proceeds (in order) as follows:
  1. look for an exact match with zero or more trivial conversions on (nontemplate) functions; if found call it
  2. look for function template from which function that can be called with exact match with zero or more trivial conversions can be generated; if found, call it
  3. try ordinary overload resolution for functions; if function found, call it; otherwise, call is error

- in each step, if more than one match found, call is ambiguous and is error
- template function only used in case of exact match, unless explicitly forced

example:

```cpp
template <class T>
T max(T x, T y) {return x > y ? x : y;}

void func(int i, int j, double x, double y) {
    double z = max(x, y); // calls max<double>
    int k = max(i, j); // calls max<int>
    z = max(i, x); // ERROR: no match
    z = max<double>(i, x); // calls max<double>
}
```
Qualified Names

- **qualified name** is a name that specifies scope

  example:

  ```cpp
  #include <iostream>

  int main(int argc, char** argv) {
      for (int i = 0; i < 10; ++i) {
          std::cout << "Hello, world!" << std::endl;
      }
  }
  ```

  In the above example, names `std::cout` and `std::endl` are qualified, while names `main`, `argc`, `argv`, and `i`, are not qualified.
■ **dependent name** is name that depends on template parameter

[C++17 §17.6.2.1/9]

■ example:

```cpp
template <class T>
void func(const T& x) {
    int i = T::magicValue;
    // ...
}
```

■ *name* `T::magicValue` is dependent
Qualified Dependent Names

- to avoid any potential ambiguities, compiler will automatically assume qualified dependent name does not name type unless `typename` keyword is used
- must precede qualified dependent name that names type by `typename`
- in following example, note use of `typename` keyword:

```cpp
#include <vector>

template <class T>
void func(const T& x) {
    std::vector<T> v(42, x);
    // std::vector<T>::const_iterator is qualified dependent name
    for (typename std::vector<T>::const_iterator i = v.begin(); i != v.end(); ++i) {
        // std::vector<T>::value_type is qualified dependent name
        typename std::vector<T>::value_type x = *i;
        // ...
    }
    // ...
```
Why `typename` is Needed

```cpp
int x = 42;

template <class T> void func() {
    /* The compiler must be able to check the syntactic correctness of this template code without knowing the type T. Without knowing the type T, however, the meaning of the following line of code is ambiguous, unless the compiler follows some fixed rule for resolving this ambiguity. In particular, is this line of code a declaration of a variable x or an expression consisting of a binary operator* with operands T::foo and x? */
    T::foo* x; // Does T::foo name a type or an object?
}

struct ContainsType {
    using foo = int; // foo is type
};

struct ContainsValue {
    static int foo; // foo is value
};

int main() {
    // Only one of the following two lines should be valid.
    func<ContainsValue>();
    func<ContainsType>();
}
```
Section 2.5.2

Class Templates
Motivation for Class Templates

consider almost identical complex number classes:

```cpp
class ComplexDouble {
public:
    ComplexDouble(double x = 0.0, double y = 0.0) : x_(x), y_(y) {} 
    double real() const { return x_; }
    double imag() const { return y_; }
    // ...
private:
    double x_, y_; // real and imaginary parts
};

class ComplexFloat {
public:
    ComplexFloat(float x = 0.0f, float y = 0.0f) : x_(x), y_(y) {} 
    float real() const { return x_; }
    float imag() const { return y_; }
    // ...
private:
    float x_, y_; // real and imaginary parts
};
```

both of above classes are special cases of following class parameterized on type T:

```cpp
class Complex {
public:
    Complex(T x = T(0), T y = T(0)) : x_(x), y_(y) {} 
    T real() const { return x_; }
    T imag() const { return y_; }
    // ...
private:
    T x_, y_; // real and imaginary parts
};
```

again, would be nice if we did not have to repeatedly type, debug, test, and maintain nearly identical code
- **class template** is family of classes parameterized on one or more parameters.
- Each template parameter can be: non-type (e.g., integral constant), type, template, or parameter pack (in case of variadic template).
- Syntax has general form:
  
  ```
  template <parameter_list> class declaration
  ```

- `parameter_list`: parameter list for class.
- `class_declaration`: class/struct declaration or definition.
- Example:

  ```
  // declaration of class template
  template <class T, unsigned int size>
  class MyArray;

  // definition of class template
  template <class T, unsigned int size>
  class MyArray {
    // ...
    T array_[size];
  };

  MyArray<
  double,
  100
  > x;
  ```
Compiler only generates code for class template when it is instantiated (i.e., used)

Since compiler only generates code for class template when it is instantiated, definition of template must be visible at point where instantiated

Consequently, class template code usually placed in header file

Template code only needs to pass basic syntax checks, unless actually instantiated

Compile errors related to class templates can often be very long and difficult to parse (especially, when template class has parameters that are template classes which, in turn, have parameters that are template classes, and so on)
// complex number class template

```cpp
template <class T>
class Complex {

public:
    Complex(T x = T(0), T y = T(0)) :
        x_(x), y_(y) {}  
    T real() const {
        return x_;        
    }
    T imag() const {
        return y_;        
    }  
};

Complex<int> zi;
Complex<double> zd;
```
class template parameters can have *default values*

example:

```cpp
template <class T = int, unsigned int size = 2>
struct MyArray {
    T data[size];
};

MyArray<> a; // MyArray<int, 2>
MyArray<double> b; // MyArray<double, 2>
MyArray<double, 10> b; // MyArray<double, 10>
```
Qualified Dependent Names Revisited

- recall, qualified dependent name assumed not to name type, unless preceded by `typename` keyword
- in following example, note use of `typename` keyword:

```cpp
#include <vector>

template <class T> class Vector {
    public:
        using Coordinate = typename T::Coordinate;
        using Distance = typename T::Distance;
    Vector(const std::vector<Coordinate>& coords) :
        coords_(coords) {}
    Distance squaredLength() const {
        Distance d = Distance(0);
        for (typename std::vector<Coordinate>::const_iterator i =
            coords_.begin(); i != coords_.end(); ++i) {
            typename std::vector<Coordinate>::value_type x = *i;
            d += x * x;
        }
        return d;
    }
    private:
        std::vector<Coordinate> coords_;}
```
Why `template` is Needed

```cpp
template<bool> struct Widget;

template<bool B> struct Gadget {
    static int g() {
        /* The compiler must be able to check the syntactic correctness of this template code without knowing the value of B. Without knowing the value of B, however, the meaning of the following line of code is ambiguous, unless the compiler follows some fixed rule for resolving this ambiguity. In particular, is this line of code using a data member called f and evaluating (f < 0 > 42) or is it calling a template member function called f with the argument 42? */
        return Widget<B>::f<0>(42);
    }
};

template<bool B> struct Widget {
    template<int I> static int f(int i) {return i + I;}
};

template<> struct Widget<false> {inline static int f = 42;};

int main() {
    // Only one of the following two lines should be valid.
    Gadget<true>::g();
    Gadget<false>::g();
}
```
```cpp
#include <vector>
#include <list>
#include <deque>
#include <memory>

template <template <class, class> class Container, class Value>
class Stack {
public:
  // ...
private:
  Container<Value, std::allocator<Value>> data_; 
};

int main() {
  Stack<std::vector, int> s1;
  Stack<std::list, int> s2;
  Stack<std::deque, int> s3;
}
```
template parameters for class template can be deduced based on arguments passed to constructor

example:

```cpp
std::tuple t(42, 'A');
// OK: deduced as tuple<int, char>
```

deduction only performed if no template arguments provided

example:

```cpp
std::tuple<int> t(1, 2);
// ERROR: missing template parameter, as no template parameter deduction takes place
```
```
#include <vector>
#include <tuple>
#include <set>
#include <string>

using namespace std::string_literals;

auto get_tuple() {
    return std::tuple("Zaphod"s, 42);
    // deduces tuple<std::string, int>
}

int main() {
    std::vector v{1, 2, 3};
    // deduces vector<int>
    std::tuple t(true, 'A', 42);
    // deduces tuple<bool, char, int>
    std::pair p(42, "Hello"s);
    // deduces pair<int, std::string>
    std::set s{0.5, 0.25};
    // deduces set<double>
    //auto ptr = new std::tuple(true, 42);
    // should deduce tuple<bool, int>?
    // fails to compile with GCC 7.1.0
    }
```
Template Deduction Guides

- can provide additional rules to be used to determine how class template parameters should be deduced when not provided
- such rules called deduction guides
- deduction guide itself can be either template or non-template
- deduction guides must be introduced in same scope as class template
- example:
  ```cpp
  // class definition
template <class T> smart_ptr {/* ... */};
  // deduction guide
template <class T>
  smart_ptr(T*) -> smart_ptr<T>;
  ```
- example:
  ```cpp
  /// class definition
template <class T> name {/* ... */};
  // deduction guide
  name(const char*) -> name<std::string>;
  ```
```cpp
#include <string>
#include <type_traits>

using namespace std::string_literals;

template <class T>
class Name {
public:
    Name(T first, T last) : first_(first), last_(last) {}
    // ...
private:
    T first_;  
    T last_;  
};

// deduction guide  
Name(const char*, const char*) -> Name<std::string>;

int main() {
    Name n("Zaphod", "Beeblebrox");  
    // deduces Name<std::string> via deduction guide
    static_assert(std::is_same_v<decltype(n), Name<std::string>>);  
    Name n2("Jane"s, "Doe"s);  
    // deduces Name<std::string> (without deduction guide)
    static_assert(std::is_same_v<decltype(n2), Name<std::string>>);  
}
```
can use `auto` keyword for non-type template parameter

in such case, type of non-type template parameter will be deduced

example:
```cpp
template <auto v>
struct constant {
    static constexpr decltype(v) value = v;
};
using forty_two_type = constant<42>;
// template parameter v deduced to have type int
```

non-type template parameter type deduction probably most useful for template metaprogramming
# Example Without Auto Non-Type Template Parameter

```cpp
#include <cstdlib>
#include <iostream>

template<class T, T v>
struct integral_constant {
    using value_type = T;
    static constexpr value_type value = v;
    using type = integral_constant;
    constexpr operator value_type() const noexcept { return value; }
    constexpr value_type operator()() const noexcept { return value; }
};

using forty_two_type = integral_constant<int, 42>;

int main() {
    constexpr forty_two_type x;
    constexpr auto v = x.value;
    std::cout << v << '
';
}
```
```cpp
#include <cstdlib>
#include <iostream>

template<auto v>
struct integral_constant {
    using value_type = decltype(v);
    static constexpr value_type value = v;
    using type = integral_constant;
    constexpr operator value_type() const noexcept {
        return value;
    }
    constexpr value_type operator()() const noexcept {
        return value;
    }
};

using forty_two_type = integral_constant<42>;

int main() {
    constexpr forty_two_type x;
    constexpr auto v = x.value;
    std::cout << v << '
';
}
```
Section 2.5.3

Variable Templates
**Variable Templates**

- **variable template** is family of variables parameterized on one or more parameters
- each template parameter can be: non-type (e.g., integral constant), type, template, or parameter pack (in case of variadic templates)
- although less frequently used than function and class templates, variable templates quite useful in some situations
- syntax has general form:

  \[
  \text{template } \langle \text{parameter\_list}\rangle \text{ variable\_declaration}
  \]

- **parameter\_list**: parameter list for variable template
- **variable\_declaration**: variable declaration or definition
- example:

  ```cpp
  \text{template } \langle \text{class } T\rangle
  T \text{ meaning\_of\_life } = T(42);\n  
  \text{int } x = \text{ meaning\_of\_life<\text{int>>};}
  ```
Variable Template Example: \( \pi \)

```cpp
#include <limits>
#include <complex>
#include <iostream>

template <typename T>
constexpr T pi =
    T(3.14159265358979323846264338327950288419716939937510L);

int main() {
    std::cout.precision(
        std::numeric_limits<long double>::max_digits10);
    std::cout
    << pi<int> << '
' << pi<float> << '
' << pi<double> << '
' << pi<long double> << '
' << pi<std::complex<float>> << '
' << pi<std::complex<double>> << '
' << pi<std::complex<long double>> << '
';
}
```
Section 2.5.4

Alias Templates
**Alias Templates**

- **alias template** is a family of types parameterized on one or more parameters.
- Each template parameter can be: non-type (e.g., integral constant), type, template, or parameter pack (in case of variadic templates).
- Syntax has general form:

  ```
  template <parameter_list> alias_declaration
  ```

  - **parameter_list**: parameter list for class.
  - **alias_declaration**: alias declaration (i.e., with `using`).

- Example:

  ```
  template <class Value,
             class Alloc = std::allocator<Value>>
  using GreaterMultiSet = 
    std::multiset<Value, std::greater<Value>, Alloc>;
  
  GreaterMultiSet<int> x{4, 1, 3, 2};
  ```
```cpp
#include <iostream>
#include <set>

// alias template for set that employs std::greater for comparison

template <typename Value, typename Alloc = std::allocator<Value>>
using GreaterSet = std::set<Value, std::greater<Value>, Alloc>;

int main() {
    std::set<int> x{1, 4, 3, 2};
    GreaterSet<int> y{1, 4, 3, 2};
    for (auto i : x) {
        std::cout << i << '
';
    }
    std::cout << '
';
    for (auto i : y) {
        std::cout << i << '
';
    }
}
```
Section 2.5.5

Variadic Templates
Variadic Templates

- The language provides the ability to specify a template that can take a variable number of arguments.

- A template that can take a variable number of arguments is called a variadic template.

- Alias templates, class templates, function templates, and variable templates may be variadic.

- A variable number of arguments is specified by using what is called a parameter pack.

- A parameter pack is a parameter that accepts (i.e., is a placeholder for) zero or more arguments (of the same kind).

- A parameter pack used in the parameter list of a template allows for a variable number of template parameters.

- Ellipsis (i.e., “...”) is used in various contexts relating to parameter packs.

- Ellipsis after a designator for the kind of template argument in a template parameter list designates that the argument is a parameter pack.

- Ellipsis after a parameter pack parameter expands the parameter pack in a context-sensitive manner.
Parameter Packs

- syntax for non-type template parameter pack named $Args$ and containing elements of type $type$ (e.g., $\text{bool}$, $\text{int}$, $\text{unsigned int}$):
  
  \[
  \text{type}\ldots Args
  \]

- example:

  \[
  \text{template} \ <\text{int}\ldots Is> \ /* \ldots */ 
  \]

  $Is$ is (non-type) template parameter pack that corresponds to zero or more (compile-time constant) values of type $\text{int}$

- syntax for type template parameter pack named $Args$:

  \[
  \text{typename}\ldots Args
  \]

  or equivalently

  \[
  \text{class}\ldots Args
  \]

- examples:

  \[
  \text{template} \ <\text{typename}\ldots Ts> \ /* \ldots */ 
  \]
  \[
  \text{template} \ <\text{class}\ldots Ts> \ /* \ldots */ 
  \]

  $Ts$ is (type) template parameter pack that corresponds to zero or more types
Parameter Packs (Continued 1)

■ syntax for template template parameter pack named Args:

```
template <parameter_list> typename... Args
```
or equivalently

```
template <parameter_list> class... Args
```

■ example:

```
template <template <class T> class... Ts>
    /* ... */
```

Ts is (template) template parameter pack that corresponds to zero or more templates

■ syntax for function parameter pack named args whose elements have types corresponding to elements of type template parameter pack Args:

```
Args... args
```

■ example:

```
template <class... Ts> void func(Ts... args);
```

args is (function) parameter pack that corresponds to zero or more function parameters whose types correspond to elements of type parameter pack Ts
Parameter Packs (Continued 2)

- in context where template arguments cannot be deduced (e.g., primary class templates), only last template parameter can be parameter pack
- in context where template arguments can be deduced (e.g., function templates and class template partial specializations), template parameter pack need not be last template parameter
- example:

```cpp
template <class U, class... Ts> class C1 { /* ... */ };
    // OK: Ts is last template parameter

template <class... Ts, class U> class C2 { /* ... */ };
    // ERROR: Ts not last and U not deduced

template <class... Ts, class U> void f1(Ts... ts)
    { /* ... */ } // NOT OK: Ts not last and U not deduced

template <class... Ts, class U> void f2(Ts... ts, U u)
    { /* ... */ } // OK: Ts not last but U is deduced

int main()
{
    f1<int, int, bool>(1, 2, true);
        // ERROR: no matching function call
    f2<int, int>(1, 2, true);  // OK
    f2(1, 2, true);  // ERROR: one argument expected
}
```
Parameter Pack Expansion

- **parameter pack expansion**: expands pack into its constituent elements
- syntax for parameter pack expansion of expression *pattern*, which must contain parameter pack:
  
  *pattern...*

- example:

```cpp
1 template <class... Ts> void f(Ts... t) { /* ... */ }
2
3 template <class... Us> void g(Us... u) {
4     f(u...);
5     // u... is pack expansion
6     // when g is called by main,
7     // u... expands to 1, 2.0, 3.0f
8 }
9
10 int main() {
11    g(1, 2.0, 3.0f);
12 }
```
#include <tuple>

// variadic alias template
template <class... T>
using My_tuple = std::tuple<bool, T...>;

// variadic class template
template <int... Values>
class Integer_sequence {
    // ...
};

// variadic function template
template <class... Ts>
void print(const Ts&... values) {
    // ...
}

// variadic variable template
template <typename T, T... Values>
constexpr T array[] = {Values...};

int main() {
    Integer_sequence<1, 3, 4, 2> x;
    auto a = array<int, 1, 2, 4, 8>;
    My_tuple<int, double> t(true, 42, 42.0);
    print(1'000'000, 1, 43.2, "Hello");
}
Parameter Pack Expansion

- parameter pack expansion allowed in following contexts:
  - inside parentheses of function call operator
  - in template argument list
  - in function parameter list
  - in template parameter list
  - base class specifiers in class declaration
  - member initializer lists
  - braced initializer lists
  - lambda captures
  - fold expressions
  - in using declarations

[C++17 §17.5.3/4]
The `sizeof...` Operator

- `sizeof...` operator yields number of elements in parameter pack

- example:

  ```cpp
template <int... Values>
constexpr int numparms = sizeof...(Values);

static_assert(numparms<1, 2, 3> == 3);
static_assert(numparms<> == 0);
```

- example:

  ```cpp
#include <cassert>

template <typename... Ts>
int number_of_arguments(const Ts&... args) {
    return sizeof...(args);
}

int main() {
    assert(number_of_arguments(1, 2, 3) == 3);
    assert(number_of_arguments() == 0);
}
```
# Variadic Function Template: `sum`

```cpp
#include <iostream>
#include <string>

using namespace std::string_literals;

template <class T>
auto sum(T x) {
    return x;
}

template <class T, class... Args>
auto sum(T x, Args... args) {
    return x + sum(args...);
}

int main() {
    auto x = sum(42.5, -1.0, 0.5f);
    auto y = sum("The "s, "answer "s, "is "s);
    std::cout << y << x << ".\n"
    // sum(); // ERROR: no matching function call
}

/* Output:
The answer is 42.
*/
```
Variadic Function Template: maximum

```cpp
#include <type_traits>
#include <string>
#include <cassert>

using namespace std::string_literals;

template <typename T>
T maximum(const T& a) { return a; }

template <typename T1, typename T2>
type_name std::common_type_t<
const T1&, const T2&>
maximum(const T1 &a, const T2 &b) {
    return a > b ? a : b;
}

template <typename T1, typename T2, typename... Args>
type_name std::common_type_t<
const T1&, const T2&,
    const Args&...>
maximum(const T1& a, const T2& b, const Args&... args) {
    return maximum(maximum(a, b), args...);
}

int main() {
    assert(maximum(1) == 1);
    assert(maximum(1, 2, 3, 4, -1.4) == 4);
    assert(maximum(-1'000'000L, -42L, 10, 42.42) == 42.42);
    assert(maximum("apple"s, "zebra"s, "c++"s) == "zebra"s);
}
```
#include <iostream>
#include <vector>
#include <string>
#include <set>

template <template <class, class...> class ContainerType, class ValueType, class... Args>
bool print_container(const ContainerType<ValueType, Args...>& c) {
    for (auto i = c.begin(); i != c.end(); ) {
        std::cout << *i;
        if (++i != c.end()) {std::cout << ' ';}  
    }
    std::cout << '\n';
    return bool(std::cout);
}

int main() {
    using namespace std::string_literals;
    std::vector vi{1, 2, 3, 4, 5};
    std::set si{5, 4, 3, 2, 1};
    std::set ss{"world\s", "hello\s"};
    print_container(vi);
    print_container(si);
    print_container(ss);
}
# Variadic Class Template: `Integer_sequence`

```cpp
#include <iostream>
#include <cstdlib>

template <class T, T... Values>
class Integer_sequence {
  public:
    using value_type = T;
    using const_iterator = const T*;
    constexpr std::size_t size() const
    { return sizeof...(Values); }
    constexpr T operator[](int i) const { return values_[i]; }
    constexpr const_iterator begin() const
    { return &values_[0]; }
    constexpr const_iterator end() const
    { return &values_[size()]; }
  private:
    static constexpr T values_[sizeof...(Values)] = {Values...};
  }

template <class T, T... Values>
constexpr T Integer_sequence<T, Values...>::values_[sizeof...(Values)];

int main() {
  Integer_sequence<std::size_t, 1, 2, 4, 8> seq;
  std::cout << seq.size() << '
' << seq[0] << '
';
  for (auto i : seq) {std::cout << i << '
';
}  ```
#include <iostream>

template <int... Args>
constexpr int int_array[] = {Args...};

int main() {
    for (auto i : int_array<1,2,4,8>) {
        std::cout << i << '
';
    }
}

/* Output:
1
2
4
8 */
#include <iostream>
#include <string>
#include <tuple>

// Variadic Alias Template: My_tuple

template <class... Ts>
using My_tuple = std::tuple<bool, Ts...>;

int main() {
    My_tuple<int, std::string> t(true, 42, "meaning of life");
    std::cout << std::get<0>(t) << ' ' << std::get<1>(t) << ' ' << std::get<2>(t) << '
';
}

/* Output:
1 42 meaning of life
*/
Fold Expressions

- may want to apply binary operator (such as +) across all elements in parameter pack
- fold expression reduces (i.e., folds) parameter pack over binary operator
- \( op \): binary operator
- \( E \): expression that contains unexpanded parameter pack
- \( I \): expression that does not contain unexpanded parameter pack

### Fold Syntax

<table>
<thead>
<tr>
<th>Fold</th>
<th>Syntax</th>
<th>Expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>unary left</td>
<td>((... \text{ op } E))</td>
<td>((E_1 \text{ op } E_2 \text{ op } ...) \text{ op } E_N)</td>
</tr>
<tr>
<td>unary right</td>
<td>((E \text{ op } ...))</td>
<td>(E_1 \text{ op } (... \text{ op } (E_{N-1} \text{ op } E_N)))</td>
</tr>
<tr>
<td>binary left</td>
<td>((I \text{ op } ... \text{ op } E))</td>
<td>(((I \text{ op } E_1) \text{ op } E_2 \text{ op } ...) \text{ op } E_N)</td>
</tr>
<tr>
<td>binary right</td>
<td>((E \text{ op } ... \text{ op } I))</td>
<td>(E_1 \text{ op } (... \text{ op } (E_{N-1} \text{ op } (E_N \text{ op } I))))</td>
</tr>
</tbody>
</table>

[C++17 §17.5.3/9]

### Unary Fold of Empty Parameter Pack

[C++17 §17.5.3/9]

<table>
<thead>
<tr>
<th>Operator</th>
<th>Value for Empty Parameter Pack</th>
</tr>
</thead>
<tbody>
<tr>
<td>&amp;&amp;</td>
<td>\texttt{true}</td>
</tr>
<tr>
<td>||</td>
<td>\texttt{false}</td>
</tr>
<tr>
<td>,</td>
<td>\texttt{void()}</td>
</tr>
</tbody>
</table>
```cpp
#include <iostream>
#include <string>

using namespace std::string_literals;

template <class T>
avo sum(T x) {
    return x;
}

template <class T, class... Args>
auto sum(T x, Args... args) {
    return x + sum(args...);
}

int main() {
    auto x = sum(42.5, -1.0, 0.5f);
    auto y = sum("The "s, "answer "s, "is "s);
    std::cout << y << x << ".\n";
    // sum(); // ERROR: no matching function call
}

/* Output:
The answer is 42.
*/
```
#include <iostream>
#include <string>

using namespace std::string_literals;

template <class T, class... Args>
auto sum(T x, Args... args) {
    return x + (... + args);
}

int main() {
    auto x = sum(42.5, -1.0, 0.5f);
    auto y = sum("The "s, "answer "s, "is "s);
    std::cout << y << x << ".\n";
    // sum(); // ERROR: no matching function call
}

/* Output:
The answer is 42.
*/
```cpp
#include <iostream>
#include <string>

using namespace std::string_literals;

std::ostream& print() { return std::cout; }

template <class T>
std::ostream& print(const T& value) {
    return std::cout << value;
}

template <class T, class... Args>
std::ostream& print(const T& value, const Args&... args) {
    if (!(std::cout << value)) {
        return std::cout;
    }
    return print(args...);
}

int main() {
    print("The "s, "answer "s, "is "s, 42, "\n"s);
    print(); // OK: no-op
}

/* Output:
The answer is 42.
*/
```
```cpp
#include <iostream>
#include <string>

using namespace std::string_literals;

template <class... Args>
std::ostream& print(const Args&... args) {
    return (std::cout << ... << args);
}

int main() {
    print("The "s, "answer "s, "is "s, 42, "\n"s);
    print(); // OK: no-op
}

/* Output:
The answer is 42.
*/
```
```cpp
#include <cassert>

// Define the fold expressions

// All elements of a given sequence are true?

template <class... Args>
bool all(Args... args)
{
    return (... && args);
}

// Any element of a given sequence is true?

template <class... Args>
bool any(Args... args)
{
    return (... || args);
}

// Exactly one element of a given sequence is true?

template <class... Args>
bool one(Args... args)
{
    return (0 + ... + args) == 1;
}

// Even number of true elements?

template <class... Args>
bool even(Args... args)
{
    return (1 + ... + args) % 2;
}

int main()
{
    assert(all(false, true, true) == false);
    assert(all(true, true, true) == true);
    assert(any(false, false, true) == true);
    assert(any(false, false, false) == false);
    assert(one(true, false, false) == true);
    assert(one(true, true, false) == false);
    assert(even(true, true, false) == true);
    assert(even(true, false, false) == false);
    assert(even() == true && one() == false);
    return 0;
}
```
```cpp
#include <iostream>
#include <tuple>

// heterogeneous list of constant values
template <auto... vs> class value_list {
  public:
    constexpr value_list() : v_(vs...) {}
    template <int n> constexpr auto get() const
    { return std::get<n>(v_); }
    constexpr int size() const { return sizeof...(vs); }
  private:
    std::tuple<decltype(v...)> v_;}

int main() {
    constexpr value_list<42, true, 'A'> v;
    constexpr auto n = v.size();
    constexpr auto a = v.get<0>();
    constexpr auto b = v.get<1>();
    constexpr auto c = v.get<2>();
    std::cout << n << ' ' << a << ' ' << b << ' ' << c << '
';
}
```
```cpp
#include <iostream>
#include <tuple>

// homogeneous list of constant values
template <auto v1, decltype(v1)... vs>
class value_list {
public:
    constexpr value_list() : v_(v1, vs...) {}
    template <int n> constexpr auto get() const
        { return std::get<n>(v_); }
    constexpr int size() const { return 1 + sizeof...(vs); }
private:
    std::tuple< decltype(v1), decltype(vs)... > v_; }

template <auto v1, decltype(v1)... vs>
int main() {
    constexpr value_list<1, 2, 3> v;
    constexpr auto n = v.size();
    constexpr auto a = v.get<0>();
    constexpr auto b = v.get<1>();
    constexpr auto c = v.get<2>();
    std::cout << n << ' ' << a << ' ' << b << ' ' << c << '
';
}
```

Section 2.5.6

Template Specialization
sometimes can be desirable to provide customized version of template for certain choices of template parameters

customized version of templates can be specified through language feature known as **template specialization**

two kinds of specialization: explicit and partial

**explicit specialization** (less formally known as full specialization): customized version of template where all template parameters are fixed

**partial specialization**: customized version of template where only some of template parameters are fixed

class templates, function templates, and variable templates can all be specialized

alias templates cannot be specialized

class templates and variable templates can be partially or explicitly specialized

function templates can only be explicitly specialized (not partially)
Explicit Specialization

- syntax for explicit specialization:

  ```cpp
  template <> declaration
  ```

- declaration: declaration of templated entity (e.g., function, class, variable)

- example:

  ```cpp
  // unspecialized template
  template <class T, class U>
  void func(T x, U y) { /* ... */ }

  // explicit specialization of template
  // (for when template parameters are bool, bool)
  template <>
  void func<bool, bool>(bool x, bool y) { /* ... */ }
  ```
Partial Specialization

- syntax for partial specialization of class template:

  ```
  template <parameter_list> class_key
class_name <argument_list> declaration
  ```

- syntax for partial specialization of variable template:

  ```
  template <parameter_list> type_name
variable_name <argument_list> declaration
  ```

- `class_key`: class or struct keyword (for class template)
- `class_name`: class being specialized (for class template)
- `type_name`: type of variable (for variable template)
- `variable_name`: variable being specialized (for variable template)
- `argument_list`: template argument list
- `declaration`: declaration of templated entity (e.g., class, variable)

- example:

  ```
  // unspecialized template
  template <class T, int N> class Widget { /* ... */ };

  // partial specialization of template
  // (for when first template parameter is bool)
  template <int N> class Widget<bool, N> { /* ... */ };
  ```
```cpp
#include <iostream>

// unspecialized version

template <class T>
    typename std::ostream& printPointee(
        typename std::ostream& out, const T* p)
    { return out << *p << ' \n'; }

// specialization

template <>
    typename std::ostream& printPointee<void>(
        typename std::ostream& out, const void* p)
    { return out << *static_cast<const char*>(p) << ' \n'; }

int main() { 
    int i = 42;
    const int* ip = &i;
    char c = 'A';
    const void* vp = &c;
    printPointee(std::cout, ip);
    printPointee(std::cout, vp);
}

/* Output: 
  42
  A */
```
Explicitly-Specialized Class Template: is_void

```cpp
template <class T>
struct is_void
{
    static constexpr bool value = false;
};

template <>
struct is_void<void>
{
    static constexpr bool value = true;
};

template <>
struct is_void<const void>
{
    static constexpr bool value = true;
};

template <>
struct is_void<volatile void>
{
    static constexpr bool value = true;
};

template <>
struct is_void<const volatile void>
{
    static constexpr bool value = true;
};

static_assert(is_void<int>::value == false);
static_assert(is_void<double*>::value == false);
static_assert(is_void<void>::value == true);
static_assert(is_void<const void>::value == true);
static_assert(is_void<volatile void>::value == true);
static_assert(is_void<const volatile void>::value == true);

int main() {}
```
```cpp
#include <iostream>

// unspecialized version
template <typename T, typename V>
struct Widget {
    Widget() {std::cout << "unspecialized\n";}
};

// partial specialization
template <typename T>
struct Widget<int, T> {
    Widget() {std::cout << "partial\n";}
};

// explicit specialization
template <>
struct Widget<int, int> {
    Widget() {std::cout << "explicit\n";}
};

int main() {
    Widget<double, int> w1; // unspecialized version
    Widget<int, double> w2; // partial specialization
    Widget<int, int> w3; // explicit specialization
    return 0;
}
```
std::vector class employs specialization

consider vector of elements of type $T$

most natural way to store elements is as array of $T$

if $T$ is `bool`, such an approach makes very inefficient use of memory, since each `bool` object requires one byte of storage

if $T$ is `bool`, would be much more memory-efficient to use array of, say, `unsigned char` and pack multiple `bool` objects in each byte

std::vector accomplishes this by providing (partial) specialization for case that $T$ is `bool`

declaration of base template for `std::vector` and its partial specialization for case when $T$ is `bool` are as follows:

```cpp
template <class T, class Alloc = allocator<T>>
class vector; // unspecialized version

template <class Alloc>
class vector<bool, Alloc>; // partial specialization
```
Explicitly-Specialized Variable Template: is_void_v

```cpp
1 template <class T>
2 constexpr bool is_void_v = false;
3
4 template <>
5 constexpr bool is_void_v<void> = true;
6
7 template <>
8 constexpr bool is_void_v<const void> = true;
9
10 template <>
11 constexpr bool is_void_v<volatile void> = true;
12
13 template <>
14 constexpr bool is_void_v<const volatile void> = true;
15
16 static_assert(is_void_v<int> == false);
17 static_assert(is_void_v<double*> == false);
18 static_assert(is_void_v<void> == true);
19 static_assert(is_void_v<const void> == true);
20 static_assert(is_void_v<volatile void> == true);
21 static_assert(is_void_v<const volatile void> == true);
22
23 int main() {}
```
template <unsigned long long N>
constexpr unsigned long long factorial = N * factorial<N - 1>;

template <>
constexpr unsigned long long factorial<0> = 1;

int main() {
    static_assert(factorial<5> == 120,
                  "factorial<5> failed");
    static_assert(factorial<12> == 479'001'600,
                  "factorial<12> failed");
}
#include <limits>

// unspecialized version
template <int X, int Y>
constexpr int quotient = X / Y;

// partial specialization (which prevents division by zero)
template <int X>
constexpr int quotient<X, 0> = (X < 0) ?
    std::numeric_limits<int>::min() : std::numeric_limits<int>::max();

static_assert(quotient<4, 2> == 2);
static_assert(quotient<5, 3> == 1);
static_assert(quotient<4, 0> == std::numeric_limits<int>::max());
static_assert(quotient<-4, 0> == std::numeric_limits<int>::min());

int main() {}
Section 2.5.7

Miscellany
when creating candidate set (of functions) for overload resolution, some or all candidates of that set may be result of instantiated templates with template arguments substituted for corresponding template parameters

process of substituting template arguments for corresponding template parameters can lead to invalid code

if certain types of invalid code result from substitution in any of following, substitution failure said to occur:

- all types used in function type (i.e., return type and types of all parameters)
- all types used in template parameter declarations
- all expressions used in function type
- all expressions used in template parameter declaration

substitution failure not treated as error

instead, substitution failure simply causes overload to be removed from candidate set

this behavior often referred to by term “substitution failure is not an error (SFINAE)”

SFINAE behavior often exploited in template metaprogramming
Some Kinds of Substitution Failures

- attempting to instantiate pack expansion containing multiple parameter packs of differing lengths
- attempting to create array with element type that is `void`, function type, reference type, or abstract class type
- attempting to create array with size that is zero or negative
- attempting to use type that is not class or enumeration type in qualified name
- attempting to use type in nested name specifier of qualified ID, when type does not contain specified member, or
  - specified member is not type where type is required
  - specified member is not template where template is required
  - specified member is not non-type where non-type is required
- attempting to create pointer to reference type
- attempting to create reference to `void`
Some Kinds of Substitution Failures (Continued)

- attempting to create pointer to member of $T$ when $T$ is not class type
- attempting to give invalid type to non-type template parameter
- attempting to perform invalid conversion in either template argument expression, or expression used in function declaration
- attempting to create function type in which parameter has type of `void`, or in which return type is function type or array type
- attempting to create function type in which parameter type or return type is abstract class
SFINAE Example: Truncate

```cpp
class Real {
public:
  using rounded_type = long long;
  rounded_type truncate() const {
    rounded_type result;
    // ...
    return result;
  }
  // ...
};

// function 1
template <class T>
typename T::rounded_type truncate(const T& x) { return x.truncate();}
  // NOTE: example would not compile if return type specified as auto

// function 2
int truncate(double x) { return x;}

int main() {
  Real r;
  float f = 3.14f;
  auto rounded_r = truncate(r);
  // calls function 1 (only trivial conversions)
  auto rounded_f = truncate(f);
  // function 2 requires nontrivial conversions
  // function 1 would only require trivial conversions but
  // substitution failure occurs
  // calls function 2 (with conversions)
}
```

[see overload resolution]
class Real {
public:
    using rounded_type = long long;
    rounded_type truncate() const {
        rounded_type result;
        // ...
        return result;
    }
    // ...
};

// function 1
template <class T, class = typename T::rounded_type>
auto truncate(const T& x) {return x.truncate();}

// function 2
int truncate(double x) {return x;}

int main() {
    Real r;
    float f = 3.14f;
    auto rounded_r = truncate(r);
    // calls function 1 (only trivial conversions)
    auto rounded_f = truncate(f);
    // function 2 requires nontrivial conversions
    // function 1 would only require trivial conversions but
    // substitution failure occurs
    // calls function 2 (with conversions)
}
to make SFINAE more convenient to exploit, class template `std::enable_if` and alias template `std::enable_if_t` are provided

declaration of class template `enable_if`:
```
template <bool B, class T = void>
struct enable_if;
```

if `B` is `true`, class has member type `type` defined as `T`; otherwise, class has no `type` member

possible implementation of `enable_if`:
```
1  template <bool B, class T = void>
2   struct enable_if {};
3
4  template <class T>
5   struct enable_if<true, T> {
6       using type = T;
7   };
```

declaration of alias template `enable_if_t`:
```
template <bool B, class T = void>
using enable_if_t = typename enable_if<B, T>::type;
```

if `enable_if_t` is used with its first parameter as `false`, substitution failure will result
```cpp
#include <type_traits>
#include <cassert>
#include <iostream>

// ISO-Pascal modulo operator for signed integral types
template <class T> inline
std::enable_if_t<std::is_integral_v<T> && std::is_signed_v<T>, T>
mod(T x, T y) {
    assert(y > 0);
    if (x < 0) {x += (((-x) / y) + 1) * y;}  
    return x % y;
}

// ISO-Pascal modulo operator for unsigned integral types
template <class T> inline
std::enable_if_t<std::is_integral_v<T> && std::is_unsigned_v<T>, T>
mod(T x, T y) {
    return x % y;
}

int main() {
    auto si = mod(-4, 3); // uses signed version
    auto ui = mod(5u, 3u); // uses unsigned version
    auto slli = mod(-5ll, 3ll); // uses signed version
    auto ulli = mod(4ull, 3ull); // uses unsigned version
    // auto f = mod(3.0, 4.0);
    // ERROR: no matching function call
    std::cout << si << ' ' << ui << ' ' << slli << ' ' << ulli << '
';
}
```
```cpp
#include <iostream>
#include <experimental/type_traits>

class Widget {
    public:
        void foo() const {}
        // ...
};

class Gadget {
    public:
        void foo() {}
        // ...
};

// helper template for testing if class has member function called
// foo that can be invoked on const object with no arguments.
template <class T>
using has_usable_foo_t = decltype(std::declval<const T&>().foo());

int main() {
    std::cout
        << "Widget "
        << std::experimental::is_detected_v<has_usable_foo_t, Widget>
        << '
' << "Gadget 
        << std::experimental::is_detected_v<has_usable_foo_t, Gadget>
        << '
';
}
```
Section 2.5.8

References


Notwithstanding the talk’s title, this talk is actually about the functionality in the Library Fundamentals TS related to is_detected, detected_or, is_detected_exact, and is_detected_convertible.
Talks II


Section 2.6

Concepts
Motivating Example: Library (Without Concepts)

```cpp
#include <algorithm>
#include <iterator>

template<class Iter, class Comp = std::less<>>
void shell_sort(Iter begin, Iter end, Comp less = {}) {
    for (auto gap = (end - begin) / 2; gap != 0; gap /= 2) {
        for (auto i = begin + gap; i != end; ++i) {
            for (auto j = i; j >= begin + gap && less(*j, j[-gap]);
                j -= gap) {std::iter_swap(j - gap, j);}
        }
    }
}
```

- implementation of `shell_sort` requires `Iter` to be random-access iterator type (and `Comp` to be valid comparator type) in order for code to compile and work correctly
- unfortunately, compiler has no way to know of this requirement
- if, for example, `Iter` is not random-access iterator type, compiler instantiates template anyways and (potentially many) unhelpful compiler errors result
Motivating Example: Application (Without Concepts)

```cpp
#include <iostream>
#include <list>
#include "shell_sort_legacy.hpp"

int main() {
    std::list<int> v{1, 7, 2, 6, 3, 5, 4, 0};
    shell_sort(v.begin(), v.end(), std::greater<>());
    for (auto&& i : v) {std::cout << i << '
';}
}
```

- `shell_sort` requires that its first two arguments have random-access iterator type
- Declaration of `shell_sort` (in included header) does not specify that random-access iterators required
- One or more compiler errors result that relate to implementation details of `shell_sort` (e.g., errors related to `operator-`, `operator+`, and `operator-=`)
- None of error messages indicate true source of problem (namely, iterator arguments to `shell_sort` not of random-access iterator type)
Motivating Example: Library (Concepts)

```cpp
#include <algorithm>
#include <concepts>
#include <iterator>
#include <utility>

template<std::random_access_iterator Iter, class Comp = std::less<>>
    requires std::indirect_binary_predicate<Comp, Iter, Iter>
    void shell_sort(Iter begin, Iter end, Comp less = {}) {
        for (auto gap = (end - begin) / 2; gap != 0; gap /= 2) {
            for (auto i = begin + gap; i != end; ++i) {
                for (auto j = i; j >= begin + gap && less(*j, j[-gap]);
                    j -= gap) {std::iter_swap(j - gap, j);}
            }
        }
    }
```

- declaration of `shell_sort` indicates requirements on template parameters `Iter` and `Comp`
- compiler aware of these constraints and can enforce them
Motivating Example: Application (Concepts)

```cpp
#include <iostream>
#include <list>
#include "shell_sort_concepts.hpp"

int main() {
  std::list<int> v{1, 7, 2, 6, 3, 5, 4, 0};
  shell_sort(v.begin(), v.end(), std::greater<>());
  for (auto&& i : v) {std::cout << i << '
';}
}
```

- declaration of `shell_sort` (in included header) now uses concepts to specify that random-access iterators required
- compiler aware of this requirement and able to enforce it
- compile error messages much more helpful
- typically error message obtained will indicate that `shell_sort` cannot be called because iterator arguments do not satisfy random-access iterator requirement (or, more precisely, deduced type for iterator arguments does not satisfy `std::random_access_iterator` concept)

Copyright © 2015–2021 Michael D. Adams

Programming in C++

Version 2021-04-01
Section 2.6.1

Basics of Concepts
class templates, function templates, variable templates, and non-template member functions of class templates can be associated with constraints.

Constraints specify requirements on template arguments, which can be used to select appropriate function overloads and template specializations.

A named set of requirements called concept.

A concept is a predicate evaluated at compile time that is part of the interface of template and constrains template.

Concepts are intended to model semantic requirements.

Concepts (as currently specified in the language) can only formally express syntactic requirements, however.

Consequently, only syntactic requirements can be checked by the compiler.
Benefits of Concepts

- being able to constrain templates has numerous benefits
- since constraints specified as part of language, compiler aware of constraints
- function template overloads and class/variable template specializations can be selected based on properties of types
- template interfaces can be specified more precisely, leading to more readable code
- improved compiler error messages are possible, since compiler can determine if template being used with invalid template arguments
- concepts and associated functionality in language provide simpler ways to do things that would otherwise require template metaprogramming techniques
Defining Concepts

- to declare named set of requirements on template arguments (i.e., concept), `concept` keyword is used
- syntax for concept definition:
  ```cpp
template<template-parameter-list>
concept concept-name = constraint-expression;
```
- `constraint-expression` is expression of type `bool`
- cannot declare concept without defining it
- definition must appear at namespace scope
- recursion not allowed in concept definitions
- although concept is itself template, cannot constrain concept (e.g., with `requires` clause after template parameter list)
- example of concept definition:
  ```cpp
template<class T>
concept integral = std::is_integral_v<T>;
```
■ concept is essentially compile-time predicate
■ consequently, can use concept in places where \textbf{bool} value is required
■ since concept is always constant expression, can use concept in constant expression
■ example:

\begin{verbatim}
template<class T>
concept integral = std::is_integral_v<T>;
constexpr bool b = integral<int>;
// OK: integral<int> is constant expression
static_assert (!integral<double>);
// OK: integral<double> is constant expression and
// has value false
\end{verbatim}
Some Examples of Concepts

```cpp
#include <type_traits>
#include <string>

template<class T>
concept integral = std::is_integral_v<T>;
static_assert(integral<int> && !integral<double>);

template<class T>
concept floating_point = std::is_floating_point_v<T>;
static_assert(floating_point<double> && !floating_point<int>);

template<class T>
concept destructible = std::is_nothrow_destructible_v<T>;
static_assert(destructible<std::string> && !destructible<void>);

template<class T, class U>
concept same_as_impl = std::is_same_v<T, U>;
template<class T, class U>
concept same_as = same_as_impl<T, U> && same_as_impl<U, T>;
static_assert(same_as<int, int> && !same_as<int, double>);

template<class T, class... Args>
concept constructible_from = destructible<T> &&
    std::is_constructible_v<T, Args...>;
static_assert(constructible_from<std::string, const char*> &&
    !constructible_from<std::string, void*>);
```
In most contexts where `auto` keyword can be used, this keyword can be prefixed by concept name in order to constrain deduced type. If deduced type does not satisfy constraint, compiler error results.

Example:

```cpp
int func1();
float func2();
std::integral auto x = func1();
// OK: deduced type is int, which satisfies constraint `std::integral`
std::integral auto y = func2();
// ERROR: deduced type is float, which violates constraint `std::integral`
```
#include <concepts>
#include <iostream>
#include <vector>

std::integral auto i = 42;
// std::integral auto j = 0.5; // ERROR: constraint violated

std::integral auto func1() {return 42;}
// std::integral auto func2() {return 0.5;}
// ERROR: constraint violated

std::integral auto func3(std::integral auto x) {return x + 1;}
std::integral auto func4(std::integral auto x) {return x + 0.5;}
// WRONG: error upon instantiation

std::predicate<int> auto f1 = [](int x) {return x < 0;};
// std::invocable<int> auto f2 = [](()){};
// ERROR: constraint violated

int main() {
  // func3(1.0);
  // ERROR: template parameter constraint violation
  // func4(1); // ERROR: return-type constraint violation
  std::vector<int> v{1, 2, 3};
  for (std::integral auto i : v) {/* ... */}
}
Requires Clauses

- can constrain template by including requires clause in template declaration
- requires clause allowed in following places:
  1. in case of function, class, or variable template: after template parameter list
  2. in case of function template or nontemplate function of class template: at end of function declaration (i.e., trailing requires clause)
- can have requires clause after template parameter list and at end of function declaration
- syntax:
  
  ```
  requires expr;
  ```

- `expr` must be compile-time constant that evaluates to type `bool`
- example:

  ```
  template<class T> requires std::floating_point<T>
  T foo(T x) { return x + T(0.5); }
  ```
- \( expr \) must be:
  - primary expression (e.g., concept name, type trait, or any parenthesized expression)
  - sequence of primary expressions joined by conjunction (\&\&) and/or disjunction (\|\|)
- requirements deemed to be met if \( expr \) is:
  1. well formed (i.e., no substitution failures); and
  2. evaluates to true
- evaluation of expression in requires clause (which is performed at compile time) uses short-circuit logic
- requires clause can also be used on nontemplate member function of class template
- (nontemplate) member function with requires clause will only be included in class if requirement satisfied
type template parameters can also be constrained by replacing `typename/class` keyword with concept name

following two declarations are functionally equivalent (but not equivalent):

- `template<concept-name<args...> T>
- `template<class T> requires concept-name<T, args...>`

for example, following declarations are functionally equivalent (but not equivalent):

- `template<class T> requires std::integral<T>
  void func(T x){/*/...  */}
- `template<std::integral T> void func(T x){/*/...  */}

non-type template parameters can only be constrained using requires clause
Combining Constraints in Template Declarations

- As seen earlier, constraints can be specified at several places in a template declaration:
  1. Type constraint in template parameter list (i.e., replacing typename/class keyword in template parameter list with concept name)
  2. Requires clause immediately following template parameter list
  3. In case of function template, type constraint in function parameter list (i.e., using auto with type constraint)
  4. In case of function template, using trailing requires clause in function declaration

- If more than one of these mechanisms is used, constraints are combined by logical AND in order listed above

- Example:

```cpp
template<widgety T> requires gadgety<T>
void func(T x, fooable auto y) requires barable<T>;
/* Constraint is
   widgety<T> && gadgety<T> && fooable<U> && barable<T>,
   where U is deduced type for y */
```
any two declarations of same template must specify constraints using same form

eample:

```cpp
template<class T> requires std::integral<T>
void func(T);
template<std::integral T> void func(T);
// ILLEGAL: no diagnostic required
```
```cpp
#include <concepts>
#include <iostream>

constexpr bool is_power_of_two(std::size_t n) {
    int count = 0;
    for (; n; n >>= 1) {
        if (n & 1) {++count;}
    }
    return count == 1;
}

template<class T, std::size_t N>
requires std::floating_point<T> && (is_power_of_two(N))
void func(T (&a)[N]) {
    std::cout << N << ' ' << sizeof(T) << '
';
    // ... (algorithm that requires power-of-two array size)
}

int main() {
    float a[1024];
    func(a); // OK: array size is power of 2
    float b[1023];
    // func(b); // ERROR: array size is not power of 2
}
```
```cpp
#include <array>
#include <concepts>
#include <cstdint>

constexpr bool is_divisible(std::size_t m, std::size_t n) {
    return !(m % n);
}

template< std::integral T, std::size_t N>
requires (is_divisible(N, 4))
class Widget {
public:
    // ...
private:
    std::array<T, N> data_;
};

int main() {
    Widget<int, 16> a; // OK: 16 is multiple of 4
    // Widget<int, 15> b; // ERROR: 15 not multiple of 4
    // Widget<float, 16> c; // ERROR: float not integral type
}
```
Example: Constrained Variable Template

```cpp
#include <cassert>
#include <string>
#include <type_traits>
#include <vector>

// Template concept
template<class T>
concept nonbool_arithmetic = std::is_arithmetic_v<T> &&
    !std::is_same_v<std::remove_cv_t<T>, bool>;

// Template
template<nonbool_arithmetic T>
const T forty_two{42};

int main() {
    auto c = forty_two<char>; assert(c == 42);
    auto i = forty_two<int>; assert(i == 42);
    auto d = forty_two<double>; assert(d == 42.0);
    // auto b = forty_two<bool>
    // ERROR: template constraint violated
    // NOTE: narrowing conversion error if template constraint removed
    // auto vi = forty_two<std::vector<int>>;
    // ERROR: template constraint violated
    // NOTE: would compile if template constraint removed
    // auto s = forty_two<std::string>
    // ERROR: template constraint violated
    // NOTE: would compile if template constraint removed
}
```
Example: Constrained Nontemplate Member Functions

```cpp
#include <iostream>

template<bool enable_foo>
class Widget {

    public:
    
        void foo() requires (enable_foo) {std::cout << "foo\n";}
        void bar() {std::cout << "bar\n";}
        // ...
    
};

int main() {
    Widget<true> a;
    a.foo(); // OK: has foo member
    a.bar();
    Widget<false> b;
    // b.foo(); // ERROR: no foo member
    b.bar();
}
```
#include <string>

template<bool I, bool S>

class widget {

    public:
        constexpr int foo(int x)
            requires I { return x; }
        constexpr std::string foo(const std::string& x)
            requires S { return x; }

};

int main() {
    using namespace std::string_literals;
    widget<1, 1> w3;
        // has foo(int) and foo(const std::string&)
    w3.foo(42);  // OK
    w3.foo("hello"s);  // OK
    widget<0, 1> w2;
        // has foo(const std::string&) but not foo(int)
    w2.foo("hello"s);  // OK
    // w2.foo(42);  // ERROR: no matching function call
    widget<0, 0> w0;
        // has neither foo(int) nor foo(const std::string&)
    // w0.foo(42);  // ERROR: no matching function call
    // w0.foo("hello"s);  // ERROR: no matching function call
}
```cpp
#include <concepts>
#include <iostream>

constexpr bool is_power_of_two(std::size_t n) {
    for (; n; n >>= 1) {
        if (n & 1) { return !(n >> 1); }
    }
    return false;
}

template<std::size_t N> concept power_of_two =
    is_power_of_two(N);

// constrained generic lambda
auto f = []<std::floating_point T, std::size_t N>(T (&a)[N])
    requires power_of_two<N> {
    std::cout << N << '
';
};

int main() {
    float x[4] = {1, 2, 3, 4};
    float y[3] = {1, 2, 3};
    f(x); // OK: array size is power of 2
    // f(y); // ERROR: no matching function call
}
```
#include <concepts>
#include <type_traits>

struct widget {using type = int;};
struct gadget {using type = float;};
struct dooodad {};

template<class T>
constexpr bool func1(T x) {return false;}
template<class T>
requires std::integral<typename T::type>
constexpr bool func1(T x) {return true;}

// func2 is not functionally equivalent to func1
template<class T>
constexpr bool func2(T x) {return true;}
template<class T>
requires (!std::integral<typename T::type>)
constexpr bool func2(T x) {return false;}

static_assert(func1(widget{}) == func2(widget{}));
static_assert(func1(gadget{}) == func2(gadget{}));
static_assert(func1(doodad{}) != func2(doodad{})); // why not equal?
static_assert(func1(42) != func2(42)); // why not equal?
```
Requires Expressions

- requires expression provides mechanism for testing requirements for types
- syntax for requires expression:
  ```
  requires parameter-list(optional) requirement-sequence
  ```
- requires expression has type `bool`
- evaluates to true if constraints satisfied and false otherwise
- requires expression always constant expression
- expressions appearing in requirement sequence not evaluated
- optional parameter list used to obtain dummy variables of specific types that can be used in body of requires expression
- expressions in body of requires expression may be ill formed but parameter list being ill formed is compile error
- example:
  ```
  template<class T> concept b = requires(T x) {++x;};
  static_assert(b<int> && !b<bool>);
  ```
Requires Expressions (Continued)

- if used outside template, requires expression evaluating to false yields compiler error
- four types of requirements are supported:
  1. simple
  2. type
  3. compound
  4. nested
Simple Requirements

- simple requirement asserts expression is valid
- expression is not evaluated
- example:

```cpp
// C<T> is true if a + b is valid expression
template<class T> concept C = requires(T a, T b) { a + b };

// incrementable<T> is true if T can be both
// pre- and post-incremented
template<class T> concept incrementable = requires(T a) { ++a; a++; };
```
- type requirement asserts validity of type

- example:

```cpp
// C<T> is true if T has type members iterator
// and const_iterator

template<class T> concept C = requires {
    typename T::iterator;
    typename T::const_iterator;
};
```
compound requirement asserts properties of expression

- in addition to asserting that expression is valid, compound requirement can assert:
  - expression is nonthrowing
  - type of expression satisfies specified concept

- if `noexcept` specified, expression must not be potentially throwing
- if requirement on type of expression specified, asserts type of expression satisfies given concept

- in particular, “{E} -> Concept<Args...>;” equivalent to “E; requires Concept<decltype((E)), Args...>;”

- example:

```cpp
/* c<T> is true if x.foo(i) is valid expression of type int and does not throw, where x has type T and i has type int */

template<class T> concept c = requires(T x, int i) {
    {x.foo(i)} noexcept -> std::same_as<int>;
};
```
Nested Requirements

- nested requirement asserts constraint expression is true
- constraint expression is simply constant expression of type `bool`
- example:

```cpp
/* c<T> is true if T does not require more storage than void pointer */

template<class T> concept c = requires {
    requires sizeof(T) <= sizeof(void*);
};
```
#include <concepts>
#include <iostream>

template<class T>
concept stream_insertable = requires(T x, std::ostream& out) {
    out << x -> std::same_as<std::ostream&>;
};

template<stream_insertable... Ts>
std::ostream& print(std::ostream& out, Ts... args) {
    return (out << ... << args);
}

struct Widget {};

int main() {
    print(std::cout, "hello", ' ', 42, ' ', 42.42f, '\n');
    //print(std::cout, Widget{});
    // ERROR: template constraint violation (stream_insertable)
```cpp
#include <concepts>

struct widget {
  int foo() {return 42;}
};

template<class T>
requires requires (T x) {
  {x.foo()} -> std::same_as<int>;
} int func(T x) {return x.foo() + 1;}

int main() {
  widget w;
  func(w);
  // func(42); // ERROR: constraint violation
}
```cpp
#include <array>

template<class T>
concept int_sized = requires {
    sizeof(T) == sizeof(int); // BUG: missing requires keyword
};

static_assert(int_sized<char> && sizeof(char) == 1);
   // OK: YIKES!
static_assert(int_sized<char[4096]> &&
 sizeof(char[4096]) == 4096);
   // OK: YIKES!
static_assert(int_sized<std::array<int, 4096>> &&
 sizeof(std::array<int, 4096>) == 4096 * sizeof(int));
   // OK: YIKES!

static_assert(!int_sized<void>);
   // OK: YIKES! void has no size
```
```cpp
#include <concepts>
#include <utility>

template<std::movable T>
void smart_swap(T& x, T& y) {
    constexpr bool has_member_swap = requires(T x, T y) {
        x.swap(y);
    };
    constexpr bool has_nonmember_swap = requires(T x, T y) {
        swap(x, y);
    };
    if constexpr(has_member_swap) {
        // use member swap
        x.swap(y);
    } else if constexpr(has_nonmember_swap) {
        // use nonmember swap
        swap(x, y);
    } else {
        // use general swap algorithm
        T tmp = std::move(x);
        x = std::move(y);
        y = std::move(tmp);
    }
}
```
#include "smart_swap.hpp"
#include <iostream>

namespace foo {
    struct widget {
        void swap(widget& other) {std::cout << "widget member swap\n";}
    }
    void swap(widget& x, widget& y) {
        std::cout << "widget nonmember swap\n";
    }
    struct gadget {};
    void swap(gadget& x, gadget& y) {
        std::cout << "gadget nonmember swap\n";
    }
    struct doodad {};
}

int main() {
    foo::widget w1, w2;
    foo::gadget g1, g2;
    foo::doodad d1, d2;
    smart_swap(w1, w2); // uses member swap
    smart_swap(g1, g2); // uses nonmember swap
    smart_swap(d1, d2); // uses general swap algorithm
}
#include <array>
#include <cassert>
#include <concepts>
#include <iterator>
#include <list>
#include <sstream>

template<std::input_iterator I, class T>
requires requires(I i, T t) {
    {t += *i} -> std::same_as<T&>;
}
constexpr T accumulate(I first, I last, T init) {
    for (; first != last; ++first) {init += *first;}
    return init;
}

int main() {
    constexpr std::array<int, 4> a{1, 2, 3};
    static_assert(accumulate(a.begin(), a.end(), 0) == 6);
    const std::list<int> b{1, 2, 3};
    assert(accumulate(b.begin(), b.end(), 0) == 6);
    std::stringstream ss("1.0 0.5 0.5");
    assert(accumulate(std::istream_iterator<float>(ss),
                      std::istream_iterator<float>(), 0.0f) == 2.0);
}
when considering template functions during overload resolution, most constrained template always preferred from those that are viable (i.e., constraints satisfied)

if explicit specialization available, chosen over all other template overloads

constrained template (whose constraints are satisfied) chosen over unconstrained template

when more than one constrained template is viable (i.e., its constraints satisfied), overload resolution prefers most constrained one

how “most constrained” is defined is somewhat complicated

to begin, we only consider some simple common cases
suppose that $c_1, c_2, \ldots, c_n$ are constraint expressions that each consist only of single concept name

$c_1 \&\& c_2 \&\& \ldots \&\& c_n$ more constrained than $c_1 \&\& c_2 \&\& \ldots \&\& c_{n-1}$

$c_1 \vert\vert c_2 \vert\vert \ldots \vert\vert c_{n-1}$ more constrained than $c_1 \vert\vert c_2 \vert\vert \ldots \vert\vert c_n$

note that if any of $c_1, c_2, \ldots, c_n$ include more than only single concept name (e.g., negation operator or more complicated boolean expression) issue of constraint ordering becomes significantly more involved

element:

```cpp
template<class T> concept widgety = /* ... */;
template<class T> concept gadgety = /* ... */;
template<class T> requires widgety<T> void func1(T) {} // A
```

```cpp
template<class T> requires widgety<T> && gadgety<T> void func1(T) {} // B
```

// B more constrained than A
Simple Overload Resolution Example

```cpp
#include <cassert>
#include <concepts>

// unconstrained primary template
template<class T> int func(T x) { return 0; }

// constrained template
template<class T> requires std::integral<T> int func(T x) { return 1; }

// more specialized template
template<class T> int func(T* x) { return 2; }

// explicit template specialization
template<> int func<char>(char x) { return 3; }

// nontemplate
int func(int x) { return 4; }

int main() {
    assert(func(0.0) == 0);
    assert(func(42L) == 1);
    int* ip = nullptr; assert(func(ip) == 2);
    assert(func('*') == 3);
    assert(func(42) == 4);
}
```
Overloading Example: Constraint Equivalence

```cpp
#include <type_traits>

template<class T>
requires std::is_integral_v<T>
constexpr int func1(T x) { return 0; }

template<class T>
requires std::is_integral_v<T> && std::is_unsigned_v<T>
constexpr int func1(T x) { return 1; }

template<class T> concept integral = std::is_integral_v<T>;
template<class T> concept notsigned = std::is_unsigned_v<T>;

template<class T>
requires integral<T>
constexpr int func2(T x) { return 0; }

template<class T>
requires integral<T> && notsigned<T>
constexpr int func2(T x) { return 1; }

static_assert(func1(42) == 0);
// static_assert(func1(42U) == 1); // ERROR: ambiguous function call
static_assert(func2(42) == 0);
static_assert(func2(42U) == 1);
```
when class/variable template instantiated, most constrained template selected from those that are viable (i.e., constraints satisfied)

if explicit specialization available, chosen over all others

constrained template chosen over unconstrained template

when more than one constrained template viable, most constrained one chosen

how “most constrained” is defined is somewhat complicated

to begin, we only consider some simple common cases
```cpp
#include <cassert>
#include <concepts>
#include <string>

// unconstrained primary template
template<class T> struct widget {
    static std::string value() { return "primary"; }
};

// partial specialization
template<std::integral T> struct widget<T> {
    static std::string value() { return "integral"; }
};

// explicit specialization
template<> struct widget<bool> {
    static std::string value() { return "explicit"; }
};

int main() {
    assert(widget<double>::value() == "primary");
    assert(widget<int>::value() == "integral");
    assert(widget<bool>::value() == "explicit");
}
```
#include <cassert>
#include <complex>
#include <optional>
#include <string>
#include <type_traits>

-template <class T>
-requires std::destructible<T>
-const auto forty_two = std::optional<T>();

-template <class T>
-requires std::destructible<T> &&
-std::constructible_from<std::optional<T>, std::in_place_t, int>
-const auto forty_two<T> = std::optional<T>(std::in_place_t{}, T(42));

-int main() {
    auto s = forty_two<std::string>;  
    assert(!s.has_value());
    auto cf = forty_two<std::complex<float>>;
    assert(cf.has_value() && *cf == 42.0f);
    auto i = forty_two<int>;  
    assert(i.has_value() && *i == 42);
    auto f = forty_two<float>;  
    assert(f.has_value() && *f == 42.0f);
}
Section 2.6.2

Constraint Ordering
in order to understand subsequent material on constraint ordering, one should be familiar with:

- basic operations in boolean algebra
- laws of boolean algebra
- subsumption relationships for boolean expressions
- disjunctive normal form
- conjunctive normal form
Ordering of Constraints

- Language often needs to choose between multiple constrained versions of template.
- Language defines set of rules for ordering constraint expressions from most constrained to least constrained.
- Ordering is partial, so some constraint expressions are incomparable.
- If two constraint expressions are comparable, the constraint that comes first in this ordering is deemed more constrained.
- Constraint expressions treated as abstract mathematical formulas in boolean algebra involving conjunction and disjunction (but not negation).
- Negation is not considered in abstract mathematical sense.
- Can express abstract mathematical formulas in various normal (i.e., canonical) forms, such as disjunctive normal form (DNF) and conjunctive normal form (CNF).
each constraint can be represented using abstract mathematical representation known as normal form

normal form of $A \lor B$ is disjunction of normal forms of $A$ and $B$

normal form of $A \land B$ is conjunction of normal forms of $A$ and $B$

normal form of concept $C<A_1, A_2, \ldots>$ is normal form of constraint expression associated with $C$ after substituting template parameters

normal form of expression $E$ that does not contain conjunctions, disjunctions, or concepts is simply $E$

two atomic constraints appearing in normal form only deemed equivalent if correspond to same location (i.e., line/column) in source code
suppose we have following definitions:

```cpp
1 template<class T> concept scalar = std::is_scalar_v<T>;
2 template<class T> concept integral = scalar<T> && std::is_integral_v<T>;
3 template<class T> concept floating_point = scalar<T> && std::is_floating_point_v<T>;
```

consider converting following constraint to normal form:

`integral<T> || floating_point<T>`

performing constraint normalization, we have:

1 `scalar<T> && std::is_integral_v<T> || scalar<T> && std::is_floating_point_v<T>`
2 `std::is_scalar_v<T> && std::is_integral_v<T> || std::is_scalar_v<T> && std::is_floating_point_v<T> (DNF)`

using distributive property, we obtain CNF:

```cpp
1 std::is_scalar_v<T> && (std::is_integral_v<T> || std::is_floating_point_v<T>)
```
suppose we have following definitions:

```cpp
1 template<class T> concept integral =
2   std::is_scalar_v<T> && std::is_integral_v<T>;
3 template<class T> concept floating_point =
4   std::is_scalar_v<T> && std::is_floating_point_v<T>;
```

consider converting following constraint to normal form:

```
integral<T> || floating_point<T>
```

performing constraint normalization, we have:

- 

```
std::is_scalar_v<T> && std::is_integral_v<T> ||
std::is_scalar_v<T> && std::is_floating_point_v<T> (DNF)
```

using distributive property, we obtain CNF:

- 

```
(\text{std::is scalar_v<T> || std::is scalar_v<T>}) \&\&
(\text{std::is scalar_v<T> || std::is floating point_v<T>}) \&\&
(\text{std::is integral_v<T> || std::is scalar_v<T>}) \&\&
(\text{std::is integral_v<T> || std::is floating point_v<T>})
```
A constraint $P$ subsumes a constraint $Q$ if and only if, for every disjunctive clause $P_i$ in the disjunctive normal form of $P$, $P_i$ subsumes every conjunctive clause $Q_j$ in the conjunctive normal form of $Q$.

A disjunctive clause $P_i$ subsumes a conjunctive clause $Q_j$ if and only if there exists an atomic constraint $P_{i,a}$ in $P_i$ for which there exists an atomic constraint $Q_{j,b}$ in $Q_j$ such that $P_{i,a}$ subsumes $Q_{j,b}$.

An atomic constraint $A$ subsumes another atomic constraint $B$ if and only if $A$ and $B$ are identical.

A declaration $D_1$ is at least as constrained as a declaration $D_2$ if $D_1$ and $D_2$ are both constrained declarations and $D_1$’s associated constraints subsume those of $D_2$; or $D_2$ has no associated constraints.

A declaration $D_1$ is more constrained than another declaration $D_2$ when $D_1$ is at least as constrained as $D_2$, and $D_2$ is not at least as constrained as $D_1$. 
Overloading Example: Constraint Subsumption

```cpp
// Overloading Example: Constraint Subsumption

// Template concept overloading example

template<bool B> concept a = B;
template<bool B> concept b = B;
template<bool B> concept c = B;

template<bool A, bool B, bool C> requires a<A> || b<B> && c<C>
constexpr int f() { return 0; }

// DNF is (a<A>) || (b<B> && c<C>); CNF is (a<A> || b<B>) && (a<A> || c<C>)

template<bool A, bool B, bool C> requires a<A> || b<B> || c<C>
constexpr int f() { return 1; }

// DNF is (a<A>) || (b<B>) || (c<C>); CNF is (a<A> || b<B> || c<C>)

// a<A> || subsumes a || b<B> || c<C>
// b<B> && c<C> subsumes a<A> || b<B> || c<C>
// a<T> || b<T> && c<T> subsumes a<A> || b<B> || c<C>
// a<A> subsumes a<A> || b<B>
// b<B> does not subsume a<A> || c<C>
// c<C> does not subsume a<A> || b<B>
// a<A> || b<B> || c<C> does not subsume a<A> || b<B> && c<C>

// static_assert(f<0, 0, 0>(); // ERROR: no matching function call
static_assert((f<0, 0, 1>() == 1)); static_assert((f<0, 1, 0>() == 1));
static_assert((f<0, 1, 1>() == 0)); static_assert((f<1, 0, 0>() == 0));
static_assert((f<1, 0, 1>() == 0)); static_assert((f<1, 1, 0>() == 0));
static_assert((f<1, 1, 1>() == 0));
```

Copyright © 2015–2021 Michael D. Adams

Programming in C++

Version 2021-04-01

template<bool B> concept a = B;

template<bool B> concept not_a = !a<B>;

template<bool B> concept b = B;

template<bool A, bool B> requires (!a<A>)
  constexpr int func1() { return 0;}

template<bool A, bool B> requires (!a<A>) && b<B>
  constexpr int func1() { return 1;}
  // (!a<A>) && b<B> does not subsume (!a<A>) and vice versa

template<bool A, bool B> requires not_a<A>
  constexpr int func2() { return 0;}

template<bool A, bool B> requires not_a<A> && b<B>
  constexpr int func2() { return 1;}
  // not_a<A> && b<B> subsumes not_a<A>

int main() {
  static_assert(func1<0, 0>() == 0);
  // func1<0, 1>(); // ERROR: ambiguous function call
  static_assert(func2<0, 0>() == 0);
  static_assert(func2<0, 1>() == 1);
}
template<bool B> concept a = B;

template<bool B> concept not_a = !a<B>;

template<bool B> concept b = B;

template<bool A, bool B> requires (!a<A>)
constexpr int func1() { return 0;}

template<bool A, bool B> requires (!a<A>) || b<B>
constexpr int func1() { return 1;}

// (!a<A>) does not subsume (!a<A>) || b<B> and vice versa

template<bool A, bool B> requires not_a<A>
constexpr int func2() { return 0;}

template<bool A, bool B> requires not_a<A> || b<B>
constexpr int func2() { return 1;}

// not_a<A> subsumes not_a<A> || b<B>

int main() {
    // func1<0, 0>(); // ERROR: ambiguous function call
    // func1<0, 1>(); // ERROR: ambiguous function call
    static_assert(func1<1, 1>() == 1);
    static_assert(func2<0, 0>() == 0);
    static_assert(func2<0, 1>() == 0);
    static_assert(func2<1, 1>() == 1);
}
Section 2.6.3

Additional Examples
#include <cassert>
#include <iterator>
#include <list>
#include <sstream>
#include <vector>

template<std::input_iterator I>
void advance(I& iter, std::iter_difference_t<I> n) {
  while (n--) {++iter;}
}

template<std::bidirectional_iterator I>
void advance(I& iter, std::iter_difference_t<I> n) {
  if (n > 0) {
    while (n--) {++iter;}
  }
  else {
    while (n++) {--iter;}
  }
}

template<std::random_access_iterator I>
void advance(I& iter, std::iter_difference_t<I> n) {iter += n;}

int main() {
  std::vector<int> v{1, 2, 3, 4};
  auto vi = v.begin();
  advance(vi, 4);
  assert(vi == v.end());
  std::list<int> l{1, 2, 3, 4};
  auto li = l.begin();
  advance(li, 4);
  assert(li == l.end());
  std::stringstream s("1 2 3 4");
  auto si = std::istream_iterator<int>(s);
  advance(si, 4);
  assert(si == std::istream_iterator<int>();
  }
Example: Sum

```cpp
#define std::conjunction_v std::conjunction_v<std::is_same<T, Ts>...>

template<class T, class... Ts>
inline constexpr bool are_same_v = std::conjunction_v<std::is_same<T, Ts>...>;

template<class T> concept accumulatable = std::copyable<T> &&
  requires(T x, T y) {{x + y} -> std::same_as<T>;};

template<class T, class... Ts>
requires are_same_v<T, Ts...> && accumulatable<T>
constexpr T sum(T first, Ts... args) {
  if constexpr (sizeof...(Ts) >= 2) {
    return std::move(first) + (... + std::move(args));
  } else {return first;}
}

int main() {
  using namespace std::literals;
  static_assert(sum(1, 1, 1) == 3);
  {int i = 1; assert(sum(i, i, i) == 3);}  
  static_assert(sum(1.0, 1.0, 1.0) == 3.0); 
  // auto x = sum(1, 1.0); // ERROR: constraints not met  
  {double d = 1.0; assert(sum(d, d, d) == 3.0);}  
  static_assert(sum(1) == 1);
  {std::string s("!"); assert(sum(s, s, s) == "!!!"s);}  
  assert(sum("Hello,"s, " "s, "World!"s) == "Hello, World!"s);
  
  return 0;
}
```

Copyright © 2015–2021 Michael D. Adams
```cpp
#include <type_traits>
#include <string>

template<class T> concept trivially_copy_constructible = std::is_trivially_copy_constructible_v<T>;

template<class T> concept trivially_move_constructible = std::is_trivially_move_constructible_v<T>;

// ...

template<class T> class optional {
public:
    constexpr optional() : has_value_(false) {} 
    constexpr optional(const optional& other) requires std::copy_constructible<T> {}
    optional(const optional&) requires std::copy_constructible<T> &&
        trivially_copy_constructible<T> = default;
    constexpr optional(optional&& other) noexcept(std::is_nothrow_move_constructible_v<T>) requires
        std::move_constructible<T> {}
    optional(optional&&) requires std::move_constructible<T> &&
        trivially_move_constructible<T> = default;
    ~optional() {}
    ~optional() requires std::is_trivially_destructible_v<T> = default;
    // ...
private:
    bool has_value_; 
    // ...
};

static_assert(std::is_trivially_destructible_v<optional<int>>);
static_assert(std::is_trivially_copy_constructible_v<optional<int>>);
static_assert(!std::is_trivially_destructible_v<optional<std::string>>);
static_assert(!std::is_trivially_copy_constructible_v<optional<std::string>>);
```
Section 2.6.4

Standard-Library Concepts
standard library defines many concepts

although concepts (as currently specified in language) can only express syntactic requirements, concepts intended to convey semantic requirements

concepts in standard library typically have implied requirements beyond syntactic ones (e.g., semantic or time-complexity requirements)

for example, some concepts imply certain operations on type should have particular time complexity (e.g., constant time)

programmer solely responsible for ensuring non-syntactic requirements are met, as compiler cannot check them

subsequent slides summarize concepts defined in standard library
### Core Language Concepts (in `concepts` Header)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>same_as</code></td>
<td>type is same as another type</td>
</tr>
<tr>
<td><code>derived_from</code></td>
<td>type is derived from another type</td>
</tr>
<tr>
<td><code>convertible_to</code></td>
<td>type is implicitly convertible to another type</td>
</tr>
<tr>
<td><code>common_reference_with</code></td>
<td>two types share common reference type</td>
</tr>
<tr>
<td><code>common_with</code></td>
<td>two types share common type</td>
</tr>
<tr>
<td><code>integral</code></td>
<td>type is integral type</td>
</tr>
<tr>
<td><code>signed_integral</code></td>
<td>type is integral type that is signed</td>
</tr>
<tr>
<td><code>unsigned_integral</code></td>
<td>type is integral type that is unsigned</td>
</tr>
<tr>
<td><code>floating_point</code></td>
<td>type is floating-point type</td>
</tr>
<tr>
<td><code>assignable_from</code></td>
<td>type is assignable from another type</td>
</tr>
<tr>
<td><code>swappable</code></td>
<td>type can be swapped</td>
</tr>
<tr>
<td><code>swappable_with</code></td>
<td>two types can be swapped with each other</td>
</tr>
<tr>
<td><code>destructible</code></td>
<td>type can be destroyed</td>
</tr>
<tr>
<td><code>constructible_from</code></td>
<td>variable of type can be constructed from or bound to set of argument types</td>
</tr>
<tr>
<td><code>default_initializable</code></td>
<td>type can be default constructed</td>
</tr>
<tr>
<td><code>move_constructible</code></td>
<td>type can be move constructed</td>
</tr>
<tr>
<td><code>copy_constructible</code></td>
<td>type can be copy (and move) constructed</td>
</tr>
</tbody>
</table>
### Comparison Concepts (in `concepts` Header)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>equality_comparable</code></td>
<td><code>operator==</code> and <code>operator!=</code> for type consistent with equality</td>
</tr>
<tr>
<td><code>equality_comparable_with</code></td>
<td><code>operator==</code> and <code>operator!=</code> between two types consistent with equality</td>
</tr>
<tr>
<td><code>totally_ordered</code></td>
<td>comparison operators for type consistent with strict total order</td>
</tr>
<tr>
<td><code>totally_ordered_with</code></td>
<td>comparison operators for type consistent with strict total order</td>
</tr>
</tbody>
</table>

### Object Concepts (in `concepts` Header)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>movable</code></td>
<td>type can be moved and swapped</td>
</tr>
<tr>
<td><code>copyable</code></td>
<td>type can be copied and is movable</td>
</tr>
<tr>
<td><code>semiregular</code></td>
<td>type can be default constructed and is copyable</td>
</tr>
<tr>
<td><code>regular</code></td>
<td>type is semiregular and <code>equality_comparable</code></td>
</tr>
<tr>
<td>Name</td>
<td>Description</td>
</tr>
<tr>
<td>---------------------------</td>
<td>------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>invocable*</td>
<td>callable type can be invoked with given set of arguments using <code>std::invoke</code></td>
</tr>
<tr>
<td>regular_invocable*</td>
<td>callable type that satisfies requirements of <code>invocable</code>, is equality preserving, and does not modify function object or arguments</td>
</tr>
<tr>
<td>predicate</td>
<td>callable type is boolean predicate</td>
</tr>
<tr>
<td>relation</td>
<td>callable type is binary relation</td>
</tr>
<tr>
<td>equivalence_relation</td>
<td>callable type is relation that imposes equivalence relation</td>
</tr>
<tr>
<td>strict_weak_order</td>
<td>callable type is relation that imposes strict weak ordering</td>
</tr>
</tbody>
</table>

*distinction between `invocable` and `regular_invocable` is purely semantic*
## Iterator Concepts (in iterator Header)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>indirectly_readable</td>
<td>type has dereferencing operator whose result can be read</td>
</tr>
<tr>
<td>indirectly_writable</td>
<td>type has dereferencing operator whose result can be written</td>
</tr>
<tr>
<td>weakly_incrementable</td>
<td>type is semiregular and can be incremented with pre- and post-increment operators</td>
</tr>
<tr>
<td>incrementable</td>
<td>type is regular, weakly_incrementable, and increment operation is equality_comparable</td>
</tr>
<tr>
<td>input_or_output_iterator</td>
<td>type is input or output iterator type</td>
</tr>
<tr>
<td>sentinel_for</td>
<td>type is sentinel for given input or output iterator type</td>
</tr>
<tr>
<td>sized_sentinel_for</td>
<td>type is sentinel for given input or output iterator type and provides constant-time difference operator</td>
</tr>
<tr>
<td>input_iterator</td>
<td>type is input iterator type</td>
</tr>
<tr>
<td>output_iterator</td>
<td>type is output iterator type</td>
</tr>
<tr>
<td>forward_iterator</td>
<td>type is forward iterator type</td>
</tr>
<tr>
<td>bidirectional_iterator</td>
<td>type is bidirectional iterator type</td>
</tr>
<tr>
<td>random_access_iterator</td>
<td>type is random-access iterator type</td>
</tr>
<tr>
<td>contiguous_iterator</td>
<td>type is random-access iterator type that refers to elements stored contiguously in memory</td>
</tr>
</tbody>
</table>
## Indirect Callable Concepts (in `iterator` Header)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>indirectly_unary_invocable</code></td>
<td>type is callable and can be invoke with result of dereferencing indirectly readable type</td>
</tr>
<tr>
<td><code>indirectly_regular_unary_invocable</code></td>
<td>type is callable and can be invoke with result of dereferencing indirectly readable type</td>
</tr>
<tr>
<td><code>indirect_unary_predicate</code></td>
<td>type is predicate that can be invoked with one argument resulting from dereferencing indirectly readable type</td>
</tr>
<tr>
<td><code>indirect_binary_predicate</code></td>
<td>type is predicate that can be invoked with two arguments resulting from dereferencing indirectly readable type</td>
</tr>
<tr>
<td><code>indirect_equivalence_relation</code></td>
<td>type is equivalent_relation that can be invoked with two arguments resulting from dereferencing indirectly readable type</td>
</tr>
<tr>
<td><code>indirect_strict_weak_order</code></td>
<td>type is strict_weak_order that can be invoked with two arguments resulting from dereferencing indirectly readable type</td>
</tr>
</tbody>
</table>
## Concepts for Common Algorithm Requirements (in `iterator` Header)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>indirectly_movable</td>
<td>values can be moved from indirectly_readable type to indirectly_writable type</td>
</tr>
<tr>
<td>indirectly_movable_storable</td>
<td>type is indirectly_movable but move may be performed via intermediate object</td>
</tr>
<tr>
<td>indirectly_copyable</td>
<td>values can be copied from indirectly_readable type to indirectly_writable type</td>
</tr>
<tr>
<td>indirectly_copyable_storable</td>
<td>type is indirectly_copyable but copy may be performed via intermediate object</td>
</tr>
<tr>
<td>indirectly_swappable</td>
<td>values referenced by two indirectly_readable types can be swapped</td>
</tr>
<tr>
<td>indirectly_comparable</td>
<td>values referenced by two indirectly_readable types can be compared</td>
</tr>
<tr>
<td>permutable</td>
<td>type meets requirements of algorithm that reorders elements in place</td>
</tr>
<tr>
<td>mergeable</td>
<td>type meets requirements of algorithm that merge sorted sequences into output sequence by copying elements</td>
</tr>
<tr>
<td>sortable</td>
<td>type meets requirements of algorithms that permute sequences into ordered sequences</td>
</tr>
</tbody>
</table>
## Range-Related Concepts

Range Concepts (in Namespace `std::ranges` in `ranges` Header)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>range</td>
<td>type is range (i.e., has <code>ranges::begin</code> and <code>ranges::end</code> operations that return iterator and sentinel, respectively)</td>
</tr>
<tr>
<td>borrowed_range</td>
<td>type is range whose iterators continue to be valid beyond end of range’s lifetime</td>
</tr>
<tr>
<td>sized_range</td>
<td>type is range that provides constant-time <code>size</code> operation</td>
</tr>
<tr>
<td>view</td>
<td>type is range that is view (i.e., has constant-time copy/move/assignment operations)</td>
</tr>
<tr>
<td>input_range</td>
<td>type is range whose iterator type satisfies <code>input_iterator</code></td>
</tr>
<tr>
<td>output_range</td>
<td>type is range whose iterator type satisfies <code>output_iterator</code></td>
</tr>
<tr>
<td>forward_range</td>
<td>type is range whose iterator type satisfies <code>forward_iterator</code></td>
</tr>
<tr>
<td>bidirectional_range</td>
<td>type is range whose iterator type satisfies <code>bidirectional_iterator</code></td>
</tr>
<tr>
<td>random_access_range</td>
<td>type is range whose iterator type satisfies <code>random_access_iterator</code></td>
</tr>
<tr>
<td>contiguous_range</td>
<td>type is range whose iterator type satisfies <code>contiguous_iterator</code></td>
</tr>
<tr>
<td>common_range</td>
<td>type is range whose iterator and sentinel types are same</td>
</tr>
<tr>
<td>viewable_range</td>
<td>type is range that can be safely converted to view</td>
</tr>
</tbody>
</table>
```cpp
#include <complex>
#include <concepts>
#include <exception>
#include <functional>
#include <mutex>
#include <thread>
#include <string>
#include <vector>

static_assert(
    std::copyable<std::string> &&
    !std::movable<std::mutex> &&
    std::regular<std::string> &&
    std::totally_ordered<std::string> &&
    !std::totally_ordered<std::complex<float>> &&
    std::predicate<std::less<int>, int, int> &&
    std::same_as<int, decltype(42)> &&
    std::floating_point<double> &&
    std::derived_from<std::logic_error, std::exception> &&
    std::integral<bool> &&
    std::swappable<std::thread> &&
    std::constructible_from<std::string, char*> &&
    std::constructible_from<std::complex<double>, double> &&
    std::equality_comparable<std::string::iterator> &&
    std::equality_comparable_with<std::string::iterator,
      std::string::const_iterator> &&
    std::assignable_from<int&, int> &&
    !std::assignable_from<int, int> &&
    std::invocable<int(int, int), double, float>
);
```
```cpp
#include <ranges>
#include <vector>
#include <list>
#include <forward_list>
#include <string>

static_assert(
    std::ranges::range<std::string> &&
    std::ranges::range<std::vector<int>> &&
    std::ranges::sized_range<std::list<int>> &&
    !std::ranges::view<std::vector<int>> &&
    std::ranges::forward_range<std::forward_list<int>> &&
    std::ranges::bidirectional_range<std::list<int>> &&
    std::ranges::random_access_range<std::vector<int>> &&
    std::ranges::contiguous_range<std::vector<int>> &&
    !std::ranges::contiguous_range<std::list<int>> &&
    std::ranges::common_range<std::vector<int>>
);
Section 2.6.5

References

References


Section 2.7

Lambda Expressions
functor classes extremely useful, especially for generic programming

writing definitions of functor classes somewhat tedious, especially if many such classes

functor classes all have same general structure (i.e., constructor, function-call operator, zero or more data members)

would be nice if functor could be created without need to explicitly write functor-class definition

lambda expressions provide compact notation for creating functors

convenience feature (not fundamentally anything new that can be done with lambda expressions that could not already have been done without them)
Lambda Expressions

- lambda expression consists of:
  1. introducer: capture list in square brackets
  2. declarator: parameter list in parentheses followed by return type using trailing return-type syntax
  3. compound statement in brace brackets

- capture list specifies objects to be captured as data members
- declarator specifies parameter list and return type of function-call operator
- compound statement specifies body of function-call operator
- if no declarator specified, defaults to ()
- if no return type specified, defaults to type of expression in return statement, or void if no return statement
- when evaluated, lambda expression yields object called closure (which is essentially a functor)
- examples:

  ```
  [](double x) -> int {return floor(x);}
  [](int x, int y) {return x < y;}
  [](std::cout << "Hello, World!\n");
  ```
Lambda Expressions (Continued)

- closure object is unnamed (temporary object)
- closure type is unnamed
- `operator()` is always inline \[ C++17 §8.1.5.1/3 \]
- `operator()` is const member function unless `mutable` keyword used \[ C++17 §8.1.5.1/4 \]
- if closure type is literal type, all members of closure type automatically constexpr
- if no capture, closure type provides conversion function to pointer to function having same parameter and return types as closure type’s function call operator; value returned is address of function that, when invoked, has same effect as invoking closure type’s function call operator (function pointer not tied to lifetime of closure object) \[ C++17 §8.1.5.1/6 \]
- although `operator()` in closure very similar to case of normal functor, not everything same (e.g., `operator()` member in closure type cannot access `this` pointer for closure type)
Hello World Program Revisited

```cpp
#include <iostream>

int main() {
    []{std::cout << "Hello, World!\n";}();
}
```

```cpp
#include <iostream>

struct Hello {
    void operator()() const {
        std::cout << "Hello, World!\n";
    }
};

int main() {
    Hello hello;
    hello();
}
```
```cpp
#include <iostream>

auto make_linear_func(float a, float b)
    { return [a, b](float x){return a * x + b;}; }

int main() {
    float a = 0.5f; float b = 1.0f;
    auto f = make_linear_func(a, b);
    std::cout << f(1.0f) << '
';
}

#include <iostream>

class linear_func {
public:
    linear_func(float a, float b) : a_(a), b_(b) {}
    float operator()(float x) const {return a_ * x + b_;}
private:
    float a_; float b_; }

linear_func make_linear_func(float a, float b)
    { return linear_func(a, b); }

int main() {
    float a = 0.5f; float b = 1.0f;
    linear_func f = make_linear_func(a, b);
    std::cout << f(1.0f) << '
';
```
```cpp
#include <iostream>
#include <algorithm>
#include <cstdlib>
#include <vector>

int main() {
    std::vector<int> v{-3, 3, 4, 0, -2, -1, 2, 1, -4};
    std::sort(v.begin(), v.end(), [] (int x, int y) {return std::abs(x) < std::abs(y);});
    for (auto x : v) std::cout << x << '
';
}

#include <iostream>
#include <algorithm>
#include <cstdlib>
#include <vector>

struct abs_less {
    bool operator() (int x, int y) const {
        return std::abs(x) < std::abs(y);}
};

int main() {
    std::vector<int> v{-3, 3, 4, 0, -2, -1, 2, 1, -4};
    std::sort(v.begin(), v.end(), abs_less());
    for (auto x : v) std::cout << x << '
';
}
```
- locals only available if captured; non-locals always available
- can capture by value or by reference
- different locals can be captured differently
- can specify default capture mode
- can explicitly list objects to be captured or not
- might be wise to explicitly list all objects to be captured (when practical) to avoid capturing objects accidentally (e.g., due to typos)
- in member function, to capture class object by value, capture *this
- in member function, can also capture this
- this must be captured by value
(unary version of) `std::transform` applies given (unary) operator to each element in range specified by pair of iterators and writes result to location specified by another iterator

**definition of `std::transform` would typically resemble:**

```cpp
template <class InputIterator, class OutputIterator,
          class UnaryOperator>
OutputIterator transform(InputIterator first,
                        InputIterator last, OutputIterator result,
                        UnaryOperator op) {
    while (first != last) {
        *result = op(*first);
        ++result;
        ++first;
    }
    return result;
}
```
Modulus Example

```cpp
#include <iostream>
#include <vector>
#include <algorithm>

int main() {
    int m = 2;
    std::vector<int> v{0, 1, 2, 3};
    std::transform(v.begin(), v.end(), v.begin(),
                   [m](int x){return x % m;});
    for (auto x : v) std::cout << x << \n;
}
```

```cpp
#include <iostream>
#include <vector>
#include <algorithm>

class mod {
public:
    mod(int m_) : m(m_) {}
    int operator()(int x) const {return x % m;}
private:
    int m;
};

int main() {
    int m = 2;
    std::vector<int> v{0, 1, 2, 3};
    std::transform(v.begin(), v.end(), v.begin(), mod(m));
    for (auto x : v) std::cout << x << \n;
}
```
Modulus Example: Without Lambda Expression

```cpp
#include <iostream>
#include <vector>
#include <algorithm>

class mod {
public:
    mod(int m_) : m(m_) {}
    int operator()(int x) const { return x % m; }

private:
    int m;
};

int main() {
    int m = 2;
    std::vector<int> v{0, 1, 2, 3};
    std::transform(v.begin(), v.end(), v.begin(), mod(m));
    for (auto x : v) std::cout << x << '
';
}
```

- approximately 8.5 lines of code to generate functor
Modulus Example: With Lambda Expression

```cpp
#include <iostream>
#include <vector>
#include <algorithm>

int main() {
    int m = 2;
    std::vector<int> v{0, 1, 2, 3};
    std::transform(v.begin(), v.end(), v.begin(),
                   [m](int x){return x % m;});
    for (auto x : v) std::cout << x << '
';
}
```

- m captured by value
- approximately 0.5 lines of code to generate functor
std::for_each applies given function/functor to each element in range specified by pair of iterators

definition of std::for_each would typically resemble:

```cpp
template<class InputIterator, class Function>
Function for_each(InputIterator first, InputIterator last, Function func) {
    while (first != last) {
        func(*first);
        ++first;
    }
    return move(func);
}
```
```cpp
#include <iostream>
#include <vector>
#include <algorithm>

int main() {
    std::vector<int> v{2, 3, 4};
    int prod = 1;
    std::for_each(v.begin(), v.end(),
        [prod](int x)->void {prod *= x;});
    std::cout << prod << '
';
}

#include <iostream>
#include <vector>
#include <algorithm>

class cum_prod {
public:
    cum_prod(int& prod_) : prod(prod_) {}  
        void operator()(int x) const {prod *= x;}
private:
    int& prod;
};

to main() {
    std::vector<int> v{2, 3, 4};
    int prod = 1;
    std::for_each(v.begin(), v.end(), cum_prod(prod));
    std::cout << prod << ' \n';
}
```
#include <iostream>
#include <vector>
#include <algorithm>

class cum_prod {
public:
    cum_prod(int& prod_) : prod(prod_) {}
    void operator()(int x) const {prod *= x;}
private:
    int& prod;
};

int main() {
    std::vector<int> v{2, 3, 4};
    int prod = 1;
    std::for_each(v.begin(), v.end(), cum_prod(prod));
    std::cout << prod << 'n';
}

- approximately 8.5 lines of code to generate functor
Product Example: With Lambda Expression

```cpp
#include <iostream>
#include <vector>
#include <algorithm>

int main() {
    std::vector<int> v{2, 3, 4};
    int prod = 1;
    std::for_each(v.begin(), v.end(),
                  [&prod](int x)->void{prod *= x;});
    std::cout << prod << '
';
}
```

- **prod** captured by reference
- approximately 1 line of code to generate functor
double a = 2.14;
double b = 3.14;
double c = 42.0;

// capture all objects by reference (i.e., a, b, and c)
([&](double x, double y){return a * x + b * y + c;})

// capture all objects by value (i.e., a, b, and c)
[=](double x, double y){return a * x + b * y + c;}

// capture all objects by value, except a
// which is captured by reference
[=,&a](double x, double y){return a * x + b * y + c;}

// capture all objects by reference, except a
// which is captured by value
[&,&a](double x, double y){return a * x + b * y + c;}

Generalized Lambda Capture

- can specify name for captured object in closure type

```cpp
int a = 1;
auto f = [x = a]() { return x;};
```

- can capture result of expression (e.g., to perform move instead of copy or to add arbitrary new state to closure type)

```cpp
std::vector<int> v(1000, 1);
auto f = [v = std::move(v)]() ->
    const std::vector<int>& { return v;};
```
```cpp
#include <iostream>

int main() {
    int x = 0;
    int y = 1;
    auto f = [&count = x, inc = y + 1](){
        return count += inc;
    }
    std::cout << f() << ' ';  
    std::cout << f() << '
';  
}

// output: 2 4
```
- can allow compiler to deduce type of lambda function parameters
- generates closure type with templated function-call operator
- one template type parameter for each occurrence of `auto` in lambda expression’s parameter declaration clause \[\text{[C++17 §8.1.5.1/3]}\]
#include <iostream>
#include <complex>
#include <string>

int main() {
    using namespace std::literals;
    auto add = [](auto x, auto y) {return x + y;};
    std::cout << add(1, 2) << ' ' << add(1.0, 2.0) << ' ' << add(1.0, 2.0i) << ' ' << add("Jell"s, "o"s) << 'n';
}

#include <iostream>
#include <complex>
#include <string>

struct Add {
    template <class T, class U>
    auto operator()(T x, U y) {return x + y;};
};

int main() {
    using namespace std::literals;
    Add add;
    std::cout << add(1, 2) << ' ' << add(1.0, 2.0) << ' ' << add(1.0, 2.0i) << ' ' << add("Jell"s, "o"s) << 'n';
}
#include <iostream>
#include <vector>
#include <algorithm>

int main() {
    std::vector<int> v{0, 1, 2, 3, 4, 5, 6, 7};
    // sort elements of vector in descending order
    std::sort(v.begin(), v.end(),
        [](auto i, auto j) {return i > j;});
    std::for_each(v.begin(), v.end(),
        [](auto i) {std::cout << i << '\n';});
}
```cpp
int main() {
    // deduced types for x and y are independent
    auto f = [](auto x, auto y) {
        // ...
    };
    // x and y must have same deduced type
    auto g = []<class T>(T x, T y) {
        // ...
    };
    f(1, 2);
    g(1, 2);
    f(1, 2.0);
    // g(1, 2.0); // ERROR
}
```
Dealing With Unnamed Types

- fact that closure types unnamed causes complications when need arises to refer to closure type
- helpful language features: `auto`, `decltype`
- helpful library features: `std::function`
- closures can be stored using `auto` or `std::function`
- closures that do not capture can be “stored” by assigning to function pointer
#include <iostream>
#include <functional>

std::function<double(double)> linear(double a, double b) {
    return [=](double x){return a * x + b;};
}

int main() {
    // type of f is std::function<double(double)>
    auto f = linear(2.0, -1.0);
    // g has closure type
    auto g = [](double x){return 2.0 * x - 1.0;};
    double (*u)(double) = [](double x){return 2.0 * x - 1.0;};
    // h has same type as g
    decltype(g) h = g;
    for (double x = 0.0; x < 10.0; x += 1.0) {
        std::cout << x << ' ' << f(x) << ' ' << g(x) << ‘ ‘ << h(x) << ‘ ‘ << (*u)(x) << ‘ ’ << ‘n’;
    }
}

- applying function-call operator to f much slower than in case of g and h
- when std::function used, inlining of called function probably not possible
- when functor used directly (via function-call operator) inlining is very likely
- prefer auto over std::function for storing closures
operator() as Non-const Member

```cpp
#include <iostream>

int main()
{
    int count = 5;
    // Must use mutable in order to be able to
    // modify count member.
    auto get_count = [count]() mutable -> int {
        return count++;
    };

    int c;
    while ((c = get_count()) < 10) {
        std::cout << c << '
';
    }
}
```

- `operator()` is declared as const member function unless `mutable` keyword used
- const member function cannot change (non-static) data members
```cpp
#include <iostream>
#include <array>

template <typename T>
constexpr auto multiply_by(T i) {
    return [i](auto j) { return i * j;};
    // OK: lambda is literal type so members
    // are automatically constexpr
}

int main() {
    constexpr auto mult_by_2 = multiply_by(2);
    std::array<int, mult_by_2(8)> a;
    std::cout << a.size() << '
';
}
```
Comparison Functors for Containers

```cpp
#include <iostream>
#include <vector>
#include <set>

int main() {
    // The following two lines are the only important ones:
    auto cmp = [](int* x, int* y){return *x < *y;};
    std::set<int*, decltype(cmp)> s(cmp);

    // Just for something to do:
    // Print the elements of v in sorted order with
    // duplicates removed.
    std::vector<int> v = {4, 1, 3, 2, 1, 1, 1, 1};
    for (auto& x : v) {
        s.insert(&x);
    }
    for (auto x : s) {
        std::cout << *x << 'n';
    }
}
```

- note that `s` is not default constructed
- since closure types not default constructible, following would fail:
  `std::set<int*, decltype(cmp)> s;`
- note use of decltype in order to specify type of functor
#include <iostream>
#include <vector>
#include <functional>

std::vector<int> vec{2000, 4000, 6000, 8000, 10000};
std::function<int(int)> func;

void do_stuff()
{
    int modulus = 10000;
    func = [&](int x){return x % modulus;};
    for (auto x : vec) {
        std::cout << func(x) << '
';
    }
}

int main()
{
    do_stuff();
    for (auto x : vec) {
        std::cout << func(x) << '
';
    }
}

above code has very serious bug; what is it?
if some objects captured by reference, closure can hold dangling references

responsibility of programmer to avoid such problems

if will not cause performance issues, may be advisable to capture by value (to avoid problem of dangling references)

dangling-reference example:

```cpp
#include <iostream>
#include <functional>

std::function<double(double)> linear(double a, double b) {
    return [&](double x){return a * x + b;};
}

int main() {
    auto f = linear(2.0, -1.0);
    // bad things will happen here
    std::cout << f(1.0) << '
';
}
```
Section 2.7.1

References

Section 2.8

Comparison: Equality/Equivalence and Ordering
Equality Relations

- Equality relation is rule for set $S$ that specifies for every two elements $a, b \in S$, if $a$ equals $b$.
- For two objects $a$ and $b$ of some type, $a$ and $b$ should be deemed equal if they represent same logical value.
- Consider `SimpleString` type:
  ```
  class SimpleString {
    bool operator==(const SimpleString& other) const;
    // ...
  private:
    char* start; // start of character buffer
    std::size_t length; // length of buffer
  };
  ```
- Two objects $a$ and $b$ of type `SimpleString` having same logical value most likely to be defined as:
  - length members are equal; and
  - buffers pointed to by `start` members contain identical sequences of characters (but `start` members themselves not required to be equal).
in some contexts, can be desirable to treat two objects of some type with unequal values as equivalent (i.e., as if equal)

two values said to be equivalent (in some context) if they are to be treated as if they were same (even though they might not be equal)
equivalence relation is rule for set $S$ that specifies for every two elements $a, b \in S$, if $a$ equivalent $b$.

consider case-insensitive comparison of two `std::string` objects

in this context, strings with values “hello” and “HELLO” are clearly not equal but must be treated as if so

effectively, equivalence relation partitions set into disjoint subsets where elements of each subset are equivalent

these subsets are known as equivalence classes

elements deemed equivalent if and only if belong to same equivalence class
ordering relation is rule for set $S$ that specifies, for every two elements $a, b \in S$, if $a$ has some particular rank relative to $b$ (e.g., precedes or follows)

for example, each of following built-in operators for type `int` constitutes ordering relation for set of all `int` values:

- less than ($<$)
- greater than ($>$)
- less than or equal ($\leq$)
- greater than or equal ($\geq$)
given set \( \{x_i\} \) of values of some type \( T \) and ordering relations, we can attempt to place values in order from least to greatest

may encounter elements that are incomparable

given any two values \( a \) and \( b \) in set, exactly one of following possibilities must be true:

1. \( a \) precedes \( b \) (i.e., \( a \) is less than \( b \))
2. \( a \) and \( b \) are comparable and \( a \) does not precede \( b \) and \( b \) does not precede \( a \) (i.e., \( a \) is equivalent to \( b \))
3. \( b \) precedes \( a \) (i.e., \( a \) is greater than \( b \))
4. \( a \) and \( b \) are incomparable

two key considerations going forward:

1. are all values comparable?
2. does equivalence imply equality?
as of C++20, language provides mechanism for querying (full) ordering relationship between two values

depending on properties of ordering relations used for set of values of some type, different kinds of outcomes can arise when comparing elements of set

different kinds of outcomes that can arise addressed in language by comparison categories

each comparison category is associated with certain key properties that comparison operation must satisfy

some comparison categories are stronger (i.e., have stricter requirements) than others

language defines following three comparison categories in order of decreasing strength:

1. strong ordering
2. weak ordering
3. partial ordering
Strong Orderings

- comparison category that is strongest (i.e., has strictest requirements) is strong ordering \([\text{C++20 §17.11.2.4}]\)

- strong ordering closely related to notion of \textit{total order} in set theory

- two distinguishing characteristics of strong ordering:
  1. every two elements in set are comparable
  2. equivalence of elements with respect to ordering relation implies equality

- given any two elements \(a\) and \(b\) in set, exactly one of following three possibilities must be true:
  1. \(a\) precedes \(b\) (i.e., \(a\) is \textit{less than} \(b\))
  2. \(a\) and \(b\) are comparable and \(a\) does not precede \(b\) and \(b\) does not precede \(a\) (i.e., \(a\) is \textit{equal to} \(b\))
  3. \(b\) precedes \(a\) (i.e., \(a\) is \textit{greater than} \(b\))
ordering relationship between values associated with strong ordering represented by `std::strong_ordering` class

`std::strong_ordering` class defines following members to represent ordering relationship:

- less
- equal and equivalent
- greater

For example, for set of `int` values, built-in comparison operators are consistent with strong ordering
second strongest comparison category is weak ordering.^{[C++20 §17.11.2.3]}  

weak ordering related to notion of total preorder in set theory  

two distinguishing characteristics of weak ordering:  

1. every two elements in set are comparable  
2. equivalence of elements with respect to ordering relation does not necessarily imply equality  

given any two elements $a$ and $b$ in set, exactly one of following three possibilities must be true:  

1. $a$ precedes $b$ (i.e., $a$ is less than $b$)  
2. $a$ and $b$ are comparable and $a$ does not precede $b$ and $b$ does not precede $a$ (i.e., $a$ is equivalent to $b$)  
3. $b$ precedes $a$ (i.e., $a$ is greater than $b$)  

two elements that are related by neither less-than nor greater-than relationship are equivalent (since not necessarily equal)  

strong ordering satisfies requirements of weak ordering
ordering relationship between values associated with weak ordering represented by `std::weak_ordering` class

`std::weak_ordering` class defines following members to represent ordering relationship:
- less
- equivalent
- greater

for set of null-terminated strings, case-insensitive string comparison performed by `strcasecmp` function (in POSIX standard) provides weak ordering

case-insensitive comparison would deem values "hello" and "HELLO" to be equivalent (even though these values not equal)
Partial Orderings (1)

- comparison category that is weakest (i.e., has least strict requirements) is partial ordering \[C++20 \S 17.11.2.2\]

- partial ordering related to notion of preorder in set theory

- two distinguishing characteristics of partial ordering:
  1. every two elements in set are not necessarily comparable
  2. equivalence of elements with respect to ordering relation does not necessarily imply equality

- given any two elements \(a\) and \(b\) in set, exactly one of following possibilities must be true:
  1. \(a\) precedes \(b\) (i.e., \(a\) is less than \(b\))
  2. \(a\) and \(b\) are comparable and \(a\) does not precede \(b\) and \(b\) does not precede \(a\) (i.e., \(a\) is equivalent to \(b\))
  3. \(b\) precedes \(a\) (i.e., \(a\) is greater than \(b\))
  4. \(a\) and \(b\) are incomparable

- strong and weak orderings satisfy requirements of partial ordering
ordering relationship between values associated with partial ordering represented by class `std::partial_ordering`

`std::partial_ordering` class defines following members to represent ordering relationship:

- less
- equivalent
- greater
- unordered

For example, for set of `double` values, built-in comparison operators consistent with partial ordering (since NaN values are incomparable with other `double` values and each other)
Hierarchy of Comparison Categories

- comparison categories in decreasing order of strength:
  1. strong_ordering
  2. weak_ordering
  3. partial_ordering

- can implicitly convert from stronger comparison category to weaker one

- as shown in table below, value in stronger category mapped to value of same name in weaker category, except case of equal, which becomes equivalent

Conversion of Ordering Category Values*

<table>
<thead>
<tr>
<th>Category</th>
<th>Corresponding Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>strong_ordering</td>
<td>less</td>
</tr>
<tr>
<td>weak_ordering</td>
<td>less</td>
</tr>
<tr>
<td>partial_ordering</td>
<td>less</td>
</tr>
</tbody>
</table>

*can only convert in stronger-to-weaker (i.e., downward) direction
Two-Way Comparison Operators

<table>
<thead>
<tr>
<th>Equality/Equivalence Operators</th>
<th>Ordering Operators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operator</td>
<td>Name</td>
</tr>
<tr>
<td>==</td>
<td>equality</td>
</tr>
<tr>
<td>!=</td>
<td>inequality</td>
</tr>
<tr>
<td>&gt;</td>
<td>greater than</td>
</tr>
</tbody>
</table>

- single equality/ordering operator does not give full information about ordering relationship
- if one of equality/ordering operators returns false, cannot tell relationship between operands without applying further ordering operators
- for example, if \( a < b \) is false, we do not know if: 1) \( a == b \) is true; 2) \( a > b \) is true; or 3) \( a \) and \( b \) are incomparable
- similarly, if \( a == b \) is false, we do not know if: 1) \( a < b \) is true; 2) \( a > b \) is true; or 3) \( a \) and \( b \) are incomparable
- incomplete nature of information provided by two-way comparison operator serves as motivation for three-way comparison operator
Three-Way Comparison (a.k.a. Spaceship) Operator (1)

- three-way comparison (a.k.a. spaceship) operator \(\leq\) is a binary operator that returns a complete ordering relationship between two values (i.e., less, equal/equivalent, greater, or incomparable).

- Return value of operator corresponds to type associated with comparison category realized by operator:

<table>
<thead>
<tr>
<th>Category</th>
<th>Return Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>strong ordering</td>
<td>std::strong_ordering</td>
</tr>
<tr>
<td>weak ordering</td>
<td>std::weak_ordering</td>
</tr>
<tr>
<td>partial ordering</td>
<td>std::partial_ordering</td>
</tr>
</tbody>
</table>

- Result of three-way comparison operator is as follows:

<table>
<thead>
<tr>
<th>Relationship Between (a) and (b)</th>
<th>Result* of (a \leq) (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) is less than (b)</td>
<td>less</td>
</tr>
<tr>
<td>(a) and (b) are equal/equivalent</td>
<td>equal/equivalent</td>
</tr>
<tr>
<td>(a) is greater than (b)</td>
<td>greater</td>
</tr>
<tr>
<td>(a) and (b) are incomparable</td>
<td>unordered</td>
</tr>
</tbody>
</table>

*value in corresponding comparison-category class
reversing order of operands for three-way comparison operator only has effect of swapping less and greater:

<table>
<thead>
<tr>
<th>Result of ( a \leftrightarrow b )</th>
<th>Result of ( b \leftrightarrow a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>less</td>
<td>greater</td>
</tr>
<tr>
<td>equal/equivalent</td>
<td>equal/equivalent</td>
</tr>
<tr>
<td>greater</td>
<td>less</td>
</tr>
<tr>
<td>unordered</td>
<td>unordered</td>
</tr>
</tbody>
</table>

- integral types yield `std::strong_ordering`
- floating-point types yield `std::partial_ordering`
- pointer types yield `std::strong_ordering` whose result is unspecified if pointers being compared do not point into same array

example:

```cpp
static_assert(2 <=> 1 == std::strong_ordering::greater);
static_assert(1.0 <=> 2.0 == std::partial_ordering::less);
```
```cpp
#include <cassert>
#include <compare>
#include <concepts>
#include <limits>
#include <numbers>

int main() {
    constexpr int one = 1;
    constexpr int two = 2;
    static_assert(std::numeric_limits<double>::is_iec559);
    constexpr double nan = std::numeric_limits<double>::quiet_NaN();
    constexpr double half = 0.5;
    constexpr double pi = std::numbers::pi_v<double>;
    static_assert((std::same_as<decltype(one <=> two), std::strong_ordering>));
    static_assert(one <=> two == std::strong_ordering::less);
    static_assert(one <=> one == std::strong_ordering::equal);
    static_assert(two <=> one == std::strong_ordering::greater);
    static_assert((std::same_as<decltype(half <=> pi), std::partial_ordering>));
    static_assert(half <=> pi == std::partial_ordering::less);
    static_assert(half <=> half == std::partial_ordering::equivalent);
    static_assert(pi <=> half == std::partial_ordering::greater);
    assert(half <=> nan == std::partial_ordering::unordered);
    static_assert((std::same_as<decltype(0.5 <=> 1), std::partial_ordering>));
    static_assert(0.5 <=> 1 == std::partial_ordering::less);
}
```

value $v$ of comparison-category type can be compared to literal 0 (where $v$ would typically result from evaluating expression of form $a \ <=> \ b$)

when literal 0 is second operand, this has following meaning:

<table>
<thead>
<tr>
<th>Expression</th>
<th>Ordering</th>
<th>Equivalent Expression$^\dagger$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v == 0$</td>
<td>strong</td>
<td>$v == C::equal$</td>
</tr>
<tr>
<td></td>
<td>weak/partial</td>
<td>$v == C::equivalent$</td>
</tr>
<tr>
<td>$v !\neq 0$</td>
<td>strong</td>
<td>!($v == C::equal$)</td>
</tr>
<tr>
<td></td>
<td>weak/partial</td>
<td>!($v == C::equivalent$)</td>
</tr>
<tr>
<td>$v &lt; 0$</td>
<td>—</td>
<td>$v == C::less$</td>
</tr>
<tr>
<td>$v &gt; 0$</td>
<td>—</td>
<td>$v == C::greater$</td>
</tr>
<tr>
<td>$v &lt;= 0$</td>
<td>strong</td>
<td>$v == C::less \</td>
</tr>
<tr>
<td></td>
<td>weak/partial</td>
<td>$v == C::less \</td>
</tr>
<tr>
<td>$v &gt;= 0$</td>
<td>strong</td>
<td>$v == C::greater \</td>
</tr>
<tr>
<td></td>
<td>weak/partial</td>
<td>$v == C::greater \</td>
</tr>
<tr>
<td>$v \ &lt;=&gt; 0$</td>
<td>—</td>
<td>$v$</td>
</tr>
</tbody>
</table>

$^\dagger$ C is comparison-category type (i.e., strong\_ordering, weak\_ordering, partial\_ordering)

abbreviated syntax above allows for less verbose code when extracting two-way comparison result from three-way comparison result
reversing order of operands for three-way comparison operator only has effect of swapping less and greater:

\[
reverse(v) = \begin{cases} 
\text{less} & \text{if } v = \text{greater} \\
\text{greater} & \text{if } v = \text{less} \\
v & \text{otherwise}
\end{cases}
\]

for each relational operator \( op \) (i.e., equality, inequality, less-than, greater-than, less-than-or-equal, greater-than-or-equal):

\( 0 \ op \ v \) is equivalent to \( reverse(v) \ op \ 0 \)

consequently, when literal 0 is first operand, we have:

<table>
<thead>
<tr>
<th>Expression</th>
<th>Equivalent Expression</th>
<th>Simplified</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 == v</td>
<td>reverse(v) == 0</td>
<td>v == 0</td>
</tr>
<tr>
<td>0 != v</td>
<td>reverse(v) != 0</td>
<td>v != 0</td>
</tr>
<tr>
<td>0 &lt; v</td>
<td>reverse(v) &lt; 0</td>
<td>v &gt; 0</td>
</tr>
<tr>
<td>0 &gt; v</td>
<td>reverse(v) &gt; 0</td>
<td>v &lt; 0</td>
</tr>
<tr>
<td>0 &lt;= v</td>
<td>reverse(v) &lt;= 0</td>
<td>v &gt;= 0</td>
</tr>
<tr>
<td>0 &gt;= v</td>
<td>reverse(v) &gt;= 0</td>
<td>v &lt;= 0</td>
</tr>
<tr>
<td>0 &lt;=&gt; v</td>
<td>reverse(v) &lt;=&gt; 0</td>
<td>reverse(v)</td>
</tr>
</tbody>
</table>

moreover, \( a \ <=> b \) equivalent to \( 0 \ <=> (b \ <=> a) \)
#include <cassert>
#include <compare>
#include <concepts>
#include <limits>
#include <numbers>

int main() {
    constexpr int one = 1;
    constexpr int two = 2;
    static_assert(std::numeric_limits<double>::is_iec559);
    constexpr double nan = std::numeric_limits<double>::quiet_NaN();
    constexpr double half = 0.5;
    constexpr double pi = std::numbers::pi_v<double>;
    static_assert((std::same_as<decltype(one <=> two),
                                std::strong_ordering>>));
    static_assert(one <=> two < 0);
    static_assert(one <=> one == 0);
    static_assert(two <=> one > 0);
    static_assert((std::same_as<decltype(half <=> pi),
                                std::partial_ordering>>));
    static_assert(half <=> pi < 0);
    static_assert(half <=> half == 0);
    static_assert(pi <=> half > 0);
    assert(half <=> nan == std::partial_ordering::unordered);
    assert(!(half <=> nan == 0) && !(half <=> nan < 0) && !(half <=> nan > 0));
}
### Named Comparison Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Corresponding Relational Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>is_eq</td>
<td>equality/equivalence</td>
</tr>
<tr>
<td>is_neq</td>
<td>inequality/inequivalence</td>
</tr>
<tr>
<td>is_lt</td>
<td>less than</td>
</tr>
<tr>
<td>is_gt</td>
<td>greater than</td>
</tr>
<tr>
<td>is_lteq</td>
<td>less than or equal</td>
</tr>
<tr>
<td>is_gteq</td>
<td>greater than or equal</td>
</tr>
</tbody>
</table>

*in namespace std

- can use above functions to convert result of three-way comparison to various two-way comparisons [C++20 §17.11.1]

- example:

```cpp
#include <compare>
static_assert(std::is_lt(1 <=> 2));
static_assert(std::is_gt(42.0 <=> 0.0));
```
Customization-Point Objects (CPOs) for Ordering

- Standard library provides customization-point objects (CPOs) that allow comparisons to be performed in alternative manner for particular type
- Functionality provided via `std::strong_order`, `std::weak_order`, and `std::partial_order` [C++20 §17.11.6]
- User provides function (i.e., `strong_order`, `weak_order`, or `partial_order`) that is found via argument-dependent lookup (ADL)
- `std::strong_order`, `std::weak_order`, and `std::partial_order` also provide alternative comparison schemes for floating-point types
```cpp
#include <compare>

namespace foo {

    class Point {
    public:
        Point(int x, int y) : x_(x), y_(y) {}
        int x() const {return x_ ;}
        int y() const {return y_ ;}
        bool operator==(const Point& other) const = default;
        // note: no operator<=> provided

    private:
        int x_;  
        int y_;  
    }

    inline std::strong_ordering
    strong_order(const Point& p, const Point& q) {
        if (auto result = p.x() <=> q.x(); result != 0)  
            {return result;}
        return p.y() <=> q.y();
    }
}

```

```
```cpp
#include <compare>
#include <iostream>
#include <map>
#include "custom_order_3.hpp"

struct Point_compare {
    bool operator()(const foo::Point& p, const foo::Point& q) const {
        return std::strong_order(p, q) < 0;
        // invokes foo::strong_order via ADL
    }
};

int main() {
    std::map<foo::Point, int, Point_compare> m({
        {{1, 1}, 3},
        {{1, 0}, 2},
        {{0, 1}, 1},
        {{0, 0}, 0},
    });
    for (auto& [p, v] : m) {
        std::cout << p.x() << ' ' << p.y() << ' ' << v << '
';
    }
}
```
Taxonomy of Relational Operators

<table>
<thead>
<tr>
<th></th>
<th>Equality</th>
<th>Ordering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>equality (==)</td>
<td>three-way comparison (&lt;&gt;&gt;)</td>
</tr>
<tr>
<td>Secondary</td>
<td>inequality (!=)</td>
<td>less than (&lt;)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>greater than (&gt;)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>less than or equal (&lt;=)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>greater than or equal (&gt;=)</td>
</tr>
</tbody>
</table>

Each relational operator can be classified in two ways:
- primary or secondary
- equality or ordering

Primary operators have ability to be reversed (e.g., \( a == b \) versus \( b == a \))

Secondary operators have ability to be rewritten in terms of corresponding primary operator (e.g., \( a > b \) versus \( a <> b > 0 \))

Rewriting performs transformation to source code does not generate new functions

Primary operators never rewritten in terms of one another

Primary and secondary operators can be defaulted
primary relational operators can be reversed according to following rules:

<table>
<thead>
<tr>
<th>Original</th>
<th>Reversed</th>
</tr>
</thead>
<tbody>
<tr>
<td>a == b</td>
<td>b == a</td>
</tr>
<tr>
<td>a &lt;=&gt; b</td>
<td>0 &lt;=&gt; (b &lt;=&gt; a)</td>
</tr>
</tbody>
</table>

secondary relational operators can be rewritten in terms of primary relational operators according to following rules (where first alternate preferred over second):

<table>
<thead>
<tr>
<th>Original</th>
<th>First Alternate</th>
<th>Second Alternate</th>
</tr>
</thead>
<tbody>
<tr>
<td>a != b</td>
<td>!(a == b)</td>
<td>!(b == a)</td>
</tr>
<tr>
<td>a &lt; b</td>
<td>a &lt;=&gt; b &lt; 0</td>
<td>0 &lt; b &lt;=&gt; a</td>
</tr>
<tr>
<td>a &gt; b</td>
<td>a &lt;=&gt; b &gt; 0</td>
<td>0 &gt; b &lt;=&gt; a</td>
</tr>
<tr>
<td>a &lt;= b</td>
<td>a &lt;=&gt; b &lt;= 0</td>
<td>0 &lt;= b &lt;=&gt; a</td>
</tr>
<tr>
<td>a &gt;= b</td>
<td>a &lt;=&gt; b &gt;= 0</td>
<td>0 &gt;= b &lt;=&gt; a</td>
</tr>
</tbody>
</table>

allowing reversing and rewriting of relational operators has potential to (greatly) reduce number of functions that programmer must provide
candidate lookup considers all operators of that name as well as all reversals and rewrites in one shot

- non-reversed candidate preferred over reversed one
- for example, for evaluating \( a == b \), \( a == b \) preferred over \( b == a \)
- non-rewritten candidate preferred over rewritten one
- for example, for evaluating \( a < b \), \( a < b \) preferred over \( a <=> b < 0 \)
- if best viable candidate is either rewritten or reversed and is invalid (e.g., due to incorrect return type), code is invalid
# Example: Equality as Member

```cpp
#include <cassert>

class Widget {
public:
    explicit Widget(int i) : i_(i) {}
    int value() const {return i_;}
    /* A */ bool operator==(const Widget& other) const
        {return i_ == other.i_.}
    /* B */ bool operator==(int i) const {return i_ == i;}
private:
    int i_;  
};

int main() {
    assert(Widget(42) == Widget(42)); // calls A
    assert(Widget(42) == 42); // calls B
    assert(42 == Widget(42));
    // reverse to Widget(42) == 42; calls B
    assert(Widget(42) != Widget(0));
    // rewrite as !(Widget(42) == Widget(0)); calls A
    assert(Widget(42) != 0);
    // rewrite as !(Widget(42) == 0); calls B
    assert(42 != Widget(0));
    // rewrite swapped as !(Widget(0) == 42); calls B
    }  
```
```cpp
#include <cassert>

class Widget {
public:
    explicit Widget(int i) : i_(i) {}
    int value() const { return i_; }
private:
    int i_;  
};
/* A */ bool operator==(const Widget& a, const Widget& b)
{ return a.value() == b.value(); }
/* B */ bool operator==(const Widget& a, int i)
{ return a.value() == i; }

int main() {
    assert(Widget(42) == Widget(42)); // calls A
    assert(Widget(42) == 42); // calls B
    assert(42 == Widget(42));
    // reverse to Widget(42) == 42; calls B
    assert(Widget(42) != Widget(0));
    // rewrite as !(Widget(42) == Widget(0)); calls A
    assert(Widget(42) != 0);
    // rewrite as !(Widget(42) == 0)); calls B
    assert(42 != Widget(0));
    // rewrite swapped as !(Widget(0) == 42); calls B
    }
```cpp
#include <cassert>
#include <compare>

class Widget {
public:
  explicit Widget(int i) : i_(i) {}  
  int value() const { return i_; }  
  /* A */ bool operator==(const Widget& other) const  
    { return i_ == other.i_; }  
  /* B */ std::strong_ordering operator<=>(const Widget& other) const  
    { return i_ <=> other.i_; }  
  /* C */ bool operator==(int i) const { return i_ == i; }  
  /* D */ std::strong_ordering operator<=>(int i) const { return i_ <=> i; }
private:
  int i_;  
};

int main() {
  assert(Widget(0) == Widget(0)); // calls A  
  assert(Widget(1) != 0);  
    // rewrite to !(Widget(1) == 0); calls C  
  assert(Widget(-1) < Widget(0));  
    // rewrite to Widget(-1) <=> Widget(0) < 0; calls B  
  assert(1 > Widget(0));  
    // rewrite swapped to 0 > Widget(0) <=> 1; calls D  
  assert(Widget(-1) < 0);  
    // rewrite to Widget(-1) <=> 0 < 0; calls D
  }
```
```cpp
#include <cassert>
#include <compare>

class Widget {
  public:
    explicit Widget(int i) : i_(i) {}
    int value() const { return i_; }
    /* A */ bool operator==(int i) const { return i_ == i; }
    /* B */ std::strong_ordering operator<=(int i) const { return i_ <= i; }
    /* C */ bool operator!=(int i) const { return i_ != i; }
    /* D */ bool operator>(int i) const { return i_ > i; }

  private:
    int i_; 
};

    /* E */ std::strong_ordering operator<=(int i, const Widget& w) {
      return i <= w.value();
    }
    /* F */ bool operator>(int i, const Widget& w) { return i > w.value(); }

  int main() {
    assert(Widget(1) != 0); // chooses C (from candidates A, C)
    assert(0 != Widget(1)); // chooses A (only candidate)
    assert(1 > Widget(0)); // chooses F (from candidates B, E, F)
    assert(Widget(0) == 0); // chooses A (only candidate)
    assert(Widget(1) > 0); // chooses D (from candidates B, D, E)
    assert(Widget(-1) < 0); // chooses B (from candidates B, E)
    assert(0 >= Widget(-1)); // chooses E (from candidates B, E) 
  } 
```
**Defaulted Primary Relational Operators**

- **defaulted equality operator** performs *memberwise equality* test of data members (and bases) using appropriate equality operators.

- **defaulted three-way comparison operator** performs *lexicographic comparison* of members (and bases) using appropriate three-way comparison operators.

- defaulted three-way comparison operator *never automatically provided* (in part because compiler does not know correct comparison category to use).

- if defaulted three-way comparison operator desired, must explicitly define as default.

- defaulted equality operator only automatically provided if:
  - no equality operator provided; and
  - three-way comparison operator is (explicitly) defaulted.
#include <compare>

class Point {
public:
    constexpr Point(int x, int y) : x_(x), y_(y) {}
    constexpr int x() const { return x_; }
    constexpr int y() const { return y_; }
    constexpr bool operator==(const Point& other) const
        { return x_ == other.x_ && y_ == other.y_; }
    constexpr std::strong_ordering operator<=>(const Point& other) const
        { return x_ < other.x_ ? std::strong_ordering::less : (x_ == other.x_ ? y_ <=> other.y_ : std::strong_ordering::greater); }
private:
    int x_;    // int y_;  // private field
};

static_assert(Point(-1, 0) < Point(0, 0));
static_assert(Point(0, 1) > Point(0, 0));
static_assert(Point(0, -1) < Point(0, 0));
static_assert(Point(0, 0) == Point(0, 0));
static_assert(Point(1, 0) != Point(0, 0));
static_assert(Point(1, 0) > Point(0, 0));
static_assert(Point(0, 0) <=> Point(0, 0) == 0);
```cpp
#include <compare>

class Point {
public:
    constexpr Point(int x, int y) : x_(x), y_(y) {}
    constexpr int x() const { return x_; }
    constexpr int y() const { return y_; }
    // The following line can be omitted since operator<=> is defaulted:
    // bool operator==(const Point&) const = default;
    std::strong_ordering operator<=>(const Point&) const = default;
private:
    int x_;  
    int y_; 
};

static_assert(Point(-1, 0) < Point(0, 0));
static_assert(Point(0, 1) > Point(0, 0));
static_assert(Point(0, -1) < Point(0, 0));
static_assert(Point(0, 0) == Point(0, 0));
static_assert(Point(1, 0) != Point(0, 0));
static_assert(Point(1, 0) > Point(0, 0));
static_assert(Point(0, 0) <=> Point(0, 0) == 0);
```
defaulted secondary relational operators are specified in terms of primary operators; that is,

- for ordering operator @: \( x \, @ \, y \) becomes \( x \, <=> \, y \, @ \, 0 \) or \( 0 \, @ \, y \, <=> \, x \)

- for inequality operator: \( x \, != \, y \) becomes \( ! (x \, == \, y) \) or \( ! (y \, == \, x) \)

defaulted secondary operator must have return type `bool`

if defaulted secondary operator desired, must explicitly define as default

normally, sufficient to provide primary relational operators (i.e., equality and three-way comparison)

defaulted secondary operators useful in order to create functions whose address can be taken (in cases where this is needed)
Example: Defaulted Secondary Relational Operators

```cpp
#include <compare>

class Widget {
public:
  constexpr Widget(int i = 0) : i_(i) {}
  Widget(const Widget& other) = default;
  Widget& operator=(const Widget& other) = default;
  bool operator==(const Widget& other) const = default;
  constexpr std::strong_ordering operator<=>(const Widget& other) const = default;
  bool operator!=(const Widget& other) const = default;
  bool operator<(const Widget& other) const = default;
  bool operator<=(const Widget& other) const = default;
  // note: operator> and operator>= not defaulted
private:
  int i_;  
};

constexpr Widget zero(0);
constexpr Widget one(1);
static_assert(zero < one && zero <= zero);  // OK: defaulted members
static_assert(one > zero && one >= one);  // OK: operators rewritten
static_assert(zero == zero && zero != one);
auto ptr1 = &Widget::operator<;
  // OK: function exists for which to take address
auto ptr2 = &Widget::operator>;
  // ERROR: no function exists for which to take address
```

#include <compare>

class Gadget;

class Widget {
public:
    explicit constexpr Widget(int x) : x_(x) {}
    constexpr int value() const { return x_; }
    constexpr bool operator==(const Gadget& other) const;

private:
    int x_;  
};

class Gadget {
public:
    explicit constexpr Gadget(int x) : x_(x) {}
    constexpr int value() const { return x_; }
    constexpr bool operator==(const Widget& other) const { return true; }

private:
    int x_;  
};

constexpr bool Widget::operator==(const Gadget& other) const {
    return x_ == other.value();
}

static_assert(Widget(1) == Gadget(1));
static_assert(Widget(1) != Gadget(2)); // A and B not equal
static_assert(Gadget(2) == Widget(1)); // INCONSISTENT: B and A are equal
Two-Way Versus Three-Way Comparisons

- in some cases, two-way comparisons are much less efficient to implement indirectly in terms of three-way comparison
- this difference is often most pronounced when testing for equality
- for example, consider testing two ranges of $n$ elements of type $T$ for equality (such as when comparing two `std::vector<T>` objects)
- when testing for equality directly using equality operator:
  - if sizes of ranges do not match, can immediately conclude not equal without need to iterate over any elements of range
- when testing for equality indirectly using three-way comparison operator:
  - if sizes of ranges do not match, must still iterate over elements until corresponding elements not equal or end of shorter range hit to determine if less or greater case applies
- for reasons of efficiency, may sometimes be necessary to define some secondary relational operators
- when performing comparison, should always prefer two-way (over three-way) comparison, unless full three-way comparison result needed
Guidelines on Relational Operators

- normally, provide only primary relational operators for type
- only provide secondary relational operators when needed for reasons of efficiency
- provide primary relational operators as member functions (as opposed to nonmember functions), unless compelling reason to do otherwise
- in generic code use of three-way comparison operator can be problematic, since types involved may not provide three-way comparison operator
- for this reason, advisable to use function similar in spirit to `synth_three_way` (presented in later example) instead of three-way comparison operator
```cpp
#include <compare>
#include <concepts>

template<class T, class U>
constexpr auto synth_three_way(const T& t, const U& u)
requires requires {
  {t < u} -> std::same_as<bool>;
  {u < t} -> std::same_as<bool>;
} {
  if constexpr (std::three_way_comparable_with<T, U>) {
    return t <=> u;
  } else {
    // assume at least a weak ordering
    if (t < u) {return std::weak_ordering::less;}
    if (u < t) {return std::weak_ordering::greater;}
    return std::weak_ordering::equivalent;
  }
}
```
Example: Use of `synth_three_way`

```cpp
#include <iostream>
#include <string>
#include "synth_three_way.hpp"

// legacy type with no operator<=>
struct legacy {
    bool operator<(const legacy& other) const { return false; }
    // ... (no operator <=>)
};

// some generic code that needs to use three-way comparison
template<class T> void print(const T& a, const T& b) {
    // auto c = a <= b;
    // BAD: will not compile if T does not have operator<=>
    auto c = synth_three_way(a, b); // GOOD
    if (c < 0) {std::cout << "less\n";}
    else if (c == 0) {std::cout << "equal/equivalent\n";}
    else if (c > 0) {std::cout << "greater\n";}
    else {std::cout << "unordered\n";}
}

int main() {
    print(1, 2);
    print(std::string("b"), std::string("a"));
    print(legacy{}, legacy{}); // GOOD: no compile error from print
}


```cpp
#include <compare>
#include <optional>

class optint {
public:

    constexpr optint() = default;
    constexpr explicit optint(int i) : v_(i) {}
    constexpr bool operator==(const optint& other) const {
        return has_value() && other.has_value() && *v_ == *other.v_;}
    constexpr std::partial_ordering operator<=>(const optint& other) const {
        if (!has_value() || !other.has_value()) {
            return std::partial_ordering::unordered;
        } else {return *v_ <=> *other.v_;}
    }
    constexpr bool has_value() const {return v_.has_value();}
    constexpr int value() const {return *v_;}

    static const optint nan;

private:

    std::optional<int> v_;}

constexpr const optint optint::nan = optint{};

static_assert(optint(0) == optint(0));
static_assert(optint(-1) < optint(0));
static_assert(optint(1) > optint(0));
static_assert(optint(1) != optint(0));
static_assert(optint(0) <=> optint::nan == std::partial_ordering::unordered);
```


Section 2.9

Classes and Inheritance
Section 2.9.1

Derived Classes and Class Hierarchies
Derived Classes

- sometimes, want to express commonality between classes
- want to create new class from existing class by adding new members or replacing (i.e., hiding/overriding) existing members
- can be achieved through language feature known as *inheritance*
- generate new class with all members of already existing class, excluding special member functions (i.e., constructors, assignment operators, and destructor)
- new class called *derived class* and original class called *base class*
- derived class said to *inherit* from base class
- can add new members (not in base class) to derived class
- can hide or override member functions from base class with new version
- syntax for specifying derived class:

  ```
  class derived_class : base_class_specifiers
  ```

  - *derived_class* is name of derived class; *base_class_specifiers* provide base-class information
can more clearly express intent by explicitly identifying relationship between classes

- can facilitate code reuse by leverage existing code
- interface inheritance: allow different derived classes to be used interchangeably through interface provided by common base class
- implementation inheritance: save implementation effort by sharing capabilities provided by base class
```cpp
#include <string>

class Person {
public:
    Person(const std::string& family_name,
            const std::string& given_name) :
        family_name_(family_name), given_name_(given_name) {}  
    std::string family_name() const {return family_name_;}
    std::string given_name() const {return given_name_;}
    std::string full_name() const
    {return family_name_ + ", " + given_name_;}
    // ...
private:
    std::string family_name_;  
    std::string given_name_;  
};
```
```cpp
#include <string>

class Student {
public:
    Student(const std::string& family_name,
             const std::string& given_name)
        : family_name_(family_name), given_name_(given_name) {}
    // NEW
    std::string family_name() const { return family_name_; }
    std::string given_name() const { return given_name_; }
    std::string full_name() const
        { return family_name_ + ", " + given_name_; }
    std::string student_id() { return student_id_; } // NEW

private:
    std::string family_name_;  
    std::string given_name_; 
    std::string student_id_;  // NEW
};
```
```cpp
// include definition of Person class here

class Student : public Person {

public:
    Student(const std::string& family_name,
             const std::string& given_name,
             const std::string& student_id) :
        Person(family_name, given_name),
        student_id_(student_id) {}  
    std::string student_id() {return student_id_;}

private:
    std::string student_id_;  
};
```
#include <string>

class Person {
public:
    Person(const std::string& family_name,
            const std::string& given_name) :
        family_name_(family_name), given_name_(given_name) {}
    std::string family_name() const {return family_name_;}
    std::string given_name() const {return given_name_;}
    std::string full_name() const
        {return family_name_ + "", " + given_name_;}
    // ... (including virtual destructor)
private:
    std::string family_name_;  
    std::string given_name_;  
};

class Student : public Person {
public:
    Student(const std::string& family_name,
            const std::string& given_name,
            const std::string& student_id) :
        Person(family_name, given_name),
        student_id_(student_id) {}  
    std::string student_id() {return student_id_;}
private:
    std::string student_id_;  
};
inheritance relationships between classes form what is called **class hierarchy**

often class hierarchy represented by directed (acyclic) graph, where nodes correspond to classes and edges correspond to inheritance relationships

class definitions:

```cpp
class A { /* ... */ };  
class B : public A { /* ... */ };  
class C : public A { /* ... */ };  
class D : public B { /* ... */ };  
class E : public B { /* ... */ };  
```

inheritance diagram:
Class Hierarchy Example

- class definitions:

```cpp
class Person { /* ... */ };
class Employee : public Person { /* ... */ };
class Student : public Person { /* ... */ };
class Alumnus : public Person { /* ... */ };
class Faculty : public Employee { /* ... */ };
class Staff : public Employee { /* ... */ };
class Grad : public Student { /* ... */ };
class Undergrad : public Student { /* ... */ };
```

- inheritance diagram:

```
  Person
   \   /  \\
  Employee /   \ Alumnus
       v   v
     Student

Faculty       Staff
/   \         /   \
Undergrad     Grad
```

- each of Employee, Student, and Alumnus is a Person; each of Faculty and Staff is an Employee; each of Undergrad and Grad is a Student
Member Access Specifiers: protected

- earlier, introduced public and private access specifiers for class members
- in context of inheritance, another access specifier becomes relevant, namely, protected
  - member declared in protected section of class can only be accessed by
    - member functions and friends of that class; and
    - by member functions and friends of derived classes
- protected members used to provide developers of derived classes access to some inner workings of base class without exposing such inner workings to everyone
- usually, bad idea to use protected access for data members (for similar reasons that using public access for data members is usually bad)
- protected access usually employed for function members
Types of Inheritance

- three types of inheritance with respect to access protection: public, protected, and private
- these three types of inheritance differ in terms of accessibility, in derived class, of members inherited from base class
- private parts of base class are always inaccessible in derived class, regardless of whether public, protected, or private inheritance used
- if this were not case, all access protection could simply be bypassed by using inheritance
- access specifiers for members accessible in derived class chosen as follows:

<table>
<thead>
<tr>
<th>Access Specifier in Base Class</th>
<th>Access Specifier in Derived Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public Inheritance</td>
<td>Protected Inheritance</td>
</tr>
<tr>
<td>public</td>
<td>public</td>
</tr>
<tr>
<td>protected</td>
<td>protected</td>
</tr>
<tr>
<td></td>
<td>protected</td>
</tr>
</tbody>
</table>
Types of Inheritance (Continued)

- for struct, defaults to public inheritance
- for class, defaults to private inheritance
- public and protected/private inheritance have different use cases, as we will see later
class Base {
  public:
    void f();
  protected:
    void g();
  private:
    int x;
};

class Derived_1 : public Base {
  // f is public
  // g is protected
  // x is not accessible from Derived_1
};

class Derived_2 : protected Base {
  // f is protected
  // g is protected
  // x is not accessible from Derived_2
};

class Derived_3 : private Base {
  // f is private
  // g is private
  // x is not accessible from Derived_3
};
```cpp
class Base { 
public:
    void func_1();
protected:
    void func_2();
private:
    int x_; 
};

class Derived : public Base { 
public:
    void func_3() { 
        func_1(); // OK
        func_2(); // OK
        x_ = 0; // ERROR: inaccessible
    }
};

struct Widget : public Derived { 
    void func_4() { func_2(); } // OK
};

int main() {
    Derived d;
    d.func_1(); // OK
    d.func_2(); // ERROR: inaccessible
    d.x_ = 0; // ERROR: inaccessible
}
```
class Base {
  public:
    void func_1();
  protected:
    void func_2();
  private:
    int x_; 
};

class Derived : protected Base {
  public:
    void func_3() {
        func_1(); // OK
        func_2(); // OK
        x_ = 0; // ERROR: inaccessible
    }
};

struct Widget : public Derived {
  void func_4() { func_2(); } // OK
};

int main() {
  Derived d; // OK: defaulted constructor is public
  d.func_1(); // ERROR: inaccessible
  d.func_2(); // ERROR: inaccessible
  d.x_ = 0; // ERROR: inaccessible
}
class Base {
  public:
    void func_1();
  protected:
    void func_2();
  private:
    int x_;
};

class Derived : private Base {
  public:
    void func_3() {
      func_1(); // OK
      func_2(); // OK
      x_ = 0; // ERROR: inaccessible
    }
};

struct Widget : public Derived {
  void func_4() { func_2(); } // ERROR: inaccessible
};

int main() {
  Derived d; // OK: defaulted constructor is public
  d.func_1(); // ERROR: inaccessible
  d.func_2(); // ERROR: inaccessible
  d.x_ = 0; // ERROR: inaccessible
}
- public inheritance is inheritance in traditional object-oriented programming sense
- public inheritance models an *is-a* relationship (i.e., derived class object is a base class object)
- most common form of inheritance
- inheritance relationship visible to all code
```cpp
#include <string>

class Person { 
public:
    Person(const std::string& family_name, const std::string& given_name) : family_name_(family_name), given_name_(given_name) {}  
    std::string family_name() const 
    { return family_name_; }  
    std::string given_name() const  
    { return given_name_; }  
    std::string full_name() const  
    { return family_name_ + ", " + given_name_; }
private:
    std::string family_name_;  
    std::string given_name_;  
};

class Student : public Person { 
public:
    Student(const std::string& family_name, const std::string& given_name, const std::string& student_id) : Person(family_name, given_name), student_id_(student_id) {}  
    std::string student_id()  
    { return student_id_; }  
private:
    std::string student_id_;  
};
```
protected and private inheritance not inheritance in traditional object-oriented programming sense (i.e., no is-a relationship)

form of implementation inheritance

implemented-in-terms-of relationship (i.e., derived class object implemented in terms of a base class object)

in case of protected inheritance, inheritance relationship only seen by derived classes and their friends and class itself and its friends

in case of private inheritance, inheritance relationship only seen by class itself and its friends (not derived classes and their friends)

except in special circumstances, normally bad idea to use inheritance for composition

one good use case for private/protected inheritance is in policy-based design, which exploits empty base optimization (EBO)
Policy-Based Design Example: Inefficient Memory Usage

```
#include <mutex>

class ThreadSafePolicy {
public:
  void lock() {mutex_.lock();}
  void unlock() {mutex_.unlock();}
private:
  std::mutex mutex_;  // no-op
};

class ThreadUnsafePolicy {
public:
  void lock() {} // no-op
  void unlock() {} // no-op
};

template<class ThreadSafetyPolicy>
class Widget {
  ThreadSafetyPolicy policy_;  // no-op
};

int main() {
  Widget<ThreadUnsafePolicy> w;
  // w.policy_ has no data members, but
  // sizeof(w.policy_) >= 1
  // inefficient use of memory
}
```
```cpp
#include <mutex>

class ThreadSafePolicy {
public:
    void lock() {mutex_.lock();}
    void unlock() {mutex_.unlock();}
private:
    std::mutex mutex_;  
};

class ThreadUnsafePolicy {
public:
    void lock() {} // no-op
    void unlock() {} // no-op
};

template<class ThreadSafetyPolicy>
class Widget : ThreadSafetyPolicy {
    // ...
};

int main() {
    Widget<ThreadUnsafePolicy> w;
    // empty-base optimization (EBO) can be applied
    // no memory overhead for no-op thread-safety policy
}
```
Inheritance and Constructors

- by default, constructors not inherited
- often, derived class introduces new data members not in base class
- since base-class constructors cannot initialize derived-class data members, inheriting constructors from base class by default would be bad idea (e.g., could lead to uninitialized data members)
- in some cases, however, base-class constructors may be sufficient to initialize derived-class objects
- in such cases, can inherit all non-special base-class constructors with `using` statement
- special constructors (i.e., default, copy, and move constructors) cannot be inherited
- constructors to be inherited with `using` statement may still be hidden by constructors in derived class
class Base {
public:
    Base() : i_(0.0), j_(0) {}  
    Base(int i) : i_(i), j_(0) {}  
    Base(int i, int j) : i_(i), j_(j) {}
    // ... (other non-constructor members)
private:
    int i_, j_;  
};

class Derived : public Base {
public:
    // inherit non-special constructors from Base  
    // (default constructor not inherited)
    using Base::Base;
    // default constructor is implicitly declared and  
    // not inherited
};

int main() {
    Derived a;
    // invokes non-inherited Derived::Derived()
    Derived b(42, 42);
    // invokes inherited Base::Base(int, int)
}
```cpp
class Base {
public:
    Base() : i_(0), j_(0), k_(0) {}
    Base(int i, int j) : i_(i), j_(j), k_(0) {}
    Base(int i, int j, int k) : i_(i), j_(j), k_(k) {}
    // ... (other non-constructor members)
private:
    int i_, j_, k_; 
};

class Derived : public Base {
public:
    // inherit non-special constructors from Base
    // (default constructor not inherited)
    using Base::Base;
    // following constructor hides inherited constructor
    Derived(int i, int j, int k) : Base(-i, -j, -k) {}
    // no implicitly-generated default constructor
};

t int main() {
    Derived b(1, 2);
    // invokes inherited Base::Base(int, int)
    Derived c(1, 2, 3);
    // invokes Derived::Derived(int, int, int)
    // following would produce compile-time error:
    // Derived a; // ERROR: no default constructor
}
```
■ by default, assignment operators not inherited (for similar reasons as in case of constructors)
■ can inherit all non-special base-class assignment operators with `using` statement
■ copy and move assignment operators cannot be inherited [C++14 §12.8/24]
■ assignment operators to be inherited with `using` statement may still be hidden by assignment operators in derived class
■ cannot inherit destructor
Inheriting Assignment Operators Example

```cpp
class Base {
public:
    explicit Base(int i) : i_(i) {}
    Base& operator=(int i) {
        i_ = i;
        return *this;
    }
private:
    int i_;  
};

class Derived : public Base {
public:
    // inherit non-special constructors
    using Base::Base;
    // inherit non-special assignment operators
    using Base::operator=;

};

int main() {
    Derived d(0);
    // invokes inherited Base::Base(int)
    d = 42;
    // invokes inherited Base::operator=(int)
}
```
Construction and Destruction Order

- **order of construction:**
  1. If most-derived class in hierarchy, initialize all *virtual base class objects* in hierarchy in order of depth-first left-to-right traversal of graph of base class declarations, where left to right refers to order of appearance of base class names in class definition (virtual base classes to be discussed later)
  2. Initialize *non-virtual (direct) base class objects* in order listed in class definition
  3. Initialize *non-static data members* in order of declaration in class definition
  4. Execute *constructor body*

- **order of destruction is exact reverse of order of construction, namely:**
  1. Execute *destructor body*
  2. Destroy *non-static data members* in reverse of construction order
  3. Destroy *non-virtual (direct) base class objects* in reverse of construction order
  4. If most-derived class in hierarchy, destroy all *virtual base class objects* in hierarchy in reverse of construction order
```cpp
#include <vector>
#include <string>

class Base {
public:
    Base(int n) : v_(n, 0) {}
    // ...
private:
    std::vector<char> v_;}

class Derived : public Base {
public:
    Derived(const std::string& s) : Base(1024), s_(s)
    { i_ = 0; }
    // ...
private:
    std::string s_; int i_;}

int main() {
    Derived d("hello");
}
```

- construction order for Derived constructor: 1) Base class object, 2) data member s_, 3) Derived constructor body (initializes data member i_)
Hiding Base-Class Member Functions in Derived Class

- can provide new versions of member functions in derived class to hide original functions in base class

```cpp
#include <iostream>

class Fruit {
public:
    void print() const {std::cout << "fruit\n";}
};

class Apple : public Fruit {
public:
    void print() const {std::cout << "apple\n";}
};

class Banana : public Fruit {
public:
    void print() const {std::cout << "banana\n";}
};

int main() {
    Fruit f;
    Apple a;
    Banana b;
    f.print(); // calls Fruit::print
    a.print(); // calls Apple::print
    b.print(); // calls Banana::print
}
```
Upcasting

- derived-class object always has base-class subobject
- given reference or pointer to derived-class object, may want to find reference or pointer to corresponding base-class object
- **upcasting**: converting derived-class pointer or reference to base-class pointer or reference
- upcasting allows us to treat derived-class object as base-class object
- upcasting always safe in sense that cannot result in incorrect type (since every derived-class object is also a base-class object)
- can upcast without explicit type-cast operator as long as casted-to type is accessible; C-style cast can used to bypass access protection (although not recommended)
- example:

  ```
  class Base { /* ... */ }; 
  class Derived : public Base { /* ... */ }; 
  void func() {
    Derived d;
    Base* bp = &d;
  }
  ```
**Downcasting**

- **Downcasting**: converting base-class pointer or reference to derived-class pointer or reference
- Downcasting allows us to force base-class object to be treated as derived-class object
- Downcasting is not always safe (since not every base-class object is necessarily also derived-class object)
- Must only downcast when known that object actually has derived type (except in case of `dynamic_cast`)
- Downcasting always requires explicit cast (e.g., `static_cast`, `dynamic_cast` for dynamically-checked cast in polymorphic case, or C-style cast)
- Example:

```cpp
class Base { /* ... (nonpolymorphic) */ };
class Derived : public Base { /* ... */ };

void func() {
    Derived d;
    Base* bp = &d;
    Derived* dp = static_cast<Derived*>(bp);
}
```
```cpp
class Base { /* ... (nonpolymorphic) */; 

class Derived : public Base { /* ... */; 

int main() {
    Base b;
    Derived d;
    Base* bp = nullptr;
    Derived* dp = nullptr;
    bp = &d;
    // OK: upcast does not require explicit cast
    dp = bp;
    // ERROR: downcast requires explicit cast
    dp = static_cast<Derived*>(bp);
    // OK: downcast with explicit cast and
    // pointer (bp) refers to Derived object
    Base& br = d;
    // OK: upcast does not require explicit cast
    Derived& dr1 = *bp;
    // ERROR: downcast requires explicit cast
    Derived& dr2 = *static_cast<Derived*>(bp);
    // OK: downcast with explicit cast and
    // object (*bp) is of Derived type
    dp = static_cast<Derived*>(&b);
    // BUG: pointer (&b) does not refer to Derived object
}
```
Upcasting Example

```cpp
class Base { /* ... */ };

class Derived : public Base { /* ... */ };

void func_1(Base& b) { /* ... */ }

void func_2(Base* b) { /* ... */ }

int main() {
    Base b;
    Derived d;
    func_1(b);
    func_1(d); // OK: Derived& upcast to Base&
    func_2(&b);
    func_2(&d); // OK: Derived* upcast to Base*
}
```
#include <iostream>
#include <string>

class Person {
public:
    Person(const std::string& family, const std::string& given) :
        family_(family), given_(given) {} 
    void print() const {std::cout << "person: " << family_ << ',' << given_ << '\n';}
protected:
    std::string family_; // family name 
    std::string given_; // given name 
};
class Student : public Person {
public:
    Student(const std::string& family, const std::string& given, 
            const std::string& id) : Person(family, given), id_(id) {} 
    void print() const {std::cout << "student: " << family_ << ',' << given_ << ',' << id_ << '\n';}
private:
    std::string id_; // student ID 
};

void processPerson(const Person& p) {
    p.print(); // always calls Person::print 
    // ...
}

int main() {
    Person p("Ritchie", "Dennis"); 
    Student s("Doe", "John", "12345678"); 
    processPerson(p); // invokes Person::print 
    processPerson(s); // invokes Person::print 
}
**slicing**: copying or moving object of derived class to object of base class (e.g., during construction or assignment), losing part of information in so doing

**example:**

```cpp
class Base {
    // ...
    int x_;}

class Derived : public Base {
    // ...
    int y_;}

int main() {
    Derived d1, d2;
    Base b = d1;
    // slicing occurs
    Base& r = d1;
    r = d2;
    // more treacherous case of slicing
    // slicing occurs
    // d1 now contains mixture of d1 and d2
    // (i.e., base part of d2 and derived part of d1)
    // (i.e., base part of d2 and derived part of d1)

    r = d2;
    // more treacherous case of slicing
    // slicing occurs
    // d1 now contains mixture of d1 and d2
    // (i.e., base part of d2 and derived part of d1)
    // (i.e., base part of d2 and derived part of d1)
    // (i.e., base part of d2 and derived part of d1)
```
- functions do not overload across scopes
- can employ `using` statement to bring base members into scope for overloading
#include <iostream>

class Base {
public:
    double f(double d) const { return d; }
    // ...
};

class Derived : public Base {
public:
    int f(int i) const { return i; }
    // ...
};

int main()
{
    Derived d;
    std::cout << d.f(0) << '\n';
    // calls Derived::f(int) const
    std::cout << d.f(0.5) << '\n';
    // calls Derived::f(int) const; probably not intended
    Derived* dp = &d;
    std::cout << dp->f(0) << '\n';
    // calls Derived::f(int) const
    std::cout << dp->f(0.5) << '\n';
    // calls Derived::f(int) const; probably not intended
}
```cpp
#include <iostream>

class Base {
public:
  double f(double d) const { return d; }
  // ...
};

class Derived : public Base {
public:
  using Base::f; // bring Base::f into scope
  int f(int i) const { return i; }
  // ...
};

int main()
{
  Derived d;
  std::cout << d.f(0) << '
';
  // calls Derived::f(int) const
  std::cout << d.f(0.5) << '
';
  // calls Base::f(double) const
  Derived* dp = &d;
  std::cout << dp->f(0) << '
';
  // calls Derived::f(int) const
  std::cout << dp->f(0.5) << '
';
  // calls Base::f(double) const
}
```
name lookup in templates takes place in two phases:

1. at template definition time
2. at template instantiation time

at template definition time, compiler parses template and looks up any \textit{nondependent} names

result of nondependent name lookup must be \textit{identical} in all instantiations of template (since, by definition, nondependent name does not depend on template parameter)

at template instantiation time, compiler looks up any \textit{dependent} names

results of dependent name lookup can differ from one template instantiation to another (since, by definition, dependent name depends on template parameters)

two-phase name lookup can interact with inheritance in ways that can sometimes lead to unexpected problems in code

may need to add "\texttt{this->}" or employ \texttt{using} statement to make name dependent (when it would otherwise be nondependent)
```cpp
#include <iostream>

template <class T>
struct Base {
    using Real = T;
    Base(Real x_ = Real()) : x(x_) {}
    void f() {std::cout << x << "\n";}
    Real x;
};

template <class T>
struct Derived : Base<T> {
    Derived(Real y_ = Real()) : y(y_) {}
    void g() {
        x = y;
        // ERROR: x assumed to be object outside class
        f();
        // ERROR: f assumed to be function outside class
    }
    Real y;
};

int main() {
    Derived<double> w(0.0);
    w.g();
}
```
```cpp
#include <iostream>

template <class T>
struct Base {
    using Real = T;
    Base(Real x_ = Real()) : x(x_) {}
    void f() {std::cout << x << "\n";};
    Real x;
};

template <class T>
struct Derived : Base<T> {
    using Real = typename Base<T>::Real;
    // OK: Base<T>::Real dependent
    Derived(Real y_ = Real()) : y(y_) {}
    void g() {
        this->x = y; // OK: this->x dependent
        this->f(); // OK: this->f dependent
        Real y;
    }
};

int main() {
    Derived<double> w(0.0);
    w.g();
}
```
Section 2.9.2

Virtual Functions and Run-Time Polymorphism
Run-Time Polymorphism

- **polymorphism** is characteristic of being able to assign different meaning to something in different contexts
- Polymorphism that occurs at run time called **run-time polymorphism** (also known as **dynamic polymorphism**)
- In context of inheritance, key type of run-time polymorphism is polymorphic function call (also known as dynamic dispatch)
- When inheritance relationship exists between two classes, type of reference or pointer to object may not correspond to actual dynamic (i.e., run-time) type of object referenced by reference or pointer
  - That is, reference or pointer to type $T$ may, in fact, refer to object of type $D$, where $D$ is either directly or indirectly derived from $T$
- When calling member function through pointer or reference, may want actual function invoked to be determined by **dynamic** type of object referenced by pointer or reference
- Function call with this property said to be **polymorphic**
Virtual Functions

- In context of class hierarchies, polymorphic function calls achieved through use of virtual functions.

- **Virtual function** is member function with polymorphic behavior.

- When call made to virtual function through reference or pointer, actual function invoked will be determined by *dynamic* type of referenced object.

- To make member function virtual, add keyword `virtual` to function declaration.

- Example:

```cpp
class Base {
    public:
        virtual void func(); // virtual function
        // ...
};
```
once function made virtual, it will *automatically* be virtual in all derived classes, regardless of whether `virtual` keyword is used in derived classes

therefore, not necessary to repeat `virtual` qualifier in derived classes (and perhaps preferable not to do so)

virtual function must be defined in class where first declared unless pure virtual function (to be discussed shortly)

derived class inherits definition of each virtual function from its base class, but may override each virtual function with new definition

function in derived class with same name and same set of argument types as virtual function in base class overrides base class version of virtual function
#include <iostream>
#include <string>

class Person {
public:
    Person(const std::string& family, const std::string& given) :
        family_(family), given_(given) {} 
    virtual void print() const
        {std::cout << "person: " << family_ << ',' << given_ << '\n';}
protected:
    std::string family_; // family name
    std::string given_; // given name
};

class Student : public Person {
public:
    Student(const std::string& family, const std::string& given,
        const std::string& id) : Person(family, given), id_(id) {} 
    void print() const 
        {std::cout << "student: " << family_ << ',' << given_ << ',' << id_ << '\n';
    }
private:
    std::string id_; // student ID
};

void processPerson(const Person& p) {
    p.print(); // polymorphic function call
    // ...
}

int main() {
    Person p("Ritchie", "Dennis");
    Student s("Doe", "John", "12345678");
    processPerson(p); // invokes Person::print
    processPerson(s); // invokes Student::print
}
Override Control: The *override* Qualifier

- when looking at code for derived class, often not possible to determine if member function intended to override virtual function in base class (or one of its base classes)
- can sometimes lead to bugs where programmer expects member function to override virtual function when function not virtual
- *override* qualifier used to indicate that member function is expected to override virtual function in parent class; must come at end of function declaration
- example:

```cpp
class Person {
public:
    virtual void print() const;
    // ...
};

class Employee : public Person {
public:
    void print() const override; // must be virtual
    // ...
};
```
sometimes, may want to prevent any further overriding of virtual function in any subsequent derived classes

adding \texttt{final} qualifier to declaration of virtual function prevents function from being overridden in any subsequent derived classes

preventing further overriding can sometimes allow for better optimization by compiler (e.g., via devirtualization)

demo:

\begin{verbatim}
  class A {
    public:
      virtual void doStuff();  // ...
  }

  class B : public A {
    public:
      void doStuff() final;  // prevent further overriding
      // ...
  }

  class C : public B {
    public:
      void doStuff();  // ERROR: cannot override
      // ...
  }
\end{verbatim}
```cpp
class Worker {
public:
    virtual void prepareEnvelope();
    // ...
};

class SpecialWorker : public Worker {
public:
    // prevent overriding function responsible for
    // overall envelope preparation process
    // but allow functions for individual steps in
    // process to be overridden
    void prepareEnvelope() final {
        stuffEnvelope(); // step 1
        lickEnvelope(); // step 2
        sealEnvelope(); // step 3
    }

    virtual void stuffEnvelope();
    virtual void lickEnvelope();
    virtual void sealEnvelope();
    // ...
};
```
except in very rare cases, destructors in class hierarchy need to be virtual
otherwise, invoking destructor through base-class pointer/reference would only destroy base-class part of object, leaving remainder of derived-class object untouched
normally, bad idea to call virtual function inside constructor or destructor
dynamic type of object changes during construction and changes again during destruction
final overrider of virtual function will change depending where in hierarchy virtual function call is made
when constructor/destructor being executed, object is of exactly that type, never type derived from it
although semantics of virtual function calls during construction and destruction well defined, easy to write code where actual overrider not what expected (and might even be pure virtual)
Problematic Code with Non-Virtual Destructor

class Base {
public:
  Base() {}
  ~Base() {} // non-virtual destructor
      // ...
};

class Derived : public Base {
public:
  Derived() : buffer_(new char[10'000]) {}
  ~Derived() {delete[] buffer_;}
      // ...
private:
  char* buffer_;
};

void process(Base* bp) {
      // ...
  delete bp; // always invokes only Base::~Base
}

int main() {
  process(new Base);
  process(new Derived); // leaks memory
}
class Base {
public:
    Base() {}
    virtual ~Base() {} // virtual destructor
    // ...
};

class Derived : public Base {
public:
    Derived() : buffer_(new char[10'000]) {}
    ~Derived() {delete[] buffer_;}
    // ...
private:
    char* buffer_;
in some situations, may want to prevent deriving from class

language provides means for accomplishing this

in class/struct declaration, after name of class can add keyword `final` to prevent deriving from class

example:

```cpp
class Widget final { /* ... */ };
class Gadget : public Widget { /* ... */ };
// ERROR: cannot derive from Widget
```

might want to prevent deriving from class with destructor that is not virtual

preventing derivation can sometimes also facilitate better compiler optimization (e.g., via devirtualization)

might want to prevent derivation so that objects can be copied safely without fear of slicing
Covariant Return Type

- in some special cases, language allows relaxation of rule that type of overriding function $f$ must be same as type of virtual function $f$ overrides.
- in particular, requirement that return type be same is relaxed.
- return type of derived-class function is permitted to be type derived (directly or indirectly) from return type of base-class function.
- this relaxation of return type more formally known as **covariant return type**.

**case of pointer return type**: if original return type $B^*$, return type of overriding function may be $D^*$, provided $B$ is public base of $D$ (i.e., may return pointer to more derived type).

**case of reference return type**: if original return type $B&$ (or $B&&$), return type of overriding function may be $D&$ (or $D&&$), provided $B$ is public base of $D$ (i.e., may return reference to more derived type).

- covariant return type can sometimes be exploited in order to avoid need for type casts.
class Base {
public:
    virtual Base* clone() const {
        return new Base(*this);
    }
    // ...}
};

class Derived : public Base {
public:
    // use covariant return type
    Derived* clone() const override {
        return new Derived(*this);
    }
    // ...}
};

int main() {
    Derived* d = new Derived;
    Derived* d2 = d->clone();
    // OK: return type is Derived*
    // without covariant return type, would need cast:
    // Derived* d2 = static_cast<Derived*>(d->clone());
    }
sometimes desirable to require derived class to override virtual function

**pure virtual function**: virtual function that must be overridden in every derived class

to declare virtual function as pure, add “= 0” at end of declaration

example:

```cpp
class Widget {
public:
    virtual void doStuff() = 0; // pure virtual
    // ...
};
```

pure virtual function can still be defined, although likely only useful in case of virtual destructor
Abstract Classes

- class with one or more pure virtual functions called **abstract class**
- cannot directly instantiate objects of abstract class (can only use them as base class objects)
- class that derives from abstract class need not override all of its pure virtual methods
- class that does not override all pure virtual methods of abstract base class will also be abstract
- most commonly, abstract classes have no state (i.e., data members) and used to provide interfaces, which can be inherited by other classes
- if class has no pure virtual functions and abstract class is desired, can make destructor pure virtual (but must provide definition of destructor since invoked by derived classes)
#include <cmath>

class Shape {
public:
    virtual bool isPolygon() const = 0;
    virtual float area() const = 0;
    virtual ~Shape() {};
};

class Rectangle : public Shape {
public:
    Rectangle(float w, float h) : w_(w), h_(h) {}
    bool isPolygon() const override { return true; }
    float area() const override { return w_ * h_; }
private:
    float w_; // width of rectangle
    float h_; // height of rectangle
};

class Circle : public Shape {
public:
    Circle(float r) : r_(r) {}
    float area() const override { return M_PI * r_ * r_; }
    bool isPolygon() const override { return false; }
private:
    float r_; // radius of circle
};
```cpp
class Abstract {
public:
  virtual ~Abstract() = 0; // pure virtual destructor
  // ... (no other virtual functions)
};

inline Abstract::~Abstract()
{ /* possibly empty */ }
```
The `dynamic_cast` Operator

- Often need to upcast and downcast (as well as cast sideways) in inheritance hierarchy
- `dynamic_cast` can be used to safely perform type conversions on pointers and references to classes
- Syntax: `dynamic_cast<T>(expr)`
- Types involved must be **polymorphic** (i.e., have at least one virtual function)
- Inspects run-time information about types to determine whether cast can be safely performed
- If conversion is valid (i.e., `expr` can validly be cast to `T`), casts `expr` to type `T` and returns result
- If conversion is not valid, cast fails
- If `expr` is of pointer type, `nullptr` is returned upon failure
- If `expr` is of reference type, `std::bad_cast` exception is thrown upon failure (where exceptions are discussed later)
```cpp
#include <cassert>

class Base {
public:
    virtual void doStuff() { /* ... */ };
    // ...
};

class Derived1 : public Base { /* ... */ };
class Derived2 : public Base { /* ... */ };

bool isDerived1(Base& b) {
    return dynamic_cast<Derived1*>(&b) != nullptr;
}

int main() {
    Base b;
    Derived1 d1;
    Derived2 d2;
    assert(isDerived1(b) == false);
    assert(isDerived1(d1) == true);
    assert(isDerived1(d2) == false);
}
```
typically, run-time polymorphism does not come without run-time cost in terms of both time and memory

in some contexts, cost can be significant

typically, virtual functions implemented using virtual function table

each polymorphic class has virtual function table containing pointers to all virtual functions for class

each polymorphic class object has pointer to virtual function table

memory cost to store virtual function table and pointer to table in each polymorphic object

in most cases, impossible for compiler to inline virtual function calls since function to be called cannot be known until run time

each virtual function call is made through pointer, which adds overhead
when derived type known at compile time, may want behavior similar to virtual functions but without run-time cost (by performing binding at compile time instead of run time)

can be achieved with technique known as **curiously-recurring template pattern (CRTP)**

class `Derived` derives from class template instantiation using `Derived` itself as template argument

eample:

```cpp
template <class Derived>
class Base {
    // ...
};

class Derived : public Base<Derived> {
    // ...
};
```
```cpp
#include <iostream>

template <class Derived>
class Base {

public:
    void interface() {
        std::cout << "Base::interface called\n";
        static_cast<Derived*>(this)->implementation();
    }
}

class Derived : public Base<Derived> {

public:
    void implementation() {
        std::cout << "Derived::implementation called\n";
    }
}

int main() {
    Derived d;
    d.interface();
    // calls Base::interface which, in turn, calls
    // Derived::implementation
    // no virtual function call, however
}
```
CRTP Example: Static Polymorphism

```cpp
class TreeNode {
public:
    enum Kind {RED, BLACK}; // kinds of nodes
    TreeNode *left(); // get left child node
    TreeNode *right(); // get right child node
    Kind kind(); // get kind of node
    // ...
};

template <class Derived>
class GenericVisitor {
public:
    void visit_preorder(TreeNode* node) {
        if (node) {
            process_node(node);
            visit_preorder(node->left());
            visit_preorder(node->right());
        }
    }
    void visit_inorder(TreeNode* node) { /* ... */ }
    void visit_postorder(TreeNode* node) { /* ... */ }
    void process_red_node(TreeNode* node) { /* ... */ }
    void process_black_node(TreeNode* node) { /* ... */ }
private:
    Derived& derived() { return *static_cast<Derived*>(this); }
    void process_node(TreeNode* node) {
        if (node->kind() == TreeNode::RED) {
            derived().process_red_node(node);
        } else {
            derived().process_black_node(node);
        }
    }
};

class SpecialVisitor : public GenericVisitor<SpecialVisitor> {
public:
    void process_red_node(TreeNode* node) { /* ... */ }
};

int main() {SpecialVisitor v;}
```
#include <cassert>

template<class Derived>
struct Comparisons {
    friend bool operator==(const Comparisons<Derived>& x, const Comparisons<Derived>& y) {
        const Derived& xr = static_cast<const Derived&>(x);
        const Derived& yr = static_cast<const Derived&>(y);
        return !(xr < yr) && !(yr < xr);
    }
    // operator!= and others
};

class Widget : public Comparisons<Widget> {
public:
    Widget(bool b, int i) : b_(b), i_(i) {}  
    friend bool operator<(const Widget& x, const Widget& y) {
        return x.i_ < y.i_;        
    }
private:
    bool b_;  
    int i_;  
};

int main() {
    Widget w1(true, 1);  
    Widget w2(false, 1);  
    assert(w1 == w2);  
}
CRTP Example: Object Counting

```cpp
#include <iostream>
#include <cstdlib>

template <class T>
class Counter {
public:
    Counter() {++count_;}
    Counter(const Counter&) {++count_;
    ~Counter() {--count_;}
    static std::size_t howMany() {return count_;}
private:
    static std::size_t count_;}

template <class T>
std::size_t Counter<T>::count_ = 0;

// inherit from Counter to count objects
class Widget: private Counter<Widget> { 
public:
    using Counter<Widget>::howMany;
    // ...
};

int main() {
    Widget w1; int c1 = Widget::howMany();
    Widget w2, w3; int c2 = Widget::howMany();
    std::cout << c1 << ' ' << c2 << '
';
}
```
Section 2.9.3

Multiple Inheritance and Virtual Inheritance
Multiple Inheritance

- Language allows derived class to inherit from more than one base class
- **Multiple inheritance (MI):** deriving from more than one base class
- Although multiple inheritance not best solution for most problems, does have some compelling use cases
- One compelling use case is for inheriting interfaces by deriving from abstract base classes with no data members
- When misused, multiple inheritance can lead to very convoluted code
- In multiple inheritance contexts, ambiguities in naming can arise
- For example, if class `Derived` inherits from classes `Base1` and `Base2`, each of which have member called `x`, name `x` can be ambiguous in some contexts
- Scope resolution operator can be used to resolve ambiguous names
class Basel {
    public:
        void func();
        // ...
    
};

class Base2 {
    void func();
    // ...
}

class Derived : public Basel, public Base2 {
    public:
        // ...
    
};

int main() {
    Derived d;
    d.func(); // ERROR: ambiguous function call
    d.Base1::func(); // OK: invokes Basel::func
    d.Base2::func(); // OK: invokes Base2::func
    
}
class Input_stream {
public:
    virtual ~Input_stream() {} 
    virtual int read_char() = 0;
    virtual int read(char* buffer, int size) = 0;
    virtual bool is_input_ready() const = 0;
    // ...(all pure virtual, no data)
};

class Output_stream {
public:
    virtual ~Output_stream() {} 
    virtual int write_char(char c) = 0;
    virtual int write(char* buffer, int size) = 0;
    virtual int flush_output() = 0;
    // ... (all pure virtual, no data)
};

class Input_output_stream : public Input_stream, public Output_stream {
    // ...
};
use of multiple inheritance can lead to so called dreaded diamond scenario

_dreaded diamond_ inheritance pattern has following form:

class D will have _two_ subobjects of class A, since class D (indirectly) inherits twice from class A

situation like one above probably undesirable and often sign of poor design
```cpp
class Base {
 public:
   // ...
 protected:
   int data_
};

class D1 : public Base { /* ... */ };

class D2 : public Base { /* ... */ };

class Join : public D1, public D2 {
 public:
   void method() {
      data_ = 1; // ERROR: ambiguous
      D1::data_ = 1; // OK: unambiguous
   }
};

int main() {
   Join* j = new Join();
   Base* b;
   b = j; // ERROR: ambiguous
   b = static_cast<D1*>(j); // OK: unambiguous
}
```
Virtual Inheritance

- when using multiple inheritance, may want to ensure that only one instance of base-class object can appear in derived-class object
- **virtual base class**: base class that is only ever included once in derived class, even if derived from multiple times
- **virtual inheritance**: when derived class inherits from base class that is virtual
- virtual inheritance can be used to avoid situations like dreaded diamond pattern
- order of construction: virtual base classes constructed first in depth-first left-to-right traversal of graph of base classes, where left-to-right refers to order of appearance of base class names in class definition
```cpp
class Base {
public:
    // ...
protected:
    int data_;
};

class D1 : public virtual Base { /* ... */ };

class D2 : public virtual Base { /* ... */ };

class Join : public D1, public D2 {
public:
    void method() {
        data_ = 1; // OK: unambiguous
    }
};

int main() {
    Join* j = new Join();
    Base* b = j; // OK: unambiguous
}
```
Section 2.9.4

References


Section 2.10

Modules
- modules are language facility that allow better organization of code
- modules provide encapsulation and isolation (from macros and declarations)
- likelihood of certain types of bugs can be reduced by improved code organization that modules allow
- by using modules, can reduce amount of redundant work needed during compilation
- use of modules fundamentally changes how code is built
- build process significantly more complicated due to additional dependencies introduced by modules
- therefore, build system support for modules is critically important
Section 2.10.1

Compilation Model
Header Model for Compilation

- header model of compilation is that of textual inclusion
- software component partitioned into interface and implementation parts
- interface part placed in header
- implementation part placed in regular (i.e., non-header) source files
- no construct in language logically groups interface and implementation
- in order to use software component, must include its corresponding header
- preprocessing stage of compilation replaces each include directive with contents of included header
- this substitution performed recursively so that include directive for header replaced with all contents of all headers directly or indirectly included by that header
- from compiler’s point of view, no distinction made between code from header and code that includes header
Legacy Compilation

Source File

Headers Included Directly or Indirectly by Source File

Compile

Object File
Example: Header Model for Compilation

Programmer’s View

```
#include "b.hpp"
```

```
#include "a.hpp"
int main() {
    // ...
}
```

Compiler’s View

Translation Unit To Be Compiled

```
#include "a.hpp"
int main() {
    // ...
}
```
Advantages of Header Model

- do not need to compile code in headers as separate entities before compiling source file that includes those headers
- so source files can be compiled with no ordering constraints (except when some source/headers generated as part of build process)
- consequently, build process is very simple and highly parallelizable
when multiple source files include same header, this leads to repeated compilation of same code

building program comprised of above three source files requires compiling code included from `vector` header three times

furthermore, amount of code added by inclusion of `vector` header not small (e.g., on order of tens of thousands of lines of code)
Amount of Code Included By System Headers

- amount of code included (either directly or indirectly) by system headers often quite significant
- so repeatedly compiling code included from system headers can entail substantial amount of extra work
- for each of several system headers, number of lines of code included by source file with single include directive for header as follows:

<table>
<thead>
<tr>
<th>Header</th>
<th>Lines of Code Included</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GCC 10.2.0 libstdc++</td>
</tr>
<tr>
<td>iosfwd</td>
<td>1289</td>
</tr>
<tr>
<td>map</td>
<td>24095</td>
</tr>
<tr>
<td>vector</td>
<td>27584</td>
</tr>
<tr>
<td>string</td>
<td>34092</td>
</tr>
<tr>
<td>iostream</td>
<td>43068</td>
</tr>
<tr>
<td>filesystem</td>
<td>59125</td>
</tr>
<tr>
<td>algorithm</td>
<td>62306</td>
</tr>
<tr>
<td>regex</td>
<td>99642</td>
</tr>
</tbody>
</table>
repeated compilation of code in header can be performed in inconsistent manner, leading to one-definition rule (ODR) violations

consider what happens if `logger.cpp` and `main.cpp` compiled with `ENABLE_STATISTICS` not consistently defined

with header model mistake like this easy to make, since code in header potentially compiled more than once
Header Model and Poor Encapsulation

**hg2g.hpp**

```cpp
#ifndef HG2G_HPP
#define HG2G_HPP

#ifndef assert
#define assert(x) /* Don’t panic! */
#endif

namespace hg2g {
    namespace detail {
        using c42_t = char[42];
        int helper() {
            return sizeof(c42_t);
        }
    } // namespace detail

    int get_answer() {
        return detail::helper();
    }
}
#endif
```

**app.cpp**

```cpp
#include <cassert>
#include "hg2g.hpp"

int main() {
    auto i = hg2g::get_answer(); // OK
    auto j = hg2g::detail::helper();
    // BAD: access to implementation
    // detail is possible
    assert(i == 42);
    // BAD: assert is noop
    return i == 42 ? 0 : 1;
}
```

- All declarations in header visible to includer, which can often expose many implementation details.
- Header can define, undefine, or redefine macros in manner that includer does not expect (and vice versa), resulting in incorrect code behavior.
changing order of include directives in `app.cpp` alters code behavior (i.e., prints "Panic!\n" instead of aborting when NDEBUG not defined)
Disadvantages of Header Model

- slow compilation resulting from repeated compilation of headers
  - header files must be parsed each time included

- increased risk of one-definition rule (ODR) violations
  - only allowed one definition (e.g., of variables, functions, and templates) per translation unit and only allowed one definition of non-inline functions and variables in entire program
  - headers greatly increase danger of multiple inconsistent definitions

- lack of encapsulation/isolation
  - aside from private members, all included entities are accessible (i.e., everything in header unavoidably becomes part of interface)
  - inclusion of header can unexpectedly change meaning of code (e.g., by defining macros or other entities not expected to define)

- ordering dependencies and cyclic dependencies
  - order in which headers are included can affect semantics of source code

- header/source split
  - often need to duplicate declarations in both header and (non-header) source files, while careful to ensure multiple declarations are consistent
interface and implementation parts of software component logically grouped into module, which is language construct

module consists of one or more translation units

two basic flavors of module translation units:
  - interface unit, which specifies interface part of software component
  - implementation unit, which provides implementation of interface

unlike header, module is independently compilable entity (i.e., translation unit that uses module is distinct from translation units that comprise module)

module interface units precompiled into compiled-module interfaces (CMIs)

module interface units may also need to be compiled to produce object files

in order to use module, translation unit must import module

before compiling translation unit, must first precompile interface units for all modules (directly or indirectly) imported by translation unit
Compilation (With Modules)

Source File Is Not Module Interface Unit

- Source File
- Headers Included By Source File
- Compile
- Object File
- CMI for Modules and Header Units Imported by Source File

Source File Is Module Interface Unit

- Source File
- Headers Included By Source File
- Compile
- Object File (If Needed in Addition to Output CMI)
- Output CMI for Module Interface
- CMI for Modules and Header Units Imported by Source File

Copyright © 2015–2021 Michael D. Adams
Greet Example: Without and With Modules

**Without Modules**

```cpp
#include <string>
namespace greetings {
    std::string get_greeting();
}
```

**With Modules**

```cpp
export module greetings;
import <string>;

namespace greetings {
    export std::string get_greeting();
}
```
Without Modules

1  # 1. compile all source files in any order
2  g++ -std=c++20 -c greetings.cpp
3  g++ -std=c++20 -c greet.cpp
4  # 2. link
5  g++ -std=c++20 -o greet greet.o greetings.o

With Modules

1  # 0. set base compiler flags
2  cxxflags="-std=c++20 -fmodules-ts"
3  # 1. generate system header units
4  g++ $cxxflags -x c++-system-header -c iostream
5  g++ $cxxflags -x c++-system-header -c string
6  # 2. generate CMI and object files for module interface units
7  # in dependency order
8  g++ $cxxflags -c greetings-m.cpp
9  # 3. compile remaining source files in any order
10 g++ $cxxflags -c greetings.cpp
11 g++ $cxxflags -c greet.cpp
12 # 4. link
13 g++ $cxxflags -o greet greet.o greetings-m.o greetings.o
# Without Modules

1. compile all source files in any order
2. `clang++ -std=c++20 -c greetings.cpp`
3. `clang++ -std=c++20 -c greet.cpp`
4. # 2. link
5. `clang++ -std=c++20 -o greet greet.o greetings.o`

---

# With Modules

1. set base compiler flags
2. `cxxflags="-std=c++20 -fmodules -stdlib=libc++ -fprebuilt-module-path=."`
3. # 1. generate CMIs for module interface units in dependency order
4. `clang++ $cxxflags --precompile -x c++-module -o greetings.pcm \
   -c greetings-m.cpp`
5. # 2. compile remaining source files in any order
6. `clang++ $cxxflags -c greetings-m.cpp`
7. `clang++ $cxxflags -c -fmodule-file=greetings.pcm greetings.cpp`
8. `clang++ $cxxflags -c greet.cpp`
9. # 3. link
10. `clang++ $cxxflags -o greet greet.o greetings-m.o greetings.o`
Without Modules

```makefile
# This makefile should work with either GCC or Clang.
CXXFLAGS = -std=c++20
PROGRAMS = greet

.PHONY: all
all: $(PROGRAMS)

.PHONY: clean
clean:
    rm -f *.o $(PROGRAMS)

greet: greet.o greetings.o
g $(CXX) $(CXXFLAGS) -o $@ ^
```
# This makefile is known to work with a development version of GCC 11.0.0.
CXX = g++
CXXFLAGS = -std=c++20 -fmodules-ts
PROGRAM = greet
HEADER_UNITS = iostream string

.PHONY: all
all: $(PROGRAM)

.PHONY: clean
clean:
    rm -f $(PROGRAM) *.o *.cmi header_units
    rm -rf gcm.cache

header_units:
    for i in $(HEADER_UNITS); do \
        $(CXX) $(CXXFLAGS) -x c++-system-header -c $$i || exit 1; \
    done
touch header_units
greet.cmi: header_units
    $(CXX) $(CXXFLAGS) -c greetings-m.cpp
touch greet.cmi
greetings.o: header_units greet.cmi
    $(CXX) $(CXXFLAGS) -c greetings.cpp
greet.o: header_units greet.cmi
    $(CXX) $(CXXFLAGS) -c greet.cpp
greet: greet.o greetings-m.o greetings.o
    $(CXX) $(CXXFLAGS) -o greet $^
Greet Example: Building With Make/Clang

With Modules

```
Makefile.clang

1  # This makefile is known to work with Clang 10.0.1.
2  CXX = clang++
3  CXXFLAGS = \n4       -Wall -std=c++20 -fmodules -stdlib=libc++ -fprebuilt-module-path=. 
5  PROGRAM = greet
6
7  .PHONY: all
8  all: $(PROGRAM)
9
10  .PHONY: clean
11  clean:
12       rm -f *.pcm *.o $(PROGRAM)
13
14  greetings.pcm: greetings-m.cpp
15      $(CXX) $(CXXFLAGS) -c --precompile -x c++-module -o $@ $<
16  greetings-m.o: greetings.pcm greetings-m.cpp
17      $(CXX) $(CXXFLAGS) -c greetings-m.cpp
18  greetings.o: greetings.pcm greetings.cpp
19      $(CXX) $(CXXFLAGS) -c -fmodule-file=greetings.pcm greetings.cpp
20  greet.o: greetings.pcm
21      $(CXX) $(CXXFLAGS) -c greet.cpp
22  greet: greet.o greetings-m.o greetings.o
23      $(CXX) $(CXXFLAGS) -o $@ $^ 
```
Benefits of Modules

- can often reduce compile times (especially in incremental builds) by avoiding repeated compilation of code in headers
- greatly reduce risk of many kinds of one-definition rule (ODR) violations
- provide encapsulation/isolation
  - imports and macros do not leak into or out of module
  - only exported declarations visible to importer of module
- are import order independent and cannot have cyclic dependencies
- offer more flexibility in file layout that can be used for code
Section 2.10.2

Writing Non-Modular Code That Uses Modules
import directive used to make interface exported by module accessible

import declaration can have following forms:

1. `import module_name;`
2. `import header_name;`

first form imports module named `module_name`

second form imports module generated from importable header `header_name`

what constitutes importable header to be discussed shortly

imports must appear at global scope

examples:

```cpp
import mymodule;
import <iostream>;
```
Module Import Example

greet.cpp (User of Module)

1 import <iostream>; // import header
2 import greetings; // import module
3
4 int main() {
5    std::cout << greetings::get_greeting() << std::endl;
6    return std::cout ? 0 : 1;
7 }

greetings-m.cpp (Module)

1 export module greetings;
2
3 import <string>; // import header
4
5 export namespace greetings {
6    std::string get_greeting() {return "Hello, World!";}
7 }
Importable Headers

- Import of header causes module to be generated that exports all exportable entities in header
- Referred to as header unit
- Wrappers for C standard library headers not required to be importable (e.g., cassert, cmath, cstdlib, and cerrno)
- All other C++ standard library headers are importable
- Whether any other header are importable is implementation defined
- Importable headers intended as transition path from headers to modules
- Importable headers have numerous restrictions:
  - Cannot rely on macros or identifiers being predefined
  - Cannot rely on macros later being undefined (by importer of header)
  - Can only have entity with internal linkage if not used outside header
### Legacy Code With Included Headers

```cpp
#include <iostream>

int main() {
    std::cout << "Hello, World!" << std::endl;
    return !std::cout;
}
```

### Code With Imported Headers

```cpp
import <iostream>;

int main() {
    std::cout << "Hello, World!" << std::endl;
    return !std::cout;
}
```
Section 2.10.3

Writing Modular Code
Overview of Modules

- translation unit that is part of module is called **module unit**
- every module unit can be classified as exactly one of following:
  - **interface unit**, which specifies interface provided by module to importers of module
  - **implementation unit**, which provides implementation of module’s interface
- interface (and corresponding implementation) for module can be split across multiple translation units by using what are called partition units
- every module unit can also be classified as either partition unit or non-partition unit
- module interface unit that is not partition unit called **primary module interface unit**
- only identifiers that module exports are visible to importer of module
- any code that wants access to exported identifiers of module must first import that module
Module Declarations (1)

- module declaration used to specify that translation unit belongs to module and to which one
- module declaration has syntax:
  \[
  \text{export}^{\text{opt}} \ \text{module} \ \text{name partition}^{\text{opt}} \ \text{attributes}^{\text{opt}}; \\
  \]
- if \text{export} specified, declares module interface unit; otherwise, declares module implementation unit
- \text{partition} consists of colon followed by partition name
- if \text{partition} specified, declares module partition unit
- some examples of module declarations given below:

<table>
<thead>
<tr>
<th>Declaration</th>
<th>Declared Entity</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{export module} foo;</td>
<td>(non-partition) interface unit for module foo</td>
</tr>
<tr>
<td>module foo;</td>
<td>(non-partition) implementation unit for module foo</td>
</tr>
<tr>
<td>\text{export module} foo:bar;</td>
<td>partition interface unit for partition bar of module foo</td>
</tr>
<tr>
<td>module foo:bar;</td>
<td>partition implementation unit for partition bar of module foo</td>
</tr>
</tbody>
</table>
- module name consists of one or more identifiers separated by dots
- dots in module names have no special meaning (e.g., no implied relationship between modules named \texttt{a}, \texttt{a.b}, and \texttt{a.c})
- modules names that begin with "\texttt{std}" followed by zero or more digits reserved for use by standard
- partition name has same naming restrictions as module name
- module declaration must be first statement in translation unit, excluding contents of global module fragment (to be discussed later)
- cannot have more than one module declaration per translation unit
- named module must have exactly one primary module interface unit
- modules and namespaces are independent of one another (i.e., modules do not impact name lookup except in sense that modules can effect visibility of identifiers)
Global Module Fragment

- All declarations made in non-module translation units placed in single unnamed module known as **global module**
- Global module is only module that is unnamed
- Module unit can place declarations in global module by specifying **global module fragment**
- Global module fragment must come first in translation unit
- Global module fragment started by "**module;**" and continues until module declaration
- Can only have preprocessor directives in global module fragment

**Example:**

```c++
module;
// start of global module fragment
#include <cassert>
#include <cmath>
// end of global module fragment
export module foo; // module declaration
// ...
```
<table>
<thead>
<tr>
<th><strong>module</strong>; (starts global module fragment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>global module fragment (which can only contain preprocessor directives); for example:</td>
</tr>
<tr>
<td><code>#include &lt;cassert&gt;</code></td>
</tr>
<tr>
<td>module declaration; for example:</td>
</tr>
<tr>
<td><code>export module foo;</code></td>
</tr>
<tr>
<td>import declarations if any; for example:</td>
</tr>
<tr>
<td><code>import &lt;iostream&gt;;</code></td>
</tr>
<tr>
<td>body of module (which starts after first non-import statement and may be empty)</td>
</tr>
<tr>
<td><strong>module</strong>: <code>private</code>; (starts private module fragment)</td>
</tr>
<tr>
<td>private module fragment</td>
</tr>
</tbody>
</table>

- items shown shaded in gray are optional
- purview of module unit starts immediately after module declaration and continues until end of translation unit
- private module fragment (to be discussed later) only permitted in interface unit of module comprised of single translation unit
- **purview of module** is set of purviews of each of its constituent module units
- all module import declarations precede all other declarations in translation unit
- in module’s purview, member function defined in body of class not implicitly inline
in module unit, all imports must appear at start of module-unit purview before any other declarations/statements

module implementation unit that is not partition unit implicitly imports its corresponding module interface unit

import that names module partition can only be in same module that to which module partition belongs

module interface unit cannot have interface dependency on itself (i.e., cannot directly or indirectly import module that imports module)

exported entities in imported header are attached to global module

import of header unit behaves as if synthesized module imported

macros from header visible in importing module after import directive

imported header unit does not depend on ambient preprocessor state at time of import (i.e., macros cannot leak in)
greetings.cpp (Primary Module Interface Unit)

1 import <string>;
2
3 namespace greetings {
4   export std::string get_greeting() {
5     return "Hello, World!";
6   }
7 }
8

Example: Greet #1 [With Module Interface Unit Only]

1 export module greetings;
2
3 import <iostream>;
4 import greetings;
5
6 int main() {
7   std::cout << greetings::get_greeting() << std::endl;
8   return !std::cout;
9 }
10

### greetings-m.cpp (Primary Module Interface Unit)

<table>
<thead>
<tr>
<th>Line</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><code>export module greetings;</code></td>
</tr>
<tr>
<td>2</td>
<td><code>import &lt;string&gt;;</code></td>
</tr>
<tr>
<td>3</td>
<td><code>namespace greetings {</code></td>
</tr>
<tr>
<td>4</td>
<td><code>    export std::string get_greeting();</code></td>
</tr>
<tr>
<td>5</td>
<td><code>}</code></td>
</tr>
</tbody>
</table>

### greetings.cpp (Module Implementation Unit)

<table>
<thead>
<tr>
<th>Line</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><code>module greetings;</code></td>
</tr>
<tr>
<td>2</td>
<td><code>import &lt;string&gt;;</code></td>
</tr>
<tr>
<td>3</td>
<td><code>namespace greetings {</code></td>
</tr>
<tr>
<td>4</td>
<td><code>    std::string get_greeting() {</code></td>
</tr>
<tr>
<td>5</td>
<td><code>        return &quot;Hello, World!&quot;;</code></td>
</tr>
<tr>
<td>6</td>
<td><code>    }</code></td>
</tr>
<tr>
<td>7</td>
<td><code>}</code></td>
</tr>
</tbody>
</table>

### greet.cpp (Normal Translation Unit Using Module)

<table>
<thead>
<tr>
<th>Line</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><code>import &lt;iostream&gt;;</code></td>
</tr>
<tr>
<td>2</td>
<td><code>import greetings;</code></td>
</tr>
<tr>
<td>3</td>
<td><code>int main() {</code></td>
</tr>
<tr>
<td>4</td>
<td><code>    std::cout &lt;&lt; greetings::get_greeting() &lt;&lt; std::endl;</code></td>
</tr>
<tr>
<td>5</td>
<td><code>    return !std::cout;</code></td>
</tr>
<tr>
<td>6</td>
<td><code>}</code></td>
</tr>
</tbody>
</table>
Example: Math #1

math-m.cpp (Primary Module Interface Unit for zeus.math Module)

```cpp
module; // start of global module fragment
#include <cmath>
export module zeus.math; // start of module unit purview

namespace zeus::math {

double answer = 42;

export double sinc(double x) {
    return (x != 0) ? sin(x) / x : 1.0;
}

export double get_answer() {return answer;}
export template <class T> T square(const T& x) {
    return x * x;
}
}
```

app.cpp (Non-Module Unit That Imports zeus.math Module)

```cpp
import <iostream>
import zeus.math

int main() {
    std::cout << zeus::math::square(2.0) << ' ' << zeus::math::sinc(0.0) << ' ' << zeus::math::get_answer() << '
';
}
```
math-m.cpp (Primary Module Interface Unit)

```cpp
// no global module fragment
// declare module interface unit
export module zeus.math; // start of module unit purview
namespace zeus::math {
    export double sinc(double);
    // note: must export template definition, not just declaration
    export template <class T> T square(const T& x) { return x * x; }
    export double get_answer();
    double answer = 42;
}
```

math.cpp (Module Implementation Unit)

```cpp
module; // start of global module fragment
#include <cmath>
// declare module implementation unit
module zeus.math; // start of module unit purview
namespace zeus::math {
    double sinc(double x) { return (x != 0) ? sin(x) / x : 1.0; }
    double get_answer() { return answer; }
}
```

app.cpp (Non-Module Translation Unit Using Module)

```cpp
// not module unit, since no module declaration
import <iostream>;
import zeus.math;
int main() {
    std::cout << zeus::math::square(2.0) << ' ' << zeus::math::sinc(0.0) << ' ' << zeus::math::get_answer() << '
';
}
```
Export Declarations (1)

- Identifiers can be made visible outside of module (i.e., exported) through use of export declaration.
- Export declaration can be formed by:
  - Adding `export` to usual declaration (e.g., “`export void foo();`”)
  - Using export block (i.e., “`export { /* ... */ }`”)
- Export block exports all declarations in block.
- Export block does not introduce new scope.
- Can export many types of declarations, including declarations of:
  - Variables, functions, classes, templates, template specializations, using directives, typedefs, namespaces, using declarations, import declarations, and linkage specification blocks (e.g., `extern "C"`)
- Export declarations can only appear in (non-partition and partition) module interface units.
- Exported declarations can only appear at namespace scope (including global namespace).
cannot export entities with internal linkage (e.g., static variables and functions, and functions/variables/classes defined in anonymous namespaces)

first declaration of exported entity must be exported declaration, while subsequent declarations may omit export keyword

exporting imported module exports all identifiers exported in imported module

exporting namespace block exports all identifiers declared in namespace block and requires that all identifiers in block are exportable

exporting entity in namespace implicitly exports name of containing namespace

using declaration can be exported unless referred to entity has internal or module linkage
Example: HG2G [Export Declarations]

hg2g-m.cpp (Primary Module Interface Unit of hg2g Module)

```cpp
1 export module hg2g;
2 import <string>;
3 namespace hg2g {
4   export using c42_t = char[42];
5   c42_t x;
6   export struct depressed_tag {};
7   export template<class T> T constexpr forty_two = sizeof(x);
8   export {
9     std::string marvin="paranoid";
10    void panic() {throw 42;}
11   }
12 }
13 export namespace hg2g {
14   int get_answer() {return sizeof(x);}
15 }
16 export namespace h2g2 = hg2g;
```

main.cpp (Importer of hg2g Module)

```cpp
1 import <iostream>;
2 import hg2g;
3 int main() try {
4   std::cout << hg2g::get_answer() << ' ' << hg2g::marvin << '
';
5   // auto x = hg2g::x[0]; // ERROR: x not visible
6   if (!std::cout.flush()) {hg2g::panic();}
7 } catch (...) {std::cerr << "Don’t panic!\n";}
```
module partitions provide means to split large interface into smaller pieces
as mentioned earlier, module declaration declares module partition if partition name specified for module
for example: \texttt{export module foo:bar;}
any number of module partition interface units allowed
module interface consists of everything specified in primary interface and all partition interfaces
primary module interface unit must export all module partition interface units; otherwise program is ill formed with no diagnostic required
module partitions can be imported only by other module units in same module (i.e, partitions invisible outside of their module)
### Example: Greet #3 [With Partition Interface Units] (1)

**greetings-m.cpp (Primary Module Interface Unit)**

```cpp
1 export module greetings;
2 export import :english;
3 export import :french;
```

**greetings_en.cpp (Module Partition Interface Unit)**

```cpp
1 export module greetings:english;
2 import <string>;
3 export namespace greetings {
4   std::string get_greeting_en() {
5     return "Hello, World!";
6   }
7 }
```

**greetings_fr.cpp (Module Partition Interface Unit)**

```cpp
1 export module greetings:french;
2 import <string>;
3 export namespace greetings {
4   std::string get_greeting_fr() {
5     return "Bonjour, Tout Le Monde!";
6   }
7 }
```
```cpp
import <iostream>;
import greetings;

int main() {
    std::cout << greetings::get_greeting_en() << '\n';
    std::cout << greetings::get_greeting_fr() << '\n';
    return !std::cout.flush();
}
```
Example: Greet #4  [With Partition Interface and Implementation Units] (1)

greetings-m.cpp (Primary Module Interface Unit)
1 export module greetings;
2 export import :english;
3 export import :french;

greetings_en-m.cpp (Module Partition Interface Unit)
1 export module greetings:english;
2 import <string>;
3 namespace greetings {
4 export std::string get_greeting_en();
5 }

greetings_en.cpp (Module Partition Implementation Unit)
1 module greetings:english;
2 import <string>;
3 namespace greetings {
4 std::string get_greeting_en() {
5 return "Hello, World!";
6 }
7 }
Example: Greet #4 [With Partition Interface and Implementation Units] (2)

```
greetings_fr-m.cpp (Module Partition Interface Unit)
1 export module greetings:french;
2 import <string>;
3 namespace greetings {
4    export std::string get_greeting_fr();
5 }

greetings_fr.cpp (Module Partition Implementation Unit)
1 module greetings:french;
2 import <string>;
3 namespace greetings {
4    std::string get_greeting_fr() {
5        return "Bonjour, Tout Le Monde!";
6    }
7 }

greet.cpp (Non-Module Translation Unit)
1 import <iostream>;
2 import greetings;
3
4 int main() {
5    std::cout << greetings::get_greeting_en() << '\n';
6    std::cout << greetings::get_greeting_fr() << '\n';
7    return !std::cout.flush();
8 }
```
private module fragment provides means to clearly distinguish implementation from interface in module that consists of only single translation unit (i.e., primary interface unit)

private module fragment must be last part of module unit

private module fragment starts with “module : private;” and continues until end of translation unit

if module has private module fragment, can only have single translation unit (namely, primary interface unit)

anything that can change interface of module not permitted in private module fragment

example of private module fragment:

```cpp
export module foo; // module declaration
// ...
module : private; // start of private module fragment
// ...
```
Example: Greet #5  [With Private Module Fragment]

greetings-m.cpp  (Primary Module Interface Unit)

```cpp
1    export module greetings;
2    import <string>;
3
4    namespace greetings {
5       export std::string get_greeting();
6    }
7
8    module: private; // start of private module fragment
9    namespace greetings {
10       std::string get_greeting()
11          {return "Hello, World!";}
12    }
```

greet.cpp

```cpp
1    import <iostream>;
2    import greetings;
3
4    int main() {
5       std::cout << greetings::get_greeting() << std::endl;
6       return !std::cout;
7    }
```
entity (such as variable, function, or type) said to be **visible** if in scope and therefore candidate for name lookup

entity said to be **reachable** if in scope but not necessarily nameable

if entity is reachable, its semantic properties are available but not necessarily candidate for name lookup

visibility implies reachability

reachability does not necessarily imply visibility

export used to control visibility

if class or enumeration is reachable, its members become visible even if containing name not visible

translation unit necessarily reachable if and only if it is module interface unit on which requesting translation unit has interface dependency
```cpp
#include <cassert>

auto func() {
    struct widget {
        int value;
    };
    return widget{42};
}

int main() {
    // widget is not visible
    // widget is reachable via return type of func
    auto x = func();
    // declare name for reachable type
    using thing = decltype(x);
    thing w{0};
    assert(w.value == 0);
    return w.value;
}
```
zeus-m.cpp
export module zeus;
namespace zeus {
struct int_point {int x; int y;};
export int_point origin() {return {0, 0};}
}

main.cpp
#include <cassert>
import zeus;

int main() {
  // zeus::int_point q; // ERROR: int_point not visible
  auto p = zeus::origin();
  assert(p.x == 0 && p.y == 0);
  using point = decltype(p);
  point q;
}
name declared in different scopes or in same scope more than once can be made to refer to same entity through notion of linkage

in order words, linkage determines whether two entities declared with same name are same entity or two distinct entities (where declarations in question may be in same or different translation units)

notion of linkage applies to names of variables, functions, namespaces, and so on

language has four types of linkage:

1. none
2. internal
3. module
4. external
- If name has **no linkage**, two declarations of same name always refer to distinct entities.

- Some examples of entities whose names have no linkage:
  - Variables declared at block scope that are not extern.
  - Local classes (i.e., classes declared inside body of function) and their member functions.
  - Typedefs, enumerations, and enumerators declared at block scope.

- If name has **internal linkage**, two declarations of same name refer to same entity if declarations *in same translation unit*.

- Examples of entities whose names have internal linkage include:
  - Namespace-scope entity that has been declared static.
  - Name of any entity declared in anonymous namespace.
  - Variable declared `const` but not inline or volatile.
  - Data members of anonymous unions.
If name has **module linkage**, two declarations of same name refer to same entity if declarations in *same module*

Examples of entities whose names have module linkage include:
- variable or function declared at namespace scope in named module that is neither static nor extern and is not exported

If name has **external linkage**, two declarations of same name refer to same entity *in all translation units*

Examples of entities whose names have external linkage include:
- variable declared as extern
### sol-m.cpp

```cpp
export module sol;
namespace {
    int x = 42; // x has internal linkage
    bool yes() {return true;} // yes has internal linkage
}
namespace sol {
    static int y = 0; // y has internal linkage
    int z = -1; // z has module linkage
    export inline constexpr int forty_two() {return 42;} // forty_two has external linkage
    int nil() {return 0;} // nil has module linkage
    export int value() {return forty_two() + nil();} // value has external linkage
    int foo() { // foo has module linkage
        struct S {}; // S has no linkage
        int i = 0; // i has no linkage
        return yes() + i + sizeof(S);
    }
}
```

Copyright © 2015–2021 Michael D. Adams
can place source for module in single file or split across multiple files

advantages of using single file:
- can avoid repetition
- facilitates module interface only library

disadvantages of using single file:
- unnecessary recompilation (when implementation changed but not interface)
- file containing interface specification also cluttered with implementation details
- may introduce additional dependencies due to implementation having dependencies that are not required by interface
- reduced compilation speed for interface unit

2. Gabriel Dos Reis. C++ Modules: What You Should Know. CPPP, Paris, France, June 15, 2019. Available online at https://youtu.be/MP6SJEBt6Ss. [This talk provides a high-level overview of modules (e.g., motivations and constraints), but does not provide many detailed examples of usage.]


Section 2.11

Coroutines
coroutine is generalization of subroutine

subroutine provides two basic operations:
1. can be invoked by its caller
2. can return control to its caller after completing execution

coroutine provides two additional operations:
1. can suspend execution and return control to its caller
2. can resume execution after being suspended

in C++, both subroutines and coroutines are functions

whether function is coroutine or normal function determined by operations performed in body of function
Subroutine Versus Coroutine

Control Transfer Involving Subroutine A

call A

A

A

return

Control Transfer Involving Asymmetric Coroutine A

call A

A

suspend

resume A

suspend

resume A

return
Why Coroutines?

- coroutines often useful for:
  - state machines and event-driven programming models
  - actor model of concurrency
  - generators
  - asynchronous tasks
  - reverse communication (sometimes used in mathematical software)

- provide means for cooperative multitasking

- offer highly scalable concurrency (i.e., can have very large number of coroutines concurrently executing)

- switching between execution of coroutines has low overhead (comparable to cost of function call instead of context switch by OS scheduler)

- since language specifies coroutines at relatively low level, coroutines very flexible

- often highly composable

- can often write asynchronous code with much simpler structure (i.e., comparable to that of synchronous code)
Coroutines

- whether or not function is coroutine is implementation detail
- from declaration of function alone, not possible to determine if function is coroutine (although functions that do not have resumable return type cannot be coroutines)
- function is coroutine if it contains:
  - `co_return` statement;
  - `co_await` expression;
  - `co_yield` expression; or
  - range-based for loop that uses `co_await`
- invoke with function call
- return with `co_return` statement
- suspend with `co_await` expression or `co_yield` expression
- resume by invoking `coroutine_handle<>::resume()` (usually via member function of resumable type)
```cpp
#include <iostream>
#include "simple_task.hpp"

simple_task<int> greet() {
    std::cout << "hello\n";
    co_await std::suspend_always();
    std::cout << "bonjour\n";
    co_await std::suspend_always();
    std::cout << "hola\n";
    co_return !std::cout.flush();
}

int main() {
    auto g = greet();
    while (g.resume()) {}
    return g.value();
}
```
Generators

- generator produces sequence of values
- values produced on demand (i.e., lazily)
- that is, instead producing and returning all values at once, generates and yields each value to caller, one at a time
- requires less memory, since only need to store one value at any given time
- since all values not computed at once, can accommodate infinite-length sequences and live data streams
- provide iterator interface via begin and end member functions
- can be used in range-based for loop (as with any class that provides begin and end)
```cpp
#include <iostream>
#include <string>
#include "generator.hpp"

using namespace std::literals;

generator<char> greet() {
    for (auto&& c : "Hello, World!\n"s) {
        co_yield c;
    }
}

int main() {
    for (auto&& c : greet()) {
        std::cout << c;
    }
    return !std::cout.flush();
}
```
```cpp
#include <iostream>
#include "generator.hpp"

generator<unsigned long long> fibonacci() {
    unsigned long long f[] = {0, 1};
    for (;;) {
        co_yield f[0];
        auto tmp = f[0] + f[1];
        f[0] = f[1];
        f[1] = tmp;
    }
}

int main() {
    for (auto&& x : fibonacci()) {
        if (x >= 1'000) {break;}
        std::cout << x << '
';
    }
}
```

consider finite state machine for turnstile

two states for turnstile:
1. locked: turnstile is locked (so customer cannot pass through it)
2. unlocked: turnstile is unlocked (so customer can pass through it)

two events for turnstile:
1. coin: customer inserted coin in turnstile
2. push: customer pushed turnstile to pass through it

state transition table:

<table>
<thead>
<tr>
<th>Current State</th>
<th>Event</th>
<th>Next State</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>locked</td>
<td>coin</td>
<td>unlocked</td>
<td>unlocks turnstile</td>
</tr>
<tr>
<td>locked</td>
<td>push</td>
<td>locked</td>
<td>none</td>
</tr>
<tr>
<td>unlocked</td>
<td>coin</td>
<td>unlocked</td>
<td>none</td>
</tr>
<tr>
<td>unlocked</td>
<td>push</td>
<td>locked</td>
<td>locks turnstile</td>
</tr>
</tbody>
</table>
Turnstile State Machine Example: fsm.cpp (1)

```cpp
#include <iostream>
#include <variant>
#include <vector>
#include "fsm.hpp"

// Overload operators
template<class... Ts> struct overloaded : Ts... { using Ts::operator()...;};
template<class... Ts> overloaded(Ts...) -> overloaded<Ts...>;

struct State_locked {};
struct State_unlocked {};
using State = std::variant<State_locked, State_unlocked>;

struct Event_coin {};
struct Event_push {};
using Event = std::variant<Event_coin, Event_push>;

std::string to_name(State state) {
    return std::visit(overloaded {
        [](State_locked arg) { return "locked"; },
        [](State_unlocked arg) { return "unlocked"; },
    }, state);
}

std::string to_name(Event state) {
    return std::visit(overloaded {
        [](Event_coin arg) { return "coin"; },
        [](Event_push arg) { return "push"; },
    }, state);
}
```

Copyright © 2015–2021 Michael D. Adams

Programming in C++

Version 2021-04-01
fsm<State, Event> make_fsm() {
    State cur_state{State_locked{}};
    for (;;) {
        auto event = co_yield cur_state;
        std::cout << "event: " << to_name(event) << '
';
        auto next_state = std::visit(overloaded {
            [](State_locked, Event_coin) {return State(State_unlocked{})};,
            [](State_unlocked, Event_push) {return State(State_locked{})};,
            [](auto state, auto) {return State(state)};
        }, cur_state, event);
        cur_state = next_state;
    }
}

int main() {
    std::vector<Event> events{Event_coin{}, Event_push{}};
    auto f = make_fsm();
    auto state = f.get_state();
    std::cout << "state: " << to_name(state) << '
';
    for (auto&& event : events) {
        f.resume(event);
        state = f.get_state();
        std::cout << "state: " << to_name(state) << '
';
    }
}
Section 2.11.1

Resumable, Promise, and Coroutine-Handle Types
Mechanics of Function Calls

- when function called, compiler must construct stack frame that contains:
  - arguments
  - local variables
  - return value
  - temporary storage for registers

- when coroutine invoked, compiler must construct coroutine frame that contains:
  - formal parameters
  - local variables
  - selected temporaries
  - execution state for coroutine needed to resume (e.g., registers and IP)
  - promise object used to return value or values to caller

- generally, coroutine frame dynamically allocated
- coroutine frame created before coroutine starts running
- compiler provides handle to coroutine frame to caller of coroutine
The `std::coroutine_handle` Class Template

- `std::coroutine_handle` class template used to give access to underlying coroutine frame
- declaration:
  ```cpp
template <class Promise = void> struct coroutine_handle;
```
- `Promise` is promise type
- promise type used to provide access to values passed back to caller (via `co_return` or `co_yield`)
- promise type may be `void` to mean no state associated with promise type
std::coroutine_handle Members (1)

- static coroutine_handle from_address(void* addr) noexcept;
  - convert generic pointer to coroutine handle

- void* to_address() const noexcept;
  - convert coroutine handle to generic pointer

- void operator()() const;
- void resume() const;
  - resume execution of coroutine (from last suspension point)
  - cannot resume if suspended at final suspension point \[C++20 \S17.12.3.4/2\]
  - can resume on different thread provided it is instance of std::thread, std::jthread, or thread executing main \[C++20 \S17.12.3.4/1\]

- void destroy();
  - destroy coroutine (i.e., coroutine frame)

- bool done() const;
  - test if coroutine is waiting at final suspension point (i.e., body of coroutine has returned)

- to_address and from_address used for converting to/from opaque handle for interoperating with other APIs (such as C APIs)
std::coroutine_handle Members (2)

- promise_type& promise() const noexcept;
  - get access to promise object
  - only for coroutine_handle<T> where T is not void

- static coroutine_handle from_promise(promise_type&)
  -> noexcept;
  - get coroutine handle associated with promise object
  - only for coroutine_handle<T> where T is not void
- return type of coroutine must be resumable type
- resumable type provides interface necessary to resume suspended coroutine
- also provides access to promise object
- required to have type member called `promise_type`, which corresponds to type of promise object
- movable (typically), but not copyable
- typically also has member functions for resuming and accessing promise value but language itself has no requirements in this regard
- can resume on different thread from suspend
Promise Types

- promise type is type of promise object, which is used to pass value from coroutine back to caller
- compiler automatically generates local variable of coroutine with promise type
- promise type only needed if coroutine passes values back to caller
- promise type is class type that must provide certain members
Promise-Type Members

- Resumable get_return_object()
  - converts promise type into resumable object and returns result

- Awaitable initial_suspend();
  - called at initial suspension point

- Awaitable final_suspend();
  - called at final suspension point

- `void` return_void()
  - called for `co_return` with no argument or falling off end of coroutine

- Awaitable return_value(T value);
  - called for `co_return` with argument
  - can be overloaded

- Awaitable yield_value(T value);
  - called for `co_yield` with argument
  - can be overloaded

- Awaitable await_transform(T value);
  - can be used to convert `co_await` argument into awaitable type
Coroutine Structure

```cpp
1 {  
2     promise-type promise promise-constructor-arguments;  
3     try {  
4         initial-suspend:  
5             co_await promise.initial_suspend();  
6         function-body  
7     } catch (...) {  
8         if (!initial-await-resume-called)  
9             throw;  
10            promise.unhandled_exception();  
11     }  
12     final-suspend:  
13         co_await promise.final_suspend();  
14 }```

- coroutine has general structure shown above [C++20 §9.5.4/5]

- `initial-await-resume-called` initially false and set to true immediately before evaluation of `await_resume` expression of initial suspend point
```cpp
#include <iostream>
#include "simple_task.hpp"

simple_task<int> greet() {
    std::cout << "hello\n";
    co_await std::suspend_always();
    std::cout << "bonjour\n";
    co_await std::suspend_always();
    std::cout << "hola\n";
    co_return !std::cout.flush();
}

int main() {
    auto g = greet();
    while (g.resume()) {} 
    return g.value();
}
```
Simple Task Example: simple_task.hpp (1)

```cpp
#include <coroutine>
#include <exception>
#include <utility>

template <class T> struct simple_task_promise {
  public:
    auto get_return_object() {return std::coroutine_handle<simple_task_promise>::from_promise(*this);}
    std::suspend_always initial_suspend() {return {}};
    std::suspend_always final_suspend() noexcept {return {}};
    void return_value(T value) {value_ = std::move(value);}
    void unhandled_exception() {std::terminate();}
    const T& value() const {return value_;}
  private:
    T value_; 
  
};

template<> struct simple_task_promise<void> {
  public:
    auto get_return_object() {return std::coroutine_handle<simple_task_promise>::from_promise(*this);}
    std::suspend_always initial_suspend() {return {}};
    std::suspend_always final_suspend() {return {}};
    void return_void() {}
    void unhandled_exception() {std::terminate();}
};
```
```cpp
template <class T = void> struct simple_task {

public:

    using promise_type = simple_task_promise<T>;

    simple_task(std::coroutine_handle<promise_type> handle) :
    handle_(handle) {}

    simple_task(simple_task&& other) : handle_(other.handle_) {
        other.handle_ = nullptr;
    }

    simple_task& operator=(simple_task&& other) {
        if (handle_) {handle_.destroy();}
        handle_ = other.handle_;  
        other.handle_ = nullptr;
        return *this;
    }

    ~simple_task() {if (handle_) {handle_.destroy();}}

    bool resume() {
        if (!handle_.done()) {handle_.resume();}
        return !handle_.done();
    }

    auto value() {
        if constexpr (std::is_same_v<T, void>) {return;}
        else {return handle_.promise().value();}
    }

private:

    std::coroutine_handle<promise_type> handle_;  
};
```
Coroutine Lifetime

- coroutine destroyed when final suspend is resumed or `coroutine_handle<>::destroy` is called whichever happens first.
- when coroutine is destroyed, cleans up local variables initialized prior to last suspension point.
Coroutine Lifetime Example

```cpp
#include <coroutine>
#include <exception>
#include <iostream>

struct resumable_widget {
  using promise_type = resumable_widget;

  resumable_widget get_return_object() {
    return resumable_widget(std::coroutine_handle<promise_type>::from_promise(*this));
  }

  std::suspend_never initial_suspend() {
    return {};
  } // Fix: std::suspend_always final_suspend() {return {};} // Oops!

  std::suspend_never final_suspend() noexcept {
    return {};
  }

  void return_value(int value) {value_ = value;}

  void unhandled_exception() {std::terminate();}

  int value_;

  resumable_widget(std::coroutine_handle<promise_type> h) : h_(h) {}

  resumable_widget(const resumable_widget&) = delete;

  ~resumable_widget() {h_.destroy();}

  int get() {return h_.promise().value_;}

  bool resume() {
    if (!h_.done()) {h_.resume();}
    return !h_.done();
  }

  std::coroutine_handle<promise_type> h_;
};

resumable_widget get_value() {
  co_await std::suspend_always{};
  co_return 42;
}

int main() {
  resumable_widget r = get_value();
  while (r.resume()) {}  
  std::cout << r.get() << ' \n';
}
```
Section 2.11.2

Awaitable and Awaiter Types
awaiters provide a mechanism to wait for an event by suspending if not ready.

- When event occurs, the awaiter is deemed to be ready.
- Often, the event corresponds to some value associated with the awaiter object becoming available.

- The awaiter type provides a means to test if the event associated with the awaiter has occurred (i.e., the awaiter is ready).
- The awaiter type specifies how to suspend if the event has not occurred (i.e., the awaiter is not ready).
- The awaiter type specifies how to produce a value (if any) associated with the event.
**Awaiter-Type Members**

- `bool await_ready();`  
  - tests if awaiter object is ready

- `Suspend await_suspend(coroutine_handle<promise_type> h);`  
  - specifies action to be taken when coroutine suspended (which may involve resuming current or other coroutine)
  - `Suspend` can be `std::coroutine_handle<T>`,` bool`, or `void`

- `Value await_resume();`  
  - called when coroutine resumed to generate result from `co_await`
std::suspend_always is example of trivial awaiter class
always indicates not ready (i.e., always results in suspension)
yields void result when coroutine resumed

definition: [C++20 §17.12.5]

```cpp
struct suspend_always {
    constexpr bool await_ready() const noexcept
    { return false; }
    constexpr void await_suspend(coroutine_handle<>)
    const noexcept {}
    constexpr void await_resume() const noexcept {}
};
```

useful in situations where coroutine should always be suspended but should not yield value when resumed
- std::never_suspend is another example of trivial awaiter class
- always indicates ready (i.e., never results in suspension)
- definition: [C++20 §17.12.5]
  ```cpp
  struct suspend_never {
    constexpr bool await_ready() const noexcept { return true; }
    constexpr void await_suspend(coroutine_handle<>)
      const noexcept {}
    constexpr void await_resume() const noexcept {}
  };
  ```
- useful in contexts where coroutine should not be suspended
Awaitable Types

- used to model type whose value may or may not be ready
- provides mechanism whereby coroutine can suspend
- usually, instance of awaitable type associated with some result
- in such cases, awaitable type provides means to suspend until result associated with awaitable type is ready
- awaitable types used in `co_await` expression
- `co_await` can only wait on expression that has awaitable type
- awaitable type must be class type
- awaiter type is awaitable type
- language provides means to specify how to generate awaiter type from another (non-awaiter) type (e.g., `co_await` operator and `await_transform`)

Copyright © 2015–2021 Michael D. Adams
Handling of `co_await` Expression

- for expression `e` evaluated by coroutine with handle `h`, `co_await e` has behavior described below [C++20 §7.6.2.3/5]
  
- if `e.await_ready()` is `false`:
  - coroutine suspended
  - if return type of `await_suspend` is `std::coroutine_handle<T>`:
    - `rh = e.await_suspend(h)` evaluated
    - coroutine associated with `rh` is resumed
  - if return type of `await_suspend` is `bool`:
    - `b = e.await_suspend(h)` evaluated
    - if `b` is `false`, coroutine resumed
  - if return type of `await_suspend` is `void`:
    - `e.await_suspend(h)` evaluated

- if `e.await_ready()` is `true` or coroutine was resumed:
  - `e.await_resume()` evaluated to produce value for `co_await` expression

- `co_yield expr` is equivalent to
  
  `co_await promise.yield_value(expr)` [C++20 §7.6.17/1]
operator co_await can be used to automatically convert types into awaier types
```cpp
#include <cassert>
#include <optional>
#include <string>
#include "sync_wait.hpp"

template<class T> class always_ready_value {
public:
  always_ready_value(const T& value) : value_(value) {}
  bool await_ready() { return true; }
  void await_suspend(auto handle) {}
  auto await_resume() { return value_; }
private:
  T value_;}

auto operator co_await(std::optional<int> x) { return always_ready_value<std::optional<int>>(x); }

task<void> hello() {
  // int i = co_await 42; // ERROR: int is not of class type
  // auto s = co_await std::string("hi");
  // ERROR: not std::string not awaitable type
  auto oi = co_await std::optional<int>(42); // OK: co_await operator
  assert(oi.value() == 42);
  int ai = co_await always_ready_value<int>(42); // OK: awaiter type
  assert(ai == 42);
}

int main() { sync_wait(hello());}
```
Section 2.11.3

More Examples
- `fsm` class provides algorithmic framework for finite state machine (FSM)
- Coroutine implements rules for state transitions in FSM
- Caller passes next event into coroutine via `resume` function member of resumable type
- Caller invokes `resume` member function in loop, passing next event for FSM to coroutine via this function
- Coroutine passes next state back to caller via `yield/await` expression
- Does not suspend at initial suspend point; only suspends at final suspect point
```cpp
#include <coroutine>
#include <exception>
#include <iterator>
#include <utility>

template <class, class> class fsm;

template <class Promise>
class fsm_awaiter {
public:
    bool await_ready() { return false; }
    void await_suspend(std::coroutine_handle<Promise> handle) {
        handle_ = handle;
    }
    typename Promise::event_type await_resume() {
        return handle_.promise().get_event();
    }
private:
    std::coroutine_handle<Promise> handle_ = nullptr;
};
```
template <class State, class Event>
class fsm_promise {
public:
  using state_type = State;
  using event_type = Event;
  using coroutine_handle = typename std::coroutine_handle<fsm_promise<state_type, event_type>>;
  auto get_return_object() {
    return coroutine_handle::from_promise(*this);
  }
  std::suspend_never initial_suspend() {
    return {};
  }
  std::suspend_always final_suspend() noexcept {
    return {};
  }
  fsm_awaiter<fsm_promise> yield_value(state_type state) {
    state_ = std::move(state);
    return {};
  }
  void unhandled_exception() {std::terminate();}
  state_type& get_state() noexcept {
    return state_;}
  void set_event(event_type event) {event_ = std::move(event);}
  event_type get_event() {return event_;}
private:
  state_type state_;  
  event_type event_;  
};
template <class State, class Event>
class fsm {
public:
    using state_type = State;
    using event_type = Event;
    using promise_type = fsm_promise<state_type, event_type>;
    using awaiter_type = fsm_awaiter<promise_type>;
    using coroutine_handle = fsm_promise<state_type, event_type>::coroutine_handle;

    fsm(coroutine_handle handle) : handle_(handle) {}
    fsm(fsm&& other) {
        handle_ = other.handle_; 
        other.handle_ = nullptr; 
    }
    ~fsm() {if (handle_) {handle_.destroy();}}
    state_type get_state() {return handle_.promise().get_state();}
    bool resume(Event event) {
        if (!handle_.done()) {
            handle_.promise().set_event(std::move(event));
            handle_.resume();
        }
        return !handle_.done();
    }
private:
    coroutine_handle handle_;
Generator is class template that provides algorithmic framework for generator.

Template parameter T specifies type produced by generator via yield operations.

Generator class provides begin and end member functions so that elements of generated sequence can be accessed via iterator interface.

When begin invoked, coroutine resumed to generate first element in sequence.

Incrementing iterator, resumes coroutine in order to generate next element in sequence.

Generated element placed in promise type for (indirect) access by caller.
```cpp
#include <coroutine>
#include <exception>
#include <iterator>
#include <utility>

// Generator class.

template <class T>
class generator_promise {

public:
    using value_type = std::remove_reference_t<T>;
    using coroutine_handle = typename std::coroutine_handle<generator_promise<T>>;

    generator<T> get_return_object() {
        return coroutine_handle::from_promise(*this);
    }

    std::suspend_always initial_suspend() { return {};
    }
    std::suspend_always final_suspend() noexcept { return {};
    }

    std::suspend_always yield_value(value_type result) {
        result_ = std::move(result);
        return {};
    }

    void unhandled_exception() { std::terminate();
    }

    value_type& value() noexcept { return result_; }

private:
    value_type result_; 
};
```
template <class T>
class generator_iterator {
public:
    using iterator_category = std::input_iterator_tag;
    using value_type = typename generator_promise<T>::value_type;
    using difference_type = std::ptrdiff_t;
    using reference = typename std::conditional_t<std::is_reference_v<T>,
        T, T&>;
    using pointer = value_type*;
    using coroutine_handle = typename generator_promise<T>::coroutine_handle;
    explicit generator_iterator(coroutine_handle handle = nullptr) noexcept :
        handle_(handle) {}
    reference operator*() const noexcept
        {return handle_.promise().value();}
    reference operator->() const noexcept
        {return std::addressof(operator*());}
    generator_iterator& operator++() {
        handle_.resume();
        if (handle_.done()) {handle_ = nullptr;}
        return *this;
    }
    bool operator==(generator_iterator other) const
        {return handle_ == other.handle_;}
    bool operator!=(generator_iterator other) const
        {return !operator==(other);}
private:
    coroutine_handle handle_; // nullptr means end
};
template <class T>
class generator {
  public:
    using promise_type = generator_promise<T>;
    using coroutine_handle = generator_promise<T>::coroutine_handle;
    using iterator = generator_iterator<T>;
    generator(coroutine_handle handle) : handle_(handle) {}
    generator(generator&& other) {
        handle_ = other.handle_;  
        other.handle_ = nullptr;
    }
    ~generator() {
        if (handle_) {handle_.destroy();
    }
    iterator begin() {
        handle_.resume();  
        return iterator(!handle_.done() ? handle_ : nullptr);
    }
    iterator end() {return iterator();}
  private:
    coroutine_handle handle_;  
};
- **task** is class template that provides means to wait for some computation to complete, possibly returning result of computation (if any) having some specific type
- **task** is awaiter type (and is therefore awaitable type)
- can **co_await** on task object to wait for task to complete and obtain return value (if any)
- at initial suspension point, always suspends
- at final suspension point, always suspends and resumes coroutine coawaiting result of task
```cpp
#include <coroutine>
#include <utility>
#include <variant>

template<class Promise_type> struct task_final_awaiter {
  bool await_ready() noexcept { return false; }
  void await_resume() noexcept {}
  auto await_suspend(std::coroutine_handle<Promise_type> me) noexcept {
    return me.promise().waiter;
  }
};

template<class T> struct task_promise_type {
  auto get_return_object() {
    return std::coroutine_handle<task_promise_type>::from_promise(*this);
  }
  void return_value(T value) {
    result.template emplace<2>(std::move(value));
  }
  void unhandled_exception() {
    result.template emplace<1>(std::current_exception());
  }
  std::suspend_always initial_suspend() { return {};
  task_final_awaiter<task_promise_type<T>> final_suspend() noexcept {
    return {};
  }
  std::variant<std::monostate, std::exception_ptr, T> result;
  std::coroutine_handle<> waiter;
};
```
```cpp
template<> struct task_promise_type<void> {
    auto get_return_object() {
        return std::coroutine_handle<task_promise_type>::from_promise(*this);
    }
    void return_void() {}
    void unhandled_exception() {
        result.template emplace<1>(std::current_exception());
    }
    std::suspend_always initial_suspend() {return {}};
    task_final_awaiter<task_promise_type<void>> final_suspend() noexcept {
        return {}};
    std::variant<std::monostate, std::exception_ptr> result;
    std::coroutine_handle<> waiter;
};
```
template<class T = void> class task {
  public:
    using promise_type = task.promise_type<T>;
    using final_awaiter = task.final_awaiter<promise_type>;
    explicit task(std::coroutine_handle<promise_type> handle) :
      handle_(handle) {}
    task(task&& other) : handle_(other.handle_) {other.handle_ = nullptr;}
    ~task() {if (handle_) {handle_.destroy();}}
    bool await_ready() {return false;}
    void await_suspend(std::coroutine_handle<> waiter) {
      handle_.promise().waiter = waiter;
      handle_.resume();
    }
    auto await_resume() {
      auto& result = handle_.promise().result;
      if (result.index() == 1)
        {std::rethrow_exception(std::get<1>(result));}
      if constexpr (std::is_same_v<T, void>) {return;}
      else {return std::get<2>(result);}
    }
    auto handle() {return handle_;}
  private:
    std::coroutine_handle<promise_type> handle_;
```cpp
#include <iostream>
#include "sync_wait.hpp"

task<int> f() {
    co_return 42;
}

task<int> g() {
    co_return co_await f() + co_await f();
}

task<void> h() {
    std::cout << "hello world\n";
    co_return;
}

int main()
{
    std::cout << sync_wait(f()) << '\n';
    std::cout << sync_wait(g()) << '\n';
    sync_wait(h());
}
```
Sync Wait Example: `sync_wait.hpp`

- may want to invoke task from non-coroutine and then wait for task to complete
- cannot use `co_await` to wait for task to complete, since `co_await` can only be used in coroutine
- create dummy task (which suspends at initial suspension point)
- dummy task set to be resumed when real task reaches final suspension point
- thus, resumption of dummy task indicates real task complete
- use latch as means for `sync_wait` to wait for dummy task to resume
- use `await_resume` for real task to obtain value returned from real task
```cpp
#include <coroutine>
#include <latch>
#include "task.hpp"

template <class Awaiter> auto sync_wait(Awaiter x) {
    if (!x.await_ready()) {
        std::latch waiters(1);
        auto helper = [&]() -> task<void> {
            waiters.count_down();
            co_return;
        };
        auto helper_task = helper();
        auto helper_handle = helper_task.handle();
        helper_handle.promise().waiter = std::noop_coroutine();
        x.await_suspend(helper_handle);
        waiters.wait();
    }
    return x.await_resume();
}
Section 2.11.4

Additional Examples
#include <iostream>
#include "simple_task.hpp"

// simple_task<int> is resumable type
// bool simple_task<int>::resume() resumes coroutine if not done
// int simple_task<int>::value() gets coroutine return value

simple_task<int> print_items() {
    // initial suspension point
    std::cout << "apple\n";
    std::cout << "grape\n";
    co_await std::suspend_always();
    std::cout << "banana\n";
    co_await std::suspend_never();
    std::cout << "orange\n";
    std::cout << std::flush;
    co_return 42;
} // final suspension point

int main() {
    std::cout << "calling print_items\n";
    auto f = print_items();
    for (;;) {
        std::cout << "resuming print_items\n";
        bool done = !f.resume();
        if (done) {break;}
    }
    int ret = f.value();
    std::cout << "print_items returned " << ret << '\n';
}
Section 2.11.5

References


Section 2.12

C++ Standard Library
C++ standard library provides huge amount of functionality (orders of magnitude more than C standard library) [C++20 §16]

uses std namespace (to avoid naming conflicts)

well worth effort to familiarize yourself with all functionality in library in order to avoid writing code unnecessarily

standard library comprised of numerous sublibraries
C++ Standard Library Components

- language support library (e.g., exceptions, memory management) [C++20 §17]
- concepts library (e.g., core concepts) [C++20 §18]
- diagnostics library (e.g., assertions, exceptions, error codes) [C++20 §19]
- general utilities library (e.g., functors, date/time) [C++20 §20]
- strings library (e.g., C++ and C-style strings) [C++20 §21]
- containers library (e.g., sequence containers and associative containers) [C++20 §22]
- iterators library (e.g., stream iterators) [C++20 §23]
- ranges library (e.g., views, range adapters, and range algorithms) [C++20 §24]
- algorithms library (e.g., searching, sorting, merging, set operations, heap operations, minimum/maximum) [C++20 §25]
- numerics library (e.g., complex numbers, math functions) [C++20 §26]
- time library (e.g., date/time manipulation, clocks) [C++20 §27]
- localization library (e.g., date/time formatting and parsing, character classification) [C++20 §28]
- input/output (I/O) library (e.g., streams, filesystem) [C++20 §29]
- regular expressions library (e.g., regular expression matching) [C++20 §30]
- atomic operations library (e.g., atomic types, fences) [C++20 §31]
- thread support library (e.g., threads, mutexes, condition variables, futures) [C++20 §32]
## Standard Library Headers (1)

### Headers Related to Basic Language/Library Utilities

<table>
<thead>
<tr>
<th>Header File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>version</td>
<td>implementation-dependent library information (e.g., __cpp_lib_assume_aligned, __cpp_lib_format)</td>
</tr>
<tr>
<td>cstddef</td>
<td>standard macros and typedefs (e.g., size_t, ptrdiff_t, byte)</td>
</tr>
<tr>
<td>cstdlib</td>
<td>run-time support, similar to stdlib.h from C (e.g., exit)</td>
</tr>
<tr>
<td>csignal</td>
<td>functions and macros for signal management</td>
</tr>
<tr>
<td>csetjmp</td>
<td>functions/macros for save/jumps to execution context</td>
</tr>
<tr>
<td>cstdarg</td>
<td>handling of variable-length argument lists</td>
</tr>
<tr>
<td>exception</td>
<td>exception handling support (e.g., set_terminate, current_exception)</td>
</tr>
<tr>
<td>compare</td>
<td>comparisons (e.g., strong_ordering, partial_ordering)</td>
</tr>
<tr>
<td>coroutine</td>
<td>coroutines (e.g., coroutine_handle)</td>
</tr>
<tr>
<td>concepts</td>
<td>concepts (e.g., forward_iterator)</td>
</tr>
<tr>
<td>utility</td>
<td>basic function and class templates (e.g., swap, move, pair)</td>
</tr>
<tr>
<td>type_traits</td>
<td>type traits (e.g., is_integral, is_reference)</td>
</tr>
<tr>
<td>source_location</td>
<td>source location (e.g., source_location)</td>
</tr>
</tbody>
</table>
### Standard Library Headers (2)

#### Headers Related to Memory Management

<table>
<thead>
<tr>
<th>Header File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>memory</td>
<td>high-level memory management facilities (e.g., unique_ptr, shared_ptr, addressof)</td>
</tr>
<tr>
<td>memory_resources</td>
<td>polymorphic allocators and memory resources (e.g., polymorphic_allocator, synchronized_pool_resource)</td>
</tr>
<tr>
<td>new</td>
<td>low-level memory management facilities</td>
</tr>
<tr>
<td>scoped_allocator</td>
<td>nested allocator class (i.e., scoped_allocator)</td>
</tr>
</tbody>
</table>

#### Headers Related to Error Handling

<table>
<thead>
<tr>
<th>Header File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>cassert</td>
<td>assertions (e.g., assert)</td>
</tr>
<tr>
<td>stdexcept</td>
<td>predefined exception types (e.g., invalid_argument, domain_error, out_of_range)</td>
</tr>
<tr>
<td>system_error</td>
<td>platform-dependent error code (e.g., error_code, error_condition)</td>
</tr>
<tr>
<td>cerrno</td>
<td>macro containing last error number</td>
</tr>
</tbody>
</table>
# Headers Related to Basic Types

<table>
<thead>
<tr>
<th>Header File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>any</td>
<td>any class and related functionality (e.g., bad_any_cast, any_cast)</td>
</tr>
<tr>
<td>bitset</td>
<td>bitset class template</td>
</tr>
<tr>
<td>optional</td>
<td>optional class template and related functionality (e.g., bad_optional_access, nullopt_t)</td>
</tr>
<tr>
<td>variant</td>
<td>variant class template and related functionality (e.g., monostate, bad_variant_access)</td>
</tr>
<tr>
<td>typeinfo</td>
<td>run-time type information utilities (e.g., type_info, bad_typeid, bad_cast)</td>
</tr>
<tr>
<td>typeindex</td>
<td>type_index class</td>
</tr>
<tr>
<td>tuple</td>
<td>tuple class template and related functionality (e.g., make_tuple, get)</td>
</tr>
<tr>
<td>initializer_list</td>
<td>initializer_list class template</td>
</tr>
</tbody>
</table>
## Headers Related to Strings

<table>
<thead>
<tr>
<th>Header File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>cstring</td>
<td>C-style strings, similar to <code>string.h</code> from C (e.g., <code>strlen</code>)</td>
</tr>
<tr>
<td>cctype</td>
<td>character classification, similar to <code>ctype.h</code> from C (e.g., <code>isdigit</code>, <code>isalpha</code>)</td>
</tr>
<tr>
<td>cwctype</td>
<td>character classification for wide characters</td>
</tr>
<tr>
<td>cwchar</td>
<td>wide and multibyte string handling functions</td>
</tr>
<tr>
<td>cuchar</td>
<td>C-style Unicode character conversion functions</td>
</tr>
<tr>
<td>string</td>
<td>C++ string classes (e.g., <code>string</code>)</td>
</tr>
<tr>
<td>string_view</td>
<td>basic_string_view class template and related functionality (e.g., <code>string_view</code>, <code>u8string_view</code>)</td>
</tr>
<tr>
<td>charconv</td>
<td>character-sequence conversion functions (e.g., <code>chars_format</code>, <code>to_chars</code>, <code>from_chars</code>)</td>
</tr>
<tr>
<td>format</td>
<td>formatting (e.g., <code>format</code>, <code>format_to</code>)</td>
</tr>
<tr>
<td>regex</td>
<td>regular expressions (e.g., <code>basic_regex</code>)</td>
</tr>
<tr>
<td>locale</td>
<td>localization utilities (e.g., <code>locale</code>, <code>money_base</code>)</td>
</tr>
<tr>
<td>localeconv</td>
<td>C localization utilities (e.g., <code>setlocale</code>, <code>localeconv</code>)</td>
</tr>
</tbody>
</table>
## Headers Related to Containers and Container Adapters

<table>
<thead>
<tr>
<th>Header File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>array</td>
<td>array class template</td>
</tr>
<tr>
<td>vector</td>
<td>vector class template</td>
</tr>
<tr>
<td>deque</td>
<td>deque class template</td>
</tr>
<tr>
<td>forward_list</td>
<td>forward_list class template</td>
</tr>
<tr>
<td>list</td>
<td>list class template</td>
</tr>
<tr>
<td>set</td>
<td>set class templates (i.e., set, multiset)</td>
</tr>
<tr>
<td>map</td>
<td>map class templates (i.e., map, multimap)</td>
</tr>
<tr>
<td>unordered_set</td>
<td>unordered set class templates (i.e., unordered_set, unordered_multiset)</td>
</tr>
<tr>
<td>unordered_map</td>
<td>unordered map class templates (i.e., unordered_map, unordered_multimap)</td>
</tr>
<tr>
<td>queue</td>
<td>queue container adapter (e.g., queue)</td>
</tr>
<tr>
<td>stack</td>
<td>stack container adapter (e.g., stack)</td>
</tr>
<tr>
<td>span</td>
<td>span view class template (e.g., span)</td>
</tr>
</tbody>
</table>
# Standard Library Headers (6)

## Headers Related to Iterators, Algorithms, and Ranges

<table>
<thead>
<tr>
<th>Header File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>iterator</td>
<td>iterators (e.g., reverse_iterator, back_inserter)</td>
</tr>
<tr>
<td>algorithm</td>
<td>algorithms (e.g., min, max, sort)</td>
</tr>
<tr>
<td>ranges</td>
<td>view, ranges adapters, and range algorithms (e.g., take, sort)</td>
</tr>
<tr>
<td>functional</td>
<td>functors (e.g., less, greater)</td>
</tr>
<tr>
<td>execution</td>
<td>execution policies for parallel versions of algorithms (e.g., seq, sequenced_policy)</td>
</tr>
</tbody>
</table>

## Headers Related to Time

<table>
<thead>
<tr>
<th>Header File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>chrono</td>
<td>clocks (e.g., system_clock, steady_clock, high_resolution_clock)</td>
</tr>
<tr>
<td>ctime</td>
<td>C-style time/date functions (e.g., clock_t, time_t)</td>
</tr>
</tbody>
</table>
### Headers Related to Numerics

<table>
<thead>
<tr>
<th>Header File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>climits</td>
<td>limits of integral types</td>
</tr>
<tr>
<td>cfloat</td>
<td>limits of floating-point types</td>
</tr>
<tr>
<td>cstdint</td>
<td>fixed-width integer types and limits of other types</td>
</tr>
<tr>
<td>cinttypes</td>
<td>integer types and conversion functions</td>
</tr>
<tr>
<td>cmath</td>
<td>C math library, similar to <code>math.h</code> from C (e.g., <code>sin</code>, <code>cos</code>)</td>
</tr>
<tr>
<td>complex</td>
<td>complex numbers (e.g., <code>complex</code>)</td>
</tr>
<tr>
<td>valarray</td>
<td>class template for representing array of values (e.g., <code>valarray</code>)</td>
</tr>
<tr>
<td>random</td>
<td>random number generation (e.g., <code>uniform_int_distribution</code>, <code>uniform_real_distribution</code>, <code>normal_distribution</code>)</td>
</tr>
<tr>
<td>numeric</td>
<td>generalized numeric operations (e.g., <code>gcd</code>, <code>lcm</code>, <code>inner_product</code>)</td>
</tr>
<tr>
<td>ratio</td>
<td>compile-time rational arithmetic (e.g., <code>ratio</code>, <code>ratio_add</code>, <code>ratio_multiply</code>)</td>
</tr>
<tr>
<td>bit</td>
<td>bit-manipulation functions (e.g., <code>bit_cast</code>, <code>has_single_bit</code>, <code>bit_width</code>)</td>
</tr>
<tr>
<td>numbers</td>
<td>math constants (e.g., <code>pi_v</code>, <code>e_v</code>)</td>
</tr>
<tr>
<td>limits</td>
<td>properties of fundamental types (e.g., <code>numeric_limits</code>)</td>
</tr>
<tr>
<td>cfenv</td>
<td>floating-point environment access functions (e.g., <code>fesetround</code>, <code>fegetround</code>)</td>
</tr>
</tbody>
</table>
# Standard Library Headers (8)

## Headers Related to I/O and Filesystem

<table>
<thead>
<tr>
<th>Header File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>iosfwd</td>
<td>forward declarations of all classes in I/O library</td>
</tr>
<tr>
<td>ios</td>
<td>base classes and other declarations for streams (e.g., ios_base, hex, fixed)</td>
</tr>
<tr>
<td>istream</td>
<td>input streams (e.g., istream)</td>
</tr>
<tr>
<td>ostream</td>
<td>output streams (e.g., ostream)</td>
</tr>
<tr>
<td>iostream</td>
<td>iostream objects (e.g., cin, cout, cerr)</td>
</tr>
<tr>
<td>fstream</td>
<td>file streams (e.g., fstream)</td>
</tr>
<tr>
<td>sstream</td>
<td>string streams (e.g., stringstream)</td>
</tr>
<tr>
<td>syncstream</td>
<td>synchronized output stream wrapper (e.g., basic_osyncstream)</td>
</tr>
<tr>
<td>iomanip</td>
<td>manipulators (e.g., setw, setprecision)</td>
</tr>
<tr>
<td>streambuf</td>
<td>stream buffer class template (e.g., basic_streambuf)</td>
</tr>
<tr>
<td>cstdio</td>
<td>C-style I/O functions (e.g., fopen, fclose)</td>
</tr>
<tr>
<td>filesystem</td>
<td>filesystem support (e.g., path, copy_file)</td>
</tr>
</tbody>
</table>
### Headers Related to Thread Support and Atomic Operations

<table>
<thead>
<tr>
<th>Header File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>atomic</td>
<td>atomic operations (e.g., atomic)</td>
</tr>
<tr>
<td>thread</td>
<td>threads (e.g., jthread, thread)</td>
</tr>
<tr>
<td>stop_token</td>
<td>stop tokens (e.g., stop_token, stop_source)</td>
</tr>
<tr>
<td>mutex</td>
<td>mutual exclusion primitives (e.g., mutex, recursive_mutex, timed_mutex)</td>
</tr>
<tr>
<td>shared_mutex</td>
<td>shared mutual exclusive primitives (e.g., shared_mutex)</td>
</tr>
<tr>
<td>future</td>
<td>promises and futures (e.g., future, shared_future, promise)</td>
</tr>
<tr>
<td>condition_variable</td>
<td>condition variables (e.g., condition_variable)</td>
</tr>
<tr>
<td>semaphore</td>
<td>semaphores (e.g., binary_semaphore, counting_semaphore)</td>
</tr>
<tr>
<td>latch</td>
<td>latches (e.g., latch)</td>
</tr>
<tr>
<td>barrier</td>
<td>barriers (e.g., barrier)</td>
</tr>
</tbody>
</table>
Section 2.12.1

Containers, Iterators, and Algorithms
large part of C++ standard library is collection of class/function templates known as standard template library (STL)

STL comprised of three basic building blocks:

1. containers
2. iterators
3. algorithms

containers store elements for processing (e.g., vector)

iterators allow access to elements for processing (which are often, but not necessarily, in containers)

algorithms perform actual processing (e.g., search, sort)
- **container**: class that represents collection/sequence of elements
- usually container classes are template classes
- **sequence container**: collection in which every element has certain position that depends on time and place of insertion
- examples of sequence containers include:
  - array (fixed-size array)
  - vector (dynamic-size array)
  - list (doubly-linked list)
- **ordered/unordered associative container**: collection in which position of element in depends on its value or associated key and some predefined sorting/hashing criterion
- examples of associative containers include:
  - set (collection of unique keys, sorted by key)
  - map (collection of key-value pairs, sorted by key, keys are unique)
### Sequence Containers

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>array</td>
<td>fixed-size array</td>
</tr>
<tr>
<td>vector</td>
<td>dynamic-size array</td>
</tr>
<tr>
<td>deque</td>
<td>double-ended queue</td>
</tr>
<tr>
<td>forward_list</td>
<td>singly-linked list</td>
</tr>
<tr>
<td>list</td>
<td>doubly-linked list</td>
</tr>
</tbody>
</table>

### Container Adapters

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>stack</td>
<td>stack</td>
</tr>
<tr>
<td>queue</td>
<td>FIFO queue</td>
</tr>
<tr>
<td>priority_queue</td>
<td>priority queue</td>
</tr>
</tbody>
</table>
## Ordered Associative Containers

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>set</td>
<td>collection of unique keys, sorted by key</td>
</tr>
<tr>
<td>map</td>
<td>collection of key-value pairs, sorted by key, keys are unique</td>
</tr>
<tr>
<td>multiset</td>
<td>collection of keys, sorted by key, duplicate keys allowed</td>
</tr>
<tr>
<td>multimap</td>
<td>collection of key-value pairs, sorted by key, duplicate keys allowed</td>
</tr>
</tbody>
</table>

## Unordered Associative Containers

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>unordered_set</td>
<td>collection of unique keys, hashed by key</td>
</tr>
<tr>
<td>unordered_map</td>
<td>collection of key-value pairs, hashed by key, keys are unique</td>
</tr>
<tr>
<td>unordered_multiset</td>
<td>collection of keys, hashed by key, duplicate keys allowed</td>
</tr>
<tr>
<td>unordered_multimap</td>
<td>collection of key-value pairs, hashed by key, duplicate keys allowed</td>
</tr>
</tbody>
</table>
Typical Sequence Container Member Functions

- some member functions typically provided by sequence container classes listed below (where \( T \) denotes name of container class)

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T() )</td>
<td>create empty container (default constructor)</td>
</tr>
<tr>
<td>( T(const\  T&amp;) )</td>
<td>copy container (copy constructor)</td>
</tr>
<tr>
<td>( T(T&amp;&amp;) )</td>
<td>move container (move constructor)</td>
</tr>
<tr>
<td>( ~T )</td>
<td>destroy container (including its elements)</td>
</tr>
<tr>
<td>empty</td>
<td>test if container empty</td>
</tr>
<tr>
<td>size</td>
<td>get number of elements in container</td>
</tr>
<tr>
<td>push_back</td>
<td>insert element at end of container</td>
</tr>
<tr>
<td>clear</td>
<td>remove all elements from container</td>
</tr>
<tr>
<td>( \texttt{operator=} )</td>
<td>assign all elements of one container to other</td>
</tr>
<tr>
<td>( \texttt{operator[]} )</td>
<td>access element in container</td>
</tr>
</tbody>
</table>
```cpp
#include <iostream>
#include <vector>

int main() {
    std::vector<int> values;

    // append elements with values 0 to 9
    for (int i = 0; i < 10; ++i) {
        values.push_back(i);
    }

    // print each element followed by space
    for (int i = 0; i < values.size(); ++i) {
        std::cout << values[i] << ' ';
    }
    std::cout << '
';

    /* This program produces the following output:
    0 1 2 3 4 5 6 7 8 9 */
}
Motivation for Iterators

- different containers organize elements (of container) differently in memory
- want uniform manner in which to access elements in any arbitrary container
- organization of elements in array/vector container:

  ![Array/Vector Organization](image)

- organization of elements in doubly-linked list container:

  ![Doubly-Linked List Organization](image)
Motivation for Iterators (Continued)

- consider array/vector container with `int` elements:
  
  \[
  \begin{array}{cccc}
  \end{array}
  \]

- suppose we want to set all elements in container to zero

- we could use code like:

  ```
  // int* begin; int* end;
  for (int* iter = begin; iter != end; ++iter)
    *iter = 0;
  ```

- could we make similar-looking code work for more complicated organization like doubly-linked list?

- yes, create user-defined type that provides all pointer operations used above (e.g., dereference, increment, comparison, assignment)

- this leads to notion of iterator
Iterators

- **iterator**: object that allows iteration over collection of elements, where elements are often (but not necessarily) in container
- iterators support many of same operations as pointers
- in some cases, iterator may actually be pointer; more frequently, iterator is user-defined type
- five different categories of iterators: 1) input, 2) output, 3) forward, 4) bidirectional, and 5) random access
- iterator has particular level of functionality, depending on category
- one of three possibilities of access order:
  1. forward (i.e., one direction only)
  2. forward and backward
  3. any order (i.e., random access)
- one of three possibilities in terms of read/write access:
  1. can only read referenced element (once or multiple times)
  2. can only write referenced element (once or multiple times)
  3. can read and write referenced element (once or multiple times)
- const and mutable (i.e., non-const) variants (i.e., read-only or read/write access, respectively)
<table>
<thead>
<tr>
<th>Category</th>
<th>Ability</th>
<th>Providers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>Reads (once only) forward</td>
<td>istream (istream_iterator)</td>
</tr>
<tr>
<td>Output</td>
<td>Writes (once only) forward</td>
<td>ostream (ostream_iterator), inserter_iterator</td>
</tr>
<tr>
<td>Forward</td>
<td>Reads and writes forward</td>
<td>forward_list, unordered_set, unordered_multiset, unordered_map, unordered_multimap</td>
</tr>
<tr>
<td>Bidirectional</td>
<td>Reads and writes forward forward and backward</td>
<td>list, set, multiset, map, multimap</td>
</tr>
<tr>
<td>Random access</td>
<td>Reads and writes with random access</td>
<td>deque</td>
</tr>
<tr>
<td>Contiguous</td>
<td>Random access and contiguous in memory</td>
<td>(built-in) array, array, vector, string</td>
</tr>
</tbody>
</table>
## Input Iterators

<table>
<thead>
<tr>
<th>Expression</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>T(a)</code></td>
<td>copies iterator (copy constructor)</td>
</tr>
<tr>
<td><code>*a</code></td>
<td>dereference as rvalue (i.e., read only); cannot dereference at old position</td>
</tr>
<tr>
<td><code>a-&gt;m</code></td>
<td>steps forward (returns new position)</td>
</tr>
<tr>
<td><code>++a</code></td>
<td>steps forward</td>
</tr>
<tr>
<td><code>a += b</code></td>
<td>test for equality</td>
</tr>
<tr>
<td><code>a != b</code></td>
<td>test for inequality</td>
</tr>
</tbody>
</table>

- not assignable (i.e., no assignment operator)
### Output Iterators

<table>
<thead>
<tr>
<th>Expression</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T(a))</td>
<td>copies iterator (copy constructor)</td>
</tr>
<tr>
<td>(*a) (a-&gt;m)</td>
<td>dereference as lvalue (i.e., write only); can only be dereferenced once; cannot dereference at old position</td>
</tr>
<tr>
<td>(++a)</td>
<td>steps forward (returns new position)</td>
</tr>
<tr>
<td>(a++)</td>
<td>steps forward (returns old position)</td>
</tr>
</tbody>
</table>

- not assignable (i.e., no assignment operator)
- no comparison operators (i.e., \(\text{operator}==, \text{operator}!\ne\))
### Forward Iterators

<table>
<thead>
<tr>
<th>Expression</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>T()</td>
<td>default constructor</td>
</tr>
<tr>
<td>T(a)</td>
<td>copy constructor</td>
</tr>
<tr>
<td>a = b</td>
<td>assignment</td>
</tr>
<tr>
<td>*a</td>
<td>dereference</td>
</tr>
<tr>
<td>a-&gt;m</td>
<td></td>
</tr>
<tr>
<td>++a</td>
<td>steps forward (returns new position)</td>
</tr>
<tr>
<td>a++</td>
<td>steps forward (returns old position)</td>
</tr>
<tr>
<td>a == b</td>
<td>test for equality</td>
</tr>
<tr>
<td>a != b</td>
<td>test for inequality</td>
</tr>
</tbody>
</table>

- must ensure that valid to dereference iterator before doing so
bidirectional iterators are forward iterators that provide additional functionality of being able to iterate backward over elements

bidirectional iterators have all functionality of forward iterators as well as those listed in table below

<table>
<thead>
<tr>
<th>Expression</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>--a</td>
<td>steps backward (returns new position)</td>
</tr>
<tr>
<td>a--</td>
<td>steps backward (returns old position)</td>
</tr>
</tbody>
</table>
Random-Access Iterators

- random access iterators provide all functionality of bidirectional iterators as well as providing random access to elements

- random access iterators provide all functionality of bidirectional iterators as well as those listed in table below

<table>
<thead>
<tr>
<th>Expression</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>a[n]</td>
<td>dereference element at index n (where n can be negative)</td>
</tr>
<tr>
<td>a += n</td>
<td>steps n elements forward (where n can be negative)</td>
</tr>
<tr>
<td>a -= n</td>
<td>steps n elements backward (where n can be negative)</td>
</tr>
<tr>
<td>a + n</td>
<td>iterator for nth next element</td>
</tr>
<tr>
<td>n + a</td>
<td>iterator for nth next element</td>
</tr>
<tr>
<td>a - n</td>
<td>iterator for nth previous element</td>
</tr>
<tr>
<td>a - b</td>
<td>distance from a to b</td>
</tr>
<tr>
<td>a &lt; b</td>
<td>test if a before b</td>
</tr>
<tr>
<td>a &gt; b</td>
<td>test if a after b</td>
</tr>
<tr>
<td>a &lt;= b</td>
<td>test if a not after b</td>
</tr>
<tr>
<td>a &gt;= b</td>
<td>test if a not before b</td>
</tr>
</tbody>
</table>

- pointers (built into language) are examples of random-access iterators
contiguous iterators provide all functionality of random-access iterators and guarantee that elements stored contiguously in memory

pointer to element in (built-in) array is example of contiguous iterator
```cpp
#include <iostream>
#include <vector>

int main() {
    std::vector<int> values(10);

    std::cout << "number of elements: " <<
    (values.end() - values.begin()) << '
';

    // initialize elements of vector to 0, 1, 2, ...
    for (std::vector<int>::iterator i = values.begin(); i != values.end(); ++i) {
        *i = i - values.begin();
    }

    // print elements of vector
    for (std::vector<int>::const_iterator i = values.cbegin(); i != values.cend(); ++i) {
        std::cout << ' ' << *i;
    }
    std::cout << '
';
}
```
do not dereference iterator unless it is known to validly reference some object

some operations on container can invalidate some or all iterators referencing elements in container

critically important to know which operations invalidate iterators in order to avoid using iterator that has been invalidated

incrementing iterator past end of container or decrementing iterator before beginning of container results in undefined behavior

input and output iterators can only be dereferenced once at each position
- **algorithm**: sequence of computations applied to some generic type
- algorithms use iterators to access elements involved in computation
- often pair of iterators used to specify *range* of elements on which to perform some computation
- what follows only provides brief summary of algorithms
- for more details on algorithms, see:
## Non-Modifying Sequence Operations

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>all_of</td>
<td>test if condition true for all elements in range</td>
</tr>
<tr>
<td>any_of</td>
<td>test if condition true for any element in range</td>
</tr>
<tr>
<td>none_of</td>
<td>test if condition true for no elements in range</td>
</tr>
<tr>
<td>for_each</td>
<td>apply function to range</td>
</tr>
<tr>
<td>for_each_n</td>
<td>apply function to first $n$ elements in sequence</td>
</tr>
<tr>
<td>find</td>
<td>find values in range</td>
</tr>
<tr>
<td>find_if</td>
<td>find element in range</td>
</tr>
<tr>
<td>find_if_not</td>
<td>find element in range (negated)</td>
</tr>
<tr>
<td>find_end</td>
<td>find last subsequence in range</td>
</tr>
<tr>
<td>find_first_of</td>
<td>find element from set in range</td>
</tr>
<tr>
<td>adjacent_find</td>
<td>find equal adjacent elements in range</td>
</tr>
<tr>
<td>count</td>
<td>count appearances of value in range</td>
</tr>
<tr>
<td>count_if</td>
<td>count number of elements in range satisfying condition</td>
</tr>
<tr>
<td>mismatch</td>
<td>get first position where two ranges differ</td>
</tr>
<tr>
<td>equal</td>
<td>test whether elements in two ranges differ</td>
</tr>
<tr>
<td>search</td>
<td>find subsequence in range</td>
</tr>
<tr>
<td>search_n</td>
<td>find succession of equal values in range</td>
</tr>
<tr>
<td>Name</td>
<td>Description</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>copy</td>
<td>copy range of elements</td>
</tr>
<tr>
<td>copy_if</td>
<td>copy certain elements of range</td>
</tr>
<tr>
<td>copy_n</td>
<td>copy $n$ elements</td>
</tr>
<tr>
<td>copy_backward</td>
<td>copy range of elements backwards</td>
</tr>
<tr>
<td>move</td>
<td>move range of elements</td>
</tr>
<tr>
<td>move_backward</td>
<td>move range of elements backwards</td>
</tr>
<tr>
<td>swap</td>
<td>exchange values of two objects (in utility header)</td>
</tr>
<tr>
<td>swap_ranges</td>
<td>exchange values of two ranges</td>
</tr>
<tr>
<td>iter_swap</td>
<td>exchange values of objects referenced by two iterators</td>
</tr>
<tr>
<td>transform</td>
<td>apply function to range</td>
</tr>
<tr>
<td>replace</td>
<td>replace value in range</td>
</tr>
<tr>
<td>replace_if</td>
<td>replace values in range</td>
</tr>
<tr>
<td>replace_copy</td>
<td>copy range replacing value</td>
</tr>
<tr>
<td>replace_copy_if</td>
<td>copy range replacing value</td>
</tr>
<tr>
<td>sample</td>
<td>selects $n$ random elements from sequence</td>
</tr>
</tbody>
</table>
### Modifying Sequence Operations (Continued)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>fill</strong></td>
<td>fill range with value</td>
</tr>
<tr>
<td><strong>fill_n</strong></td>
<td>fill sequence with value</td>
</tr>
<tr>
<td><strong>generate</strong></td>
<td>generate values for range with function</td>
</tr>
<tr>
<td><strong>generate_n</strong></td>
<td>generate values for sequence with function</td>
</tr>
<tr>
<td><strong>remove</strong></td>
<td>remove value from range (by shifting elements)</td>
</tr>
<tr>
<td><strong>remove_if</strong></td>
<td>remove elements from range (by shifting elements)</td>
</tr>
<tr>
<td><strong>remove_copy</strong></td>
<td>copy range removing value</td>
</tr>
<tr>
<td><strong>remove_copy_if</strong></td>
<td>copy range removing values</td>
</tr>
<tr>
<td><strong>unique</strong></td>
<td>remove consecutive duplicates in range</td>
</tr>
<tr>
<td><strong>unique_copy</strong></td>
<td>copy range removing duplicates</td>
</tr>
<tr>
<td><strong>reverse</strong></td>
<td>reverse range</td>
</tr>
<tr>
<td><strong>reverse_copy</strong></td>
<td>copy range reversed</td>
</tr>
<tr>
<td><strong>rotate</strong></td>
<td>rotate elements in range</td>
</tr>
<tr>
<td><strong>rotate_copy</strong></td>
<td>copies and rotates elements in range</td>
</tr>
<tr>
<td><strong>shuffle</strong></td>
<td>randomly permute elements in range</td>
</tr>
</tbody>
</table>
### Partition Operations

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>is_partitioned</td>
<td>test if range is partitioned by predicate</td>
</tr>
<tr>
<td>partition</td>
<td>partition range in two</td>
</tr>
<tr>
<td>partition_copy</td>
<td>copies range partition in two</td>
</tr>
<tr>
<td>stable_partition</td>
<td>partition range in two (stable ordering)</td>
</tr>
<tr>
<td>partition_point</td>
<td>get partition point</td>
</tr>
</tbody>
</table>

### Sorting

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>is_sorted</td>
<td>test if range is sorted</td>
</tr>
<tr>
<td>is_sorted_until</td>
<td>find first unsorted element in range</td>
</tr>
<tr>
<td>sort</td>
<td>sort elements in range</td>
</tr>
<tr>
<td>stable_sort</td>
<td>sort elements in range, preserving order of equivalents</td>
</tr>
<tr>
<td>partial_sort</td>
<td>partially sort elements in range</td>
</tr>
<tr>
<td>partial_sort_copy</td>
<td>copy and partially sort range</td>
</tr>
<tr>
<td>nth_element</td>
<td>sort element in range</td>
</tr>
</tbody>
</table>
### Binary Search (operating on sorted ranges)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>lower_bound</td>
<td>get iterator to lower bound</td>
</tr>
<tr>
<td>upper_bound</td>
<td>get iterator to upper bound</td>
</tr>
<tr>
<td>equal_range</td>
<td>get subrange of equal elements</td>
</tr>
<tr>
<td>binary_search</td>
<td>test if value exists in sorted range</td>
</tr>
</tbody>
</table>

### Set Operations (on sorted ranges)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>merge</td>
<td>merge sorted ranges</td>
</tr>
<tr>
<td>inplace_merge</td>
<td>merge consecutive sorted ranges</td>
</tr>
<tr>
<td>includes</td>
<td>test whether sorted range includes another sorted range</td>
</tr>
<tr>
<td>set_union</td>
<td>union of two sorted ranges</td>
</tr>
<tr>
<td>set_intersection</td>
<td>intersection of two sorted ranges</td>
</tr>
<tr>
<td>set_difference</td>
<td>difference of two sorted ranges</td>
</tr>
<tr>
<td>set_symmetric_difference</td>
<td>symmetric difference of two sorted ranges</td>
</tr>
</tbody>
</table>
### Heap Operations

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>is_heap</td>
<td>test if range is heap</td>
</tr>
<tr>
<td>is_heap_until</td>
<td>first first element not in heap order</td>
</tr>
<tr>
<td>push_heap</td>
<td>push element into heap range</td>
</tr>
<tr>
<td>pop_heap</td>
<td>pop element from heap range</td>
</tr>
<tr>
<td>make_heap</td>
<td>make heap from range</td>
</tr>
<tr>
<td>sort_heap</td>
<td>sort elements of heap</td>
</tr>
<tr>
<td>Name</td>
<td>Description</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------------------------------------------------------</td>
</tr>
<tr>
<td>min</td>
<td>get minimum of given values</td>
</tr>
<tr>
<td>max</td>
<td>get maximum of given values</td>
</tr>
<tr>
<td>minmax</td>
<td>get minimum and maximum of given values</td>
</tr>
<tr>
<td>min_element</td>
<td>get smallest element in range</td>
</tr>
<tr>
<td>max_element</td>
<td>get largest element in range</td>
</tr>
<tr>
<td>minmax_element</td>
<td>get smallest and largest elements in range</td>
</tr>
<tr>
<td>clamp</td>
<td>clamp value between pair of boundary values</td>
</tr>
<tr>
<td>lexicographic_compare</td>
<td>lexicographic less-than comparison</td>
</tr>
<tr>
<td>is_permutation</td>
<td>test if range permutation of another</td>
</tr>
<tr>
<td>next_permutation</td>
<td>transform range to next permutation</td>
</tr>
<tr>
<td>prev_permutation</td>
<td>transform range to previous permutation</td>
</tr>
</tbody>
</table>
### Numeric Operations

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>iota</strong></td>
<td>fill range with successive values</td>
</tr>
<tr>
<td><strong>accumulate</strong></td>
<td>accumulate values in range</td>
</tr>
<tr>
<td><strong>adjacent_difference</strong></td>
<td>compute adjacent difference of range</td>
</tr>
<tr>
<td><strong>inner_product</strong></td>
<td>compute inner product of range</td>
</tr>
<tr>
<td><strong>partial_sum</strong></td>
<td>compute partial sums of range</td>
</tr>
<tr>
<td><strong>reduce</strong></td>
<td>similar to accumulate except out of order</td>
</tr>
<tr>
<td><strong>exclusive_scan</strong></td>
<td>similar to partial_sum, excludes (i)th input element from (i)th sum</td>
</tr>
<tr>
<td><strong>inclusive_scan</strong></td>
<td>similar to partial_sum, includes (i)th input element in (i)th sum</td>
</tr>
<tr>
<td><strong>transform_reduce</strong></td>
<td>applies functor, then reduces out of order</td>
</tr>
<tr>
<td><strong>transform_exclusive_scan</strong></td>
<td>applies functor then, calculates exclusive scan</td>
</tr>
<tr>
<td><strong>transform_inclusive_scan</strong></td>
<td>applies functor, then calculates inclusive scan</td>
</tr>
</tbody>
</table>
Other Numeric Algorithms

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>gcd</td>
<td>compute greatest common divisor of two integers</td>
</tr>
<tr>
<td>lcm</td>
<td>compute least common multiple of two integers</td>
</tr>
</tbody>
</table>
```cpp
#include <iostream>
#include <vector>
#include <algorithm>
#include <random>

int main() {
    std::vector<int> values;

    int x;
    while (std::cin >> x) {values.push_back(x);}

    std::cout << "zero count: " << std::count(
        values.begin(), values.end(), 0) << '\n';

    std::default_random_engine engine;
    std::shuffle(values.begin(), values.end(), engine);
    std::cout << "random order:
    for (auto i : values) {std::cout << ' ' << i;}
    std::cout << '\n';

    std::sort(values.begin(), values.end());
    std::cout << "sorted order:
    for (auto i : values) {std::cout << ' ' << i;}
    std::cout << '\n';
```

Prelude to Functor Example

- Consider `std::transform function template`:

  ```
  template<class InputIterator, class OutputIterator, class UnaryOperator>
  OutputIterator transform(InputIterator first, InputIterator last, OutputIterator result, UnaryOperator op);
  ```

- Applies `op` to each element in range `[first, last)` and stores each returned value in range beginning at `result` (where ranges can overlap)

- `std::transform` might be written as:

  ```
  template<class InputIterator, class OutputIterator, class UnaryOperator>
  OutputIterator transform(InputIterator first, InputIterator last, OutputIterator result, UnaryOperator op) {
      while (first != last) {
          *result = op(*first);
          ++first;
          ++result;
      }
      return result;
  }
  ```

- `op` is entity that can be used with function call syntax (i.e., function or functor)
```cpp
#include <iostream>
#include <vector>
#include <algorithm>

struct MultiplyBy { // Functor class
    MultiplyBy(double factor) : factor_(factor) {}
    double operator()(double x) const
        {return factor_ * x;}

private:
    double factor_; // multiplicative factor
};

int main() {
    MultiplyBy mb(2.0);
    std::vector v{1.0, 2.0, 3.0};
    // v contains 1 2 3
    std::transform(v.begin(), v.end(), v.begin(), mb);
    // v contains 2 4 6
    for (auto i : v) {std::cout << i << 'n';}
}
```
Section 2.12.2

The `std::array` Class Template
The \texttt{std::array} Class Template

- one-dimensional array type, where size of array is fixed at compile time
- array declared as:
  \begin{verbatim}
  template <class T, std::size_t N>
  class array;
  \end{verbatim}
- \texttt{T}: type of elements in array
- \texttt{N}: number of elements in array
- what follows only intended to provide overview of \texttt{array}
- for additional details on \texttt{array}, see:
  - \url{http://en.cppreference.com/w/cpp/container/array}
### Member Types

<table>
<thead>
<tr>
<th>Member Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>value_type</td>
<td>T (i.e., element type)</td>
</tr>
<tr>
<td>size_type</td>
<td>type used for measuring size (i.e., std::size_t)</td>
</tr>
<tr>
<td>difference_type</td>
<td>type used to measure distance (i.e., std::ptrdiff_t)</td>
</tr>
<tr>
<td>reference</td>
<td>value_type&amp;</td>
</tr>
<tr>
<td>const_reference</td>
<td>const value_type&amp;</td>
</tr>
<tr>
<td>pointer</td>
<td>value_type*</td>
</tr>
<tr>
<td>const_pointer</td>
<td>const value_type*</td>
</tr>
<tr>
<td>iterator</td>
<td>random-access iterator type</td>
</tr>
<tr>
<td>const_iterator</td>
<td>const random-access iterator type</td>
</tr>
<tr>
<td>reverse_iterator</td>
<td>reverse iterator type</td>
</tr>
<tr>
<td>const_reverse_iterator</td>
<td>const reverse iterator type</td>
</tr>
</tbody>
</table>

---

**Copyright © 2015–2021 Michael D. Adams**

*Programming in C++*  
*Version 2021-04-01*
### Member Functions

#### Construction, Destruction, and Assignment

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>initializes array</td>
</tr>
<tr>
<td>destructor</td>
<td>destroys each element of array</td>
</tr>
<tr>
<td><code>operator=</code></td>
<td>overwrites every element of array with corresponding element of another array</td>
</tr>
</tbody>
</table>

#### Iterators

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>begin</td>
<td>return iterator to beginning</td>
</tr>
<tr>
<td>end</td>
<td>return iterator to end</td>
</tr>
<tr>
<td>cbegin</td>
<td>return const iterator to beginning</td>
</tr>
<tr>
<td>cend</td>
<td>return const iterator to end</td>
</tr>
<tr>
<td>rbegin</td>
<td>return reverse iterator to beginning</td>
</tr>
<tr>
<td>rend</td>
<td>return reverse iterator to end</td>
</tr>
<tr>
<td>crbegin</td>
<td>return const reverse iterator to beginning</td>
</tr>
<tr>
<td>crend</td>
<td>return const reverse iterator to end</td>
</tr>
</tbody>
</table>
### Capacity

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>empty</td>
<td>test if array is empty</td>
</tr>
<tr>
<td>size</td>
<td>return size</td>
</tr>
<tr>
<td>max_size</td>
<td>return maximum size</td>
</tr>
</tbody>
</table>

### Element Access

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>operator[]</code></td>
<td>access element (no bounds checking)</td>
</tr>
<tr>
<td>at</td>
<td>access element (with bounds checking)</td>
</tr>
<tr>
<td>front</td>
<td>access first element</td>
</tr>
<tr>
<td>back</td>
<td>access last element</td>
</tr>
<tr>
<td>data</td>
<td>return pointer to start of element data</td>
</tr>
</tbody>
</table>

### Modifiers

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>fill</td>
<td>fill container with specified value</td>
</tr>
<tr>
<td>swap</td>
<td>swap contents of two arrays</td>
</tr>
</tbody>
</table>
```cpp
#include <array>
#include <iostream>
#include <algorithm>
#include <experimental/iterator>

int main() {
    std::array<int, 3> a1{3, 1, 2};
    std::array<int, 3> a2;
    a2.fill(42);
    for (auto i : a2) {
        std::cout << i << '
';
    }
    a2 = a1;
    std::sort(a1.begin(), a1.end());
    std::copy(a1.begin(), a1.end(),
              std::experimental::make_ostream_joiner(std::cout, "", "));
    std::cout << '
';
    for(auto i = a2.begin(); i != a2.end(); ++i) {
      std::cout << *i;
      if (i != a2.end() - 1) {std::cout << "", ";}  
    }
    std::cout << '
';
}``
```cpp
#include <array>
#include <iostream>
#include <algorithm>

int main() {
    // Fixed-size array with 4 elements.
    std::array<int, 4> a{2, 4, 3, 1};

    // Print elements of array.
    for (auto i = a.cbegin(); i != a.cend(); ++i) {
        std::cout << ' ' << *i;
    }
    std::cout << '
';

    // Sort elements of array.
    std::sort(a.begin(), a.end());

    // Print elements of array.
    for (auto i = a.cbegin(); i != a.cend(); ++i) {
        std::cout << ' ' << *i;
    }
    std::cout << '
';
}
```
Section 2.12.3

The std::vector Class Template
The std::vector Class Template

- dynamically-sized one-dimensional array type, where type of array elements and storage allocator specified by template parameters

  vector declared as:

  ```cpp
template <class T, class Allocator = allocator<T>>
class vector;
```

- T: type of elements in vector
- Allocator: type of object used to handle storage allocation (unless custom storage allocator needed, use default allocator<T>)

  what follows only intended to provide overview of vector

  for additional details on vector, see:

## Member Types

<table>
<thead>
<tr>
<th>Member Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>value_type</code></td>
<td>T (i.e., element type)</td>
</tr>
<tr>
<td><code>allocator_type</code></td>
<td>Allocator (i.e., allocator)</td>
</tr>
<tr>
<td><code>size_type</code></td>
<td>type used for measuring size (typically unsigned integral type)</td>
</tr>
<tr>
<td><code>difference_type</code></td>
<td>type used to measure distance (typically signed integral type)</td>
</tr>
<tr>
<td><code>reference</code></td>
<td><code>value_type</code>&amp;</td>
</tr>
<tr>
<td><code>const_reference</code></td>
<td><code>const value_type</code>&amp;</td>
</tr>
<tr>
<td><code>pointer</code></td>
<td><code>allocator_traits&lt;Allocator&gt;::pointer</code></td>
</tr>
<tr>
<td><code>const_pointer</code></td>
<td><code>allocator_traits&lt;Allocator&gt;::const_pointer</code></td>
</tr>
<tr>
<td><code>iterator</code></td>
<td><code>random-access</code> iterator type</td>
</tr>
<tr>
<td><code>const_iterator</code></td>
<td><code>const random-access</code> iterator type</td>
</tr>
<tr>
<td><code>reverse_iterator</code></td>
<td>reverse iterator type</td>
</tr>
<tr>
<td><code>const_reverse_iterator</code></td>
<td><code>const reverse iterator</code> type</td>
</tr>
</tbody>
</table>

Copyright © 2015–2021 Michael D. Adams

Programming in C++

Version 2021-04-01

818
## Member Functions

### Construction, Destruction, and Assignment

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>construct vector (overloaded)</td>
</tr>
<tr>
<td>destructor</td>
<td>destroy vector</td>
</tr>
<tr>
<td><code>operator=</code></td>
<td>assign vector</td>
</tr>
</tbody>
</table>

### Iterators

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>begin</code></td>
<td>return iterator to beginning</td>
</tr>
<tr>
<td><code>end</code></td>
<td>return iterator to end</td>
</tr>
<tr>
<td><code>cbegin</code></td>
<td>return const iterator to beginning</td>
</tr>
<tr>
<td><code>cend</code></td>
<td>return const iterator to end</td>
</tr>
<tr>
<td><code>rbegin</code></td>
<td>return reverse iterator to beginning</td>
</tr>
<tr>
<td><code>rend</code></td>
<td>return reverse iterator to end</td>
</tr>
<tr>
<td><code>crbegin</code></td>
<td>return const reverse iterator to beginning</td>
</tr>
<tr>
<td><code>crend</code></td>
<td>return const reverse iterator to end</td>
</tr>
</tbody>
</table>
### Member Functions (Continued 1)

#### Capacity

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>empty</td>
<td>test if vector is empty</td>
</tr>
<tr>
<td>size</td>
<td>return size</td>
</tr>
<tr>
<td>max_size</td>
<td>return maximum size</td>
</tr>
<tr>
<td>capacity</td>
<td>return allocated storage capacity</td>
</tr>
<tr>
<td>reserve</td>
<td>request change in capacity</td>
</tr>
<tr>
<td>shrink_to_fit</td>
<td>shrink to fit</td>
</tr>
</tbody>
</table>

#### Element Access

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>operator[]</td>
<td>access element (no bounds checking)</td>
</tr>
<tr>
<td>at</td>
<td>access element (with bounds checking)</td>
</tr>
<tr>
<td>front</td>
<td>access first element</td>
</tr>
<tr>
<td>back</td>
<td>access last element</td>
</tr>
<tr>
<td>data</td>
<td>return pointer to start of element data</td>
</tr>
</tbody>
</table>
### Member Functions (Continued 2)

#### Modifiers

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>clear</td>
<td>clear content</td>
</tr>
<tr>
<td>assign</td>
<td>assign vector content</td>
</tr>
<tr>
<td>insert</td>
<td>insert elements</td>
</tr>
<tr>
<td>emplace</td>
<td>insert element, constructing in place</td>
</tr>
<tr>
<td>push_back</td>
<td>add element at end</td>
</tr>
<tr>
<td>emplace_back</td>
<td>insert element at end, constructing in place</td>
</tr>
<tr>
<td>erase</td>
<td>erase elements</td>
</tr>
<tr>
<td>pop_back</td>
<td>delete last element</td>
</tr>
<tr>
<td>resize</td>
<td>change size</td>
</tr>
<tr>
<td>swap</td>
<td>swap content of two vectors</td>
</tr>
</tbody>
</table>

#### Allocator

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>get_allocator</td>
<td>get allocator used by vector</td>
</tr>
</tbody>
</table>
- **capacity**: total number of elements that vector could hold without requiring reallocation of memory

- any operation that causes reallocation of memory used to hold elements of vector invalidates *all* iterators, references, and pointers referring to elements in vector

- any operation that changes capacity of vector causes reallocation of memory

- any operation that adds or deletes elements can invalidate references, iterators, and pointers

- operations that can potentially invalidate references, iterators, and pointers to elements in vector include:

  ```
  insert, erase, push_back, pop_back, emplace, emplace_back, 
  resize, reserve, operator=, assign, clear, shrink_to_fit, swap 
  (past-the-end iterator only)  
  ```

[C++17 §26.2.1/9]
Iterator Invalidation Example

- **start** denotes pointer to first element in array holding elements of `vector`
- **i** is iterator for `vector` (e.g., `vector<T>::const_iterator` or `vector<T>::iterator`)
- initial vector has three elements and capacity of three

```
| a | b | c |
```

- push_back(d) invoked
- new larger array is allocated (say, twice size of original); elements in old array moved/copied to new array; then new element added

```
| ? | ? | ? |
```
```
| a | b | c | d | unused | unused |
```

- elements in old array destroyed and memory for old array deallocated; iterator `i` is now *invalid*:

```
X X X X X X
```
```
| a | b | c | d | unused | unused |
```

Copyright © 2015–2021 Michael D. Adams
Programming in C++  ||  Version 2021-04-01
std::vector<double> v0;
   // empty vector

std::vector<double> v1(10);
   // vector with 10 elements, each initialized to 0.0
   // (effectively via value initialization)

std::vector<double> v2(10, 5.0);
   // vector with 10 elements, each initialized to 5.0

std::vector<int> v3{1, 2, 3};
   // vector with 3 elements: 1, 2, 3
   // std::initializer_list (note brace brackets)
vector Example: Iterators

```cpp
#include <iostream>
#include <vector>

int main() {
    std::vector v{0, 1, 2, 3};
    for (auto& i : v) {++i;}
    for (auto i : v) {
        std::cout << ' ' << i;
    }
    std::cout << '
';
    for (auto i = v.begin(); i != v.end(); ++i) {
        --(*i);
    }
    for (auto i = v.cbegin(); i != v.cend(); ++i) {
        std::cout << ' ' << *i;
    }
    std::cout << '
';
    for (auto i = v.crbegin(); i != v.crend(); ++i) {
        std::cout << ' ' << *i;
    }
    std::cout << '
';
}
```

- program output:

```
1 2 3 4
0 1 2 3
3 2 1 0
```
#include <iostream>
#include <vector>

int main() {
    std::vector<double> values;
    // ...

    // Erase all elements and then read elements from
    // standard input.
    values.clear();
    double x;
    while (std::cin >> x) {
        values.push_back(x);
    }
    std::cout << "number of values read: " <<
        values.size() << "\n";

    // Loop over all elements and print the number of
    // negative elements found.
    int count = 0;
    for (auto i = values.cbegin(); i != values.cend(); ++i) {
        if (*i < 0.0) {
            ++count;
        }
    }
    std::cout << "number of negative values: " << count << "\n";
}
```cpp
#include <iostream>
#include <vector>

int main() {
    std::vector<std::vector<int>> v{{1, 2, 3}, {4, 5, 6}};
    v.emplace_back(10, 0);
    // The above use of emplace_back is more efficient than:
    // v.push_back(std::vector<int>(10, 0));
    for (const auto& i : v) {
        for (const auto& j : i) {
            std::cout << ' ' << j;
        }
        std::cout << '
';
    }
}
```

- program output:
  1 2 3
  4 5 6
  0 0 0 0 0 0 0 0 0 0
Section 2.12.4

The \texttt{std::basic\_string} Class Template
The std::basic_string Class Template

- character string type, parameterized on character type, character traits, and storage allocator

- basic_string declared as:

  ```cpp
  template <class CharT,
             class Traits = char_traits<CharT>,
             class Allocator = allocator<CharT>>
  class basic_string;
  ```

- CharT: type of characters in string
- Traits: class that describes certain properties of CharT (normally, use default)
- Allocator: type of object used to handle storage allocation (unless custom storage allocator needed, use default)
- string is simply abbreviation for basic_string<char>
- what follows is only intended to provide overview of basic_string template class (and string class)
- for more details on basic_string, see:
  - [http://en.cppreference.com/w/cpp/string/basic_string](http://en.cppreference.com/w/cpp/string/basic_string)
### Member Types

<table>
<thead>
<tr>
<th>Member Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>traits_type</code></td>
<td>Traits (i.e., character traits)</td>
</tr>
<tr>
<td><code>value_type</code></td>
<td>Traits::char_type (i.e., character type)</td>
</tr>
<tr>
<td><code>allocator_type</code></td>
<td>Allocator</td>
</tr>
<tr>
<td><code>size_type</code></td>
<td>allocator_traits&lt;Allocator&gt;::size_type</td>
</tr>
<tr>
<td><code>difference_type</code></td>
<td>allocator_traits&lt;Allocator&gt;::difference_type</td>
</tr>
<tr>
<td><code>reference</code></td>
<td><code>value_type&amp;</code></td>
</tr>
<tr>
<td><code>const_reference</code></td>
<td><code>const value_type&amp;</code></td>
</tr>
<tr>
<td><code>pointer</code></td>
<td>allocator_traits&lt;Allocator&gt;::pointer</td>
</tr>
<tr>
<td><code>const_pointer</code></td>
<td>allocator_traits&lt;Allocator&gt;::const_pointer</td>
</tr>
<tr>
<td><code>iterator</code></td>
<td>random-access iterator type</td>
</tr>
<tr>
<td><code>const_iterator</code></td>
<td>const random-access iterator type</td>
</tr>
<tr>
<td><code>reverse_iterator</code></td>
<td>reverse iterator type (reverse_iterator&lt;iterator&gt;)</td>
</tr>
<tr>
<td><code>const_reverse_iterator</code></td>
<td>const reverse iterator type (reverse_iterator&lt;const_iterator&gt;)</td>
</tr>
</tbody>
</table>
### Member Functions

#### Construction, Destruction, and Assignment

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>construct</td>
</tr>
<tr>
<td>destructor</td>
<td>destroy</td>
</tr>
<tr>
<td>operator=</td>
<td>assign</td>
</tr>
</tbody>
</table>

#### Iterators

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>begin</td>
<td>return iterator to beginning</td>
</tr>
<tr>
<td>end</td>
<td>return iterator to end</td>
</tr>
<tr>
<td>cbegin</td>
<td>return const iterator to beginning</td>
</tr>
<tr>
<td>cend</td>
<td>return const iterator to end</td>
</tr>
<tr>
<td>rbegin</td>
<td>return reverse iterator to reverse beginning</td>
</tr>
<tr>
<td>rend</td>
<td>return reverse iterator to reverse end</td>
</tr>
<tr>
<td>crbegin</td>
<td>return const reverse iterator to reverse beginning</td>
</tr>
<tr>
<td>crend</td>
<td>return const reverse iterator to reverse end</td>
</tr>
</tbody>
</table>
## Member Functions (Continued 1)

### Capacity

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>empty</td>
<td>test if string empty</td>
</tr>
<tr>
<td>size</td>
<td>get length of string</td>
</tr>
<tr>
<td>length</td>
<td>same as size</td>
</tr>
<tr>
<td>max_size</td>
<td>get maximum size of string</td>
</tr>
<tr>
<td>capacity</td>
<td>get size of allocated storage</td>
</tr>
<tr>
<td>reserve</td>
<td>change capacity</td>
</tr>
<tr>
<td>shrink_to_fit</td>
<td>shrink to fit</td>
</tr>
</tbody>
</table>

### Element Access

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>operator[]</td>
<td>access character in string (no bounds checking)</td>
</tr>
<tr>
<td>at</td>
<td>access character in string (with bounds checking)</td>
</tr>
<tr>
<td>front</td>
<td>access first character in string</td>
</tr>
<tr>
<td>back</td>
<td>access last character in string</td>
</tr>
</tbody>
</table>
### Operations

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>clear</td>
<td>clear string</td>
</tr>
<tr>
<td>assign</td>
<td>assign content to string</td>
</tr>
<tr>
<td>insert</td>
<td>insert into string</td>
</tr>
<tr>
<td>push_back</td>
<td>append character to string</td>
</tr>
<tr>
<td><code>operator+=</code></td>
<td>append to string</td>
</tr>
<tr>
<td>append</td>
<td>append to string</td>
</tr>
<tr>
<td>erase</td>
<td>erase characters from string</td>
</tr>
<tr>
<td>pop_back</td>
<td>delete last character from string</td>
</tr>
<tr>
<td>replace</td>
<td>replace part of string</td>
</tr>
<tr>
<td>resize</td>
<td>resize string</td>
</tr>
<tr>
<td>swap</td>
<td>swap contents with another string</td>
</tr>
</tbody>
</table>
### Operations (Continued)

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>c_str</td>
<td>get nonmodifiable C-string equivalent</td>
</tr>
<tr>
<td>data</td>
<td>obtain pointer to first character of string</td>
</tr>
<tr>
<td>copy</td>
<td>copy sequence of characters from string</td>
</tr>
<tr>
<td>substr</td>
<td>generate substring</td>
</tr>
<tr>
<td>compare</td>
<td>compare strings</td>
</tr>
</tbody>
</table>

### Search

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>find</td>
<td>find first occurrence of content in string</td>
</tr>
<tr>
<td>rfind</td>
<td>find last occurrence of content in string</td>
</tr>
<tr>
<td>find_first_of</td>
<td>find first occurrence of characters in string</td>
</tr>
<tr>
<td>find_first_not_of</td>
<td>find first absence of characters in string</td>
</tr>
<tr>
<td>find_last_of</td>
<td>find last occurrence of characters in string</td>
</tr>
<tr>
<td>find_last_not_of</td>
<td>find last absence of characters in string</td>
</tr>
</tbody>
</table>
### Allocator

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>get_allocator</code></td>
<td>get allocator</td>
</tr>
<tr>
<td>Name</td>
<td>Description</td>
</tr>
<tr>
<td>-------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>stoi</td>
<td>convert string to <code>int</code></td>
</tr>
<tr>
<td>stol</td>
<td>convert string to <code>long</code></td>
</tr>
<tr>
<td>stoll</td>
<td>convert string to <code>long long</code></td>
</tr>
<tr>
<td>stoul</td>
<td>convert string to <code>unsigned long</code></td>
</tr>
<tr>
<td>stoull</td>
<td>convert string to <code>unsigned long long</code></td>
</tr>
<tr>
<td>stof</td>
<td>convert string to <code>float</code></td>
</tr>
<tr>
<td>stod</td>
<td>convert string to <code>double</code></td>
</tr>
<tr>
<td>stold</td>
<td>convert string to <code>long double</code></td>
</tr>
<tr>
<td>to_string</td>
<td>convert integral or floating-point value to <code>string</code></td>
</tr>
<tr>
<td>to_wstring</td>
<td>convert integral or floating-point value to <code>wstring</code></td>
</tr>
</tbody>
</table>
#include <iostream>
#include <string>

int main() {
    std::string s;
    if (!(std::cin >> s)) {
        s.clear();
    }
    std::cout << "string: " << s << '
';
    std::cout << "length: " << s.size() << '
';
    std::string b;
    for (auto i = s.crbegin(); i != s.crend(); ++i) {
        b.push_back(*i);
    }
    std::cout << "backwards: " << b << '
';

    std::string msg = "Hello";
    msg += ", World!"; // append ", World!"
    std::cout << msg << '
';

    const char* cstr = s.c_str();
    std::cout << "C-style string: " << cstr << '
';
}
```
#include <iostream>
#include <string>

int main() {
    double x = 42.24;
    // Convert double to string.
    std::string s = std::to_string(x);
    std::cout << s << '
';

    s = "3.14";
    // Convert string to double.
    x = std::stod(s);
    std::cout << x << '
';
}
```
Section 2.12.5

Other Container Classes
collection of two heterogeneous objects

pair declared as:

```cpp
template <class T1, class T2>
struct pair;
```

T1: type of first element in pair

T2: type of second element in pair

first and second elements accessible via data members `first` and `second`, respectively

elements of `pair` can also be accessed with `std::get` function template

pair is effectively equivalent to `std::tuple` (to be discussed shortly) with two elements
```cpp
#include <tuple>
#include <cassert>

int main() {
    std::pair p(true, 42);
    assert(p.first && p.second == 42);
    assert(p.first == std::get<0>(p) &&
           p.second == std::get<1>(p));
    std::pair q(true, 42);
    assert(p == q);
    p = {false, 0};
    assert(p != q);
    p.swap(q);
    auto [b, i] = p;
    assert(b == true && i == 42);
    assert(std::get<bool>(p) && std::get<0>(p));
    assert(std::get<int>(p) == 42 &&
            std::get<1>(p) == 42);
}
```
The `std::tuple` Class Template

- fixed-size collection of heterogeneous values
- `tuple` is generalization of `std::pair`
- `tuple` declared as:
  ```cpp
template <class... Ts>
  class tuple;
  ```
- `Ts`: types of elements that tuple holds (which may be empty)
- elements of `tuple` can be accessed with `std::get` function template
```cpp
#include <tuple>
#include <cassert>

int main() {
    std::tuple t(true, 42, 'Z');
    auto u = std::tuple(true, 42, 'Z');
    assert(t == u);
    assert(std::get<bool>(t) && std::get<0>(t));
    assert(std::get<char>(t) == 'Z' && std::get<2>(t) == 'Z');
    std::get<0>(t) = false;
    assert(t != u);
    std::tuple v(false, 0, '0');
    u = std::tuple(true, 1, '1');
    v.swap(u);
    assert(std::get<0>(v));
}
```
The `std::optional` Class Template

- simple container that manages optional value (i.e., value that may or may not be present)

- declaration:
  ```cpp
template <class T> class optional;
  ```

- `T` is type of optional value

- `T` cannot be reference type

- at any given point in time, object either contains value or does not

- object can be given value by initialization or assignment

- common use case is return value of function that can fail

- `std::bad_optional_access` exception indicates checked access to optional object that does not contain value

- optional value is required to be stored directly in optional object itself

[C++17 §23.6.3/1]
## Member Functions

### Construction, Destruction, and Assignment

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>constructs optional object</td>
</tr>
<tr>
<td>destructor</td>
<td>destroys optional object (and contained value)</td>
</tr>
<tr>
<td>operator=</td>
<td>assigns contents</td>
</tr>
</tbody>
</table>

### Observers

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>operator-&gt;</td>
<td>accesses contained value</td>
</tr>
<tr>
<td>operator*</td>
<td>accesses contained value</td>
</tr>
<tr>
<td>operator bool</td>
<td>tests if object contains value</td>
</tr>
<tr>
<td>has_value</td>
<td>tests if object contains value</td>
</tr>
<tr>
<td>value</td>
<td>returns contained value</td>
</tr>
<tr>
<td>value_or</td>
<td>returns contained value if available and specified default value otherwise</td>
</tr>
</tbody>
</table>
## Optional Member Functions (Continued)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>swap</td>
<td>exchange contents</td>
</tr>
<tr>
<td>reset</td>
<td>clear any contained value</td>
</tr>
<tr>
<td>emplace</td>
<td>constructs contained value in place</td>
</tr>
</tbody>
</table>
```cpp
#include <optional>
#include <string>
#include <exception>
#include <cassert>
#include <iostream>

int main() {
    using namespace std::literals;
    auto s = std::optional("Hello!"s);
    assert(s && s.has_value());
    assert(s.value() == "Hello!");
    auto t = std::optional("Goodbye!"s);
    s.swap(t);
    assert(*s == "Goodbye!" && *t == "Hello!");
    s.reset();
    assert(!s && !s.has_value());
    std::cout << s.value_or("Goodbye!") << '\n';
    try {
        std::cout << s.value() << '\n';
    } catch (const std::bad_optional_access&) {
        std::cout << "caught exception\n";
    }
    s.emplace("Salut!";
    std::cout << s.value() << '\n';
}
```

---

Copyright © 2015–2021 Michael D. Adams

Programming in C++

Version 2021-04-01

847
```cpp
#include <optional>
#include <string>
#include <fstream>
#include <iostream>

std::optional<std::string> read_file(const char* file_name) {
    std::ifstream in(file_name);
    std::optional<std::string> result;
    result.emplace(std::istreambuf_iterator<char>(in),
                   std::istreambuf_iterator<char>());
    if (in.fail() && !in.eof()) {
        result.reset();
    }
    return result;
}

int main(int argc, char** argv) {
    if (argc <= 1) {return 1;}
    auto s = read_file(argv[1]);
    if (!s) {
        std::cerr << "unable to read file\n";
        return 1;
    }
    std::cout << *s;
    return 0;
}
```
The `std::variant` Class Template

- simple container that corresponds to type-safe union
- can hold single value of one of set of allowable types
- declaration:
  ```cpp
template <class... Ts> class variant;
```
- Ts parameter pack containing all allowable types of value that can be stored in object
- container cannot hold references, arrays, or void
- can hold same type more than once and can hold differently cv-qualified versions of same type
- default initialized variant holds value of first alternative, which is default constructed
- `std::monostate` can be used as placeholder for empty type
- invalid accesses to value of `variant` object result in `std::bad_variant_access` exception being thrown

## Variant Member Functions

### Construction, Destruction, and Assignment

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>constructs variant object</td>
</tr>
<tr>
<td>destructor</td>
<td>destroys variant object (and contained value)</td>
</tr>
<tr>
<td><code>operator=</code></td>
<td>assigns variant</td>
</tr>
</tbody>
</table>

### Observers

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>index</td>
<td>returns zero-based index of alternative held by variant</td>
</tr>
<tr>
<td><code>valueless_by_exception</code></td>
<td>tests if variant in invalid state</td>
</tr>
</tbody>
</table>

### Modifiers

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>emplace</td>
<td>constructs value in variant in place</td>
</tr>
<tr>
<td>swap</td>
<td>swaps value with another variant</td>
</tr>
</tbody>
</table>
```cpp
#include <variant>
#include <cassert>
#include <iostream>

int main() {
    std::variant<int, double> x;
    std::variant<int, double> y;
    x = 2;
    assert(std::get<int>(x) == std::get<0>(x));
    assert(!x.valueless_by_exception());
    y = 0.5;
    assert(std::get<double>(y) == std::get<1>(y));
    std::cout << std::get<int>(x) << '
';
    std::cout << std::get<double>(y) << '
';
    try {
        std::cout << std::get<double>(x) << '
';
    } catch (const std::bad_variant_access&) {
        std::cout << "bad variant access\n";
    }
}
```
The `std::any` Class

- type-safe container for single value of any type
- container may also hold no value
- declaration:
  ```cpp
  class any;
  ```
- at any given time, object may or may not hold value
- non-member function `any_cast` provides type-safe access to contained object
- `std::bad_any_cast` exception thrown by value-returning forms of `any_cast` upon type mismatch
Member Functions

### Construction, Destruction, and Assignment

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>constructs any object</td>
</tr>
<tr>
<td>destructor</td>
<td>destroys any object</td>
</tr>
<tr>
<td><code>operator=</code></td>
<td>assigns any object</td>
</tr>
</tbody>
</table>

### Observers

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>has_value</td>
<td>tests if object holds value</td>
</tr>
<tr>
<td>type</td>
<td>returns typeid of contained value</td>
</tr>
</tbody>
</table>

### Modifiers

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>emplace</td>
<td>change contained object by constructing new value in place</td>
</tr>
<tr>
<td>reset</td>
<td>clear any contained object</td>
</tr>
<tr>
<td>swap</td>
<td>swaps contents of two any objects</td>
</tr>
</tbody>
</table>
```cpp
#include <any>
#include <cassert>
#include <string>
#include <iostream>

int main() {
    std::any x{std::string("Hello")};
    assert(x.has_value() && x.type() == typeid(std::string));
    std::any y;
    assert(!y.has_value());
    x.swap(y);
    assert(!x.has_value() && y.has_value());
    x = y;
    std::cout << std::any_cast<std::string>(x) << '\n';
    y.reset();
    assert(!y.has_value());
    try {std::any_cast<int>(x);} catch (const std::bad_any_cast&) {
        std::cout << "any_cast failed\n";
    }
}
```
Section 2.12.6

Time Measurement
- time measurement capabilities provided by part of general utilities library (of standard library)
- header `chrono`
- identifiers in namespace `std::chrono`
- **time point**: specific point in time (measured relative to epoch)
- **duration**: time interval
- **clock**: measures time in terms of time points
- several clocks provided for measuring time
- what follows only intended to provide overview of chrono part of library
- for additional information on chrono part of library, see:
# std::chrono Types

## Time Points and Intervals

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>duration</td>
<td>time interval</td>
</tr>
<tr>
<td>time_point</td>
<td>point in time</td>
</tr>
</tbody>
</table>

## Clocks

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>system_clock</td>
<td>system clock (which may be adjusted)</td>
</tr>
<tr>
<td>steady_clock</td>
<td>monotonic clock that ticks at constant rate</td>
</tr>
<tr>
<td>high_resolution_clock</td>
<td>clock with shortest tick period available</td>
</tr>
</tbody>
</table>
```cpp
#include <iostream>
#include <chrono>
#include <cmath>

double get_result() {
    double sum = 0.0;
    for (long i = 0L; i < 1000000L; ++i) {
        sum += std::sin(i) * std::cos(i);
    }
    return sum;
}

int main() {
    // Get the start time.
    auto start_time = std::chrono::high_resolution_clock::now();
    // Do some computation.
    double result = get_result();
    // Get the end time.
    auto end_time = std::chrono::high_resolution_clock::now();
    // Compute elapsed time in seconds.
    double elapsed_time = std::chrono::duration<double>(end_time - start_time).count();
    // Print result and elapsed time.
    std::cout << "result " << result << " time (in seconds) " << elapsed_time << std::endl;
}
```
Example: Determining Clock Resolution

```cpp
#include <iostream>
#include <chrono>

// Get the granularity of a clock in seconds.

template <class C>
double granularity() {
    return std::chrono::duration<double>(
        typename C::duration(1)).count();
}

int main() {
    std::cout << "system clock:
" << "period "
    << granularity<std::chrono::system_clock>() << '\n'
    << "steady "
    << std::chrono::system_clock::is_steady << '\n';
    std::cout << "high resolution clock:
" << "period "
    << granularity<std::chrono::high_resolution_clock>()
    << '\n' << "steady "
    << std::chrono::high_resolution_clock::is_steady << '\n';
    std::cout << "steady clock:
" << "period "
    << granularity<std::chrono::steady_clock>() << '\n'
    << "steady "
    << std::chrono::steady_clock::is_steady << '\n';
}
```
Section 2.12.7

Miscellany
std::basic_string_view class template represents constant contiguous sequence of char-like objects (i.e., read-only view of string)

basic_string_view declared as:

```cpp
template <class CharT,
    class Traits = char_traits<CharT>>
class basic_string_view;
```

- CharT: type of characters in string
- Traits: class that describes certain properties of CharT (normally, use default)

string_view is simply abbreviation for basic_string_view<char>

for more details on basic_string_view, see:
- [http://en.cppreference.com/w/cpp/string/basic_string_view](http://en.cppreference.com/w/cpp/string/basic_string_view)
```cpp
#include <string_view>
#include <string>
#include <iostream>
#include <cassert>

void output(std::string_view s) {
    std::cout << s << '
';
}

int main() {
    std::string_view hello("hello");
    assert(!hello.empty());
    std::string_view he = hello.substr(0, 2);
    assert(he.size() == 2);
    assert(he[0] == 'h' && he[1] == 'e');
    assert(hello.find("ell") == 1);
    assert(hello.rfind("l") == 3);

    std::string goodbye("goodbye");
    std::string_view bye(goodbye);
    bye.remove_prefix(4);
    std::cout << bye << '
';
    std::string_view good(goodbye);
    good.remove_suffix(3);
    std::cout << good << '
';
    assert(goodbye.substr(4, 3) == bye);
    output(bye);
}
```
## Mathematical Constants (in Namespace `std::numbers`)

<table>
<thead>
<tr>
<th>Variable</th>
<th>For Template</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>e_v</code></td>
<td><code>e</code></td>
<td>Euler’s number (i.e., ( e ))</td>
</tr>
<tr>
<td><code>log2e_v</code></td>
<td><code>log2e</code></td>
<td>( \log_2 e )</td>
</tr>
<tr>
<td><code>log10e_v</code></td>
<td><code>log10e</code></td>
<td>( \log_{10} e )</td>
</tr>
<tr>
<td><code>pi_v</code></td>
<td><code>pi</code></td>
<td>( \pi )</td>
</tr>
<tr>
<td><code>inv_pi_v</code></td>
<td><code>inv_pi</code></td>
<td>( \frac{1}{\pi} )</td>
</tr>
<tr>
<td><code>inv_sqrt2pi_v</code></td>
<td><code>inv_sqrt2pi</code></td>
<td>( \frac{1}{\sqrt{\pi}} )</td>
</tr>
<tr>
<td><code>ln2_v</code></td>
<td><code>ln2</code></td>
<td>( \ln 2 )</td>
</tr>
<tr>
<td><code>ln10_v</code></td>
<td><code>ln10</code></td>
<td>( \ln 10 )</td>
</tr>
<tr>
<td><code>sqrt2_v</code></td>
<td><code>sqrt2</code></td>
<td>( \sqrt{2} )</td>
</tr>
<tr>
<td><code>sqrt3_v</code></td>
<td><code>sqrt3</code></td>
<td>( \sqrt{3} )</td>
</tr>
<tr>
<td><code>inv_sqrt3_v</code></td>
<td><code>inv_sqrt3</code></td>
<td>( \frac{1}{\sqrt{3}} )</td>
</tr>
<tr>
<td><code>egamma_v</code></td>
<td><code>gamma</code></td>
<td>Euler-Mascheroni constant</td>
</tr>
<tr>
<td><code>phi_v</code></td>
<td><code>phi</code></td>
<td>golden ratio (i.e., ( \frac{1+\sqrt{5}}{2} ))</td>
</tr>
</tbody>
</table>
Section 2.12.8

References
Section 2.13

C++ Standard Library — Ranges
ranges library is component of C++ standard library

■ can be thought of as next generation of STL part of standard library

■ identifiers in `std::ranges` namespace

■ algorithms from old STL part of standard library do not compose well (due to performing operations eagerly)

■ ranges library offers better composability of algorithms

■ supports infinite ranges and ranges whose end is marked by sentinel

■ main components of range library:
  - ranges
  - views
  - range factories
  - range adapters
  - range algorithms
Motivating Example

- consider function with declaration:
  ```cpp
  void print(std::ostream& out, const vector<int> v);
  ```
- print function should print square of each even integer in v
- three key operations involved:
  1. dropping some values (i.e., dropping odd integers)
  2. transforming values (i.e., squaring integers)
  3. outputting values (i.e., printing integers to stream)
- solving problem using standard library algorithms without ranges is cumbersome
- as we shall see, non-range-based algorithms do not compose well
Motivating Example: Legacy Approach

```cpp
#include <algorithm>
#include <iostream>
#include <iterator>
#include <ranges>
#include <vector>

void print(std::ostream& out, const std::vector<int>& v) {  
    auto is_even = [](int i) { return (i % 2) == 0;};  
    auto square = [](int i) { return i * i;};  
    std::vector<int> tmp;  
    std::copy_if(v.begin(), v.end(), std::back_inserter(tmp), is_even);  
    std::transform(tmp.begin(), tmp.end(), tmp.begin(), square);  
    std::copy(tmp.begin(), tmp.end(), std::ostream_iterator<int>(out, "\n");
}

int main() {
    std::vector<int> v{-4, -3, -2, -1, 0, 1, 2, 3, 4};
    print(std::cout, v);
}
```

- eager evaluation of results makes composition of algorithms difficult (i.e., each of copy_if and transform process entire range before returning)
- temporary vector object needed; each algorithm makes pass over entire range
Motivating Example: Approach With Ranges

```cpp
#include <algorithm>
#include <iostream>
#include <iterator>
#include <ranges>
#include <vector>

void print(std::ostream& out, const std::vector<int>& v) {
    auto is_even = [](int i) { return (i % 2) == 0;};
    auto square = [](int i) { return i * i;};
    auto view = v | std::views::filter(is_even) |
        std::views::transform(square);
    std::ranges::copy(view, std::ostream_iterator<int>(out, "\n");
}

int main() {
    std::vector<int> v{-4, -3, -2, -1, 0, 1, 2, 3, 4};
    print(std::cout, v);
}
```

- creating `view` does not perform any iteration (only creates object that can later be used to perform iteration)
- all iteration takes place when `copy` invoked
- `filter` and `transform` perform processing (lazily) as range traversed
- **range** is object for which `ranges::begin` and `ranges::end` can be used
- `begin` returns iterator that refers to first element in range
- `end` returns sentinel that corresponds to after-last-element position in range and is equality comparable with iterator
- ranges do not replace iterators, but instead build on them
- essentially, range is generalization of pair of iterators (i.e., begin and end) where end iterator can be sentinel
- can dereference iterator
- can increment iterator until equals end value
- range can represent finite or infinite sequence of elements
- for example, any class that provides `begin` and `end` member functions (returning iterator and sentinel) constitutes range
- containers in standard library, such as `std::array` and `std::vector`, are examples of ranges
<table>
<thead>
<tr>
<th>Concept</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>range</td>
<td>begin returns iterator type and end returns sentinel type</td>
</tr>
<tr>
<td>input_range</td>
<td>iterator type satisfies input_iterator concept (e.g., boost::range::istream_range)</td>
</tr>
<tr>
<td>output_range</td>
<td>iterator type satisfies output_iterator concept</td>
</tr>
<tr>
<td>forward_range</td>
<td>iterator type satisfies forward_iterator concept (e.g., forward_list, unordered_set, unordered_map, unordered_multiset, and unordered_multimap)</td>
</tr>
<tr>
<td>bidirectional_range</td>
<td>iterator type satisfies bidirectional_iterator concept (e.g., list, set, map, multiset, and multimap)</td>
</tr>
<tr>
<td>random_access_range</td>
<td>iterator type satisfies random_access_iterator concept (e.g., deque)</td>
</tr>
<tr>
<td>contiguous_range</td>
<td>iterator type satisfies contiguous_iterator concept and data yields pointer to first element (e.g., built-in array type, array, vector, and string)</td>
</tr>
</tbody>
</table>
### Range Concepts (2)

<table>
<thead>
<tr>
<th>Concept</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>common_range</td>
<td>sentinel type same as iterator type (e.g., all standard library containers at time of C++20)</td>
</tr>
<tr>
<td>sized_range</td>
<td>range that provides amortized constant time size operation</td>
</tr>
<tr>
<td>view</td>
<td>type is range that is view (i.e., has constant-time copy/-move/assignment operations)</td>
</tr>
<tr>
<td>viewable_range</td>
<td>range that can be safely converted into view</td>
</tr>
<tr>
<td>borrowed_range</td>
<td>type is range whose iterators outlive range</td>
</tr>
</tbody>
</table>
Range Iterator-Category Hierarchy

- input_range
- output_range
- forward_range
- bidirectional_range
- random_access_range
- contiguous_range
**Views**

- **view** is lightweight range with following properties:
  - default constructible
  - has constant-time destruction operation
  - has constant-time move construction and assignment operations
  - if copyable, has constant-time copy construction and assignment operations

- motivation: view can be cheaply passed by value

- views do not usually own their elements (as this would typically preclude some of above constant-time complexity requirements)

- views can accommodate infinite ranges

- to signal that type is view: either use `view_enable` trait or inherit from `ranges::view_base`

- can convert borrowed range to view via `ranges::views::all`

- together views and borrowed ranges called **viewable ranges**

- range adapters only operate on viewable ranges
Views (in Namespace `std::ranges`)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>views::all</code></td>
<td>view that includes all elements of range</td>
</tr>
<tr>
<td><code>ref_view</code></td>
<td>view of elements of some other range</td>
</tr>
<tr>
<td><code>filter_view</code></td>
<td>view consisting of elements of range satisfying predicate</td>
</tr>
<tr>
<td><code>transform_view</code></td>
<td>view that applies transformation function to each element of range</td>
</tr>
<tr>
<td><code>take_view</code></td>
<td>view consisting of first $n$ elements of another view</td>
</tr>
<tr>
<td><code>take_while_view</code></td>
<td>view that takes elements from beginning of another view until first element encountered that does not satisfy predicate</td>
</tr>
<tr>
<td><code>drop_view</code></td>
<td>view consisting of elements of another view, skipping first $n$ elements</td>
</tr>
<tr>
<td><code>drop_while_view</code></td>
<td>view consisting of elements of another view, skipping initial subsequence whose elements each satisfy predicate</td>
</tr>
<tr>
<td><code>join_view</code></td>
<td>view consisting of sequence obtain by flattening view of ranges</td>
</tr>
<tr>
<td><code>split_view</code></td>
<td>view over subranges obtained from splitting another view using delimiter</td>
</tr>
</tbody>
</table>
## Views (in Namespace `std::ranges`)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>common_view</td>
<td>convert view into <code>common_range</code></td>
</tr>
<tr>
<td>reverse_view</td>
<td>view that iterates over elements of another bidirectional view in reverse order</td>
</tr>
<tr>
<td>elements_view</td>
<td>view consisting of ( n )th element taken from each element in range of tuple-like values</td>
</tr>
<tr>
<td>keys_view</td>
<td>view consisting of first element taken from each element in range of pair-like values</td>
</tr>
<tr>
<td>values_view</td>
<td>view consisting of second element taken from each element in range of pair-like values</td>
</tr>
</tbody>
</table>
```cpp
#include <cassert>
#include <ranges>
#include <string>
#include <vector>

int main() {
    const std::vector<std::string> v{
        "This", " ", "is", " ", "a", " ", "very", " ", "very", " ", "very", " ", "very", " ", "very", " ", "very", " ", "long", " ", "sentence", "."\n    };
    std::string a;
    for (auto&& i : v) {a += i;}  // "This is a very very very very long sentence."
    assert(a == "This is a very very very very long sentence.");
    const auto first_very = std::find(v.begin(), v.end(), "very");
    const auto sentence = std::find(v.begin(), v.end(), "sentence");
    std::string s;
    for (auto&& i : std::ranges::subrange(v.begin(), first_very))
        {s += i;}
    assert(s == "This is a ");
    for (auto&& i : std::ranges::subrange(sentence, v.end()))
        {s += i;}
    assert(s == "This is a sentence.");
}
```
#include <type_traits>
#include <cstdint>
#include <ranges>

template<class T> requires std::is_object_v<T>
class empty_view : public std::ranges::view_interface<empty_view<T>> {
public:
    static constexpr T* begin() noexcept {return nullptr;}
    static constexpr T* end() noexcept {return nullptr;}
    static constexpr T* data() noexcept {return nullptr;}
    static constexpr std::size_t size() noexcept {return 0;}
    static constexpr bool empty() noexcept {return true;}
};
Range Factories

- range factory (perhaps, more accurately called “view factory”) is utility used to create view
- standard library provides several range factories (listed on next slide)
Range Factories

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>empty_view</td>
<td>view that contains no elements (i.e., empty range)</td>
</tr>
<tr>
<td>single_view</td>
<td>view that contains single elements of specified value</td>
</tr>
<tr>
<td>iota_view</td>
<td>view consisting of sequence generated by repeatedly incrementing initial value</td>
</tr>
<tr>
<td>basic_istream_view</td>
<td>view consisting of elements obtained by successive application of stream extraction operator on associated basic_istream stream</td>
</tr>
<tr>
<td>istream_view</td>
<td>view consisting of elements obtained by successive application of stream extraction operator on associated istream stream</td>
</tr>
</tbody>
</table>
```cpp
#include <algorithm>
#include <cassert>
#include <ranges>
#include <sstream>
#include <vector>

int main() {
  std::ranges::empty_view<int> ev;
  assert(ev.begin() == ev.end());
  std::ranges::single_view<int> sv{42};
  assert(sv.size() == 1 && sv[0] == 42);
  auto iv = std::ranges::iota_view(1, 4);
  assert((std::ranges::equal(iv, std::vector{1, 2, 3})));  
  std::istringstream is("1 2 3 4 5");
  std::vector<int> vi;
  for (auto i : std::ranges::istream_view<int>(is))
    {vi.push_back(i);}  
  assert((vi == std::vector{1, 2, 3, 4, 5}));
```

- Range adapters transform range into view with custom behaviors
- Range adapters are easily composable
- Range adapters generate views from ranges
- With range adapters, can create pipelines of transformations that are lazily evaluated
- Pipe syntax (i.e., using `operator|`) allows easy composition
- Range adapters declared in `std::ranges::views`
- `std::views` is abbreviation for `std::ranges::views`
<table>
<thead>
<tr>
<th>Adapter*</th>
<th>Corresponding View†</th>
</tr>
</thead>
<tbody>
<tr>
<td>all</td>
<td>all</td>
</tr>
<tr>
<td>ref</td>
<td>ref_view</td>
</tr>
<tr>
<td>filter</td>
<td>filter_view</td>
</tr>
<tr>
<td>transform</td>
<td>transform_view</td>
</tr>
<tr>
<td>take</td>
<td>take_view</td>
</tr>
<tr>
<td>take_while</td>
<td>take_while_view</td>
</tr>
<tr>
<td>drop</td>
<td>drop_view</td>
</tr>
<tr>
<td>drop_while</td>
<td>drop_while_view</td>
</tr>
<tr>
<td>join</td>
<td>join_view</td>
</tr>
<tr>
<td>split</td>
<td>split_view</td>
</tr>
<tr>
<td>common</td>
<td>common_view</td>
</tr>
<tr>
<td>reverse</td>
<td>reverse_view</td>
</tr>
<tr>
<td>elements</td>
<td>elements_view</td>
</tr>
<tr>
<td>keys</td>
<td>keys_view</td>
</tr>
<tr>
<td>values</td>
<td>values_view</td>
</tr>
</tbody>
</table>

*in namespace `std::ranges::views` †in namespace `std::ranges`
#include <cassert>
#include <cmath>
#include <ranges>
#include <vector>

int main() {
    auto is_odd = [](int n) { return (n % 2) != 0; };
    auto is_perfect_square = [](int n) {
        int s = std::sqrt(n);
        return s * s == n;
    };
    std::vector<int> x{7, 8, 9, 16, 25, 36, 81};
    auto v = x |
        std::ranges::views::filter(is_odd) |
        std::ranges::views::filter(is_perfect_square) |
        std::ranges::views::take(2) | std::views::common;
    // take first two odd perfect squares from x
    std::vector<int> result(v.begin(), v.end());
    assert((result == std::vector<int>{9, 25}));
}
```cpp
#include <cassert>
#include <cctype>
#include <iostream>
#include <ranges>
#include <string>

std::string trim_string(const std::string& s) {
    auto is_space = [](char c) -> bool
        { return std::isspace(static_cast<unsigned char>(c));};
    auto trim_front = std::ranges::views::drop_while(is_space);
    auto trim_back = std::ranges::views::reverse |
        std::ranges::views::drop_while(is_space) |
        std::ranges::views::reverse;
    auto trim = trim_front | trim_back;
    auto v = s | trim | std::views::common;
    return std::string(v.begin(), v.end());
}

int main() {
    assert(trim_string("  hi  ") == "hi");
    assert(trim_string("  bye  ") == "bye");
}
```
```cpp
#include <cctype>
#include <cassert>
#include <iostream>
#include <ranges>
#include <string>
#include <vector>

int main() {
    std::vector<std::string> x{
        "Hello", ",", " ", "World", "!", "\n"
    };
    auto to_upper = [](char c) -> char {
        return std::toupper(static_cast<unsigned char>(c));
    };
    auto v = x | std::views::join | std::views::transform(to_upper) | std::views::common;
    std::string s(v.begin(), v.end());
    assert(s == "HELLO, WORLD!\n");
    std::cout << s;
    return !std::cout.flush();
}
```
#include <cassert>
#include <map>
#include <ranges>
#include <string>
#include <vector>

int main() {
    using namespace std::literals;

    std::map<int, std::string> m{{1, "one"}, {2, "two"}, {3, "three"}};
    std::vector<int> vi;
    for (auto i : std::ranges::views::elements<0>(m))
        {vi.push_back(i);}
    assert((vi == std::vector{1, 2, 3}));
    std::vector<std::string> vs;
    for (auto s : std::ranges::views::elements<1>(m))
        {vs.push_back(s);}
    assert((vs == std::vector{"one", "two", "three"}));
    vi.clear();
    for (auto i : std::ranges::views::keys(m))
        {vi.push_back(i);}
    assert((vi == std::vector{1, 2, 3}));
    vs.clear();
    for (auto i : std::ranges::views::values(m))
        {vs.push_back(i);}
    assert((vs == std::vector{"one", "two", "three"}));
}

Range Adapter Example

---

Copyright © 2015–2021 Michael D. Adams

Programming in C++

Version 2021-04-01

888
```cpp
#include <ranges>
#include <numeric>

constexpr int sum_of_squares(int n) {
    auto square = [](int n) { return n * n; };
    auto v = std::ranges::iota_view(1, n + 1) |
             std::views::transform(square) |
             std::views::common;
    return std::accumulate(v.begin(), v.end(), 0);
}

static_assert(sum_of_squares(2) == 5);
static_assert(sum_of_squares(3) == 14);
```
```cpp
#include <cassert>
#include <ranges>
#include <vector>

int main() {
    std::vector<int> v{1, 2, 0, 3, 4, 5, 0, 6};
    std::vector<std::vector<int>> result;
    for (auto&& i : std::views::split(v, 0)) {
        auto cv = std::ranges::common_view(i);
        result.emplace_back(cv.begin(), cv.end());
    }
    std::vector<std::vector<int>> desired = {
        {{1, 2}}, {{3, 4, 5}}, {{6}}
    };
    assert(result == desired);
}
```
#include <cassert>
#include <ranges>
#include <string>
#include <vector>

int main() {
    auto garble = [](char c) {
        if (c == 'e' || c == 'E') { return '3'; }
        else if (c == 'o' || c == 'O') { return '0'; }
        else if (c == 'l' || c == 'L') { return '1'; }
        else { return c; }
    };
    std::string text("one two three eleven");
    auto v = text | std::views::transform(garble) |
             std::views::split(' ');
    std::vector<std::string> words;
    for (auto&& i : v) {
        auto cv = std::ranges::common_view(i);
        words.emplace_back(cv.begin(), cv.end());
    }
    std::vector<std::string> desired = {
        "0n3", "tw0", "thr33", "313v3n"
    };
    assert(words == desired);
}
- range algorithms like STL algorithms
- execute immediately
- added projection arguments
- return values improved
- not always drop-in replacement
- range versions of algorithms from algorithm header provided
- range versions of algorithms from numeric header not yet available (maybe C++23)
```cpp
#include <algorithm>
#include <cassert>
#include <ranges>

int main() {
    std::vector v{3, 1, 4, 2};
    std::ranges::sort(v);
    assert((v == std::vector{1, 2, 3, 4}));
    std::ranges::sort(v, std::greater{});
    assert((v == std::vector{4, 3, 2, 1}));
}
```
```cpp
#include <concepts>
#include <functional>
#include <iterator>
#include <ranges>

template<std::input_iterator I, std::sentinel_for<I> S,
    class Init = std::iter_value_t<I>, class Op = std::plus<>,
    class Proj = std::identity>
Init accumulate(I first, S last, Init init = Init{}, Op op = {},
    Proj proj = {}) {
    while (first != last) {
        init = std::invoke(op, std::move(init),
            std::invoke(proj, *first));
        ++first;
    }
    return init;
}

template<std::ranges::input_range R, class Init =
    std::ranges::range_value_t<R>, class Op = std::plus<>,
    class Proj = std::identity>
Init accumulate(R&& r, Init init = Init{}, Op op = {},
    Proj proj = {}) {
    return accumulate(std::ranges::begin(r),
        std::ranges::end(r), std::move(init), std::move(op),
        std::move(proj));
}
```
Projections

- projection is unary callable that can be passed to most algorithms
- projection modifies view of data that algorithm sees
#include <algorithm>
#include <iostream>
#include <ranges>
#include <vector>

struct Point {
    int x;
    int y;
};

std::ostream& operator<<(std::ostream& out, const Point& p) {
    return out << '(' << p.x << ',' << p.y << ')';
}

int main() {
    std::vector<Point> p{{-1, 8}, {3, 7}, {-2, 6}, {0, 0}};
    std::ranges::sort(p, {}, &Point::x);
    for (auto&& i : p) {std::cout << i << '
';}
    std::cout << '
';
    std::ranges::sort(p, {}, &Point::y);
    for (auto&& i : p) {std::cout << i << '
';}
}


References


Section 2.14

Text Formatting
ideally, would like text formatting utility to have following properties:

- type safe
- extensible (i.e., supports user defined types)
- localizable (e.g., can accommodate region-specific formatting and easy to translate formatted text into different languages)
- yields highly readable source code
- efficient
Motivating Example 1: `sprintf` Family of Functions

```cpp
#include <cassert>
#include <cstdarg>
#include <cstdio>
#include <iostream>
#include <memory>
#include <string>

std::string format(const char* fmt, ...) {
    std::va_list ap;
    va_start(ap, fmt);
    int size = std::vsnprintf(nullptr, 0, fmt, ap);
    va_end(ap);
    if (size < 0) { return {};}++size;
    auto p = std::make_unique<char[]>(size);
    va_start(ap, fmt);
    size = std::vsnprintf(p.get(), size, fmt, ap);
    va_end(ap);
    return std::string(p.get(), size);
}

int main() {
    std::string s = format("%04x", 255);
    assert(s == "00ff"); // OK
    s = format("%08d", 3.1415);
    // BAD: code clearly wrong but no error at compile or run time
    std::cout << s << '\n';
}
```

quite readable but not type safe and not extensible
Motivating Example 2: I/O Streams

```cpp
#include <cassert>
#include <iomanip>
#include <iostream>
#include <sstream>
#include <string>

template <class... Args>
std::string format(const Args&... args) {
    std::stringstream ss;
    (ss << ... << args);
    return ss.str();
}

struct widget {};
std::ostream& operator<<(std::ostream& out, const widget& w) {
    return out << "hello";
}

int main() {
    std::string s = format(std::setw(4), std::setfill('0'),
                           std::hex, 255);
    assert(s == "00ff"); // OK
    widget w;
    s = format(std::setw(8), std::setfill('*'), w);
    assert(s == "***hello"); // OK
}
```

type safe and extensible but not efficient; only moderately readable
very powerful text formatting capabilities provided by `std::format` function and several other functions in same family

functions in `std::format` family have numerous benefits:
  - type safe
  - extensible
  - yield highly readable source code
  - can easily accommodate localization/translation
  - efficient

when invoking formatting function, specify:
  1. format string; and
  2. zero or more items to be formatted (or values used by formatting)

format string controls what formatting is performed in order to produce formatted result

example:

```cpp
std::string s1 = std::format("The answer is {:b}.", 42);
std::string s2 = std::format("Hello, World!");
// valid, but not useful
```
<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>format</code></td>
<td>returns formatted representation of items as string</td>
</tr>
<tr>
<td><code>format_to</code></td>
<td>writes formatted representation of items through output iterator</td>
</tr>
<tr>
<td><code>format_to_n</code></td>
<td>writes formatted representation of items through output iterator without exceeding specified size</td>
</tr>
<tr>
<td><code>formatted_size</code></td>
<td>returns number of characters in string resulting from formatting items</td>
</tr>
<tr>
<td><code>vformat</code></td>
<td>similar for <code>format</code> but items to be formatted specified as single argument</td>
</tr>
<tr>
<td><code>vformat_to</code></td>
<td>similar for <code>format_to</code> but items to be formatted specified as single argument</td>
</tr>
</tbody>
</table>
Format Strings

- format string is sequence of:
  - replacement fields (i.e., placeholders for formatted text)
  - escape sequences
  - characters other than left and right braces (i.e., “{” and “}”)

- escape sequence is one of:
  - double left brace (i.e., “{{”)
  - double right brace (i.e., “}}”)

- replacement field is started by left brace that is not part of escape sequence and ended by right brace that is not part of escape sequence

- characters not part of replacement field or escape sequence copied unchanged to output

- example:
  - `std::format("{{},{}!", "Hello", "World")` yields string "Hello,World!"
  - `std::format("{ {{{}},{}}}", 1, 2)` yields string "{1,2}"
replacement field excluding enclosing braces consists of (in order):
- optional argument specifier
- optional format specifier prefixed by colon (i.e., “:”)

if argument specifier omitted for all replacement fields, items to be formatted automatically numbered from 0

replacement fields must use all automatic indexing or all manual indexing

example:
- `std::format("{0}, {1}!", "Hello", "World")` yields "Hello, World!
- `std::format("{1}, {0}!", "World", "Hello")` yields "Hello, World!
- `std::format("{0:b} {0:o} {0:d} {0:x}", 10)` yields "1010 12 10 a"
- `std::format("{0}, {}!
", "Hello", "World")` is not valid and will throw exception (which may be changed to compile error in future)
Format Specifiers

- format specifier consists of number of components
- all components are optional although some components require inclusion of others
- some components only allow for certain types of data
- components of format specifier (if present) must appear in following order:
  1. fill character and alignment
  2. sign
  3. alternate form (#)
  4. leading-zero padding (0)
  5. minimum field width
  6. precision or maximum field size
  7. locale-specific formatting (L)
  8. type
## Type Options for Integer Types

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>binary format with alternate form having 0b prefix</td>
</tr>
<tr>
<td>B</td>
<td>same as b option except using uppercase</td>
</tr>
<tr>
<td>c</td>
<td>character</td>
</tr>
<tr>
<td>d</td>
<td>decimal format</td>
</tr>
<tr>
<td>o</td>
<td>octal format with alternate form having 0 prefix for nonzero values</td>
</tr>
<tr>
<td>x</td>
<td>hexadecimal format with lowercase and alternate form having 0x prefix</td>
</tr>
<tr>
<td>X</td>
<td>same as x format except using uppercase</td>
</tr>
<tr>
<td>none</td>
<td>same as d for integer types</td>
</tr>
</tbody>
</table>

### Examples

<table>
<thead>
<tr>
<th>Format String and Items</th>
<th>Formatting Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;{0:d}{0:d}&quot;, 42</td>
<td>&quot;42 42&quot;</td>
</tr>
<tr>
<td>&quot;{0:b}{0:#b}{0:#B}&quot;, 10</td>
<td>&quot;1010 0b1010 0B1010&quot;</td>
</tr>
<tr>
<td>&quot;{0:c}&quot;, int('A')</td>
<td>&quot;A&quot;</td>
</tr>
<tr>
<td>&quot;{0:o}{0:#o}{1:#o}&quot;, 10, 0</td>
<td>&quot;12 012 0&quot;</td>
</tr>
<tr>
<td>&quot;{0:x}{0:#x}{0:#X}&quot;, 42</td>
<td>&quot;2a 0x2a 0X2A&quot;</td>
</tr>
</tbody>
</table>
### Type Options for Character Types

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>none, \texttt{c}</td>
<td>copies character to output</td>
</tr>
<tr>
<td>\texttt{b, B, d, o, x, X}</td>
<td>same as for integer types</td>
</tr>
</tbody>
</table>

#### Examples

<table>
<thead>
<tr>
<th>Format String and Items</th>
<th>Formatting Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;{0}{0:\texttt{c}}', 'a'</td>
<td>&quot;a_a&quot;</td>
</tr>
<tr>
<td>&quot;{0:\texttt{b}}{0:#b}{0:#B}', '\n'</td>
<td>&quot;0101_0b1010_0B1010&quot; (for ASCII)</td>
</tr>
<tr>
<td>&quot;{:d}', '*'</td>
<td>&quot;42&quot; (for ASCII)</td>
</tr>
<tr>
<td>&quot;{0:o}{0:#o}', '\052'</td>
<td>&quot;52_052&quot;</td>
</tr>
<tr>
<td>&quot;{0:x}{0:#x}{0:#X}', '\x2a'</td>
<td>&quot;2a_0x2a_0X2A&quot;</td>
</tr>
</tbody>
</table>
### Type Options for Boolean Type

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>none, s</code></td>
<td>copies textual representation true or false to output</td>
</tr>
<tr>
<td><code>b, B, c, D, o, x, X</code></td>
<td>same as for integer type</td>
</tr>
</tbody>
</table>

### Examples

<table>
<thead>
<tr>
<th>Format String and Items</th>
<th>Formatting Result</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>{}</code>_{}&quot;, false, true</td>
<td>&quot;false_true&quot;</td>
</tr>
<tr>
<td><code>{:s}</code>_`{:s}&quot;&quot;, false, true</td>
<td>&quot;false_true&quot;</td>
</tr>
<tr>
<td><code>{:b}</code>_`{:B}&quot;&quot;, false, true</td>
<td>&quot;0b0_0B1&quot;</td>
</tr>
<tr>
<td><code>{:c}</code>_`{:c}&quot;&quot;, false, true</td>
<td>&quot;\0\1&quot;s</td>
</tr>
<tr>
<td><code>{:d}</code>_`{:d}&quot;&quot;, false, true</td>
<td>&quot;0_1&quot;</td>
</tr>
<tr>
<td><code>{:o}</code>_`{:o}&quot;&quot;, false, true</td>
<td>&quot;0_01&quot;</td>
</tr>
<tr>
<td><code>{:x}</code>_`{:X}&quot;&quot;, false, true</td>
<td>&quot;0x0_0X1&quot;</td>
</tr>
</tbody>
</table>
Type Options for Floating-Point Types

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>hex floating-point format</td>
</tr>
<tr>
<td>A</td>
<td>same as a except uses uppercase letters</td>
</tr>
<tr>
<td>e</td>
<td>scientific format (i.e., exponential notation) with default precision of 6</td>
</tr>
<tr>
<td>E</td>
<td>same as e except uses uppercase letters</td>
</tr>
<tr>
<td>f, F</td>
<td>fixed format (i.e., no exponential notation) with default precision of 6</td>
</tr>
<tr>
<td>g</td>
<td>general format with default precision of 6</td>
</tr>
<tr>
<td>G</td>
<td>same as g except uses uppercase letters</td>
</tr>
<tr>
<td>none</td>
<td>if precision specified, same as g; otherwise, use shorter of fixed and scientific formats</td>
</tr>
</tbody>
</table>

Examples

<table>
<thead>
<tr>
<th>Format String and Items</th>
<th>Formatting Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;{}&quot;, 16.75</td>
<td>&quot;16.75&quot;</td>
</tr>
<tr>
<td>&quot;{0:a}&quot;_{0:A}, 16.75</td>
<td>&quot;0x1.0cp+4 _0X1.0CP+4&quot;</td>
</tr>
<tr>
<td>&quot;{0:e}&quot;_{0:E}, 16.75</td>
<td>&quot;1.675000e+01 _1.675000E+01&quot;</td>
</tr>
<tr>
<td>&quot;{0:f}&quot;_{0:F}, 16.75</td>
<td>&quot;16.750000 _16.750000&quot;</td>
</tr>
<tr>
<td>&quot;{0:g}&quot;_{0:G}, 16.75</td>
<td>&quot;16.75 _16.75&quot;</td>
</tr>
</tbody>
</table>
# Type Options for String Types

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>none, s</td>
<td>copies string to output</td>
</tr>
</tbody>
</table>

## Examples

<table>
<thead>
<tr>
<th>Format String and Items</th>
<th>Formatting Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;{}&quot;, &quot;hello&quot;</td>
<td>&quot;hello&quot;</td>
</tr>
<tr>
<td>&quot;{:s}&quot;&quot;, &quot;hello&quot;</td>
<td>&quot;hello&quot;</td>
</tr>
</tbody>
</table>
## Sign Options

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>use sign for both negative and nonnegative numbers</td>
</tr>
<tr>
<td>−</td>
<td>use sign only for negative numbers</td>
</tr>
<tr>
<td>space</td>
<td>use leading space for nonnegative numbers and minus sign for negative numbers</td>
</tr>
<tr>
<td>none</td>
<td>same as −</td>
</tr>
</tbody>
</table>

### Examples

<table>
<thead>
<tr>
<th>Format String and Items</th>
<th>Formatting Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;{0}</td>
<td>{0:-}</td>
</tr>
<tr>
<td>&quot;{0}</td>
<td>{0:-}</td>
</tr>
<tr>
<td>&quot;{0:}</td>
<td>{0:-}</td>
</tr>
<tr>
<td>&quot;{0:x}</td>
<td>{0:-x}</td>
</tr>
</tbody>
</table>

- sign option only allowed for arithmetic types
### Field Width and Precision Options

#### Examples

<table>
<thead>
<tr>
<th>Format String and Items</th>
<th>Formatting Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;{:4d}&quot; , 42</td>
<td>&quot;__42&quot;</td>
</tr>
<tr>
<td>&quot;{:8}&quot; , &quot;hello&quot;</td>
<td>&quot;hello__&quot;</td>
</tr>
<tr>
<td>&quot;{:}{}&quot; , &quot;hello&quot; , 8</td>
<td>&quot;hello__&quot;</td>
</tr>
<tr>
<td>&quot;{:}.4&quot; , &quot;goodbye&quot;</td>
<td>&quot;good&quot;</td>
</tr>
<tr>
<td>&quot;{:}.{}&quot; , &quot;goodbye&quot; , 4</td>
<td>&quot;good&quot;</td>
</tr>
<tr>
<td>&quot;{:}.1f&quot; , 75.125</td>
<td>&quot;75.1&quot;</td>
</tr>
<tr>
<td>&quot;{:}.10f&quot; , 0.00390625</td>
<td>&quot;__0.003906&quot;†</td>
</tr>
<tr>
<td>&quot;{:}.{}.f&quot; , 16.125 , 6 , 1</td>
<td>&quot;__16.1&quot;</td>
</tr>
</tbody>
</table>

† precision defaults to 6

- width option is positive decimal number or nested replacement field specifying minimum field width
- precision option is dot followed by nonnegative integer or nested replacement field specifying precision (for floating-point type) or maximum field size (for string type)
## Fill Character and Alignment Options

### Alignment Options

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>&lt;</code></td>
<td>left justify</td>
</tr>
<tr>
<td><code>&gt;</code></td>
<td>right justify</td>
</tr>
<tr>
<td><code>^</code></td>
<td>center</td>
</tr>
</tbody>
</table>

### Examples

<table>
<thead>
<tr>
<th>Format String and Items</th>
<th>Formatting Result</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>{:&lt;9}</code>, &quot;hello&quot;</td>
<td>&quot;hello_     _ _&quot;</td>
</tr>
<tr>
<td><code>{:&gt;9}</code>, &quot;hello&quot;</td>
<td>&quot;_ _ _ _ _ _hello&quot;</td>
</tr>
<tr>
<td><code>{:^9}</code>, &quot;hello&quot;</td>
<td>&quot;_ _ <em>hello</em> _ _&quot;</td>
</tr>
<tr>
<td><code>{:^8}</code>, &quot;hello&quot;</td>
<td>&quot;_ _ <em>hello</em> _ _&quot;</td>
</tr>
<tr>
<td><code>{:x^6}</code>, 42</td>
<td>&quot;xx42xx&quot;</td>
</tr>
</tbody>
</table>

- default alignment depends on type of item
- alignment option may be immediately preceded by fill character
- fill character used to fill any unused space in field and can be any character other than left or right brace
### Locale-Specific Formatting

**Examples**

<table>
<thead>
<tr>
<th>Locale</th>
<th>Format String and Items</th>
<th>Formatting Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>en_US.utf8</td>
<td>&quot;{:L}&quot;, 1234567</td>
<td>&quot;1,234,567&quot;</td>
</tr>
<tr>
<td>en_DK.utf8</td>
<td>&quot;{:L}&quot;, 1234567</td>
<td>&quot;1.234.567&quot;</td>
</tr>
<tr>
<td>en_US.utf8</td>
<td>&quot;{:L}&quot;, 1.25</td>
<td>&quot;1.25&quot;</td>
</tr>
<tr>
<td>en_DK.utf8</td>
<td>&quot;{:L}&quot;, 1.25</td>
<td>&quot;1,25&quot;</td>
</tr>
</tbody>
</table>

- formatting functions allow locale to be specific as argument
- can optionally enable locale-specific formatting for replacement field
- locale-specific formatting can affect behavior such as:
  - symbol used for radix point (e.g., period or comma)
    - "3.1415" versus "3,1415"
  - symbol (if any) used to separate digit groups
    - "1,234,567" versus "1.234.567"
#include <cassert>
#include <format>
#include <iostream>
#include <locale>

#define approx_equal(x, y) 
{ 
    if (((x) != (y))) {std::cout << (x) << ' ' << (y) << '
';} 
}

int main() {
    std::locale us("en_US.utf8"); // English locale for USA
    std::locale dk("en_DK.utf8"); // English locale for Denmark
    assert(
        std::format(us, "{:L}", 1234567890) == "1,234,567,890" &&
        std::format(dk, "{:L}", 1234567890) == "1.234.567.890"
    );
    approx_equal(std::format(us, "{:3L}" , 1024.125), "1.02e+03");
    approx_equal(std::format(dk, "{:3L}" , 1024.125), "1,02e+03");
}
#include <cassert>
#include <format>

int main() {
    assert(
        std::format("{}", 42) == "42" &&
        std::format("{:+}", 42) == "+42" &&
        std::format("{-}", 42) == "-42" &&
        std::format("{:}", 42) == "42" &&
        std::format("{:4}", 42) == "\n\n\n42" &&
        std::format("{>:4}", 42) == "\n\n\n42" &&
        std::format("{:<4}", 42) == "42\n\n\n" &&
        std::format("{:^4}", 42) == "\n\n\n42\n\n\n" &&
        std::format("{:^}", 42) == "\n\n\n42\n\n\n" &&
        std::format("{:b}", 42) == "101010" &&
        std::format("{:#b}", 42) == "0b101010" &&
        std::format("{:#B}", 42) == "0B101010" &&
        std::format("{:x}", 42) == "2a" &&
        std::format("{:X}", 42) == "2A" &&
        std::format("{:#x}", 42) == "0x2a" &&
        std::format("{:#X}", 42) == "0X2A" &&
        std::format("{:o}", 42) == "52" &&
        std::format("{:#o}", 42) == "052" &&
        std::format("{:^}{{}}", 42, 4) == "\n\n\n42\n\n\n"
    );
}
#include <cassert>
#include <format>

int main() {
    assert(
        std::format("{:^12}", "hello") == "***hello****" &&
        std::format("{}", "hello") == "hello" &&
        std::format("{:4}", "goodbye") == "good" &&
        std::format("{:8.4}", "goodbye") == "good     ");
}
# Formatting Examples for Floating-Point Types

```cpp
#include <cassert>
#include <format>
#include <iostream>
#include <limits>

#define approx_equal(x, y) \
    {if ((x) != (y)) {std::cout << (x) << '|' << (y) << '
';}}

int main() {
    approx_equal(std::format("{}", 1.25), "1.25");
    approx_equal(std::format("{0:a}|{0:A}", 7.75), "0x1.fp+2|0X1.FP+2");
    approx_equal(std::format("{0:e}|{0:E}", 1'048'576.0625),
                 "1.048576e+06|1.048576E+06");
    approx_equal(std::format("{0:f}|{0:F}", 1'048'576.0625),
                 "1048576.062500|1048576.062500")
    approx_equal(std::format("{0:g}|{0:G}", 1'048'576.0625),
                 "1.04858e+06|1.04858E+06");
    approx_equal(std::format("{:e}"), 16.25, "1.625000e+01");
    auto inf = std::numeric_limits<double>::infinity();
    approx_equal(std::format("{0}|{0:+}|{1}", inf, -inf), "inf|+inf|-inf");
    if constexpr (std::numeric_limits<double>::has_quiet_NaN) {
        auto nan = std::numeric_limits<double>::quiet_NaN();
        assert(std::format("{0}|{0:+}|{1}", nan, -nan) == "nan|+nan|-nan");
    }
}
```

Copyright © 2015–2021 Michael D. Adams
Programming in C++
Version 2021-04-01
Example: Formatting to a Buffer

```
#include <cassert>
#include <cstddef>
#include <format>
#include <iterator>
#include <string>
#include <string_view>
#include <vector>

template<std::size_t N, class... Args>
void format_to_array(char (&a)[N], std::string_view format, const Args&... items) {
    char* out = std::format_to_n(a, N - 1, format, items...).out;
    *out = '\0';
}

template<class... Args>
std::vector<char> make_vector(std::string_view format, const Args&... items) {
    std::size_t size = std::formatted_size(format, items...);
    std::vector<char> buffer;
    buffer.reserve(size + 1);
    std::format_to(std::back_inserter(buffer), format, items...);
    buffer.push_back('\0');
    return buffer;
}

int main() {
    char a[6];
    format_to_array(a, "{},\n{},!", "Hello", "World");
    assert(std::string(a) == "Hello");
    std::vector<char> v = make_vector("{},\n{},!", "Hello", "World");
    assert(std::string(v.data()) == "Hello,\nWorld!");
}
```
standard library provides `std::formatter` class template to allow formatting of user-defined types that are not part of standard library

declaration:
```cpp
template<
class T,
class CharT = char>
struct formatter;
```

to provide support for formatting particular type, define specialization of `template std::formatter`

- `T` is type to be formatted
- `CharT` is character type employed (e.g., `char`, `wchar_t`)

template class needs to provide two member functions:
1. `parse`, which parses format specifier
2. `format`, which performs formatting requested in format specifier
```cpp
#include <format>
#include <iostream>

struct Point { int x; int y;};

template<> class std::formatter<Point> { 
public:
    std::format_parse_context::iterator
    parse(std::format_parse_context& pc) {
        auto i = pc.begin();
        for (; i != pc.end() && *i != '}'; ++i) {
            if (*i == '#') {curly_ = true;}
            else {throw std::format_error{"bad_format_specifier"};}
        }
        return i;
    }
    std::format_context::iterator
    format(Point p, std::format_context& fc) {
        return std::format_to(fc.out(), "{}{},{}{}",
            (curly_ ? '{' : '('), p.x, p.y, (curly_ ? '}' : ')'));
    }
private:
    bool curly_ = false;
};
```
#include <cassert>
#include <iostream>
#include <string>
#include "custom_1.hpp"

int main() try {
    Point p{1, -2};
    std::string s = std::format("{}", p);
    assert(s == "(1,-2)" );
    s = std::format("{:#}" , p);
    assert(s == "{1,-2}" );
    s = std::format("{:#x}" , p);
    // ERROR: throws exception due to bad format specifier
} catch (std::format_error& e) {
    std::cerr << e.what() << '\n';
}
# Range Formatter Example: *custom_2.hpp* (1)

```cpp
#include <format>
#include <iterator>
#include <ranges>

// range wrapper class
template< std::ranges::forward_range R >
class my_range : public std::ranges::view_interface< my_range<R> > {
public:
  my_range( R range ) : begin_( std::ranges::begin( range ) ),
    end_( std::ranges::end( range ) ) {}
  auto begin() const { return begin_; }
  auto end() const { return end_; }

private:
  using iterator = std::ranges::iterator_t<R>;
  iterator begin_; 
  iterator end_; 
};

// formatter class
template< class T > class std::formatter< my_range<T> > {
public:
  std::format_parse_context::iterator parse( std::format_parse_context& pc );
  std::format_context::iterator format( const my_range<T>& r, std::format_context& fc );

private:
  std::string efs_; // element format specifier
};
```
template<class T>
std::format_parse_context::iterator
std::formatter<my_range<T>>::parse(std::format_parse_context& pc) {
  auto i = pc.begin();
  for (; i != pc.end() && *i != '}' ; ++i) {}
  efs_ = std::string(pc.begin(), i);
  return i;
}

template<class T>
std::format_context::iterator
std::formatter<my_range<T>>::format(const my_range<T>& r, std::format_context& fc) {
  using namespace std::string_literals;
  std::format_to(fc.out(), "[");
  if (r.begin() != r.end()) {
    auto i = r.begin();
    std::string fs = "{"s + "::"s + efs_ + "}"s;
    std::format_to(fc.out(), fs, *i);
    ++i;
    fs = ","s + fs;
    for (; i != r.end(); ++i) {std::format_to(fc.out(), fs, *i);}
  }
  return std::format_to(fc.out(), "]") ;
}
```cpp
#include <cassert>
#include <iostream>
#include <list>
#include <string>
#include <vector>
#include "custom_2.hpp"

int main() try {
    const int x[] = {0xde, 0xad, 0xbe, 0xef};
    std::string s = std::format("{:x}", my_range(std::views::all(x)));
    assert(s == "[de_ad_be_ef]");
    const std::vector<int> v{0, 1, 2, 3, 4, 42};
    s = std::format("{:b}", my_range(v));
    assert(s == "[0_1_10_11_100_101010]");
    s = std::format("{:x}", my_range(v));
    assert(s == "[0_1_2_3_4_2a]");
    const std::list<double> w{1.75, 42.24, 3.14};
    s = std::format("{:6.1f}", my_range(w));
    assert(s == "[1.8_42.2_3.1]");
    s = std::format("{:Z}", my_range(v));
    // ERROR: throws exception due to invalid type specifier
} catch (std::format_error& e)
{std::cerr << e.what() << '
';}
```

2 Victor Zverovich. A modern formatting library for C++. CppCon, Bellevue, WA, USA, Sept. 25, 2017. Available online at https://youtu.be/ptba_AqFYCM. [This talk describes the library upon which the formatting functionality in the C++ standard library is based.]
Since C++ name lookup rules are quite complicated, we only present a simplified (and therefore not fully correct) description of them here.

**Qualified lookup.** If the name $A$ is preceded by the scope-resolution operator, as in ::$A$ or $X$::$A$, then use qualified name lookup.

- In the first case, look in the global namespace for $A$. In the second case, look up $X$, and then look inside it for $A$.
- If $X$ is a class and $A$ is not a direct member, look in all of the direct bases of $X$ (and then each of their bases). If $A$ is found in more than one base, fail.

**Argument-dependent lookup.** Otherwise, if the name is used as a function call, such as $A(X)$, use argument-dependent lookup.

- Look for $A$ in the namespace in which the type of $X$ was declared, in the friends of $X$, and if $X$ is a template instantiation, similarly for each of the arguments involved.

**Unqualified lookup.** Start with unqualified lookup if argument-dependent lookup does not apply.

- Start at the current scope and work outwards until the name is found.
Argument-Dependent Lookup (ADL)

- argument-dependent lookup (ADL) applies to lookup of unqualified function name
- during ADL, other namespaces not considered during normal lookup may be searched
- in particular, namespace that declares each function argument type is included in search
- ADL also commonly referred to as Koenig lookup
```
#include <iostream>

namespace N {
    class C { /* ... */};
    void f(C x) {std::cout << "N::f\n";}
    void g(int x) {std::cout << "N::g\n";}
    void h(C x) {std::cout << "N::h\n";}
}

struct D {
    struct E { glossy
    static void p(E e) {std::cout << "D::p\n";};
    }

    void h(N::C x) {std::cout << "::h\n";}
}

int main() {
    N::C x;
    f(x);      // OK: calls N::f via ADL
    N::f(x);   // OK: calls N::f
    g(42);     // ERROR: g not found
    N::g(42);  // OK: calls N::g
    h(x);      // ERROR: ambiguous function call due to ADL
    ::h(x);    // OK: calls ::h
    N::h(x);   // OK: calls N::h
    D::E e;
    p(e);      // ERROR: ADL only considers namespaces
    D::p(e);   // OK: calls D::p
}
```
```cpp
#include <iostream>

namespace N {
    struct W {};  
    void f(W x) {std::cout << "N::f\n";}
}

struct C {
    void f(N::W x) {std::cout << "C::f\n";}
    void g() {
        N::W x;
        f(x); // calls C::f (not N::f)
    }
};

int main() {
    C c;
    c.g();
}
```
```cpp
#include <iostream>
#include <string>

using namespace std::string_literals;

namespace N {
    struct C {};
    void f(int) {std::cout << "N::f\n";}
    void g(C x) {std::cout << "N::g\n";}
    void h(const std::string& x) {std::cout << "N::h\n";}
    namespace M {
        void f(int x) {std::cout << "N::M::f\n";}
        // hides N::f
        void g(int x) {std::cout << "N::M::g\n";}
        // hides N::g
        void h() {std::cout << "N::M::h\n";} // hides N::h
        void u() {
            N::C c;
            f(42); // calls N::M::f (ADL looks nowhere)
            g(c); // calls N::g via ADL (ADL looks in N)
            h("hi"s); // ERROR: lookup finds N::M::h
            // (ADL does not look in N)
        }
    }
}

int main() {N::M::u();}
```
Consider two objects \( x \) and \( y \) of class type \( T \) whose values are to be swapped.

If the class \( T \) provides its own `swap` function for reasons of efficiency, one would normally want to use it.

In the absence of such a function, one would normally want to fall back on the use of `std::swap`.

The above behavior can be achieved using code like the following:

```cpp
using std::swap;
swap(x, y);
```

If the type \( T \) provides its own `swap` function, the name lookup on `swap` will yield this function through ADL.

Otherwise, the name lookup will find `std::swap`.

Thus, code like the above will result in a more efficient `swap` function being used if available, with the `std::swap` function used as a fallback.
Part 3

More C++
Section 3.1

Initialization
Typical Memory Organization for Program

- memory organized into several regions: code segment, initialized data segment, uninitialized data segment, heap, and stack
- **code segment** (also known as text segment) contains machine code of compiled program; may be marked read only
- **initialized data segment** contains variables that are initialized to particular program-specified values upon program loading (i.e., prior to execution)
- **uninitialized data segment** (also known as BSS segment) contains variables that are not initialized to particular program-specified values upon program loading; typically cleared to zero when program loaded
- **heap** is where dynamic memory allocation takes place
- **stack** consists of stack frames used for local variables, function arguments, function return values, and caller return addresses
- stack and heap grow towards each other, with stack usually being at higher address in memory than heap
Typical Memory Organization for Program: Diagram

- High Address
  - Environment and Program Arguments
  - Uninitialized Data Segment
  - Initialized Data Segment
  - Code Segment
  - Stack
  - Heap

- Low Address
  - loaded from program image
  - cleared to zero before program execution

Copyright © 2015–2021 Michael D. Adams
Programming in C++  Version 2021-04-01
**Storage Duration**

- **storage duration**: how long memory for object exists
- four types of storage duration:
  1. automatic
  2. static
  3. dynamic
  4. thread

- **automatic storage duration**: storage allocated at start of enclosing code block and deallocated at end
- all local objects have automatic storage duration, except those declared with `static`, `extern`, or `thread_local` qualifiers
- objects with automatic storage duration stored on stack

- **static storage duration**: storage is allocated at start of program and deallocated when program ends
- all objects declared at namespace scope (including global namespace) have static storage duration as well as those declared with `static` or `extern` qualifiers (e.g., static data members and static function-local variables)
objects with static storage duration stored in initialized and uninitialized data segments

**dynamic storage duration**: storage is allocated and deallocated upon request using dynamic memory allocation functions (e.g., `operator new` and `operator delete`)

objects with dynamic storage duration stored in heap

**thread storage duration**: storage allocated when thread starts and deallocated when thread ends

all objects declared as `thread_local` have thread storage duration

how objects with thread storage duration handled is very platform dependent (e.g., may involve additional segments such as .tbss and .tdata sections in ELF)
Initialization

- initialization provides initial value to object at time of construction
- initialization in C++ somewhat complicated
- initializer: specifies initial value for object and appears in initializer section of declarator or new expression
- initializer may be one of following:
  1. braced initializer list (i.e., possibly-empty comma-separated list of expressions and other braced initializer lists); for example:
     ```cpp
     std::vector<int> v{1, 2, 3};
     // initializer is {1, 2, 3}
     ```
  2. comma-separated list of expressions and braced initializer lists in parentheses; for example:
     ```cpp
     std::vector<int> v(10, 42);
     // initializer is (10, 42)
     ```
  3. equals sign followed by expression; for example:
     ```cpp
     std::string s = "hello";
     // initializer is "=" plus literal "hello"
     ```
Types of Initialization

- constant initialization (used to initialize objects of static storage duration from constant expressions)
  ```
  int x; // where x is local object
  ```

- zero initialization (for initializing to zero)

- default initialization; for when no initializer is provided, such as:
  ```
  int x; // where x is local object
  ```

- value initialization; for when initializer is empty, such as:
  ```
  Widget::Widget() : x() {} // where x is data member
  ```

- direct initialization; for when initializer is explicit set of constructor arguments, such as:
  ```
  int x(1); // where x is local object
  ```

- copy initialization; for when initializing object from another object, such as:
  ```
  int x = 1; // where x is local object
  ```

- list initialization; for when initializer is braced initializer list, such as:
  ```
  int x{1}; // where x is local object
  ```

- aggregate initialization; for initializing aggregate type from braced initializer list (as part of list initialization), such as:
  ```
  int a[] = {1, 2, 3}; // where a is local object
  ```
- constant initialization can use all other types of initialization (i.e., zero, default, value, direct, copy, list, and aggregate)
Initialization performed in two phases:

1. **static initialization**: initialization that is conceptually performed when program loaded (i.e., before program begins execution)
2. **dynamic initialization**: initialization that takes place at run time

**static initialization**: all static initialization happens before any dynamic initialization

**dynamic initialization**: for static initialization, only constant and zero initialization used directly (but constant initialization can result in other types of initialization being invoked indirectly)

For dynamic initialization, all types of initialization other than constant initialization can be used
#include <complex>
#include <string>
#include <array>

using Complex = std::complex<float>;

Complex gz{0, 1}; // gz is constant initialized (statically)
int gi; // gi is zero initialized (statically)
char buf[1024]; // buf is zero initialized (statically)

int main() {
    int i; // i is default initialized (to indeterminate value)
    Complex z1; // z1 is default initialized
    Complex z2(); // function declaration
    Complex z3{}; /* z3 is value initialized as part of
                   direct-list initialization */
    Complex z4{1, -1}; /* z4 is direct initialized as part of
                       direct-list initialization */
    Complex z5(1, -1); // z5 is direct initialized
    Complex z6 = {1, -1}; /* z6 is copy initialized as part of
                         copy-list initialization */
    Complex z7 = Complex(1, -1); // z7 is copy initialized
    static Complex u = Complex(); // u is constant initialized (statically)
    z1 = {1, -1}; /* temporary object is direct initialized as part of
                    direct-list initialization */
    z1 = {}; /* temporary object is value initialized as part of
              direct-list initialization */
    std::array<int, 3> a{1, 2, 3}; /* a is aggregate initialized as part
                                      of direct-list initialization */
    std::string s1{'h', 'i'}; // s1 is direct-list initialized
}
must be careful about dynamic initialization order of namespace-scope objects with static storage duration (e.g., global variables)

language makes no guarantees about order of initialization of such objects across translation units

that is, if \( x \) and \( y \) are namespace-scope objects with static storage duration defined in different translation units, order in which \( x \) and \( y \) initialized is arbitrary

in practice, initialization order will typically be determined by order in which linker processes corresponding object files

language only guarantees order of initialization within translation unit, namely, initialization takes place in order of appearance of definitions

that is, if \( x \) and \( y \) are namespace-scope objects with static storage duration defined in same translation unit, \( x \) and \( y \) initialized in order of appearance of their definitions

initialization of namespace-scope object with static storage duration behaves as if performed prior to main function being called
dynamic initialization of block-scope (i.e., local) object with static storage duration performed (in thread-safe manner) first time control passes through declaration of object \[^{[C++17 \S9.7/4]}\]
# Example: Initialization Order Fiasco

## util_1.cpp
```cpp
#include <vector>

std::vector<int> v{1, 2, 3, 4};

// invoked constructor is not constexpr; cannot use constant initialization;
// constructor invoked as part of dynamic initialization
```

## util_2.cpp
```cpp
#include <vector>

extern std::vector<int> v;

std::vector<int> w{v[0], v[1]};

// arguments for invoked constructor not constant
// expressions; cannot use constant initialization;
// constructor invoked as part of dynamic initialization;
// construction of w can invoke undefined behavior
// since v might not yet have been constructed
```

## main.cpp
```cpp
int main() {
    // ...
}
```
constant initialization is type of initialization that relates to (possibly non-const) object with static or thread storage duration being initialized with constant expression

approximately speaking, constant initialization is performed: \[\text{[C++17 §6.6.2/2]}\]
  - if object/reference with static or thread storage duration is initialized by constant expression

effect of constant initialization is same as effect of corresponding initialization except must be performed before any dynamic initialization (i.e., as part of static initialization)

this usually means, in practice, constant initialization performed at compile time and computed object stored as part of program image

constant initialization provides means to initialize objects with static and thread storage duration that eliminates some potential problems due to data races and dependencies on initialization order
```cpp
#include <memory>
#include <string>

constinit std::unique_ptr<std::string> p1;
/* std::unique_ptr<std::string> not of literal type, but...
   constructor being invoked is constexpr; p1 is constant
   initialized */

constinit std::unique_ptr<std::string> p2(nullptr);
/* std::unique_ptr<std::string> not of literal type, but...
   constructor being invoked is constexpr and argument to
   constructor is constant expression; p2 is constant
   initialized */

constinit std::unique_ptr<std::string> q1;
/* std::shared_ptr<std::string> not of literal type, but...
   constructor being invoked is constexpr; q1 is constant
   initialized */

constinit std::shared_ptr<std::string> q2(nullptr);
/* std::shared_ptr<std::string> not of literal type, but...
   constructor being invoked is constexpr and argument to
   constructor is constant expression; q2 is constant
   initialized */
```
Constant Initialization Example: Fiasco-Free Initialization

```cpp
#include <complex>

extern std::complex<double> z0;
extern std::complex<double> z1;
```

util_1.cpp

```cpp
#include "constant_initialization_2_util.hpp"
constexpr double x{1};
constexpr double y{2};
constinit std::complex<double> z0{x, y};
// invoked constructor is constexpr; all arguments to
// constructor are constant expressions; as part of static
// initialization, z0 is constant initialized to (1, 2)
```

util_2.cpp

```cpp
#include "constant_initialization_2_util.hpp"
std::complex<double> z1 = z0 - std::complex<double>{0, 2};
// as part of dynamic initialization, z1 is copy
// initialized to (1, 2) - (0, 2) = (1, 0); static
// initialization of z0 guaranteed to have been already
// performed
```

main.cpp

```cpp
int main() { /* ... */}
```
Zero initialization

- **zero initialization**: initial value of object, including any padding, set to zero

- zero initialization is performed:
  1. for every named variable with static or thread storage duration that is not subject to constant initialization (i.e., initialized by constant expression)  
     
     [C++17 §6.6.2/2]
  2. when character array initialized with string literal that is too short to fill entire array, unfilled part of array is zero initialized  
     
     [C++17 §11.6.2/3]
  3. as part of value initialization in certain situations  
     
     [C++17 §11.6/8.2] [C++17 §11.6/8.4]  
     
     (see later slides on value initialization for details)

- every object of static storage duration is either constant or zero initialized at program startup before any other initialization takes place  

  [C++17 §11.6/10]
Zero Initialization (Continued)

- zero initialization of object of type \( T \) has following behavior: \([\text{C++17 §11.6/6}]\)
  - if \( T \) is scalar type, object is initialized to value obtained by converting integer literal \( 0 \) to \( T \)
  - if \( T \) is class type, each of following is zero initialized and any padding initialized to zero bits:
    - each non-static data member
    - each non-virtual base class subobject
    - if object is not base class subobject (i.e., \( T \) is most-derived class), each virtual base class subobject anywhere in inheritance hierarchy
  - if \( T \) is union type, object's first non-static named data member is zero initialized and any padding is initialized to zero bits
  - if \( T \) is array type, each element is zero initialized
  - if \( T \) is reference type, nothing is done

- note that zero initialization not same as setting all bits of storage to zero, since some types may have zero value that is not represented as all zero bits (such as null pointer to member in case of some C++ language implementations)
#include <string>

struct Point { int x; int y;};

static int ga[2]; /* ga is statically zero initialized (to {0, 0}) */
static int gb[2] = {1}; /* gb[1] is statically zero initialized (to 0) as part of constant initializing gb to {1, 0} */
char *gp; /* gp is statically zero initialized (to null pointer) */
std::string gs; /* gs is statically zero initialized (to indeterminate value) and (later) dynamically default initialized to empty string */
int gi; // gi is statically zero initialized (to 0)

int main() {
    char buf[4] = "hi"; /* buf[3] is zero initialized (to 0) as part of initializing buf to {'h', 'i', '\0', 0} */
    static float f; /* f is statically zero initialized (to 0.0f) */
    int i{}; /* i is zero initialized (to 0) as part of list initialization */
    const Point& p = Point(); /* referenced object is zero initialized (to {0, 0}) as part of value initialization */
}
**default initialization**: object constructed with no initializer; for example:
```cpp
int x; // where x is local object
```

**default initialization performed when:**

1. variable with automatic, static, or thread storage duration declared with no initializer
   [C++17 §11.6/12]
2. object created by new expression with no initializer
   [C++17 §8.3.4/18]
3. non-static data member or base class not mentioned in constructor initializer list of invoked constructor
   [C++17 §15.6.2/(9.3)]

**default initialization of object of type $T$ has following behavior:**

- if $T$ is class type, default constructor invoked through overload resolution against empty argument list and called constructor provides initial value for new object
- if $T$ is array type, each element of array is default initialized
- otherwise, nothing is done (which results in indeterminate value in case of object with automatic storage duration)
Default Initialization Example

```cpp
#include <string>

struct Widget {
    Widget() {} /* w is default initialized to indeterminate value */
    int w;
};

static std::string gs; /* gs is (statically) zero initialized and then (dynamically) default initialized to empty string */

int main() {
    std::string s; /* s is default initialized to empty string */
    std::string* sp = new std::string; /* heap-allocated object is default initialized to empty string */
    int i; /* i is default initialized to indeterminate value */
    int* ip = new int; /* heap-allocated object is default initialized to indeterminate value */
    
    return 0;
}
```
- **value initialization**: object constructed with empty initializer; for example:
  ```cpp
  Widget::Widget() : x() {}
  // where x is data member of Widget class
  ```

- **value initialization performed when**:
  1. (unnamed) temporary created with initializer consisting of empty pair of parentheses or braces [C++17 §11.6/11]
  2. object created by new expression with initializer consisting of empty pair of parentheses or braces
  3. non-static data member or base class initialized using member initializer list with empty pair of parentheses or braces [C++17 §11.6/11]
  4. named object declared with initializer consisting of empty pair of braces
value initialization of object of type $T$ has following behavior: \cite{cpp17 §11.6/8}

- if $T$ is class type with no default constructor or with user-provided or deleted default constructor, object is default initialized
- if $T$ is class type with default constructor that is neither user-provided nor deleted (i.e., class where default constructor is implicitly-defined or defaulted), object is zero initialized and then, if $T$ has non-trivial default constructor, default initialized
- if $T$ is array type, each element of array is value initialized
- otherwise, object is zero initialized

- if $T$ is aggregate type and initializer is empty pair of braces, aggregate initialization is performed (as part of list initialization) instead of value initialization
- if $T$ is class type with no default constructor but with constructor taking `std::initializer_list`, list initialization is performed
```cpp
#include <string>

struct Point { int x; int y; };

struct Widget {
    Widget() : x() {} // x is value initialized to 0
    int x; int y{}; // y is value initialized to 0
};

int main() {
    Point p; // p is default initialized to indeterminate value
    Point q{}; /* q is aggregate initialized to {0, 0} as part of list initialization */
    Point* p1 = new Point(); /* heap-allocated object is value initialized to {0, 0} */
    Point* p2 = new Point{}; /* heap-allocated object is aggregate initialized to {0, 0} as part of list initialization */
    std::string s{}; /* s is value initialized to empty string as part of list initialization */
    const Point& pr = Point(); /* referenced object is value initialized to {0, 0} */
    const Point& pr2 = Point{}; /* referenced object is aggregate initialized to {0, 0} as part of list initialization */
    const std::string& sr = std::string{}; /* referenced object is value initialized to empty string as part of list initialization */
    Widget w{}; /* w is value initialized to {0, 0} as part of list initialization */
    int i{}; /* i is value initialized to 0 as part of list initialization */
}
```
Direct Initialization

- **direct initialization**: object initialized from explicit set of constructor arguments; for example:
  
  ```cpp
  int x(1); // where x is local object
  ```

- **direct initialization performed when**: [C++17 §11.6/16]

  1. initializing with nonempty list of expressions in parentheses or braces [C++17 §11.6/16]
  2. initializing object by new expression with nonempty initializer [C++17 §8.3.4/(18.2)]
  3. initializing temporary by `static_cast` expression [C++17 §8.2.9/4]
  4. initializing temporary by functional-notation conversions [C++17 §8.2.3/2]
  5. initializing non-static member or base object with constructor initializer list [C++17 §15.6.2/7]
  6. initializing closure member from object captured by value in lambda expression [C++17 §8.1.5.2/15]
direct initialization of object of type $T$ has following behavior:

- if $T$ is class type:
  - if initializer is prvalue expression whose type is same as $T$ ignoring cv-qualification, initializer expression used to directly initialize object without materializing temporary (i.e., mandatory copy elision takes place)  
  \[\text{[C++17 §11.6/(17.6.1)]}\]
  - constructors of $T$ examined, and best match obtained by overload resolution invoked to initialize object  
  \[\text{[C++17 §11.6/(17.6.2)]} \text{ [C++17 §11.6/(17.7)]}\]

- if $T$ is non-class type but source type is class type, conversion functions of source type and its base classes, if any, examined and best match selected by overload resolution used to convert initializer expression into object being initialized  
  \[\text{[C++17 §11.6/(17.6.3)]}\]

- if $T$ is bool and source type is \texttt{std::nullptr_t}, value of initialized object is \texttt{false}  
  \[\text{[C++17 §7.14/1]}\]

- otherwise (neither $T$ nor source type is class type), standard conversions used, if needed, to convert source value to same type as $T$ and this (possibly converted) value used to set initial value of object  
  \[\text{[C++17 §11.6/(17.8)]}\]
```cpp
#include <string>
#include <vector>

struct Widget {
    Widget() : s("hi") {} // s is direct initialized to "hi"

    explicit Widget(const std::string& s_) : s(s_) {}

    std::string s;

    std::string t{"bye"}; /* t is direct initialized to "bye" via direct-list initialization */

};

int main() {
    int i(1); // i is direct initialized to 1
    int j{1}; /* j is direct initialized to 1 as part of direct-list initialization */
    double d = static_cast<double>(i); /* temporary object is direct initialized to 1.0 */
    std::string* sp = new std::string("hi"); /* heap-allocated object is direct initialized to "hi" */
    [s](){return s.size();}(); /* s data member in closure is direct initialized to value of s in main */
    Widget w = Widget("hi"); /* temporary object is direct initialized to {"hi", "bye"} */
}
```
- **copy initialization**: initialize object from another object; for example:
  ```
  int x = 1; // where x is local object
  ```

- **copy initialization performed in following situations**: [C++17 §11.6/15]
  1. when named variable of non-reference type declared with initializer that consist of equals sign followed by expression (including default member initializer) [C++17 §11.6/15] [C++17 §9.4]
  2. when passing argument to function by value [C++17 §11.3.6/5] [C++17 §11.6/15]
  3. when returning from function that returns by value [C++17 §9.6.3/2]
  4. when throwing exception by value [C++17 §18.1/3]
  5. when catching exception by value [C++17 §18.3/15]
  6. as part of aggregate initialization, to initialize each element for which initializer provided (see later slides on aggregate initialization for details) [C++17 §11.6.1/3]
copy initialization of object of type $T$ has following behavior:

- if $T$ is class type and initializer is prvalue expression whose cv-unqualified type same as $T$, initializer expression itself (rather than temporary materialized therefrom) used to initialize object (i.e., mandatory copy elision takes place)
- if $T$ is class type and cv-unqualified version of source type is $T$ or class derived from $T$, non-explicit constructors of $T$ examined and best match selected by overload resolution used to initialize object
- if $T$ is class type and cv-unqualified version of source type is not $T$ or derived from $T$ or $T$ is non-class type but source type is class type, user-defined conversion sequences that can convert from source type to $T$ (or type derived from $T$) examined and best match selected by overload resolution used to direct initialize object
- otherwise (i.e., if neither $T$ nor source type is class type), standard conversions used, if necessary, to convert source value to cv-unqualified version of $T$
```cpp
#include <string>
using namespace std::literals;

struct Widget {
    std::string s = "hi"; // s is copy initialized to "hi"
};

std::string identity(std::string p) {
    return p; // return value copy initialized from p
}

int main() {
    std::string a[2] = {"hi", "bye"}; /* as part of aggregate initialization:
    a[0] is copy initialized to "hi" and
    a[1] is copy initialized to "bye"
    */
    std::string s = "hello"s; // s is copy initialized to "hello"
    std::string t = {3, 'A'}; /* t is copy initialized to "AAA" as
    part of copy-list initialization
    */
    s = identity(s); // function parameter is copy initialized from s
    try {
        throw t; // exception object copy initialized from t
    } catch (std::string s) {
        // s is copy initialized from exception object
    }
    if (auto i = s.begin(); i != s.end()) {/* ... */}
    // i is copy initialized from s.begin()
}
```
**Aggregates**

- **aggregate** is array or class with: [C++17 §11.6.1/1]
  - no user-provided, explicit, or inherited constructors
  - no private or protected non-static data members
  - no virtual functions
  - no virtual, private, or protected base classes

- elements of aggregate are: [C++17 §11.6.1/2]
  - for array: array elements in increasing subscript order
  - for class: direct base classes in declaration order, followed by direct non-static data members that are not members of anonymous union in declaration order

- example:

  ```cpp
  // aggregate type
  struct Point {
      int x;
      int y;
  };
  ```
**aggregate initialization**: initializes aggregate from braced initializer list (or string literal)

aggregate initialization is used:
- when aggregate is initialized by braced initializer list (or string literal in case of initializing character array, since braces around string literal are implied) [C++17 §11.6.1/3]

approximately speaking, aggregate initialization has following behavior:
- each direct public base, array element, or non-static class member in order of array subscript or appearance in class definition copy initialized from corresponding clause of initializer list
  - if initializer clause is expression, only non-narrowing implicit conversions allowed
  - if initializer clause is braced initializer list, base-element/member list initialized from clause
- if number of initializer clauses less than number of members and bases, remaining members and bases initialized by default initializer if provided in class definition and otherwise by empty lists in accordance with usual list initialization rules (e.g., performs value initialization for non-class types and non-aggregate classes with default constructors)
- if \(T\) is union type, only first non-static data member initialized
```c++
struct Point { int x; int y; };

static Point gp{1, 2}; /* aggregate initialized to {1, 2} as part of constant initialization */

int main() {
    int a[3] = {1, 2, 3}; /* aggregate initialized to {1, 2, 3} as part of copy-list initialization */
    int b[3]{1, 2, 3}; /* aggregate initialized to {1, 2, 3} as part of direct-list initialization */
    int c[4]{1, 2}; /* aggregate initialized to {1, 2, 0, 0} as part of direct-list initialization */
    Point p{1, 2}; /* aggregate initialized to {1, 2} as part of direct-list initialization */
    Point q{1}; /* aggregate initialized to {1, 0} as part of direct-list initialization */
}
```
**List Initialization**

- **list initialization**: initialize object from braced initializer list
- if initializer is braced initializer list (possibly preceded by equals sign), list initialization always used (which may then, in turn, directly invoke other types of initialization, such as value, direct, copy, or aggregate initialization)
- list initialization can occur in both direct and copy initialization contexts
- **direct-list initialization**: list initialization used in direct-initialization context; for example:
  ```cpp
  int x{1}; // where x is local object
  ```
- direct-list initialization used: [C++17 §11.6.4/1]
  1. to initialize named variable with braced initializer list
  2. to initialize (unnamed) temporary with braced initializer list
  3. to initialize object created by new expression that has braced initializer list as initializer
  4. for non-static data member initializer that does not use equals sign
  5. in constructor initializer list where braced initializer list used for initializer
**copy-list initialization**: list initialization used in copy-initialization context; for example:

```cpp
int x = {1}; // where x is local variable
```

**copy-list initialization used**: [C++17 §11.6.4/1]

1. to initialize named variable where initializer is braced initializer list that follows equals sign
2. to initialize function parameter for function call where braced initializer list used for corresponding function argument
3. to initialize returned object for return statement where return expression is braced initializer list
4. to initialize parameter of overloaded subscript operator in subscript expression where braced initializer list used
5. to initialize parameter of overloaded assignment operator in assignment expression where right-hand side of assignment is braced initializer list
6. to initialize parameter of constructor in functional cast expression where corresponding constructor argument is braced initializer list
7. for non-static data member initializer that uses equals sign
list initialization does not allow narrowing conversions

direct-list initialization is allowed to use explicit constructors, whereas copy-list initialization is not

approximately speaking, list initialization of object of aggregate type $T$ has following behavior: \[\text{[C++17 §11.6.4/3]}\]

- if initializer list has single element of same or derived type (possibly cv-qualified), object initialized from element by copy initialization (for copy-list initialization) or direct initialization (for direct-list initialization) \[\text{[C++17 §11.6.4/(3.1)]}\]

- otherwise, if $T$ is character array and initializer list has single element of appropriately-typed string literal, array initialized from string literal in usual manner \[\text{[C++17 §11.6.4/(3.2)]}\]

- otherwise, object is aggregate initialized \[\text{[C++17 §11.6.4/(3.3)]}\]
approximately speaking, list initialization of object of non-aggregate type $T$ has following behavior: 

- if $T$ is class type with default constructor and braced initializer list empty, object is value initialized. \[\text{[C++17 §11.6.4/(3.4)]}\]
- if $T$ is specialization of `std::initializer_list`, object is direct initialized or copy initialized, depending on context, from braced initializer list. \[\text{[C++17 §11.6.4/(3.5)]}\]
- if $T$ is class type, constructors of $T$ considered in two phases (first, using constructors that can be called with `std::initializer_list` as single argument; then using all constructors). \[\text{[C++17 §11.6.4/(3.6)]}\]
- if $T$ is enumeration type, if braced initializer list has only one initializer (and some other constraints satisfied), enumeration initialized with result of converting initializer to enumeration's underlying type. \[\text{[C++17 §11.6.4/(3.7)]}\]
- if $T$ is not class type and braced initializer list has exactly one element and either $T$ is not reference type or is reference type that is compatible with type of element, object is direct initialized (for direct-list initialization) or copy initialized (for copy-list initialization). \[\text{[C++17 §11.6.4/(3.8)]}\]
- if $T$ is reference type that is not compatible with type of element, temporary of referenced type is list initialized and reference bound to temporary. \[\text{[C++17 §11.6.4/(3.9)]}\]
- otherwise, if braced initializer list empty, object is value initialized. \[\text{[C++17 §11.6.4/(3.10)]}\]
Direct-List Initialization Example

```cpp
#include <initializer_list>
#include <vector>

struct Widget {
    Widget() : w{1, 2, 3} {} // w is direct-list initialized
    Widget(std::initializer_list<int> w_) : w{w_} {} /* w is
direct initialized as part of direct-list initialization */
    std::vector<int> v{3, 2, 1}; // v is direct-list initialized
    std::vector<int> w;
};

int main() {
    Widget w1{1, 2, 3}; // w1 is direct-list initialized
    const Widget& w2 = Widget{1, 2, 3};
    // temporary object is direct-list initialized
    Widget* w3 = new Widget{1, 2, 3};
    // heap-allocated object is direct-list initialized
    for (auto&& i : {1, 2, 3}) {}
    // temporary object is direct-list initialized
}
```

Copy-List Initialization Example

```cpp
#include <vector>
#include <tuple>
#include <initializer_list>

struct Widget {
    Widget() : v({1, 2, 3}) {}  // constructor argument is copy-list initialized
    Widget(std::initializer_list<int> v_) : v{v_} {}  // template specialization
    const int& operator[](std::pair<int, int> i) const {
        return i.first ? v[i.second] : w[i.second];}
    std::vector<int> v;
    std::vector<int> w = {3, 2, 1};  // w is copy-list initialized
};

Widget func(Widget w) {
    return {1, 2, 3};  // returned value is copy-list initialized
}

int main() {
    Widget w = {1, 2, 3};  // w is copy-list initialized
    w = {1, 2, 3};  // temporary object is copy-list initialized
    func({1, 2, 3});  // function argument is copy-list initialized
    Widget({1, 2, 3});  // constructor argument is copy-list initialized
    int i = w[{0, 1}];  // operator[] function parameter is copy-list initialized
```
- special rule employed for initializing character array from string literal  
  [C++17 §11.6/17.3]
- array element type and character type of string literal must be compatible
- each character in string literal (including null-terminator) placed in order into successive array elements  
  [C++17 §11.6.2]
- if number of characters in initializer less than number of array elements, remaining array elements are zero initialized
- number of characters in initializer must not exceed array capacity
- special initialization rule invoked either directly or via list initialization  
  [C++17 §11.6.4/(3.2)]  
  [C++17 §16.3.3.1.5/3]
```c
int main() {
    char a1[] = "hi";  
    // initialized to {'h', 'i', '\0'} from string literal
    char a2[] = {"hi"]; /* initialized to {'h', 'i', '\0'} as part of copy-list initialization */
    char a3[]="hi"];
    char a4[3]="hi"];  
    /* each of a3 and a4 is initialized to {'h', 'i', '\0'} as part of direct-list initialization */
    
    char b1[4] = "hi"];
    char b2[4] = {"hi"];
    char b3[4]="hi"];  
    /* each of b1, b2, and b3 is initialized to {'h', 'i', '\0', '\0'} */
    
    char16_t c[] = u"hi"; /* initialized to {u'h', u'i', u'\0'} from string literal */
    char32_t d[] = U"hi"; /* initialized to {U'h', U'i', U'\0'} from string literal */
    wchar_t e[4]{L"hi"}; /* initialized to {L'h', L'i', L'\0', L'\0'} as part of direct-list initialization */
}
```
struct Gadget {
    int x;
    int y;
};

struct Widget {
    Gadget g;
    int i;
};

int main() {
    int x[2][2] = {{1, 2}, {3, 4}};
    // effectively initializer is {{1, 2}, {3, 4}}
    Widget v = {{1, 2}, {3, 4}};
    // effectively initializer is {{1, 2}, 3}
    Widget w = {1, 2};
    // effectively initializer is {{1, 2}}
    // w initialized to {{1, 2}, 0}
    }
```cpp
#include <initializer_list>

auto i1 = 42; // type of i1 deduced as int
auto i2(42); // type of i2 deduced as int
auto i3{42}; // type of i3 deduced as int
// auto i4{42, 42}; // ERROR: exactly one element required
auto i5 = {42};
// type of i5 deduced as std::initializer_list<int>
```
```cpp
#include <initializer_list>

struct Widget {
    Widget();
    Widget(std::initializer_list<int>);
    Widget(int);
};

int main() {
    Widget w{};
    // invokes default constructor; for empty
    // braced initializer list, default constructor
    // preferred over std::initializer_list constructor
    Widget v{42};
    // invokes constructor taking std::initializer_list;
    // for non-empty braced initializer list, constructor
    // taking std::initializer_list preferred over those
    // that do not
}
```
```cpp
#include <map>
#include <vector>
#include <string>

std::map<int, std::string> m{
    {42, "forty two"},
    {0, "zero"}
}; // initialized to map with two elements

std::vector<std::string> v1{"hi", "bye"};
// initialized to vector with two elements

std::vector<std::string> v2{"hi", "bye"};
// ERROR: will try to initialize to vector with
// one element; invokes std::string constructor that
// takes two iterators as parameters; pointers
// to "hi" and "bye" passed as begin and end
// iterators; this results in undefined behavior
```
```cpp
struct Widget {
    Widget(int i_) : i(i_) {}
    int i;
};

int main() {
    Widget v(42.0);
    // OK: narrowing conversion allowed in
    // direct initialization
    // Widget w{42.0};
    // ERROR: narrowing conversion not allowed in
    // list initialization

```
```cpp
#include <vector>
#include <string>

std::vector<int> v1(3, 42);
// initialized to vector with elements 42, 42, 42
std::vector<int> v2{3, 42};
// initialized to vector with elements 3, 42

std::string s1(3, 'a');
// initialized to string consisting of 3 'a' characters
std::string s2{3, 'a'};
// initialized to string consisting of characters '\3', 'a'
```
```cpp
#include <iostream>
#include <initializer_list>

auto f(int a, int b, int c) {
    return std::initializer_list<int>{a, b, c};
    // ERROR: initializer_list references elements in
    // temporary array whose lifetime need not extend
    // beyond lifetime of initializer_list;
    // therefore, returned initializer_list
    // likely references invalid data
}

int main() {
    // nothing good likely to happen here
    for (auto i : f(1, 2, 3)) {
        std::cout << i << '
';
    }
}
```
Section 3.1.1

References


Section 3.2

Temporary Objects
A temporary object is an unnamed object introduced by the compiler. Temporary objects may be used during:
- evaluation of expressions
- argument passing
- function returns (that return by value)
- reference initialization

It is important to understand when temporary objects can be introduced, since the introduction of temporaries impacts performance.

Evaluation of expression:

```cpp
std::string s1("Hello ");
std::string s2("World");
std::string s;
s = s1 + s2; // must create temporary
    // std::string _tmp(s1 + s2);
    // s = _tmp;
```

Argument passing:

```cpp
double func(const double& x);
func(3); // must create temporary
    // double _tmp = 3;
    // func(_tmp);
```
■ Reference initialization:

```cpp
int i = 2;
const double& d = i; // must create temporary
// double _tmp = i;
// const double& d = _tmp;
```

■ Function return:

```cpp
std::string getMessage();
std::string s;
s = getMessage(); // must create temporary
// std::string _tmp(getMessage());
// s = _tmp;
```

■ In most (but not all) circumstances, a temporary object is destroyed as the last step in evaluating the full expression that contains the point where the temporary object was created. [C++17 §15.2/4]
class Complex {
    public:
        Complex(double re = 0.0, double im = 0.0) : re_(re), im_(im) {}  
        Complex(const Complex& a) = default;
        Complex(Complex&& a) = default;
        Complex& operator=(const Complex& a) = default;
        Complex& operator=(Complex&& a) = default;
        ~Complex() = default;
        double real() const {return re_;}
        double imag() const {return im_;}
    private:
        double re_; // The real part.
        double im_; // The imaginary part.
};

Complex operator+(const Complex& a, const Complex& b) {  
    return Complex(a.real() + b.real(), a.imag() + b.imag());
}

int main() {  
    Complex a(1.0, 2.0);
    Complex b(1.0, 1.0);
    Complex c;
    // ...
    c = a + b;
}
Original code:

```c++
int main() {
    Complex a(1.0, 2.0);
    Complex b(1.0, 1.0);
    Complex c;
    // ...
    c = a + b;
}
```

Code showing temporaries:

```c++
int main() {
    Complex a(1.0, 2.0);
    Complex b(1.0, 1.0);
    Complex c;
    // ...
    Complex _tmp(a + b);
    c = _tmp;
}
```
```cpp
class Counter {

public:
    Counter() : count_(0) {}

    int getCount() const { return count_; }

    Counter& operator++() { // prefix increment
        ++count_
        return *this;
    }

    Counter operator++(int) { // postfix increment
        Counter old(*this);
        ++count_
        return old;
    }

private:
    int count_; // counter value
};

int main() {
    Counter x;
    Counter y;

    y = ++x;
    // no temporaries, int increment, operator=
    y = x++;
    // 1 temporary, 1 named, 2 constructors,
    // 2 destructors, int increment, operator=
    return 0;
}
```
```cpp
#include <complex>
using std::complex;

int main() {
    complex<double> a(1.0, 1.0);
    complex<double> b(1.0, -1.0);
    complex<double> z(0.0, 0.0);

    // 2 temporary objects
    // 2 constructors, 2 destructors
    // 1 operator=, 1 operator+, 1 operator*
    z = b * (z + a);

    // no temporary objects
    // only 1 operator+= and 1 operator*=
    z += a;
    z *= b;
}
```
Lifetime of Temporary Objects

- Normally, a temporary object is destroyed as the last step in evaluating the full expression that contains point where temporary object was created. [C++17 §15.2/5] [C++17 §15.2/6]

- First exception: When a default constructor with one or more default arguments is called to initialize an element of an array. [C++17 §15.2/5]

- Second exception: When a reference is bound to a temporary (or a subobject of a temporary), the lifetime of the temporary is extended to match the lifetime of the reference, with following exceptions: [C++17 §15.2/6]
  - A temporary bound to a reference member in a constructor initializer list persists until the constructor exits.
  - A temporary bound to a reference parameter in a function call persists until the completion of the full expression containing the call.
  - A temporary bound to the return value of a function in a return statement is not extended, and is destroyed at end of the full expression in the return statement.
  - A temporary bound to a reference in an initializer used in a new-expression persists until the end of the full expression containing that new-expression.
Example:

```cpp
void func() {
    std::string s1("Hello");
    std::string s2(" ");
    std::string s3("World!\n");
    const std::string& s = s1 + s2 + s3;
    std::cout << s; // OK?
}
```

Example:

```cpp
const std::string& getString() {
    return std::string("Hello");
}
void func() {
    std::cout << getString(); // OK?
}
```
Temporary Object Creation

- temporary objects are created: [C++17 §15.2/1]
  - when prvalue is materialized so that it can be used as xvalue
  - when needed to pass or return object of trivially-copyable type
  - when throwing exception

- materialization of temporary object is always delayed as long as possible in order to avoid creating unnecessary temporary objects [C++17 §15.2/2]

- temporary objects are materialized: [C++17 §15.2/2][C++17 §7.4/1][C++17 §8/10]
  - when binding a reference to a prvalue
  - when performing member access on a class prvalue
  - when performing array-to-pointer conversion or subscripting on array prvalue
  - when initializing object of type `std::initializer_list` from braced initializer list
  - for certain unevaluated operands
  - when prvalue appears as discarded expression
Section 3.3

Lvalues and Rvalues
Expressions

- An expression is a sequence of operators and operands that specifies a computation. [C++17 §8/1]
- An expression has a type and, if the type is not void, a value.
- Example:

```cpp
int x = 0;
int y = 0;
int* p = &x;
double d = 0.0;
// Evaluate some
// expressions here.
```

<table>
<thead>
<tr>
<th>Expression</th>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>int</td>
<td>0</td>
</tr>
<tr>
<td>y = x</td>
<td>int</td>
<td>reference to y</td>
</tr>
<tr>
<td>x + 1</td>
<td>int</td>
<td>1</td>
</tr>
<tr>
<td>x * x + 2 * x</td>
<td>int</td>
<td>0</td>
</tr>
<tr>
<td>y = x * x</td>
<td>int&amp;</td>
<td>0</td>
</tr>
<tr>
<td>x == 42</td>
<td>int</td>
<td>reference to y</td>
</tr>
<tr>
<td>*p</td>
<td>int&amp;</td>
<td>1</td>
</tr>
<tr>
<td>p == &amp;x</td>
<td>bool</td>
<td>false</td>
</tr>
<tr>
<td>x &gt; 2 * y</td>
<td>bool</td>
<td>true</td>
</tr>
<tr>
<td>std::sin(d)</td>
<td>double</td>
<td>false</td>
</tr>
</tbody>
</table>

Every expression can be classified into \textit{exactly one} of three \textbf{value categories}: \cite{c++17 §6.10/1}

1. \textit{lvalue}
2. \textit{xvalue} (which stands for “expiring value”)
3. \textit{prvalue} (which stands for “pure rvalue”)

An expression that is an \textit{lvalue} or \textit{xvalue} is called a \textbf{glvalue} (which stands for “generalized lvalue”).

An expression that is a \textit{prvalue} or an \textit{xvalue} is called an \textbf{rvalue}.

Every expression is either an \textit{lvalue} or \textit{rvalue} (but not both).

Every expression is either a \textbf{glvalue} or \textbf{prvalue} (but not both).
How an expression can be used is dictated, in part, by its value category.

Whether or not it is safe to move (instead of copy) depends on whether an lvalue or rvalue is involved.

In the context of values categories, the notion of identity is important.

An entity (such as an object or function) is said to have an identity if it can be distinguished from other like entities with identical attributes.

For example, any object that is stored at a well-defined location in memory has an identity, since, given two objects with well-defined locations (and possibly identical values), one can always determine if these objects are the same object by comparing their locations.
Lvalues

- An **lvalue** is an expression that:  
  - denotes a function, object, or bitfield; and  
  - has an identity.

- Since an lvalue establishes the identity of a function, object, or bitfield, an lvalue is always associated with some well-defined location in memory (which, in some cases, can be determined by the address-of operator).

- If an lvalue expression corresponds to an object, the resources of that object are **not guaranteed** to be safe to reuse (i.e., the object is not guaranteed to be safe to use as the source for a move operation).
A **named object** or **named function** is an lvalue. \[C++17 \S 8.1.4.1/1\] \[C++17 \S 8.1.4.2/2\] Example:

```cpp
int get_value();
int i;
int j;
i = get_value();
    // i and get_value are lvalues
    // Note: get_value is not the same as get_value()
j = i + 1; // i and j are lvalues
```

The result of calling a function whose **return type is an lvalue reference type** is an lvalue. \[C++17 \S 8.2.2/11\] Example:

```cpp
int & get_value();
++get_value(); // get_value() is an lvalue
```

A **string literal** is an lvalue. \[C++17 \S 8.1.1/1\] Example:

```cpp
const char *s = "Hello"; // "Hello" is an lvalue
```

A **named rvalue reference** is an lvalue. \[C++17 \S 8/7\] Example:

```cpp
int && i = 1 + 3;
int j = i; // i is an lvalue
```
An **rvalue reference to a function** (both named and unnamed) is an lvalue. [C++17 §8/7]

Example:

```cpp
void func();
void (&&f)() = func;
f(); // f is an lvalue
std::move(func)(); // std::move(func) is an lvalue
```

The result of each of the following built-in operators is an lvalue:

- built-in subscripting operator (except when array rvalue involved) [C++17 §8.2.1/1]
- built-in indirection operator [C++17 §8.3.1/1]
- built-in pre-increment and pre-decrement operators [C++17 §8.3.2/1] [C++17 §8.3.2/2]
- built-in assignment and compound-assignment operators [C++17 §8.18/1]

Example:

```cpp
char buffer[] = "Hello";
char* s = buffer;
*s = 'a'; // *s is an lvalue
*(s + 1) = 'b'; // *(s + 1) is an lvalue
++s; // ++s is an lvalue
--s; // --s is an lvalue
s += 2; // s += 2 is an lvalue
s = &buffer[1];
// s = &buffer[1] is an lvalue
// buffer[1] is an lvalue
```
Moving and Lvalues

- Using a move (instead of a copy) is \textit{not guaranteed to be safe} when the source is an lvalue (since other code can access the associated object by name or through a pointer or reference).

- Example:

```cpp
void func() {
    std::vector<int> x;
    std::vector<int> y(x);
    /* can we construct by moving (instead of copying)?
    source x is lvalue; not safe to move x to y since
    value of x might be used later */
    y = x;
    /* can we assign by moving (instead of copying)?
    source x is lvalue; not safe to move x to y since
    value of x might be used later */
    // ...
}
```
A **prvalue** (i.e., pure rvalue) is an expression whose evaluation: [C++17 §6.10/1]
- computes the value of an operand of an operator; or
- initializes an object or a bitfield.

A prvalue never corresponds to an object (but, in some contexts, might be used to materialize a temporary object).

A prvalue does not have an identity.

An **xvalue** (i.e., expiring value) is an expression that: [C++17 §6.10/1]
- denotes an object or bitfield (usually near the end of its lifetime);
- has an identity; and
- the resources of the object/bitfield can safely be reused (i.e., is **deemed to be safe** to use as the source for a move).

An xvalue is associated with certain kinds of expressions involving rvalue references or the materialization of a temporary object.

An **rvalue** is an expression that is either a prvalue or an xvalue.

Unlike an lvalue, an rvalue need not have an identity.

Therefore, applying the (built-in) address-of operator to an rvalue (corresponding to an object) is not allowed. [C++17 §8.3.1/3]
- The result of calling a function that returns by value (i.e., the return type is not a reference type) is a prvalue. [C++17 §8.2.2/11] Example:

```cpp
int get_value();
int i = get_value();
// get_value() is a prvalue
// Note: get_value() is not the same as get_value
```

- All literals other than string literals are prvalues. [C++17 §8.1.1/1] Example:

```cpp
double pi = 3.1415; // 3.1415 is a prvalue
int i = 42; // 42 is a prvalue
i = 2 * i + 1; // 2 and 1 are prvalues
char c = 'A'; // 'A' is a prvalue
```

- The this keyword is a prvalue. [C++17 §8.1.2/2]
The result of each of the following built-in operators is a prvalue:

- built-in post-increment and post-decrement operators [C++17 §8.2.6/1]
- built-in arithmetic operators excluding increment and decrement operators (e.g., unary plus, unary minus, addition, subtraction, multiplication, division, and modulus) [C++17 §8.3.1/2 unary?] [C++17 §8.7 missing?]
- built-in bitwise operators (e.g., bitwise NOT, bitwise AND, and bitwise OR)
- built-in logical operators (e.g., logical NOT, logical AND, and logical OR)
- built-in relational operators (e.g., equal, not equal, and less than)
- built-in address-of operator [C++17 §8.3.1/3]

Example:

```cpp
int i;
int j;
i = -(3 + 5); // 3 + 5 and -(3 + 5) are prvalues
j = i * i; // i * i is a prvalue
j = (i == 42); // i == 42 is a prvalue
j = (i & 7) | 2; // (i & 7) and (i & 7) | 2 are prvalues
i = j++; // j++ is a prvalue
int *ip = &i; // &i is a prvalue
```
The result of calling a function whose return type is an rvalue reference type is an xvalue. [C++17 §8/7.1] Example:

```cpp
std::string s("Hello");
std::string t = std::move(s); // std::move(s) is xvalue
    // Note: std::move returns rvalue reference type
```

An unnamed rvalue reference to an object is an xvalue. [C++17 §8/7] Example:

```cpp
std::string s("Hello");
std::string t;
t = static_cast<std::string&&>(s);
    // static_cast<std::string&&>(s) is xvalue
s = std::move(t); // std::move(t) is an xvalue
```

A temporary object materialized from a prvalue is an xvalue. [C++17 §7.4/1] Example:

```cpp
std::vector<int> v;
v = std::vector<int>(10, 2);
    // temporary object materialized from prvalue
    // std::vector<int>(10, 2) is an xvalue
std::complex<double> u;
u = std::complex<double>(1, 2);
    // temporary object materialized from prvalue
    // std::complex<double>(1, 2) is an xvalue
```
Moving and Rvalues

- When the source object whose value is to be propagated is an rvalue, using a move (instead of a copy) is *always safe* (either because this must be so or the programmer has explicitly deemed this to be so).

- Example (move from temporary object):

```cpp
void func() {
    std::vector<int> x;
    x = std::vector<int>(42, 0);
    /* safe to move from temporary object materialized from prvalue std::vector<int>(42, 0) since any change to its value cannot be observed by other code */
    // ...
}
```

- Example (forced move):

```cpp
void func() {
    std::string s("hello");
    std::cout << s << \n;
    std::string t(std::move(s));
    /* safe to move from s to t since std::move(s) is xvalue; programmer has, in effect, said "trust me, it is safe to use move here"; of course, if programmer is wrong, bad things will happen; programmer correct in this case, since value of s not used again */
    std::cout << t << \n;
}
```
More on Lvalues and Rvalues

- Lvalues and rvalues can be either *modifiable* or *nonmodifiable*. Example:

```cpp
int i = 0;
const int j = 2;
i = j + 3;
// i is modifiable lvalue
// j is nonmodifiable lvalue
// j + 3 is modifiable rvalue
const std::string getString();
std::string s = getString();
// getString() is nonmodifiable rvalue
```

- Class rvalues can have cv-qualified types, while non-class rvalues *always have cv-unqualified types*. [C++17 §8/6] Example:

```cpp
const int getConstInt(); // const is ignored
const std::string getConstString();
int i = getConstInt();
// getConstInt() is modifiable rvalue of type int
// (not const int)
std::string s = getConstString();
// getConstString() is nonmodifiable rvalue
```
With regard to propagating the value from one object to another, we can summarize the results from the earlier slides as follows:

- If the source for a copy operation is an *lvalue*, the copy operation is *not guaranteed* to be safely replaceable by a move operation.
- If the source for a copy operation is an *rvalue*, the copy operation is *guaranteed* to be safely replaceable by a move operation (where the guarantee may effectively come from the programmer in some cases).

It would be highly desirable if the language would provide a mechanism that would automatically allow a move to be used in the rvalue case and a copy to be employed otherwise.

In fact, this is exactly what the language does.

The rules in the language for reference binding and overload resolution conspire to achieve the following final overall effect:

- When the value of an object must be propagated to another object, a move operation is used if such an operation is *available* and the source object is an *rvalue*; otherwise, a copy operation is employed.
Consider the following code with respect to moving/copying:

```cpp
/* Note: std::string provides copy and move constructors and copy and move assignment operators. */

std::string get_value();
const std::string get_const_value(); // WARNING: bad idea

void func() {
    std::string s(get_value());
    // move elided (for reasons to be seen later)
    std::string t(s); // copy construction
    std::string u(std::move(t)); // move construction
    t = s; // copy assignment
    t = std::string("Hello"); // move assignment
    s = std::move(t); // move assignment
    t = get_const_value(); // copy assignment (not move!)
}
```

One further complication exists that is yet to be discussed.

In some circumstances, a move/copy operation is either allowed or required to be elided (i.e., copy elision).

This complication will be considered in detail later.
Aside from the exceptions noted below, all of the built-in operators require operands that are prvalues.

The operand of each of the following built-in operators must be an lvalue:
- address of
- pre- and post-increment
- pre- and post-decrement

The left operand of the following built-in operators must be an lvalue:
- assignment
- compound assignment
Whether an operator for a class type requires operands that are lvalues or rvalues or yield lvalues or rvalues is determined by the parameter types and return type of the operator function.

The member selection operator may yield an lvalue or rvalue, depending on the particular manner in which the operator is used. (The behavior is fairly intuitive.) [C++17 §8.2.5/4]

The value category and type of the result produced by the ternary conditional operator depends on the particular manner in which the operator is employed. [C++17 §8.16/5] [C++17 §8.16/6]
The **lvalue-to-rvalue conversion** (which would be more accurately called the glvalue-to-prvalue conversion) is an implicit conversion from lvalues and xvalues to prvalues, which can be used in numerous circumstances. [C++17 §7.1/1]

For non-class types, the above conversion also removes cv-qualifiers.

Whenever an lvalue/xvalue appears as an operand of an operator that expects a prvalue operand, the lvalue-to-rvalue conversion is applied to convert the expression to a prvalue. [C++17 §8/9] Example:

```cpp
int i = 1;
int j = 2;
int k = i + j;
/* since built-in binary addition operator requires prvalue operands, i and j implicitly converted from lvalues to prvalues */
```

The lvalue-to-rvalue conversion is not used for reference binding. [C++17 §11.6.3/5]
Copy Elision

- normally, compiler forbidden from applying optimizations to code that would change its observable behavior (i.e., so called “as if” rule)
- one important exception to as-if rule is copy elision
- **copy elision** is code transformation that omits copy/move operation by constructing object in place to which it would later be copied/moved
- copy elision allows copy/move operations to be eliminated, thus avoiding cost of copy/move constructors
- copy elision may also eliminate need for some temporary objects, which avoids cost of constructing and destroying those objects
- copy elision either allowed or required in several contexts:
  - initialization
  - returning by value
  - passing by value
  - throwing by value
  - catching by value
- in cases where copy elision is mandatory, copy/move constructors need not be accessible or even provided at all, which provides more flexibility in dealing with non-movable non-copyable types
in return statement of function with class return type, when expression is name of non-volatile automatic object (other than function or catch-clause parameter) with same cv-unqualified type as function return type, automatic object can be constructed directly in function’s return value

[C++20 §11.10.5/(1.1)]

copy elision required if (allowed as per above and) return expression is prvalue (i.e., placeholder for temporary object) [C++20 §9.4/(17.6.1)]

example:

```cpp
struct Widget {
    Widget();
    Widget(const Widget&);
    Widget(Widget&&);
    // ...
};

Widget func1() {return Widget();}
// returns prvalue (i.e., placeholder for temporary object)
Widget func2() {Widget w; return w;} // returns named object

int main() {
    Widget w(func1());
    // required copy elision (not named object returned)
    Widget x(func2());
    // possible copy elision (named object returned)
}
```
in context of returning by value, two forms of copy elision known by special names

code transformation that eliminates copy from unnamed object associated with prvalue return expression to returned value in caller known as return value optimization (RVO)

that is, RVO is copy elision in case that return expression is prvalue

as seen previously, RVO is mandatory

code transformation that eliminates copy from named object specified by return expression to returned value in caller known as named return value optimization (NRVO)

that is, NRVO is copy elision in case that return expression is named object (i.e., not prvalue)

as seen previously, NRVO is allowed but not required

terms RVO and NRVO frequently used when discussing copy elision in context of returning by value
Consider the following code (where type $T$ is default constructible):

```
1 T callee() {return T();}
2 void caller() {T x(callee()); /* ... */}
```

- The goal is to construct object $x$ in `caller` with value corresponding to $T()$ (i.e., default constructed $T$).

- Without copy elision, this would be achieved by:

```
default construct

T callee() {return T();}
```

```
T x(callee()); /* ... */
```

- By maximally utilizing copy elision (and delaying creation of any temporary objects as long as possible), this can be reduced to a single step:

```
T callee() {return T();}
```

```
T x = callee(); /* ... */
```

- Not only were two copy/move operations eliminated, but the need for any temporary objects was also eliminated.
again, consider following code (where type \( T \) is default constructible):

```cpp
T callee() {\textbf{return} T();}
void caller() {T x(callee()); /* ... */}
```

consider what happens without copy elision (in violation of standard in this case)

executing body of \texttt{caller} proceeds as follows:

1. storage for temporary object allocated in \texttt{caller} to hold return value of \texttt{callee}
2. \texttt{caller} invokes \texttt{callee}
3. expression in return statement of \texttt{callee} evaluated, resulting in construction of temporary object in \texttt{callee} (via default constructor) to hold return value
4. before \texttt{callee} returns, value of temporary object in \texttt{callee} propagated to temporary object in \texttt{caller} (via move/copy construction)
5. \texttt{callee} returns (after destroying its temporary object holding return value)
6. value of temporary object in \texttt{caller} propagated to \( x \) (via move/copy construction); then temporary object destroyed

overhead: two temporary objects created (two constructor and destructor invocations); must propagate value into and out of temporary objects
again, consider following code (where type \( T \) is default constructible):

\[
\begin{align*}
T \text{ callee}() & \{ \text{return } T(); \} \\
\text{void caller}() & \{ T \ x(\text{callee}()); /* ... */ \}
\end{align*}
\]

consider what happens with copy elision (which is required by standard in this case)

executing body of \text{caller} proceeds as follows:

1. \text{caller} invokes \text{callee}
2. expression in return statement of \text{callee} evaluated, resulting in return value of \text{callee} being constructed directly in \( x \) in \text{caller} (via default constructor)

no overhead: no temporary objects created and therefore no need to propagate values into or out of temporary objects
Return-By-Value Example 2: Summary

- Consider following code (where type `T` is default constructible and copyable/movable):
  ```
  1 T callee() {return T();}
  2 void caller() {T x; x = callee(); /* ... */}
  ```
- Goal is to assign value corresponding to `T()` to `x` in `caller`.
- Without copy elision, this would be achieved by:
  - Temporary object in `callee`
  - Copy/move construct
  - Temporary object in `caller`
  - Copy/move assign
  - `x` in `caller`

- With copy elision, this can be reduced to:
  - Temporary object in `caller`
  - Copy/move assign
  - `x` in `caller`

- Able to eliminate one move/copy operation and one temporary object.
- Unlike in case of previous example, cannot eliminate temporary object in `caller` since temporary object must be materialized in order to perform assignment to `x` in `caller`.
Return-By-Value Example 2: Without Copy Elision

again, consider following code (where type T is default constructible and copyable/movable):

```cpp
T callee() {return T();}
void caller() {T x; x = callee(); /* ... */}
```

consider what happens without copy elision (in violation of standard in this case)

executing body of caller proceeds as follows:

1. storage for temporary object allocated in caller to hold return value of callee
2. caller invokes callee
3. expression in return statement of callee evaluated, resulting in construction of temporary object in callee (via default constructor) to hold return value
4. before callee returns, value of temporary object in callee propagated to temporary object in caller (via move/copy construction)
5. callee returns (after destroying its temporary object holding return value)
6. value of temporary object in caller propagated to x (via move/copy assignment); then temporary object destroyed

overhead: two temporary objects created; must propagate value from temporary object in callee to temporary object in caller
again, consider following code (where type \( T \) is default constructible and copyable/movable):

```cpp
T callee() {\textbf{return} T();}
void caller() {T x; x = callee(); /* ... */}
```

consider what happens with copy elision (which is required by standard in this case)

executing body of \texttt{caller} proceeds as follows:

1. storage for temporary object allocated in \texttt{caller} to hold return value of \texttt{callee}
2. \texttt{caller} invokes \texttt{callee}
3. expression in return statement of \texttt{callee} evaluated, resulting in return value of \texttt{callee} being constructed directly in temporary object in \texttt{caller} (via default constructor)
4. \texttt{callee} returns
5. value of temporary object in \texttt{caller} propagated to \( x \) (via move/copy assignment); then temporary object destroyed

overhead: one temporary object created; but no need to propagate value from temporary object in \texttt{callee} to temporary object in \texttt{caller}
class Widget {
public:
    Widget(int) {/* ... */}
    Widget(const Widget&) = default;
    Widget(Widget&&) = default;
    // ...
};

bool get_flag();

// eliding copy of return value is not possible
Widget func() {
    Widget w(0);
    // w must be constructed before it is known if
    // w will be returned; so cannot know whether to
    // construct w in returned value
    Widget v(42);
    // v must be constructed before it is known if
    // v will be returned; so cannot know whether to
    // construct v in returned value
    if (get_flag()) {return w;}
    else {return v;}
}

int main() {
    Widget w(func());
}
in function call, when temporary class object not bound to reference would be copied/moved to class object with same cv-unqualified type, temporary object can be constructed directly in target of omitted copy/move

[C++20 §9.4/15][C++20 §8.2.2/7]

copy elision always required if allowed (as per above)  
[C++20 §9.4/(17.6.1)]

example:

```cpp
struct Widget {
    Widget();
    Widget(const Widget&);
    Widget(Widget&&);
    // ...
};

void func(Widget w) { /* ... */}

int main() {
    func(Widget()); // required copy elision
    func(std::move(Widget())); /* BAD IDEA: copy elision not allowed; move performed */
    
    }  
```
Pass-By-Value Example: Summary

- consider following code (where type $T$ is default constructible):
  
  ```
  void callee(T p) {/* ... */}
  void caller() {callee(T());}
  ```

- goal is to invoke `callee` with its function parameter $p$ having value corresponding to $T()$ (i.e., default constructed $T$)

- without copy elision, this would be accomplished by:

  ![Diagram showing default construct and temporary object]

- with copy elision, this can be reduced to:

  ![Diagram showing default construct with parameter]

- by using copy elision, not only was one copy/move operation eliminated, but temporary object also eliminated
again, consider following code (where type \( T \) is default constructible):

```cpp
void callee(T p) {/* ... */}
void caller() {callee(T());}
```

consider what happens without copy elision (in violation of standard in this case)

executing body of `caller` proceeds as follows:

1. temporary object created in `caller` with value corresponding to \( T() \) (via default constructor)
2. storage for `callee`'s function parameter \( p \) allocated (on stack)
3. value of temporary object in `caller` propagated (via move/copy constructor) to `callee`'s function parameter \( p \)
4. `caller` transfers control to `callee`
5. `callee` returns, resulting in its function parameter being destroyed (and deallocated)
6. temporary object in `caller` destroyed (and deallocated)

overhead: one temporary object created (constructor and destructor invocations); one move/copy required to propagate value from temporary object elsewhere
again, consider following code (where type \( T \) is default constructible):

```cpp
void callee(T p) {/* ... */}
void caller() {callee(T());}
```

call what happens with copy elision (as required by standard in this case)

eexecuting body of `caller` proceeds as follows:

1. function parameter \( p \) constructed (on stack) with value corresponding to \( T() \) (via default constructor)
2. `caller` transfers control to `callee`
3. `callee` returns, resulting in its function parameter being destroyed (and deallocated)

no overhead: no temporary objects created and therefore no need to propagate values into or out of temporary objects
Copy Elision and Throwing by Value

- in throw expression, when operand is name of non-volatile automatic object (other than function or catch-clause parameter) whose scope does not extend beyond end of innermost enclosing try block (if there is one), copy/move operation from operand to exception object can be omitted by constructing automatic object directly into exception object \([\text{C++20 §11.10.5/(1.2)}]\)

- copy elision required if (allowed as per above and) throw expression is prvalue \([\text{C++20 §9.4/(17.6.1)}]\)

- example:

```cpp
struct Widget {
    Widget();
    Widget(const Widget &);
    Widget(Widget&&);
    // ...
};

void func_1()
{
    throw Widget(); // required copy elision (prvalue)
}

void func_2()
{
    Widget w; throw w; // possible copy elision (not prvalue)
}
```
when exception declaration of exception handler declares object of same type (except for cv-qualification) as exception object, copy/move operation can be omitted by treating exception declaration as alias for exception object if meaning of program will be unchanged except for execution of constructors and destructors for object declared by exception declaration

[C++20 §11.10.5/(1.4)]

in this context, copy elision never required

element:

```cpp
struct Widget {
  Widget();
  Widget(const Widget &);
  Widget(Widget&&);
  // ...
};

int main() {
  try {throw Widget();}
  catch (Widget foo) { // possible copy elision
    /* ... (foo not modified) */
  }
}
```
if prvalue used as initializer of object with same type (except for cv-qualification), object must be initialized directly [C++20 §9.4/(17.6.1)]

element:

```cpp
class Widget {
public:
    Widget();
    Widget(const Widget&);
    Widget(Widget&&);
    // ...
};

Widget func();

int main() {
    Widget w = Widget(func());
    // copy elision required for initialization;
    // no copy/move in main function;
    // returned value from func directly constructed in w;
    // func may need copy/move to propagate return value
    // out of func, if not elided
    Widget u{Widget()};
    // copy elision required for initialization;
    // no copy/move; new Widget object is default
    // constructed directly in u
```
```cpp
class Widget {

public:
    Widget() {/* ... */}
    // not copyable
    Widget(const Widget&) = delete;
    Widget& operator=(const Widget&) = delete;
    // not movable
    Widget(Widget&&) = delete;
    Widget& operator=(Widget&&) = delete;
    // ...

};

Widget make_widget() {
    return Widget();
}

int main() {
    Widget w(make_widget());
    // OK: copy elision required
    Widget v{Widget();}
    // OK: copy elision required
    Widget u(Widget());
    // function declaration
}
```
```cpp
#include <cassert>

class Widget {
public:
    Widget() : c_(0) {}
    Widget(const Widget& other) : c_(other.c_ + 1) {}
    Widget& operator=(const Widget& other) {c_ = other.c_ + 1; return *this;}
    int count() const {return c_;}
private:
    int c_;}

Widget widget_1() {return Widget();}
    // mandatory copy elision for return value
Widget widget_2() {return widget_1();}
    // mandatory copy elision for return value
Widget widget_3() {return widget_2();}
    // mandatory copy elision for return value

int main() {
    Widget w{widget_3()}; // no temporary object; no copy/move
    assert(w.count() == 0);
    w = widget_3();
    // widget_1 directly constructs return value into
    // temporary object in main
    assert(w.count() == 1);
    Widget v{Widget(Widget(Widget(Widget(Widget(Widget())))))};
    // default constructs directly into v; no copy/move
    assert(v.count() == 0);
}
**implicitly movable** entity is variable of automatic storage duration that is either non-volatile object or rvalue reference to non-volatile object type

[C++20 §11.10.5/3]

if expression in return (or coreturn) statement is (possibly parenthesized) expression that names implicitly movable entity declared in body or parameter list of function, this handled as described below [C++20 §8.7.3/2]

[C++20 §11.10.5/(3.1)]

overload resolution to select constructor for copy (or return_value overload to call) is first performed as if return expression were rvalue

if overload resolution fails or was not performed, overload resolution is performed again, considering return expression as lvalue
#include <string>

class Widget {

public:
    Widget(const std::string&) {/* ... */}
    Widget(const Widget&) = default;
    Widget(Widget&&) = default;
    // ...
};

Widget get_value_1() {
    Widget w("goodbye");
    return w;
    // copy elision is allowed, but not required;
    // if move/copy not elided:
    // since return expression w is implicitly movable and is declared in
    // function body, w first treated as if rvalue, resulting in move
    // constructor being selected to propagate return value to caller
}

Widget get_value_2() {
    std::string s("hello");
    return s;
    // effectively: return Widget(s);
    // copy elision required (since returning prvalue)
}

int main() {
    Widget w(get_value_1());
    Widget v(get_value_2());
}
consider function that returns by value

for such function, almost never desirable to use result of invocation of `std::move` as return expression, since this prohibits copy elision

example (bad use of `std::move`):

```cpp
Widget make_widget() {
    return std::move(Widget());
    // BAD: move performed instead of eliding move
}
```

only use result of invoking `std::move` as return expression if:

1. copy elision cannot be used; and
2. copy would be performed instead of move
```cpp
#include <string>

class Widget {
public:
    Widget(const std::string&) {/* ... */}
    Widget(const Widget&) = default;
    Widget(Widget&&) = default;
    // ...
};

Widget get_value_1() {
    return Widget("hello");
    // copy elision required
}

// Note: This type of usage of std::move is highly undesirable,
// as it prevents copy elision.
Widget get_value_2() {
    return std::move(Widget("hello"));
    // since cv-unqualified return-expression type and cv-unqualified
    // return type differ, copy elision is not allowed; move constructor
    // is selected to propagate return value to caller; if std::move had
    // not been used, copy/move/ would have been completely eliminated
    // (due to required copy elision)
}

int main() {
    Widget w(get_value_1());
    Widget v(get_value_2());
}
```
#include <utility>

class Widget {
public:
    Widget();
    Widget(const Widget&);
    Widget(Widget&&);
    Widget& operator=(const Widget&);
    Widget& operator=(Widget&&);
    // ...
};

Widget func_0(Widget w) {
    // copy elision for return value is not allowed since object being
    // returned is function parameter; since w is implicitly movable and
    // declared in function parameter list, w is first treated as rvalue,
    // resulting in move being performed
    return w;
}

Widget func_1() {
    try {
        // copy elision for exception object is required
        throw Widget();
    } catch (Widget w) {
        // copy elision for return value is not allowed since object being
        // returned is catch-clause parameter; treating return expression as
        // rvalue results in move being performed
        return w;
    }
}
Copy/Move/Elide Example: Widget (2)

```c++
Widget func_2(Widget& w) {
    // copy elision for return value is not allowed for several reasons (e.g.,
    // function parameter, not automatic, cv-unqualified type mismatch); return
    // expression cannot be treated as rvalue since w is not implicitly
    // movable; so copy is performed
    return w;
}

Widget func_3() {
    static Widget w;
    // copy elision for return value is not allowed since w is not automatic
    // object; return expression cannot be treated as rvalue since w is not
    // implicitly movable; so copy is performed
    return w;
}

Widget g;
Widget func_4() {
    // copy elision for return value is not allowed since g is not automatic;
    // return expression cannot be treated as rvalue since g is not implicitly
    // movable; so copy is performed
    return g;
}

void func_5() {
    Widget w;
    // copy elision for exception object is allowed; if copy not elided: since
    // w is implicitly movable and declared in function body, w first treated
    // as rvalue, resulting in move being performed
    throw w;
}
void func_6(Widget w) {
    // copy elision is not allowed since object in throw expression is function
    // parameter; since return expression w is implicitly movable and function
    // parameter, w first treated as rvalue, resulting in move being performed
    // (as of C++20)
    throw w;
}

Widget func_7(Widget&& w) {
    // copy elision is not allowed for several reasons (e.g., cv-unqualified
    // return type does not match cv-unqualified return-expression type, not
    // automatic object); since return expression w is implicitly movable and
    // function parameter, w first treated as rvalue, resulting in move being
    // performed (as of C++20)
    return w;
}

Widget func_8(Widget& w) {
    Widget&& x = std::move(w);
    // copy elision is not allowed for several reasons (e.g., cv-unqualified
    // return type does not match cv-unqualified return-expression type and not
    // automatic object); since return expression x is implicitly movable and
    // declared in function body, x first treated as rvalue, resulting in move
    // being performed (as of C++20)
    return x;
}
class Widget {
public:
    Widget();
    Widget(const Widget&);
    Widget(Widget&&);
    // ...
};

class Gadget {
public:
    Gadget();
    Gadget(const Gadget&);
    Gadget(Gadget&&);
    Gadget(const Widget& w); // copying converting constructor
    Gadget(Widget&& w); // moving converting constructor
    // ...
};

class Doodad {
public:
    Doodad();
    Doodad(const Doodad&);
    Doodad(Doodad&&);
    operator Widget() const &; // copying conversion operator
    operator Widget() &&; // moving conversion operator
    // ...
};
Gadget func_1() {
    Widget w;
    // copy elision is not permitted since cv-unqualified return type and
    // cv-unqualified return-expression type do not match; since return
    // expression w is implicitly movable and declared in function body, w
    // first treated as rvalue, resulting in move being performed via moving
    // converting constructor
    return w;
}

Widget func_2() {
    Doodad t;
    // copy elision is not permitted since cv-unqualified return type does not
    // match cv-unqualified return-expression type; since return expression t
    // is implicitly movable and declared in function body, t first treated as
    // rvalue, resulting in move being performed via moving conversion operator
    // (as of C++20)
    return t;
}
```cpp
#include <iostream>

class Base {
public:
    Base();
    Base(const Base&);
    Base(Base&&);
    Base& operator=(const Base&);
    Base& operator=(Base&&);
    // ...
};

class Derived : public Base {
public:
    Derived();
    Derived(const Derived&);
    Derived(Derived&&);
    Derived& operator=(const Derived&);
    Derived& operator=(Derived&&);
    // ...
};

Base base_1() {
    Derived x;
    // copy elision is not permitted since cv-unqualified return-expression
    // type does not match cv-unqualified return type; since return expression
    // x is implicitly movable and declared in function body, x first treated
    // as rvalue, resulting in move being performed (as of C++20)
    return x;
}
```
```cpp
class BigInt {
public:
    BigInt();
    BigInt(const BigInt&);
    BigInt(BigInt&&);
    BigInt& operator=(const BigInt&);
    BigInt& operator=(BigInt&&);
    BigInt& operator+=(int);
    BigInt& operator++();
    // ...
};

BigInt func_1(BigInt c) {
    c += 1;
    // copy elision for return value is not allowed since return expression is
    // function parameter; since return expression c is implicitly movable and
    // declared in function parameter list, c first treated as rvalue,
    // resulting in move being performed
    return c;
}
```
BigInt func_2(BigInt c) {
    // copy elision for return value is not allowed since cv-unqualified
    // return-expression type does not match cv-unqualified return type;
    // since return expression is not implicitly movable, copy is performed
    return c += 1;
}

BigInt func_3(const BigInt& c) {
    // copy elision for return value not allowed for several reasons (e.g.,
    // function parameter, not automatic, cv-unqualified type mismatch); since
    // return expression is not implicitly movable, copy is performed
    return BigInt(c) += 1;
}
class Widget {
public:
    Widget();
    Widget(const Widget&);
    Widget(Widget&&);
    // ...
};

Widget func_0() {
    Widget w;
    // copy elision is permitted
    // if not elided, move is performed
    return w;
}

Widget func_1() {
    Widget w;
    // standard seems to suggest copy elision is not permitted since
    // return expression (w) is not name of object, but:
    // Clang 11.0.1 (-std=c++20 -O2) elides copy;
    // MSVC 19.28 (/std:c++20 /O2) elides copy;
    // GCC 10.2 (-std=c++20 -O3) performs move
    return (w);
}
Section 3.5

Rvalue References
Section 3.5.1

Introduction
Rvalue references were added to the language in C++11 in order to provide support for:

1. move operations; and
2. perfect forwarding.

A move operation is used to propagate the value from one object to another, much like a copy operation, except that a move operation makes fewer guarantees, allowing for greater efficiency and flexibility in many situations.

Perfect forwarding relates to being able to pass function arguments from a template function through to another function (called by the template function) while preserving certain properties of those arguments.
A type that includes one or both of the qualifiers `const` and `volatile` is called a cv-qualified type.

A type that is not cv-qualified is called cv-unqualified. [C++17 §6.9.3/1]

Example:
The types `const int` and `volatile char` are cv-qualified. The types `int` and `char` are cv-unqualified.

An object or function that is named by an identifier is said to be named.

An object or function that cannot be referred to by name is said to be unnamed.

Example:
```cpp
std::vector<int> v = {1, 2, 3, 4};
std::vector<int> w;
w = v; // w and v are named
w = std::vector<int>(2, 0);
    // w is named
    // std::vector<int>(2, 0) is unnamed
```
Section 3.5.2

Copying and Moving
Suppose that we have two objects of the same type and we want to propagate the value of one object (i.e., the source) to the other object (i.e., the destination).

This can be accomplished in one of two ways:
1. **Copying** propagates the value of the source object to the destination object without modifying the source object.
2. **Moving** propagates the value of the source object to the destination object and is permitted to modify the source object.

**Copying** is always at least as efficient as copying, and for many types, moving is more efficient than copying.

For some types, **copying does not make sense**, while moving does (e.g., `std::ostream` and `std::istream`).
Consider a class that represents a character buffer (whose size is fixed at run time).

```cpp
class Buffer {
public:
    // ...
private:
    char* data_; // pointer to buffer data
    std::size_t size_; // buffer size (in characters)
};
```

Pictorially, the data structure looks like the following:

How would copying be implemented?

How would moving be implemented?
Buffer Example: Copying

- code for copying from source \( src \) to destination \( dst \) (not self assignment):
  ```cpp
delete [] dst.data_;  
dst.data_ = new T[src.size_];  
dst.size_ = src.size_;  
std::copy_n(src.data_, src.size_, dst.data_);
```

- copying requires: one array delete, one array new, copying of element data, and updating data_ and size_ data members

- copying proceeds as follows:

```
data_       data_       data_
size_       size_       size_
    n          s0         d0
    s1          s1         d1
    ...         ...        ...
    sn-1        sn-1       sm-1
```
Buffer Example: Moving

- code for moving from source `src` to destination `dst`:
  ```cpp
  std::swap(src.data_, dst.data_);
  std::swap(src.size_, dst.size_);
  ```

- moving only requires updating `data_` and `size_` data members
- although not considered here, could also free data array associated with `src` if desirable to release memory as soon as possible
- moving proceeds as follows:

```
src
  data_  
  size_  
    n     

移动前:

dst
  data_  
  size_  
    m     

移动后:

src
  data_  
  size_  
    m     

dst
  data_  
  size_  
    n     
```

```
src
  data_  
  size_  
    n     

移动前:

dst
  data_  
  size_  
    m     

移动后:

src
  data_  
  size_  
    m     

dst
  data_  
  size_  
    n     
```
Moving Versus Copying

- Moving is usually more efficient than copying, often by very large margin.
- So, we should prefer moving to copying.
- We can safely replace a copy by a move when subsequent code does not depend on the value of source object.
- It would be convenient if the language could provide a mechanism for automatically using a move (instead of a copy) in situations where doing so is always guaranteed to be safe.
- For reasons of efficiency, it would also be desirable for the language to provide a mechanism whereby the programmer can override the normal behavior and force a move (instead of a copy) in situations where such a transformation is known to be safe only due to some special additional knowledge about program behavior.
- Rvalue references (in concert with the rules for reference binding and overload resolution) provide the above mechanisms.
Section 3.5.3

References, Reference Binding, and Overload Resolution
A **reference** is an alias (i.e., nickname) for an already existing object.

The language has two kinds of references:

1. Lvalue references
2. Rvalue references

An **lvalue reference** is denoted by `&` (often read as “ref”).

```cpp
int i = 5;
int& j = i; // j is lvalue reference to int
const int& k = i; k is lvalue reference to const int
```

An **rvalue reference** is denoted by `&&` (often read as “ref ref”).

```cpp
int&& i = 5; // i is rvalue reference to int
const int&& j = 17; // j is rvalue reference to const int
```

The act of initializing a reference is known as **reference binding**.

Lvalue and rvalues references differ only in their properties relating to:

- reference binding; and
- overload resolution.
The kinds of expressions, to which lvalue and rvalue references can bind, differ.

For a nonreference type $T$ (such as `int` or `const int`), what kinds of expressions can validly be placed in each of the boxes in the example below?

\[
T & \ r = \boxed{} ; \\
T && \ r = \boxed{} ;
\]

Lvalue and rvalue references also behave differently with respect to overload resolution.

Let $T$ be a cv-unqualified nonreference type. Which overloads of `func` will be called in the example below?

```cpp
T \ operator+(const T&, const T&); 
void \ func(const T&); 
void \ func(T&&); 
T \ x;  
func(x); // calls which version of func? 
func(x + x); // calls which version of func?
```
Implicit lvalue-to-rvalue conversion is disabled when binding to references.\textsuperscript{[C++17 §11.6.3?][C++17 §16.3.3.1.4/1][C++17 §7.1]}

An lvalue reference can bind to an lvalue as long as doing so would not result in the \textit{loss} of any cv qualifiers.

```cpp
const int i = 0;
int& r1 = i; // ERROR: drops const
const int& r2 = i; // OK
const volatile int& r3 = i; // OK
```

The loss of cv qualifiers must be avoided for \textit{const and volatile correctness}.

Similarly, an rvalue reference can bind to an rvalue as long as doing so would not result in the \textit{loss} of any cv qualifiers.

```cpp
const std::string getValue();
std::string&& r1 = getValue(); // ERROR: drops const
const std::string&& r2 = getValue(); // OK
```

Again, the loss of cv qualifiers must be avoided for \textit{const and volatile correctness}. 
An lvalue reference can be bound to an rvalue only if doing so would not result in the *loss* of any cv qualifier and the lvalue reference is `const`.

```cpp
class MyClass {
public:
  std::string& r1 = getConstValue(); // ERROR: drops const
  std::string getConstValue();
  std::string& r2 = getValue(); // OK
  const std::string& r2 = getValue(); // OK
}
```

The requirement that the lvalue reference be `const` is to prevent temporary objects from being modified in a very uncontrolled manner, which can lead to subtle bugs.

An rvalue reference can *never* be bound to an lvalue.

```cpp
int i = 0;
int&& r1 = i; // ERROR: cannot bind to lvalue
int&& r2 = 42; // OK
```

Allowing rvalue reference to bind to lvalues would violate the principle of type-safe overloading, which can lead to subtle bugs.
In effect, rvalue references were introduced into the language to allow a function to know if one of its reference parameters is bound to an object whose value is safe to change without impacting other code, namely, an rvalue (i.e., a temporary object or xvalue).

Since an rvalue reference can only bind to an rvalue, any rvalue reference parameter to a function is *guaranteed* to be bound to a temporary object or xvalue.

Example:

```cpp
class Thing {
public:
    // Move constructor
    // parameter x known to be safe to use as source for move
    Thing(Thing&& x);
    // Move assignment operator
    // parameter x known to be safe to use as source for move
    Thing& operator=(Thing&& x);
    // ...
};
// parameter x known to be safe to modify
void func(Thing&& x);
```

If rvalue references could bind to lvalues, the above guarantee could not be made, as an rvalue reference could then refer to an object whose value cannot be changed safely, namely, an lvalue.
If non-const lvalue references could bind to rvalues, temporary objects could be modified in many undesirable circumstances.

```cpp
void func(int& x) {
    // ...
}

int main() {
    int i = 1;
    int j = 2;
    func(i + j);
    // ERROR: cannot bind non-const lvalue
    // reference to rvalue
    // What would be consequence if allowed?
}
```
## Reference Binding Summary

<table>
<thead>
<tr>
<th></th>
<th>Rvalue</th>
<th></th>
<th>Lvalue</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T</td>
<td>const</td>
<td>volatile</td>
<td>const</td>
<td>volatile</td>
</tr>
<tr>
<td>T&amp;</td>
<td>✓</td>
<td>✓ C</td>
<td>✓ V</td>
<td>✓ C,V</td>
<td>✓ X</td>
</tr>
<tr>
<td>const</td>
<td>✓ ✓</td>
<td>✓ ✓ V</td>
<td>✓ V</td>
<td>✓ X</td>
<td>✓ X</td>
</tr>
<tr>
<td>T&amp;</td>
<td>✓ ✓</td>
<td>✓ ✓ ✓</td>
<td>✓ ✓</td>
<td>✓ X</td>
<td>✓ X</td>
</tr>
<tr>
<td>volatile</td>
<td>✓ ✓</td>
<td>✓ ✓ ✓</td>
<td>✓ ✓</td>
<td>✓ X</td>
<td>✓ X</td>
</tr>
<tr>
<td>T&amp;</td>
<td>✓ ✓</td>
<td>✓ ✓ ✓ ✓</td>
<td>✓ ✓</td>
<td>✓ X</td>
<td>✓ X</td>
</tr>
<tr>
<td>const</td>
<td>✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓</td>
<td>✓ X</td>
<td>✓ X</td>
</tr>
<tr>
<td>volatile</td>
<td>✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓</td>
<td>✓ X</td>
<td>✓ X</td>
</tr>
<tr>
<td>T&amp;</td>
<td>✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓</td>
<td>✓ X</td>
<td>✓ X</td>
</tr>
<tr>
<td>const</td>
<td>✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓</td>
<td>✓ X</td>
<td>✓ X</td>
</tr>
<tr>
<td>volatile</td>
<td>✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td>✓ ✓</td>
<td>✓ X</td>
<td>✓ X</td>
</tr>
</tbody>
</table>

✓: allowed  
C: strips `const`  
V: strips `volatile`  
X: other
#include <string>
using std::string;

string value() {
    return string("Hello");
}

const string constValue() {
    return string("World");
}

int main() {
    string i("mutable");
    const string j("const");

    string& r01 = i;  // ERROR: drops const
    string& r02 = j;  // ERROR: drops const
    string& r03 = value();  // ERROR: non-const lvalue reference from rvalue
    string& r04 = constValue();  // ERROR: non-const lvalue reference from rvalue

    const string& r05 = i;  // ERROR: rvalue reference from lvalue
    const string& r06 = j;  // ERROR: rvalue reference from lvalue
    const string& r07 = value();    
    const string& r08 = constValue();

    string&& r09 = i;  // ERROR: rvalue reference from lvalue
    string&& r10 = j;  // ERROR: rvalue reference from lvalue
    string&& r11 = value();    
    string&& r12 = constValue();  // ERROR: drops const

    const string&& r13 = i;  // ERROR: rvalue reference from lvalue
    const string&& r14 = j;  // ERROR: rvalue reference from lvalue
    const string&& r15 = value();    
    const string&& r16 = constValue();
}
Lvalues strongly prefer binding to lvalue references.

Rvalues strongly prefer binding to rvalue references.

Modifiable lvalues and rvalues weakly prefer binding to non-const references.
# Overload Resolution Summary

<table>
<thead>
<tr>
<th></th>
<th>Priority</th>
<th>Rvalue</th>
<th>Lvalue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>T</td>
<td>const</td>
<td>volatile</td>
<td>volatile</td>
</tr>
<tr>
<td>T&amp;&amp;</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>const</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>T&amp;&amp;</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>volatile</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T&amp;&amp;</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>const volatile</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>T&amp;</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>const T&amp;</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>volatile</td>
<td>T&amp;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>const volatile</td>
<td>T&amp;</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>volatile</td>
<td>T&amp;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>const volatile</td>
<td>T&amp;</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>
#include <iostream>
#include <string>

void func(std::string& x) {
    std::cout << "func(std::string&) called\n";
}

void func(const std::string& x) {
    std::cout << "func(const std::string&) called\n";
}

void func(std::string&& x) {
    std::cout << "func(std::string&&) called\n";
}

void func(const std::string&& x) {
    std::cout << "func(const std::string&&) called\n";
}

const std::string&& constValue(const std::string&& x) {
    return static_cast<const std::string&&>(x);
}

int main() {
    const std::string cs("hello");
    std::string s("world");
    func(s);    
    func(cs);   
    func(cs + s);
    func(constValue(cs + s));
}

/* Output:
func(std::string&) called
func(const std::string&) called
func(std::string&&) called
func(const std::string&&) called
*/
```cpp
#include <iostream>
#include <string>

void func(const std::string& x) {
    std::cout << "func(const std::string&) called\n";
}

void func(std::string&& x) {
    std::cout << "func(std::string&&) called\n";
}

const std::string&& constValue(const std::string&& x) {
    return static_cast<const std::string&&>(x);
}

int main() {
    const std::string cs("hello");
    std::string s("world");
    func(s);
    func(cs);
    func(cs + s);
    func(constValue(cs + s));
}

/* Output:
func(const std::string&) called
func(const std::string&) called
func(const std::string&) called
func(const std::string&) called
*/
```
If an rvalue reference could bind to an lvalue, this would violate the principle of type-safe overloading.

```cpp
#include <iostream>
#include <string>

template <class T>
class Container {
public:
    // ...
    // Forget to provide the following function:
    // void push_back(const T& value); // Copy semantics
    void push_back(T&& value); // Move semantics
private:
    // ...
};

int main() {
    std::string s("Hello");
    Container<std::string> c;
    // What would happen here if lvalues
    // could bind to rvalue references?
    c.push_back(s);
    std::cout << s << '\n';
}
```
Section 3.5.4

Moving
A non-template constructor for class \( T \) is a **move constructor** if it can be called with one parameter that is of type \( T&&, \) \texttt{const T&&, volatile T&&, or const volatile T&&}. [C++17 §15.8.1/2]

Example:

```cpp
class T {
public:
    T();
    T(const T&); // copy constructor
    T(T&&); // move constructor
    // ...
};

T a;
T b(std::move(a)); // calls T::T(T&&)
T c(b); // calls T::T(const T&)
```
A **move assignment operator** `T::operator=` is a non-static non-template member function of class `T` with exactly one parameter of type `T&&`, `const T&&`, `volatile T&&`, or `const volatile T&&`.

[C++17 §15.8.2/3]

Example:

```cpp
class T {
public:
    T();
    T(const T&); // copy constructor
    T(T&&); // move constructor
    T& operator=(const T&); // copy assignment operator
    T& operator=(T&&); // move assignment operator
    // ...
};

T func(int);
T a;
T b;
a = func(1); // calls T::operator=(T&&)
b = a; // calls T::operator=(const T&)
```
Recall the class from earlier that represents a character buffer (whose size is fixed at run time).

```cpp
class Buffer {
public:
    // ...
private:
    char* data_; // pointer to buffer data
    std::size_t size_; // buffer size (in characters)
};
```

Pictorially, the data structure looks like the following:

![Buffer Diagram](image)
```cpp
#include <algorithm>
#include <cstddef>

class Buffer {
public:
    Buffer(std::size_t size, char value = 0) :
        size_(size), data_(new char[size])
    {std::fill_n(data_, size, value);} 
    Buffer(const Buffer& b) : size_(b.size_), data_(new char[b.size_])
    {std::copy_n(b.data_, b.size_, data_);} 
    Buffer& operator=(const Buffer& b) {
        if (this != &b) {
            delete[] data_; 
            size_ = b.size_; data_ = new char[b.size_];
            std::copy_n(b.data_, b.size_, data_); 
        }
        return *this;
    }
    ~Buffer() {delete[] data_;}
private:
    char* data_; // pointer to buffer data 
    std::size_t size_; // buffer size (in characters)
};

Buffer getBuffer() {return Buffer(65536, 'A');}

int main() {
    Buffer x(0);
    Buffer y = getBuffer(); // construct from temporary object 
    x = Buffer(32768, 'B'); // assign from temporary object
}```
# Example With Move Construction/Assignment

```cpp
#include <algorithm>
#include <cstddef>
#include <utility>

class Buffer {
public:
    Buffer(std::size_t size, char value = 0) :
        size_(size), data_(new char[size])
    {std::fill_n(data_, size, value);}
    Buffer(const Buffer& b) : size_(b.size_), data_(new char[b.size_])
    {std::copy_n(b.data_, b.size_, data_);}
    Buffer& operator=(const Buffer& b) {
        if (this != &b) {
            delete[] data_;  
            size_ = b.size_; data_ = new char[b.size_];
            std::copy_n(b.data_, b.size_, data_);
        }
        return *this;
    }
    // Move constructor
    Buffer(Buffer&& b) : size_(b.size_), data_(b.data_)
    {b.size_ = 0; b.data_ = nullptr;}
    // Move assignment operator
    Buffer& operator=(Buffer&& b) {
        std::swap(size_, b.size_);
        std::swap(data_, b.data_);
        return *this;
    }
    ~Buffer() {delete[] data_;}
private:
    char* data_; // pointer to buffer data
    std::size_t size_; // buffer size (in characters)
};

Buffer getBuffer() {return Buffer(65536, 'A');}

int main() {
    Buffer x(0);
    Buffer y = getBuffer(); // construct from temporary object
    x = Buffer(32768, 'B'); // assign from temporary object
}
```
As we have seen, a reference parameter of a function that is bound to modifiable rvalue can be modified safely (i.e., no observable change in behavior outside of function).

Sometimes may want to allow a move to be used instead of a copy, when this would not normally be permitted.

We can allow moves by casting to a non-const rvalue reference.

This casting can be accomplished by `std::move`, which is declared (in the header file `utility`) as:

```cpp
template <class T>
constexpr typename std::remove_reference<T>::type&& move(T&&) noexcept;
```

For an object `x` of type `T`, `std::move(x)` is similar to `static_cast<T&&>(x)` but saves typing and still works correctly when `T` is a reference type (a technicality yet to be discussed).
Prior to C++11, a swap function (such as `std::swap`) would typically look like this:

```cpp
template <class T>
void swap(T& x, T& y) {
    T tmp(x); // copy x to tmp
    x = y;    // copy y to a
    y = tmp;  // copy tmp to y
}
```

In the above code, a swap requires three *copy* operations (namely, one copy constructor call and two copy assignment operator calls).

For many types `T`, this use of copying is *very inefficient*.

Furthermore, the above code requires that `T` *must be copyable* (i.e., `T` has a copy constructor and copy assignment operator).

In C++11, we can write a much better swap function.
As of C++11, a swap function would typically look like this:

```
1 template <class T>
2 void swap(T& x, T& y) {
3     T tmp(std::move(x)); // move x to tmp
4     x = std::move(y);  // move y to x
5     y = std::move(tmp); // move tmp to y
6 }
```

- The function `std::move` casts its argument to an rvalue reference.
- Assuming that `T` provides a move constructor and move assignment operator, a swap requires three `move` operations (i.e., one move constructor call and two move assignment operator calls) and no copying.
- The use of `std::move` above is essential in order for copying to be avoided.
Implication of Rvalue-Reference Type Function Parameters

- Due to the properties of rvalue references, a function parameter of rvalue-reference type may be regarded as being bound to an object whose value will not be relied upon in the caller.

- Therefore, an object associated with a function parameter of rvalue-reference type can always be safely modified (i.e., without fear of adversely affecting the caller).

- This fact can often be exploited in order to obtain more efficient code.

- Consider the code for a function with the following declaration:

  ```cpp
  void func(std::vector<double>&& x);
  ```

- Since `x` is of rvalue-reference type, we are guaranteed that the caller will not rely upon the value of the object referenced by `x`.

- If obliterating the value of `x` would allow us to more efficiently implement `func`, we can safely do so.

- For example, we could safely modify `x` in place or move from it, without fear of adversely affecting the caller.
every nonstatic member function has implicit parameter *this
possible to provide reference qualifiers for implicit parameter
allows overloading member functions on lvalueness/rvalueness of *this
cannot mix reference qualifiers and non-reference qualifiers in single overload set
provides mechanism for treating lvalue and rvalue cases differently
useful for facilitating move semantics or preventing operations not appropriate for lvalues or rvalues
```cpp
#include <iostream>

class Widget {
public:
    void func() const &
    {
        std::cout << "const lvalue\n";
    }
    void func() &
    {
        std::cout << "non-const lvalue\n";
    }
    void func() const &&
    {
        std::cout << "const rvalue\n";
    }
    void func() &&
    {
        std::cout << "non-const rvalue\n";
    }
};

const Widget getConstWidget() { return Widget(); }

int main(){
    Widget w;
    const Widget cw;
    w.func(); // non-const lvalue
    cw.func(); // const lvalue
    Widget().func(); // non-const rvalue
    getConstWidget().func(); // const rvalue
}
```
```cpp
class Int {
  public:
    Int(int x = 0) : value_(x) {} // only allow prefix increment for lvalues
    Int& operator++() & {++value_; return *this;}
    // The following allows prefix increment for rvalues:
    // Int& operator++() {++value_; return *this;}
    // ...
  
  private:
    int value_;};

int one() {return 1;} int main() {
  int i = 0;
  int j = ++i; // OK
  // int k = ++one(); // ERROR (not lvalue)
  Int x(0);
  Int y = ++x; // OK
  // Int z = ++Int(1); // ERROR (not lvalue)
}
```cpp
#include <iostream>
#include <vector>
#include <utility>

class Buffer {
public:
    Buffer(char value = 0) : data_(1024, value) {}
    void data(std::vector<char>& x) const &
        {x = data_;}
    void data(std::vector<char>& x) &&
        {x = std::move(data_);} 
    // ...

private:
    std::vector<char> data_; 
};

Buffer getBuffer() {return Buffer(42);} 

int main() {
    std::vector<char> d;
    Buffer buffer;
    buffer.data(d); // copy into d
    getBuffer().data(d); // move into d 
} 
```
Section 3.5.5

Reference Collapsing and Forwarding References
A reference to a reference is not allowed, since such a construct clearly makes no sense. [C++17 §11.3.2/5]

```cpp
int i = 0;
int& & j = i; // ILLEGAL: reference to reference
```

Although one cannot directly create a reference to a reference, a reference to a reference can arise indirectly in several contexts.

**Typedef name:**

```cpp
typedef int& RefToInt;
typedef RefToInt& T; // reference to reference
```

**Template function parameters:**

```cpp
template <class T> T func(const T& x) { return x; }
int x = 1;
func<int&>(x); // reference to reference
```

**Decltype specifier:**

```cpp
int i = 1;
decltype((i))& j = i; // reference to reference
```
Auto specifier:

```cpp
int i = 0;
auto&& j = i; // reference to reference
```

Class templates:

```cpp
template <class T>
struct Thing {
    void func(T&&) {} // reference to reference
    // if T is reference type
};

Thing<int&> x;
```

If, during type analysis, a reference to a reference type is obtained, the reference to reference is converted to a simple reference via a process called reference collapsing.
Let $TR$ denote a type that is a reference to type $T$ (where $T$ may be cv qualified).

The effect of reference collapsing is summarized below. [C++17 §11.3.2/6].

<table>
<thead>
<tr>
<th>Before Collapse</th>
<th>After Collapse</th>
</tr>
</thead>
<tbody>
<tr>
<td>$TR$&amp;</td>
<td>$T$&amp;</td>
</tr>
<tr>
<td>$const$ $TR$&amp;</td>
<td>$T$&amp;</td>
</tr>
<tr>
<td>$volatile$ $TR$&amp;</td>
<td>$T$&amp;</td>
</tr>
<tr>
<td>$const$ $volatile$ $TR$&amp;</td>
<td>$T$&amp;</td>
</tr>
<tr>
<td>$TR$&amp;&amp;</td>
<td>$TR$</td>
</tr>
<tr>
<td>$const$ $TR$&amp;&amp;</td>
<td>$TR$</td>
</tr>
<tr>
<td>$volatile$ $TR$&amp;&amp;</td>
<td>$TR$</td>
</tr>
<tr>
<td>$const$ $volatile$ $TR$&amp;&amp;</td>
<td>$TR$</td>
</tr>
</tbody>
</table>

In other words:

- An rvalue reference to an lvalue reference yields an lvalue reference.
- Any cv qualifiers applied to a reference type are discarded (since cv qualifiers cannot be applied to a reference).
Due to reference collapsing, `T&&` syntax may not always be an rvalue reference. Example:

```cpp
using IntRef = int&;
int i = 0;
IntRef&& r = i; // r is int& (i.e., lvalue reference)
```

Example:

```cpp
using IntRef = int&;
using IntRefRef = int&&;
using ConstIntRefRefRef = const int&&;
using ConstIntRef = const int&;
using T1 = const IntRef&; // T1 is int&
using T2 = const IntRefRef&; // T2 is int&
using T3 = IntRefRef&&; // T3 is int&&
using T4 = ConstIntRef&&; // T4 is const int&
using T5 = ConstIntRefRef&&; // T5 is const int&&
```

Example:

```cpp
int i = 0;
int& j = i;
auto&& k = j;
// j cannot be inferred to have type int
// since rvalue reference cannot be bound to lvalue
// j inferred to have type int&
// reference collapsing of int& && yields int&
A *cv-unqualified* rvalue reference that appears in a type-deducing context for template parameters is called a **forwarding reference**. [C++17 §17.8.2.1/3]

Type deduction for template parameters of template functions is defined in such a way as to facilitate perfect forwarding.

Consider the following template-parameter type-deduction scenario:

```cpp
template<class T>
void f(T&& p);
f(expr); // invoke f
```

Let \( E \) denote the type of the expression \( expr \). The type \( T \) is then deduced as follows:

1. If \( expr \) is an *lvalue*, \( T \) is deduced as \( E& \), in which case the type of \( p \) yielded by reference collapsing is \( E& \).
2. If \( expr \) is an *rvalue*, \( T \) is deduced as \( E \), in which case \( p \) will have the type \( E&& \).

Thus, the type \( T&& \) will be an lvalue reference type if \( expr \) is an lvalue, and an rvalue reference type if \( expr \) is an rvalue.

Therefore, the lvalue/rvalue-ness of \( expr \) can be determined *inside* \( f \) based on whether \( T&& \) is an lvalue reference type or rvalue reference type.
```cpp
#include <utility>

template <class T> void f(T&& p);

int main() {
    int i = 42;
    const int ci = i;
    const int& rci = i;
    f(i);
    // i is lvalue with type int
    // T is int&
    // p has type int&
    f(ci);
    // ci is lvalue with type const int
    // T is const int&
    // p has type const int&
    f(rci);
    // rci is lvalue with type const int&
    // T is const int&
    // p has type const int&
    f(2);
    // 2 is rvalue with type int
    // T is int
    // p has type int&&
    f(std::move(i));
    // std::move(i) is rvalue with type int&&
    // T is int
    // p has type int&&
}
```
Section 3.5.6

Perfect Forwarding
- **Perfect forwarding** is the act of passing a template function’s arguments to another function:
  - without rejecting any arguments that can be passed to that other function
  - without losing any information about the arguments’ cv-qualifications or lvalue/rvalue-ness; and
  - without requiring overloading.

- In C++03, for example, the best approximations of perfect forwarding turn all rvalues into lvalues and require at least two (and often more) overloads.
Consider a template function `wrapper` and another function `func`, each of which takes one argument.

Suppose that we want to perfectly forward the argument of `wrapper` to `func`.

The function `wrapper` is to do nothing other than simply call `func`.

In doing so, `wrapper` must pass its actual argument through to `func`.

This must be done in such a way that the argument to `wrapper` and argument to `func` have identical properties (i.e., match in terms of cv-qualifiers and lvalue/rvalue-ness).

In other words, the following two function calls must have identical behavior, where `expr` denotes an arbitrary expression:

```
wrapper(expr);
func(expr);
```

The solution to a perfect-forwarding problem, such as this one, turns out to be more difficult than it might first seem.
For our first attempt, we propose the following code for the (template) function \texttt{wrapper}:

```cpp
template <class T>
void wrapper(T p) {
    func(p);
}
```

If \texttt{func} takes its parameter by reference, calls to \texttt{wrapper} and \texttt{func} (with the same argument) can have different behaviors.

Suppose, for example, that we have the following declarations:

```cpp
void func(int&); // uses pass by reference
int i;
```

Then, the following two function calls are \textit{not equivalent}:

```cpp
wrapper(i);
// T is deduced as int
// copy of i passed to func
// wrapper cannot change i

func(i);
// i passed by reference
// func can change i
```

Problem: The original and forwarded arguments are \textit{distinct objects}.
For our second attempt, we propose the following code for the (template) function `wrapper`:

```cpp
template <class T>
void wrapper(T& p) {
    func(p);
}
```

If, for example, the function argument is an rvalue (such as a non-string literal or temporary object), calls to `wrapper` and `func` (with the same argument) can have different behaviors.

Suppose, for example, that we have the following declaration:

```cpp
void func(int); // uses pass by value
```

Then, the following two function calls are not equivalent:

```cpp
wrapper(42);
// T is deduced as int
// ERROR: cannot bind rvalue to nonconst lvalue reference

func(42);
// OK
```

Problem: The original and forwarded arguments do not match in terms of lvalue/rvalue-ness.
For our third attempt, we propose the following code for the (template) function wrapper:

```cpp
#include<iostream>
using namespace std;

template <class T>
void wrapper(const T& p) {
    func(p);
}
```

If, for example, the function argument is a non-const object, calls to wrapper and func (with the same argument) will have different behaviors.

Suppose, for example, that we have the following declaration:

```cpp
void func(int&);
int i;
```

Then, the following two function calls are not equivalent:

```cpp
wrapper(i);
// ERROR: wrapper cannot call func, as this
// would discard const qualifier

func(i);
// OK
```

Problem: The original and forwarded arguments do not match in terms of cv-qualifiers.
Finally, we propose the following code for the (template) function \texttt{wrapper}:

\begin{verbatim}
template <class T>
void wrapper(T&& p) {
    func(static_cast<T&&>(p));
}
\end{verbatim}

Consider now, for example, the following scenario:

\begin{verbatim}
int i = 42;
const int ci = i;
int& ri = i;
const int& rci = i;
wrapper(expr); // invoke wrapper
\end{verbatim}

The parameter \texttt{p} is an alias for the object yielded by the expression \texttt{expr}.

The argument \texttt{expr} and argument to \texttt{func} match in terms of cv-qualifiers and lvalue/rvalue-ness.

<table>
<thead>
<tr>
<th>expr</th>
<th>Type</th>
<th>Category</th>
<th>T</th>
<th>Type (T&amp;&amp;)</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>int</td>
<td>lvalue</td>
<td>int&amp;</td>
<td>int&amp;</td>
<td>lvalue</td>
</tr>
<tr>
<td>ci</td>
<td>const int</td>
<td>lvalue</td>
<td>const int&amp;</td>
<td>const int&amp;</td>
<td>lvalue</td>
</tr>
<tr>
<td>ri</td>
<td>int&amp;</td>
<td>lvalue</td>
<td>int&amp;</td>
<td>int&amp;</td>
<td>lvalue</td>
</tr>
<tr>
<td>rci</td>
<td>const int&amp;</td>
<td>lvalue</td>
<td>const int&amp;</td>
<td>const int&amp;</td>
<td>lvalue</td>
</tr>
<tr>
<td>42</td>
<td>int</td>
<td>rvalue</td>
<td>int</td>
<td>int</td>
<td>rvalue</td>
</tr>
</tbody>
</table>
Although we only considered one specific scenario on the previous slide, the solution works in general.

That is, the wrapper function from the previous slide will perfectly forward its single argument, regardless of what the argument happens to be (or which overload of func is involved).

Thus, we have a general solution to the perfect-forwarding problem in the single-argument case.

This solution is easily extended to an arbitrary number of arguments.
The `std::forward` Template Function

- To avoid the need for an explicit type-cast operation when forwarding an argument, the standard library provides the `std::forward` function specifically for performing such a type conversion.

- The template function `forward` is defined as:

  ```cpp
  template<class T>
  T&& forward(typename std::remove_reference<T>::type& x) noexcept {
      return static_cast<T&&>(x);
  }
  ```

- A typical usage of `forward` might look something like:

  ```cpp
  template <class T1, class T2>
  void wrapper(T1&& x1, T2&& x2) {
      func(std::forward<T1>(x1), std::forward<T2>(x2));
  }
  ```

- The expression `forward<T>(a)` is an lvalue if `T` is an lvalue reference type and an rvalue otherwise.

- The use of `std::forward` instead of an explicit type cast improves code readability by making the programmer’s intent clear.
We now revisit the perfect-forwarding example from earlier.

In the earlier example, perfect forwarding was performed by the following function:

```cpp
template <class T>
void wrapper(T&& e) {
    func(static_cast<T&&>(e));
}
```

The above code can be made more readable, however, by rewriting it to make use of `std::forward` as follows:

```cpp
template <class T>
void wrapper(T&& e) {
    func(std::forward<T>(e));
}
```
```cpp
#include <iostream>
#include <string>
#include <utility>

void func(std::string& s) {
    std::cout << "func(std::string&) called\n";
}

void func(std::string&& s) {
    std::cout << "func(std::string&&) called\n";
}

template <class T>
void wrapper(T&& x) {
    func(std::forward<T>(x));
}

template <class T>
void buggy_wrapper(T x) {func(x);}

int main() {
    using namespace std::literals;
    std::string s("Hi"s);
    wrapper(s); // which overload of func called?
    buggy_wrapper(s); // which overload of func called?
    wrapper("Hi"s); // which overload of func called?
    buggy_wrapper("Hi"s); // which overload of func called?
}
```
A **wrapper function** is simply a function used to invoke another function, possibly with some additional processing.

**Example:**

```cpp
#include <iostream>
#include <utility>
#include <string>

std::string emphasize(const std::string& s)
{
    return s + "!";
}

std::string emphasize(std::string&& s)
{
    return s + "!!!!!";
}

template <class A>
auto wrapper(A&& arg) {
    std::cout << "Calling with argument " << arg << "\n";
    auto result = emphasize(std::forward<A>(arg));
    std::cout << "Return value " << result << "\n";
    return result;
}

int main() {
    std::string s("Bonjour");
    wrapper(s);
    wrapper(std::string("Hello"));
}
```
Perfect-Forwarding Use Case: Factory Functions
A factory function is simply a function used to create objects.
Often, perfect forwarding is used by factory functions in order to pass
arguments through to a constructor, which performs the actual object
creation.
■ Example:
■

■

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19

#include
#include
#include
#include
#include

<iostream>
<string>
<complex>
<utility>
<memory>

// Make an object of type T.
template<typename T, typename Arg>
std::shared_ptr<T> factory(Arg&& arg) {
return std::shared_ptr<T>(
new T(std::forward<Arg>(arg)));
}
int main() {
using namespace std::literals;
auto s(factory<std::string>("Hello"s));
auto z(factory<std::complex<double>>(1.0i));
std::cout << *s << ’ ’ << *z << ’\n’;
}

Copyright © 2015–2021 Michael D. Adams

Programming in C++

Version 2021-04-01

1107


Many container classes provide an operation that creates a new element directly inside the container, often referred to as an **emplace operation**.

Some or all of the arguments to a member function performing an emplace operation correspond to arguments for a constructor invocation.

Thus, an emplace operation typically employs perfect forwarding.

The member function performing the emplace operation forwards some or all of its arguments to the constructor responsible for actually creating the new object.

Some examples of emplace operations in the standard library include:

- `std::list` class: `emplace`, `emplace_back`, `emplace_front`
- `std::vector` class: `emplace`, `emplace_back`
- `std::set` class: `emplace`, `emplace_hint`
- `std::forward_list` class: `emplace_front`, `emplace_after`
Other Perfect-Forwarding Examples

- `std::thread` constructor uses forwarding to pass through arguments to thread function
- `std::packaged_task` function-call operator uses forwarding to pass through arguments to associated function
- `std::async` uses forwarding to pass through arguments to specified callable entity
- `std::make_unique` forwards arguments to `std::unique_ptr` constructor
- `std::make_shared` forwards arguments to `std::shared_ptr` constructor
Section 3.5.7

References


2. S. Meyers. Adventures in Perfect Forwarding, Facebook C++ Conference. Menlo Park, CA, USA, June 2, 2012. Available online at https://www.facebook.com/Engineering/videos/10151094464083109. This talk introduces perfect forwarding and discusses matters such as how to specialize forwarding templates and how to address interactions between forwarding and the pimpl idiom.

Section 3.6

Exceptions
Section 3.6.1

Introduction
Exceptions

- exceptions are language mechanism for handling exceptional (i.e., abnormal) situations
- exceptional situation perhaps best thought of as case when code could not do what it was asked to do and usually (but not always) corresponds to error condition
- exceptions often employed for error handling
- exceptions propagate information from point where error detected to point where error handled
- code that encounters error that it is unable to handle throws exception
- code that wants to handle error catches exception and performs processing necessary to handle error
- exceptions provide convenient way in which to separate error detection from error handling
The Problem

- error detected in low-level code
- want to handle error in high-level code
- must propagate error information up call chain
Traditional Error Handling

- if any error occurs, terminate program
  - overly draconian

- pass error code back from function (via return value, reference parameter, or global object) and have caller check error code
  - errors are ignored by default (i.e., explicit action required to check for error condition)
  - caller may forget to check error code allowing error to go undetected
  - code can become cluttered with many checks of error codes, which can adversely affect code readability and maintainability

- call error handler if error detected
  - may not be possible or practical for handler to recover from particular error (e.g., handler may not have access to all information required to recover from error)
Example: Traditional Error Handling

```cpp
#include <iostream>

bool func3() {
    bool success = false;
    // ...
    return success;
}

bool func2() {
    if (!func3()) { return false; }
    // ...
    return true;
}

bool func1() {
    if (!func2()) { return false; }
    // ...
    return true;
}

int main() {
    if (!func1()) {
        std::cout << "failed\n";
        return 1;
    }
    // ...
}
```
Error Handling With Exceptions

- when error condition detected, signalled by throwing exception (with `throw` statement)
- exception is object that describes error condition
- thrown exception caught by handler (in `catch` clause of `try` statement), which takes appropriate action to handle error condition associated with exception
- handler can be in different function from where exception thrown
- error-free code path tends to be relatively simple, since no need to explicitly check for error conditions
- error condition less likely to go undetected, since uncaught exception terminates program
# Example: Exceptions

```cpp
#include <iostream>
#include <stdexcept>

void func3() {
    bool success = false;
    // ...
    if (!success) { throw std::runtime_error("Yikes!"); }
}

void func2() {
    func3();
    // ...
}

void func1() {
    func2();
    // ...
}

int main() {
    try { func1(); }
    catch (...) {
        std::cout << "failed\n";
        return 1;
    }
    // ...
}
```

```cpp
#include <iostream>
#include <vector>
#include <utility>

std::pair<bool, int> safe_divide(int x, int y) {
    if (!y) {
        return std::pair(false, 0);
    }
    return std::pair(true, x / y);
}

int main() {
    std::vector<std::pair<int, int>> v = {{10, 2}, {10, 0}};
    for (auto p : v) {
        auto result = safe_divide(p.first, p.second);
        if (result.first) {
            int quotient = result.second;
            std::cout << quotient << '
';
        } else {
            std::cerr << "division by zero\n";
        }
    }
}
```
#include <iostream>
#include <stdexcept>
#include <utility>
#include <vector>

int safe_divide(int x, int y) {
    if (!y) {
        throw std::overflow_error("divide by zero");
    }
    return x / y;
}

int main() {
    std::vector<std::pair<int, int>> v = {{10, 2}, {10, 0}};
    for (auto p : v) {
        try {
            std::cout << safe_divide(p.first, p.second) << '
';
        } catch (const std::overflow_error& e) {
            std::cerr << "division by zero\n";
        }
    }
}
safe_add Example: Traditional Error Handling

```c++
#include <limits>
#include <vector>
#include <iostream>

std::pair<bool, int> safe_add(int x, int y) {
    return ((y > 0 && x > std::numeric_limits<int>::max() - y) 
        || (y < 0 && x < std::numeric_limits<int>::min() - y)) ? 
        std::pair(false, 0) : std::pair(true, x + y);
}

int main() {
    constexpr int int_min = std::numeric_limits<int>::min();
    constexpr int int_max = std::numeric_limits<int>::max();
    std::vector<std::pair<int, int>> v{
        {int_max, int_max}, {1, 2}, {int_min, int_min},
        {int_max, int_min}, {int_min, int_max}
    };
    for (auto x : v) {
        auto result = safe_add(x.first, x.second);
        if (result.first) {
            std::cout << result.second << '
';
        } else {
            std::cout << "overflow\n";
        }
    }
}
```
safe_add Example: Exceptions

```cpp
#include <limits>
#include <vector>
#include <iostream>
#include <stdexcept>

int safe_add(int x, int y) {
    return ((y > 0 && x > std::numeric_limits<int>::max() - y) 
             || (y < 0 && x < std::numeric_limits<int>::min() - y)) ? 
       throw std::overflow_error("addition") : x + y;
}

int main() {
    constexpr int int_min = std::numeric_limits<int>::min();
    constexpr int int_max = std::numeric_limits<int>::max();
    std::vector<std::pair<int, int>> v{ 
        {int_max, int_max}, {1, 2}, {int_min, int_min},
        {int_max, int_min}, {int_min, int_max}
    };
    for (auto x : v) {
        try {
            int result = safe_add(x.first, x.second);
            std::cout << result << '
';
        }
        catch (const std::overflow_error&) {
            std::cout << "overflow\n";
        }
    }
}
```
advantages of exceptions:

- exceptions allow for error handling code to be easily separated from code that detects error
- exceptions can easily pass error information many levels up call chain
- passing of error information up call chain managed by language (no explicit code required)

disadvantages of exceptions:

- writing code that always behaves correctly in presence of exceptions requires great care (as we shall see)
- although possible to have no execution-time cost when exceptions not thrown, still have memory cost (to store information needed for stack unwinding for case when exception is thrown)
Section 3.6.2

Exceptions
- exceptions are objects
- type of object used to indicate kind of error
- value of object used to provide details about particular occurrence of error
- exception object can have any type (built-in or class type)
- for convenience, standard library provides some basic exception types
- all exception classes in standard library derived (directly or indirectly) from `std::exception` class
- exception object is propagated from one part of code to another by throwing and catching
- exception processing disrupts normal control flow
### Standard Exception Classes

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>logic_error</td>
<td>faulty logic in program</td>
</tr>
<tr>
<td>runtime_error</td>
<td>error caused by circumstances beyond scope of program</td>
</tr>
<tr>
<td>bad_typeid</td>
<td>invalid operand for <code>typeid</code> operator</td>
</tr>
<tr>
<td>bad_cast</td>
<td>invalid expression for <code>dynamic_cast</code></td>
</tr>
<tr>
<td>bad_weak_ptr</td>
<td><code>bad weak_ptr</code> given</td>
</tr>
<tr>
<td>bad_function_call</td>
<td>function has no target</td>
</tr>
<tr>
<td>bad_alloc</td>
<td>storage allocation failure</td>
</tr>
<tr>
<td>bad_exception</td>
<td>use of invalid exception type in certain contexts</td>
</tr>
<tr>
<td>bad_variant_access</td>
<td>variant accessed in invalid way</td>
</tr>
</tbody>
</table>
### Exception Classes Derived from `bad_cast` Class

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>bad_any_cast</code></td>
<td>invalid cast for any</td>
</tr>
</tbody>
</table>

### Exception Classes Derived from `logic_error` Class

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>domain_error</code></td>
<td>domain error (e.g., square root of negative number)</td>
</tr>
<tr>
<td><code>invalid_argument</code></td>
<td>invalid argument</td>
</tr>
<tr>
<td><code>length_error</code></td>
<td>length too great (e.g., resize <code>vector</code> beyond <code>max_size</code>)</td>
</tr>
<tr>
<td><code>out_of_range</code></td>
<td>out of range argument (e.g., subscripting error in <code>vector::at</code>)</td>
</tr>
<tr>
<td><code>future_error</code></td>
<td>invalid operations on future objects</td>
</tr>
<tr>
<td><code>bad_optional_access</code></td>
<td>optional accessed in invalid way</td>
</tr>
</tbody>
</table>
### Exception Classes Derived from `runtime_error` Class

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>range_error</code></td>
<td>range error</td>
</tr>
<tr>
<td><code>overflow_error</code></td>
<td>arithmetic overflow error</td>
</tr>
<tr>
<td><code>underflow_error</code></td>
<td>arithmetic underflow error</td>
</tr>
<tr>
<td><code>regex_error</code></td>
<td>error in regular expressions library</td>
</tr>
<tr>
<td><code>system_error</code></td>
<td>operating-system or other low-level error</td>
</tr>
</tbody>
</table>

### Exception Classes Derived from `runtime_error::system_error` Class

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>ios_base::failure</code></td>
<td>I/O failure</td>
</tr>
</tbody>
</table>
Section 3.6.3

Throwing and Catching Exceptions
Throwing Exceptions

- throwing exception accomplished by `throw` statement
- throwing exception transfers control to handler
- object is passed
- type of object determines which handlers can catch it
- handlers specified with `catch` clause of `try` block
- for example:
  ```
  throw "OMG!";
  
  can be caught by handler of `const char*` type, as in:
  ```
  try {
      // ...
  }
  catch (const char* p) {
      // handle character string exceptions here
  }
  ```
- throw statement initializes temporary object called **exception object**
- type of exception object determined by `static` type of operand of `throw` (so slicing can occur) [C++17 §18.1/3]
- if thrown object is class object, copy/move constructor and destructor must be accessible [C++17 §18.1/5]
- temporary may be moved/copied several times before caught
- advisable for type of exception object to be user defined to reduce likelihood of different parts of code using type in conflicting ways
exception can be caught by `catch` clause of `try-catch` block
- code that might throw exception placed in `try` block
- code to handle exception placed in `catch` block
- `try-catch` block can have multiple `catch` clauses
- `catch` clauses checked for match in order specified and only first match used
- `catch (...)` can be used to catch any exception

example:

```cpp
try {
    // code that might throw exception
}
catch (const std::logic_error& e) {
    // handle logic_error exception
}
catch (const std::runtime_error& e) {
    // handle runtime_error exception
}
catch (...) {
    // handle other exception types
}
```
catch exceptions by reference in order to:

- avoid copying, which might throw
- allow exception object to be modified and then rethrown
- avoid slicing
```cpp
#include <iostream>
#include <stdexcept>

class Error {
public:
    Error(int value) : value_(value) {}
    Error(Error&& e) : value_(e.value_) {}
    Error(const Error&) { throw std::runtime_error("copy"); }
    int get() const { return value_; }

private:
    int value_; // error code
};

void func2() { throw Error(42); } // might move

void func1() {
    try { func2(); }
    // catch by value (copy throws)
    catch (Error e) {
        std::cerr << "yikes\n";
    }
}

int main() {
    try { func1(); }
    catch (...) { std::cerr << "exception\n"; }
}
```
#include <iostream>

class Base {}

class Derived : public Base {}

void func(Base& x) {
    throw x; // always throws Base
}

int main() {
    Derived d;
    try {func(d);}
    catch (Derived& e) {
        std::cout << "Derived\n";
    }
    catch (...) {
        std::cout << "not Derived\n";
    }
}
```cpp
#include <iostream>

class Base {
public:
    virtual void raise() {throw *this;}
};
class Derived : public Base {
public:
    virtual void raise() {throw *this;}
};

void func(Base& x) {
    x.raise();
}

int main() {
    Derived d;
    try {func(d);}
    catch (Derived& e) {
        std::cout << "Derived
";
    }
    catch (...) {
        std::cout << "not Derived
";
    }
}
```
caught exception can be rethrown by `throw` statement with no operand

eexample:

```cpp
try {
    // code that may throw exception
}
catch (...) {
    throw; // rethrow caught exception
}
```
Rethrowing Example: Exception Dispatcher Idiom

```cpp
void handle_exception() {
    try {throw;}
    catch (const exception_1& e) {
        log_error("exception_1 occurred");
        // ...
    }
    catch (const exception_2& e) {
        log_error("exception_2 occurred");
        // ...
    }
    // ...
}

void func() {
    try {operation();}
    catch (...) {handle_exception();}
    // ...
    try {another_operation();}
    catch (...) {handle_exception();}
}
```

- allows reuse of exception handling code
Transfer of Control from Throw Site to Handler

- when exception is thrown, control is transferred to nearest handler (in catch clause) with matching type, where “nearest” means handler for try block most recently entered (by thread) and not yet exited [C++17 §18.1/2]

- if no matching handler found, `std::terminate()` is called [C++17 §18.3/9]

- as control passes from throw expression to handler, destructors are invoked for all automatic objects constructed since try block entered, where automatic objects destroyed in reverse order of construction [C++17 §18.2/2]

- process of calling destructors for automatic objects constructed on path from try block to throw expression called **stack unwinding** [C++17 §18.2/1]

- object not deemed to be constructed if constructor exits due to exception (in which case destructor will not be invoked)

- do not throw exception in destructor since destructors called during exception processing and throwing exception during exception processing will terminate program
calling `func1` will result in exception being thrown in `func3`  

during stack unwinding, destructors called in order for `second`, `first`, `hello`, `world`, and `bye` (i.e., reverse order of construction); `dave` unaffected
```cpp
#include <iostream>
#include <stdexcept>
#include <string>
#include <utility>

class Widget {
public:
    Widget(const std::string& s) : s_(s) {}
    Widget(const Widget& other) : s_(other.s_) {std::cerr << "copy ctor\n";}
    Widget(Widget&& other) : s_(std::move(other.s_)) {std::cerr << "move ctor\n";}
    std::string get() const { return s_; }
    ~Widget() {std::cerr << "dtor " << s_ << '\n';}
private:
    std::string s_;}

Widget func_1(Widget w) {
    Widget bjarne("bjarne");
    { Widget hello("hello");
        Widget bye("bye");
        throw std::runtime_error("Yikes");
        Widget bonjour("bonjour");
    }
    return bjarne;
}

int main() {
    Widget zaphod("zaphod");
    try {
        Widget ford("ford");
        Widget u = func_1(zaphod);
        Widget arthur("arthur");
    } catch (...) {std::cerr << "exception\n";}
}
```

**objects destroyed during stack unwinding:** bye, hello, bjarne, w, ford
Function Try Blocks

- function try blocks allow entire function to be wrapped in try block
- function returns when control flow reaches end of catch block (return statement needed for non-void function)
- example:

```cpp
#include <iostream>
#include <stdexcept>

int main()
try {
    throw std::runtime_error("yikes");
} 

catch (const std::runtime_error& e) {
    std::cerr << "runtime error " << e.what() << '\n';
}
```

- although function try blocks can be used for any function, most important use cases are for constructors and destructors
- function try block only way to catch exceptions thrown during construction of data members or base objects (which happens before constructor body is entered) or during destruction of data members or base objects (which happens after destructor body exited)
Exceptions and Construction/Destruction

- order of construction (assuming no virtual base classes):
  1. non-virtual base class objects as listed from left to right in class definition
  2. non-static data members as listed from top to bottom in class definition
  3. constructor body

- order of destruction is exact reverse of order of construction, namely:
  1. destructor body
  2. non-static data members as listed from bottom to top in class definition
  3. non-virtual base class objects as listed from right to left in class definition

- lifetime of object begins when constructor completes

- constructor might throw in:
  - constructor of base class object
  - constructor of data member
  - constructor body

- need to perform cleanup for constructor body

- will assume destructors do not throw (since very bad idea to throw in destructor)

- any exception caught in function try block of constructor or destructor rethrown implicitly (at end of catch block) \[C++17 \S 18.3/14\]
```cpp
#include <string>
#include <iostream>

struct Base {
    Base() {}
    ~Base() {};
};

class Widget : public Base {
public:
    Widget() {}
    ~Widget() {};
    // ...
private:
    std::string s_; 
    std::string t_; 
};

int main() {
    Widget w;
    // ...
}
```
```cpp
#include <iostream>
#include <stdexcept>

class Gadget {
public:
    Gadget() {throw std::runtime_error("ctor");}
~Gadget() {} 
};

class Widget {
public:
    // constructor uses function try block
    Widget()
        try {std::cerr << "ctor body\n";}
        catch (...) {std::cerr << "exception in ctor\n";}
    ~Widget() {std::cerr << "dtor body\n";}
private:
    Gadget g_; 
};

int main()
    try {Widget w;}
    catch (...) {
        std::cerr << "terminating due to exception\n";
        return 1;
    }
```
```cpp
#include <iostream>
#include <stdexcept>

struct Gadget {
    Gadget(bool b) {
        if (b) {throw std::runtime_error("yikes");}
    }
};

struct Widget : public Gadget {
    Widget(bool b) try : Gadget(b) {} 
    catch(const std::exception& e) {
        std::cerr << e.what() << ' \n';
        // exception automatically rethrown
    }
};

int main() try {
    Widget v(true);
} catch (const std::exception& e) {
    std::cerr << e.what() << ' \n';
}
```
```cpp
#include <iostream>
#include <stdexcept>

struct Gadget {
    ~Gadget() noexcept(false) {
        throw std::runtime_error("yikes");
    }
};

class Widget : public Gadget {
public:
    ~Widget() try {} 
    catch (const std::exception& e) {
        std::cerr << e.what() << '\n';
        // exception automatically rethrown
    }
};

int main() try {
    Widget w;
} catch (const std::exception& e) {
    std::cerr << e.what() << '\n';
}
```
```cpp
#include <iostream>
#include <stdexcept>

int func(int x) try {
    throw std::runtime_error("whatever");
} catch(const std::exception& e) {
    std::cerr << e.what() << '
';
    return x;
    // exception not automatically rethrown
    // function does not emit exception
}

int main() {
    std::cout << func(42) << '
';
}
```
Section 3.6.4

Exception Specifications
The `noexcept` Specifier

- `noexcept` specifier in function declaration indicates whether or not function can throw exceptions
- `noexcept` specifier with `bool` constant expression argument indicates function does not throw exceptions if expression `true` (otherwise, may throw)
- `noexcept` without argument equivalent to `noexcept(true)`
- except for destructors, not providing `noexcept` specifier equivalent to `noexcept(false)`
- if `noexcept` specifier not provided for destructor, specifier identical to that of implicit declaration (which is, in practice, usually `noexcept`)

[C++17 §15.4/3]

- example:

```cpp
void func1(); // may throw anything
void func2() noexcept(false); // may throw anything
void func3() noexcept(true); // does not throw
void func4() noexcept; // does not throw
template <class T>
void func5(T) noexcept(sizeof(T) <= 4); // does not throw if sizeof(T) <= 4
```
The `noexcept` Specifier (Continued 1)

- exception specification for function is *part of function’s type*
  - example:
    ```cpp
    void f() noexcept;
    auto g = f; // g is noexcept
    ```

- exception specification for function is *not part of function’s signature*
  - consequently, cannot overload on noexcept specifier
  - example:
    ```cpp
    void f();
    void f() noexcept;
    // ERROR: both functions have same signature
    ```
nontrivial `bool` expression for `noexcept` specifier often useful in templates

example (swap function):

```cpp
#include <type_traits>
#include <utility>

// swap two values

template <class T>
void exchange(T& a, T& b) noexcept(
    std::is_nothrow_move_constructible_v<T> &&
    std::is_nothrow_moveAssignable_v<T>) {
    T tmp(std::move(a)); // move construction
    a = std::move(b); // move assignment
    b = std::move(tmp); // move assignment
}
```
if function with `noexcept (true)` specifier throws exception, `std::terminate` is called immediately

example:

```cpp
// This function will terminate the program.
void die_die_die() noexcept {
    throw 0;
}
```

advisable not to use `noexcept (true)` specifier unless clear that no reasonable usage of function can throw (in current or *any future* version of code)

in practice, can often be difficult to guarantee that function will never throw exception (especially when considering *all future* versions of code)
for some (nonreference) class type `T` and some constant `bool` expression `expr`, consider code such as:

```cpp
T func(T) noexcept(expr);
T x;
T y = func(x); // function call
```

function call can throw exception as result of:

1. parameter passing (if pass by value)
2. function execution *including return statement*

in parameter passing, construction and destruction of each parameter happens in context of *calling* function [C++17 §8.2.2/4]

consequently, invocation of noexcept function can still result in exception being thrown due to parameter passing

in case of return by value, construction of temporary (if not elided) to hold return value happens in context of *called* function [C++17 §9.6.3/2] [C++17 §9.6.3/3]

consequently, must exercise care not to violate noexcept contract if noexcept function returns by value
Avoiding Exceptions Due to Function Calls

- if exception due to parameter passing must be avoided:
  - pass by reference; or
  - ensure `noexcept` move and/or copy constructor as appropriate; or
  - ensure function invoked in manner such that copy elision is guaranteed

- if exception due to return by value must be avoided:
  - ensure `noexcept` move or copy constructor as appropriate; or
  - ensure that function invoked in manner such that copy elision is guaranteed
noexcept Operator

- **noexcept** operator takes expression and returns **bool** indicating if expression can throw exception
- does not actually evaluate expression
- in determining result, only considers **noexcept** specifications for functions involved

**Example:**

```cpp
#include <cstdlib>
#include <utility>

void increment(int&) noexcept;
char* memAlloc(std::size_t);

// does not throw exception, but not declared noexcept
void doesNotThrow() {}

int main() {
    static_assert(noexcept(1 + 1) == true);
    static_assert(noexcept(memAlloc(0)) == false);
    // Note: does not evaluate expression
    static_assert(noexcept(increment(*((int*)0))) == true);
    static_assert(noexcept(increment(std::declval<int&>()))) == true);
    // Note: only uses noexcept specifiers
    static_assert(noexcept(doesNotThrow()) == false);
}
```
**noexcept** operator particularly useful for templates

**example:**

```cpp
#include <iostream>
#include <type_traits>

class Int256 { /* ... */ }; // 256-bit integer
class BigInt { /* ... */ }; // arbitrary-precision integer

// function will not throw exception
Int256 operator+(const Int256& x, const Int256& y) noexcept;

// function may throw exception
BigInt operator+(const BigInt& x, const BigInt& y);

// whether function may throw exception depends on T
template <class T>
T add(const T& x, const T& y) noexcept(noexcept(x + y) &&
      std::is_nothrow_move_constructible_v<T>)
{ return x + y; }

int main() {
    Int256 i1, i2;
    BigInt b1, b2;
    std::cout << "int " << noexcept(add(1, 1)) << '
' << "Int256 " << noexcept(add(i1, i2)) << '
' << "BigInt " << noexcept(add(b1, b2)) << '
';
}
```
Section 3.6.5

Storing and Retrieving Exceptions
might want to store exception and then later retrieve and rethrow it

exception can be stored using `std::exception_ptr` type

current exception can be retrieved with `std::current_exception`

rethrow exception stored in `exception_ptr` object using `std::rethrow_exception`

provides mechanism for moving exceptions between threads:
- store exception on one thread
- then retrieve and rethrow stored exception on another thread

`std::make_exception_ptr` can be used to make `exception_ptr` object
Example: Storing and Retrieving Exceptions

```cpp
#include <exception>
#include <stdexcept>

void yikes() {
    throw std::runtime_error("Yikes!");
}

std::exception_ptr getException() {
    try {
        yikes();
    }
    catch (...) {
        return std::current_exception();
    }
    return nullptr;
}

int main() {
    std::exception_ptr e = getException();
    std::rethrow_exception(e);
}
```
Section 3.6.6

Exception Safety
- **resource**: physical or virtual component of limited availability within computer system
- examples of resources include: memory, files, devices, network connections, processes, threads, and locks
- essential that acquired resource properly released when no longer needed
- when resource not properly released when no longer needed, **resource leak** said to occur
- exceptions have important implications in terms of resource management
- must be careful to avoid resource leaks
Resource Leak Example

```c++
void useBuffer(char* buf) { /* ... */ }

void doWork() {
    char* buf = new char[1024];
    useBuffer(buf);
    delete[] buf;
}
```

- If `useBuffer` throws an exception, code that deletes `buf` is never reached
cleanup operations should always be performed in destructors

following structure for code is *fundamentally flawed*:

```c
void func()
{
    initialize();
    do_work();
    cleanup();
}
```

code with preceding structure *not exception safe*

if `do_work` throws exception, `cleanup` never called and cleanup operation not performed

in best case, not performing cleanup will probably cause resource leak
in order for exception mechanism to be useful, must know what can be assumed about state of program when exception thrown

operation said to be **exception safe** if it leaves program in valid state when operation is terminated by exception

several levels of exception safety: basic, strong, nothrow

**basic guarantee**: all invariants preserved and no resources leaked

with basic guarantee, partial execution of failed operation may cause side effects

**strong guarantee**: in addition to basic guarantee, failed operation guaranteed to have no side effects (i.e., commit semantics)

with strong guarantee, operation can still fail causing exception to be thrown

**nothrow guarantee**: in addition to basic guarantee, promises not to emit exception (i.e., operation guaranteed to succeed even in presence of exceptional circumstances)
Exception Guarantees

- assume all functions throw if not known otherwise
- code must always provide basic guarantee
- nothrow guarantee should always be provided by destructors
- whenever possible, nothrow guarantee should be provided by:
  - move operations (i.e., move constructors and move assignment operators)
  - swap operations
- provide strong guarantee when natural to do so and not more costly than basic guarantee
- examples of strong guarantee:
  - `push_back` for container, subject to certain container-dependent conditions being satisfied (e.g., for `std::vector`, element type has nonthrowing move or is copyable)
  - `insert` on `std::list`
- examples of nothrow guarantee:
  - `swap` of two containers
  - `pop_back` for container
resource acquisition is initialization (RAII) is programming idiom used to *avoid resource leaks* and *provide exception safety*

- associate resource with owning object (i.e., RAII object)
- period of time over which resource held is tied to lifetime of RAII object
- resource acquired during creation of RAII object
- resource released during destruction of RAII object
- provided RAII object properly destroyed, resource leak cannot occur
Resource Leak Example Revisited

- implementation 1 (not exception safe; has memory leak):

```c++
void useBuffer(char* buf) { /* ... */ }

void doWork() {
    char* buf = new char[1024];
    useBuffer(buf);
    delete[] buf;
}
```

- implementation 2 (exception safe):

```c++
#include <new>

template <class T>
class SmartPtr {
public:
    SmartPtr(int size) : ptr_(new T[size]) {}
    ~SmartPtr() { delete[] ptr_; }
    SmartPtr(SmartPtr&& other) { ptr_ = other.ptr_; other.ptr_ = nullptr; }
    SmartPtr& operator=(SmartPtr&& other) {
        delete[] ptr_; ptr_ = other.ptr_; other.ptr_ = nullptr;
        return *this;
    }
    T* get() const { return ptr_; }
private:
    T* ptr_; }

void useBuffer(char* buf) { /* ... */ }

void doWork() {
    SmartPtr<char> buf(1024);
    useBuffer(buf.get());
}
```
RAII Example: Stream Formatting Flags

```cpp
#include <iostream>
#include <ios>
#include <boost/io/ios_state.hpp>

// not exception safe
void unsafeOutput(std::ostream& out, unsigned int x) {
  auto flags = out.flags();
  // if exception thrown during output of x, old
  // formatting flags will not be restored
  out << std::hex << std::showbase << x << '\n';
  out.flags(flags);
}

// exception safe
void safeOutput(std::ostream& out, unsigned int x) {
  boost::io::ios_flags_saver ifs(out);
  out << std::hex << std::showbase << x << '\n';
}
```

- RAII objects can be used to save and restore state
Other RAII Examples

- `std::unique_ptr` and `std::shared_ptr` can be used to manage memory; memory is released in destructor [see smart pointers]
- `std::scoped_lock` `std::unique_lock`, `and std::shared_lock` (and `std::lock_guard`) can be used to manage locks held on mutexes; lock is released in destructor
- `std::ifstream`, `std::ofstream`, and `std::fstream` can be used to manage files; file is closed in destructor
- `std::string` can be used to manage strings; string buffer freed in destructor
- `std::vector` can be used to manage dynamic arrays; array data freed in destructor
Section 3.6.7

Exceptions: Implementation, Cost, and Usage
Implementation of Exception Handling

- standard does not specify how exception handling is to be implemented; only specifies behavior of exception handling
- consider typical implementation here
- potentially significant memory overhead for storing exception object and information required for stack unwinding
- possible to have zero time overhead if no exception thrown
- time overhead significant when exception thrown
- not practical to create exception object on stack, since object frequently needs to be propagated numerous levels up call chain
- exception objects tend to be small
- exception object can be stored in small fixed-size buffer falling back on heap if buffer not big enough
memory required to maintain sufficient information to unwind stack when exception thrown

two common strategies for maintaining information for stack unwinding: stack-based and table-based strategies

stack-based strategy:
- information for stack unwinding is saved on call stack, including list of destructors to execute and exception handlers that might catch exception
- when exception is thrown, walk stack executing destructors until matching catch found

table-based strategy:
- store information to assist in stack unwinding in static tables outside stack
- call stack used to determine which scopes entered but not exited
- use look-up operation on static tables to determine where thrown exception will be handled and which destructors to execute

table-based strategy uses less space on stack but potentially requires considerable storage for tables
Appropriateness of Using Exceptions

- use of exceptions not appropriate in all circumstances
- in practice, exceptions can sometimes (depending on C++ implementation) have prohibitive memory cost for systems with very limited memory (e.g., some embedded systems)
- since throwing exception has significant time overhead only use for infrequently occurring situations (not common case)
- in code where exceptions can occur, often much more difficult to bound how long code path will take to execute
- since difficult to predict response time of code in presence of exceptions, exceptions often cannot be used in time critical component of real-time system (where operation must be guaranteed to complete in specific maximum time)
- considerable amount of code in existence that is not exception safe, especially legacy code
- cannot use exceptions in manner that would allow exceptions to propagate into code that is not exception safe
whether invariants should be enforced by exceptions or assertions somewhat controversial

would recommend only using exceptions for errors from which recovery is likely to be possible

if error condition detected is indicative of serious programming error, program state may already be sufficiently invalid (e.g., stack trampled, heap corrupted) that exception handling will not work correctly anyhow

tendency amongst novice programmers is to use exceptions in places where their use is either highly questionable or clearly inappropriate
Section 3.6.8

Exception Gotchas
```cpp
#include <memory>

class T1 { /* ... */ };
class T2 { /* ... */ };

void func(std::shared_ptr<T1> p, std::shared_ptr<T2> q)
{ /* ... */ }

void doWork()
{
    // potential memory leak
    func(std::shared_ptr<T1>(new T1),
         std::shared_ptr<T2>(new T2));
    // ...
}

one problematic order:
1. allocate memory for T1
2. construct T1
3. allocate memory for T2
4. construct T2
5. construct shared_ptr<T1>
6. construct shared_ptr<T2>
7. call func

if step 3 or 4 throws, memory leaked

another problematic order:
1. allocate memory for T1
2. allocate memory for T2
3. construct T1
4. construct T2
5. construct shared_ptr<T1>
6. construct shared_ptr<T2>
7. call func

if step 3 or 4 throws, memory leaked
```

Copyright © 2015–2021 Michael D. Adams
Programming in C++
Version 2021-04-01
```cpp
#include <memory>

class T1 { /* ... */ };
class T2 { /* ... */ };

void func(std::shared_ptr<T1> p, std::shared_ptr<T2> q) {
    /* ... */
}

void doWork() {
    func(std::make_shared<T1>(), std::make_shared<T2>());
    // ...
}
```

- previously problematic line of code now does following:
  1. perform following operations in any order:
     - construct `shared_ptr<T1>` via `make_shared<T1>`
     - construct `shared_ptr<T2>` via `make_shared<T2>`
  2. call `func`

- each of `T1` and `T2` objects managed by `shared_ptr` at all times so no memory leak possible if exception thrown

- similar issue arises in context of `std::unique_ptr` and can be resolved by using `std::make_unique` in similar way as above
stack class template parameterized on element type T

```cpp
template <class T>
class Stack {

public:
   // ...
   // Pop the top element from the stack.
   T pop() {
      // If the stack is empty...
      if (top_ == start_)
         throw "stack is empty";
      // Remove the last element and return it.
      return *(--top_);
   }

private:
   T* start_; // start of array of stack elements
   T* end_;  // one past end of array
   T* top_;  // one past current top element
};
```

what is potentially problematic about this code with respect to exceptions?
Section 3.6.9

References
References


Section 3.7

Smart Pointers
Section 3.7.1

Introduction
- responsibility of owner of chunk of dynamically-allocated memory to deallocate that memory when no longer needed
- so managing dynamically-allocated memory essentially reduces to problem of ownership management
- raw pointer does not have any ownership relationship with memory to which pointer refers
- consequently, raw pointer does not itself directly participate in memory management (e.g., deallocation)
- raw pointers often problematic in presence of exceptions, since such pointers do not know how to free their pointed-to memory
- raw pointers should only be used in situations where no ownership responsibility for pointees is needed (e.g., to simply observe object without managing its associated memory)
**Smart Pointers**

- **smart pointer** is object that has interface similar to raw pointer (e.g., provides operations such as indirection/dereferencing and assignment) but offers some additional functionality
- smart pointers provide RAII mechanism for managing memory resource (i.e., pointed-to memory)
- unlike raw pointer, smart pointer owns its pointed-to memory
- consequently, smart pointer must provide mechanism for deallocating pointed-to memory when no longer needed
- some smart-pointer types allow only exclusive ownership, while others allow shared ownership
- destructor for smart pointer releases memory to which pointer refers if no longer needed (i.e., no other owners remain)
- smart pointers play crucial role in writing exception-safe code
- smart pointers should always be used (instead of raw pointers) when ownership of piece of memory needs to be tracked (e.g., so that it can be deallocated when no longer needed)
Section 3.7.2

The `std::unique_ptr` Class Template
The `std::unique_ptr` Template Class

- **`std::unique_ptr`** is *smart pointer* that retains *exclusive* ownership of object through pointer

- **Declaration:**
  ```cpp
template <class T, class Deleter = std::default_delete<T>>
  class unique_ptr;
  ```

- **T** is type of object to be managed (i.e., owned object)
- **Deleter** is callable entity used to delete owned object
- Also correctly handles array types via partial specialization (e.g., T could be array of `char`)

- Owned object destroyed when `unique_ptr` object goes out of scope

- No two `unique_ptr` objects can own same object

- `unique_ptr` object is *movable*; move operation transfers ownership

- `unique_ptr` object is *not copyable*, as copying would create additional owners

- `std::make_unique` template function often used to create `unique_ptr` objects (for exception-safety reasons)
**The `std::unique_ptr` Template Class (Continued)**

- `unique_ptr<T>`
  - Pointer to T Object
  - Managed Object
  - T Object

- `unique_ptr<T,D>`
  - Pointer to T Object
  - Managed Object
  - T Object
  - Deleter State (if any)

- **reasonable implementation would have zero memory cost for deleter state in case of:**
  - default deleter
  - deleter of functor/closure type with no state

- **if no memory cost for deleter state, `unique_ptr` has same memory cost as raw pointer**
## std::unique_ptr Member Functions

### Construction, Destruction, and Assignment

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>constructs new unique_ptr</td>
</tr>
<tr>
<td>destructor</td>
<td>destroys managed object (if any)</td>
</tr>
<tr>
<td><code>operator=</code></td>
<td>assigns unique_ptr</td>
</tr>
</tbody>
</table>

### Modifiers

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>release</td>
<td>returns pointer to managed object and releases ownership</td>
</tr>
<tr>
<td>reset</td>
<td>replaces managed object</td>
</tr>
<tr>
<td>swap</td>
<td>swaps managed objects</td>
</tr>
</tbody>
</table>

### Observers

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>get</td>
<td>returns pointer to managed object</td>
</tr>
<tr>
<td>get_deleter</td>
<td>returns deleter used for destruction of managed object</td>
</tr>
<tr>
<td><code>operator bool</code></td>
<td>checks if there is associated managed object</td>
</tr>
</tbody>
</table>
### Dereferencing/Subscripting

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>operator*</code></td>
<td>dereferences pointer to managed object</td>
</tr>
<tr>
<td><code>operator-&gt;</code></td>
<td>dereferences pointer to managed object</td>
</tr>
<tr>
<td><code>operator[]</code></td>
<td>provides indexed access to managed array</td>
</tr>
</tbody>
</table>
#include <memory>
#include <cassert>

void func() {
    auto p1(std::make_unique<int>(42));
    assert(*p1 == 42);

    // std::unique_ptr<int> p3(p1); // ERROR: not copyable
    // p3 = p1; // ERROR: not copyable

    std::unique_ptr<int> p2(std::move(p1)); // OK: movable
    // Transfers ownership from p1 to p2, invalidating p1.
    assert(p1.get() == nullptr && *p2 == 42);

    p1 = std::move(p2); // OK: movable
    // Transfers ownership from p2 to p1, invalidating p2.
    assert(p2.get() == nullptr && *p1 == 42);

    p1.reset();
    // Invalidates p1.
    assert(p1.get() == nullptr);
}
```cpp
#include <memory>
#include <cassert>

int main() {
    auto p0 = std::make_unique<int>(0);
    assert(*p0 == 0);
    int* r0 = p0.get();
    auto p1 = std::make_unique<int>(1);
    assert(*p1 == 1);
    auto r1 = p1.get();
    p0.swap(p1);
    assert(p0.get() == r1 && p1.get() == r0);
    p1.swap(p0);
    assert(p0.get() == r0 && p1.get() == r1);
    p1.reset();
    assert(p1.get() == nullptr);
    assert(!p1);
    int* ip = p1.release();
    assert(!p1);
    // ... Do not throw exceptions here.
    delete ip;
    p1.reset(new int(42));
    assert(*p1 == 42);
}
```
```cpp
#include <memory>
#include <iostream>
#include <cstring>
#include <cstdlib>

using up = std::unique_ptr<char[], void(*)(char*)>;

char *allocate(std::size_t n) {
    return static_cast<char*>(std::malloc(n));
}

void deallocate(char* p) {
    std::cout << "deallocate called\n";
    std::free(p);
}

up string_duplicate(const char *s) {
    std::size_t len = std::strlen(s);
    up result(allocate(len + 1), deallocate);
    std::strcpy(result.get(), s);
    return result;
}

int main() {
    auto p = string_duplicate("Hello, World!");
    std::cout << p.get() << '\n';
}
```
TwoBufs Example With Resource Leak

```cpp
#include <cstdint>
#include <limits>

class TwoBufs {

public:
    TwoBufs(std::size_t aSize, std::size_t bSize) :
        a_(nullptr), b_(nullptr) {
        a_ = new char[aSize];
        // If new throws, a_ will be leaked.
        b_ = new char[bSize];
    }

    ~TwoBufs() {
        delete[] a_;  
        delete[] b_;  
    }

private:
    char* a_;  
    char* b_; 
}

void doWork() {
    // This may leak memory.
    TwoBufs x(1000000, 
        std::numeric_limits<std::size_t>::max());
    // ...
}
```
```cpp
#include <cstdint>
#include <limits>
#include <memory>

class TwoBufs {
public:
    TwoBufs(std::size_t aSize, std::size_t bSize) :
        a_(std::make_unique<char[]>(aSize)),
        b_(std::make_unique<char[]>(bSize)) {} 
    ~TwoBufs() {} 
    // ...

private:
    std::unique_ptr<char[]> a_; 
    std::unique_ptr<char[]> b_; 
};

void doWork() {
    // This will not leak memory. 
    TwoBufs x(1000000, 
              std::numeric_limits<std::size_t>::max());
}
```
Section 3.7.3

The `std::shared_ptr` Class Template
The `std::shared_ptr` Template Class

- `std::shared_ptr` is *smart pointer* that retains *shared* ownership of object through pointer
- declaration:
  
  ```
  template <class T> class shared_ptr;
  ```
- `T` is type of pointed-to object, where pointed-to object is object being managed (i.e., owned) or subobject thereof
- multiple `shared_ptr` objects may own same object
- owned object is deleted when last remaining owning `shared_ptr` object is destroyed, assigned another pointer via assignment, or reset via `reset`
- `shared_ptr` object is *movable*, where move transfers ownership
- `shared_ptr` object is *copyable*, where copy creates additional owner
- `shared_ptr` only guarantees access to underlying control block is thread safe (e.g., no guarantee made for accesses to owned object)
- `std::make_shared` (and `std::allocate_shared`) often used to create `shared_ptr` objects (for both efficiency and exception-safety reasons)
- `shared_ptr` has more overhead than `unique_ptr` so `unique_ptr` should be preferred unless shared ownership required
The `std::shared_ptr` Template Class (Continued)

- **Each `shared_ptr<T>` object contains:**
  - pointer to object of type `T` (i.e., managed object or subobject thereof)
  - pointer to control block

- **Control block contains:**
  - pointer to managed object (for deletion)
  - use count: number of `shared_ptr` instances pointing to object
  - weak count: to be discussed later
  - other data (i.e., deleter and allocator)

- Managed object is deleted when use count reaches zero

- `make_shared` can allow memory for control block and managed object to be allocated together in single memory allocation
std::shared_ptr

Reference Counting Example

shared_ptr<T>

Pointer to T Object

Pointer to Control Block

Control Block

Pointer to Managed Object

Managed Object

Use Count (1)

Weak Count (1)

Other Data

T Object
Reference Counting Example (Continued 1)

- `std::shared_ptr`:
  - Pointer to `T` Object
  - Pointer to Control Block

- Control Block:
  - Pointer to Managed Object
    - Use Count (2)
    - Weak Count (1)
    - Other Data
  - Managed Object
    - `T` Object
    - :
std::shared_ptr

**Reference Counting Example (Continued 2)**

```
weak_count (1)
use_count (3)
other_data
```

```
pointer to managed object
```

```
control block
```

```
shared_ptr<T>
pointer to managed object
use_count (3)
weak_count (1)
other_data
```

```
shared_ptr<T>
pointer to control block
```

```
shared_ptr<T>
pointer to control block
```

```
managed object
```

```
t object
```

```
other data
```
**std::shared_ptr** Member Functions

## Construction, Destruction, and Assignment

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>constructs new <code>shared_ptr</code></td>
</tr>
<tr>
<td>destructor</td>
<td>destroys managed object if no other references to it remain</td>
</tr>
<tr>
<td><code>operator=</code></td>
<td>assigns <code>shared_ptr</code></td>
</tr>
</tbody>
</table>

## Modifiers

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>reset</td>
<td>replaces managed object</td>
</tr>
<tr>
<td>swap</td>
<td>swaps values of two <code>shared_ptr</code> objects</td>
</tr>
</tbody>
</table>
### Observers

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>get</td>
<td>returns pointer to pointed-to object</td>
</tr>
<tr>
<td>use_count</td>
<td>returns number of <code>shared_ptr</code> objects referring to same managed object</td>
</tr>
<tr>
<td><code>operator bool</code></td>
<td>checks if there is associated pointed-to/managed object</td>
</tr>
<tr>
<td>owner_before</td>
<td>provides owner-based ordering of shared pointers</td>
</tr>
</tbody>
</table>

### Dereferencing/Subscripting

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>operator*</code></td>
<td>dereferences pointer to pointed-to object</td>
</tr>
<tr>
<td><code>operator-&gt;</code></td>
<td>dereferences pointer to pointed-to object</td>
</tr>
<tr>
<td><code>operator[]</code></td>
<td>provides indexed access to pointed-to array</td>
</tr>
</tbody>
</table>
when creating `std::shared_ptr` objects, prefer to use `std::make_shared` (as opposed to explicit use of `new` with `shared_ptr`)

- use of `make_shared` allows for greater efficiency
- control block and owned object can be allocated together
- **one less memory-allocation operation** required
- **better cache efficiency** due to control block and owned object being placed contiguously in memory
- **better exception safety** (avoid resource leaks)
```
#include <memory>
#include <cassert>

int main() {
    auto p1(std::make_shared<int>(0));
    assert(*p1 == 0 && p1.use_count() == 1);

    std::shared_ptr<int> p2(p1);
    assert(*p2 == 0 && p2.use_count() == 2);

    *p2 = 42;
    assert(*p1 == 42);

    p2.reset();
    assert(!p2);
    assert(*p1 == 42 && p1.use_count() == 1);

    int* ip = p1.get();
    assert(*ip == 42);

    ip = p2.get();
    assert(ip == nullptr);
}
```
```cpp
#include <memory>
#include <iostream>
#include <string>

int main() {
    std::shared_ptr<std::string> s =
        std::make_shared<std::string>("hello");

    std::shared_ptr<const std::string> cs = s;

    *s = "goodbye";

    // *cs = "bonjour"; // ERROR: const

    std::cout << *cs.get() << '\n';
}
```
Example: Shared Pointer to Subobject of Managed Object

```cpp
#include <memory>
#include <vector>
#include <cassert>
#include <iostream>

struct Widget {
    Widget(const std::vector<int>& v_, int i_) :
        v(v_), i(i_) {}
    ~Widget() {std::cout << "destructor called\n";}
    std::vector<int> v;
    int i;
};

int main() {
    auto wp(std::make_shared<Widget>(
        std::vector<int>{1, 2, 3}, 42));
    assert(wp.use_count() == 1);
    assert(wp->i == 42 && wp->v.size() == 3);
    std::shared_ptr<std::vector<int>> vp(wp, &wp->v);
    assert(wp.use_count() == 2 && vp.use_count() == 2);
    assert(vp->size() == 3);
    wp = nullptr; // equivalently: wp.reset();
    // managed Widget object not destroyed
    assert(wp.use_count() == 1 && vp->size() == 3);
    vp = nullptr; // equivalently: vp.reset();
    // managed Widget object destroyed
    // ...
}
auto wp(std::make_shared<Widget>(
    std::vector<int>{1, 2, 3, 42});
assert(wp.use_count() == 1);
assert(wp->i == 42 && wp->v.size() == 3);
Example: Shared Pointer to Subobject of Managed Object (Continued 2)

```cpp
std::shared_ptr<std::vector<int>> vp(wp, &wp->v);
assert(wp.use_count() == 2 && vp.use_count() == 2);
assert(vp->size() == 3);
```
wp = nullptr; // equivalently: wp.reset();
// managed Widget object not destroyed
assert(vp.use_count() == 1 && vp->size() == 3);
Example: Shared Pointer to Subobject of Managed Object (Continued 4)

25        vp = \texttt{nullptr};  // equivalently: \texttt{vp.reset()};
26        \hspace{0.5cm} // managed Widget object destroyed
may want class object to be able to generate additional `shared_ptr` instances referring to itself

requires object to have access to information in its associated `shared_ptr` control block

access to such information obtained through use of `std::enable_shared_from_this` class template

declaration:

```
template <class T> class enable_shared_from_this;
```

T is type of object being managed by `shared_ptr`

class can inherit from `enable_shared_from_this` to inherit `shared_from_this` member functions that can be used to obtain `shared_ptr` instance pointing to `*this`

`shared_from_this` is overloaded to provide both const and non-const versions
```cpp
#include <memory>
#include <cassert>

// Aside: This is an example of the CRTP.
class Widget : public std::enable_shared_from_this<Widget>
{
    public:
        std::shared_ptr<Widget> getSharedPtr() {
            return shared_from_this();
        }
        std::shared_ptr<const Widget> getSharedPtr() const {
            return shared_from_this();
        }
        // ...
};

int main() {
    std::shared_ptr<Widget> a(new Widget);
    std::shared_ptr<Widget> b = a->getSharedPtr();
    assert(b == a);
    std::shared_ptr<const Widget> c = a->getSharedPtr();
    assert(c == a);
}
```
```cpp
#include <memory>
#include <array>
#include <string>
#include <iostream>

using namespace std::literals;

int main() {
    std::array<std::shared_ptr<const std::string>, 3> all = {
        std::make_shared<const std::string>("apple"s),
        std::make_shared<const std::string>("orange"s),
        std::make_shared<const std::string>("banana"s)
    };
    std::array<std::shared_ptr<const std::string>, 2> some = {all[0], all[1]};

    for (auto& x : all) {
        std::cout << *x << ' ' << x.use_count() << '
';
    }
}

/* output:
apple 2
orange 2
banana 1
*/
```
Section 3.7.4

The `std::weak_ptr` Class Template
std::shared_ptr and Circular References

- reference counting nature of std::shared_ptr causes it to leak memory in case of circular references
- such cycles should be broken with std::weak_ptr (to be discussed shortly)
#include <memory>
#include <iostream>
#include <cassert>

struct Node {
    Node(int id_) : id(id_) {}
    ~Node() {std::cout << "destroying node " << id << '\n';}
    std::shared_ptr<Node> parent;
    std::shared_ptr<Node> left;
    std::shared_ptr<Node> right;
    int id;
};

void func() {
    std::shared_ptr<Node> root(std::make_shared<Node>(1));
    assert(root.use_count() == 1);
    root->left = std::make_shared<Node>(2);
    assert(root.use_count() == 1 &&
           root->left.use_count() == 1);
    root->left->parent = root;
    assert(root.use_count() == 2 &&
           root->left.use_count() == 1);
    // When root is destroyed, the reference count for each
    // of the managed Node objects does not reach zero, and
    // no Node object is destroyed.
    // Node::~Node is not called here
}
create new node, referenced by root
create new node, making it left child of root node (parent link not set)
set parent link for left child of root node
after destroying root, neither node destroyed
The `std::weak_ptr` Template Class

- `std::weak_ptr` is *smart pointer* that holds *non-owning* (i.e., “weak”) reference to object managed by `std::shared_ptr`
- `weak_ptr` must be converted to `std::shared_ptr` in order to access referenced object
- declaration:
  ```cpp
template <class T> class weak_ptr;
```
- `T` is type of referenced object
- `weak_ptr` object is *movable* and *copyable*
- `std::weak_ptr` is used to break circular references with `std::shared_ptr`
## std::weak_ptr Member Functions

### Construction, Destruction, and Assignment

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>constructs new weak_ptr</td>
</tr>
<tr>
<td>destructor</td>
<td>destroys weak_ptr</td>
</tr>
<tr>
<td><code>operator=</code></td>
<td>assigns weak_ptr</td>
</tr>
</tbody>
</table>

### Modifiers

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>reset</td>
<td>releases reference to managed object</td>
</tr>
<tr>
<td>swap</td>
<td>swaps values of two weak_ptr objects</td>
</tr>
</tbody>
</table>
### Observers

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>use_count</td>
<td>returns number of <code>std::shared_ptr</code> objects referring to same managed object</td>
</tr>
<tr>
<td>expired</td>
<td>checks if referenced object was already deleted</td>
</tr>
<tr>
<td>lock</td>
<td>creates <code>std::shared_ptr</code> that manages referenced object</td>
</tr>
<tr>
<td>owner_before</td>
<td>provides owner-based ordering of weak pointers</td>
</tr>
</tbody>
</table>
Typical `shared_ptr/weak_ptr` Implementation

- **`shared_ptr<T>` or `weak_ptr<T>`**

  - Pointer to `T` Object
  - Pointer to Control Block
  - Control Block
    - Pointer to Managed Object
    - Use Count
    - Weak Count
    - Other Data
  - Managed Object
    - ...:
    - ...:

- **each `shared_ptr<T>` and `weak_ptr<T>` object contains:**
  - pointer to object of type `T` (i.e., managed object or subobject thereof)
  - pointer to control block

- **control block contains:**
  - pointer to managed object (for deletion)
  - use count: number of `shared_ptr` instances pointing to object
  - weak count: number of `weak_ptr` instances pointing to object, plus one if use count is nonzero
  - other data (i.e., deleter and allocator)

- **managed object is deleted when use count reaches zero**

- **control block is deleted when weak count reaches zero (which implies use count is also zero)**
shared_ptr destructor pseudocode:

```cpp
    decrement use count and if it reaches zero {
        delete managed object
        decrement weak count and if it reaches zero {
            delete control block
        }
    }
```

weak_ptr destructor pseudocode:

```cpp
    decrement weak count and if it reaches zero {
        delete control block
    }
```

must be thread safe
```cpp
#include <memory>
#include <iostream>
#include <cassert>

void func(std::weak_ptr<int> wp) {
    auto sp = wp.lock();
    if (sp) {
        std::cout << *sp << '
';
    } else {
        std::cout << "expired\n";
    }
}

int main() {
    std::weak_ptr<int> wp;
    {
        auto sp = std::make_shared<int>(42);
        wp = sp;
        assert(wp.use_count() == 1 && wp.expired() == false);
        func(wp);
        // When sp destroyed, wp becomes expired.
    }
    assert(wp.use_count() == 0 && wp.expired() == true);
    func(wp);
}
```
Avoiding Circular References With `std::weak_ptr`

```cpp
#include <memory>
#include <iostream>
#include <cassert>

struct Node {
    Node(int id_) : id(id_) {}
    ~Node() {std::cout << "destroying node " << id << '\n';}
    std::weak_ptr<Node> parent;
    std::shared_ptr<Node> left;
    std::shared_ptr<Node> right;
    int id;
};

void func() {
    std::shared_ptr<Node> root(std::make_shared<Node>(1));
    assert(root.use_count() == 1);
    root->left = std::make_shared<Node>(2);
    assert(root.use_count() == 1 &&
           root->left.use_count() == 1);
    root->left->parent = root;
    assert(root.use_count() == 1 &&
           root->left.use_count() == 1);
    // The reference count for each of the managed Node
    // objects reaches zero, and these objects are
    // destroyed.
    // Node::~Node is called twice here
}
```

created new node, referenced by root
created new node, making it left child of root node (parent link not set)
Avoiding Circular References Example (Continued 3)

- set parent link (which is `weak_ptr`) for left child of root node
started to destroy `root`; decremented use count, which reaches zero
Avoiding Circular References Example (Continued 5)

- started to destroy root node; \( r \) has been destroyed; about to destroy \( l \)
Avoiding Circular References Example (Continued 6)

- started to destroy 1 (in root node); decremented use count, which reaches zero
Avoiding Circular References Example (Continued 7)

- started to destroy left node
started to destroy $p$ in left node; decremented weak count (which is not yet zero)
Avoiding Circular References Example (Continued 9)

- destroyed $p$ in left node, and completed destruction of left node
Avoiding Circular References Example (Continued 10)

- left node has been destroyed
continue destruction of \( p \) in root node; decrement weak count, which reaches zero
Avoiding Circular References Example (Continued 12)

- destroyed control block for (previously destroyed) left child of root node
Avoiding Circular References Example (Continued 13)

- finished destroying \( l \) in root node; destroyed \( p \) in root node; and completed destruction of root node
Avoiding Circular References Example (Continued 14)

root node has been destroyed
continuing with destruction of root; decremented weak count, which reaches zero
Avoiding Circular References Example (Continued 16)

root

- destroyed control block
root has been destroyed
The `boost::intrusive_ptr` Class Template
boost::intrusive_ptr provides intrusive shared pointer type

aside from being intrusive, similar to boost::shared_ptr (which is similar to std::shared_ptr)

declaration:

```cpp
template <class T> class intrusive_ptr;
```

T is type of referenced object

new reference is added by calling user-provided function with signature:

```cpp
void intrusive_ptr_add_ref(T*)
```

reference is eliminated by calling user-provided function with signature:

```cpp
void intrusive_ptr_release(T*)
```

intrusive_ptr_release responsible for destroying underlying object when reference count reaches zero

functions intrusive_ptr_add_ref and intrusive_ptr_release must be provided in such way as to be found when called unqualified
intrusive_ptr<T>

- **intrusive_ptr** itself has same memory cost as raw pointer
- managed object (of type \( T \)) must provide means for reference counting, which is accessed through user-provided functions
  - intrusive_ptr_add_ref and intrusive_ptr_release
# intrusive_ptr Example

```cpp
#include <boost/intrusive_ptr.hpp>
#include <iostream>
#include <string>
#include <cassert>

class Person {
public:
    Person(const std::string& name) : name_(name), refCount_(0) {}
    void hold() {++refCount_;
    void release() {if (--refCount_ == 0) {delete this;}}
    unsigned refCount() const {return refCount_;}

private:
    ~Person() {std::cout << "dtor called\n";}
    std::string name_;
    unsigned refCount_; // reference count
};

void intrusive_ptr_add_ref(Person* p) {p->hold();}
void intrusive_ptr_release(Person* p) {p->release();}

int main() {
    boost::intrusive_ptr<Person> a(new Person("Bjarne"));
    {
        boost::intrusive_ptr<Person> b = a;
        assert(a->refCount() == 2);
    }
    assert(a->refCount() == 1);
}
```
Section 3.7.6

Smart-Pointer Usage Examples
Temporary Heap-Allocated Objects

- create heap-allocated object for temporary use inside function/block
- object will be automatically deallocated upon leaving function/block

```cpp
#include <memory>

void func() {
    // ...
    int size = /* ... */;
    auto buffer = std::make_unique<char[]>(size);
    // ... (use buffer)
    // when buffer destroyed, pointee automatically freed
}
```
Decoupled Has-A Relationship

- instead of making object member of class, store object outside class and make pointer to object member of class
- might want to do this for object that:
  - is optional (e.g., is not always used or is lazily initialized)
  - has one of several base/derived types
- pointer in class object owns decoupled object

```cpp
#include <memory>

class Widget {
    // ...
private:
    // ...
    std::unique_ptr<Type> item_;  // decoupled object has type Type
};
```
Decoupled Fixed-But-Dynamically-Sized Array

- array stored outside class object, where array size fixed but determined at run time
- class object has pointer that owns decoupled array

```cpp
#include <memory>

class Widget {

public:
    using Element = int;
    Widget(std::size_t size) :
        array_(std::make_unique<Element[]>(size),
        size_(size) {}
        // ...

private:
    // ...
    std::unique_ptr<Element[]> array_;
    std::size_t size_;
};
```
with **pimpl idiom**, interface and implementation split across two classes, namely, handle class and implementation class

handle object has pointer that owns implementation object

```cpp
#include <experimental/propagate_const>
#include <memory>

class Widget {
public:
    // ... (member functions that forward calls to
    // implementation object)
private:
    class WidgetImpl; // implementation class defined elsewhere
    std::experimental::propagate_const<std::unique_ptr<
        WidgetImpl>> impl_; // incomplete type WidgetImpl is allowed
    // ...
};
```
- tree, where tree owns root node and each node owns its children
- recursive destruction of nodes may cause stack-overflow problems, especially for unbalanced trees (but such problems can be avoided by dismantling tree from bottom upwards)

```cpp
#include <memory>
#include <array>

class Tree {
    public:
        class Node {
            // ...
            private:
                std::array<std::unique_ptr<Node>, 2> children_;  // owning pointers (parent owns children)
                Node* parent_;  // non-owning pointer
            // ...
        }
    // ...

    private:
        std::unique_ptr<Node> root_;  // ...
    // ...
};
```
Doubly-Linked List

- doubly-linked list, where list owns first list node and each list node owns its successor
- recursive destruction of nodes can cause stack-overflow problems, for sufficiently large lists (but deep recursions can be avoided with extra work)

```cpp
#include <memory>

class List {
public:
    class Node {
        // ...
        private:
            std::unique_ptr<Node> next_; // owning pointer (node owns successor)
            Node* prev_; // non-owning pointer
    }
    // ...
    private:
        // ...
        std::unique_ptr<Node> head_;
};
```
Tree That Provides Strong References

- tree that provides strong references to data in nodes
- tree owns root node and each node owns its children
- accessor for node data returns object having pointer that keeps node alive

```cpp
#include <memory>
#include <array>

class Tree {
public:
    using Data = /* ... */;
    class Node {
        // ...
    private:
        std::array<std::shared_ptr<Node>, 2> children_;  
        std::weak_ptr<Node> parent_;  
        Data data_;  
    }
    std::shared_ptr<Data> find(/* ... */) {
        std::shared_ptr<Node> sp;
        // ...
        return {sp, &(sp->data)};
        // use shared_ptr aliasing constructor
    }
private:
    std::shared_ptr<Node> root_;  
};
```
Directed Acyclic Graph

- encapsulated directed acyclic graph (DAG), where graph owns root nodes and each node owns its children
- pointers in graph object own root nodes
- pointers in each node object owns children
- care needed for destruction, otherwise may overflow stack

```cpp
#include <memory>
#include <vector>

class Dag {
public:
    class Node {
        // ...
    private:
        std::vector<std::shared_ptr<Node>> children_;  // owning pointers
        std::vector<Node*> parents_;  // non-owning pointers
        // ...
    }
private:
    std::vector<std::shared_ptr<Node>> roots_;  // owning pointers
};
```
Factory Function

- factory function that returns object on heap
- factory function should use `std::unique_ptr` if object will not be shared
- factory function should use `std::shared_ptr` if object will be shared
- provide factory functions using each of `std::unique_ptr` and `std::shared_ptr` if both sharing and non-sharing cases are common

```cpp
#include <memory>

std::unique_ptr<Widget> makeWidget() {
    return std::make_unique<Widget>();
}

std::shared_ptr<Gadget> makeGadget() {
    return std::make_shared<Gadget>();
}
```
Factory Function With Cache

- cache of objects on heap
- object in cache should only continue to live while it has external user
- object returned to user is owning pointer
- cache entries have non-owning pointers to corresponding objects

```cpp
#include <memory>

std::shared_ptr<Widget> makeWidget(int id) {
    static std::map<int, std::weak_ptr<Widget>> cache;
    static std::mutex mut;
    std::scoped_lock<std::mutex> lock(mut);
    auto sp = cache[id].lock();
    if (!sp) {
        sp = std::make_shared<Widget>(id);
        cache[id] = sp;
    }
    return sp;
}
```
Section 3.7.7

References

Section 3.8

Memory Management
- object said to have **dynamic storage duration** if its lifetime is independent of scope in which object created (i.e., lifetime of object does not end until explicitly ended)
- often need to use objects (or arrays of objects) with dynamic storage duration
- in what follows, we consider how such objects are managed
- *new expressions* used to create objects or arrays of objects with dynamic storage duration
- *delete expressions* used to destroy such objects
- in order to handle any necessary memory allocation and deallocation, new and delete expressions in turn use (single-object and array) *operator new* and (single-object and array) *operator delete*
Potential Problems Arising in Memory Management

- **leaked object**: object created but not destroyed when no longer needed
- leaked objects are problematic because can cause program to waste memory or exhaust all available memory

- **premature deletion** (a.k.a. *dangling references*): object is deleted when one or more references to object still exist
- premature deletion is problematic because, if object accessed after deletion, results of doing so will be unpredictable (e.g., read garbage value or overwrite other variables in program)

- **double deletion**: object is deleted twice, invoking destructor twice
- double deletion is problematic invoking destructor on nonexistent object is unpredictable and furthermore double deletion can often corrupt data structures used by memory allocator
Alignment

- Type can have restriction on address at which objects of that type can start, called **alignment requirement** [C++17 §6.11/1].

- For given object type \( T \), starting address for objects of type \( T \) must be integer multiple of \( N \) bytes, where integer \( N \) is called **alignment** of type.

- Alignment of 1 corresponds to no restriction on alignment (since starting address of object can be any address in memory).

- Alignment of 2 restricts starting address of object to be even (i.e., integer multiple of 2).

- For efficiency reasons and due to restrictions imposed by hardware, alignment of particular type may be greater than 1.

- For fundamental type \( T \), not uncommon for alignment of \( T \) to equal \( \text{sizeof}(T) \).
The `alignof` Operator

- `alignof` operator is used to query alignment of type
- for object type `T`, `alignof(T)` yields alignment used for objects of this type
- `alignof(char), alignof(signed char), and alignof(unsigned char)` guaranteed to be 1
- fundamental types of size greater than 1 often have alignment greater than 1
- `std::max_align_t` is type having maximum alignment supported by implementation in all contexts
- **extended alignment** is alignment exceeding `alignof(std::max_align_t)`
- in some contexts, may be possible to use extended alignment
- every alignment value must be nonnegative power of two
The `alignas` Specifier

- In some contexts, alignment can be controlled using `alignas` specifier.
- When declaring variable, can specify its alignment in memory with `alignas` specifier.
- When defining class, can impose stricter alignment on class with `alignas` specifier.

Example:

```cpp
// Widget objects have maximal alignment
struct alignas(std::max_align_t) Widget {
    char c;
};
static_assert(alignof(Widget) == alignof(std::max_align_t));

alignas(4096) static char x[8192];
static_assert(alignof(x) == 4096);
// x is aligned on 4096-byte boundary

alignas(double) float f;
static_assert(alignof(f) == alignof(double));
// f has same alignment as double
```

Section 3.8.1

New and Delete Expressions
new expression used to create object or array of objects with dynamic storage duration

new expression has one of following forms:

\[
\text{scope\_prefix } \textbf{new} \text{ placement\_args type initializer} \\
\text{scope\_prefix } \textbf{new} \text{ placement\_args (type) initializer}
\]

\textit{scope\_prefix}: optional unary :: operator which controls lookup of allocation function

\textit{placement\_args}: optional list of additional arguments for memory allocation function enclosed in parentheses

\textit{type}: type of object to be created which may be array type

\textit{initializer}: optional list of arguments used to initialize newly created object or array (e.g., constructor arguments for class type object)

new expression where optional placement arguments provided referred to \textbf{placement new} expression

new expression returns pointer to object created for non-array type or pointer to first element in array for array type
examples of new expressions:

```cpp
int* ip1 = new int;
int* ip2 = new int(42);
std::vector<int>* vp1 = new std::vector<int>(100, 42);
int* aip1 = new int[256];
std::string* asp = new std::string[64];
int* aip2 = new (std::nothrow) int[10000];
alignas(std::string) char buf[sizeof(std::string)];
std::string* sp = new (static_cast<void*>(&buf))
    std::string("Hello");
Widget* wp = ::new Widget;  // Note: Widget is class
```

evaluating new expression performs following:

1. invokes allocation function to obtain address in memory where new object or array of objects should be placed
2. invokes constructors to create objects in storage obtained from allocation function
3. if constructor fails (i.e., throws), any successfully constructed objects are destroyed (in reverse order from construction) and deallocation function called to free memory in which object or array was being constructed
Delete Expressions

- delete expression used to destroy object or array of objects created by new expression and deallocate associated memory

- delete expression has one of two forms:
  
  ```
  scope_prefix delete expr
  ```
  
  ```
  scope_prefix delete[] expr
  ```

- `scope_prefix`: optional unary :: operator which controls lookup of deallocation function

- `expr`: pointer to object or array previously created by new expression or null pointer

- first form (sometimes called **single-object delete expression**) is used to dispose of single object obtained from new expression

- second form (sometimes called **array delete expression**) is used to dispose of array of objects obtained from new expression

- delete expression has void type

- if `expr` is null pointer, evaluation of delete expression effectively does nothing (i.e., no destructors called and no deallocation function called)
Delete Expressions (Continued 1)

- single object created by new expression must be deleted with single-object delete expression
- array created by new expression must be deleted with array delete expression
- examples of delete expressions:
  ```
  int *ip = new int(42);
  delete ip;
  std::vector<int> *vp = new std::vector<int>;
  delete vp;
  std::string* asp = new std::string[1024];
  delete[] asp;
  ```
- examples of incorrect delete expressions:
  ```
  std::string* sp = new std::string;
  delete[] sp;
  // ERROR: must use single-object delete expression
  std::string* asp = new std::string[1024];
  delete asp;
  // ERROR: must use array delete expression
  ```
evaluating single-object delete expression performs following:
1. if object of class type, invokes destructor
2. invokes deallocation function for object

evaluating array delete expression performs following:
1. if array element of class type (with non-trivial destructor):
   1. determines size of array (which is typically stored just before array element data)
   2. invokes destructor for each array element (in reverse order from construction, namely, backwards order)
2. invokes deallocation function for array
# Typical Strategy for Determining Array Size in Array Delete

```cpp
#include <cassert>
#include <cstdlib>
#include <iostream>

// A class with a nontrivial destructor.
struct Widget {
    ~Widget();
    // ...
};

int main(int argc, char** argv) {
    for (std::size_t n = 1; n < 1024; ++n) {
        /* Allocate an array of a class type with a nontrivial destructor. */
        Widget* p = new Widget[n];
        std::cout << p << '
';
        /* Assert that the array size n is stored immediately before the first array element. This approach is not required by the C++ language standard, but some C++ implementations do this. */
        assert(reinterpret_cast<std::size_t*>(p)[-1] == n);
        /* The array delete expression must invoke the destructor for n objects before deallocating memory. What is at issue here is how n is determined, since it is not specified in the delete expression. */
        delete[] p;
    }
}
```
new expression uses allocation function to determine where object (or array of objects) to be created should be placed in memory
for non-array types, allocation function is single-object operator new (i.e., \texttt{operator new}) (discussed later), which can be overloaded
for array types, allocation function is array operator new (i.e., \texttt{operator new[]}) (discussed later), which can be overloaded
allocation function need not allocate memory (since placement arguments of new expression may be used to specify address at which to place new object)
if allocation function has non-throwing exception specification, new expression returns null pointer upon failure otherwise \texttt{std::bad_alloc} exception is thrown
for array type, requested size of memory may exceed size of actual array data (i.e., overhead to store size of array for use at deletion time)
if new expression begins with unary :: operator, allocation function’s name looked up in global scope; otherwise, looked up in class scope if applicable and then global scope
overload resolution for (single-object and array) operator new performed using argument list consisting of:

1. amount of space requested, which has type `std::size_t`
2. if type has extended alignment, type’s alignment, which has type `std::align_val_t`
3. if placement new expression, placement arguments

if no matching function found, alignment removed from argument list and overload resolution performed again

expression “`new T`” results in one of following calls:

```
operator new(sizeof(T))
operator new(sizeof(T), std::align_val_t(alignof(T)))
```

expression “`new(42, f) T`” results in one of following calls:

```
operator new(sizeof(T), 42, f)
operator new(sizeof(T), std::align_val_t(alignof(T), 42, f))
```
expression “new T[7]” results in one of following calls:

- `operator new[] (sizeof(T) * 7 + x)`
- `operator new[] (sizeof(T) * 7 + x, std::align_val_t(alignof(T)))`

where x is nonnegative implementation-dependent constant representing array allocation overhead (typically, x > 0 if T has nontrivial destructor)

expression “new (42, f) T[7]” results in one of following calls:

- `operator new[] (sizeof(T) * 7 + x, 42, f)`
- `operator new[] (sizeof(T) * 7 + x, std::align_val_t(alignof(T)), 42, f)`

where x is nonnegative implementation-dependent constant representing array allocation overhead (typically, x > 0 if T has nontrivial destructor)
when evaluating new expression, if allocation function succeeds but construction fails, must invoke deallocation function (as part of cleanup)

for non-array types, deallocation function is single-object operator delete (i.e., `operator delete`) (to be discussed shortly)

for array types, deallocation function is array operator delete (i.e., `operator delete[]`) (to be discussed shortly)

if new expression begins with unary `::` operator, deallocation function’s name looked up in global scope; otherwise, looked up in class scope and then global scope
- for single-object delete expression, deallocation function is single-object operator delete (i.e., `operator delete`) (to be discussed shortly)
- for array delete expression, deallocation function is array operator delete (i.e., `operator delete[]`) (to be discussed shortly)
- if delete expression prefixed by unary `::` operator, deallocation function’s name looked up only at global scope; otherwise at class scope if applicable and then global scope
single-object operator new (i.e., `operator new`) is operator used to determine address at which to place new object to be created

most frequently invoked indirectly via new expression, but can be called directly

operator new may or may not allocate memory

operator can be overloaded as global function or (implicitly static) member function

operator has return type `void*` and returns address at which new object to be created should be placed

first parameter to operator always of type `std::size_t` and specifies number of bytes of storage needed for new object to be created

several overloads of global operator new provided by language and standard library

`std::nothrow` is dummy variable of type `const std::nothrow_t` that can be used for overload disambiguation
Single-Object Operator New Overloads

- **void* operator new**(std::size_t size);
  - allocates size bytes of storage that is suitably aligned for any object of this size not having extended alignment
  - throws std::bad_alloc exception upon failure

- **void* operator new**(std::size_t size, std::align_val_t align);
  - allocates size bytes of storage with guaranteed alignment of align
  - throws std::bad_alloc exception upon failure

- **void* operator new**(std::size_t size, const std::nothrow_t& tag);
  - allocates size bytes of storage suitably aligned for any object of this size not having extended alignment
  - returns null pointer upon failure

- **void* operator new**(std::size_t size, std::align_val_t align, const std::nothrow_t& tag);
  - allocates size bytes of storage with guaranteed alignment of align
  - returns null pointer upon failure
void* operator new(std::size_t size, void* ptr) noexcept;

- non.allocating
- simply returns ptr, assuming ptr points to storage of at least size bytes with appropriate alignment
- cannot fail
- not useful to invoke directly, since function effectively does nothing
- intended to be invoked by non.allocating placement new expressions
Single-Object Operator New Examples

```cpp
#include <new>
#include <cassert>
#include <string>

void func_1() {
    // allocating operator new
    std::string* sp = static_cast<std::string*>(::operator new(sizeof(std::string)));  
    // allocation succeeded since no exception thrown
    assert(sp);
    // ... (deallocate memory)
}

void func_2() {
    // allocating and non-throwing operator new
    std::string* sp = static_cast<std::string*>(::operator new(sizeof(std::string), std::nothrow));
    // sp may be null since allocation might have failed
    // ... (deallocate memory)
}

void func_3() {
    int i;
    // non-allocating operator new
    int* ip = static_cast<int*>(::operator new(sizeof(int),
        static_cast<void*>(&i)));
    assert(ip == &i);
}
```
array operator new (i.e., `operator new []`) is operator used to determine address at which to place array of objects to be created

array operator new may or may not allocate memory

array operator new can be overloaded as global function or (implicitly static) member function

operator has return type `void*` and returns address at which new array of objects to be created should be placed

first parameter to operator always of type `std::size_t` and specifies number of bytes of storage needed for new array of objects to be created

several overloads of global array operator new provided by language and standard library

`std::nothrow` is dummy variable of type `const std::nothrow_t` that can be used for overload disambiguation
**Array Operator New Overloads**

- **void* operator new[]**(std::size_t size);
  - allocates size bytes of storage that is suitably aligned for any object of this size not having extended alignment
  - throws std::bad_alloc exception upon failure

- **void* operator new[]**(std::size_t size, std::align_val_t align);
  - allocates size bytes of storage with alignment of align
  - throws std::bad_alloc exception upon failure

- **void* operator new[]**(std::size_t size, const std::nothrow_t& tag);
  - allocates size bytes of storage suitably aligned for any object of this size not having extended alignment
  - returns *null pointer* upon failure

- **void* operator new[]**(std::size_t size, std::align_val_t align, const std::nothrow_t& tag);
  - allocates size bytes of storage with guaranteed alignment of align
  - returns *null pointer* upon failure
Array Operator New Overloads (Continued)

- `void* operator new[](std::size_t size, void* ptr)`
  - **non-allocating**
  - simply returns `ptr`, assuming `ptr` points to storage of at least `size` bytes with appropriate alignment
  - cannot fail
  - not useful to invoke directly, since function effectively does nothing
  - intended to be invoked by non-allocating (array) `placement new` expressions
# include <new>
# include <cassert>
# include <string>

void func_1() {
    // allocating array operator new
    std::string* sp = static_cast<std::string*>(::operator new[](1000 * sizeof(std::string)));
    // allocation succeeded since no exception thrown
    assert(sp);
    // ... (deallocate)
}

void func_2() {
    std::string* sp = static_cast<std::string*>(::operator new[](1000 * sizeof(std::string), std::nothrow));
    // sp may be null since allocation might have failed
    // ... (deallocate)
}

void func_3() {
    static int a[1000];
    int* ip = static_cast<int*>(::operator new[](1000 * sizeof(int), static_cast<void*>(a)));
    assert(ip == a);
}
single-object operator delete (i.e., `operator delete`) is operator used to deallocate memory for object allocated with operator new

- can be invoked through delete expression or through new expression if constructor throws exception
- always has return type of `void`
- first parameter always pointer of type `void*`
- standard library deallocation functions do nothing if pointer is null
- can be overloaded as global function or (implicitly static) member function
void operator delete(void* ptr) noexcept;
void operator delete(void* ptr, std::size_t size) noexcept;
void operator delete (void* ptr, std::align_val_t align) noexcept;
void operator delete (void* ptr, std::size_t size, std::align_val_t align) noexcept;

- deallocates storage associated with object at address ptr, which was allocated by single-object operator new
#include <new>
#include <cassert>
#include <string>

void func_1() {
    // allocating operator new
    std::string* sp = static_cast<std::string*>(
        ::operator new(sizeof(std::string)));
    // allocation succeeded since no exception thrown
    assert(sp);
    ::operator delete(sp);
}

void func_2() {
    // allocating and non-throwing operator new
    std::string* sp = static_cast<std::string*>(
        ::operator new(sizeof(std::string), std::nothrow));
    // sp may be null since allocation might have failed
    // deleting null pointer is allowed
    ::operator delete(sp);
}
array operator delete (i.e., `operator delete[]`) is operator used to deallocate memory for array of objects allocated with array operator new

can be invoked through delete expression or through new expression if constructor throws exception

always has return type of `void`

first parameter always pointer of type `void*`

standard library deallocation functions do nothing if pointer is null

can be overloaded as global function or (implicitly static) member function
void operator delete[] (void* ptr) noexcept;
void operator delete[] (void* ptr, std::size_t size) noexcept;
void operator delete[] (void* ptr, std::align_val_t align) noexcept;
void operator delete[] (void* ptr, std::size_t size, std::align_val_t align) noexcept;

- deallocates storage associated with array of objects at address `ptr`, which was allocated by array operator new
```cpp
#include <new>
#include <cassert>
#include <string>

void func_1() {
    // allocating array operator new
    std::string* sp = static_cast<std::string*>(::operator new[](1000 * sizeof(std::string)));
    // allocation succeeded since no exception thrown
    assert(sp);
    ::operator delete[](sp);
}

t void func_2() {
    std::string* sp = static_cast<std::string*>(::operator new[](1000 * sizeof(std::string), std::nothrow));
    // sp may be null since allocation might have failed
    // deleting null pointer is allowed
    ::operator delete[](sp);
}
```
#include <cstddef>
#include <new>

// Gadget does not have extended alignment
struct Gadget {
    int i;
};

// Widget has extended alignment
struct alignas(2 * alignof(std::max_align_t)) Widget {
    int i;
};

int main() {
    Gadget* gp = new Gadget;
    // invokes operator new(std::size_t)
    delete gp;
    // invokes operator delete(void *)
    Widget* wp = new Widget;
    // invokes operator new(std::size_t, std::align_val_t)
    delete wp;
    // invokes operator delete(void *, std::align_val_t)
}
- some global versions of single-object and array operator `new` and `operator delete` can be replaced
- to replace function, define in single translation unit
- undefined behavior if more than one replacement provided in program or if replacement defined with inline specifier
Example: Replacing Global Operator New/Delete

```cpp
#include <cstdio>
#include <cstdlib>
#include <new>
#include <string>

void* operator new(std::size_t size) {
    auto ptr = std::malloc(size);
    if (!ptr) {throw std::bad_alloc();}
    std::printf("operator new(%zu) returning %p\n", size, ptr);
    return ptr;
}

void operator delete(void* ptr) noexcept {
    std::printf("operator delete(%p)\n", ptr);
    std::free(ptr);
}

void* operator new[](std::size_t size) {
    auto ptr = std::malloc(size);
    if (!ptr) {throw std::bad_alloc();}
    std::printf("operator new[](%zu) returning %p\n", size, ptr);
    return ptr;
}

void operator delete[](void* ptr, std::size_t size) noexcept {
    std::printf("operator delete[](%p)\n", ptr);
    std::free(ptr);
}

int main() {
    std::string* ip = new std::string;
    delete ip;
    std::string* ap = new std::string[10];
    delete[] ap;
}
```
Example: Overloading Operator New/Delete

```c++
#include <cstdlib>
#include <cstdio>
#include <stdexcept>

class Widget {
public:
    void *operator new(std::size_t size) {
        std::printf("Widget::operator new\n");
        if (void *p = std::malloc(size); !p) {throw std::bad_alloc();}
        else {return p;}
    }

    void operator delete(void* p) noexcept {
        std::printf("Widget::operator delete\n");
        std::free(p);
    }

    // ...
};

int main() {
    Widget* wp = new Widget; // invokes Widget::operator new
    delete wp; // invokes Widget::operator delete
    Widget* vp = ::new Widget; // invokes global operator new
    ::delete vp; // invokes global operator delete
}
```
```cpp
#include <cstdint>

// heap-allocated array of bounded size

// why is this implementation extremely inefficient?

template <class T>
class bvec {

public:

// create empty vector that can hold max_size elements
// why is this implementation extremely inefficient?
bvec(std::size_t max_size) {
    start_ = new T[max_size];
    end_ = start_ + max_size;
    finish_ = start_; // mark array empty
}

// why is this implementation extremely inefficient?
~bvec() {
    delete[] start_;
}

// ...

private:
T* start_; // start of storage for element data
T* finish_; // one past end of element data
T* end_; // end of storage for element data
};
```
Motivation for Placement New: Diagram

bvec<T>

start_

finish_

end_

Array of T

\[ x_0 \]
\[ x_1 \]
\[ \vdots \]
\[ x_{n-1} \]
\[ x_n \]
\[ x_{n+1} \]
\[ \vdots \]
\[ x_{m-1} \]
Placement New

- placement new expression is new expression that specifies one or more (optional) placement arguments
- often, placement new used for purpose of constructing object at specific place in memory
- this is accomplished by forcing non-allocating overload of operator new to be used (via placement arguments of new expression)
- example:

  ```cpp
  alignas(std::string) char buffer[sizeof(std::string)];
  std::string* sp =
      new (static_cast<void*>(buffer)) std::string("Hello");
  assert(static_cast<void*>(sp) == buffer);
  // ... (destroy)
  ```

- although, in principle, placement new can also be used with new expressions for arrays, not very practically useful (since objects in array can always be created using single-object placement new expressions)
#include <new>
#include <vector>
#include <string>
#include <cassert>
#include <utility>

void func_1() {
    alignas(int) char buffer[sizeof(int)];
    int* ip = ::new (static_cast<void*>(buffer)) int(42);
    assert(static_cast<void*>(ip) == buffer && *ip == 42);
}

void func_2() {
    alignas(std::string) char buffer[sizeof(std::string)];
    std::string* vp = ::new (static_cast<void*>(buffer)) std::string("hello");
    assert(static_cast<void*>(vp) == buffer && vp->size() == 5 &&
           (*vp)[0] == 'h');
    // ... (destroy)
}

template <class T, class... Args> T* construct_at(void* ptr, Args&&... args)
    { return ::new (ptr) T(std::forward<Args>(args)...);}

void func_3() {
    alignas(std::vector<int>) char buffer[sizeof(std::vector<int>)];
    std::vector<int>* vp = construct_at<std::vector<int>>(buffer, 1000, 42);
    assert(static_cast<void*>(vp) == buffer && vp->size() == 1000 &&
           (*vp)[0] == 42);
    // ... (destroy vector)
}
Direct Destructor Invocation

- can directly invoke destructor of class object
- only very special circumstances necessitate direct invocation of destructor
- used in situations where deallocation must be performed separately from destruction (in which case delete expression cannot be used as it performs both destruction and deallocation together)
- typical use case is for implementing container classes where destruction of object stored in container and deallocation of memory occupied by that object done at different points in time
- given pointer \( p \) to class object of type \( T \), can directly invoke destructor through pointer using syntax \( p->\sim T() \) or \( (*p).\sim T() \)

Example:

```cpp
alignas(std::vector<int>) char buf[
    sizeof(std::vector<int>)];
std::vector<int>* vp = ::new (static_cast<void*>(buf))
    std::vector<int>(1024);
vp->~vector();
```
Pseudodestructors

- as discussed previously, given identifier T that names type and pointer p to object of that type, can directly invoke destructor with syntax p->~T();
- language allows for T to name built-in type \([C++17 \S 8.2.4/1]\)
- if T names built-in type, above syntax invokes placeholder for destructor called pseudodestructor, which effectively does nothing
- example:
  ```cpp
  void func() {
    using T = int;
    int i = 0;
    int* ip = &i;
    ip->~T();
    // OK: pseudodestructor invocation (does nothing)
    //ip->~int(); // ERROR: int is not identifier
  }
  ```
  - consequently, in code that directly invokes destructor, do not need to treat built-in type as special case
  - pseudodestructor functionality often extremely useful in template code that directly invokes destructors
Section 3.8.2

More on Memory Management
**std::addressof Function Template**

- for memory management purposes, often necessary to obtain address of object
- if class overloads address-of operator, obtaining address of object becomes more difficult
- for convenience, standard library provides `std::addressof` function template for querying address of object, which yields correct result even if class overloads address-of operator
- declaration:
  ```cpp
template <class T>
  constexpr T* addressof(T& arg) noexcept;
template <class T>
  const T* addressof(const T&&) = delete;
  ```
- `addressof` function should be used any time address of object is required whose class may have overloaded address-of operator
- example:
  ```cpp
template <class T> foo(const T& x) {
    const T* p = std::addressof(x);
    // ...
  }
  ```
```cpp
#include <iostream>
#include <cassert>
#include <memory>

// class that overloads address-of operator
class Foo {
public:
    Foo(int i) : i_(i) {}
    const Foo* operator&() const { return nullptr; }
    Foo* operator&() { return nullptr; }
    int get() const { return i_; }
    // ...
private:
    int i_;
};

int main() {
    Foo f(42);
    assert(&f == nullptr);
    assert(std::addressof(f) != nullptr &&
           std::addressof(f)->get() == 42);
    std::cout << std::addressof(f) << '
';
}
```
often need can arise for buffer of particular size and alignment

for convenience, standard library provides \texttt{std::aligned_storage class template} for specifying such buffers

declaration:
\begin{verbatim}
    template <std::size_t Size, std::size_t Align = __default_alignment>
    struct aligned_storage;
\end{verbatim}

\texttt{Size} is size of storage buffer in bytes

\texttt{Align} is alignment of storage buffer (which has implementation-dependent default)

for additional convenience, \texttt{std::aligned_storage_t alias template} also provided

declaration:
\begin{verbatim}
    template <std::size_t Size, std::size_t Align = __default_alignment>
    using aligned_storage_t = typename aligned_storage<Len, Align>::type;
\end{verbatim}

example:
\begin{verbatim}
    std::aligned_storage_t<\texttt{sizeof}(std::string),
                        \texttt{alignof}(std::string)> buffer;
\end{verbatim}
Optional Value Example

- consider container class template called `optval` that can hold optional value
- class templated on type `T` of optional value
- container object in one of two states:
  1. holding value of type `T`
  2. not holding any value
- can query if container is holding value, and if so, access held value
- somewhat similar in spirit to `std::optional`
- want to store object of type `T` in `optval` object itself
- no memory allocation required
- example demonstrates use of placement new (to construct object at particular place in memory) and direct invocation of destructor
Optional Value Example: Diagram

```cpp
optval<T>

valid_
storage_
```
```cpp
#include <new>
#include <type_traits>

template <class T> class optval {

public:
    optval() : valid_(false) {}
    ~optval() {clear();}
    optval(const optval&) = delete; // for simplicity
    optval& operator=(const optval&) = delete; // for simplicity

    bool has_value() const noexcept { return valid_; }
    const T& get() const { return reinterpret_cast<const T&>(storage_); }

    void clear() noexcept {
        if (valid_) {
            valid_ = false;
            reinterpret_cast<T*>(&storage_)->~T();
        }
    }

    void set(const T& value) {
        clear();
        ::new (static_cast<void*>(&storage_)) T(value);
        valid_ = true;
    }

private:
    bool valid_; // is value valid?
    std::aligned_storage_t<sizeof(T), alignof(T)> storage_; // storage for value
    // or alternatively: alignas(T) char storage_[sizeof(T)];
};
```
```cpp
#include <cassert>
#include <string>
#include <iostream>
#include "optional_1_util.hpp"

int main() {
    optval<std::string> s;
    assert(!s.has_value());
    s.set("Hello, World");
    assert(s.has_value());
    std::cout << s.get() << "\n";
    s.clear();
    assert(!s.has_value());
}
```
sometimes need may arise to work with uninitialized storage

may want to construct objects in uninitialized storage (by using placement new to invoke constructor) and later destroy objects

may want to move or copy objects into uninitialized storage (by using placement new to invoke move or copy constructor)

code required to perform above operations is not very long, but must be written with some care to ensure that exceptions handled correctly

standard library provides functions that perform these operations for convenience

these functions useful for code that manages memory without using standard-compliant allocators
## Functions for Uninitialized Storage

### Operations on Uninitialized Memory

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>uninitialized_copy</td>
<td>copy range of objects to uninitialized area of memory</td>
</tr>
<tr>
<td>uninitialized_copy_n</td>
<td>copy number of objects to uninitialized area of memory</td>
</tr>
<tr>
<td>uninitialized_fill</td>
<td>copy object to uninitialized area of memory, defined by range</td>
</tr>
<tr>
<td>uninitialized_fill_n</td>
<td>copy object to uninitialized area of memory, defined by start and count</td>
</tr>
<tr>
<td>uninitialized_move</td>
<td>move range of objects to uninitialized area of memory</td>
</tr>
<tr>
<td>uninitialized_move_n</td>
<td>move number of objects to uninitialized area of memory</td>
</tr>
</tbody>
</table>
## Operations on Uninitialized Memory (Continued)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>uninitialized_default_construct</td>
<td>construct objects by default initialization in uninitialized area of memory defined by range</td>
</tr>
<tr>
<td>uninitialized_default_construct_n</td>
<td>construct objects by default initialization in uninitialized area of memory defined by start and count</td>
</tr>
<tr>
<td>uninitialized_value_construct</td>
<td>construct objects by value initialization in uninitialized area of memory defined by range</td>
</tr>
<tr>
<td>uninitialized_value_construct_n</td>
<td>construct objects by value initialization in uninitialized area of memory defined by start and count</td>
</tr>
<tr>
<td>destroy_at</td>
<td>destroy object at given address</td>
</tr>
<tr>
<td>destroy</td>
<td>destroy range of objects</td>
</tr>
<tr>
<td>destroy_n</td>
<td>destroy number of objects in range</td>
</tr>
</tbody>
</table>
template<class InputIter, class ForwardIter>
ForwardIter uninitialized_copy(InputIter first, InputIter last,
    ForwardIter result) {
    using Value = typename std::iterator_traits<ForwardIter>::value_type;
    ForwardIter current = result;
    try {
        for (; first != last; ++first, (void) ++current) {
            ::new (static_cast<void*>(std::addressof(*current))) Value(*first);
        }
    } catch (...) {
        for (; result != current; ++result) {
            result->~Value();
        }
        throw;
    }
    return current;
}

template<class ForwardIter>
void destroy(ForwardIter first, ForwardIter last) {
    for (; first != last; ++first) {
        std::destroy_at(std::addressof(*first));
    }
}

template<class T>
void destroy_at(T* p) {p->~T();}
consider class template `array` for bounded one-dimensional array whose maximum size is compile-time constant

class templated on element type `T` and number `N` of elements in array
array element data is stored `in array object itself`

no memory allocation required
provide only basic container functionality in order to keep example to reasonable size for slides
example demonstrates handling of uninitialized memory using standard library functions

similar in spirit to `boost::static_vector`
Bounded Array Example: Diagram

array<T, N>

finish_

buf_

\[ x_0 \]
\[ x_1 \]
\[ \vdots \]
\[ x_{s-1} \]
\[ x_s \]
\[ x_{s+1} \]
\[ \vdots \]
\[ x_{N-1} \]
// type-aware aligned buffer class
// provides buffer suitably aligned for N elements of type T

template <class T, std::size_t N>
class aligned_buffer {

public:
    const T* start() const noexcept
    { return reinterpret_cast<const T*>(storage_); }
    T* start() noexcept { return reinterpret_cast<T*>(storage_); }
    const T* end() const noexcept { return start() + N; }
    T* end() noexcept { return start() + N; }

private:
    alignas(T) char storage_[N * sizeof(T)]; // aligned buffer
};
Bounded Array Example: \texttt{array.hpp} (1)

```cpp
#include <memory>
#include <algorithm>
#include <type_traits>
#include "aligned_buffer.hpp"

// Template class for a bounded array
template <class T, std::size_t N>
class array {
public:
    array() {finish_ = buf_.start();}
    array(const array& other);
    array(array&& other);
    ~array() {clear();}
    array& operator=(const array& other);
    array& operator=(array&& other);
    explicit array(std::size_t size);
    array(std::size_t size, const T& value);
    constexpr std::size_t max_size() const noexcept {return N;}
    std::size_t size() const noexcept {return finish_ - buf_.start();}
    T& operator[](std::size_t i) {return buf_.start()[i];}
    const T& operator[](std::size_t i) const {return buf_.start()[i];}
    T& back() {return finish_-1;}
    const T& back() const {return finish_-1;}
    void push_back(const T& value);
    void pop_back();
    void clear() noexcept;

private:
    T* finish_; // one past last element in buffer
    aligned_buffer<T, N> buf_; // buffer for array elements
};
```
template <class T, std::size_t N>
array<T, N>::array(const array& other) {
    finish_ = std::uninitialized_copy(other.buf_.start(),
      static_cast<const T*>(other.finish_), buf_.start());
}

template <class T, std::size_t N>
array<T, N>::array(array&& other) {
    finish_ = std::uninitialized_move(other.buf_.start(), other.finish_,
      buf_.start());
}

template <class T, std::size_t N>
array<T, N>& array<T, N>::operator=(const array& other) {
    if (this != &other) {
        clear();
        finish_ = std::uninitialized_copy(other.buf_.start(),
          static_cast<const T*>(other.finish_), buf_.start());
    }
    return *this;
}

template <class T, std::size_t N>
array<T, N>& array<T, N>::operator=(array&& other) {
    if (this != &other) { // self-assignment check of questionable value
        clear();
        finish_ = std::uninitialized_move(other.buf_.start(), other.finish_,
          buf_.start());
    }
    return *this;
}
template <class T, std::size_t N>
array<T, N>::array(std::size_t size) {
    if (size > max_size()) {size = max_size();}
    std::uninitialized_default_construct_n(buf_.start(), size);
    finish_ = buf_.start() + size;
}

template <class T, std::size_t N>
array<T, N>::array(std::size_t size, const T& value) {
    if (size > max_size()) {size = max_size();}
    finish_ = std::uninitialized_fill_n(buf_.start(), size, value);
}

template <class T, std::size_t N>
void array<T, N>::push_back(const T& value) {
    if (finish_ == buf_.end()) {return;}
    finish_ = std::uninitialized_fill_n(finish_, 1, value);
}

template <class T, std::size_t N>
void array<T, N>::pop_back() {
    --finish_;
    std::destroy_at(finish_);
}
```cpp
template <class T, std::size_t N>
void array<T, N>::clear() noexcept {
    std::destroy(buf_.start(), finish_);
    finish_ = buf_.start();
}
```
consider class template `vec` that is one-dimensional dynamically-resizable array

- class templated on array element type `T`
- storage for element data allocated with `operator new`
- similar in spirit to `std::vector` but much simplified:
  - cannot specify allocator to be used (i.e., always uses `operator new` and `operator delete` for memory allocation)
  - does not provide iterators
  - only provides strong exception-safety guarantee for element insertion if move constructor for container element type does not throw
Vector Example: Diagram

vec<T>

start_

finish_

der_  

Array of T

\( x_0 \)

\( x_1 \)

\( x_{n-1} \)

\( x_n \)

\( x_{n+1} \)

\( x_{m-1} \)
Vector Example: vec.hpp (1)

```cpp
#include <new>
#include <algorithm>
#include <type_traits>
#include <memory>

template <class T> class vec {
public:
    vec() noexcept : start_(nullptr), finish_(nullptr), end_(nullptr) {}
    vec(const vec& other);
    vec(vec&& other) noexcept;
    ~vec();
    vec& operator=(const vec& other);
    vec& operator=(vec&& other) noexcept;
    explicit vec(std::size_t size);
    vec(std::size_t n, const T& value);
    std::size_t capacity() const noexcept { return end_ - start_; }
    std::size_t size() const noexcept { return finish_ - start_; }
    T& operator[](int i) { return start_[i]; }
    const T& operator[](int i) const { return start_[i]; }
    T& back() { return finish_[-1]; }
    const T& back() const { return finish_[-1]; }
    void push_back(const T& value);
    void pop_back();
    void clear() noexcept;
private:
    void grow(std::size_t n);
    T* start_; // start of element storage
    T* finish_; // one past last valid element
    T* end_; // end of element storage
};
```
template <class T>
vec<T>::vec(const vec& other) {
    start_ = static_cast<T*>(::operator new(other.size() * sizeof(T)));
    end_ = start_ + other.size();
    try {
        finish_ = std::uninitialized_copy(other.start_, other.finish_, start_);
    } catch (...) {
        ::operator delete(start_);
        throw;
    }
}

template <class T>
vec<T>::vec(vec&& other) noexcept {
    start_ = other.start_;
    other.start_ = nullptr;
    end_ = other.end_;
    other.end_ = nullptr;
    finish_ = other.finish_;
    other.finish_ = nullptr;
}

template <class T>
vec<T>::~vec() {
    clear();
    ::operator delete(start_);
}
```cpp
template <class T>
vec<T>& vec<T>::operator=(const vec& other) {
    if (this != &other) {
        clear();
        if (other.size() > capacity()) {grow(other.size());}
        finish_ = std::uninitialized_copy(other.start_, other.finish_, start_);
    }
    return *this;
}

template <class T>
vec<T>& vec<T>::operator=(vec&& other) noexcept {
    if (this != &other) { // self-assignment check of questionable value
        clear();
        ::operator delete(start_);
        start_ = other.start_;
        other.start_ = nullptr;
        finish_ = other.finish_;
        other.finish_ = nullptr;
        end_ = other.end_;
        other.end_ = nullptr;
    }
    return *this;
}
```

template <class T>
vec<T>::vec(std::size_t n) {
    start_ = static_cast<T*>(::operator new(n * sizeof(T)));  
    end_  = start_ + n;
    try  {std::uninitialized_default_construct_n(start_, n);}  
    catch (...) {
        ::operator delete(start_);  
        throw;
    }
    finish_ = end_;  
}

//opt

template <class T>
vec<T>::vec(std::size_t n, const T& value) {
    start_ = static_cast<T*>(::operator new(n * sizeof(T)));  
    end_  = start_ + n;
    try  {std::uninitialized_fill_n(start_, n, value);}  
    catch (...) {
        ::operator delete(start_);  
        throw;
    }
    finish_ = end_;  
}
template <class T>
void vec<T>::push_back(const T& value) {
    if (finish_ == end_) {
        // might want to check for overflow here
        grow(2 * capacity());
    }
    finish_ = std::uninitialized_fill_n(finish_, 1, value);
}

template <class T>
void vec<T>::pop_back() {
    --finish_;    
    std::destroy_at(finish_);
}

template <class T>
void vec<T>::clear() noexcept {
    if (size()) {
        std::destroy(start_, finish_);
        finish_ = start_;    
    }
}
```
template <class T>
void vec<T>::grow(std::size_t n) {
    T* new_start = static_cast<T*>(::operator new(n * sizeof(T)));
    std::size_t old_size = size();
    try {
        std::uninitialized_move(start_, finish_, new_start);
    } catch (...) {
        ::operator delete(new_start);
        throw;
    }
    ::operator delete(start_);
    start_ = new_start;
    finish_ = new_start + old_size;
    end_ = new_start + n;
}
```
Section 3.8.3

Allocators
Allocators

- allocators provide uniform interface for allocating and deallocating memory for object of particular type
- interface that allocator must provide specified in C++ standard
- each allocator type embodies particular memory allocation policy
- perform allocation, construction, destruction, and deallocation
- allocation separate from construction
- destruction separate from deallocation
- encapsulate information about allocation strategy and addressing model
- hide memory management and addressing model details from containers
- allow reuse of code implementing particular allocation strategy with any allocator-aware container
Containers, Allocators, and the Default Allocator

- container class templates typically take allocator type as parameter
- this allows more than one memory allocation policy to be used with given container class template
- in case of standard library, many container class templates take allocator type as template parameter, including:
  - vector, list
  - set, multiset, map, multimap
  - unordered_set, unordered_multiset, unordered_map, unordered_multimap
- all container class templates in standard library that take allocator as parameter use default of `std::allocator<T>` where `T` must be type of element held by container
- `std::allocator` employs operator `new` and operator `delete` for memory allocation
- in many contexts, default allocator is quite adequate
```
#include <memory>
#include <vector>
#include <map>
#include <cassert>
#include <boost/pool/pool_alloc.hpp>

int main() {
    // use default allocator
    std::vector<int> u;
    u.push_back(42);

    // explicitly specify default allocator
    std::vector<int, std::allocator<int>> v;
    static_assert(std::is_same_v<decltype(u), decltype(v)>);
    assert(u.get_allocator() == v.get_allocator());
    v.push_back(42);

    // specify an allocator type from Boost
    std::vector<int, boost::pool_allocator<int>> w;
    w.push_back(42);

    // explicitly specify default allocator
    std::map<int, long, std::less<int>, 
             std::allocator<std::pair<const int, long>>> x;
    x.insert({1, 2});
}
```
custom allocators used when greater control is needed over how memory is managed

often this greater control is desired for:
- improved efficiency (e.g., better locality and less contention)
- debugging
- performance analysis (e.g., collecting statistics on memory allocation)
- testing (e.g., forcing allocation failures)
- security (e.g., locking and clearing memory)

since many allocation strategies are possible, one strategy cannot be best in all situations

some allocation strategies include:
- stack-based allocation
- per-container allocation
- per-thread allocation (which avoids synchronization issues)
- pooled allocation
- arena allocation

may want to handle relocatable data (e.g., shared memory)

may want to use memory mapped files
Examples of Allocators

- other examples of (standard-compliant) allocators include:
  - `std::pmr::polymorphic_allocator` (allocator whose behavior depends on memory resource with which it was constructed)
  - `boost::interprocess::allocator` (shared memory allocator)
  - `boost::pool_alloc` (pool allocator)
  - `boost::fast_pool_alloc` (pool allocator)
Allocators

- allocator handles memory allocation for objects of specific type (e.g., allocator for `int`s)
- allocator normally accessed by container type through interface of traits class called `std::allocator_traits`
- container class typically use allocator for managing memory associated with container element data
- four basic types of operations provided by allocator through traits class:
  - allocate memory
  - deallocate memory
  - construct object
  - destroy object
- two allocator instances deemed *equal* if memory allocated with each instance can be deallocated with other
- allocator objects may have state
Allocator Members

- allocator type for objects of (cv-unqualified) type \( T \)
- many members are optional, with `std::allocator_traits` class effectively providing defaults for omitted members

**value_type:**
- type \( T \) of object for which allocator manages (i.e., allocates and deallocates) memory

**pointer:**
- pointer type used to refer to storage obtained from allocator (not necessarily \( T^* \))
- optional: default of \( T^* \) provided by `allocator_traits`

**const_pointer:**
- const version of `pointer`
- optional: default of `const T^*` provided by `allocator_traits`

**pointer allocate(size_type n):**
- allocate storage suitable for \( n \) objects of type \( T \)

**void deallocate(pointer ptr, size_type n):**
- deallocates storage pointed to by `ptr`, where `ptr` must have been obtained by previous call to `allocate` and \( n \) must match value given in that call
void construct(value_type* ptr, Args&&... args):
  constructs object of type T in storage pointed to by ptr using specified arguments args
  optional: default behavior provided by allocator_traits is to use placement new expression

void destroy(value_type* ptr):
  destroys object of type T in storage pointed to by ptr
  optional: default behavior provided by allocator_traits is to directly invoke destructor
Remarks on Allocators

- `pointer` and `const_pointer` must satisfy requirements of random-access and contiguous iterators \([\text{C++17 §20.5.3.5/5}]\)
- `pointer` and `const_pointer` can be fancy pointers (i.e., smart pointers)
- Fancy pointers useful, for example, in allocating storage in shared memory region
# Malloc-Based Allocator: Allocator Code

```cpp
#include <cstdlib>
#include <limits>
#include <new>

// Malloc-based allocator

template <class T> struct mallocator {
    using value_type = T;

    mallocator() noexcept {}  

    template <class U> mallocator(const mallocator<U>&) noexcept {}  

    template <class U> T* allocate(std::size_t n) const;  

    void deallocate(T* p, std::size_t n) const noexcept;  

    template <class U> bool operator==(const mallocator<U>&) const noexcept { return true; }  

    template <class U> bool operator!=(const mallocator<U>&) const noexcept { return false; }
};

template <class T> T* mallocator<T>::allocate(std::size_t n) const {
    if (!n) { return nullptr; }
    if (n > std::numeric_limits<std::size_t>::max() / sizeof(T)) {
        throw std::bad_array_new_length();
    }
    void* p = std::malloc(n * sizeof(T));
    if (!p) { throw std::bad_alloc(); }
    return static_cast<T*>(p);
}

template <class T> void mallocator<T>::deallocate(T* p, std::size_t)
    const noexcept
{ std::free(p); }
```
#include "mallocator.hpp"
#include <cassert>
#include <vector>
#include <type_traits>

int main() {
    std::vector<int, mallocator<int>> v;
    // uses mallocator<int> for memory allocation
    std::vector<int> w;
    // or equivalently, std::vector<int, std::allocator<int>>
    // uses std::allocator<int> for memory allocation
    static_assert(!std::is_same_v<decltype(v)::allocator_type,
        decltype(w)::allocator_type>);
    for (int i = 0; i < 128; ++i) {
        v.push_back(42);
        w.push_back(42);
    }
    std::vector<int, mallocator<int>> x;
    assert(v.get_allocator() == x.get_allocator());
}
in certain contexts, must consider if and how allocators should be propagated between container objects

- **lateral propagation** refers to propagation of allocator when copying, moving, and swapping containers:
  - when container copy/move constructed, what allocator does new container receive?
  - when container copy/move assigned, what allocator does copied-to/moved-to container receive?
  - when containers swapped, what allocator does each container receive?

- **deep propagation** refers to propagation of allocator from parent container to its descendants in hierarchy of nested containers:
  - if container contains types which themselves require allocators, how can contained elements be made aware of container’s allocator so that compatible allocator can be used?

- each allocator has its own lateral propagation properties, which can be accessed via `std::allocator_traits`

- deep allocator propagation can be controlled via `std::scoped_allocator_adaptor`
#include <limits>
#include <new>
#include <type_traits>

template <class T> struct allocator {
    using value_type = T;
    using propagate_on_container_move_assignment = std::true_type;
    using is_always_equal = std::true_type;

    allocator() noexcept {};
    allocator(const allocator&) noexcept {};
    template <class U> allocator(const allocator<U>&) noexcept {};
    ~allocator() {};

    T* allocate(std::size_t n);
    void deallocate(T* p, std::size_t n) const noexcept
    { ::operator delete(p); }
};

template <class T> T* allocator<T>::allocate(std::size_t n) {
    if (n > std::numeric_limits<std::size_t>::max() / sizeof(T))
        {throw std::bad_array_new_length();}
    return static_cast<T*>(::operator new(n * sizeof(T)));
}

template <class T, class U> inline bool operator==(const allocator<T>&, const allocator<U>&) noexcept
{ return true; }

template <class T, class U> inline bool operator!=(const allocator<T>&, const allocator<U>&) noexcept
{ return false; }
Consider example of simple allocator that allocates memory from fixed-size buffer.

- Arena class (called `arena`) provides memory allocation from fixed-size buffer with some prescribed minimum alignment.
- Allocator class (called `salloc`) provides interface to particular arena instance.
- `salloc` object holds pointer to arena object (so allocator is stateful).
- Arena object makes no attempt to deallocate memory (i.e., deallocate operation does nothing).
- Allocator might be used for relatively small allocations from stack (where arena object would be local variable).
- Allocator always propagated for copy, move, and swap (i.e., POCMA, POCCA, and POCS, as defined later, all true).
- Two instances of allocator not necessarily equal.
```cpp
#include <cstddef>
#include <limits>
#include <memory>
#include <new>

// Fixed-Size Arena Allocator

template <std::size_t N, std::size_t Align = alignof(std::max_align_t)>
class arena {
public:
    arena() : ptr_(buf_) {}
    arena(const arena&) = delete;
    arena& operator=(const arena&) = delete;
    ~arena() = default;

    constexpr std::size_t alignment() const {return Align;}
    constexpr std::size_t capacity() const {return N;}
    constexpr std::size_t used() const {return ptr_ - buf_;}
    constexpr std::size_t free() const {return N - used();}

    template <std::size_t ReqAlign>
    void* allocate(std::size_t n);

    void deallocate(void* ptr, std::size_t n) {}
    void clear() {ptr_ = buf_;}

private:
    template <std::size_t ReqAlign>
    static char* align(char* ptr, std::size_t n, std::size_t max);
    alignas(Align) char buf_[N]; // storage buffer
    char* ptr_; // pointer to first unused byte
};
```
template <std::size_t N, std::size_t Align>

template <std::size_t ReqAlign>
char* arena<N, Align>::align(char* ptr, std::size_t n, std::size_t max) {
    void* p = ptr;
    return static_cast<char*>(std::align(ReqAlign, n, p, max));
}

template <std::size_t N, std::size_t Align>

void* arena<N, Align>::allocate(std::size_t n) {
    char* ptr = this->align<std::max(Align, ReqAlign)>(ptr_, n, free());
    if (!ptr) {throw std::bad_alloc();}
    ptr_ = ptr + n;
    return ptr;
}
template <class T, std::size_t N, std::size_t Align = alignof(T)>
class salloc {
public:
  using value_type = T;
  using propagate_on_container_move_assignment = std::true_type;
  using propagate_on_container_copy_assignment = std::true_type;
  using propagate_on_container_swap = std::true_type;
  using is_always_equal = std::false_type;
  using arena_type = arena<N, Align>;
salloc select_on_container_copy_construction() const { return *this; }

  template <class U> struct rebind { using other = salloc<U, N, Align>; };

  template <class T2>
  salloc(const salloc<T2, N, Align>& other) : a_(other.a_) {}
salloc(arena_type& a) : a_(a) {}

  ~salloc() = default;
salloc(const salloc&) = default;
salloc(salloc&& other) = default;
salloc& operator=(const salloc&) = default;
salloc& operator=(salloc&& other) = default;
  T* allocate(std::size_t n) {
    if (n > std::numeric_limits<std::size_t>::max() / sizeof(T))
      { throw std::bad_alloc(); }
    return static_cast<T*>(a_->template allocate<alignof(T)>(
      n * sizeof(T)));
  }

  void deallocate(T* p, std::size_t n) {
    return a_->deallocate(p, n * sizeof(T));
  }
};
private:
    template <class T1, std::size_t N1, std::size_t A1, class T2, std::size_t N2, std::size_t A2>
    friend bool operator==(const salloc<T1, N1, A1>&, const salloc<T2, N2, A2>&);
    template <class, std::size_t, std::size_t> friend class salloc;
    arena_type* a_; // arena from which to allocate storage
};

template <class T1, std::size_t N1, std::size_t A1, class T2, std::size_t N2, std::size_t A2>
inline bool operator==(const salloc<T1, N1, A1>& a, const salloc<T2, N2, A2>& b) {
    return N1 == N2 && A1 == A2 && a.a_ == b.a_;}

template <class T1, std::size_t N1, std::size_t A1, class T2, std::size_t N2, std::size_t A2>
inline bool operator!=(const salloc<T1, N1, A1>& a, const salloc<T2, N2, A2>& b) {
    return !(a == b);}
```cpp
#include <vector>
#include <list>
#include <iostream>
#include "salloc.hpp"

int main() {
    using alloc = salloc<int, 1024, sizeof(int)>;
    alloc::arena_type a;
    std::vector<int, alloc> v{{0, 1, 2, 3}, a};
    std::vector<int, alloc> w{{0, 2, 4, 6}, a};
    std::list<int, alloc> p{{1, 3, 5, 7}, a};
    std::cout << a.free() << '
';
    v.push_back(42);
    for (auto&& i : v) {std::cout << i << '
';}
    for (auto&& i : w) {std::cout << i << '
';}
    for (auto&& i : p) {std::cout << i << '
';}
    std::cout << a.free() << '
';

    // std::vector<int, alloc> x(1024);
    // std::list<int, alloc> y;
    // ERROR: allocator cannot be default constructed
    }
```
- container that uses allocator sometimes referred to as **allocator aware**
- typically much more difficult to develop allocator-aware container than container that does not use allocator
- type of pointer returned by allocator not necessarily same as pointer to element type, which sometimes complicates code somewhat
- much of complexity in implementing allocator-aware container, however, arises from issue of allocator propagation
allocators intended to be used via allocator user (e.g., container) indirectly through traits class `std::allocator_traits`

declaration:
```cpp
template <class Alloc> struct allocator_traits;
```

`allocator_traits` provides uniform interface to allocators used by containers

some properties of allocator types are optional

in cases where allocator type did not specify optional properties, `allocator_traits` provides default
properties of allocator in `std::allocator_traits` used to control lateral allocator propagation

- container copy constructor obtains allocator for new container by invoking `select_on_container_copy_construction` in `allocator_traits`
- container move constructor always propagates allocator by move
- container copy assignment replaces allocator (in copied-to container) only if `propagate_on_container_copy_assignment` (POCCA) in `allocator_traits` is true
- container move assignment replaces allocator (in moved-to container) only if `propagate_on_container_move_assignment` (POCMA) in `allocator_traits` is true
- container swap will swap allocators of two containers only if `propagate_on_container_swap` (POCS) in `allocator_traits` is true
  - if POCS is false, swapping two standard-library containers with unequal allocators is undefined behavior (since swap must not invalidate iterators and iterators would have to be invalidated in this case)
Allocator-Traits Querying Example

```cpp
#include <memory>
#include <type_traits>
#include <boost/interprocess/managed_shared_memory.hpp>
#include <boost/interprocess/allocators/allocator.hpp>
#include <iostream>

// Querying template traits

template <class T> void print(std::ostream& out = std::cout) {
    out << std::is_same_v<typename T::pointer, typename T::value_type*> << ' ' 
        << std::is_same_v<typename T::const_pointer, const typename T::value_type*> << ' ' 
        << T::is_always_equal::value << ' ' 
        << T::propagate_on_container_move_assignment::value << ' ' 
        << T::propagate_on_container_copy_assignment::value << ' ' 
        << T::propagate_on_container_swap::value << '
';
}

int main() {
    namespace bi = boost::interprocess;
    print<std::allocator_traits<std::allocator<int>>>();
    print<std::allocator_traits<bi::allocator<int, 
        bi::managed_shared_memory::segment_manager>>>();
    
    /* Output: */
    1 1 1 1 0 0
    0 0 0 0 0
    */
```
• consider container class template called `optval` that can hold optional value

• class templated on element type `T` and allocator type

• container object in one of two states:
  1. holding value of type `T`
  2. not holding any value

• can query if container is holding value, and if so, access held value

• want to store object of type `T` in memory obtained *from allocator*

• example illustrates basic use of allocator in container class
```cpp
#include <memory>
#include <type_traits>
#include <utility>

template <class T, class Alloc = std::allocator<T>>
class optval : private Alloc {
public:
    using value_type = T;
    using allocator_type = Alloc;
private:
    using traits = typename std::allocator_traits<Alloc>);
public:
    using pointer = typename traits::pointer;
    using const_pointer = typename traits::const_pointer;

    optval(std::allocator_arg_t, const allocator_type& alloc) :
        Alloc(alloc), value_(nullptr) {} 
    optval() : optval(std::allocator_arg, allocator_type()) {} 
    optval(std::allocator_arg_t, const allocator_type& alloc, 
        const optval& other);
    optval(optval&& other) noexcept;

    optval(optval&& other) noexcept;
    optval(std::allocator_arg_t, const allocator_type& alloc, const T& value);
    optval(const T& value);
    ~optval();
    optval& operator=(const optval& other);
    optval& operator=(optval&& other)
        noexcept(traits::propagate_on_container_move_assignment::value);
    void swap(optval& other) noexcept;
};
```
allocator_type get_allocator() const {return alloc_();}
bool has_value() const noexcept {return value_;
const T& get() const {return *value_;
void clear() noexcept;
void set(const T& value);
private:
  pointer copy_(allocator_type a, const value_type& value);
  allocator_type& alloc_() {return *this;
  const allocator_type& alloc_() const {return *this;
  pointer value_; // pointer to optional value
};

template <class T, class Alloc>
optval<T, Alloc>::optval(const optval& other) : optval(std::allocator_arg,
  traits::select_on_container_copy_construction(other.alloc_()), other) {}

template <class T, class Alloc>
optval<T, Alloc>::optval(std::allocator_arg_t, const allocator_type& alloc,
  const optval& other) : Alloc(alloc), value_(nullptr) {
  if (other.value_) {value_ = copy_(alloc_(), *other.value_);
}

template <class T, class Alloc>
optval<T, Alloc>::optval(optval&& other) noexcept : Alloc(std::move(other)) {
  value_ = other.value_;
  other.value_ = nullptr;
}
```cpp
template <class T, class Alloc>
optval<T, Alloc>::optval(std::allocator_arg_t, const allocator_type& alloc,
    optval&& other) noexcept : Alloc(alloc) {
    value_ = other.value_;  
    other.value_ = nullptr;
}

template <class T, class Alloc>
optval<T, Alloc>::optval(std::allocator_arg_t, const allocator_type& alloc,
    const T& value) : Alloc(alloc), value_(nullptr)
    {value_ = copy_(alloc_(), value);}

template <class T, class Alloc>
optval<T, Alloc>::optval(const T& value) : optval(std::allocator_arg,
    allocator_type(), value) {}

template <class T, class Alloc>
optval<T, Alloc>::~optval()
    {clear();}
```
```cpp
template <class T, class Alloc>
auto optval<T, Alloc>::operator=(const optval& other) -> optval& {
    if (this != &other) {
        if constexpr (traits::propagate_on_container_copy_assignment::value) {
            allocator_type a = other.alloc_();
            pointer p = other.value_ ? copy_(a, *other.value_) : nullptr;
            clear();
            alloc_() = other.alloc_();
            value_ = p;
        } else {
            pointer p = other.value_ ? copy_(alloc_(), *other.value_) : nullptr;
            clear();
            value_ = p;
        }
    }
    return *this;
}
```
template <class T, class Alloc>
auto optval<T, Alloc>::operator=(optval&& other) noexcept (traits::propagate_on_container_move_assignment::value) -> optval& {
    using std::swap;
    if (this != &other) {
        if constexpr (traits::propagate_on_container_move_assignment::value) {
            clear();
            swap(alloc_(), other.alloc_());
            swap(value_, other.value_);
        } else if (alloc_() == other.alloc_()) {
            clear();
            swap(value_, other.value_);
        } else {
            pointer p = copy_(alloc_(), other.value_);
            swap(value_, other.value_);
            other.clear();
            value_ = p;
        }
    }
    return *this;
}

template <class T, class Alloc>
void optval<T, Alloc>::swap(optval& other) noexcept {
    using std::swap;
    assert(traits::propagate_on_container_swap::value ||
           alloc_() == other.alloc_());
    if constexpr (traits::propagate_on_container_swap::value)
    {swap(alloc_(), other.alloc_());}
    swap(value_, other.value_);
}
```cpp
template <class T, class Alloc>
void optval<T, Alloc>::clear() noexcept {
    if (value_)
        traits::destroy(alloc_(), std::addressof(*value_));
    traits::deallocate(alloc_(), value_, 1);
    value_ = nullptr;
}

template <class T, class Alloc>
void optval<T, Alloc>::set(const T& value) {
    pointer p = copy_(alloc_(), value);
    clear();
    value_ = p;
}

template <class T, class Alloc>
auto optval<T, Alloc>::copy_(allocator_type a, const value_type& value) ->
    pointer {
    pointer p = traits::allocate(alloc_(), 1);
    try {traits::construct(a, std::addressof(*p), value);} catch (...) {
        traits::deallocate(a, p, 1);
        throw;
    }
    return p;
}
```
when using stateful allocators with nested containers, often need to ensure that allocator state is propagated from parent container to its descendants

`std::scoped_allocator_adaptor` can be used to address this type of allocator propagation problem (i.e., deep allocator propagation)

declaration:
```
template <class OuterAlloc, class... InnerAllocs>
class scoped_allocator_adaptor : public OuterAlloc;
```

`OuterAlloc`: allocator type for outermost container in nesting

`InnerAllocs`: parameter pack with allocator types for each subsequent container in nesting

if `InnerAllocs` has too few allocator types for number of nesting levels, last allocator type repeated as necessary

`scoped_allocator_adaptor` useful when all containers in nesting must use same stateful allocator, such as typically case when using shared-memory-segment allocator
```cpp
#include <scoped_allocator>
#include <vector>
#include <list>
#include <iostream>
#include "salloc.hpp"

int main() {
    constexpr std::size_t align = alignof(std::max_align_t);
    using inner_alloc = salloc<int, 1024, align>;
    using inner = inner_alloc::value_type;
    using outer_alloc = salloc<std::list<int, inner_alloc>, 1024, align>;
    using outer = outer_alloc::value_type;
    using alloc = std::scoped_allocator_adaptor<outer_alloc, inner_alloc>;

    using container = std::vector<outer, alloc>;
    alloc::arena_type a;
    container v(container::allocator_type(a, a));
    v.reserve(4);
    std::list<inner, inner_alloc> p({1, 2, 3}, a);
    v.push_back(p);
    for (auto&& y : v) {
        for (auto&& x : y) {
            std::cout << x << '
';
        }
    }
}
```
```cpp
#include <vector>
#include <scoped_allocator>
#include <boost/interprocess/managed_shared_memory.hpp>
#include <boost/interprocess/allocators/adaptive_pool.hpp>

namespace bi = boost::interprocess;

template <class T>
using alloc = typename bi::adaptive_pool<T, typename bi::managed_shared_memory::segment_manager>;

int main () {
    using row = std::vector<int, alloc<int>>;
    using matrix = std::vector<row, std::scoped_allocator_adaptor<alloc<row>>>;
    bi::managed_shared_memory s(bi::create_only, "data", 8192);
    matrix v(s.get_segment_manager());
    v.resize(4);
    for (int i = 0; i < 4; ++i) {v[i].push_back(0);}
    bi::shared_memory_object::remove("data");
}
```
Section 3.8.4

References


This talk discusses how to write allocators for C++14/C++17 and how to use such allocators in containers.

This talk briefly introduces allocators and then describes a test suite for allocators and presents some results obtained with this test suite.

This talk introduces polymorphic allocators and considers a simple example of a polymorphic allocator and a container that uses a polymorphic allocator.


Michael Spencer. Alignment in C++: Use, Limitations, and Extension. C++Now, Aspen, CO, USA, May 12–17, 2013. Available online at https://youtu.be/uSZFrmhayIM. [The part of the talk in 00:00-34:13 is likely to be of most interest.]
Section 3.9

Concurrency
Section 3.9.1

Preliminaries
A **core** is an independent processing unit that reads and executes program instructions, and consists of registers, an arithmetic logic unit (ALU), a control unit, and usually a cache.

A **processor** is a computing element that consists of one or more cores, an external bus interface, and possibly a shared cache.

A **thread** is a sequence of instructions (which can be executed by a core).

At any given time, a core can execute one thread or, if the core supports simultaneous multithreading (such as hyperthreading), multiple threads.

In the simultaneous multithreading case, the threads share the resources of the core.

A processor with more than one core is said to be **multicore**.

Most modern processors are multicore.

Multicore processors can *simultaneously* execute *multiple* threads.
A multicore processor said to be **homogeneous** if all of its cores are identical.

A multicore processor said to be **heterogeneous** if it has more than one type of core.

Different types of cores might be used in order to:
- provide different types of functionality (e.g., CPU and GPU)
- provide different levels of performance (e.g., high-performance CPU and energy-efficient CPU)
The component of a system that stores program instructions and data is called **main memory**.

A **cache** is fast memory used to store copies of instructions and/or data from main memory.

Main memory is **very slow** compared to the speed of a processor core.

Due to the latency of main memory, caches are **essential** for good performance.

Instruction and data caches may be **separate** or **unified** (i.e., combined).

A cache may be **local** to single core or **shared** between two or more cores.

The lowest-level (i.e., L1) cache is usually on the core and local to the core.

The higher-level (i.e., L2, L3, ..., LL [last level]) caches are usually shared between some or all of the cores.
Examples of Multicore Processors

- **Intel Core i7-3820QM Processor (Q2 2012)**
  - used in Lenovo W530 notebook
  - 64 bit, 2.7 GHz
  - 128/128 KB L1 cache, 1 MB L2 cache, 8 MB L3 cache
  - **4 cores**
  - **8 threads** (2 threads/core)

- **Intel Core i7-5960X Processor Extreme Edition (Q3 2014)**
  - targets desktops/notebooks
  - 64 bit, 3 GHz
  - 256/256 KB L1 cache, 2 MB L2 cache, 20 MB L3 cache
  - **8 cores**
  - **16 threads** (2 threads/core)

- **Intel Xeon Processor E7-8890 v2 (Q1 2014)**
  - targets servers
  - 64 bit, 2.8 GHz
  - 480/480 KB L1 cache, 3.5 MB L2 cache, 37.5 MB L3 cache
  - **15 cores**
  - **30 threads** (2 threads/core)
Examples of Multicore SoCs

- Qualcomm Snapdragon 805 SoC (Q1 2014)
  - used in *Google Nexus 6*
  - 32-bit 2.7 GHz *quad-core* Qualcomm Krait 450 (ARMv7-A)
  - 16/16 KB L1 cache (per core), 2 MB L2 cache (shared)
  - 600 MHz Qualcomm Adreno 420 GPU

- Samsung Exynos 5 Octa 5433 SoC
  - used in *Samsung Galaxy Note 4*
  - high-performance 1.9 GHz *quad-core* ARM Cortex-A57 paired with energy-efficient 1.3 GHz *quad-core* ARM Cortex-A53 (big.LITTLE); both 32-bit (64-bit capable but disabled) (ARMv8-A)
  - Cortex-A57: 48/32 KB L1 cache, 512 KB to 2 MB L2 cache?
  - 700 MHz Mali-T760MP6 GPU

- Apple A8 SoC (2014)
  - used in *Apple iPhone 6, Apple iPhone 6 Plus*
  - 64-bit 1.4 GHz *dual-core* CPU (ARMv8-A)
  - 64/64 KB L1 cache (per core), 1 MB L2 cache (shared), 4 MB L3 cache
  - PowerVR Series 6XT GX6450 (quad-core) GPU
Why Multicore Processors?

- in past, greater processing power obtained through \textit{higher clock rates}
- \textit{clock rates have stopped rising}, topping out at about 5 GHz (little change since about 2005)
- power consumption is linear in clock frequency and quadratic in voltage, but higher frequency typically requires higher voltage; so, considering effect of frequency and voltage together, power consumption grows approximately with \textit{cube} of frequency
- greater power consumption translates into \textit{increased heat production}
- higher clock rates would result in processors \textit{overheating}
- transistor counts \textit{still increasing} (Moore’s law: since 1960s, transistor count has doubled approximately every 18 months)
- instead of increasing processing power by raising clock rate of processor core, simply \textit{add more processor cores}
- $n$ cores running at clock rate $f$ use significantly less power and generate less heat than single core at clock rate $nf$
- going multicore allows for \textit{greater processing power with lower power consumption and less heat production}
Section 3.9.2

Multithreaded Programming
Concurrency

- A thread is a sequence of instructions that can be independently managed by the operating-system scheduler.
- A process provides the resources that program needs to execute (e.g., address space, files, and devices) and at least one thread of execution.
- All threads of a process share the same address space.
- Concurrency is the situation where multiple threads execute over time periods (i.e., from start of execution to end) that overlap (but no threads are required to run simultaneously).
- Parallelism refers to the situation where multiple threads execute simultaneously.

Concurrency can be achieved with:
1. multiple single-threaded processes; or
2. a single multithreaded process.

A single multithreaded process is usually preferable, since this approach is typically much less resource intensive and data can often be shared much more easily between threads in a single process (due to the threads having a common address space).
Why Multithreading?

- Keep all of the processor cores busy (i.e., *fully utilize* all cores).
  - Most modern systems have multiple processor cores, due to having either multiple processors or a single processor that is multicore.
  - A single thread cannot fully utilize the computational resources available in such systems.

- Keep processes *responsive*.
  - In graphics applications, keep the GUI responsive while the application is performing slow operations such as I/O.
  - In network server applications, keep the server responsive to new connections while handling already established ones.

- *Simplify* the coding of cooperating tasks.
  - Some programs consist of several logically distinct tasks.
  - Instead of having the program manage when the computation associated with different tasks is performed, each task can be placed in a separate thread and the operating system can perform scheduling.
  - For certain types of applications, multithreading can significantly reduce the conceptual complexity of the program.
Section 3.9.3

Multithreaded Programming Models
A memory model (also known as a memory-consistency model) is a formal specification of the effect of read and write operations on the memory system, which in effect describes how memory appears to programs.

A memory model is essential in order for the semantics of a multithreaded program to be well defined.

The memory model must address issues such as:
- ordering
- atomicity

The memory model affects:
- programmability (i.e., ease of programming)
- performance
- portability
Sequential Consistency (SC)

- The environment in which a multithreaded program is run is said to have **sequential consistency (SC)** if the result of any execution of the program is the same as if the operations of all threads are executed in *some sequential order*, and the operations of each individual thread appear in this sequence in *the order specified by the program*.

- In other words, in a sequentially-consistent execution of a multithreaded program, threads behave as if their operations were simply *interleaved*.

- Consider the multithreaded program (with two threads) shown below, where \( x, y, a, \) and \( b \) are all integer variables and initially zero.

<table>
<thead>
<tr>
<th>Thread 1 Code</th>
<th>Thread 2 Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x = 1; )</td>
<td>( y = 1; )</td>
</tr>
<tr>
<td>( a = y; )</td>
<td>( b = x; )</td>
</tr>
</tbody>
</table>

- Some sequentially-consistent executions of this program include:
  - \( x = 1; y = 1; b = x; a = y; \)
  - \( y = 1; x = 1; a = y; b = x; \)
  - \( x = 1; a = y; y = 1; b = x; \)
  - \( y = 1; b = x; x = 1; a = y; \)
Since SC implies that memory must behave in a particular manner, SC implicitly defines a memory model, known as the **SC memory model**.

In particular, SC implies that each write operation is **atomic** and becomes visible to all threads **simultaneously**.

Thus, with the SC model, **all** threads see write operations on memory occur **atomically in the same order**, leading to all threads having a **consistent view** of memory.

The SC model precludes (or makes extremely difficult) many hardware optimizations, such as:

- store buffers
- caches
- out-of-order instruction execution

The SC model also precludes many compiler optimizations, including:

- reordering of loads and stores

Although the SC model very is **intuitive**, it comes at a **very high cost** in terms of performance.
Consider the program with the code below, where \( x \) and \( y \) are integer variables, all initially zero.

Original Thread 1 Code

```
x = 1;
y = 1;
// ...  
```

Suppose that, during optimization, the compiler transforms the preceding code to that shown below, effectively *reordering two stores*.

Optimized Thread 1 Code

```
y = 1;
x = 1;
// ...  
```

The execution of the optimized code is *indistinguishable* from a sequentially-consistent execution of the original code.

The optimized program runs *as if* it were the original program.

In a *single-threaded* program, loads and stores can be reordered without invalidating the SC model (if data dependencies are correctly considered).
Consider the addition of a second thread to the program to yield the code below.

<table>
<thead>
<tr>
<th>Original Thread 1 Code</th>
<th>Thread 2 Code</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>x = 1;</code></td>
<td><code>if (y == 1) {</code></td>
</tr>
<tr>
<td><code>y = 1;</code></td>
<td><code>assert(x == 1);</code></td>
</tr>
<tr>
<td><code>// ...</code></td>
<td><code>}</code></td>
</tr>
</tbody>
</table>

Suppose that the compiler makes the same optimization to the code for thread 1 as on the previous slide, yielding the code below.

<table>
<thead>
<tr>
<th>Optimized Thread 1 Code</th>
<th>(Unchanged) Thread 2 Code</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>y = 1;</code></td>
<td><code>if (y == 1) {</code></td>
</tr>
<tr>
<td><code>x = 1;</code></td>
<td><code>assert(x == 1);</code></td>
</tr>
<tr>
<td><code>// ...</code></td>
<td><code>}</code></td>
</tr>
</tbody>
</table>

Thread 2 can observe `x` and `y` being modified in the wrong order (i.e., an order that is inconsistent with SC execution).

The assertion in thread 2 can never fail in the original program, but can sometimes fail in the optimized program.

In a multithreaded program, the reordering of loads and stores must be avoided if SC is to be maintained.
Consider the program below, where \( x, y, a, \) and \( b \) are integer variables, all initially zero.

\[
\begin{align*}
\text{Thread 1 Code} \quad & \quad \text{Thread 2 Code} \\
& \quad \begin{align*}
x &= 1; \\
a &= y;
\end{align*} \\
& \quad \begin{align*}
y &= 1; \\
b &= x;
\end{align*}
\end{align*}
\]

Some possible sequentially-consistent executions of the program include:

- \( x = 1; y = 1; b = x; a = y; \) (\( a \) is 1, \( b \) is 1)
- \( y = 1; x = 1; a = y; b = x; \) (\( a \) is 1, \( b \) is 1)
- \( x = 1; a = y; y = 1; b = x; \) (\( a \) is 0, \( b \) is 1)
- \( y = 1; b = x; x = 1; a = y; \) (\( a \) is 1, \( b \) is 0)

In every sequentially-consistent execution of the program, one of \( "x = 1;" \) or \( "y = 1;" \) must execute first.

- If \( "x = 1;" \) executes first, then \( b \) cannot be assigned 0.
- If \( "y = 1;" \) executes first, then \( a \) cannot be assigned 0.

- No sequentially-consistent execution can result in \( a \) and \( b \) both being 0.
Store-Buffer Example: Store Buffer

1. Transfer data from register to store buffer.
2. Flush store buffer to memory.

Diagram:
- Processor
  - Register
  - Store Buffer: write \( r \) to \( x \)
- Memory:
  - \( x \)
### Store-Buffer Example: With Store Buffer (Not SC)

<table>
<thead>
<tr>
<th>Core 1</th>
<th>Core 2</th>
<th>Memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code</td>
<td>Store Buffer</td>
<td>Code</td>
</tr>
<tr>
<td>x = 1;</td>
<td>write 1 to x</td>
<td>y = 1;</td>
</tr>
<tr>
<td></td>
<td>pending</td>
<td></td>
</tr>
<tr>
<td></td>
<td>no change</td>
<td>y = 1;</td>
</tr>
<tr>
<td>a = y;</td>
<td>no change</td>
<td></td>
</tr>
<tr>
<td>//a = 0;</td>
<td>no change</td>
<td></td>
</tr>
<tr>
<td></td>
<td>no change</td>
<td>b = x;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>//b = 0;</td>
</tr>
<tr>
<td></td>
<td>write 1 to x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>completed</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>write 1 to y</td>
</tr>
<tr>
<td></td>
<td></td>
<td>completed</td>
</tr>
</tbody>
</table>

- The execution of the program results in `a` and `b` both being 0, which violates SC.
- The program behaves as if the lines of code in each thread were reordered (i.e., reversed), yielding: `a = y; b = x; x = 1; y = 1;`.
- A store buffer (or cache) must be avoided, if SC is to be maintained.
Atomicity of Memory Operations

- A fundamental property of SC is that all memory operations are atomic.
- Atomic memory operations require synchronization between processor cores.
- This synchronization greatly increases the time required to access memory, as a result of the time needed by processor cores to communicate and coordinate access to memory.
- Therefore, requiring all memory operations to be atomic is not desirable.
- Allowing non-atomic memory operations, however, would be inconsistent with a fundamental property of SC.
Data Races

- If memory operations are *not all atomic*, the possibility exists for something known as a data race.
- Two memory operations are said to **conflict** if they access the *same* memory location and *at least one* of the operations is a write.
- Two conflicting memory operations form a **data race** if they are from different threads and can be executed *at the same time*.
- A program with data races usually has unpredictable behavior (e.g., due to torn reads, torn writes, or worse).
- **Example (data race):**
  - Consider the multithreaded program listed below, where \( x \), \( y \), and \( z \) are (nonatomic) integer variables shared between threads and are initially zero.

<table>
<thead>
<tr>
<th>Thread 1 Code</th>
<th>Thread 2 Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x = 1; )</td>
<td>( y = 1; )</td>
</tr>
<tr>
<td>( a = y + z; )</td>
<td>( b = x + z; )</td>
</tr>
</tbody>
</table>

- The program has data races on both \( x \) and \( y \).
- Since \( z \) is not modified by any thread, \( z \) cannot participate in a data race.
Torn Reads

- A **torn read** is a read operation that (due to lack of atomicity) has only partially read its value when another (concurrent) write operation on the same location is performed.

- Consider a two-byte unsigned (big-endian) integer variable `x`, which is initially 1234 (hexadecimal).

- Suppose that the following (nonatomic) memory operations overlap in time:
  - thread 1 reads `x`; and
  - thread 2 writes 5678 (hexadecimal) to `x`.

- Initially, `x` is 1234:

<table>
<thead>
<tr>
<th>Byte 0</th>
<th>Byte 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>34</td>
</tr>
</tbody>
</table>

- Thread 1 reads 12 from the first byte of `x`.

- Thread 2 writes 56 and 78 to the first and seconds bytes of `x`, respectively, yielding:

<table>
<thead>
<tr>
<th>Byte 0</th>
<th>Byte 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>78</td>
</tr>
</tbody>
</table>

- Thread 1 reads the second byte of `x` to obtain the value 78.

- The value read by thread 1 (i.e., 1278) is neither the value of `x` prior to the write by thread 2 (i.e., 1234) nor the value of `x` after the write by thread 2 (i.e., 5678).
A **torn write** is a write operation that (due to lack of atomicity) has only partially written its value when another (concurrent) read or write operation on the same location is performed.

Consider a two-byte unsigned (big-endian) integer variable \( x \), which is initially 0.

Suppose that the following (nonatomic) memory operations overlap in time:

- thread 1 writes 1234 (hexadecimal) to \( x \); and
- thread 2 writes 5678 (hexadecimal) to \( x \).

Initially, \( x \) is 0:

<table>
<thead>
<tr>
<th>Byte 0</th>
<th>Byte 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>00</td>
</tr>
</tbody>
</table>

Thread 1 writes 12 to the first byte of \( x \), yielding:

<table>
<thead>
<tr>
<th>Byte 0</th>
<th>Byte 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>00</td>
</tr>
</tbody>
</table>

Thread 2 writes 56 and 78 to the first and second bytes of \( x \), respectively, yielding:

<table>
<thead>
<tr>
<th>Byte 0</th>
<th>Byte 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>78</td>
</tr>
</tbody>
</table>

Thread 1 writes 34 to the second byte of \( x \), yielding:

<table>
<thead>
<tr>
<th>Byte 0</th>
<th>Byte 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>34</td>
</tr>
</tbody>
</table>

The resulting value in \( x \) (i.e., 5634) is neither the value written by thread 1 (i.e., 1234) nor the value written by thread 2 (i.e., 5678).
From a programmability standpoint, SC is extremely desirable, as it allows one to reason easily about the behavior of a multithreaded program.

Unfortunately, as we saw earlier, SC precludes almost all useful compiler optimizations and hardware optimizations.

As it turns out, if we drop the requirement that all memory operations be atomic and then restrict programs to be data-race free, SC can be provided while still allowing most compiler and hardware optimizations.

This observation is the motivation behind the so called SC-DRF memory model.

The **sequential-consistency for data-race free programs (SC-DRF) model** provides SC **only for programs that are data-race free**.

The data-race free constraint is not overly burdensome, since data races will likely result in bugs anyhow.

Several programming languages have used SC-DRF as the basis for their memory model, including C++, C, and Java.
The C++ programming language employs, at its default memory model, the $\textit{SC-DRF}$ model.

Again, with the SC-DRF model, a program behaves as if its execution is sequentially consistent, provided that the program is data-race free.

Support is also provided for other (more relaxed) memory models.

For certain memory accesses, it is possible to override the default (i.e., SC-DRF) memory model, if desired.

The execution of a program that is not data-race free results in $\textit{undefined behavior}$. 
Section 3.9.4

Thread Management
The `std::thread` Class

- `std::thread` class provides means to create new thread of execution, wait for thread to complete, and perform other operations to manage and query state of thread
- thread object may or may not be associated with thread (of execution)
- thread object that is associated with thread said to be **joinable**
- default constructor creates thread object that is **unjoinable**
- can also construct thread object by providing callable entity (e.g., function or functor) and arguments (if any), resulting in new thread invoking callable entity
- thread function provided with *copies* of arguments so must use reference wrapper class like `std::reference_wrapper` for reference semantics
- thread class is movable but **not copyable** \[C++17 §33.3.2/1\]
- each thread object has ID
- IDs of joinable thread objects are **unique** \[C++17 §33.3.2.1/1\]
- all unjoinable thread objects have **same** ID, distinct from ID of every joinable thread object \[C++17 §33.3.2.1/1\]
- **join operation** waits for thread object’s thread to complete execution and results in object becoming unjoinable.

- **detach operation** dissociates thread from thread object (allowing thread to continue to execute independently) and results in object becoming unjoinable.

- Using thread object as source for move operation results in object becoming unjoinable. [*C++17 §33.3.2.2/10*]

- If thread object joinable when destructor called, exception is thrown.

- Static member function *hardware_concurrency* returns number of hardware threads that can run simultaneously (or zero if not well defined).

- Thread creation and join operations establish **synchronizes-with** relationship (to be discussed later).
### std::thread Members

#### Member Types

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>id</td>
<td>thread ID type</td>
</tr>
<tr>
<td>native_handle_type</td>
<td>system-dependent handle type for underlying thread entity</td>
</tr>
</tbody>
</table>

#### Construction, Destruction, and Assignment

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>construct thread (overloaded)</td>
</tr>
<tr>
<td>destructor</td>
<td>destroy thread</td>
</tr>
<tr>
<td>operator=</td>
<td>move assign thread</td>
</tr>
</tbody>
</table>
### Member Functions

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>joinable</td>
<td>check if thread joinable</td>
</tr>
<tr>
<td>get_id</td>
<td>get ID of thread</td>
</tr>
<tr>
<td>native_handle</td>
<td>get native handle for thread</td>
</tr>
<tr>
<td>hardware_concurrency (static)</td>
<td>get number of concurrent threads supported by hardware</td>
</tr>
<tr>
<td>join</td>
<td>wait for thread to finish executing</td>
</tr>
<tr>
<td>detach</td>
<td>permit thread to execute independently</td>
</tr>
<tr>
<td>swap</td>
<td>swap threads</td>
</tr>
</tbody>
</table>
#include <iostream>
#include <thread>

void hello()
{
    std::cout << "Hello World!\n";
}

int main()
{
    std::thread t(hello);
    t.join();
}

#include <iostream>
#include <thread>

int main()
{
    std::thread t([](){
        std::cout << "Hello World!\n";
    });
    t.join();
}
std::jthread class similar to std::thread class except gives ability to:
  - provide stop_token to new thread of execution
  - make stop requests
  - automatically join (upon destruction)

if thread joinable when destructor invoked, destructor issues stop request and performs join

unlike std::thread, destructor may invoked if thread still joinable

in most circumstances, std::jthread likely to be preferable to std::thread
### Some `std::jthread` Members

#### Stop Token Handling

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>get_stop_source</code></td>
<td>returns <code>stop_source</code> object associated with shared stop state of thread</td>
</tr>
<tr>
<td><code>get_stop_token</code></td>
<td>returns <code>stop_token</code> associated with shared stop state of thread</td>
</tr>
<tr>
<td><code>request_stop</code></td>
<td>requests execution stop via shared stop state of thread</td>
</tr>
</tbody>
</table>
```cpp
#include <iostream>
#include <thread>

void hello()
{
    std::cout << "Hello World!\n";
}

int main()
{
    std::jthread t(hello);
    // t.join() not required
}
```

```cpp
#include <iostream>
#include <thread>

int main()
{
    std::jthread t([]()
    {
        std::cout << "Hello World!\n";
    });
    // t.join() not required
}
```
```cpp
#include <iostream>
#include <vector>
#include <utility>
#include <thread>

void doWork(const std::vector<int>& v) {
    for (auto i : v) {
        std::cout << i << '
';
    }
}

int main() {
    std::vector v{1, 2, 3, 4};
    // copy semantics
    std::jthread t1(doWork, v);
    // move semantics
    std::jthread t2(doWork, std::move(v));
}````
Example: Thread-Function Argument Passing (Reference Semantics)

```cpp
#include <iostream>
#include <vector>
#include <functional>
#include <thread>

void doWork(const std::vector<int>& v) {
    for (auto i : v) {
        std::cout << i << '
';
    }
}

int main() {
    std::vector v{1, 2, 3, 4};

    // copy semantics
    std::jthread t1(doWork, v);

    // reference semantics
    std::jthread t2(doWork, std::ref(v));
}
```
```cpp
#include <thread>
#include <iostream>
#include <utility>

// Return a thread that prints a greeting message.
std::jthread makeThread() {
    return std::jthread([](){
        std::cout << "Hello World!\n";
    });
}

// Return the same thread that was passed as an argument.
std::jthread identity(std::jthread t) {
    return t;
}

int main() {
    std::jthread t1(makeThread());
    std::jthread t2(std::move(t1));
    t1 = std::move(t2);
    t1 = identity(std::move(t1));
}
```
```
#include <iostream>
#include <vector>
#include <algorithm>
#include <chrono>
#include <thread>
#include <numeric>

void threadFunc(const std::vector<int>* v) {
    std::cout << std::accumulate(v->begin(), v->end(), 0) << '
';
}

void startThread() {
    std::vector<int> v(1000000, 1);
    std::jthread t(threadFunc, &v);
    t.detach();
    // v is destroyed here but detached thread
    // may still be using v
}

int main() {
    startThread();
    // Give the thread started by startThread
    // sufficient time to complete its work.
    std::this_thread::sleep_for(std::chrono::seconds(5));
}
```
### The `std::this_thread` Namespace

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>get_id</code></td>
<td>get ID of current thread</td>
</tr>
<tr>
<td><code>yield</code></td>
<td>suggest rescheduling current thread so as to allow other threads to run</td>
</tr>
<tr>
<td><code>sleep_for</code></td>
<td>blocks execution of current thread for at least specified duration</td>
</tr>
<tr>
<td><code>sleep_until</code></td>
<td>blocks execution of current thread until specified time reached</td>
</tr>
</tbody>
</table>
```cpp
#include <thread>
#include <iostream>

// main thread ID
std::jthread::id mainThread;

void func() {
    if (std::this_thread::get_id() == mainThread) {
        std::cout << "called by main thread\n";
    } else {
        std::cout << "called by secondary thread\n";
    }
}

int main() {
    mainThread = std::this_thread::get_id();
    std::jthread t([](){
        // call func from secondary thread
        func();
    });
    // call func from main thread
    func();
}
```
Cooperative Thread Cancellation

- Often necessary to notify running thread that it should terminate its execution in timely manner
- Stop requests provide mechanism for achieving this
- Stop state is essentially shared state that includes boolean flag indicating if thread is being requested to terminate its execution
- Stop state is shared between one or more `stop_source` and `stop_token` objects
- Stop state can be accessed through `stop_source` and `stop_token` objects
- `stop_source` can both query and set stop state
- `stop_token` can query stop state
- `stop_callback` can be used to register function to be called if stop request made
The `std::stop_source` Class

- `std::stop_source` class provides mean to issue stop request, such as for `std::jthread` cancellation
- Stop request made to `stop_source` object is visible to all `stop_source` and `stop_token` objects associated with same stop state
- Stop request cannot be withdrawn
- Additional stop requests after first have no effect
### std::stop_source Members

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>request_stop</td>
<td>issue stop request for associated stop state if any</td>
</tr>
<tr>
<td>get_token</td>
<td>return stop_token for associated stop state</td>
</tr>
<tr>
<td>stop_requested</td>
<td>checks if associated stop state has been requested to stop</td>
</tr>
<tr>
<td>stop_possible</td>
<td>checks if requested stop state can be requested to stop</td>
</tr>
<tr>
<td>swap</td>
<td>swaps two stop_source objects</td>
</tr>
</tbody>
</table>
- `stop_token` provides means to check if stop request has been made or can be made for its associated `stop_source` object.
- Provides thread-safe view of associated stop state.
- `stop_token` object can also be passed to interruptible waiting functions of `std::condition_variable_any` to interrupt condition-variable wait if stop requested.
- Usually `stop_token` object not created independently, but rather obtained from `stop_source` (or `jthread`) object so stop state can be shared with `stop_source` object.
## std::stop_token Members

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>stop_requested</td>
<td>checks if associated stop state has been requested to stop</td>
</tr>
<tr>
<td>stop_possible</td>
<td>checks if requested stop state can be requested to stop</td>
</tr>
<tr>
<td>swap</td>
<td>swaps two stop_token objects</td>
</tr>
</tbody>
</table>
The `std::stop_callback` Class Template

- `stop_callback` class template provides RAII object type that registers callback function for associated `stop_token` object such that callback invoked when stop request made.

- declaration:
  ```cpp
template<class Callback> class stop_callback;
```

- allows for asynchronous notification of stop requests
- callback registered in constructor
- callback deregistered in destructor
#include <chrono>
#include <format>
#include <iostream>
#include <stop_token>
#include <thread>

void worker(std::stop_token token) {
    unsigned long long count = 0;
    while (!token.stop_requested()) {++count;}
    std::cout << std::format("count: {}
", count);
}

int main() {
    using namespace std::chrono_literals;
    std::jthread t1(worker);
    std::jthread t2(worker);
    std::this_thread::sleep_for(100ms);
    t2.request_stop();
    std::this_thread::sleep_for(400ms);
    t1.request_stop();
}
Thread Local Storage

- **thread storage duration**: object initialized before first use in thread and, if constructed, destroyed on thread exit
- each thread has its own instance of object
- only objects declared `thread_local` have this storage duration
- `thread_local` implies `static` for variable of block scope
- `thread_local` can appear together with `static` or `extern` to adjust linkage
- example:

  ```cpp
  thread_local int counter = 0;
  static thread_local int x = 0;
  thread_local int y;

  void func() {
    thread_local int counter = 0;
    // equivalent to:
    // static thread_local int counter = 0;
  }
  ```
# Example: Thread Local Storage

```cpp
#include <iostream>
#include <vector>
#include <thread>

thread_local int counter = 0;

void doWork(int id) {
    static const char letters[] = "abcd";
    for (int i = 0; i < 10; ++i) {
        std::cout << letters[id] << counter << '\n';
        ++counter;
    }
}

int main() {
    std::vector<std::thread> workers;
    for (int i = 1; i <= 3; ++i) {
        // invoke doWork in new thread
        workers.emplace_back(doWork, i);
    }

    // invoke doWork in main thread
    doWork(0);
    for (auto& t : workers) { t.join(); }
}
```
Section 3.9.5

Sharing Data Between Threads
In multithreaded programs, it is often necessary to *share resources* between threads.

Shared resources might include such things as variables, memory, files, devices, and so on.

The sharing of resources, however, can lead to various problems when multiple threads want access to the same resource simultaneously.

The most commonly shared resource is *variables*.

When variables are shared between threads, the possibility exists that one thread may attempt to access a variable while another thread is modifying the same variable.

Such *conflicting accesses* to variables can lead to data corruption and other problems.

More generally, when any resource is shared, the potential for problems exists.

Therefore, mechanisms are needed for ensuring that shared resources can be accessed safely.
A race condition is a behavior where the outcome depends on the relative ordering of the execution of operations on two or more threads.

Sometimes, a race condition may be benign (i.e., does not cause any problem).

Usually, the term “race condition” used to refer to a race condition that is not benign (i.e., breaks invariants or results in undefined behavior).

A data race is a particularly evil type of race condition.

A deadlock is a situation in which two or more threads are unable to make progress due to being blocked waiting for resources held by each other.

A livelock is a situation in which two or more threads are not blocked but are unable to make progress due to needing resources held by each other.

Often, race conditions can lead to deadlocks, livelocks, crashes, and other unpredictable behavior.
A **critical section** is a piece of code that accesses a shared resource (e.g., data structure) that must not be simultaneously accessed by more than one thread.

A synchronization mechanism is needed at the entry to and exit from a critical section.

The mechanism needs to provide *mutual exclusion* (i.e., prevent critical sections in multiple threads from executing simultaneously).

Example (FIFO queue):
- One thread is adding an element to a queue while another thread is removing an element from the same queue.
- Since both threads modify the queue at the same time, they could corrupt the queue data structure.
- Synchronization must be employed so that the execution of the parts of the code that add and remove elements are executed in a *mutually exclusive* manner (i.e., cannot run at the same time).
### Data-Race Example

#### Shared (Global) Data

```cpp
double balance = 100.00; // bank account balance
double credit = 50.00;  // amount to deposit
double debit = 10.00;   // amount to withdraw
```

#### Thread 1 Code

```cpp
// double tmp = balance;
// tmp = tmp + credit;
// balance = tmp;
balance += credit;
```

#### Thread 2 Code

```cpp
// double tmp = balance;
// tmp = tmp - debit;
// balance = tmp;
balance -= debit;
```

- **above code has data race on** `balance` **object (i.e., more than one thread may access** `balance` **at same time with at least one thread writing)**
```cpp
#include <iostream>
#include <thread>

unsigned long long counter = 0;

void func() {
    for (unsigned long long i = 0; i < 1’000’000; ++i) {
        ++counter;
    }
}

int main() {
    std::jthread t1(func);
    std::jthread t2(func);
    t1.join();
    t2.join();
    std::cout << counter << '
';
}
```
Example: Data Race and/or Race Condition (IntSet)

```cpp
#include <iostream>
#include <thread>
#include <unordered_set>

class IntSet {
public:
    bool contains(int i) const
    {
        return s_.find(i) != s_.end();
    }
    void add(int i)
    {
        s_.insert(i);
    }
private:
    std::unordered_set<int> s_;
};

IntSet s;

int main() {
    std::jthread t1([](){
        for (int i = 0; i < 10'000; ++i) {s.add(2 * i);}
    });
    std::jthread t2([](){
        for (int i = 0; i < 10'000; ++i) {s.add(2 * i + 1);}
    });
t1.join(); t2.join();
    std::cout << s.contains(1000) << '
';
}
```
Section 3.9.6

Mutexes
A mutex is a locking mechanism used to synchronize access to a shared resource by providing mutual exclusion.

A mutex has two basic operations:
- **acquire**: lock (i.e., hold) the mutex
- **release**: unlock (i.e., relinquish) the mutex

A mutex can be held by only one thread at any given time.

If a thread attempts to acquire a mutex that is already held by another thread, the operation will either block until the mutex can be acquired or fail with an error.

A thread holding a (nonrecursive) mutex cannot relock the mutex.

A thread acquires the mutex before accessing the shared resource and releases the mutex when finished accessing the resource.

Since only one thread can hold a mutex at any given time and the shared resource is only accessed by the thread holding the mutex, mutually-exclusive access is guaranteed.
The `std::mutex` Class

- `std::mutex` class provides mutex functionality
- *not movable* and *not copyable* [C++17 §30.4.1.2/3]
- `lock` member function acquires mutex (blocking as necessary)
- `unlock` member function releases mutex
- thread that owns mutex should not attempt to lock mutex again [C++17 §33.4.3.2/7]
- all prior `unlock` operations on given mutex *synchronize with* `lock` operation (on *same* mutex) (*synchronizes-with* relationship to be discussed later) [C++17 §33.4.3.2/11]
## std::mutex Members

### Member Types

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>native_handle_type</td>
<td>system-dependent handle type for underlying mutex entity</td>
</tr>
</tbody>
</table>

### Construction, Destruction, and Assignment

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>construct mutex</td>
</tr>
<tr>
<td>destructor</td>
<td>destroy mutex</td>
</tr>
</tbody>
</table>

### Other Member Functions

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>lock</td>
<td>acquire mutex, blocking if not available</td>
</tr>
<tr>
<td>try_lock</td>
<td>try to lock mutex without blocking</td>
</tr>
<tr>
<td>unlock</td>
<td>release mutex</td>
</tr>
<tr>
<td>native_handle</td>
<td>get handle for underlying mutex entity</td>
</tr>
</tbody>
</table>
```cpp
#include <iostream>
#include <thread>
#include <mutex>

std::mutex m;
unsigned long long counter = 0;

void func() {
    for (unsigned long long i = 0; i < 1'000'000; ++i) {
        m.lock(); // acquire mutex
        ++counter;
        m.unlock(); // release mutex
    }
}

int main() {
    std::jthread t1(func);
    std::jthread t2(func);
    t1.join();
    t2.join();
    std::cout << counter << '
';
}

above code fixes data race from earlier example
```
std::scoped_lock is RAII class for mutexes

**Declaration:**

```cpp
template <class... Ts> class scoped_lock;
```

- Parameter pack `Ts` specifies types of mutexes to be locked
- Can be used with any mutex types providing necessary locking interface (e.g., `std::mutex` and `std::recursive_mutex`)
- Constructor takes one or more mutexes as arguments
- Mutexes acquired in constructor and released in destructor
- `scoped_lock` objects are *not movable* and *not copyable*

- Using `scoped_lock` avoids problem of inadvertently failing to release mutexes (e.g., due to exception or forgetting `unlock` calls)
- In multiple mutex case, employs deadlock avoidance algorithm from `std::lock` (discussed later) when acquiring mutexes
- Advisable to use `scoped_lock` instead of calling `lock` and `unlock` explicitly
- `scoped_lock` effectively replaces (and extends) `lock_guard`
### Member Types

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>mutex_type</td>
<td>underlying mutex type if only one</td>
</tr>
</tbody>
</table>

### Construction, Destruction, and Assignment

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>construct scoped lock, optionally locking given mutexes</td>
</tr>
<tr>
<td>destructor</td>
<td>destroy scoped lock, releasing underlying mutexes</td>
</tr>
</tbody>
</table>
```cpp
#include <iostream>
#include <thread>
#include <mutex>

std::mutex m;
unsigned long long counter = 0;

void func() {
    for (unsigned long long i = 0; i < 1'000'000; ++i) {
        // scoped_lock constructor acquires mutex
        std::scoped_lock lock(m);
        ++counter;
        // scoped_lock destructor releases mutex
    }
}

int main() {
    std::thread t1(func);
    std::thread t2(func);
    t1.join();
    t2.join();
    std::cout << counter << '
';
}
```

- above code improves upon earlier example by avoiding possibility of not releasing mutex (e.g., due to exception or forgetting to call `unlock`)
#include <iostream>
#include <mutex>
#include <thread>
#include <unordered_set>

class IntSet {
public:
  bool contains(int i) const {
    std::scoped_lock lock(m_);
    return s_.find(i) != s_.end();
  }
  void add(int i) {
    std::scoped_lock lock(m_);
    s_.insert(i);
  }
private:
  std::unordered_set<int> s_;  // shared by both threads
  mutable std::mutex m_;  // scoped_lock
};

IntSet s;

int main() {
  std::jthread t1([](){
    for (int i = 0; i < 10’000; ++i) {s.add(2 * i);}
  });
  std::jthread t2([](){
    for (int i = 0; i < 10’000; ++i) {s.add(2 * i + 1);}
  });
t1.join(); t2.join();
  std::cout << s.contains(1000) << ‘\n’;
}
if multiple locks must be acquired, critical that locks always acquired in same order; otherwise, deadlock can occur

for example, consider scenario in which two mutexes must be acquired before performing some processing

if two mutexes not acquired in consistent order, situations like following can arise:

1. thread 1 acquires mutex 1
2. thread 2 acquires mutex 2
3. thread 1 tries to acquire mutex 2 and blocks waiting for thread 2 to release this mutex
4. thread 2 tries to acquire mutex 1 and blocks waiting for thread 1 to release this mutex, resulting in **deadlock**

if, in above example, two mutexes instead always acquired in same order, this type of deadlock cannot occur
Example: Acquiring Two Locks for Swap (Incorrect)

```cpp
#include <mutex>
#include <thread>
#include <utility>
#include <vector>

class BigBuf // A Big Buffer
{

public:
    static constexpr long size() { return 16 * 1024L * 1024L; }
    BigBuf() : data_(size()) {}
    BigBuf& operator=(const BigBuf&) = delete;
    BigBuf& operator=(BigBuf&&) = delete;
    void swap(BigBuf& other) {
        if (this == &other) { return; }
        // acquiring the two mutexes in this way can result in deadlock
        std::scoped_lock lock1(m_);
        std::scoped_lock lock2(other.m_);
        std::swap(data_, other.data_);
    }

private:
    std::vector<char> data_;  // mutable std::mutex m_;
};

BigBuf a;
BigBuf b;

int main() {
    std::jthread t1([](){
        for (long i = 0; i < 1’000’000; ++i) a.swap(b);
    });
    std::jthread t2([](){
        for (long i = 0; i < 1’000’000; ++i) b.swap(a);
    });
}
```
#include <mutex>
#include <thread>
#include <utility>
#include <vector>

class BigBuf // A Big Buffer
{
public:
  static constexpr long size() {return 16 * 1024L * 1024L;}
  BigBuf() : data_(size()) {}
  BigBuf& operator=(const BigBuf&) = delete;
  BigBuf& operator=(BigBuf&&) = delete;
  void swap(BigBuf& other) {
    if (this == &other) {return;}
    std::scoped_lock sl(m_, other.m_);
    std::swap(data_, other.data_);
  }
  // ...
private:
  std::vector<char> data_;  
  mutable std::mutex m_;  
};

BigBuf a;
BigBuf b;

int main() {
  std::jthread t1([](){
    for (long i = 0; i < 1'000'000; ++i) a.swap(b);
  });
  std::jthread t2([](){
    for (long i = 0; i < 1'000'000; ++i) b.swap(a);
  });
}
The `std::unique_lock` Template Class

- `std::unique_lock` is another RAII class for mutexes.
- Declaration:
  ```cpp
template <class T> class unique_lock;
```
- Template parameter `T` specifies type of mutex (e.g., `std::mutex`, `std::recursive_mutex`).
- Unlike case of `std::scoped_lock`, in case of `unique_lock` do not have to hold mutex over entire lifetime of RAII object.
- Have choice of whether to acquire mutex upon construction.
- Also can acquire and release mutex many times throughout lifetime of `unique_lock` object.
- Upon destruction, if mutex is held, it is released.
- Since mutex is always guaranteed to be released by destructor, cannot forget to release mutex.
- `unique_lock` is used in situations where want to be able to transfer ownership of lock (e.g., return from function) or RAII object needed for mutex but do not want to hold mutex over entire lifetime of RAII object.
- **Movable but not copyable** [C++17 §33.4.4.3]
std::unique_lock Members

### Member Types

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>mutex_type</td>
<td>underlying mutex type</td>
</tr>
</tbody>
</table>

### Construction, Destruction, and Assignment

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>construct unique lock</td>
</tr>
<tr>
<td>destructor</td>
<td>destroy unique lock</td>
</tr>
<tr>
<td>operator=</td>
<td>move assign</td>
</tr>
</tbody>
</table>

### Locking Functions

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>lock</td>
<td>acquire mutex, blocking if not available</td>
</tr>
<tr>
<td>try_lock</td>
<td>try to lock mutex without blocking</td>
</tr>
<tr>
<td>try_lock_for</td>
<td>try to lock mutex without blocking</td>
</tr>
<tr>
<td>try_lock_until</td>
<td>try to lock mutex without blocking</td>
</tr>
<tr>
<td>unlock</td>
<td>release mutex</td>
</tr>
</tbody>
</table>
### Observer Functions

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>owns_lock</td>
<td>tests if lock owns associated mutex</td>
</tr>
<tr>
<td>operator bool</td>
<td>tests if lock owns associated mutex</td>
</tr>
</tbody>
</table>
Example: Avoiding Data Race Using Mutex (unique_lock)

```cpp
#include <iostream>
#include <thread>
#include <mutex>

unsigned long counter = 0;
std::mutex m;

void func() {
    for (unsigned long i = 0; i < 1'000'000; ++i) {
        // Create a lock object without acquiring the mutex.
        std::unique_lock lock(m, std::defer_lock);
        // ...
        lock.lock(); // Acquire the mutex.
        ++counter;
        lock.unlock(); // Release the mutex.
        // ...
        lock.lock(); // Acquire the mutex.
        ++counter;
        lock.unlock(); // Release the mutex.
        // ...
        // The unique_lock destructor releases the mutex (if held).
    }
}

int main() {
    std::jthread t1(func);
    std::jthread t2(func);
    t1.join();
    t2.join();
    std::cout << counter << '
';
}
```
std::lock variadic template function that can acquire multiple locks simultaneously without risk of deadlock (assuming the only locks involved are ones passed to lock)

declaration:

```cpp
template <class T1, class T2, class... TN>
void lock(T1&, T2&, TN& ...);
```

takes as arguments one or more locks to be acquired
#include <mutex>
#include <thread>
#include <utility>
#include <vector>

class BigBuf // A Big Buffer
{

public:

    static constexpr long size() { return 16 * 1024L * 1024L; }
    BigBuf() : data_(size()) {}
    BigBuf& operator=(const BigBuf&) = delete;
    BigBuf& operator=(BigBuf&&) = delete;

    void swap(BigBuf& other) {
        if (this == &other) { return; }
        std::unique_lock lock1(m_, std::defer_lock);
        std::unique_lock lock2(other.m_, std::defer_lock);
        std::lock(lock1, lock2);
        std::swap(data_, other.data_);
    }

    // ...

private:

    std::vector<char> data_;  
    mutable std::mutex m_; 
};

BigBuf a;
BigBuf b;

int main() {
    std::jthread t1([](){
    for (long i = 0; i < 1’000’000; ++i) a.swap(b);
    });
    std::jthread t2([](){
    for (long i = 0; i < 1’000’000; ++i) b.swap(a);
    });
}
The `std::timed_mutex` Class

- `std::timed_mutex` class provides mutex that allows timeout to be specified when acquiring mutex
- If mutex cannot be acquired in time specified, acquire operation fails (i.e., does not lock mutex) and error returned
- Adds `try_lock_for` and `try_lock_until` member functions to try to lock mutex with timeout
#include <vector>
#include <iostream>
#include <thread>
#include <mutex>
#include <chrono>

std::timed_mutex m;

void doWork() {
    for (int i = 0; i < 10000; ++i) {
        std::unique_lock lock(m, std::defer_lock);
        int count = 0;
        while (!lock.try_lock_for(
                std::chrono::microseconds(1))) {++count;}
        std::cout << count << '\n';
    }
}

int main() {
    std::vector<std::jthread> workers;
    for (int i = 0; i < 16; ++i) {
        workers.emplace_back(doWork);
    }
}
A recursive mutex is a mutex for which a thread may own multiple locks at the same time.

After a mutex is first locked by thread A, thread A can acquire additional locks on the mutex (without releasing the lock already held).

The mutex is not available to other threads until thread A releases all of its locks on the mutex.

A recursive mutex is typically used when code that locks a mutex must call other code that locks the same mutex (in order to avoid deadlock).

For example, a function that acquires a mutex and recursively calls itself (resulting in the mutex being relocked) would need to employ a recursive mutex.

A recursive mutex has more overhead than a nonrecursive mutex.

Code that uses recursive mutexes can often be more difficult to understand and therefore more prone to bugs.

Consequently, the use of recursive mutexes should be avoided if possible.
- recursive mutexes provided by classes `std::recursive_mutex` and `std::recursive_timed_mutex`
- `recursive_mutex` class similar to `std::mutex` class except allows relocking
- `recursive_timed_mutex` class similar to `std::timed_mutex` class except allows relocking
- implementation-defined limit to number of levels of locking allowed by recursive mutex
A **shared mutex** (also known as a **multiple-reader/single-writer mutex**) is a mutex that allows both *shared and exclusive* access.

A shared mutex has **two types of locks**: shared and exclusive.

**Exclusive lock:**
- *Only one* thread can hold an *exclusive* lock on a mutex.
- While a thread holds an exclusive lock on a mutex, no other thread can hold any type of lock on the mutex.

**Shared lock:**
- *Any number* of threads (within implementation limits) can take a *shared* lock on a mutex.
- While any thread holds a shared lock on a mutex, no thread may take an exclusive lock on the mutex.

A shared mutex would typically be used to protect shared data that is seldom updated but cannot be safely updated if any thread is reading it.

A thread takes a shared lock for reading, thus allowing *multiple readers*.
A thread takes an exclusive lock for writing, thus allowing *only one writer with no readers*.

A shared mutex need not be fair in its granting of locks (e.g., readers could starve writers).
The `std::shared_mutex` Class

- `std::shared_mutex` class provides shared mutex functionality
- *not movable* and *not copyable*
- `lock` member function acquires exclusive ownership of mutex (blocking as necessary)
- `unlock` member function releases exclusive ownership
- `lock_shared` member function acquires shared ownership of mutex (blocking as necessary)
- `unlock_shared` member function releases shared ownership
## Construction, Destruction, and Assignment

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>construct mutex</td>
</tr>
<tr>
<td>destructor</td>
<td>destroy mutex</td>
</tr>
<tr>
<td><code>operator=</code></td>
<td>[deleted] not movable or copyable</td>
</tr>
</tbody>
</table>

## Exclusive Locking Functions

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>lock</td>
<td>acquire exclusive ownership of mutex, blocking if not available</td>
</tr>
<tr>
<td>try_lock</td>
<td>try to acquire exclusive ownership of mutex without blocking</td>
</tr>
<tr>
<td>unlock</td>
<td>release exclusive ownership of mutex</td>
</tr>
</tbody>
</table>
## Shared Locking Functions

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>lock_shared</td>
<td>acquire shared ownership of mutex, blocking if not available</td>
</tr>
<tr>
<td>try_lock_shared</td>
<td>try to acquire shared ownership of mutex without blocking</td>
</tr>
<tr>
<td>unlock_shared</td>
<td>release shared ownership of mutex</td>
</tr>
</tbody>
</table>

## Other Functions

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>native_handle</td>
<td>get handle for underlying mutex entity</td>
</tr>
</tbody>
</table>
std::shared_lock is RAII class for shared mutexes

declaration:

```cpp
template <class T> class shared_lock;
```

template parameter T specifies type of mutex (e.g., std::shared_mutex or std::shared_timed_mutex)

similar interface as std::unique_lock but uses shared locking

constructor may optionally acquire mutex

may acquire and release mutex many times throughout lifetime of object

destructor releases mutex if held

all operations mapped onto shared locking primitives (e.g., lock mapped to lock_shared, unlock mapped to unlock_shared)

for exclusive locking with shared mutexes, std::unique_lock and std::scoped_lock (and std::lock_guard) can be used
```cpp
#include <thread>
#include <mutex>
#include <iostream>
#include <vector>
#include <shared_mutex>

std::mutex coutMutex;
int counter = 0;
std::shared_mutex counterMutex;

void writer() {
    for (int i = 0; i < 10; ++i) {
        {
            std::scoped_lock lock(counterMutex);
            ++counter;
        }
        std::this_thread::sleep_for(std::chrono::milliseconds(100));
    }
}

void reader() {
    for (int i = 0; i < 100; ++i) {
        int c;
        {
            std::shared_lock lock(counterMutex);
            c = counter;
        }
        {
            std::scoped_lock lock(coutMutex);
            std::cout << std::this_thread::get_id() << ' ' << c << '
';
        }
        std::this_thread::sleep_for(std::chrono::milliseconds(10));
    }
}

int main() {
    std::vector<std::jthread> threads;
    threads.emplace_back(writer);
    for (int i = 0; i < 16; ++i) threads.emplace_back(reader);
}
```


- The **std::shared_timed_mutex** class provides shared mutex
- **shared_timed_mutex** interface similar to that of **shared_mutex** but allows timeout for acquiring mutex
- adds **try_lock_for** and **try_lock_until** member functions to try to acquire exclusive ownership of mutex with timeout
- adds **try_lock_shared_for** and **try_lock_shared_until** member functions to try to acquire shared ownership of mutex with timeout
```cpp
#include <thread>
#include <mutex>
#include <iostream>
#include <vector>
#include <shared_mutex>

std::mutex coutMutex;
int counter = 0;
std::shared_timed_mutex counterMutex;

void writer() {
  for (int i = 0; i < 10; ++i) {
    std::scoped_lock lock(counterMutex);
    ++counter;
  }
  std::this_thread::sleep_for(std::chrono::milliseconds(100));
}

void reader() {
  for (int i = 0; i < 100; ++i) {
    int c;
    std::shared_lock lock(counterMutex);
    c = counter;
    std::scoped_lock lock(coutMutex);
    std::cout << std::this_thread::get_id() << ' ' << c << '
';
    std::this_thread::sleep_for(std::chrono::milliseconds(10));
  }
}

int main() {
  std::vector<std::jthread> threads;
  threads.emplace_back(writer);
  for (int i = 0; i < 16; ++i) threads.emplace_back(reader);
}
```
sometimes may want to perform action only once in code executed in multiple threads

**can be achieved through use of std::once_flag type in conjunction with std::call_once template function**

**std::once_flag class represents flag used to track if action performed**

**declaration of std::call_once:**

```cpp
template <class Callable, class ... Args>
void call_once(std::once_flag& flag, Callable&& f, Args&&... args);
```

**std::call_once invokes f only once based on value of flag object**

**first invocation of f is guaranteed to complete before any threads return from call_once**

**useful for one-time initialization of dynamically generated objects**
#include <iostream>
#include <vector>
#include <thread>
#include <mutex>

std::once_flag flag;

void worker(int id) {
    std::call_once(flag, [id](){
        // This code will be invoked only once.
        std::cout << "first: " << id << '\n';
    });
}

int main() {
    std::vector<std::jthread> threads;
    for (int i = 0; i < 16; ++i) {
        threads.emplace_back(worker, i);
    }
}
Example: One-Time Initialization

```cpp
#include <vector>
#include <thread>
#include <mutex>
#include <cassert>
#include <memory>

std::unique_ptr<int> value;
std::once_flag initFlag;

void initValue() {value = std::make_unique<int>(42);}

const int& getValue() {
    std::call_once(initFlag, initValue);
    return *value.get();
}

void doWork() {
    const int& v = getValue();
    assert(v == 42);
    // ...
}

int main() {
    std::vector<std::thread> threads;
    for (int i = 0; i < 4; ++i)
        {threads.emplace_back(doWork);}
initialization of static local object is thread safe \cite{C++17 §9.7/4}

object is initialized first time control passes through its declaration

object deemed initialized upon completion of initialization

if control enters declaration concurrently while object being initialized, concurrent execution waits for completion of initialization

code like following is thread safe:

```cpp
const std::string& meaningOfLife() {
    static const std::string x("42");
    return x;
}
```
Section 3.9.7

Condition Variables
In concurrent programs, the need often arises for a thread to *wait until a particular event occurs* (e.g., I/O has completed or data is available).

Having a thread *repeatedly check* for the occurrence of an event can be *inefficient* (i.e., can waste processor resources).

It is often better to have the thread block and then only resume execution after the event of interest has occurred.

A *condition variable* is a synchronization primitive that allows threads to *wait (by blocking)* until a particular condition occurs.

A condition variable corresponds to some event of interest.

A thread that wants to wait for an event, performs a *wait operation* on the condition variable.

A thread that wants to notify one or more waiting threads of an event performs a *signal operation* on the condition variable.

When a signalled thread resumes, however, the signalled condition is not guaranteed to be true (and must be rechecked), since, for example, another thread may have caused the condition to change or a spurious awakening may have occurred.
std::condition_variable class provides condition variable

*not movable* and *not copyable*

wait, wait_for, and wait_until member functions used to wait for condition

notify_one and notify_all used to signal waiting thread(s) of condition

must re-check condition when awaking from wait since:

- spurious awakenings are permitted
- between time thread is signalled and time it awakens and locks mutex, another thread could cause condition to change

concurrent invocation is allowed for notify_one, notify_all, wait, wait_for, wait_until

each of wait, wait_for, and wait_until atomically releases mutex and blocks

notify_one and notify_all are atomic
### std::condition_variable Members

#### Member Types

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>native_handle_type</td>
<td>system-dependent handle type for underlying condition variable entity</td>
</tr>
</tbody>
</table>

#### Construction, Destruction, and Assignment

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>construct object</td>
</tr>
<tr>
<td>destructor</td>
<td>destroy object</td>
</tr>
<tr>
<td>operator=</td>
<td>[deleted] not movable or copyable</td>
</tr>
</tbody>
</table>

---

Copyright © 2015–2021 Michael D. Adams

Programming in C++  Version 2021-04-01
### Notification and Waiting Member Functions

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>notify_one</td>
<td>notify one waiting thread</td>
</tr>
<tr>
<td>notify_all</td>
<td>notify all waiting threads</td>
</tr>
<tr>
<td>wait</td>
<td>blocks current thread until notified</td>
</tr>
<tr>
<td>wait_for</td>
<td>blocks current thread until notified or specified duration passed</td>
</tr>
<tr>
<td>wait_until</td>
<td>blocks current thread until notified or specified time point reached</td>
</tr>
</tbody>
</table>

### Native Handle Member Functions

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>native_handle</td>
<td>get native handle associated with condition variable</td>
</tr>
</tbody>
</table>
#include <iostream>
#include <vector>
#include <thread>
#include <mutex>
#include <condition_variable>

class IntStack {
public:
  IntStack() {}
  IntStack(const IntStack&) = delete;
  IntStack& operator=(const IntStack&) = delete;
  int pop() {
    std::unique_lock lock(m_);
    c_.wait(lock, [this](){return !v_.empty();});
    int x = v_.back();
    v_.pop_back();
    return x;
  }
  void push(int x) {
    std::scoped_lock lock(m_);
    v_.push_back(x);
    c_.notify_one();
  }
private:
  std::vector<int> v_;  // not empty
  mutable std::mutex m_;  // not empty
  mutable std::condition_variable c_;  // not empty
};

constexpr int numIters = 1000;
IntStack s;

int main() {
  std::jthread t1([]() {
    for (int i = 0; i < numIters; ++i) s.push(2 * i + 1);
  });
  std::jthread t2([]() {
    for (int i = 0; i < numIters; ++i) std::cout << s.pop() << '
';
  });
}
**latch**: basic one-time synchronization mechanism that allows threads to block until particular event occurs certain number of times

- latch maintains count as state
- count is initialized to some nonzero value when latch created
- can decrement count
- can block until count reaches zero
- latch can only be used once (i.e., count cannot be reset after it reaches zero)
```c++
#include <functional>
#include <thread>
#include <vector>
#include "latch_1.hpp"

void worker(latch& ready) {
    // ... (perform very slow initialization)
    // wait for all threads to complete initialization
    ready.count_down_and_wait();
    // ... (perform real work)
}

int main() {
    constexpr int num_workers = 32;
    latch ready(num_workers);
    std::vector<std::jthread> workers;
    for (int i = 0; i < num_workers; ++i) {
        workers.emplace_back(worker, std::ref(ready));
    }
    for (auto& i : workers) {i.join();}
}
```
# Latch Example: latch_1.hpp

```cpp
#include <condition_variable>
#include <cstddef>
#include <mutex>

class latch {
public:
    explicit latch(std::size_t count) : count_(count) {}  
    // ... (not movable, not copyable, destructor)
    void count_down() {
        std::scoped_lock<std::mutex> lock(mutex_);
        if (!--count_) {ready_.notify_all();}
    }
    void wait() {
        std::unique_lock<std::mutex> lock(mutex_);
        ready_.wait(lock, [this](){return !count_;});
    }
    bool try_wait() {
        std::scoped_lock<std::mutex> lock(mutex_);
        return !count_;  
    }
    void count_down_and_wait() {
        std::unique_lock<std::mutex> lock(mutex_);
        if (!--count_) {ready_.notify_all();}
        else {ready_.wait(lock, [this](){return !count_;});}
    }
private:
    mutable std::mutex mutex_;  
    mutable std::condition_variable ready_; // count reached zero
    std::size_t count_;  
};
```

Copyright © 2015–2021 Michael D. Adams  
Programming in C++  
Version 2021-04-01  
1475
The `std::condition_variable_any` Class

- With `std::condition_variable` class, `std::unique_lock<std::mutex>` class must be used for wait operation.
- `std::condition_variable_any` class allows any mutex type (meeting certain basic requirements) to be used.
- Interface of `std::condition_variable_any` class similar to that of `std::condition_variable` class.
- Prefer `condition_variable` to `condition_variable_any` since former may be more efficient.
#include <chrono>
#include <condition_variable>
#include <iostream>
#include <mutex>
#include <thread>

using namespace std::chrono_literals;

template <class R, class P>
void wait_for(std::stop_token token, std::chrono::duration<R, P> const& time) {
    std::mutex m;
    std::condition_variable_any cv;
    std::unique_lock<std::mutex> lock(m);
    cv.wait_for(lock, token, time, []{return false;});
}

void worker(std::stop_token token) {
    std::cout << "thread: starting wait\n";
    wait_for(token, 5s);
    std::cout << "thread: finished wait\n";
}

int main(int argc, char** argv) {
    std::jthread t1(worker);
    std::this_thread::sleep_for(100ms);
    if (argc >= 2) {t1.request_stop();}
    std::cout << "main: performing join\n";
    t1.join();
    std::cout << "main: join finished\n";
}
thread pool is collection of threads which stand ready to be given work (i.e., tasks to execute)

number of threads in thread pool may be fixed or dynamic, depending on particular thread-pool variant

each thread in thread pool can be either idle or executing task

typically, tasks given to thread pool are placed on queue and then assigned to threads as they become available

after done executing task, thread returns to idle state, waiting to be assigned another task

thread pool allows overhead of many thread creation operations to be avoided

by using thread pool can also more easily control total number of threads and number of running threads

thread pool preferred over creating new threads for each task when there is large number of short-running tasks (rather than small number of long-running ones)
Simple Thread Pool Interface Example

thread_pool_1_1.hpp

```cpp
#include <functional>
#include <cstddef>

class thread_pool {
public:
    using size_type = std::size_t;
    thread_pool(size_type num_threads);
    thread_pool(const thread_pool&) = delete;
    thread_pool& operator=(const thread_pool&) = delete;
    ~thread_pool();
    size_type num_threads() const;
    void schedule(std::function<void()> &&task);
    void shutdown();
private:
    // ...
};
```

app.cpp

```cpp
#include <iostream>
#include "thread_pool_1_1.hpp"

int main() {
    thread_pool tp(8);
    for (int i = 0; i < 10'000; ++i) {
        tp.schedule([](){std::cout << "Hello, World\n";});
    }
    tp.shutdown();
}
```
Section 3.9.8

Promises and Futures
Promises and Futures

- promise and future together form **one-time** communication channel for passing result (i.e., value or exception) of computation from one thread to same or another thread
- **promise**: object associated with promised result (i.e., value or exception) to be produced
- **future**: object through which promised result later made available
- **shared state**: holds promised result for access through future object (shared by promise object and corresponding future object)
- producer of result uses promise object to store result in shared state
- consumer uses future object (corresponding to promise) to retrieve result from shared state
promises and futures useful in both single-threaded and multithreaded programs

in single-threaded programs, might be used to propagate exception to another part of program

in multithreaded program, often need arises to do some computation asynchronously and then later get result when ready

requires synchronization between threads producing and consuming result

thread consuming result must wait until result is available

must avoid data races when accessing result shared between threads

this type of synchronization can be accomplished via promise and future
std::promise provides access to promise-future shared state for writing result

declaration:

```cpp
template <class T> class promise;
```

T is type of result associated with promise (which can be void)

movable but not copyable

set_value member function sets result to particular value

set_exception member function sets result to exception

can set result only once

get_future member function retrieves future associated with promise

get_future may be called only once

if promise object is destroyed before its associated result is set, std::future_error exception will be thrown if attempt made to retrieve result from corresponding future object
Construction, Destruction, and Assignment

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>construct object</td>
</tr>
<tr>
<td>destructor</td>
<td>destroy object</td>
</tr>
<tr>
<td>operator=</td>
<td>move assignment</td>
</tr>
</tbody>
</table>
### Other Functions

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>swap</td>
<td>swap two promise objects</td>
</tr>
<tr>
<td>get_future</td>
<td>get future associated with promised result</td>
</tr>
<tr>
<td>set_value</td>
<td>set result to specified value</td>
</tr>
<tr>
<td>set_value_at_thread_exit</td>
<td>set result to specified value while delivering notification only at thread exit</td>
</tr>
<tr>
<td>set_exception</td>
<td>set result to specified exception</td>
</tr>
<tr>
<td>set_exception_at_thread_exit</td>
<td>set result to specified exception while delivering notification only at thread exit</td>
</tr>
</tbody>
</table>
The `std::future` Template Class

- `std::future` provides access to promise-future shared state for reading result
- declaration:
  ```cpp
template <class T> class future;
  ``
- T is type of result associated with future (which can be `void`)
- movable but *not copyable*
- get member function retrieves result, blocking if result not yet available
- get may be called *only once*
- wait member function waits for result to become available without actually retrieving result
# std::future Members

## Construction, Destruction, and Assignment

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>construct object</td>
</tr>
<tr>
<td>destructor</td>
<td>destroy object</td>
</tr>
<tr>
<td>operator=</td>
<td>move assignment</td>
</tr>
</tbody>
</table>

## Other Functions

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>share</td>
<td>transfer shared state to shared_future object</td>
</tr>
<tr>
<td>get</td>
<td>get result</td>
</tr>
<tr>
<td>valid</td>
<td>check if future object refers to shared state</td>
</tr>
<tr>
<td>wait</td>
<td>wait for result to become available</td>
</tr>
<tr>
<td>wait_for</td>
<td>wait for result to become available or time duration to expire</td>
</tr>
<tr>
<td>wait_until</td>
<td>wait for result to become available or time point to be reached</td>
</tr>
</tbody>
</table>
Example: Promises and Futures (Without `std::async`)

```cpp
#include <future>
#include <thread>
#include <iostream>
#include <utility>

double computeValue() {
    return 42.0;
}

void produce(std::promise<double> p) {
    // write result to promise
    p.set_value(computeValue());
}

int main() {
    std::promise<double> p;
    auto f = p.get_future(); // save future before move
    std::jthread producer(produce, std::move(p));
    std::cout << f.get() << '
';
    producer.join();
}
```
The std::shared_future Template Class

- std::shared_future similar to future except object can be copied
- shared_future object can be obtained by using share member function of future class to transfer contents of future object into shared_future object
- shared_future is copyable (unlike future)
- allows multiple threads to wait for same result (associated with shared_future object)
- get member can be called multiple times
Example: `std::shared_future`

```cpp
#include <iostream>
#include <vector>
#include <thread>
#include <future>

void consume(std::shared_future<int> f) {
    std::cout << f.get() << 'n';
}

int main() {
    std::promise<int> p;
    std::shared_future f = p.get_future().share();
    std::vector<std::jthread> consumers;
    for (int i = 0; i < 16; ++i) {
        consumers.emplace_back(consume, f);
    }
    p.set_value(42);
    for (auto& i : consumers) {
        i.join();
    }
}
```
The `std::async` Template Function

- **std::async** template function used to launch callable entity (e.g., function or functor) asynchronously

- **declaration (uses default launch policy):**
  ```cpp
template <class Func, class... Args>
future<typename result_of<typename decay<Func>::type(
  typename decay<Args>::type...)>::type>
async(Func&& f, Args&&... args);
```

- **declaration (with launch policy parameter):**
  ```cpp
template <class Func, class... Args>
future<typename result_of<typename decay<Func>::type(
  typename decay<Args>::type...)>::type>
async(launch policy, Func&& f, Args&&... args);
```

- **numerous launch policies supported via bitmask** `std::launch`
  - if **async** bit set, execute on new thread
  - if **deferred** bit set, execute on calling thread when result needed
  - if multiple bits set, implementation free to choose between them
  - in asynchronous execution case, essentially creates promise to hold result and returns associated future; launches thread to execute function/functor and sets promise when function/functor returns
future (i.e., future and shared_future) objects created by async function have slightly different behavior than future objects created in other ways.

in case of future object created by async function: if future object is last future object referencing its shared state, destructor for future object will block until result associated with future object becomes ready.
```cpp
#include <future>
#include <iostream>

double computeValue() {
    return 42.0;
}

int main() {
    // invoke computeValue function asynchronously in
    // separate thread
    auto f = std::async(std::launch::async, computeValue);
    std::cout << f.get() << 'n';
}
```
```cpp
#include <iostream>
#include <vector>
#include <cmath>
#include <future>
#include <stdexcept>

double squareRoot(double x) {
    if (x < 0.0) {
        throw std::domain_error(
            "square root of negative number");
    }
    return std::sqrt(x);
}

int main() {
    std::vector values{1.0, 2.0, -1.0};
    std::vector<std::future<double>> results;
    for (auto x : values) {
        results.push_back(std::async(squareRoot, x));
    }
    for (auto& x : results) {
        try {
            std::cout << x.get() << ' 
';
        } catch (const std::domain_error&) {
            std::cout << "error
";
        }
    }
}
```
std::packaged_task template class provides wrapper for callable entity (e.g., function or functor) that makes return value available via future

declaration:

```cpp
template <class R, class... Args>
class packaged_task<R(Args...)>;
```

template parameters R and Args specify return type and arguments for callable entity

similar to std::function except return value of wrapped function made available via future

packaged task often used as thread function

movable but not copyable

get_future member retrieves future associated with packaged task

get_future can be called only once
### std::packaged_task Members

#### Construction, Destruction, and Assignment

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>construct object</td>
</tr>
<tr>
<td>destructor</td>
<td>destroy object</td>
</tr>
<tr>
<td><code>operator=</code></td>
<td>move assignment</td>
</tr>
</tbody>
</table>

#### Other Functions

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>valid</td>
<td>check if task object currently associated with shared state</td>
</tr>
<tr>
<td>swap</td>
<td>swap two task objects</td>
</tr>
<tr>
<td>get_future</td>
<td>get future associated with promised result</td>
</tr>
<tr>
<td><code>operator()</code></td>
<td>invoke function</td>
</tr>
<tr>
<td><code>make_ready_at_thread_exit</code></td>
<td>invoke function ensuring result ready only once current thread exits</td>
</tr>
<tr>
<td>reset</td>
<td>reset shared state, abandoning any previously stored result</td>
</tr>
</tbody>
</table>
```cpp
#include <iostream>
#include <thread>
#include <future>
#include <utility>
#include <chrono>

int getMeaningOfLife() {
    // Let the suspense build before providing the answer.
    std::this_thread::sleep_for(std::chrono::milliseconds(1000));
    // Return the answer.
    return 42;
}

int main() {
    std::packaged_task<int()> pt(getMeaningOfLife);
    // Save the future.
    auto f = pt.get_future();
    // Start a thread running the task and detach the thread.
    std::jthread t(std::move(pt));
    t.detach();
    // Get the result via the future.
    int result = f.get();
    std::cout << "The meaning of life is " << result << '\n';
}
```
```cpp
#include <iostream>
#include <cmath>
#include <thread>
#include <future>

double power(double x, double y) {
    return std::pow(x, y);
}

int main() {
    // invoke task in main thread
    std::packaged_task<double(double, double)> task(power);
    task(0.5, 2.0);
    std::cout << task.get_future().get() << '
';
    // reset shared state
    task.reset();
    // invoke task in new thread
    auto f = task.get_future();
    std::jthread t(std::move(task), 2.0, 0.5);
    t.detach();
    std::cout << f.get() << '
';
    return 0;
}
```
Section 3.9.9

Atomics
To avoid data races when sharing data between threads, it is often necessary to employ *synchronization* (e.g., by using mutexes).

Atomic types are another mechanism for providing synchronized access to data.

An operation that is indivisible is said to be *atomic* (i.e., no parts of any other operations can interleave with any part of an atomic operation).

Most processors support atomic memory operations via special machine instructions.

Atomic memory operations cannot result in torn reads or torn writes.

The standard library offers the following types in order to provide support for atomic memory operations:

- `std::atomic_flag`
- `std::atomic`

These types provide a uniform interface for accessing the atomic memory operations of the underlying hardware.
An atomic type provides guarantees regarding:

1. atomicity; and
2. ordering.

An ordering guarantee specifies the manner in which memory operations can become visible to threads.

Several memory ordering schemes are supported by atomic types.

The default memory order is sequentially consistent (std::memory_order_seq_cst).

Initially, only this default will be considered.
The `std::atomic_flag` Class

- `std::atomic_flag` provides flag with basic atomic operations
- Flag can be in one of two states: set (i.e., true) or clear (i.e., false)
- Two operations for flag:
  - **test and set**: set state to true and query previous state
  - **clear**: set state to false
- Default constructor initializes flag to *unspecified* state
- *not movable* and *not copyable*
- Implementation-defined macro `ATOMIC_FLAG_INIT` can be used to set flag to clear state in (static or automatic) initialization using statement of the form “`std::atomic_flag f = ATOMIC_FLAG_INIT;`” [C++17 §32.8/4]
- Guaranteed to be **lock free**
- Intended to be used as building block for higher-level synchronization primitives, such as spinlock mutex
### Member Functions

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>constructs object</td>
</tr>
<tr>
<td>clear</td>
<td>atomically sets flag to false</td>
</tr>
<tr>
<td>test_and_set</td>
<td>atomically sets flag to true and obtains its previous value</td>
</tr>
</tbody>
</table>
Example: Suboptimal Spinlock Mutex

```cpp
#include <iostream>
#include <thread>
#include <atomic>
#include <mutex>

class SpinLockMutex {
public:
    SpinLockMutex() {f_.clear();}
    void lock() {while (f_.test_and_set()) {}}
    void unlock() {f_.clear();}

private:
    std::atomic_flag f_; // true if thread holds mutex
};

SpinLockMutex m;
unsigned long long counter = 0;

void doWork() {
    for (unsigned long long i = 0; i < 100'000ULL; ++i)
        {std::scoped_lock lock(m); ++counter;}
}

int main() {
    std::jthread t1(doWork), t2(doWork);
    t1.join(); t2.join();
    std::cout << counter << '
';
}
```

- default memory order is suboptimal (and will be revisited later)
Example: One-Time Wait

```cpp
#include <iostream>
#include <atomic>
#include <thread>
#include <chrono>

// notReady flag initially not set
std::atomic_flag notReady = ATOMIC_FLAG_INIT;

int result = 0;

int main() {
    notReady.test_and_set(); // indicate result not ready
    std::thread producer([](){
        std::this_thread::sleep_for(std::chrono::seconds(1));
        result = -42;
        notReady.clear(); // indicate result ready
    });
    std::thread consumer([](){
        // loop until result ready
        while (notReady.test_and_set()) {}
        std::cout << result << '
';
    });
    producer.join();
    consumer.join();
    return 0;
}
```

This is not a particularly good use of `atomic_flag`. 
The \texttt{std::atomic} Template Class

- \texttt{std::atomic} class provides types with atomic operations
- declaration:
  \begin{verbatim}
  template <class T> struct atomic;
  \end{verbatim}
- provides object of type \( T \) with atomic operations
- has partial specializations for integral types and pointer types
- full specializations for all fundamental types
- in order to use class type for \( T \), \( T \) must be trivially copyable \footnote{C++17 §32.6/1} and bitwise equality comparable
- not required to be lock free
- on most popular platforms \texttt{atomic} is lock free when \( T \) is built-in type
- \textit{not move constructible} and \textit{not copy constructible}
- assignable but assignment operator returns value not reference
- most operations have memory order argument
- default memory order is SC (\texttt{std::memory_order_seq_cst})
### std::atomic Members

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>constructor</td>
<td>constructs object</td>
</tr>
<tr>
<td><code>operator=</code></td>
<td>atomically store value into atomic object</td>
</tr>
<tr>
<td><code>is_lock_free</code></td>
<td>check if atomic object is lock free</td>
</tr>
<tr>
<td><code>store</code></td>
<td>atomically replaces value of atomic object with given value</td>
</tr>
<tr>
<td><code>load</code></td>
<td>atomically reads value of atomic object</td>
</tr>
<tr>
<td><code>operator T</code></td>
<td>obtain result of <code>load</code></td>
</tr>
<tr>
<td><code>exchange</code></td>
<td>atomically replaces value of atomic object with given value and obtain value of previous value</td>
</tr>
<tr>
<td><code>compare_exchange_weak</code></td>
<td>similar to <code>exchange_strong</code> but may fail spuriously</td>
</tr>
<tr>
<td><code>compare_exchange_strong</code></td>
<td>atomically compare value of atomic object to given value and perform <code>exchange</code> if equal or <code>load</code> otherwise</td>
</tr>
<tr>
<td>Member Name</td>
<td>Description</td>
</tr>
<tr>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>fetch_add</td>
<td>atomically adds given value to value stored in atomic object and obtains value held previously</td>
</tr>
<tr>
<td>fetch_sub</td>
<td>atomically subtracts given value from value stored in atomic object and obtains value held previously</td>
</tr>
<tr>
<td>fetch_and</td>
<td>atomically replaces value of atomic object with bitwise AND of atomic object’s value and given value, and obtains value held previously</td>
</tr>
<tr>
<td>fetch_or</td>
<td>atomically replaces value of atomic object with bitwise OR of atomic object’s value and given value, and obtains value held previously</td>
</tr>
<tr>
<td>fetch_xor</td>
<td>atomically replaces value of atomic object with bitwise XOR of atomic object’s value and given value, and obtains value held previously</td>
</tr>
</tbody>
</table>
## std::atomic Members (Continued 2)

### Increment and Decrement

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>operator++</code></td>
<td>atomically increment the value of atomic object by one and obtain value after incrementing</td>
</tr>
<tr>
<td><code>operator++(int)</code></td>
<td>atomically increment the value of atomic object by one and obtain value before incrementing</td>
</tr>
<tr>
<td><code>operator--</code></td>
<td>atomically decrement the value of atomic object by one and obtain value after decrementing</td>
</tr>
<tr>
<td><code>operator--(int)</code></td>
<td>atomically decrement the value of atomic object by one and obtain value after decrementing</td>
</tr>
</tbody>
</table>
## Compound Assignment

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>operator+=</code></td>
<td>atomically adds given value to value stored in atomic object</td>
</tr>
<tr>
<td><code>operator-=</code></td>
<td>atomically subtracts given value from value stored in atomic object</td>
</tr>
<tr>
<td><code>operator&amp;=</code></td>
<td>atomically performs bitwise AND of given value with value stored in atomic object</td>
</tr>
<tr>
<td>`operator</td>
<td>=`</td>
</tr>
<tr>
<td><code>operator^=</code></td>
<td>atomically performs bitwise XOR of given value with value stored in atomic object</td>
</tr>
</tbody>
</table>

## Constants

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>is_always_lock_free</code></td>
<td>indicates if type always lock free</td>
</tr>
</tbody>
</table>
Example: Atomic Counter

```cpp
#include <iostream>
#include <vector>
#include <thread>
#include <atomic>

class AtomicCounter {
public:
    AtomicCounter() : c_(0) {}
    int operator++() {return ++c_;
    int get() const {return c_.load();}
private:
    std::atomic<int> c_;  
};

AtomicCounter counter;

void doWork() {
    for (int i = 0; i < 10000; ++i) {++counter;}
}

int main() {
    std::vector<std::jthread> v;
    for (int i = 0; i < 10; ++i)
       {v.emplace_back(doWork);}  
    for (auto& t : v) {t.join();} 
    std::cout << counter.get() << '
';
}
```

Example: Atomic Increment With Compare and Swap

```cpp
#include <atomic>

template <class T>
void atomicIncrement(std::atomic<T>& x) {
    T curValue = x;
    while (!x.compare_exchange_weak(curValue, curValue + 1)) {}
}
```
```cpp
#include <iostream>
#include <vector>
#include <atomic>
#include <thread>

constexpr int numThreads = 10;
std::atomic ready(false);
std::atomic done(false);
std::atomic startCount(0);

void doCounting(int id) {
    ++startCount;
    while (!ready) {}
    for (volatile int i = 0; i < 20000; ++i) {}
    bool expected = false;
    if (done.compare_exchange_strong(expected, true))
        {std::cout << "winner: " << id << '\n';}
}

int main() {
    std::vector<std::jthread> threads;
    for (int i = 0; i < numThreads; ++i)
        {threads.emplace_back(doCounting, i);}  
    while (startCount != numThreads) {}
    ready = true;
    // for (auto& t : threads) {t.join();}
}```
An Obligatory Note on `volatile`

- `volatile` qualifier not useful for multithreaded programming
- `volatile` qualifier makes *no guarantee of atomicity*
- can create object of `volatile`-qualified type whose size is sufficiently large that no current processor can access object atomically
- some platforms may happen to guarantee memory operations on (suitably-aligned) `int` object to be atomic, but in such cases this is normally true *even without `volatile` qualifier*
- `volatile` qualifier *does not adequately address issue of memory consistency*
- `volatile` qualifier does not imply use of memory barriers or other mechanisms needed for memory consistency
- optimizer and hardware might reorder operations (on non-`volatile` objects) across operations on `volatile` objects
Section 3.9.10

Atomics and the Memory Model
To be able to reason about the behavior of a program, we must know:

- the *order* in which the operations of the program are performed; and
- when the effects of each operation become *visible* to other operations in the program, which may be performed in different threads.

In a single-threaded program, the ordering of operations and when the effects of operations become visible is quite intuitive.

In a multi-threaded program, this matter becomes *considerably more complicated*.

In what follows, we examine the above matter more closely (which essentially relates to the memory model).
For two operations $A$ and $B$ performed in the same or different threads, $A$ is said to happen before $B$ if the effects of $A$ become visible to the thread performing $B$ before $B$ is performed.

The happens-before relationship is a much stronger condition than “happens earlier in time”.

If operation $A$ happens earlier in time than operation $B$, this does not imply that the effects of $A$ must be visible to the thread performing $B$ before $B$ is performed, due to the effects of caches, store buffers, and so on, which delay the visibility of results.

Happening earlier in time is only a necessary but not sufficient condition for a happens-before relationship to exist.

Happens-before relationships are not always transitive.

In the absence of something known as a dependency-ordered-before relationship (to be discussed later), which arise relatively less frequently, happens-before relationships are transitive (i.e., if $A$ happens before $B$ and $B$ happens before $C$ then $A$ happens before $C$).
Consider the multithreaded program (with two threads) shown below, where \( x \) and \( y \) are integer variables, initially zero.

<table>
<thead>
<tr>
<th>Thread 1 Code</th>
<th>Thread 2 Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x = 1; ) // A</td>
<td>( y = x; ) // B</td>
</tr>
</tbody>
</table>

Suppose that the run-time platform is such that memory operations on \( x \) are atomic so the program is data-race free.

Consider what happens when the program executes with the particular timing shown below, where \textit{operation A occurs earlier in time than operation B}.

\[
\begin{array}{c|c}
\text{Time} & \text{Thread 1 (on Core 1)} & \text{Thread 2 (on Core 2)} \\
\hline
\text{x = 1; // A} & \text{y = x; // B} \\
\end{array}
\]

The value read for \( x \) in operation \( B \) will not necessarily be 1, since the result of \( A \) \textit{may not yet be visible} to thread 2 (e.g., due to caching).
Sequenced-Before Relationships

- Given two operations \( A \) and \( B \) performed in the same thread, the operation \( A \) is sequenced before \( B \) if \( A \) precedes \( B \) in program order (i.e., source-code order).
- Sequenced-before relationships are transitive (i.e., if \( A \) is sequenced before \( B \), and \( B \) is sequenced before \( C \), then \( A \) is sequenced before \( C \)).
- Example: In the code below, statement \( A \) is sequenced before statement \( B \); \( B \) is sequenced before statement \( C \); and, by transitivity, \( A \) is sequenced before \( C \).

```c
x = 1; // A
y = 2; // B
z = x + 1; // C
```

- Example:
  - Consider the line of code below, which performs (in order) the following operations: 1) multiplication, 2) addition, and 3) assignment.
    ```c
    y = a * x + b; // (y = ((a * x) + b));
    ```
  - Multiplication is sequenced before addition.
  - Addition is sequenced before assignment.
  - Thus, by transitivity, multiplication is sequenced before assignment.
Sequenced-Before Relationships (Continued)

- For two operations $A$ and $B$ in the same thread, if $A$ is sequenced before $B$ then $A$ happens before $B$.
- In other words, program order establishes happens-before relationships for operations within a single thread.
- A sequenced-before relationship is essentially an intra-thread happens-before relationship. (Note that “intra” means “within”.)
- Example: In the code below, statement $A$ is sequenced before statement $B$. Therefore, $A$ happens before $B$. Similarly, $B$ happens before statement $C$, and $A$ happens before $C$.

```cpp
x = 1;    // A
y = 2;    // B
z = x + 1; // C
```
Establishing whether a happens-before relationship exists between operations in different threads is somewhat more complicated than the same-thread case.

Inter-thread happens-before relationships establish happens-before relationships for operations in different threads.

For two operations $A$ and $B$ in different threads, if $A$ inter-thread happens before $B$ then $A$ happens before $B$.

Inter-thread happens-before relationships are transitive (i.e., if $A$ inter-thread happens before $B$ and $B$ inter-thread happens before $C$ then $A$ inter-thread happens before $C$).

Some form of synchronization is required to establish an inter-thread happens-before relationship.

The various forms that this synchronization may take will be introduced on later slides.
Summary of Happens-Before Relationships

For two operations \( A \) and \( B \) in either the \textit{same or different} threads, \( A \) happens before \( B \) if:

1. \( A \) and \( B \) are in the \textit{same} thread and \( A \) is sequenced before (i.e., intra-thread happens before) \( B \); or
2. \( A \) and \( B \) are in \textit{different} threads and \( A \) inter-thread happens before \( B \).

In other words, \( A \) happens before \( B \) if \( A \) either intra-thread happens before or inter-thread happens before \( B \).

Intra-thread happens-before (i.e., sequenced-before) relationships are \textit{transitive}.

Inter-thread happens-before relationships are \textit{transitive}.

Happens-before relationships are \textit{mostly but not always transitive}.

A happens-before relationship is important because it tells us if the result of one operation \textit{can be seen} by a thread performing another operation.
Synchronizes-With Relationships

- A variety of relationships can imply an inter-thread happens-before relationship, with one being the synchronizes-with relationship.
- For two operations $A$ and $B$ in different threads, if $A$ synchronizes with $B$ then $A$ inter-thread happens before $B$.
- Example:
  - Consider the two-threaded program shown below, with the shared variable $x$ of type int, where $x$ is initially zero.

```
Thread 1 Code
1  x = 1;
2  // A (call of foo)
3  foo();
```

```
Thread 2 Code
1  bar();
2  // B (return from bar)
3  assert(x == 1);
```

- Suppose that the foo and bar functions are such that:
  1. any calls to bar will block until foo is called for the first time; and
  2. if a call to foo is made prior to a call to bar returning, then the call to foo synchronizes with the return of the call to bar.
- In this example, the call to foo is always made prior to bar returning.
- Consequently, $A$ synchronizes with $B$, which implies that $A$ must inter-thread happen before $B$, which in turn implies that $A$ happens before $B$.
- Therefore, the assertion in thread 2 can never fail.
Examples of Synchronizes-With Relationships

- **Thread creation.** The completion of the constructor for a thread object \( T \) synchronizes with the start of the invocation of the thread function for \( T \).  
  
  [C++17 §33.3.2.2/6]

- **Thread join.** The completion of the execution of a thread function for a thread object \( T \) synchronizes with (the return of) a join operation on \( T \).  
  
  [C++17 §33.3.2.5/4]

- **Mutex unlock/lock.** All prior unlock operations on a mutex \( M \) synchronize with (the return of) a lock operation on \( M \).  
  
  [C++17 §33.4.3.2/11]

- **Atomic.** A suitably tagged atomic write operation \( W \) on a variable \( x \) synchronizes with a suitably tagged atomic read operation on \( x \) that reads the value stored by \( W \) (where the meaning of “suitably tagged” will be discussed later).  

```cpp
#include <thread>
#include <cassert>

int x = 0;

void doWork() {
    // A1 (start of thread execution)
    assert(x == 1); // OK: M1 synchronizes with A1
    x = 2;
    // A2 (end of thread execution)
}

int main() {
    x = 1;
    std::thread t(doWork); // M1 (completion of constructor)
    t.join(); // M2 (return from join)
    assert(x == 2); // OK: A2 synchronizes with M2
}
```

- since construction of thread (M1) synchronizes with start of thread function execution (A1), M1 happens before A1 implying that assertion in doWork cannot fail
- since completion of execution of thread function (A2) synchronizes with join operation (M2), A2 happens before M2 implying that assertion in main cannot fail
Synchronizes-With Relationship: Mutex Lock/Unlock

Shared Data

```cpp
std::mutex m;
int x = 0;
int y = 0;
```

Thread 1 Code

```cpp
m.lock();
x = 1;
m.unlock();
```

Thread 2 Code

```cpp
m.lock();
y = x;
m.unlock();
```

Execution

Thread 1 Execution

```
A
m.lock();
x = 1;
m.unlock();
```

Thread 2 Execution

```
B
m.lock();
y = x;
m.unlock();
```

- since unlock synchronizes with lock, A happens before B; thus, for timing shown, B must see 1 for x
Most operations on atomic types allow a memory order to be specified.

Example:

```cpp
std::atomic<int> x = 0;
x.store(42, std::memory_order_seq_cst);
int y = x.load(std::memory_order_seq_cst);
```

The following memory orders are supported:

- sequentially consistent (`std::memory_order_seq_cst`)
- acquire-release (`std::memory_order_acq_rel`)
- acquire (`std::memory_order_acquire`)
- release (`std::memory_order_release`)
- consume (`std::memory_order_consume`)
- relaxed (`std::memory_order_relaxed`)

Read operations can use the orders:

- sequentially consistent, acquire, consume, and relaxed.

Write operations can use the orders:

- sequentially consistent, release, and relaxed.

Read-modify-write operations can use:

- all of the orders allowed for read and write operations; and
- acquire-release.
Although several memory orders can be employed for operations on atomic types, these orders support four basic models:

1. sequentially consistent,
2. acquire release,
3. consume release, and
4. relaxed.

These models differ in the guarantees that they make regarding:

- whether all writes to all atomic objects become visible to all threads simultaneously (i.e., total order for all writes to all atomic objects); and
- whether operations on atomic objects in different threads can establish a synchronization relationship (namely, a synchronizes-with or dependency-ordered-before [discussed later] relationship).

The models listed from strongest (i.e., makes the most guarantees) to weakest (i.e., makes the least guarantees) are:

1. sequentially consistent,
2. acquire release,
3. consume release, and
4. relaxed.
These models are *hierarchical* in the sense that each model makes at least all of the same guarantees as its weaker counterparts.

As we proceed from stronger to weaker models, more guarantees are lost.

A stronger model may require additional synchronization by hardware, which can *degrade performance*.

A weaker model *may not provide sufficient guarantees* for the correct functioning of code.

Using a model that fails to provide sufficient guarantees for correct code behavior will result in *bugs*.

Also, as the model is weakened, it becomes more difficult to reason about the behavior of code, leading to *incomprehensible code* and an *increased likelihood of (often very subtle) bugs*.
All writes to a particular atomic object $M$ (over its lifetime) occur in some particular total order, called its **modification order**.

Each atomic object has its own well-defined modification order.

For a particular atomic object $M$, **all** threads in a program are guaranteed to see $M$ change in a manner **consistent with its modification order**.

Essentially, this guarantee ensures that, once a given thread has seen a particular value of an atomic object, a subsequent read by that thread cannot retrieve an earlier value of the object.

If such a guarantee were not made, the memory model would be so weak as to be impractical to use.

Modification order is primarily a **conceptual** tool that is useful for describing memory-model behavior.

In practice, a thread is unlikely to actually observe every change in the modification order of an object.
For each atomic object $M$, each thread has its own current position in the object’s modification order.

A thread’s current position in the modification order of a particular atomic object need not be the same for all threads.

A read from an atomic object $M$ by a thread $T$ can optionally move $T$’s current position to a later position in the modification order of $M$ and then returns the value at the current position.

A write to an atomic object $M$ by a thread $T$ appends the value to be written to the modification order of $M$ and updates $T$’s current position in the modification order of $M$ to correspond to the value written.

An read-modify-write operation $A$ on an atomic object $M$ reads the last value in the modification order of $M$, modifies the value read appropriately, appends the resulting value to the modification order of $M$, and updates $T$’s current position in the modification order of $M$ to correspond to the value written.
Consider an atomic object $M$ with the modification sequence:
- 0, 1, 2, 3, 4, 5, 6, 7, 8.

A thread could, for example, legitimately see $M$ undergo any of the following sequences of updates:
- 0, 4, 8
- 8
- 2, 7
- 0, 1, 2, 5, 7, 8
- 0, 1, 2, 3, 4, 5, 6, 7, 8

A thread would, for example, be guaranteed *never* to see $M$ undergo any of the following sequences of updates, as all of these sequences are *inconsistent* with the modification order of $M$:
- 1, 0
- 1, 2, 1
- 42
- 0, 1, 2, 3, 4, 5, 6, 7, 6, 8
Although each atomic object has its own well-defined modification order, it is not necessarily the case that the modification orders for individual objects can be combined into a single total order over all atomic objects. Practically speaking, the reason for this is the delay in the visibility of results introduced by store buffers, caches, and so on. If a single total order for writes to all atomic objects is not guaranteed, this implies that the relative order of changes to different atomic objects need not appear the same to different threads. Ensuring the existence of a single total order over all atomic objects would require a significant amount of additional processor synchronization, which can significantly degrade performance. Therefore, this guarantee is not required to be made in all cases, the idea being that we only ask for the guarantee when it is needed for correct code behavior.
Consider a program with two threads and two shared integer atomic objects $x$ and $y$, each having the modification order: 0, 1.

Suppose that no requirement is imposed to guarantee the existence of a single total order on writes to all atomic objects.

Thread 1 could see $x$ and $y$ change in the following manner, consistent with their stated modification order:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Updates to Value Seen By Thread</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td>0 ... 1 ...........................</td>
</tr>
<tr>
<td>$y$</td>
<td>0 ................................. 1</td>
</tr>
</tbody>
</table>

Thread 2 could see $x$ and $y$ change in the following manner, consistent with their stated modification order:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Updates to Value Seen By Thread</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td>0 ................................. 1</td>
</tr>
<tr>
<td>$y$</td>
<td>0 ... 1 ...........................</td>
</tr>
</tbody>
</table>

Observe that thread 1 and thread 2 do not see $x$ and $y$ change in the same order relative to one another (i.e., thread 1 sees $x$ change before $y$, while thread 2 sees $y$ change before $x$).
The sequentially-consistent model simply corresponds to the default memory model for the language, namely, SC-DRF. (Since data races cannot occur on atomic objects, SC-DRF degenerates into SC for such objects.)

For the sequentially-consistent model, all memory operations (i.e., read, write, and read-modify-write) must use the sequentially-consistent memory order (`std::memory_order_seq_cst`).

A total ordering is guaranteed on all sequentially-consistent writes to all atomic objects.

All sequentially-consistent writes to atomic objects must become visible to all threads simultaneously.

A sequentially-consistent write operation \( W \) on an atomic object \( M \) (in one thread) synchronizes with a sequentially-consistent operation on \( M \) (in another thread) that reads the value written by \( W \).

This model allows for relatively easy reasoning about code behavior.
Example: Sequentially-Consistent Model

- shared data:
  - \( x \) and \( y \) are of type `std::atomic<int>` and both are initially zero
- thread 1 code (writes \( x \)):
  - `x.store(1, std::memory_order_seq_cst);`
- thread 2 code (writes \( y \)):
  - `y.store(1, std::memory_order_seq_cst);`
- thread 3 code (reads \( x \) then \( y \)):
  - `int x1 = x.load(std::memory_order_seq_cst);`
  - `int y1 = y.load(std::memory_order_seq_cst);`
- thread 4 code (reads \( y \) then \( x \)):
  - `int y2 = y.load(std::memory_order_seq_cst);`
  - `int x2 = x.load(std::memory_order_seq_cst);`

- memory order guarantees total order for all writes to all atomic objects
- so, thread 3 and thread 4 must agree about order in which \( x \) and \( y \) are modified
- not possible to see \( x1 == 1 \) and \( y1 == 0 \) in thread 3 (implying \( x \) modified before \( y \)) and \( x2 == 0 \) and \( y2 == 1 \) in thread 4 (implying \( y \) modified before \( x \))
Example: Sequentially-Consistent Model

```cpp
#include <atomic>
#include <thread>
#include <cassert>

std::atomic<int> x, y, c;

void w_x() {x.store(1, std::memory_order_seq_cst);}

void w_y() {y.store(1, std::memory_order_seq_cst);}

void r_xy() {
    while (!x.load(std::memory_order_seq_cst)) {}
    if (y.load(std::memory_order_seq_cst)) {++c;}
}

void r_yx() {
    while (!y.load(std::memory_order_seq_cst)) {}
    if (x.load(std::memory_order_seq_cst)) {++c;}
}

int main() {
    x = 0; y = 0; c = 0;
    std::jthread t1(w_x), t2(w_y), t3(r_xy), t4(r_yx);
    t1.join(); t2.join(); t3.join(); t4.join();
    assert(c != 0); // assertion cannot fail
}
```

assertion cannot fail: when `while` loop in `r_xy` terminates, all threads must see `x` as nonzero; when `while` loop in `r_yx` terminates, all threads must see `y` as nonzero; at least one of these must happen before `if` statements in both `r_xy` and `r_yx` executed
For the acquire-release model, the memory order is chosen as follows:
- a read operation uses the acquire order (`std::memory_order_acquire`)
- a write operation uses the release order (`std::memory_order_release`)
- a read-modify-write operation uses one of the orders allowed for read and write operations, or the acquire-release order (`std::memory_order_acq_rel`), which results in read acquire and write release.

No total ordering exists on all writes to all atomic objects (unlike in the sequentially-consistent model).

Consequently, threads do not necessarily have to agree on the relative order in which different atomics objects are modified.

A write-release operation $W$ on an atomic object $M$ synchronizes with a read-acquire operation on $M$ that reads the value written by $W$ (or a value written by the release sequence headed by $W$). \cite{C++17 §32.4/2}

The acquire-release model is useful for situations that involve pairwise synchronization of threads, such as with mutexes.

With the acquire-release model, it is often still possible to reason about code behavior without too much difficulty.
Example: Acquire-Release Model

- shared data:
  - x and y are of type `std::atomic<int>` and both are initially zero

- thread 1 code (writes x):
  - `x.store(1, std::memory_order_release);`

- thread 2 code (writes y):
  - `y.store(1, std::memory_order_release);`

- thread 3 code (reads x then y):
  - `int x1 = x.load(std::memory_order_acquire);`
  - `int y1 = y.load(std::memory_order_acquire);`

- thread 4 code (reads y then x):
  - `int y2 = y.load(std::memory_order_acquire);`
  - `int x2 = x.load(std::memory_order_acquire);`

- no ordering relationship between stores to x and y
- so, thread 3 and thread 4 do not need to agree about order in which x and y are modified
- possible to see `x1 == 1` and `y1 == 0` in thread 3 (i.e., thread 3 sees x change before y) and `x2 == 0` and `y2 == 1` in thread 4 (i.e., thread 4 sees y change before x)
Example: Acquire-Release Model

```cpp
#include <atomic>
#include <thread>
#include <cassert>

std::atomic<int> x, y, c;

void w_x() {x.store(1, std::memory_order_release);}
void w_y() {y.store(1, std::memory_order_release);}

void r_xy() {
    while (!x.load(std::memory_order_acquire)) {}
    if (y.load(std::memory_order_acquire)) {++c;}
}

void r_yx() {
    while (!y.load(std::memory_order_acquire)) {}
    if (x.load(std::memory_order_acquire)) {++c;}
}

int main() {
    x = 0; y = 0; c = 0;
    std::jthread t1(w_x), t2(w_y), t3(r_xy), t4(r_yx);
    t1.join(); t2.join(); t3.join(); t4.join();
    assert(c != 0); // assertion can fail
}
```

- assertion can fail: one thread seeing \( x \) or \( y \) being nonzero does not imply other thread sees same
Example: Spinlock Mutex Using `std::atomic_flag`

```cpp
#include <iostream>
#include <thread>
#include <atomic>

class SpinLockMutex {
public:
    SpinLockMutex() {f_.clear();}
    void lock() {
        while (f_.test_and_set(std::memory_order_acquire)) {} 
    }
    void unlock() {f_.clear(std::memory_order_release);}
private:
    std::atomic_flag f_; // true if thread holds mutex
}

SpinLockMutex m;
unsigned long long counter = 0;

void doWork() {
    for (unsigned long long i = 0; i < 100’000ULL; ++i)
        {m.lock(); ++counter; m.unlock();}
}

int main() {
    std::jthread t1(doWork), t2(doWork);
    t1.join(); t2.join();
    std::cout << counter << '
';
}
```

- uses acquire-release model
Example: Spinlock Mutex and `std::scoped_lock`

```cpp
#include <iostream>
#include <thread>
#include <atomic>
#include <mutex>

class SpinLockMutex {
public:
    SpinLockMutex() {f_.clear();}
    void lock() {
        while (f_.test_and_set(std::memory_order_acquire)) {} 
    }
    void unlock() {f_.clear(std::memory_order_release);}
private:
    std::atomic_flag f_; // true if thread holds mutex
};

SpinLockMutex m;

unsigned long long counter = 0;

void doWork() {
    for (unsigned long long i = 0; i < 100'000ULL; ++i)
        {std::scoped_lock lg(m); ++counter;}
}

int main() {
    std::jthread t1(doWork), t2(doWork);
    t1.join(); t2.join();
    std::cout << counter << 'n';
}
```
For two operations $A$ and $B$ performed in the \textit{same} thread, $A$ is said to \textbf{carry a dependency} to $B$ if the result of $A$ is used as an operand for $B$ (ignoring some special cases). \textsuperscript{[C++17 §4.7.1/7]}

Example: In the code below, statement $A$ \textit{carries a dependency} to statement $B$ but not statement $C$.

\begin{verbatim}
x = 42; // A
y = x + 1; // B
z = 0; // C
\end{verbatim}

Note that “carries a dependency to” is a subset of “is sequenced before” (i.e., the former implies the latter). \textsuperscript{[C++17 §4.7.1/7]}

The carries-a-dependency-to relationship is \textit{transitive} (i.e., if $A$ carries a dependency to $B$ and $B$ carries a dependency to $C$ then $A$ carries a dependency to $C$).

Example: In the code below, statement $A$ \textit{carries a dependency} to statement $B$; and $B$ \textit{carries a dependency} to statement $C$. Therefore, transitively, $A$ \textit{carries a dependency} to $C$.

\begin{verbatim}
x = 42; // A
y = x + 1; // B
z = 2 * y; // C
\end{verbatim}
Another type of synchronization relationship is known as a dependency-ordered-before relationship.

A write-release operation $A$ is *dependency ordered before* a read-consume operation $B$ if $B$ reads the value written by $A$ (or any side effect in the release sequence headed by $A$).

For two operations $A$ and $B$ performed in different threads, if $A$ is dependency ordered before $B$ then $A$ *inter-thread happens before* $B$.

Thus, dependency-ordered-before relationships can also establish happens-before relationships.
The inter-thread happens before relation describes an *arbitrary concatenation* of sequenced-before, synchronizes-with, and dependency-ordered-before relations, *with two exceptions*: \[\text{[C++17 §4.7.1/9]}\]

1. a concatenation is not permitted to end with dependency ordered before followed by (one or more) sequenced before; and
2. a concatenation is not permitted to consist entirely of sequenced-before relations.

The first restriction is required since a dependency-ordered-before relationship synchronizes *only data dependencies*.

The second restriction is required since inter-thread happens-before relationship must (by definition) involve operations in *different* threads.
- For the consume-release model, the memory order is chosen as follows:
  - a write operation uses release order (`std::memory_order_release`)
  - a read operation uses the consume order (`std::memory_order_consume`)
- The consume-release model is identical to the acquire-release model with one important difference, namely the type of synchronization relationship established.
- A write-release operation $W$ is *dependency ordered before* a read-consume operation (in a different thread) that reads the value stored by $W$ (or any side effect in the release sequence headed by $W$).
- In other words, the consume-release model establishes a *dependency-ordered-before* relationship, whereas the acquire-release model establishes a *synchronizes-with* relationship.
- In this sense, the consume-release model is weaker than the acquire-release model (i.e., less data is synchronized).
Example: Consume-Release Model

```cpp
#include <thread>
#include <atomic>
#include <cassert>

int x = 0;
std::atomic y(0);

void producer() {
    x = 42;
    y.store(1, std::memory_order_release);
}

void consumer() {
    int a;
    while (!(a = y.load(std::memory_order_consume))) {}
    assert(x == 42); // data race
}

int main() {
    std::jthread t1(producer);
    std::jthread t2(consumer);
    // t1.join();
    // t2.join();
}
```

- program has **data race** on x; a does not carry dependency to x so x = 42 does not necessarily happen before x used in assertion
- if consume changed to acquire, no data race and assertion cannot fail
Example: Publishing Data Via Pointer

```cpp
#include <thread>
#include <atomic>
#include <cassert>
#include <string>

std::atomic<std::string*> p(nullptr);
int x = 0;

void producer() {
    std::string* s = new std::string("Hello");
    x = 42;
    p.store(s, std::memory_order_release);
}

void consumer() {
    std::string* s;
    while (!(s = p.load(std::memory_order_consume))) {}  
    assert(*s == "Hello");
    // assert(x == 42); would result in data race
}

int main() {
    std::jthread t1(producer), t2(consumer);
    // t1.join(); t2.join();
}
```

- assertion cannot fail; store to p is dependency ordered before load and load carries dependency to *s in assertion
For the relaxed model, all memory operations use the relaxed order (`std::memory_order_relaxed`).

Like in the acquire-release model, no total order exists on updates to all atomic objects (collectively).

Operations on the same variable within a single thread satisfy a happens-before relationship (i.e., within a single thread, accesses to a single atomic variable must follow program order).

Unlike in the acquire-release model, no inter-thread synchronization relationship is established.

No requirement exists on the ordering relative to other threads.

The relaxed order is sometime suitable for updating counters (e.g., blind event counters).

Except in very trivial cases, it can be extremely difficult to reason about the meaning and/or correctness of code that uses relaxed order.
Behavior of Relaxed Model

- consider atomic memory operations with relaxed order
- for each individual atomic object, all threads have view of updates that is consistent with single modification sequence

read operation (e.g., `load`):
- if current position not set, return any element in sequence and set current position to that of returned element
- otherwise, either leave current position unchanged or move later in sequence and return value at current position

write operation (e.g., `store`):
- append value to end of sequence
- set current position to correspond to appended value

read-modify-write operation (e.g., increment, decrement, `exchange`, `compare_exchange`):
- read last value from sequence
- modify read value as appropriate to obtain new value
- append new value to end of sequence
- set current position to correspond to that of appended value

considerable flexibility in value returned by read
Example: Relaxed Model

```cpp
#include <atomic>
#include <thread>
#include <cassert>

std::atomic<int> x, y, c;

void w_x() {x.store(1, std::memory_order_relaxed);}
void w_y() {y.store(1, std::memory_order_relaxed);}

void r_xy() {
    while (!x.load(std::memory_order_relaxed)) {} 
    if (y.load(std::memory_order_relaxed)) {++c;}
}

void r_yx() {
    while (!y.load(std::memory_order_relaxed)) {} 
    if (x.load(std::memory_order_relaxed)) {++c;}
}

int main() {
    x = 0; y = 0; c = 0;
    std::jthread t1(w_x), t2(w_y), t3(r_xy), t4(r_yx);
    t1.join(); t2.join(); t3.join(); t4.join();
    assert(c != 0); // assertion can fail
}
```

- assertion can fail: one thread seeing \(x\) or \(y\) being nonzero does not imply other thread sees same
Example: Blind Event Counters

```cpp
#include <vector>
#include <iostream>
#include <thread>
#include <atomic>

std::atomic<unsigned long long> counter(0);

void doWork() {
    for (long i = 0; i < 100'000L; ++i)
        {counter.fetch_add(1, std::memory_order_relaxed);}
}

int main() {
    std::vector<std::jthread> workers;
    for (int i = 0; i < 10; ++i) {workers.emplace_back(doWork);}
    for (auto& t : workers) {t.join();}
    std::cout << "counter " << counter << '
';
}
```

- `fetch_add` can use *relaxed* order, since only incrementing counter *blindly* (i.e., not taking action based on value of counter)
- Thread join operations provide synchronization to ensure desired value read for counter when output
Example: Done Flag

```cpp
#include <atomic>
#include <chrono>
#include <thread>
#include <vector>

std::atomic<bool> done;

void doWork() {
    while (!done.load(std::memory_order_relaxed)) {
        // do something here
    }
}

int main() {
    std::vector<std::jthread> workers;
    done.store(false, std::memory_order_relaxed); // I hope? ;)
    for (int i = 0; i < 16; ++i) {workers.emplace_back(doWork);}
    std::this_thread::sleep_for(std::chrono::seconds(5));
    done = true; // not relaxed
    // for (auto& t : workers) {t.join();}
}
```

- `done.store` can be relaxed due to synchronization from thread create
- `done.load` can be relaxed since order not important; different order as if other threads ran at different speeds
- `assign to done` must be sequentially-consistent to prevent assign from floating past join (due to single-thread optimization)
The copy constructor for `shared_ptr` (which increments a reference count) would look something like:

```cpp
// ...
controlBlockPtr = other->controlBlockPtr;
controlBlockPtr->refCount.fetch_add(1,
    std::memory_order_relaxed);
// ...
```

The destructor for `shared_ptr` (which decrements a reference count) would look something like:

```cpp
// ...
if (!controlBlockPtr->refCount.fetch_sub(1,
    std::memory_order_acq_rel)) {
    delete controlBlockPtr;
}
// ...
```

The increment operation can use `relaxed` order, since *no action is taken* based on the reference count value.

The decrement operation needs to use `acquire-release` order so that the decrement cannot float and the correct view of the data is seen by the thread doing the delete (all decrements form a *synchronization chain*).
Release semantics is a property that can only apply to operations that **write to memory** (i.e., read-modify-write operations or plain writes).

A write operation that has release semantics is called a **write release**.

A write release operation $W$ cannot be reordered with any read or write operation that **precedes** $W$ in program order (i.e., memory operations cannot be moved from before $W$ to after $W$).

The term release semantics originates from mutexes.

In the context of mutexes, the operations prior to a mutex release operation, which correspond to operations in a critical section, must not be moved after the mutex release operation, as operations after the mutex release operation are not protected by the mutex.
Acquire semantics is a property that can only apply to operations that *read from memory* (i.e., read-modify-write operations or plain reads).

A read operation that has acquire semantics is called a **read acquire**.

A read acquire operation $R$ cannot be reordered with any read or write operation that follows $R$ in program order (i.e., memory operations cannot be moved from after $R$ to before $R$).

The term acquire semantics originates from mutexes.

In the context of mutexes, the operations following a mutex acquire operation, which correspond to operations in a critical section, must not be moved before the mutex acquire operation, as operations before the mutex acquire operation are not protected by the mutex.
A release sequence headed by a release operation $A$ on an atomic object $M$ is a maximal contiguous subsequence of side effects in the modification order of $M$, where the first operation is $A$, and every subsequent operation is performed by the same thread that performed $A$, or is an atomic read-modify-write operation.\[\text{[C++17 §4.7.1/5]}\]
stores to y in A and B constitute release sequence headed by store in A
when while loop terminates, load in C will have read value written by store in B (not store in A)
A synchronizes with C, since C reads value in release sequence headed by A
assertion cannot fail, since A happens before C
A **memory fence** (also known as a **memory barrier**) is an operation that causes the processor and compiler to enforce an **ordering constraint** on memory operations issued before and after the fence operation.

Certain types of memory operations before a fence are guaranteed not to be reordered with certain types of memory operations after the fence.

A fence may also introduce **synchronizes-with** relationships under certain circumstances.

An **acquire fence** prevents the reordering of any **read or write** following the fence (in program order) with any **read** prior to the fence (in program order). (That is, a memory operation after the fence cannot be moved before any read operation before the fence.)

A **release fence** prevents the reordering of any **read or write** prior to the fence (in program order) with any **write** following the fence (in program order). (That is, a memory operation before the fence cannot be moved after any write operation after the fence.)

A fence is **not** a release or acquire operation. as it does not read/write memory.
memory fences can be inserted via function `std::atomic_thread_fence`

**Declaration:**

```cpp
void atomic_thread_fence(std::memory_order order) noexcept;
```

- **No effect** if order is `std::memory_order_relaxed`
- **Acquire fence** if order is `std::memory_order_acquire` or `std::memory_order_consume`
- **Release fence** if order is `std::memory_order_release`
- **Both acquire and release fence** if order is `std::memory_order_acq_rel`
- **Sequentially consistent acquire and release fence** if order is `std::memory_order_seq_cst`
Fences and Synchronizes-With Relationships

- **Release fence and acquire fence.** A release fence $A$ synchronizes with an acquire fence $B$ if there exist atomic operations $X$ and $Y$, both operating on some atomic object $M$, such that $A$ is sequenced before $X$, $X$ modifies $M$, $Y$ is sequenced before $B$, and $Y$ reads the value written by $X$ or a value written by any side effect in the hypothetical release sequence $X$ would head if it were a release operation. [C++17 §32.9/2]

- **Release fence and acquire operation.** A release fence $A$ synchronizes with an atomic operation $B$ that performs an acquire operation on an atomic object $M$ if there exists an atomic operation $X$ such that $A$ is sequenced before $X$, $X$ modifies $M$, and $B$ reads the value written by $X$ or a value written by any side effect in the hypothetical release sequence $X$ would head if it were a release operation. [C++17 §32.9/3]

- **Release operation and acquire fence.** An atomic operation $A$ that is a release operation on an atomic object $M$ synchronizes with an acquire fence $B$ if there exists some atomic operation $X$ on $M$ such that $X$ is sequenced before $B$ and reads the value written by $A$ or a value written by any side effect in the release sequence headed by $A$. [C++17 §32.9/4]
```cpp
#include <thread>
#include <atomic>
#include <iostream>

std::atomic ready(false);

int data = 0;

void produce() {
  data = 42; // write to data can move after store in A
  // release fence needed here
  ready.store(true, std::memory_order_relaxed); // A
}

void consume() {
  while (!ready.load(std::memory_order_relaxed)) {} // B
  // acquire fence needed here
  std::cout << data << '
';
  // read of data can move before load in B
}

int main() {
  std::jthread t1(produce);
  std::jthread t2(consume);
  // t1.join(); t2.join();
}
```

- atomic store (to ready) does not synchronize with atomic load (of ready), due to relaxed order; results in race on data
```cpp
#include <thread>
#include <atomic>
#include <iostream>

std::atomic ready(false);
int data = 0;

void produce() {
    data = 42;
    std::atomic_thread_fence(std::memory_order_release);
    ready.store(true, std::memory_order_relaxed);
}

void consume() {
    while (!ready.load(std::memory_order_relaxed)) {} // fence
    std::atomic_thread_fence(std::memory_order_acquire);
    std::cout << data << '
';
}

int main() {
    std::jthread t1(produce);
    std::jthread t2(consume);
    // t1.join(); t2.join();
}
```

- release fence synchronizes with acquire fence, due to atomic load (of `ready`) reading from result of atomic store (to `ready`)
Memory Orders: The Bottom Line

- Use sequentially-consistent order unless there is a compelling case to do otherwise.
- In situations where semantics dictate a clear pairwise synchronization between threads, consider the use of acquire-release order if it can be easily seen to yield correct code.
- Only consider relaxed order in situations where the performance penalty of using a stronger order would be unacceptable.
- Be very wary of using relaxed order. Even world experts on the C++ memory model acknowledge that this can be tricky.
- Always have any code using relaxed order thoroughly reviewed by people who are extremely knowledgeable about memory models.
Section 3.9.11

References

This is a fairly comprehensive book on concurrency and multithreaded programming in C++. It is arguably the best book available for those who want to learn how to write multithreaded code using C++.


This very well written Ph.D. thesis introduces the C++11/C11 memory model and presents work in mathematically formalizing, refining, and validating this model.


This set of slides appear to have been used for part of a course on multicore programming at the University of Cambridge.


A good reference for concurrent programming.


http://www.open-std.org/jtc1/sc22/wg14/www/docs/n1479.htm


Section 3.10

Compilers and Linkers
Application Binary Interfaces (ABIs)

- Application Binary Interface (ABI) specifies how data structures or subroutines accessed at machine-code level.
- In other words, ABI is like API, but at level of machine code.
- ABI typically covers details such as:
  - Processor instruction set
  - Sizes, layouts, and alignments of data types
  - Calling conventions, which include details such as:
    - How parameters passed to functions
    - How return values passed back from functions
    - What state (e.g., registers) needs to be preserved by caller/callee
  - How exceptions handled
  - How source code identifiers should be mapped to identifiers in object code (i.e., name mangling)
  - How calls made to operating system
- Compilers need to adhere to ABI to allow object-code compatibility between different compilers.
name mangling is process that maps set of names to another set of names

typically name mangling used to map names in source code (which may be overloaded) to names in object code

to keep linkers from becoming overly complex, do not want linkers to have to support overloaded identifiers

thus, each overloaded function must have distinct name in object code

unique names in object code obtained by applying name mangling to names from source code

name mangling rules not specified by C++ standard

typically, name mangling rules addressed by ABI standard, such as Itanium ABI

some examples of name mangling results with Itanium ABI as follows:

<table>
<thead>
<tr>
<th>Declaration</th>
<th>Mangled Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>bool func(int)</td>
<td>_Z4funci</td>
</tr>
<tr>
<td>bool func(double, double)</td>
<td>_Z4funcdd</td>
</tr>
</tbody>
</table>

Copyright © 2015–2021 Michael D. Adams

Programming in C++

Version 2021-04-01

1573
Section 3.10.1

Itanium C++ ABI
- one ABI followed by number of popular C++ compilers is Itanium C++ ABI
- Itanium C++ ABI builds on various other ABI documents (some of which are related to either System V or Intel Itanium architecture)
- amongst other things, Itanium C++ ABI specifies:
  - some implementation details for constructors and destructors
  - name mangling rules
- web site:
- developed jointly by informal industry coalition consisting of CodeSourcery, Compaq, EDG, HP, IBM, Intel, Red Hat, and SGI
- Itanium C++ ABI followed by GCC and Clang on most platforms (with Microsoft Windows being notable exception)
Constructors

- each constructor written by programmer nominally results in compiler emitting code for *multiple* functions, which together implement several variations on construction

- each constructor for class $T$ nominally associated with three functions:
  1. **base object constructor**: function that creates non-virtual (direct) base class objects and non-static data members of $T$ and initializes $T$ object itself
  2. **complete object constructor**: function that creates all virtual base class objects of $T$ and then additionally performs all work of base object constructor
  3. **allocating object constructor**: function that performs all work of complete object constructor after obtaining storage for new $T$ object from allocation function (i.e., `operator new`)

- if no virtual base classes, complete object constructor and base object constructor are same (e.g., one function is alias for other)

- ABI specification seems to suggest that allocating constructor only required if class has virtual destructor

- this said, however, GCC appears to never emit code for allocating object constructor
Destructors

- each destructor written by programmer nominally results in compiler emitting code for *multiple* functions, which together implement several variations on destruction

- destructor for class \( T \) nominally associated with three functions:
  1. **base object destructor**: function that performs any clean-up action for \( T \) object itself and destroys non-static data members and non-virtual (direct) base class objects of \( T \)
  2. **complete object destructor**: function that, in addition to actions of base object destructor, destroys all virtual base class objects of \( T \)
  3. **deleting destructor**: function that, in addition to actions of complete object destructor, invokes appropriate deallocation function for \( T \)

- complete object destructor in charge of destroying virtual base class objects, whereas base object destructor is not

- if no virtual base classes, base object destructor and complete object destructor are same (e.g., one is alias for other)

- deleting destructor must be emitted when \( T \) has virtual destructor; otherwise, may be emitted but not required
Name Mangling

- many rules for name mangling; only a few mentioned here
- all mangled symbols begin with \_Z
- nested name delimited by N and E
- St denotes std namespace; Sa denotes std::allocator
- template arguments delimited by I and E
- letter codes for some built-in types:

<table>
<thead>
<tr>
<th>Letter Code</th>
<th>Built-In Type</th>
<th>Letter Code</th>
<th>Built-In Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>v</td>
<td>void</td>
<td>j</td>
<td>unsigned int</td>
</tr>
<tr>
<td>b</td>
<td>bool</td>
<td>l</td>
<td>long</td>
</tr>
<tr>
<td>c</td>
<td>char</td>
<td>m</td>
<td>unsigned long</td>
</tr>
<tr>
<td>h</td>
<td>unsigned char</td>
<td>f</td>
<td>float</td>
</tr>
<tr>
<td>i</td>
<td>int</td>
<td>d</td>
<td>double</td>
</tr>
</tbody>
</table>

- letter codes for cv-qualifiers:

<table>
<thead>
<tr>
<th>Letter Code</th>
<th>Qualifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>volatile</td>
</tr>
<tr>
<td>K</td>
<td>const</td>
</tr>
</tbody>
</table>
- **Letter codes for type qualifiers:**

<table>
<thead>
<tr>
<th>Letter Code</th>
<th>Qualifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>pointer</td>
</tr>
<tr>
<td>R</td>
<td>lvalue reference</td>
</tr>
<tr>
<td>O</td>
<td>rvalue reference</td>
</tr>
</tbody>
</table>

- **Codes for constructors and destructors:**

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>complete object constructor</td>
</tr>
<tr>
<td>C2</td>
<td>base object constructor</td>
</tr>
<tr>
<td>C3</td>
<td>allocating constructor</td>
</tr>
<tr>
<td>D0</td>
<td>deleting destructor</td>
</tr>
<tr>
<td>D1</td>
<td>complete object destructor</td>
</tr>
<tr>
<td>D2</td>
<td>base object destructor</td>
</tr>
</tbody>
</table>
#include <iostream>
#include <vector>

struct Widget {
    Widget();
    Widget(int);
    ~Widget();
    int grog() const;
};

Widget::Widget() {} // Widget::Widget() -> _ZN6WidgetC1Ev, _ZN6WidgetC2Ev

Widget::Widget(int i) {} // Widget::Widget(int) -> _ZN6WidgetC1Ei, _ZN6WidgetC2Ei

Widget::~Widget() {} // Widget::~Widget() -> _ZN6WidgetD1Ev, _ZN6WidgetD2Ev

int Widget::grog() const { return 42; } // Widget::grog() const -> _ZNK6Widget4grogEv

namespace foo {
    void func() {} // foo::func() -> _ZN3foo4funcEv
}

void squander(const std::vector<int>& v) {} // squander(const std::vector<int>& v) -> _Z8squanderRKSt6vectorIiSaIiEE

int main() {
    std::cout << "Hello, World!\n"; // std::cout -> _ZSt4cout
}
Name-Demangling Tools

- **C++Filt:**
  - `c++filt` program, which is part of GNU Binary Utilities
  - Filter that copies character stream from standard input to standard output replacing any mangled names with their unmangled forms
  - Web site: [https://www.gnu.org/software/binutils](https://www.gnu.org/software/binutils)

- **LLVM Cxxfilt:**
  - `llvm-cxxfilt` program, which is part of LLVM software
  - Filter that copies character stream from standard input to standard output replacing any mangled names with their unmangled forms (in similar fashion as `c++filt`)
  - LLVM Web site: [https://llvm.org](https://llvm.org)

- **Online name demangler:**
  - [http://demangler.com](http://demangler.com)
Section 3.10.2

References
References


Part 4

Even More C++
Section 4.1

Undefined Behavior and Other Evil Stuff
Undefined, Unspecified, and Implementation-Defined Behavior

- **undefined behavior**: behavior for which standard imposes no requirements (i.e., anything could happen) [C++17 §3.27]

- **unspecified behavior**: behavior, for a well-formed program construct and correct data, that depends on the implementation; implementation is not required to document which behavior occurs; range of possible behaviors usually specified in standard [C++17 §3.28]

- **implementation-defined behavior**: behavior, for a well-formed program construct and correct data, that depends on the implementation and that each implementation documents (i.e., only know what will happen for a particular implementation) [C++17 §3.12]

- *always avoid undefined behavior* and *do not rely on unspecified behavior*; otherwise cannot guarantee correct behavior of program

- *try to avoid relying on implementation-defined behavior*; otherwise cannot guarantee correct behavior of program across all language implementations (i.e., code will not be portable)
Examples of Undefined Behavior

- dereferencing a null pointer; for example:
  ```c
  char* p = nullptr;
  char c = *p; // undefined behavior
  ```

- attempting to modify a string literal or any other const object (excluding mutable data members):
  ```c
  const int x = 0;
  const_cast<int&>(x) = 42; // undefined behavior
  ```

- signed integer overflow

- evaluating an expression that is not mathematically defined; for example:
  ```c
  double z = 0.0;
  double x = 1.0 / z; // undefined behavior
  ```

- not returning a value from a value-returning function (other than `main`)
  ```c
  int get_value() {
    // undefined behavior
  }
  ```

- multiple definitions of the same entity
Examples of Undefined Behavior (Continued)

- performing pointer arithmetic that yields a result before start of or after end (i.e., one past last element) of an array; for example:
  ```c
  int v[10];
  int* p = &v[0];
  --p; // undefined behavior
  ```

- using pointers to objects whose lifetime has ended

- left-shifting values by a negative amount; for example:
  ```c
  int i = 1;
  i <<= (-3); // undefined behavior
  ```

- shifting values by an amount greater than or equal to the number of bits in the number; for example:
  ```c
  int i = 42;
  i >>= 10000; // undefined behavior
  ```

- using an automatic variable whose value has not been initialized; for example:
  ```c
  void func() {
  int i;
  ++i; // undefined behavior
  }
  ```
order in which arguments to a function are evaluated; for example:

```cpp
#include <iostream>

int count() {
    static int c = 0;
    return c++;
}

void func(int x, int y) {
    std::cout << x << ' ' << y << '
';
}

int main() {
    func(count(), count());
    // what values are passed to func?
    // 0, 1; or 1, 0?
    // 0, 1; or 1, 0?
```
Examples of Implementation-Defined Behavior

- meaning of `#pragma` directive
- nesting limit for `#include` directives
- search locations for "" and <> headers
- sequence of places searched for header
- signedness of char
- size of built-in types other than `char`, `signed char`, `unsigned char`
- type of `size_t`, `ptrdiff_t`
- parameters to `main` function
- alignment (i.e., restrictions on the addresses at which an object of a particular type can be placed)
- result of right shift of negative value
- precise types used in various parts of C++ standard library (e.g., actual type named by `vector<T>::iterator` [C++17 §26.3.11.1/2])
- meaning of `asm` declaration
- for more examples, see “Index of implementation-defined behavior” section in C++11 standard
#include <iostream>

template <typename Tag>
typename Tag::type saved_private_v;

template <typename Tag, typename Tag::type x>
bool save_private_v = (saved_private_v<Tag> = x);

class Widget {
public:
   Widget(int i) : i_(i) {}
private:
   int i_;
   int f_() const {return i_;}
};

struct Widget_i_ {using type = int Widget::*;};
struct Widget_f_ {using type = int (Widget::*)( ) const;};

template bool save_private_v<Widget_i_, &Widget::i_>;
template bool save_private_v<Widget_f_, &Widget::f_>;

int main() {
   Widget w(42);
   std::cout << w.*saved_private_v<Widget_i_> << '
';
   std::cout << (w.*saved_private_v<Widget_f_>)( ) << '
';
}
Section 4.2

C++ Compatibility
many changes have been made to C++ language and standard library during evolution of C++ from C++98 to present

some changes resulted in incompatibilities between different versions of C++ standard

subsequent slides list some reference material that discusses how C++ standard changed from one version to next

knowing such changes helps to understand incompatibilities between different versions


Section 4.3

C Compatibility
Although C++ attempted to maintain compatibility with C where possible, numerous incompatibilities between the languages exist.

Unfortunately, as C++ and C continue to evolve, the number of incompatibilities between these languages continues to grow.

In practice, many C programs are valid C++ programs and can therefore be compiled with a C++ compiler.

Some C programs, however, may require a significant number of changes to be valid C++.

Moreover, in some cases, the semantics of the source code may change, depending on whether it is interpreted as C++ or C.

A few examples of incompatibilities between C++ and C are given on the subsequent slides.

More detailed information on incompatibilities between C++ and C can be found at:

Conflicts with New Keywords

- C++ introduces many new keywords.
- Some C programs might use some of these keywords as identifiers (e.g., `new`, `delete`).

```c
#include <stdio.h>
#include <unistd.h>

/* Delete a file. */
int delete(const char* filename) { /* note function name */
    return unlink(filename);
}

int main(int argc, char** argv) {
    if (argc >= 2) {
        if (delete(argv[1])) {
            printf("cannot delete file\n");
            return 1;
        }
    }
    return 0;
}
```
In C, a function declaration without arguments implies that the arguments are unspecified.

In C++, a function declaration without arguments implies that the function takes no arguments.
In C, if the return type of a function is not specified, it is treated as `int`.

In C++, the return type of a function must always be explicitly specified.
More Restrictive Conversions Involving \texttt{void*}

```c
int main(int argc, char** argv) {
    int i;
    int* ip;
    void* vp;
    ip = &i;
    vp = ip;
    ip = vp; /* problematic */
    return 0;
}
```

- C provides an implicit conversion from \texttt{void*} to any pointer type, while C++ does not.
### Scoping Rules for Nested Structs

```c
struct outer {
    struct inner {
        int i;
    };
    int j;
};

struct inner a = {1}; /* inner vs. outer::inner */

int main(int argc, char** argv) {
    return 0;
}
```

- C and C++ both allow nested `struct` types, but the scoping rules differ.
A character literal (such as 'A') is of type `char` in C++, but type `int` in C.

Consequently, the above program will print a value of 1 when compiled as C++ and a value greater than 1 (namely, the value of `sizeof(int)` when compiled as C.

Thus, the same source code can have different semantics, depending on whether it is interpreted as C++ or C.
Part 5

Libraries
Section 5.1

Boost Libraries
Section 5.1.1

Introduction
- Boost libraries are collection of free peer-reviewed portable C++ source libraries
- license encourages both commercial and non-commercial use
- often Boost libraries later adopted by C++ standard
- web site: http://www.boost.org
### Containers and Data Structures

<table>
<thead>
<tr>
<th>Library</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bimap</td>
<td>bidirectional maps (i.e., associative containers in which both types stored in map can be used as key)</td>
</tr>
<tr>
<td>Container</td>
<td>standard library containers and extensions</td>
</tr>
<tr>
<td>Heap</td>
<td>priority queue data structures</td>
</tr>
<tr>
<td>Intrusive</td>
<td>intrusive containers and algorithms</td>
</tr>
<tr>
<td>Multi-Array</td>
<td>generic N-dimensional array</td>
</tr>
<tr>
<td>Multi-Index</td>
<td>containers that maintain one or more indices with different sorting and access semantics</td>
</tr>
</tbody>
</table>

### Iterators

<table>
<thead>
<tr>
<th>Library</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iterator</td>
<td>concepts that extend C++ standard iterator requirements and components for building iterators based on these concepts; includes several iterator adaptors</td>
</tr>
</tbody>
</table>
### Math and Numerics

<table>
<thead>
<tr>
<th>Library</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interval</td>
<td>interval arithmetic</td>
</tr>
<tr>
<td>Math</td>
<td>various numeric types and math functions</td>
</tr>
<tr>
<td>Multiprecision</td>
<td>extended precision arithmetic types for floating-point, integer, and rational arithmetic</td>
</tr>
<tr>
<td>Rational</td>
<td>rational number class</td>
</tr>
</tbody>
</table>

### String and Text Processing

<table>
<thead>
<tr>
<th>Library</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lexical Cast</td>
<td>general literal text conversions, such as converting int to std::string or vice versa</td>
</tr>
<tr>
<td>Tokenizer</td>
<td>break a string or other character sequence into a series of tokens</td>
</tr>
</tbody>
</table>
## Image and Geometry Processing

<table>
<thead>
<tr>
<th>Library</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>geometric algorithms, primitives, and spatial index</td>
</tr>
<tr>
<td>GIL</td>
<td>generic image library</td>
</tr>
<tr>
<td>Graph</td>
<td>graph types and algorithms</td>
</tr>
</tbody>
</table>

## Input/Output

<table>
<thead>
<tr>
<th>Library</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I/O State Savers</td>
<td>classes for saving/restoring state associated with I/O streams</td>
</tr>
</tbody>
</table>

## Miscellaneous

<table>
<thead>
<tr>
<th>Library</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Program Options</td>
<td>process program options via command line or configuration file</td>
</tr>
</tbody>
</table>
## Concurrent Programming

<table>
<thead>
<tr>
<th>Library</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber</td>
<td>userland threads library</td>
</tr>
<tr>
<td>Compute</td>
<td>parallel/GPU computing library</td>
</tr>
<tr>
<td>Lockfree</td>
<td>lock-free containers (e.g., stacks and queues)</td>
</tr>
<tr>
<td>Process</td>
<td>child process management</td>
</tr>
</tbody>
</table>
Section 5.1.2

Boost Container Library
Boost Container library provides support for numerous *nonintrusive* containers

containers provided by library include:

- enhanced versions of several containers from standard library
- several non-standard containers

online documentation:

## Standard Container Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>vector</td>
<td>similar to <code>std::vector</code></td>
</tr>
<tr>
<td>list</td>
<td>similar to <code>std::list</code></td>
</tr>
<tr>
<td>deque</td>
<td>similar to <code>std::deque</code></td>
</tr>
<tr>
<td>set</td>
<td>similar to <code>std::set</code></td>
</tr>
<tr>
<td>multiset</td>
<td>similar to <code>std::multiset</code></td>
</tr>
<tr>
<td>map</td>
<td>similar to <code>std::map</code></td>
</tr>
<tr>
<td>multimap</td>
<td>similar to <code>std::multimap</code></td>
</tr>
</tbody>
</table>
### Non-Standard Container Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>stable_vector</td>
<td>vector with non-contiguous elements and stable element references</td>
</tr>
<tr>
<td>flat_set</td>
<td>set based on sorted vector</td>
</tr>
<tr>
<td>flat_multiset</td>
<td>multiset based on sorted vector</td>
</tr>
<tr>
<td>flat_map</td>
<td>map based on sorted vector</td>
</tr>
<tr>
<td>flat_multimap</td>
<td>multimap based on sorted vector</td>
</tr>
<tr>
<td>slist</td>
<td>singly-linked list</td>
</tr>
<tr>
<td>static_vector</td>
<td>vector of bounded size with storage for elements that is contiguous and statically allocated</td>
</tr>
<tr>
<td>small_vector</td>
<td>vector-like container optimized for case of containing few elements</td>
</tr>
</tbody>
</table>
```cpp
#include <iostream>
#include <cassert>
#include <boost/container/flat_set.hpp>

int main() {
    namespace bc = boost::container;
    bc::flat_set<std::string> c;
    c.reserve(4);
    c.insert("hi");
    c.insert("apple");
    c.insert("bye");
    c.insert("foo");
    for (auto&& i : c) {
        std::cout << i << '
';
    }
    std::cout << '
';
    auto j = c.find("foo");
    assert(j != c.end() && *j == "foo");
    c.erase(j);
    c.shrink_to_fit();
    for (auto&& i : c) {
        std::cout << i << '
';
    }
}
```
Section 5.1.3

Boost Intrusive Library
Boost Intrusive Library

- Boost Intrusive library provides support for numerous *intrusive* and *semi-intrusive* containers
- Containers provided by library include those based on:
  - linked lists
  - trees
  - hash tables
- Uses namespace `boost::intrusive`
- Online documentation:
## Container Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>slist</td>
<td>singly-linked list</td>
</tr>
<tr>
<td>list</td>
<td>doubly-linked list</td>
</tr>
<tr>
<td>set</td>
<td>set/map based on red-black tree</td>
</tr>
<tr>
<td>multiset</td>
<td>multiset/multimap based on red-black tree</td>
</tr>
<tr>
<td>rbtree</td>
<td>red-black tree</td>
</tr>
<tr>
<td>avl_set</td>
<td>set/map based on AVL tree</td>
</tr>
<tr>
<td>avl_multiset</td>
<td>multiset/multimap based on AVL tree</td>
</tr>
<tr>
<td>avltree</td>
<td>AVL tree</td>
</tr>
<tr>
<td>splay_set</td>
<td>set/map based on splay tree</td>
</tr>
<tr>
<td>splay_multiset</td>
<td>multiset/multimap based on splay tree</td>
</tr>
<tr>
<td>splaytree</td>
<td>splay tree</td>
</tr>
<tr>
<td>sg_set</td>
<td>set/map based on scapegoat tree</td>
</tr>
<tr>
<td>sg_multiset</td>
<td>multiset/multimap based on scapegoat tree</td>
</tr>
<tr>
<td>sgtree</td>
<td>scapegoat tree</td>
</tr>
</tbody>
</table>
## Semi-Intrusive Container Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>unordered_set</td>
<td>unordered set/map based on hash table</td>
</tr>
<tr>
<td>unordered_multiset</td>
<td>unordered multiset/multimap based on hash table</td>
</tr>
</tbody>
</table>
- **value type** is type of element stored in container
- for intrusive containers, value type is same as type of node used to store elements in container
- associative containers also have key type
- **key type** is type of key used for finding elements in container
- if associative container is ordered, elements ordered by key type (where this ordering determines iteration order)
- more information about intrusive containers can be found [here](#)
- **Hook** is a class object that must be added to user’s class in order for user’s class to be usable with intrusive container.
- Hook encapsulates data used to manage nodes in container, such as:
  - Pointers to successor/predecessor nodes for linked lists
  - Pointers to parent/child nodes for trees
- Two kinds of hooks:
  1. Base hook
  2. Member hook
- Base hook is included in user’s class as base class object using *public* inheritance.
- Member hook included in user’s class as *public* data member.
- **slist** provides intrusive singly-linked list
- hook type stores pointer to successor node in list
- base hook type:
  ```cpp
template<class... Options> class slist_base_hook;
```
- member hook type:
  ```cpp
template<class... Options> class slist_member_hook;
```
```cpp
#include <iostream>
#include <vector>
#include <boost/intrusive/slist.hpp>

namespace bi = boost::intrusive;

struct Widget : public bi::slist_base_hook<> {
    explicit Widget(int i_) : i(i_) {}  
    int i;
};

using WidgetList = bi::slist<Widget>;

int main() {
    std::vector<Widget> storage;
    for (int i = 0; i < 10; ++i) {storage.emplace_back(i);}  
    WidgetList widgets;
    for (auto&& w : storage) {widgets.push_front(w);}
    for (auto i = widgets.begin(); i != widgets.end(); ++i) {
        if (i != widgets.begin()) {std::cout << ' ';}  
        std::cout << i->i;
    }
    std::cout << '\n';
    while (!widgets.empty())
        {widgets.erase_after(widgets.before_begin());}
}
```
#include <iostream>
#include <vector>
#include <boost/intrusive/slist.hpp>

namespace bi = boost::intrusive;

struct Widget {
    explicit Widget(int i_) : i(i_) {}
    int i;
    bi::slist_member_hook<> hook;
};

using WidgetList = bi::slist<Widget, bi::member_hook<Widget, bi::slist_member_hook<>>, &Widget::hook>>;

int main() {
    std::vector<Widget> storage;
    for (int i = 0; i < 10; ++i) {storage.emplace_back(i);}
    WidgetList widgets;
    for (auto&& w : storage) {widgets.push_front(w);}
    for (auto i = widgets.begin(); i != widgets.end(); ++i) {
        if (i != widgets.begin()) {std::cout << ' ';
        std::cout << i->i;
    }
    std::cout << '
';
    while (!widgets.empty())
        {widgets.erase_after(widgets.before_begin());}
}
Intrusive Doubly-Linked List: list

- list provides intrusive doubly-linked list
- hook type stores pointers to successor and predecessor nodes in list
- base hook type:
  \[ \text{template} \langle \text{class} \ldots \text{Options} \rangle \ \text{class} \ \text{list}_\text{base}_\text{hook}; \]
- member hook type:
  \[ \text{template} \langle \text{class} \ldots \text{Options} \rangle \ \text{class} \ \text{list}_\text{member}_\text{hook}; \]
```cpp
#include <iostream>
#include <vector>
#include <boost/intrusive/list.hpp>

namespace bi = boost::intrusive;

struct Widget : public bi::list_base_hook<> {
    explicit Widget(int i__) : i(i__) {}
    int i;
};

using WidgetList = bi::list<Widget>;

int main() {
    std::vector<Widget> storage;
    for (int i = 0; i < 10; ++i) {storage.emplace_back(i);}
    WidgetList widgets;
    for (auto&& w : storage) {widgets.push_back(w);}
    for (auto i = widgets.begin(); i != widgets.end(); ++i) {
        if (i != widgets.begin()) {std::cout << ' ';
        std::cout << i->i;
    }
    std::cout << '
';
    while (!widgets.empty()) {widgets.erase(widgets.begin());}
}
#include <iostream>
#include <vector>
#include <boost/intrusive/list.hpp>

namespace bi = boost::intrusive;

struct Widget {
    explicit Widget(int i_) : i(i_) {}
    int i;
    bi::list_member_hook<> hook;
};

using WidgetList = bi::list<Widget, bi::member_hook<Widget, bi::list_member_hook<>, &Widget::hook>>;

int main() {
    std::vector<Widget> storage;
    for (int i = 0; i < 10; ++i) {storage.emplace_back(i);}
    WidgetList widgets;
    for (auto&& w : storage) {widgets.push_back(w);}
    for (auto i = widgets.begin(); i != widgets.end(); ++i) {
        if (i != widgets.begin()) {std::cout << ' ';}
        std::cout << i->i;
    }
    std::cout << '
';
    while (!widgets.empty()) {widgets.erase(widgets.begin());}
}
#include <iostream>
#include <vector>
#include <boost/intrusive/list.hpp>

namespace bi = boost::intrusive;

struct Alpha {};
struct Beta {};
struct Widget : public bi::list_base_hook<bi::tag<Alpha>>,
                   public bi::list_base_hook<bi::tag<Beta>> {
    Widget(int i_) : i(i_) {}
    int i;
};

int main() {
    std::vector<Widget> storage;
    for (int i = 0; i < 10; ++i) {storage.emplace_back(i);}
    bi::list<Widget, bi::base_hook<bi::list_base_hook<bi::tag<Alpha>>>> a;
    bi::list<Widget, bi::base_hook<bi::list_base_hook<bi::tag<Beta>>>> b;
    for (auto&& i : storage) {a.push_back(i); b.push_front(i);}
    for (auto&& w : a) {std::cout << w.i << '
';}
    std::cout << '
';
    for (auto&& w : b) {std::cout << w.i << '
';}
    while (!a.empty()) {a.erase(a.begin());}
    while (!b.empty()) {b.erase(b.begin());}
}
often need can arise to obtain iterator from reference to element in container

for nonintrusive containers, obtaining iterator from element reference can often require time that is linear in size of container

for intrusive containers provided by Boost library, this operation can be performed in constant time

for converting reference to element in container to iterator referring to that element, each container class provides nonstatic member function `iterator_to`

most container classes also provide static member function `s_iterator_to` for same purpose
```cpp
#include <iostream>
#include <vector>
#include <boost/intrusive/list.hpp>

namespace bi = boost::intrusive;

struct Widget : public bi::list_base_hook<> {
    Widget(int i_, int j_) : i(i_), j(j_) {}
    int i;
    int j;
};

using WidgetList = bi::list<Widget>;

int main() {
    std::vector<Widget> storage;
    for (int i = 0; i < 10; ++i) {storage.emplace_back(i, -i);}
    WidgetList widgets;
    for (auto&& w : storage) {widgets.push_back(w);}
    auto iter1 = WidgetList::s_iterator_to(storage[3]);
    widgets.erase(iter1);
    auto iter2 = widgets.iterator_to(storage[5]);
    widgets.erase(iter2);
    for (auto&& w : widgets) {std::cout << w.i << ' ' << w.j << '
';}
    while (!widgets.empty()) {widgets.erase(widgets.begin());}
}
```
Intrusive Associative Containers: set and multiset

- set provides intrusive set
- multiset provides intrusive multiset
- information stored in hook type includes pointers to parent and child nodes in tree
- base hook type:
  \[
  \text{template}<\text{class}... \text{Options}> \text{ class set_base_hook;}
  \]
- member hook type:
  \[
  \text{template}<\text{class}... \text{Options}> \text{ class set_member_hook;}
  \]
```cpp
#include <iostream>
#include <vector>
#include <boost/intrusive/set.hpp>

namespace bi = boost::intrusive;

struct Widget : public bi::set_base_hook<> {
  explicit Widget(int i_) : i(i_) {}  
  bool operator<(const Widget& other) const { return i < other.i; }
  int i;
};

int main() {
  int values[] = {1, 3, 5, 7, 9, 0, 2, 4, 6, 8};
  std::vector<Widget> storage;
  for (auto i : values) {storage.emplace_back(i);}
  bi::set<Widget> a;
  for (auto&& w : storage) {a.insert(a.end(), w);}
  for (auto&& w : a) {std::cout << w.i << std::endl;}
  while (!a.empty()) {a.erase(a.begin());}
}
```
#include <iostream>
#include <vector>
#include <boost/intrusive/set.hpp>

namespace bi = boost::intrusive;

struct Widget {
    explicit Widget(int i_) : i(i_) {}
    bi::set_member_hook<> hook;
    int i;
};

struct WidgetCompare {
    bool operator()(const Widget& x, const Widget& y) const
    { return x.i > y.i; }
};

int main() {
    int values[] = {1, 3, 5, 7, 9, 0, 2, 4, 6, 8};
    std::vector<Widget> storage;
    for (auto i : values) {storage.emplace_back(i);}
    bi::set<Widget, bi::compare<WidgetCompare>,
    bi::member_hook<Widget, bi::set_member_hook<>>, &Widget::hook>> a;
    for (auto&& w : storage) {a.insert(a.end(), w);}
    for (auto&& w : a) {std::cout << w.i << '\n';}
    while (!a.empty()) {a.erase(a.begin());}
}
Find Operations for Associative Containers

- for sets and multisets, key type is (by definition) same as value type
- in case of container such as `std::set` and `std::multiset`, find operations can only perform lookup based on key type of container
- in case of Boost Intrusive containers, find operation can perform lookup based on type different from key type
- accomplished by providing alternate key type and functor class used to compare alternate key type to value type
- ordering associated with alternate key type and corresponding comparison class must be consistent with ordering induced by key type used by container
- allowing lookup using type different from key type, eliminates need to create value-type object in order to perform find operation
- effectively, this allows set and multiset to provide functionality similar to map and multimap, respectively
Example: set and Lookup Not Using Value Type

```cpp
#include <cassert>
#include <iostream>
#include <vector>
#include <boost/intrusive/set.hpp>

namespace bi = boost::intrusive;

struct Widget : public bi::set_base_hook<> {
    Widget(int i_, int j_) : i(i_), j(j_) {}
    int i; int j;
};

struct WidgetCompare {
    bool operator()(const Widget& x, const Widget& y) const { return x.i < y.i; }
};

struct WidgetKeyCompare {
    bool operator()(int i, const Widget& w) const { return i < w.i; }
    bool operator()(const Widget& w, int i) const { return w.i < i; }
};

int main() {
    int values[] = {1, 3, 5, 7, 9, 0, 2, 4, 6, 8};
    std::vector<Widget> storage;
    for (auto v : values) {storage.emplace_back(v, -v);}
    bi::set<Widget, bi::compare<WidgetCompare>> a(storage.begin(), storage.end());
    for (auto&& w : a) {std::cout << w.i << '
';}
    for (auto v : values) {
        auto i = a.find(v, WidgetKeyCompare());
        assert(i->i == v && i->j == -v);
    }
    while (!a.empty()) {a.erase(a.begin());}
}
```
since find operations can perform lookups using type different from key type of container, set and multiset can provide similar functionality to maps and multimaps

- can also use `key_of_value` option for set and multiset class templates to specify member of value type as key
- this can be helpful when key corresponds to one of data members in value type
#include <iostream>
#include <vector>
#include <boost/intrusive/set.hpp>

namespace bi = boost::intrusive;

struct Widget {
    Widget(int i_, int j_) : i(i_), j(j_) {}
    bi::set_member_hook<> hook;
    int i; int j;
};

struct WidgetKey {
    using type = int;
    const int& operator()(const Widget& w) { return w.i; }
};

struct WidgetKeyCompare {
    bool operator()(int x, int y) const { return x > y; }
};

using WidgetSet = bi::set<Widget, bi::key_of_value<WidgetKey>,
                        bi::compare<WidgetKeyCompare>,
                        bi::member_hook<Widget, bi::set_member_hook<>, &Widget::hook>>;

int main() {
    int values[] = {1, 3, 5, 7, 9, 0, 2, 4, 6, 8};
    std::vector<Widget> storage;
    for (auto i : values) {storage.emplace_back(i, -i);}
    WidgetSet a;
    for (auto&& w : storage) {a.insert(a.end(), w);}
    for (auto&& w : a) {std::cout << w.i << \n;}
    if (a.find(7) != a.end()) {std::cout << "found key 7\n";}
    while (!a.empty()) {a.erase(a.begin());}
}
#include <iostream>
#include <vector>
#include <boost/intrusive/set.hpp>
#include <boost/intrusive/list.hpp>

namespace bi = boost::intrusive;

struct Widget : public bi::set_base_hook<>,
    public bi::list_base_hook<> {
    explicit Widget(int i_) : i(i_) {}
    bool operator<(const Widget& other) const { return i < other.i; }

    int i;
};

int main() {
    int values[] = {1, 3, 5, 7, 9, 0, 2, 4, 6, 8};
    std::vector<Widget> storage;
    for (auto i : values) {storage.emplace_back(i);}
    bi::set<Widget> a;
    bi::list<Widget> b;
    for (auto&& w : storage)
        {a.insert(a.end(), w); b.push_back(w);}
    if (a.find(Widget(7)) != a.end()) {std::cout << "found\n\n";}
    for (auto&& w : a) {std::cout << w.i << \n;}
    std::cout << \n;
    for (auto&& w : b) {std::cout << w.i << \n;}
    while (!a.empty()) {a.erase(a.begin());}
    while (!b.empty()) {b.erase(b.begin());}
}
unordered_set provides semi-intrusive unordered set
unordered_multiset provides semi-intrusive unordered multiset
referred to as semi-intrusive, as memory needed in addition to hook stored in value type
additional memory passed into constructor of container
base hook type:

```cpp
template<class... Options>
class unordered_set_base_hook;
```

member hook type:

```cpp
template<class... Options>
class unordered_set_member_hook;
```
```cpp
#include <iostream>
#include <vector>
#include <boost/intrusive unordered_set.hpp>

namespace bi = boost::intrusive;

class Widget : public bi::unordered_set_base_hook<> {
public:
    Widget(int value = 0) : value_(value) {}
    int get_value() const { return value_; }
private:
    int value_;  
};

bool operator==(const Widget& a, const Widget& b) { return a.get_value() == b.get_value(); }

std::size_t hash_value(const Widget& a) { return std::size_t(a.get_value()); }

int main() {
    std::vector<Widget> widgets;
    for (int i = 0; i < 10; ++i) { widgets.push_back(Widget(i)); }
    using bucket_type = bi::unordered_set<Widget>::bucket_type;
    using bucket_traits = bi::unordered_set<Widget>::bucket_traits;
    bucket_type buckets[100];
    bi::unordered_set<Widget> s(bucket_traits(buckets, 100));
    for (auto&& w : widgets) { s.insert(w); }
    for (auto&& i : s) { std::cout << i.get_value() << '\n'; }
    if (s.find(7) != s.end()) { std::cout << "found 7\n"; }
    return 0;
}
```
Section 5.1.4

Boost Iterator Library
Boost iterator library consists of two parts:

1. system of concepts which extend C++ standard iterator requirements
2. framework of components for building iterators based on these concepts

tricky to write standard-conforming iterators

by using Boost Iterator library, can often significantly reduce amount of code needed to implement standard-conforming iterators

online documentation:

Forward Iterator Example: Iterator Class Without Boost (1)

```cpp
#include <cstdlib>
#include <iterator>
#include <type_traits>

// singly-linked list node base (for intrusive container)
template <class T>
struct slist_node_base {
    slist_node_base(T* next_ = nullptr) : next(next_) {}
    T* next; // pointer to next node in list
};

// singly-linked list iterator (const and non-const)
template <class T>
class slist_iter {
public:
    using iterator_category = std::forward_iterator_tag;
    using value_type = typename std::remove_const_t<T>;
    using difference_type = std::ptrdiff_t;
    using reference = T&;
    using pointer = T*;
    slist_iter(T* node = nullptr) : node_(node) {}

    template <class OtherT> requires std::is_convertible_v<OtherT*, T*> 
    slist_iter(const slist_iter<OtherT>& other) : node_(other.node_) {}

    reference operator*() { return *node_; }
    pointer operator->() { return node_; }
};
```
slist_iter& operator++() {
    node_ = node_->next;
    return *this;
}

slist_iter operator++(int) {
    slist_iter old(*this);
    node_ = node_->next;
    return old;
}

template <class OtherT>
bool operator==(const slist_iter<OtherT>& other) const {
    return node_ == other.node_;
}

private:
    template <class> friend class slist_iter;
    T* node_; // pointer to list node
```
#include <type_traits>
#include <boost/iterator/iterator_facade.hpp>

template <class T> struct slist_node_base {
    slist_node_base(T* next_) : next(next_) {}  
    T* next; // pointer to next node in list
};

template <class T> class slist_iter : public boost::iterator_facade<slist_iter<T>, T, boost::forward_traversal_tag> {
public:
    using base = typename boost::iterator_facade<slist_iter<T>, T, boost::forward_traversal_tag>;
    using typename base::reference;
    using typename base::value_type;
    slist_iter(T* node = nullptr) : node_(node) {}  
    template <class OtherT> requires std::is_convertible_v<OtherT*, T*>  
    slist_iter(const slist_iter<OtherT>& other) : node_(other.node_) {}  

private:
    reference dereference() const {return *node_;}  
    template <class OtherT> bool equal(const slist_iter<OtherT>& other) const  
        {return node_ == other.node_;}
    void increment() {node_ = node_ -> next;}
    template <class> friend class slist_iter;
    friend class boost::iterator_core_access;
    T* node_;  // pointer to list node
};
```
```cpp
#include <iostream>
#include <vector>
#include "iterator_facade_2.hpp"

struct Node : public slist_node_base<Node> {
    Node(Node* next_, int value_) : slist_node_base<Node>(next_),
        value(value_) {}
    int value;
};

int main() {
    constexpr int num_nodes = 10;
    std::vector<Node> nodes; nodes.reserve(num_nodes);
    for (int i = 0; i < num_nodes - 1; ++i)
        {nodes.push_back(Node(&nodes[i + 1], i));}
    nodes.push_back(Node(nullptr, num_nodes - 1));
    slist_iter<Node> begin(&nodes[0]);
    slist_iter<Node> end;
    slist_iter<const Node> cbegin(begin);
    slist_iter<const Node> cend(end);
    for (auto i = cbegin; i != cend; ++i) {std::cout << i->value << '\n';}
    slist_iter<Node> i(begin);
    slist_iter<const Node> ci(cbegin);
    // slist_iter<Node> j(cbegin); // ERROR
    i = begin;
    // i = ci; // ERROR
    ci = cbegin;
    ci = i;
}
```
Random-Access Iterator Example: Iterator Class Without Boost (1)

1  #include <compare>
2  #include <iterator>
3  #include <type_traits>

4  // array element iterator
5  template <class T> class array_iter {
6    public:
7      using iterator_category = typename std::random_access_iterator_tag;
8      using value_type = std::remove_const_t<T>;
9      using reference = T&;
10     using pointer = T*;
11     using difference_type = std::ptrdiff_t;
12     array_iter(T* ptr = nullptr) : ptr_(ptr) {}  
13     template <class OtherT> requires std::is_convertible_v<OtherT*, T*>  
14          array_iter(const array_iter<OtherT>& other) : ptr_(other.ptr_) {}  
15     reference operator*() const { return *ptr_;}  
16     pointer operator->() const { return ptr_;}  
17     array_iter& operator++() {  
18         ++ptr_;  
19         return *this;  
20     }  
21     array_iter operator++(int) {  
22         array_iter old(*this);  
23         ++ptr_;  
24         return old;  
25     }  
26     array_iter& operator--() {  
27         --ptr_;  
28         return *this;  
29     }  
30  }

Random-Access Iterator Example: Iterator Class Without Boost (2)

```cpp
array_iter operator-(int) {
    array_iter old(*this);
    --ptr_;
    return old;
}
array_iter& operator+=(difference_type n) {
    ptr_ += n;
    return *this;
}
array_iter& operator-=(difference_type n) {
    ptr_ -= n;
    return *this;
}
reference operator[](difference_type n) const { return ptr_[n]; }
array_iter operator+(difference_type n) const
    { return array_iter(ptr_ + n); }
difference_type operator-(const array_iter& other) const
    { return ptr_ - other.ptr_; }
array_iter operator-(difference_type n) const
    { return array_iter(ptr_ - n); }

    template <class OtherT> bool operator==(const array_iter<OtherT>& other) const
        { return ptr_ == other.ptr_; }
    template <class OtherT>
        std::strong_ordering operator<(const array_iter<OtherT>& other) const
            { return ptr_ < other.ptr_; }

private:
    template <class> friend class array_iter;
    T* ptr_; // pointer to array element
};
```
template <class T>
array_iter<T> operator+(typename array_iter<T>::difference_type n,
const array_iter<T>& iter) { return array_iter<T>(iter) += n;}
Random-Access Iterator Example: Iterator Class With Boost

```cpp
#include <boost/iterator/iterator_facade.hpp>
#include <type_traits>

// array element iterator
template <class T> class array_iter : public boost::iterator_facade<
    array_iter<T>, T, boost::random_access_traversal_tag> {
public:
    using typename boost::iterator_facade<array_iter<T>, T,
        boost::random_access_traversal_tag>::reference;
    using typename boost::iterator_facade<array_iter<T>, T,
        boost::random_access_traversal_tag>::difference_type;
    array_iter(T* ptr = nullptr) : ptr_(ptr) {
    }
    template <class OtherT> requires std::is_convertible_v<OtherT*, T*> 
    array_iter(const array_iter<OtherT>& other) : ptr_(other.ptr_) {
    }
private:
    reference dereference() const { return *ptr_; }
    template <class OtherT> bool equal(const array_iter<OtherT>& other) const 
        { return ptr_ == other.ptr_; }
    void increment() { ++ptr_; }
    void decrement() { --ptr_; }
    void advance(difference_type n) { ptr_ += n; }
    difference_type distance_to(const array_iter& other) const 
        { return other.ptr_ - ptr_; }
    template <class> friend class array_iter;
    friend class boost::iterator_core_access;
    T* ptr_; // pointer to array element
};
```

Random-Access Iterator Example: User Code

```cpp
#include <iostream>
#include <cassert>
#include "iterator_facade_1.hpp"

int main() {
    char buffer[] = "Hello, World!\n";
    std::size_t length = sizeof(buffer) - 1;
    array_iter<char> begin(buffer);
    array_iter<char> end(buffer + length);
    array_iter<const char> cbegin = begin;
    array_iter<const char> cend = end;
    assert(begin + length == end);
    assert(cbegin + length == end);
    for (auto i = cbegin; i != cend; ++i)
        {std::cout << *i << '\n';}
    array_iter<char> i(begin);
    array_iter<const char> ci(cbegin);
    // array_iter<char> j(cbegin); // ERROR
    i = begin;
    // i = ci; // ERROR
    ci = cbegin;
    ci = i;
}
```

Section 5.1.5

Boost Process Library
Boost Process is library for basic management of child processes

- library can be used to:
  - create child processes with control over I/O redirection and environment settings
  - communicate with child processes via I/O streams
  - wait for processes to exit
  - terminate processes

- online documentation:
# include <boost/process.hpp>
#include <iostream>
#include <string>
#include <vector>

namespace bp = boost::process;

int main(int argc, char** argv) {
    if (argc < 2)
        {std::cerr << "no program specified\n"; return 1;}
    std::vector<std::string> args;
    for (int i = 2; i < argc; ++i) {args.push_back(argv[i]);}
    bp::ipstream in;
    bp::child child(bp::search_path(argv[1]), bp::args(args),
        bp::std_out > in);
    std::string line;
    while (std::getline(in, line)) {
        if (!(std::cout << line << '\n'))
            {std::cerr << "output error\n"; return 1;}
    }
    if (!in.eof())
        {std::cerr << "input error\n"; return 1;}
    child.wait();
    if (child.exit_code())
        {std::cerr << "child failed\n"; return 1;}
}
```cpp
#include <boost/process.hpp>
#include <iostream>
#include <string>
#include <vector>

namespace bp = boost::process;

int main(int argc, char** argv) {
    if (argc < 2) {
        std::cerr << "no program specified\n"; return 1;}
    std::vector<std::string> args;
    for (int i = 2; i < argc; ++i) {args.push_back(argv[i]);}
    bp::opstream out;
    bp::child child(bp::search_path(argv[1]), bp::args(args),
                    bp::std_in < out);
    std::string line;
    for (int i = 0; i < 10; ++i) {
        if (!(out << i << '\n'))
            {std::cerr << "output error\n"; return 1;}
    }
    if (!out.flush())
        {std::cerr << "output error\n"; return 1;}
    out.close();
    out.pipe().close();
    child.wait();
    if (child.exit_code())
        {std::cerr << "child failed\n"; return 1;}
}
```
# Example: Initializing Environment for Child Process

```cpp
#include <boost/process.hpp>
#include <iostream>

namespace bp = boost::process;

int main() {
    auto env = boost::this_process::environment();
    bp::environment child_env = env;
    child_env["ANSWER"] = "42";
    child_env["MY_PATH"] = {"/bin", "/usr/bin"};
    bp::child child(bp::search_path("printenv"), child_env);
    child.wait();
    if (child.exit_code()) {
        std::cerr << "child failed\n"; return 1;}
}
```
Section 5.1.6

Miscellaneous Examples
```cpp
#include <cmath>
#include <boost/multiprecision/gmp.hpp>
#include <iostream>

using boost::multiprecision::mpz_int;

mpz_int factorial(const mpz_int& n) {
    mpz_int result = 1;
    for (mpz_int i = n; i >= 2; --i) {
        result *= i;
    }
    return result;
}

int main() {
    std::cout << factorial(200) << '\n';
}
/* Output:
788657867364790503552363213932185062295135977687173263294
742533244359449963403342920304284011984623904177212138919
638830257642790242637105061926624952829931113462857270763
317237396988943922445621451664240254033291864131227428294
853277524242407573903240321257405579568660226031904170324
06235170085879617892222789623703897374720000000000000000
00000000000000000000000000000000
*/
```cpp
#include <boost/multi_array.hpp>
#include <iostream>
#include <iomanip>

int main() {
    using Array2 = boost::multi_array<int, 2>;
    int num_rows = 5;
    int num_cols = 7;
    Array2 a(boost::extents[num_rows][num_cols]);
    for (int row = 0; row < num_rows; ++row) {
        for (int col = 0; col < num_cols; ++col) {
            a[row][col] = num_cols * row + col;
        }
    }

    Array2 b(a);
    assert(b.shape()[0] == num_rows && b.shape()[1] == num_cols);
    Array2 c;
    c.resize(boost::extents[b.shape()[0]][b.shape()[1]]);
    c = b;
    for (int row = 0; row < num_rows; ++row) {
        for (int col = 0; col < num_cols; ++col) {
            if (col) {std::cout << ' ';
            }
            std::cout << std::setw(2) << c[row][col];
        }
        std::cout << '\n';
    }
}
```
2-D Array Class With multi_array

```cpp
#include <boost/multi_array.hpp>
#include <iostream>
#include <iomanip>

template <class T>
class array2 {
  public:
    using value_type = T;
    array2(int num_rows = 0, int num_cols = 0) :
        a_(boost::extents[num_rows][num_cols]) {} 
    array2(const array2& other) : a_(other.a_) {} 
    array2& operator=(const array2& other) {
      if (this != &other) {
        a_.resize(boost::extents[other.a_.shape()[0]][
          other.a_.shape()[1]]);
        a_ = other.a_;  
      }
      return *this;
    }
    int num_rows() const {return a_.shape()[0];}
    int num_cols() const {return a_.shape()[1];}
    const value_type& operator()(int row, int col) const
    {return a_[row][col];}
    value_type& operator()(int row, int col) {return a_[row][col];}
  private:
    using array = boost::multi_array<T, 2>;
    array a_;  
};
```
template <class T>
std::ostream& operator<<(std::ostream& out, const array2<T>& a) {
    auto width = out.width();
    for (int row = 0; row < a.num_rows(); ++row) {
        for (int col = 0; col < a.num_cols(); ++col) {
            if (col) {out << ' ';
            out << std::setw(width) << a(row, col);
            }
        out << '
';
    } return out;
}

int main() {
    array2<int> a(5, 7);
    for (int row = 0; row < a.num_rows(); ++row) {
        for (int col = 0; col < a.num_cols(); ++col) {
            a(row, col) = a.num_cols() * row + col;
        }
    } array2<int> b(a);
    std::cout << "a:\n" << std::setw(2) << a;
    std::cout << "b:\n" << std::setw(2) << b;
}
# Multi_array Array Layout Example

```cpp
#include <algorithm>
#include <iostream>
#include <boost/multi_array.hpp>

template <class T> std::ostream& operator<<(std::ostream& out, const boost::multi_array_ref<T, 2>& x) {
    const int m = x.shape()[0];
    const int n = x.shape()[1];
    for (int i = 0; i < m; ++i) {
        for (int j = 0; j < n; ++j) {
            out << ((j != 0) ? " " : "") << x[i][j];
        }
        out << '\n';
    }
    return out;
}

int main() {
    constexpr int n = 3;
    float data[n * n] = {
        1, 2, 3,
        4, 5, 6,
        7, 8, 9
    };
    int row_major[] = {1, 0};
    bool ascending[] = {false, true};
    // use column-major order
    boost::multi_array_ref<float, 2> x(data, boost::extents[n][n],
                                      boost::general_storage_order<2>(boost::fortran_storage_order()));
    // use row-major order but with rows in reverse order
    boost::multi_array_ref<float, 2> y(data, boost::extents[n][n],
                                       boost::general_storage_order<2>(row_major, ascending));
    // use row-major order
    boost::multi_array<float, 2> z(boost::extents[n][n]);
    std::copy_n(data, n * n, z.data());
    std::cout << x << '\n' << y << '\n' << z << '\n';
}
```

Copyright © 2015–2021 Michael D. Adams
Programming in C++  Version 2021-04-01  1664
#include <iostream>
#include <string>
#include <boost/program_options.hpp>

int main(int argc, char** argv) {
    namespace po = boost::program_options;
    po::options_description desc("Allowed options");
    desc.add_options()
        ("help,h", "Print help information.")
        ("count,c", po::value<int>()->default_value(1), "Specify count.")
        ("file,f", po::value<std::string>(), "Specify file name.");
    po::variables_map vm;
    try {
        po::store(po::parse_command_line(argc, argv, desc), vm);
        po::notify(vm);
    } catch (po::error& e) {
        std::cerr << "usage:
" << desc << '
';
        return 1;
    }
    if (vm.count("help")) {std::cout << desc << "\n"; return 1;}
    if (vm.count("file")) {
        std::cout << "file: " << vm["file"].as<std::string>() << "\n";
    }
    if (vm.count("count")) {
        std::cout << "count: " << vm["count"].as<int>() << "\n";
    }
    return 0;
}
```cpp
#include <iostream>
#include <cassert>
#include <boost/rational.hpp>
#include <exception>

int main() {
    using boost::rational;
    const rational<int> zero;
    rational<int> three(3);
    rational<int> ninth(1, 9);
    rational<int> third(1, 3);
    auto result = three * ninth;
    assert(result == third);
    try {
        std::cout << three / zero << '
';
    } catch (const boost::bad_rational& e) {
        std::cout << "bad rational " << e.what() << '
';
    }
    // rational<int> x(1.5); // ERROR: no matching call
    // result = 3.0; // ERROR: no matching call
    result = 42;
    assert(result == rational<int>(42));
    std::cout << result << '
';
}
```
Section 5.1.7

References


Section 5.2

Computational Geometry Algorithms Library (CGAL)
very powerful open-source C++ library for geometric computation
used by many commercial organizations, such as: British Telecom, Boeing, France Telecom, GE Health Care, The MathWorks
very well documented (extensive manual, more than 4000 pages)
provides data types for representing various geometric objects, such as:
  - points, lines, planes, polygons
  - Voronoi diagrams
  - 2D, 3D and dD triangulations
  - polygon meshes
  - kinetic data structures
provides algorithms for manipulating these data types
available for Microsoft Windows and Unix/Linux platforms
some Linux distributions already have packages for CGAL (e.g., Fedora packages: CGAL, CGAL-devel, CGAL-demos-source)
web site: http://www.cgal.org
online manual (latest version): http://www.cgal.org/Manual/latest
provides support for polygon meshes

- can read/write polygon mesh data in various common formats
- built-in support for several subdivision schemes
- by using CGAL, can greatly simplify amount of effort required to implement methods using subdivision surfaces or wavelet transforms for polygon meshes

- in CGAL manual, most relevant material is that pertaining to:
  - 2D and 3D linear geometry kernels
  - 3D polyhedral surfaces
  - 3D surface subdivision methods
- **handle**: object used to reference element stored in some data structure (i.e., object can be dereferenced to obtain access to element)

- for data structure storing elements of type $T$, handle type might be:
  - simple pointer (i.e., $T^*$)
  - smart pointer (i.e., user-defined type that behaves like pointer)

- examples of handle types:
  - types used to access vertices, facets, halfedges of polygon mesh
Linear Sequences Versus Circular Sequences

- **linear sequence:**
  - has well defined first and last element
  - fits well with iterator model

- **circular sequence:**
  - does not have well defined first and last element
  - does not fit well with iterator model
- ** iterators are very useful, but intended for use with linear sequences of elements (i.e., sequences with well-defined first and last element) 
- often want iterator-like functionality for circular sequences of elements 
- ** circulator**: object that allows iteration over elements in circular sequence of elements  
- examples of circulator types:  
  - type to allow iteration over all halfedges incident on vertex in polygon mesh  
  - type to allow iteration over all halfedges incident on facet in polygon mesh  
- circulators come in const and mutable (i.e., non-const) forms  
- mutable circulator can be used to modify referenced element, while const circulator cannot
Section 5.2.1

Geometry Kernels
Real Number Types

- **float**: single-precision floating point type
- **double**: double-precision floating point type
- **Interval_nt**: interval-arithmetic type
- **MP_Float**: arbitrary-precision floating-point type
MP_Float Class

- MP_Float is arbitrary-precision floating-point type
- additions, subtractions, and multiplications computed exactly
- does not provide division or square root (which is not typically problematic as division rarely needed and square root almost always avoided in geometric computation)
- no roundoff error
- no overflow error unless astronomically large numbers involved (arbitrary length mantissa; integral-valued double exponent can overflow, but extremely unlikely)
- very slow, can require considerable memory (unbounded)
- default constructor does not initialize to particular value
- stream inserter (i.e., `operator<<`) for MP_Float first converts MP_Float to double and then outputs result
- stream extractor (i.e., `operator>>`) for MP_Float first reads double and then converts to MP_Float
```cpp
#include <iostream>
#include <CGAL/MP_Float.h>

int main() {
    CGAL::MP_Float x;
    CGAL::MP_Float y;
    if (!(std::cin >> x >> y)) {return 1;}
    if (x < y) {
        std::cout << x << " is less than " << y << 'n';
    }
    CGAL::MP_Float z = -(x + y) * (x - y) + x;
    std::cout << z << 'n';
}
```
**Interval_nt Class**

- declared as: `template <bool M = true> Interval_nt<M>`
- M indicates if safe rounding mode enabled
- if safe rounding mode enabled, rounding mode always restored to round towards zero (required by C++); must be careful if safe rounding mode not used
- when safe rounding mode not used, faster but need to worry about things like compiler options like `-frounding-math`
- using `Interval_nt_advanced = Interval_nt<false>;` (i.e., `Interval_nt_advanced` is `Interval_nt` with safe rounding mode disabled)
- interval-arithmetic number type (internally uses floating-point type)
- represents interval \([a, b]\)
- every arithmetic operation performed twice, once while rounding towards \(−\infty\) to produce result \(a'\) and once while rounding towards \(+\infty\) to produce result \(b'\)
- true answer must lie on interval \([a', b']\)
- approximately twice of time cost of built-in floating-point type
Geometry Kernels

- represent geometric objects (e.g., point, line, line segment, ray, plane, triangle, circle,)
- points in 2 or 3 dimensions
- provide operations on geometric objects (e.g., intersection, composition)
- allow certain conditions to be tested involving geometric objects (e.g., collinear, coplanar, equality)
Point Representation

- Cartesian kernels: coordinates represented in Cartesian form
- homogeneous kernels: coordinates represented in homogeneous form
Simple_cartesian and Cartesian Classes

- geometry kernel that represents coordinates in Cartesian form
- declaration:
  ```template <class F> Simple_cartesian<F>
  ```
- declaration:
  ```template <class F> Cartesian<F>
  ```
- F field number type (used to represent coordinates)
- F often chosen as `double`
- Cartesian is reference counted version of Simple_cartesian, which allows more efficient copying of objects
- Cartesian probably preferred if frequent copying occurs
Simple_homogeneous and Homogeneous Classes

- geometry kernel that represents coordinates in homogeneous form
- declaration:
  ```cpp
template <class R> Simple_homogeneous<R>
  ```
- declaration:
  ```cpp
template <class R> Homogeneous<R>
  ```
- \( R \) ring number type used for representing numerator and denominator of rational coordinates
- Homogeneous is reference counted version of Simple_homogeneous, which allows more efficient copying of objects
- Homogeneous probably preferred if frequent copying occurs
Constructions

- produces new geometric object from other objects
- result is not one of a small number of enumerable values
- result is numerical (e.g., involves real numbers)
- create line segment from two points
- create triangle from three points
- create plane from three (non-coplanar) points
- create circle from three (non-collinear) points
- find intersection of line and plane
- exact construction: any newly created geometric objects resulting from construction are exactly represented (i.e., no roundoff/overflow error)
- inexact construction: newly created geometric objects are not guaranteed to be exactly represented (e.g., due to roundoff error)
- extremely important to be aware of whether kernel being used provides exact constructions; affects how you write code!!!
Predicates

- does not involve any newly computed numerical data
- result is one of very small set of values, such as boolean or enumerated type
- typically used to make decisions (i.e., affect control flow)
- are three points collinear (true or false)
- are four points coplanar (true or false)
- what is position of point relative to oriented line (left of, right of, or on)
- what is position of point relative to oriented circle (inside, outside, or on)
- exact predicate: result of test is guaranteed to be correct (i.e., result determined as if by exact computation)
- inexact predicate: result of test may be incorrect (e.g., due to roundoff/overflow error)
- extremely important to be aware of whether kernel being used provides exact predicates; affects how you write code!!!
<table>
<thead>
<tr>
<th>Member Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT</td>
<td>field number type (e.g., <code>double</code>)</td>
</tr>
<tr>
<td>RT</td>
<td>ring number type (e.g., <code>int</code>)</td>
</tr>
<tr>
<td>Boolean</td>
<td>boolean type (<code>bool</code> or <code>Uncertain&lt;bool&gt;</code>)</td>
</tr>
<tr>
<td>Sign</td>
<td>sign (<code>Sign</code> or <code>Uncertain&lt;Sign&gt;</code>)</td>
</tr>
<tr>
<td>Comparison_result</td>
<td>comparison result (<code>Comparison_result</code> or <code>Uncertain&lt;Comparison_result&gt;</code>)</td>
</tr>
<tr>
<td>Orientation</td>
<td>orientation (<code>Orientation</code> or <code>Uncertain&lt;Orientation&gt;</code>)</td>
</tr>
<tr>
<td>Oriented_side</td>
<td>oriented side (<code>Oriented_side</code> or <code>Uncertain&lt;Oriented_side&gt;</code>)</td>
</tr>
<tr>
<td>Bounded_side</td>
<td>bounded side (<code>Bounded_side</code> or <code>Uncertain&lt;Bounded_side&gt;</code>)</td>
</tr>
<tr>
<td>Angle</td>
<td>angle (<code>Angle</code> or <code>Uncertain&lt;Angle&gt;</code>)</td>
</tr>
<tr>
<td>Member Type</td>
<td>Description</td>
</tr>
<tr>
<td>------------------</td>
<td>-------------------------------------------------------</td>
</tr>
<tr>
<td>Point_2</td>
<td>point in two dimensions</td>
</tr>
<tr>
<td>Vector_2</td>
<td>vector in two dimensions</td>
</tr>
<tr>
<td>Direction_2</td>
<td>direction in two dimensions</td>
</tr>
<tr>
<td>Line_2</td>
<td>line in two dimensions</td>
</tr>
<tr>
<td>Ray_2</td>
<td>ray in two dimensions</td>
</tr>
<tr>
<td>Segment_2</td>
<td>line segment in two dimensions</td>
</tr>
<tr>
<td>Triangle_2</td>
<td>triangle in two dimensions</td>
</tr>
<tr>
<td>Iso_rectangle_2</td>
<td>axis-aligned rectangle in two dimensions</td>
</tr>
<tr>
<td>Circle_2</td>
<td>circle in two dimensions</td>
</tr>
</tbody>
</table>
### Kernel Member Types: Geometric Objects in Three Dimensions

<table>
<thead>
<tr>
<th>Member Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point_3</td>
<td>point in three dimensions</td>
</tr>
<tr>
<td>Vector_3</td>
<td>vector in three dimensions</td>
</tr>
<tr>
<td>Direction_3</td>
<td>direction in three dimensions</td>
</tr>
<tr>
<td>Iso_cuboid_3</td>
<td>axis-aligned cuboid in three dimensions</td>
</tr>
<tr>
<td>Line_3</td>
<td>line in three dimensions</td>
</tr>
<tr>
<td>Ray_3</td>
<td>ray in three dimensions</td>
</tr>
<tr>
<td>Circle_3</td>
<td>circle in three dimensions</td>
</tr>
<tr>
<td>Sphere_3</td>
<td>sphere in three dimensions</td>
</tr>
<tr>
<td>Segment_3</td>
<td>line segment in three dimensions</td>
</tr>
<tr>
<td>Plane_3</td>
<td>plane in three dimensions</td>
</tr>
<tr>
<td>Triangle_3</td>
<td>triangle in three dimensions</td>
</tr>
<tr>
<td>Tetrahedron_3</td>
<td>tetrahedron in three dimensions</td>
</tr>
</tbody>
</table>
Kernel Selection

- coordinate representation
- exact or inexact constructions
- exact or inexact predicates
- in practice, almost always require exact predicates
- if code well designed, need for exact constructions can usually be avoided
- for $T$ chosen as any numeric type that has roundoff/overflow error (e.g., `float`, `double`, `long double`), the following kernels do not provide exact constructions or exact predicates:
  
  ```cpp
  Simple_cartesian<T>
  Cartesian<T>
  Simple_homogeneous<T>
  Homogeneous<T>
  ```
Filtered_kernel Class

- class to convert kernel with inexact predicates into one with exact predicates
- declared as:
  
  \[
  \text{template } \langle \text{class } K \rangle \text{ Filtered_kernel}<K>
  \]

- \(K\) is kernel from which to make filtered kernel
- predicates of \(K\) replaced by predicates using numeric type \(\text{Interval_nt}\)
- if interval arithmetic can yield reliable answer, result used
- otherwise, exception thrown and caught by class and predicate using \(\text{MP_Float}\) used

- for exact predicates with \(\text{Simple_cartesian}<\text{double}\rangle\), use:
  
  \[
  \text{Filtered_kernel<Simple_cartesian<double>}}\text{ or equivalently Exact_predicates_inexact_constructions_kernel}
  \]

- \(\text{Exact_predicates_inexact_constructions_kernel}\) very commonly used
Writing Custom Exact Predicates

- exact predicate cannot at any point rely on a computation that is not exact
- no floating point arithmetic (since it has roundoff error)
- no integer arithmetic that might overflow
- no inexact constructions
- no inexact predicates
- `Filtered_predicate` may be helpful
Filtered_predicate Class

- adapter for predicate functors for producing efficient exact predicates
- declared as:

  ```cpp
  template <class EP, class FP, class CE, class CF>
  Filtered_predicate<EP, FP, CE, CF>
  ```

- **EP** is exact predicate (typically uses arbitrary-precision type such as *MP_Float*).
- **FP** is filtering predicate (typically uses interval-arithmetic type like *Interval_nt*).
- **CE** and **CF** are function objects for converting arguments of unfiltered predicate to types used by exact and filtering predicates.
- must be careful about operation used in unfiltered predicate being plugged into *Filtered_kernel*
- for kernel ring number type *RT*, can safely use addition, subtraction, multiplication
- can also safely use *sign*
execution of code for filtered predicate functor proceeds as follows:

1. invoke unfiltered (i.e., original) predicate functor for numeric type `CGAL::Interval_nt<false>`
   if any operation on interval arithmetic type yields uncertain result (e.g., `CGAL::sign`), exception is thrown, with thrown exception being caught by filtered predicate functor

2. if no exception thrown (so that unfiltered functor returns normally), return return value of unfiltered functor (and we are done); otherwise, continue

3. invoke unfiltered predicate functor for numeric type `CGAL::MP_Float`

4. return return value of unfiltered functor
```cpp
#include <CGAL/Cartesian.h>
#include <CGAL/MP_Float.h>
#include <CGAL/Interval_nt.h>
#include <CGAL/Filtered_predicate.h>
#include <CGAL/Cartesian_converter.h>

template <class K>
struct Test_orientation_2 {
    using RT = typename K::RT;
    using Point_2 = typename K::Point_2;
    using result_type = typename K::Orientation;

    result_type operator()(const Point_2& p, const Point_2& q,
                           const Point_2& r) const {
        RT prx = p.x() - r.x();
        RT pry = p.y() - r.y();
        RT qrx = q.x() - r.x();
        RT qry = q.y() - r.y();
        return CGAL::sign(prx * qry - qrx * pry);
    }
};

using Kernel = CGAL::Cartesian<double>;
using Ia_kernel = CGAL::Cartesian<CGAL::Interval_nt<false>>;
using Exact_kernel = CGAL::Cartesian<CGAL::MP_Float>;
using Test_orientation = CGAL::Filtered_predicate<
    Test_orientation_2<Exact_kernel>,
    Test_orientation_2<Ia_kernel>,
    CGAL::Cartesian_converter<Kernel, Exact_kernel>,
    CGAL::Cartesian_converter<Kernel, Ia_kernel> >;

int main() {
    double big = 1e50;
    Kernel::Point_2 p(0.0, 0.0), q(1.0, 1.0), r(2.0 * big, 2.0 * big);
    Test_orientation orientation;
    std::cout << orientation(p, q, r) << "\n";
}
```
for example on previous slide, execution of filtered predicate functor proceeds as follows:

1. invoke
   
   ```cpp
   Test_orientation_2<Cartesian<CGAL::Interval_nt<false>>>
   ```

   functor with points \([0, 0], [0, 0]\), \([1, 1], [1, 1]\), 
   
   \([2 \cdot 10^{50}, 2 \cdot 10^{50}], [2 \cdot 10^{50}, 2 \cdot 10^{50}]\)

2. `CGAL::sign` called for \([-1.55414 \cdot 10^{85}, 1.55414 \cdot 10^{85}]\), which results in exception being thrown

3. exception caught by filtered predicate code

4. invoke `Test_orientation_2<Cartesian<CGAL::MP_Float>>` functor

   with points \((0, 0), (1, 1), (2 \cdot 10^{50}, 2 \cdot 10^{50})\)

5. `CGAL::sign` called for 0, resulting in return value of 0

6. filtered predicate returns 0

- critically important that \(RT\) used for all arithmetic operations and not `double` (or `float`); otherwise, arithmetic computation done using wrong numeric type, which will prevent predicate from being correct (i.e., exact)
Section 5.2.2

Polygon Meshes
represents polyhedral surface (i.e., polygon mesh), which consists of vertices, edges, and facets and incidence relationship amongst them

each edge represented by pair of halfedges

declaration for Polyhedron_3 class:

```cpp
template <class Kernel,
    class PolyhedronItems = CGAL::Polyhedron_items_3,
    template <class T, class I>
    class HalfedgeDS = CGAL::HalfedgeDS_default,
    class Alloc = CGAL_ALLOCATOR(int)>
    class Polyhedron_3;
```

Kernel is geometry kernel, which specifies such things as how points are represented and provides basic geometric operations/predicates (e.g., CGAL::Cartesian<double> and CGAL::Filtered_kernel<CGAL::Cartesian<double>>)

PolyhedronItems specifies data types for representing vertices and facets (in many cases, default will suffice)

HalfedgeDS specifies halfedge data structure for representing polygon mesh and Alloc specifies allocator (defaults should suffice)
## Polyhedron_3 Type Members

### Basic Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex</td>
<td>vertex type</td>
</tr>
<tr>
<td>Halfedge</td>
<td>halfedge type</td>
</tr>
<tr>
<td>Facet</td>
<td>facet type</td>
</tr>
<tr>
<td>Point_3</td>
<td>point type (for vertices)</td>
</tr>
</tbody>
</table>

### Handles

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex_const_handle</td>
<td>const handle to vertex</td>
</tr>
<tr>
<td>Vertex_handle</td>
<td>handle to vertex</td>
</tr>
<tr>
<td>Halfedge_const_handle</td>
<td>const handle to halfedge</td>
</tr>
<tr>
<td>Halfedge_handle</td>
<td>handle to halfedge</td>
</tr>
<tr>
<td>Facet_const_handle</td>
<td>const handle to facet</td>
</tr>
<tr>
<td>Facet_handle</td>
<td>handle to facet</td>
</tr>
</tbody>
</table>
### Polyhedron_3 Type Members (Continued 1)

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex_const_iterator</td>
<td>const iterator over all vertices</td>
</tr>
<tr>
<td>Vertex_iterator</td>
<td>iterator over all vertices</td>
</tr>
<tr>
<td>Halfedge_const_iterator</td>
<td>const iterator over all halfedges</td>
</tr>
<tr>
<td>Halfedge_iterator</td>
<td>iterator over all halfedges</td>
</tr>
<tr>
<td>Facet_const_iterator</td>
<td>const iterator over all facets</td>
</tr>
<tr>
<td>Facet_iterator</td>
<td>iterator over all facets</td>
</tr>
<tr>
<td>Edge_const_iterator</td>
<td>const iterator over all edges (every other halfedge)</td>
</tr>
<tr>
<td>Edge_iterator</td>
<td>iterator over all edges (every other halfedge)</td>
</tr>
</tbody>
</table>
## Circulators

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>Halfedge_around_vertex_const_circulator</code></td>
<td>const circulator of halfedges around vertex (CW)</td>
</tr>
<tr>
<td><code>Halfedge_around_vertex_circulator</code></td>
<td>circulator of halfedges around vertex (CW)</td>
</tr>
<tr>
<td><code>Halfedge_around_facet_const_circulator</code></td>
<td>const circulator of halfedges around facet (CCW)</td>
</tr>
<tr>
<td><code>Halfedge_around_facet_circulator</code></td>
<td>circulator of halfedges around facet (CCW)</td>
</tr>
</tbody>
</table>
## Polyhedron_3 Function Members

### Size

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>size_of_vertices</td>
<td>get number of vertices</td>
</tr>
<tr>
<td>size_of_halfedges</td>
<td>get number of halfedges</td>
</tr>
<tr>
<td>size_of_facets</td>
<td>get number of facets</td>
</tr>
</tbody>
</table>

### Iterators

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>vertices_begin</td>
<td>iterator for first vertex in mesh</td>
</tr>
<tr>
<td>vertices_end</td>
<td>past-the-end vertex iterator</td>
</tr>
<tr>
<td>halfedges_begin</td>
<td>iterator for first halfedge in mesh</td>
</tr>
<tr>
<td>halfedges_end</td>
<td>past-the-end halfedge iterator</td>
</tr>
<tr>
<td>facets_begin</td>
<td>iterator for first facet in mesh</td>
</tr>
<tr>
<td>facets_end</td>
<td>past-the-end facet iterator</td>
</tr>
<tr>
<td>edges_begin</td>
<td>iterator for first edge in mesh</td>
</tr>
<tr>
<td>edges_end</td>
<td>past-the-end edge iterator</td>
</tr>
</tbody>
</table>
### Combinatorial Predicates

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>is_closed</td>
<td>true if no border edges (no boundary)</td>
</tr>
<tr>
<td>is_pure_triangle</td>
<td>true if all facets are triangles</td>
</tr>
<tr>
<td>is_pure_quad</td>
<td>true if all facets are quadrilaterals</td>
</tr>
</tbody>
</table>
## Border Halfedges

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>normalized_border_is_valid</td>
<td>true if border is normalized</td>
</tr>
<tr>
<td>normalize_border</td>
<td>sort halfedges such that non-border edges precede border edges (i.e., normalize border)</td>
</tr>
<tr>
<td>size_of_border_halfedges</td>
<td>get number of border halfedges (border must be normalized)</td>
</tr>
<tr>
<td>size_of_border_edges</td>
<td>get number of border edges (border must be normalized)</td>
</tr>
<tr>
<td>border_halfedges_begin</td>
<td>halfedge iterator starting with border edges (border must be normalized)</td>
</tr>
<tr>
<td>border_edges_begin</td>
<td>edge iterator starting with border edges (border must be normalized)</td>
</tr>
</tbody>
</table>
Polyhedron_3::Facet

- Facet type represents facet (i.e., face) in polyhedral surface
- actual class type to which Facet corresponds depends on choice of PolyhedronItems template parameter for Polyhedron_3 class
- depending on actual class type to which Facet refers, level of functionality offered by Facet class may differ (e.g., available function members may differ)
- Facet class may contain following optional information:
  - plane equation (corresponding to plane containing facet)
  - handle for halfedge that is incident on facet
- some member functions in Facet class provide access to halfedge-around-facet circulator
- halfedge-around-facet circulator may be either forward or bidirectional
## Facet Function Members

### Operations Available If Facet Plane Supported

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>plane</td>
<td>get plane equation</td>
</tr>
</tbody>
</table>

### Operations Available If Facet Halfedge Supported

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>halfedge</td>
<td>get halfedge incident on facet</td>
</tr>
<tr>
<td>facet_begin</td>
<td>get circulator of halfedges around facet (CCW)</td>
</tr>
<tr>
<td>set_halfedge</td>
<td>set incident halfedge</td>
</tr>
<tr>
<td>facet_degree</td>
<td>get degree of facet (i.e., number of edges on boundary of facet)</td>
</tr>
<tr>
<td>is_triangle</td>
<td>true if facet is triangle</td>
</tr>
<tr>
<td>is_quad</td>
<td>true if facet is quadrilateral</td>
</tr>
</tbody>
</table>
**Polyhedron_3::Vertex**

- **Vertex** type represents vertex in polyhedral surface
- **actual class type to which** `Vertex` **corresponds** depends on choice of `PolyhedronItems` **template parameter** for `Polyhedron_3` **class**
- **depending on actual class type to which** `Vertex` **refers**, level of functionality offered by `Vertex` **class** may differ (e.g., available function members may differ)
- **Vertex** **class** may contain following optional information:
  - point (corresponding to vertex position)
  - handle for halfedge that is incident on vertex
- **some member functions in** `Vertex` **class** provide access to halfedge-around-vertex circulator
- halfedge-around-vertex circulator may be either forward or bidirectional
### Operations Available If Vertex Point Supported

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>point</td>
<td>get point associated with vertex</td>
</tr>
</tbody>
</table>

### Operations Available If Vertex Halfedge Supported

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>halfedge</td>
<td>get halfedge incident on vertex</td>
</tr>
<tr>
<td>vertex_begin</td>
<td>circulator of halfedges around vertex (CW)</td>
</tr>
<tr>
<td>set_halfedge</td>
<td>set incident halfedge</td>
</tr>
<tr>
<td>vertex_degree</td>
<td>get valence of vertex</td>
</tr>
<tr>
<td>is_bivalent</td>
<td>true if vertex has valence two</td>
</tr>
<tr>
<td>is_trivalent</td>
<td>true if vertex has valence three</td>
</tr>
</tbody>
</table>
- **Halfedge** type represents halfedge in polyhedral surface
- actual class type to which **Halfedge** corresponds depends on choice of `PolyhedronItems` template parameter for `Polyhedron_3` class
- depending on actual class type to which **Halfedge** refers, level of functionality offered by **Halfedge** class may differ (e.g., available function members may differ)
- each halfedge directly associated with one vertex and one facet, referred to as incident vertex and incident facet, respectively
- **incident vertex** is vertex at *terminal end* of halfedge
- **incident facet** is facet to *left* of halfedge
Polyhedron_3::Halfedge (Continued)

- halfedge contains:
  - handle for next halfedge around incident facet in CCW direction
  - handle for opposite halfedge

- together, these two handles allow for efficient iteration around:
  - halfedges incident on facet in CCW direction only; and
  - halfedges incident on vertex in CW direction only

- halfedge may optionally contain:
  - handle for previous halfedge around incident facet in CCW direction

- addition of this optional handle allows for efficient iteration around:
  - halfedges incident on facet in both (CW and CCW) directions; and
  - halfedges incident on vertex in both (CW and CCW) directions

- halfedge may also contain following optional information:
  - handle for incident vertex
  - handle for incident facet

- if halfedge class provides prev member function, halfedge-around-vertex and halfedge-around-facet circulators are bidirectional; otherwise, they are forward only
### Adjacency Queries

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>opposite</td>
<td>get opposite halfedge</td>
</tr>
<tr>
<td>next</td>
<td>get next halfedge incident on same facet in CCW order</td>
</tr>
<tr>
<td>prev</td>
<td>get previous halfedge incident on same facet in CCW order</td>
</tr>
<tr>
<td>next_on_vertex</td>
<td>get next halfedge incident on same vertex in CW order</td>
</tr>
<tr>
<td>prev_on_vertex</td>
<td>get previous halfedge incident on same vertex in CW order</td>
</tr>
</tbody>
</table>

### Circulators

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>vertex_begin</td>
<td>get halfedge-around-vertex circulator for incident vertex (CW order)</td>
</tr>
<tr>
<td>facet_begin</td>
<td>get halfedge-around-facet circulator for incident facet (CCW order)</td>
</tr>
</tbody>
</table>
### Border Queries

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>is_border</code></td>
<td>true if border halfedge</td>
</tr>
<tr>
<td><code>is_border_edge</code></td>
<td>true if associated edge on border</td>
</tr>
</tbody>
</table>

### Vertex Valence Queries

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>vertex_degree</code></td>
<td>get valence of incident vertex</td>
</tr>
<tr>
<td><code>is_bivalent</code></td>
<td>true if incident vertex has valence two</td>
</tr>
<tr>
<td><code>is_trivalent</code></td>
<td>true if incident vertex has valence three</td>
</tr>
</tbody>
</table>

### Facet Degree Queries

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>facet_degree</code></td>
<td>get degree of incident facet</td>
</tr>
<tr>
<td><code>is_triangle</code></td>
<td>true if incident facet is triangle</td>
</tr>
<tr>
<td><code>is_quad</code></td>
<td>true if incident facet is quadrilateral</td>
</tr>
</tbody>
</table>
### Operations Available If Halfedge Vertex Supported

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>vertex</td>
<td>get handle for incident vertex of halfedge</td>
</tr>
</tbody>
</table>

### Operations Available If Halfedge Facet Supported

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>facet</td>
<td>get handle for incident facet of halfedge</td>
</tr>
</tbody>
</table>
Adjacency Example

\[ h \rightarrow \text{opposite}() \rightarrow \text{vertex}() \]

\[ h \rightarrow \text{facet}() \]

\[ h \rightarrow \text{next}_\text{on}_\text{vertex}() \]

\[ h \rightarrow \text{prev}() \rightarrow h \rightarrow \text{next}() \]

\[ h \rightarrow \text{opposite}() \]

\[ h \rightarrow \text{prev}_\text{on}_\text{vertex}() \]

\[ h \rightarrow \text{opposite}() \rightarrow \text{facet}() \]
- `operator<<` and `operator>>` are overloaded for I/O
- read and write polygon mesh data in OFF format
Polyhedron_3 Gotchas

- be mindful of operations on Polyhedron_3 that may invalidate handles, iterators, or circulators
- halfedge-around-vertex circulators and halfedge-around-facet circulators iterate in opposite directions (i.e., CCW versus CW)
- be careful about const correctness (e.g., const versus mutable handles/iterators/circulators)
- some Polyhedron_3 operations only valid if border normalized (e.g., size_of_border_halfedges, size_of_border_edges)
- exactly one of two halfedges associated with border edge is border halfedge
Section 5.2.3

Surface Subdivision Methods
Subdivision Methods

- several functions provided for performing subdivision of polygon meshes (represented by Polyhedron_3)
- generic subdivision functions apply specific topologic refinement rule but allow arbitrary geometric refinement rule
- specific subdivision functions apply specific subdivision method
- contained in CGAL::Subdivision_method_3 namespace
### Generic Subdivision Methods

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PQQ</td>
<td>perform primal quadrilateral quadrisection with arbitrary geometric refinement rule</td>
</tr>
<tr>
<td>PTQ</td>
<td>perform primal triangle quadrisection with arbitrary geometric refinement rule</td>
</tr>
<tr>
<td>DQQ</td>
<td>perform dual quadrilateral quadrisection with arbitrary geometric refinement rule</td>
</tr>
<tr>
<td>Sqrt3</td>
<td>perform ( \sqrt{3} ) topologic refinement with arbitrary geometric refinement rule</td>
</tr>
</tbody>
</table>

### Specific Subdivision Methods

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CatmullClark_subdivision</td>
<td>perform Catmull-Clark subdivision</td>
</tr>
<tr>
<td>Loop_subdivision</td>
<td>perform Loop subdivision</td>
</tr>
<tr>
<td>DooSabin_subdivision</td>
<td>perform Doo-Sabin subdivision</td>
</tr>
<tr>
<td>Sqrt3_subdivision</td>
<td>perform Kobbelt ( \sqrt{3} ) subdivision</td>
</tr>
</tbody>
</table>
Section 5.2.4

Example Programs
This program generates a simple triangle mesh corresponding to a tetrahedron.

First, a polygon mesh corresponding to a tetrahedron is constructed.

Then, the resulting mesh is written to standard output in Object File Format (OFF).
This program extracts some basic information from a polygon mesh.

First, a polygon mesh is read from standard input in Object File Format (OFF).

Then, various information is extracted from the mesh, including:
- the type of mesh (e.g., triangle, quadrilateral, or general)
- the number of vertices, edges, faces, and halfedges in the mesh
- the minimum, maximum, and average valence of vertices in the mesh
- the number of nonplanar faces in the mesh

The above information is printed to standard output.
This program performs subdivision on a polygon mesh.

First, a mesh is read from standard input in Object File Format (OFF).

Next, the mesh is refined using the given number of iterations of the specified subdivision method.

Finally, the refined mesh is written to standard output in OFF.

Several subdivision schemes are supported, including: Loop, Catmull-Clark, Doo-Sabin, and Kobbelt $\sqrt{3}$. 
Section 5.3

OpenGL Utility Toolkit (GLUT)
OpenGL Utility Toolkit (GLUT)

- simple windowing API for OpenGL
- intended to be used with small to medium sized OpenGL programs
- language binding for C
- window-system independent
- supports most mainstream operating systems (Microsoft Windows, Linux/Unix)
- provides window management functionality (e.g., creating/destroying windows, displaying/resizing windows, and querying/setting window attributes)
- allows for user input (e.g., via keyboard, mouse)
- routines for drawing common wireframe/solid 3-D objects such as sphere, torus, and well-known teapot model
- register callback functions to handle various types of events (e.g., display, resize, keyboard, special keyboard, mouse, timer, idle) and then loop processing events
- open-source implementation of GLUT called Freeglut is available from http://sourceforge.net/projects/freeglut
event-driven model: flow of program determined by events (e.g., mouse clicks, key presses)

application making use of event-driven model performs some initialization and then enters an event-processing loop for duration of execution

each iteration of event-processing loop does following:
1. wait for event
2. process event

many libraries for building graphical user interfaces (GUIs) employ event-driven model

GLUT uses event-driven model
Structure of GLUT Application

1. initialize GLUT library by calling `glutInit`
2. set display mode (via `glutInitDisplayMode`)
3. perform any additional initialization such as:
   - create windows (via `glutCreateWindow`)
   - register callback functions for handling various types of events (e.g., via `glutDisplayFunc`, `glutReshapeFunc`, `glutKeyboardFunc`)
   - setup initial OpenGL state (e.g., depth buffering, shading, lighting, clear color)
4. enter main event-processing loop by calling `glutMainLoop` [Note that `glutMainLoop` never returns.]
- OpenGL and GLUT header files in GL (or GLUT) directory
- to use GLUT, need to include `glut.h` in GL (or GLUT) directory
- header file `glut.h` also includes all necessary OpenGL header files (e.g., `gl.h`, `glu.h`, `gles.h`)
## Event Types

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>display</strong></td>
<td>window contents needs to be displayed</td>
</tr>
<tr>
<td>overlay display</td>
<td>overlay plane contents needs to be displayed</td>
</tr>
<tr>
<td><strong>reshape</strong></td>
<td>window has been resized</td>
</tr>
<tr>
<td><strong>keyboard</strong></td>
<td>key has been pressed</td>
</tr>
<tr>
<td><strong>mouse</strong></td>
<td>mouse button has been pressed or released</td>
</tr>
<tr>
<td>motion</td>
<td>mouse moved within window while one or more buttons pressed</td>
</tr>
<tr>
<td>passive motion</td>
<td>mouse moved within window while no buttons pressed</td>
</tr>
<tr>
<td>visibility</td>
<td>visibility of window has changed (covered versus uncovered)</td>
</tr>
<tr>
<td>entry</td>
<td>mouse has left or entered window</td>
</tr>
<tr>
<td><strong>special keyboard</strong></td>
<td>special key has been pressed (e.g., arrow keys, function keys)</td>
</tr>
<tr>
<td>Event Type</td>
<td>Description</td>
</tr>
<tr>
<td>------------------</td>
<td>-------------------------------------------------------</td>
</tr>
<tr>
<td>spaceball motion</td>
<td>spaceball translation has occurred</td>
</tr>
<tr>
<td>spaceball rotate</td>
<td>spaceball rotation has occurred</td>
</tr>
<tr>
<td>spaceball button</td>
<td>spaceball button has been pressed or released</td>
</tr>
<tr>
<td>button box</td>
<td>button box activity has occurred</td>
</tr>
<tr>
<td>dials</td>
<td>dial activity has occurred</td>
</tr>
<tr>
<td>tablet motion</td>
<td>tablet motion has occurred</td>
</tr>
<tr>
<td>tablet button</td>
<td>tablet button has been pressed or released</td>
</tr>
<tr>
<td>menu status</td>
<td>menu status change</td>
</tr>
<tr>
<td>idle</td>
<td>no event activity has occurred</td>
</tr>
<tr>
<td>timer</td>
<td>timer has expired</td>
</tr>
</tbody>
</table>
### Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glutInit</td>
<td>initialize GLUT library</td>
</tr>
<tr>
<td>glutInitWindowSize</td>
<td>set initial window size for glutCreateWindow</td>
</tr>
<tr>
<td>glutInitWindowPosition</td>
<td>set initial window position for glutCreateWindow</td>
</tr>
<tr>
<td>glutInitDisplayMode</td>
<td>set initial display mode</td>
</tr>
</tbody>
</table>

### Beginning Event Processing

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glutMainLoop</td>
<td>enter GLUT event-processing loop</td>
</tr>
<tr>
<td>Function</td>
<td>Description</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>glutCreateWindow</td>
<td>create top-level window</td>
</tr>
<tr>
<td>glutCreateSubWindow</td>
<td>create subwindow</td>
</tr>
<tr>
<td>glutSetWindow</td>
<td>set current window</td>
</tr>
<tr>
<td>glutGetWindow</td>
<td>get current window</td>
</tr>
<tr>
<td>glutDestroyWindow</td>
<td>destroys specified window</td>
</tr>
<tr>
<td>glutPostRedisplay</td>
<td>mark current window as needing to be redisplayed</td>
</tr>
<tr>
<td>glutSwapBuffers</td>
<td>swaps buffers of current window if double buffered (flushes graphics output via <code>glFlush</code>)</td>
</tr>
<tr>
<td>glutPositionWindow</td>
<td>request change to position of current window</td>
</tr>
<tr>
<td>glutReshapeWindow</td>
<td>request change to size of current window</td>
</tr>
<tr>
<td>glutFullScreen</td>
<td>request current window to be made full screen</td>
</tr>
<tr>
<td>glutSetTitle</td>
<td>set title of current top-level window</td>
</tr>
<tr>
<td>glutSetIconTitle</td>
<td>set title of icon for current top-level window</td>
</tr>
<tr>
<td>glutSetCursor</td>
<td>set cursor image for current window</td>
</tr>
<tr>
<td>Function</td>
<td>Description</td>
</tr>
<tr>
<td>------------------------------</td>
<td>-------------------------------------------------------</td>
</tr>
<tr>
<td>glutCreateMenu</td>
<td>create new pop-up menu</td>
</tr>
<tr>
<td>glutSetMenu</td>
<td>set current menu</td>
</tr>
<tr>
<td>glutGetMenu</td>
<td>get current menu</td>
</tr>
<tr>
<td>glutDestroyMenu</td>
<td>destroy specified menu</td>
</tr>
<tr>
<td>glutAddMenuEntry</td>
<td>add menu entry to bottom of current menu</td>
</tr>
<tr>
<td>glutAddSubMenu</td>
<td>add submenu trigger to bottom of current menu</td>
</tr>
<tr>
<td>glutChangeToMenuEntry</td>
<td>change specified menu item in current menu into menu entry</td>
</tr>
<tr>
<td>glutChangeToSubMenu</td>
<td>change specified menu item in current menu into submenu trigger</td>
</tr>
<tr>
<td>glutRemoveMenuItem</td>
<td>remove specified menu item</td>
</tr>
<tr>
<td>glutAttachMenu</td>
<td>attach mouse button for current window to current menu</td>
</tr>
<tr>
<td>glutDetachMenu</td>
<td>detach attached mouse button from current window</td>
</tr>
</tbody>
</table>
## Callback Registration

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glutDisplayFunc</td>
<td>sets display callback for current window</td>
</tr>
<tr>
<td>glutReshapeFunc</td>
<td>sets reshape callback for current window</td>
</tr>
<tr>
<td>glutKeyboardFunc</td>
<td>sets keyboard callback for current window</td>
</tr>
<tr>
<td>glutMouseFunc</td>
<td>sets mouse callback for current window</td>
</tr>
<tr>
<td>glutMotionFunc</td>
<td>set motion callback for current window</td>
</tr>
<tr>
<td>glutPassiveMotionFunc</td>
<td>set passive motion callback for current window</td>
</tr>
<tr>
<td>glutVisibilityFunc</td>
<td>set visibility callback for current window</td>
</tr>
<tr>
<td>glutEntryFunc</td>
<td>set mouse enter/leave callback for current window</td>
</tr>
<tr>
<td>glutSpecialFunc</td>
<td>sets special keyboard callback for current window</td>
</tr>
<tr>
<td>glutIdleFunc</td>
<td>set global idle callback</td>
</tr>
<tr>
<td>glutTimerFunc</td>
<td>registers timer callback to be triggered in specified number of milliseconds</td>
</tr>
</tbody>
</table>
### State Retrieval

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glutGet</td>
<td>retrieves simple GLUT state (e.g., size or position of current window)</td>
</tr>
<tr>
<td>glutDeviceGet</td>
<td>retrieves GLUT device information (e.g., keyboard, mouse, spaceball, tablet)</td>
</tr>
<tr>
<td>glutGetModifiers</td>
<td>retrieve modifier key state when certain callbacks generated (i.e., state of shift, control, and alt keys)</td>
</tr>
</tbody>
</table>

### Font Rendering

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glutBitmapCharacter</td>
<td>renders bitmap character using OpenGL</td>
</tr>
<tr>
<td>glutBitmapWidth</td>
<td>get width of bitmap character</td>
</tr>
<tr>
<td>glutStrokeCharacter</td>
<td>renders stroke character using OpenGL</td>
</tr>
<tr>
<td>glutStrokeWidth</td>
<td>get width of stroke character</td>
</tr>
<tr>
<td>Function</td>
<td>Description</td>
</tr>
<tr>
<td>------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>glutSolidSphere</td>
<td>render solid sphere</td>
</tr>
<tr>
<td>glutWireSphere</td>
<td>render wireframe sphere</td>
</tr>
<tr>
<td>glutSolidCube</td>
<td>render solid cube</td>
</tr>
<tr>
<td>glutWireCube</td>
<td>render wireframe cube</td>
</tr>
<tr>
<td>glutSolidCone</td>
<td>render solid cone</td>
</tr>
<tr>
<td>glutWireCone</td>
<td>render wireframe cone</td>
</tr>
<tr>
<td>glutSolidTorus</td>
<td>render solid torus</td>
</tr>
<tr>
<td>glutWireTorus</td>
<td>render wireframe torus</td>
</tr>
<tr>
<td>glutSolidOctahedron</td>
<td>render solid octahedron</td>
</tr>
<tr>
<td>glutWireOctahedron</td>
<td>render wireframe octahedron</td>
</tr>
<tr>
<td>glutSolidTetrahedron</td>
<td>render solid tetrahedron</td>
</tr>
<tr>
<td>glutWireTetrahedron</td>
<td>render wireframe tetrahedron</td>
</tr>
<tr>
<td>glutSolidTeapot</td>
<td>render solid teapot</td>
</tr>
<tr>
<td>glutWireTeapot</td>
<td>render wireframe teapot</td>
</tr>
</tbody>
</table>
Minimalist GLUT Program

- minimalist program using GLUT
- create window that is cleared to particular color
// Create a window that is cleared to a particular color
// when drawn.

#include <GL/glut.h>

void display() {
    glClearColor(0.0, 1.0, 1.0, 0.0);
    glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
    glutSwapBuffers();
}

int main(int argc, char** argv) {
    glutInit(&argc, argv);
    glutInitDisplayMode(GLUT_DOUBLE | GLUT_RGB);
    glutInitWindowSize(512, 512);
    glutCreateWindow(argv[0]);
    glutDisplayFunc(display);
    glutMainLoop();
    return 0;
}
GLUT References


3. GLUT home page: http://www.opengl.org/resources/libraries/glut

Section 5.4

OpenGL Framework (GLFW) Library
lightweight open-source windowing API for OpenGL, OpenGL ES, and Vulkan

language binding for C

window-system independent

supports most mainstream operating systems (e.g., Microsoft Windows, OS X, and Linux/Unix)

provides window management functionality (e.g., creating/destroying windows, displaying/resizing windows, and querying/setting window attributes)

allows for user input (e.g., via keyboard, mouse, and joystick)

allows application to register callback functions to handle various types of events (e.g., window refresh, window resize, keyboard, and mouse) and then loop processing events

web site: http://www.glfw.org
GLFW Versus GLUT

- GLFW and modern GLUT (e.g., FreeGLUT) offer somewhat similar functionality
- GLFW allows greater control over event processing loop
- GLFW has clipboard support
- GLFW supports dragging and dropping of files/directories in window
- GLUT has much longer history than GLFW (which can make code examples and tutorials using GLUT relatively easier to find)
- GLUT has built-in support for rendering text and some basic geometric objects
- GLUT has primitive support for menus
event-driven model: flow of program determined by events (e.g., mouse clicks and key presses)

application making use of event-driven model performs some initialization and then enters event-processing loop for duration of execution

each iteration of event-processing loop does following:
1. wait for event
2. process event

many libraries for building graphical user interfaces (GUIs) employ event-driven model

GLFW uses event-driven model
Structure of GLFW Application

1. initialize GLFW library by calling `glfwInit`
2. perform any additional initialization such as:
   - select type of OpenGL (or OpenGL ES) context to be used for subsequently created windows (via `glfwWindowHint`)
   - create windows (via `glfwCreateWindow`)
   - register callback functions for handling various types of events (e.g., via `glfwRefreshCallback`, `glfwSetWindowSizeCallback`, `glfwSetCharCallback`)
   - configure initial OpenGL state (e.g., depth buffering and clear color) and shaders
3. enter main event-processing loop, which repeatedly calls `glfwWaitEvents`, `glfwPollEvents`, or other similar functions
4. cleanup GLFW library by calling `glfwTerminate`
GLFW header files in directory `GLFW`

to use GLFW, need to include `glfw3.h`:

```cpp
#include <GLFW/glfw3.h>
```

header file `glfw3.h` also includes all necessary OpenGL header files (e.g., `gl.h`, `glu.h`, `glext.h`)

if using OpenGL extension loading library (such as GLEW), header for this library should be included before `glfw3.h`
## Event Types

### Keyboard, Mouse, and Joystick Events

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>key</strong></td>
<td>key has been pressed, released, or repeated</td>
</tr>
<tr>
<td><strong>character</strong></td>
<td>character has been typed without modifiers</td>
</tr>
<tr>
<td><strong>character with modifiers</strong></td>
<td>character has been typed with modifiers</td>
</tr>
<tr>
<td><strong>mouse button</strong></td>
<td>mouse button has been pressed or released</td>
</tr>
<tr>
<td>cursor position</td>
<td>cursor has moved</td>
</tr>
<tr>
<td>cursor enter</td>
<td>cursor has entered or left client area of window</td>
</tr>
<tr>
<td>scroll</td>
<td>scrolling device has been used (e.g., mouse wheel or touchpad scrolling area)</td>
</tr>
<tr>
<td>joystick</td>
<td>joystick has been connected or disconnected</td>
</tr>
<tr>
<td>drop</td>
<td>files/directories have been dropped on window</td>
</tr>
</tbody>
</table>
Framebuffer, Window, and Monitor Events

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>framebuffer size</td>
<td>framebuffer has been resized</td>
</tr>
<tr>
<td>window close</td>
<td>window has been closed</td>
</tr>
<tr>
<td>window refresh</td>
<td>window contents need to be redrawn</td>
</tr>
<tr>
<td>window size</td>
<td>window size has changed</td>
</tr>
<tr>
<td>window position</td>
<td>window position has changed</td>
</tr>
<tr>
<td>window iconify</td>
<td>window has been iconified or deiconified</td>
</tr>
<tr>
<td>window focus</td>
<td>window focus has changed (i.e., been gained or lost)</td>
</tr>
<tr>
<td>monitor</td>
<td>monitor has been connected or disconnected</td>
</tr>
</tbody>
</table>

Other Events

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>error</td>
<td>error has occurred in GLFW library</td>
</tr>
</tbody>
</table>
### Functions

#### Initialization and Termination

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glfwInit</td>
<td>initialize GLFW library</td>
</tr>
<tr>
<td>glfwTerminate</td>
<td>cleanup GLFW library</td>
</tr>
</tbody>
</table>

#### Version

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glfwGetVersion</td>
<td>get version of GLFW library</td>
</tr>
<tr>
<td>glfwGetVersionString</td>
<td>get version string of GLFW library</td>
</tr>
</tbody>
</table>

#### Window Creation and Destruction

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glfwCreateWindow</td>
<td>create window and its associated OpenGL or OpenGL ES context</td>
</tr>
<tr>
<td>glfwDestroyWindow</td>
<td>destroy window and its associated context</td>
</tr>
<tr>
<td>glfwDefaultWindowHints</td>
<td>reset all window hints to their default values</td>
</tr>
<tr>
<td>glfwWindowHint</td>
<td>set window hints for subsequently created windows</td>
</tr>
</tbody>
</table>
### Setting and Querying Window Attributes

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>glfwWindowShouldClose</code></td>
<td>get close flag for specified window</td>
</tr>
<tr>
<td><code>glfwSetWindowShouldClose</code></td>
<td>set close flag for specified window</td>
</tr>
<tr>
<td><code>glfwSetWindowTitle</code></td>
<td>set title of specified window</td>
</tr>
<tr>
<td><code>glfwSetWindowIcon</code></td>
<td>set icon for specified window</td>
</tr>
<tr>
<td><code>glfwGetWindowPos</code></td>
<td>get position of client area of specified window</td>
</tr>
<tr>
<td><code>glfwSetWindowPos</code></td>
<td>set position of client area of specified window</td>
</tr>
<tr>
<td><code>glfwGetWindowSize</code></td>
<td>get size of client area of specified window</td>
</tr>
<tr>
<td><code>glfwSetWindowSize</code></td>
<td>set size of client area of specified window</td>
</tr>
<tr>
<td><code>glfwSetWindowSizeLimits</code></td>
<td>set size limits of client area of specified window</td>
</tr>
<tr>
<td><code>glfwSetWindowAspectRatio</code></td>
<td>set required aspect ratio of client area of specified window</td>
</tr>
<tr>
<td>Function</td>
<td>Description</td>
</tr>
<tr>
<td>---------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>glfwGetFramebufferSize</td>
<td>get size of framebuffer of specified window</td>
</tr>
<tr>
<td>glfwGetWindowFrameSize</td>
<td>get size of frame of window</td>
</tr>
<tr>
<td>glfwGetWindowMonitor</td>
<td>get monitor that specified window uses for full-screen mode</td>
</tr>
<tr>
<td>glfwSetWindowMonitor</td>
<td>set monitor that specified window uses for full-screen mode</td>
</tr>
<tr>
<td>glfwGetWindowAttrib</td>
<td>get attribute of specified window</td>
</tr>
<tr>
<td>glfwGetWindowUserPointer</td>
<td>get user pointer of specified window</td>
</tr>
<tr>
<td>glfwSetWindowUserPointer</td>
<td>set user pointer of specified window</td>
</tr>
</tbody>
</table>
## Window Management

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glfwIconifyWindow</td>
<td>iconifies specified window</td>
</tr>
<tr>
<td>glfwRestoreWindow</td>
<td>restores (i.e., deiconifies) specified window</td>
</tr>
<tr>
<td>glfwMaximizeWindow</td>
<td>maximizes specified window</td>
</tr>
<tr>
<td>glfwShowWindow</td>
<td>make specified window visible</td>
</tr>
<tr>
<td>glfwHideWindow</td>
<td>hide specified window</td>
</tr>
<tr>
<td>glfwFocusWindow</td>
<td>bring specified window to front and give it input focus</td>
</tr>
<tr>
<td>glfwSwapBuffers</td>
<td>swap front and back buffers of specified window when rendering</td>
</tr>
<tr>
<td></td>
<td>with OpenGL or OpenGL ES</td>
</tr>
<tr>
<td>glfwSwapInterval</td>
<td>set swap interval for current OpenGL or OpenGL ES context</td>
</tr>
</tbody>
</table>
### Callback Registration

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glfwSetErrorCallback</td>
<td>sets error callback function</td>
</tr>
<tr>
<td>glfwSetWindowPosCallback</td>
<td>sets window-position callback function for specified window</td>
</tr>
<tr>
<td>glfwSetWindowSizeCallback</td>
<td>sets window-size callback function for specified window</td>
</tr>
<tr>
<td>glfwSetWindowCloseCallback</td>
<td>sets window-close callback function for specified window</td>
</tr>
<tr>
<td>glfwSetWindowRefreshCallback</td>
<td>sets window-refresh callback function for specified window</td>
</tr>
<tr>
<td>glfwSetWindowFocusCallback</td>
<td>sets window-focus callback function for specified window</td>
</tr>
</tbody>
</table>
### Callback Registration (Continued 1)

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>glfwSetWindowIconifyCallback</code></td>
<td>sets window-iconify callback function for specified window</td>
</tr>
<tr>
<td><code>glfwSetFramebufferSizeCallback</code></td>
<td>sets callback function for framebuffer size event</td>
</tr>
<tr>
<td><code>glfwSetKeyCallback</code></td>
<td>sets (physical) key callback function for specified window</td>
</tr>
<tr>
<td><code>glfwSetCharCallback</code></td>
<td>sets character callback function for specified window</td>
</tr>
<tr>
<td><code>glfwSetCharModsCallback</code></td>
<td>sets character-with-modifiers callback function for specified window</td>
</tr>
<tr>
<td><code>glfwSetMouseButtonCallback</code></td>
<td>sets mouse-button callback function for specified window</td>
</tr>
<tr>
<td><code>glfwGetMonitorCallback</code></td>
<td>set monitor configuration callback function</td>
</tr>
</tbody>
</table>
## Callback Registration (Continued 2)

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glfwSetCursorPosCallback</td>
<td>sets cursor-position callback function for specified window</td>
</tr>
<tr>
<td>glfwSetCursorEnterCallback</td>
<td>sets cursor-boundary-crossing callback function for specified window</td>
</tr>
<tr>
<td>glfwSetScrollCallback</td>
<td>sets scroll callback function for specified window</td>
</tr>
<tr>
<td>glfwSetDropCallback</td>
<td>sets file-drop callback function for specified window</td>
</tr>
<tr>
<td>glfwSetJoystickCallback</td>
<td>sets joystick-configuration callback function</td>
</tr>
</tbody>
</table>
### Event Handling

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glfwPostEmptyEvent</td>
<td>post empty event to event queue</td>
</tr>
<tr>
<td>glfwPollEvents</td>
<td>process any pending events and return immediately</td>
</tr>
<tr>
<td>glfwWaitEvents</td>
<td>wait until at least one event is pending, then process all pending events and return</td>
</tr>
<tr>
<td>glfwWaitEventsTimeout</td>
<td>wait until at least one event pending or timeout expires, then process any pending events and return</td>
</tr>
</tbody>
</table>

### Timing

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glfwGetTime</td>
<td>get value of timer in seconds</td>
</tr>
<tr>
<td>glfwSetTime</td>
<td>set value of timer</td>
</tr>
<tr>
<td>glfwGetTimerValue</td>
<td>get value of timer in clock ticks</td>
</tr>
<tr>
<td>glfwGetTimerFrequency</td>
<td>get frequency of clock tick</td>
</tr>
</tbody>
</table>
### Keyboard, Mouse, Joystick, and Cursor

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glfwGetInputMode</td>
<td>get value of input option for specified window (e.g., cursor, sticky keys/buttons)</td>
</tr>
<tr>
<td>glfwSetInputMode</td>
<td>set input option for specified window</td>
</tr>
<tr>
<td>glfwGetKeyName</td>
<td>get localized name of specified printable key</td>
</tr>
<tr>
<td>glfwGetKey</td>
<td>get last reported state of keyboard key for specified window</td>
</tr>
<tr>
<td>glfwGetMouseButton</td>
<td>get last reported state of mouse button for specified window</td>
</tr>
<tr>
<td>glfwGetCursorPos</td>
<td>get position of cursor relative to client area of specified window</td>
</tr>
<tr>
<td>glfwSetCursorPos</td>
<td>set position of cursor relative to client area of specified window</td>
</tr>
</tbody>
</table>
### Keyboard, Mouse, Joystick, and Cursor (Continued)

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glfwCreateCursor</td>
<td>create custom cursor</td>
</tr>
<tr>
<td>glfwCreateStandardCursor</td>
<td>creates cursor with standard shape</td>
</tr>
<tr>
<td>glfwDestroyCursor</td>
<td>destroys cursor</td>
</tr>
<tr>
<td>glfwSetCursor</td>
<td>set cursor for use in specified window</td>
</tr>
<tr>
<td>glfwJoystickPresent</td>
<td>test if joystick is present</td>
</tr>
<tr>
<td>glfwGetJoystickAxes</td>
<td>get values of all axes of specified joystick</td>
</tr>
<tr>
<td>glfwGetJoystickButtons</td>
<td>get state of all buttons of specified joystick</td>
</tr>
<tr>
<td>glfwGetJoystickName</td>
<td>get name of specified joystick</td>
</tr>
</tbody>
</table>

### Clipboard

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glfwGetClipboardString</td>
<td>gets contents of clipboard as string</td>
</tr>
<tr>
<td>glfwSetClipboardString</td>
<td>sets clipboard to specified string</td>
</tr>
</tbody>
</table>
## Monitor Management

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glfwGetMonitors</td>
<td>get currently connected monitors</td>
</tr>
<tr>
<td>glfwGetPrimaryMonitor</td>
<td>get primary monitor</td>
</tr>
<tr>
<td>glfwGetMonitorPos</td>
<td>get position of specified monitor’s viewport on virtual screen</td>
</tr>
<tr>
<td>glfwGetMonitorPhysicalSize</td>
<td>get physical size of specified monitor</td>
</tr>
<tr>
<td>glfwGetMonitorName</td>
<td>get name of specified monitor</td>
</tr>
<tr>
<td>glfwGetVideoModes</td>
<td>get available video modes for specified monitor</td>
</tr>
<tr>
<td>glfwGetVideoMode</td>
<td>get current video mode of specified monitor</td>
</tr>
<tr>
<td>glfwSetGamma</td>
<td>set gamma for specified monitor</td>
</tr>
<tr>
<td>glfwGetGammaRamp</td>
<td>get current gamma ramp for specified monitor</td>
</tr>
<tr>
<td>glfwSetGammaRamp</td>
<td>set current gamma ramp for specified monitor</td>
</tr>
</tbody>
</table>
## Contexts and Extensions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>glfwMakeContextCurrent</code></td>
<td>make context of specified window current for calling thread</td>
</tr>
<tr>
<td><code>glfwGetCurrentContext</code></td>
<td>get window whose context is current on calling thread</td>
</tr>
<tr>
<td><code>glfwExtensionSupported</code></td>
<td>tests if specified API extension is supported by current OpenGL or OpenGL ES context</td>
</tr>
<tr>
<td><code>glfwGetProcAddress</code></td>
<td>get address of specified OpenGL or OpenGL ES core or extension function (if supported) for current context</td>
</tr>
</tbody>
</table>
## Vulkan

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glfwVulkanSupported</td>
<td>tests if Vulkan loader has been found</td>
</tr>
<tr>
<td>glfwGetRequiredInstanceExtensions</td>
<td>get Vulkan instance extensions required by GLFW</td>
</tr>
<tr>
<td>glfwGetInstanceProcAddress</td>
<td>get address of specified Vulkan instance function</td>
</tr>
<tr>
<td>glfwGetPhysicalDevicePresentationSupport</td>
<td>test if specified queue family can present images</td>
</tr>
<tr>
<td>glfwCreateWindowSurface</td>
<td>create Vulkan surface for specified Window</td>
</tr>
</tbody>
</table>
- minimalist program using GLFW
- create window that is cleared to particular color
```c
#include <cstdlib>
#include <GLFW/glfw3.h>

void display(GLFWwindow* window) {
    glClearColor(0.0, 1.0, 1.0, 0.0);
    glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
    glfwSwapBuffers(window);
}

int main(int argc, char** argv) {
    if (!glfwInit()) {return EXIT_FAILURE;}
    glfwSwapInterval(1);
    GLFWwindow* window = glfwCreateWindow(512, 512, argv[0], nullptr, nullptr);
    if (!window) {
        glfwTerminate();
        return EXIT_FAILURE;
    }
    glfwMakeContextCurrent(window);
    glfwSetWindowRefreshCallback(window, display);
    while (!glfwWindowShouldClose(window)) {
        glfwWaitEvents();
    }
    glfwTerminate();
    return EXIT_SUCCESS;
}
```
GLFW References

Section 5.5

OpenGL Mathematics (GLM) Library
- open-source mathematics library for graphics software based on OpenGL Shading Language (GLSL)
- intended for use with OpenGL
- written in C++
- developed by Christophe Riccio
- provides classes and functions with similar naming conventions and functionality as in GLSL
- web site: http://glm.g-truc.net
- library has numerous header files
- header files under `glm` directory
- all header files for core GLM functionality can be included by including header file `glm.hpp`
- for matrix transformation functionality, include `gtc/matrix_transform.hpp`
- for string conversion functionality, include `gtx/string_cast.hpp`
- for type value functionality, include `gtc/type_ptr.hpp`
- all identifiers placed in namespace `glm`
Types

- provides vector and matrix types similar to GLSL

- **vector types:**
  - `vec2`, `vec3`, `vec4`
  - `bvec2`, `bvec3`, `bvec4`
  - `ivec2`, `ivec3`, `ivec4`
  - `uvec2`, `uvec3`, `uvec4`
  - `dvec2`, `dvec3`, `dvec4`

- **matrix types:**
  - `mat2x2`, `mat2x3`, `mat2x4`, `mat2`,
    `mat3x2`, `mat3x3`, `mat3x4`, `mat3`,
    `mat4x2`, `mat4x3`, `mat4x4`, `mat4`
  - `dmat2x2`, `dmat2x3`, `dmat2x4`, `dmat2`,
    `dmat3x2`, `dmat3x3`, `dmat3x4`, `dmat3`,
    `dmat4x2`, `dmat4x3`, `dmat4x4`, `dmat4`
- provides GLSL functions (e.g., inverse and transpose)
- provides functions that offer functionality similar to legacy OpenGL/GLU functions (e.g., rotate, scale, translate, frustum, ortho, lookAt, perspective, pickMatrix, project, and unProject)
```cpp
#include <iostream>
#include <glm/glm.hpp>
#include <glm/gtc/matrix_transform.hpp>
#include <glm/gtx/string_cast.hpp>
#include <cmath>

int main() {
    glm::mat4 mv(1.0f);
    mv = mv * glm::lookAt(glm::vec3(0.0f, 0.0f, 0.0f),
                        glm::vec3(1.0f, 0.0f, 0.0f),
                        glm::vec3(0.0f, 0.0f, 1.0f));
    mv = mv * glm::translate(mv, glm::vec3(1.0f, 1.0f, 1.0f));
    mv = mv * glm::rotate(mv, glm::radians(90.0f),
                          glm::vec3(0.0f, 0.0f, 1.0f));
    mv = mv * glm::scale(mv, glm::vec3(1.0f, 1.0f, 2.0f));
    glm::mat4 p = glm::perspective(glm::radians(90.0f), 1.0f,
                                   1.0f, 2.0f);
    glm::mat4 mvp = p * mv;
    glm::vec4 v(1.0f, -1.0f, -1.0f, 1.0f);
    std::cout << glm::to_string(glm::vec3(mv * v)) << '
';
    std::cout << glm::to_string(glm::vec3(mvp * v)) << '
';
    std::cout << glm::radians(180.0f) << '
';
    std::cout << glm::degrees(M_PI) << '
';
}
```
```cpp
#include <GL/glew.h>
#include <GL/gl.h>
#include <glm/glm.hpp>
#include <glm/gtc/type_ptr.hpp>

void setUniform(GLint loc) {
    glm::mat4 m(1.0f);
    // ...
    glUniform4fv(loc, 4, glm::value_ptr(m));
}
```
Open Graphics Library (OpenGL)

- application programming interface (API) for high-performance high-quality 2-D and 3-D graphics rendering
- most widely adopted 2-D and 3-D graphics API in industry
- bindings for numerous programming languages (i.e., C, Java, and Fortran)
- focus exclusively on C language binding herein
- window-system and operating-system independent
- available on all mainstream systems (e.g., Microsoft Windows, OS X, and Linux/Unix)
- vendor-neutral, controlled by independent consortium with many organizations as members (including companies such as Intel, NVIDIA, and AMD)
- official web site: http://www.opengl.org
- OpenGL ES provides (simplified) subset of OpenGL API for embedded systems (e.g., mobile phones, game consoles, personal navigation devices, personal media players, automotive systems, settop boxes)
OpenGL Functionality

- geometric primitives include points, line segments, and triangles
- arrange geometric primitives in 3-D space and select desired vantage point for viewing composed scene
- calculate colors of objects (e.g., by explicit assignment, lighting, texture mapping, or combination thereof)
- convert mathematical description of objects to pixels on screen (i.e., rasterization)
- can eliminate hidden parts of objects (via depth buffering), perform antialiasing, and so on
- some functionality relies on shaders provided by application program
- only concerned with rendering
- no mechanism provided for creating windows or obtaining user input (e.g., via mouse or keyboard)
- another library must be used in conjunction with OpenGL in order to manage windows and handle user input
main responsibility of application is to provide graphics data to GPU
application program running on CPU sends graphics data to GPU
programs running on GPU called shaders control rendering
GPU performs all rendering
high performance achieved by offloading rendering work to GPU, with GPU being highly specialized for rendering
image formed and stored in framebuffer
shaders written in OpenGL Shading Language (GLSL)
application program uses OpenGL to compile and link shader source code to yield executable shader program that runs on GPU
OpenGL State Machine

- OpenGL is state machine
- OpenGL functions can be roughly classified into two categories:
  1. primitive generation
  2. state management
- primitive-generation functions:
  - produce graphics output if primitive is visible
  - how vertices are processed and appearance of primitive controlled by OpenGL state
- state-management functions:
  - enabling/disabling OpenGL functionality (e.g., depth buffering)
  - configuring shader programs
  - setting/querying shader variables
feature that may be removed in future version of OpenGL is said to be **deprecated**

**profile** defines subset of OpenGL functionality targeted to specific application domains

two profiles: core and compatibility

**core profile** provides functionality mandated by particular version of OpenGL (which does not include deprecated and removed features)

**compatibility profile** restores support for all functionality that has been removed from OpenGL

all OpenGL implementations must support core profile, but are not required to support compatibility profile

for given profile, two types of contexts: full or forward compatible

**forward compatible context** does not support deprecated features from profile

**full context** supports deprecated features from profile
- header files for OpenGL located in GL (or OpenGL) directory
- definitions necessary for OpenGL can be found in header file `gl.h`
- above header file provides definitions of all constants and data types (e.g., `GLint` and `GLfloat`) and function declarations for OpenGL
- on some platforms, in order to access newer OpenGL functionality, may need to include `glew.h` (typically in GL directory) before `gl.h`
- normally, OpenGL used in conjunction with another helper library such as GLFW or GLUT
- other helper libraries also have header files of their own that must be included
- often header files for helper libraries include `gl.h`
### Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLboolean</td>
<td>boolean</td>
</tr>
<tr>
<td>GLbyte</td>
<td>8-bit signed two’s complement integer</td>
</tr>
<tr>
<td>GLubyte</td>
<td>8-bit unsigned integer</td>
</tr>
<tr>
<td>GLchar</td>
<td>8-bit character</td>
</tr>
<tr>
<td>GLshort</td>
<td>16-bit signed two’s complement integer</td>
</tr>
<tr>
<td>GLushort</td>
<td>16-bit unsigned integer</td>
</tr>
<tr>
<td>GLint</td>
<td>32-bit signed two’s complement integer</td>
</tr>
<tr>
<td>GLuint</td>
<td>32-bit unsigned integer</td>
</tr>
<tr>
<td>GLfloat</td>
<td>single-precision floating-point value</td>
</tr>
<tr>
<td>GLdouble</td>
<td>double-precision floating-point value</td>
</tr>
</tbody>
</table>

- OpenGL types do not necessarily correspond to similarly named C types (e.g., GLint is not necessarily int)
all OpenGL functions begin with gl

some OpenGL commands have numerous variants that differ in number and type of parameters

such commands are named using following pattern:

\[ \text{generic\_name} \, N \, T \, V \]

where \( \text{generic\_name} \) is generic name of function, \( N \) is digit (i.e., 2, 3, 4) indicating number of components, \( T \) is one or two letters indicating data type of components, \( V \) is either nothing or letter v to indicate component data specified as individual values or as vector (i.e., pointer to array), respectively

<table>
<thead>
<tr>
<th>Number ( N )</th>
<th>( (x, y) )</th>
<th>( (x, y, z) )</th>
<th>( (x, y, z, w) )</th>
</tr>
</thead>
</table>

| Data Type \( T \) | \( \text{b} \) GLbyte | \( \text{ub} \) GLubyte | \( \text{s} \) GLshort | \( \text{us} \) GLushort | \( \text{i} \) GLint | \( \text{ui} \) GLuint | \( \text{f} \) GLfloat | \( \text{d} \) GLdouble |

\( \text{glUniform3f} \): specific version of generic \( \text{glUniform} \) function that takes data in form of three \( \text{GLfloat} \) parameters

\( \text{glUniform3fv} \): specific version of generic \( \text{glUniform} \) function that takes data in form of pointer to array of triples of \( \text{GLfloat} \) values
geometric objects represented using vertices

- each vertex has variety of attributes, such as:
  - positional coordinates
  - color
  - texture coordinates
  - surface normal
  - any other data associated with point in space

- position represented using homogeneous coordinates
- vertex data must be stored in vertex buffer objects (VBOs)
- VBOs must be associated with vertex array objects (VAOs)
- VAOs/VBOs allow application program to transfer data to GPU once and then select between different data on GPU by activating different VAOs/VBOs
Geometric Primitives

- **points**
- **lines**
- **line strip**
- **line loop**

- **triangles**
- **triangle strip**
- **triangle fan**

- All primitives specified by vertices
each primitive has provoking vertex

one of two conventions can be used to determine provoking vertex: first vertex or last vertex

for example, with last vertex convention, provoking vertex for triangle is third (i.e., last) vertex of triangle

convention defaults to last vertex

convention can be set with `glProvokingVertex`

provoking vertex becomes important, for example, when using flat interpolation
- vertex buffer objects (VBOs) store vertex attributes (e.g., positions, normals, colors, and texture coordinates)
- storage for VBOs resides in GPU memory
- vertex array objects (VAOs) allow data stored in VBOs to be associated with vertex attributes for vertex shader
- VAOs specify layout (e.g., offset and stride) and format (e.g., type) of data in VBOs
- to render primitives need VAO (which, in turn, is associated with one or more VBOs)
Vertex Array Objects (VAOs)

- VAOs store data for geometric object
- VAO identified by name, which is integer of type `GLuint`
- create one or more VAOs by generating VAO names via `glGenVertexArrays`
- VAO initialized as follows:
  1. bind specific VAO for initialization via `glBindVertexArray`
  2. update VBOs associated with VAO, and specify layout and format of VBO data and its correspondence with vertex attributes for rendering via `glVertexAttribPointer`
- data in VAO rendered as follows:
  1. bind VAO for use in rendering via `glBindVertexArray`
  2. draw content of currently enabled arrays via `glDrawArrays`
- only enabled attributes will be used for rendering (where attributes are enabled with `glEnableVertexAttribArray`)
- vertex buffer objects (VBOs) provide means to transfer data to GPU memory
- vertex data must be stored in VBO associated with VAO
- each VBO associated with name, which is integer of type GLuint
- generate VBO names via `glGenBuffers`
- bind specific VBO for initialization via `glBindBuffer` (after first binding associated VAO)
- allocate underlying storage for VBO (and optionally load data into VBO) via `glBufferData`
- load data into VBO via `glBufferSubData`
- **object coordinates**: coordinates of object relative to its local origin
- **world coordinates**: coordinates of three-dimensional environment (i.e., world) being rendered
- **eye coordinates**: coordinates relative to camera from which world is being viewed
- **clip coordinates**: coordinates normalized such that viewing volume falls in $[-1, 1] \times [-1, 1] \times [-1, 1]$
- **normalized device coordinates**: result of converting clip coordinates to Cartesian coordinates by perspective division (i.e., dividing by $w$ coordinate)
- **window coordinates**: coordinates relative to graphics window
OpenGL Camera

- appearance of rendered scene determined by camera position, orientation, and viewing volume
- camera positioned at origin
- camera oriented to point in negative z direction with positive y axis pointing up
- orthographic projection in direction of z axis with clipping planes $x = -1$, $x = 1$, $y = -1$, $y = 1$, $z = -1$, and $z = 1$
- viewing volume is $[-1, 1] \times [-1, 1] \times [-1, 1]$ (i.e., cube centered at origin with sides of length 2)
- different camera position, orientation, and viewing volume can be achieved by employing transformations
- perspective projection accomplished by applying transformation that warps viewing volume into frustum
Transformations

- often modelling and viewing transformations combined into single transformation called modelview transformation

- \( p_{\text{eye}} = M_{\text{mv}} p_{\text{obj}} \)

- \( p_{\text{clip}} = M_{\text{p}} p_{\text{eye}} = M_{\text{p}} M_{\text{mv}} p_{\text{obj}} \)

- clip coordinates and normalized device coordinates still retain depth (i.e., \( z \)) information in order to facilitate depth buffering
Transformations (Continued)

- viewport transformation determines drawable region within window
- viewport transformation set via `glViewport`
Depth Buffering

- in above figure, darker triangle is partially occluded by lighter triangle from vantage point of camera
- in OpenGL, camera always pointing in direction of negative $z$ axis
- therefore, $z$ coordinate can be used to determine distance of fragment from eye, with lesser value (i.e., closer to $-\infty$) corresponding to greater distance
- if depth buffering enabled, fragment not drawn if its $z$ coordinate less than $z$ coordinate of previously drawn pixel
Face Culling

- winding order used to distinguish front and back sides of triangles
- which winding order corresponds to front side of triangle specified via `glFrontFace`
- which side (or sides) of triangle should be culled specified via `glCullFace`
- if face culling enabled, culled side of triangles not rendered
glEnable and glEnable used to enable and disable specific functionality

<table>
<thead>
<tr>
<th>Value</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>GL_CULL_FACE</td>
<td>if enabled, cull polygons based on their winding in window coordinates (e.g., do not render backs of faces)</td>
</tr>
<tr>
<td>GL_DEPTH_TEST</td>
<td>if enabled, do depth comparisons and update depth buffer</td>
</tr>
<tr>
<td>GL_LINE_SMOOTH</td>
<td>if enabled, draw lines with antialiasing</td>
</tr>
</tbody>
</table>
### Other Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>glClear</td>
<td>clear buffer to preset values</td>
</tr>
<tr>
<td>glClearColor</td>
<td>specify clear values for color buffers</td>
</tr>
</tbody>
</table>
program typically consists of steps like following:

1. create window associated with OpenGL context
2. initialize shaders (e.g., compile and link) and other OpenGL state (e.g., depth buffering and clear color)
3. initialize data to be drawn
4. register callback functions to process events
5. enter main event-processing loop, which repeatedly waits for event of interest and then handles it by invoking appropriate callback function

events of interest typically include such things as:

- request to redraw window
- window-resize notification
- keyboard input
- mouse-button press/release
Section 5.6.1

Simple OpenGL Program
- consider very simple OpenGL application program (which utilizes GLFW)
- draws triangle in window
- rendered output shown below
#include <cstdlib>
#include <string>
#include <GL/glew.h>
#include <GLFW/glfw3.h>
void fatalError() {
    glfwTerminate();
    std::exit(EXIT_FAILURE);
}

int main(int argc, char** argv) {
    if (!glfwInit()) {return EXIT_FAILURE;}
    GLFWwindow* window = makeWindow(512, 512, argv[0]);
    if (!window) {fatalError();}
    glfwMakeContextCurrent(window);
    glewExperimental = GL_TRUE;
    if (glewInit() != GLEW_OK) {fatalError();}
    GLuint program = makeProgram(vShaderSource, fShaderSource);
    if (!program) {fatalError();}
    glUseProgram(program);
    glClearColor(0.0, 0.0, 0.0, 0.0);
    GLuint vbo;
    makeVao(program, vao, vbo);
    glfwSetWindowRefreshCallback(window, refresh);
    while (!glfwWindowShouldClose(window))
    {
        glfwWaitEvents();
        glfwTerminate();
        return EXIT_SUCCESS;
    }
}
```c++
GLFWwindow* makeWindow(int width, int height,
    const std::string& title) {
    glfwWindowHint(GLFW_CONTEXT_VERSION_MAJOR, 3);
    glfwWindowHint(GLFW_CONTEXT_VERSION_MINOR, 3);
    glfwWindowHint(GLFW_OPENGL_FORWARD_COMPAT, GL_TRUE);
    glfwWindowHint(GLFW_OPENGL_PROFILE, GLFW_OPENGL_CORE_PROFILE);
    GLFWwindow* window = glfwCreateWindow(width, height,
        title.c_str(), nullptr, nullptr);
    return window;
}
```
const std::basic_string<GLchar> vShaderSource = R"(
#version 330
in vec3 aPosition;
void main() {
    gl_Position = vec4(aPosition, 1.0);
}
)";

const std::basic_string<GLchar> fShaderSource = R"(
#version 330
out vec4 fColor;
void main() {
    fColor = vec4(0.0, 1.0, 1.0, 1.0);
}
)";
```cpp
GLuint compileShader(GLuint type,
const std::basic_string<GLchar>& source) {
    GLuint shader = glCreateShader(type);
    if (!shader) {return 0;}
    const GLchar* cp = &source[0];
    GLint len = source.size();
    glShaderSource(shader, 1, &cp, &len);
    glCompileShader(shader);
    GLint status = GL_FALSE;
    glGetShaderiv(shader, GL_COMPILE_STATUS, &status);
    if (status != GL_TRUE)
        {glDeleteShader(shader); return 0;}
    return shader;
}
GLuint makeProgram(
    const std::basic_string<GLchar>& vShaderSource,
    const std::basic_string<GLchar>& fShaderSource) {
    GLuint vShader = compileShader(GL_VERTEX_SHADER, vShaderSource);
    if (!vShader) {return 0;}
    GLuint fShader = compileShader(GL_FRAGMENT_SHADER, fShaderSource);
    if (!fShader) {glDeleteShader(vShader); return 0;}
    GLuint program = glCreateProgram();
    GLint status = GL_FALSE;
    if (program) {
        glAttachShader(program, vShader);
        glAttachShader(program, fShader);
        glLinkProgram(program);
        glGetProgramiv(program, GL_LINK_STATUS, &status);
    }
    glDeleteShader(vShader);
    glDeleteShader(fShader);
    if (!program) {return 0;}
    if (status != GL_TRUE)
        {glDeleteProgram(program); return 0;}
    return program;
}
void makeVao(GLuint program, GLuint& vao,
    GLuint& vbo) {
    static const GLfloat vertices[][3] = {
        {-0.50, -0.50, 0.0},
        { 0.50, -0.50, 0.0},
        { 0.00, 0.50, 0.0}
    };
    glGenVertexArrays(1, &vao);
    glGenBuffers(1, &vbo);
    glBindVertexArray(vao);
    glBindBuffer(GL_ARRAY_BUFFER, vbo);
    glBufferData(GL_ARRAY_BUFFER, sizeof(vertices),
        vertices, GL_STATIC_DRAW);
    GLuint aPosition = glGetAttribLocation(program,
        "aPosition");
    glVertexAttribPointer(aPosition, 3, GL_FLOAT, GL_FALSE,
        0, 0);
    glEnableVertexAttribArray(aPosition);
}
GLuint vao = 0;

void refresh(GLFWwindow* window) {
    glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
    glBindVertexArray(vao);
    glDrawArrays(GL_TRIANGLES, 0, 3);
    glfwSwapBuffers(window);
}
Section 5.6.2

Shaders
Shaders

- shader is user-defined program that runs on GPU and provides functionality associated with some particular stage of rendering pipeline
- shaders written in OpenGL Shading Language (GLSL)
- as of OpenGL 3.1, application program must provide shaders as no default shaders provided (in core profile)
- several types of shaders:
  - vertex shader
  - tessellation control shader
  - tessellation evaluation shader
  - geometry shader
  - fragment shader
  - compute shader
- each type of shader performs specific type of task on GPU
each type of shader performs distinct task within rendering pipeline

- vertex shader (which is associated with vertex processor block) provides any last geometric transformation of vertices before being fed to remainder of rendering pipeline

- geometry shader (which is associated with vertex processor block) generates actual primitives to be rendered based on primitives received from previous pipeline stage

- fragment shader (which is associated with fragment processor block) provides color to each pixel in framebuffer
- shaders written in GLSL
- GLSL is portable multiplatform C-like language
- GLSL borrows heavily from C syntax
- provides simplified subset of C language with numerous modifications:
  - adds new data types, such as matrix and vector types
  - adds overloaded operators and constructors
- supports C and C++ style comments
- GLSL keywords cannot be used as identifiers
- names beginning with “gl_” prefix reserved by GLSL
<table>
<thead>
<tr>
<th>reserved keyword</th>
<th>data type</th>
<th>data type</th>
</tr>
</thead>
<tbody>
<tr>
<td>attribute</td>
<td>inout</td>
<td>mat4x4</td>
</tr>
<tr>
<td>const</td>
<td>float</td>
<td>vec2</td>
</tr>
<tr>
<td>uniform</td>
<td>int</td>
<td>vec3</td>
</tr>
<tr>
<td>varying</td>
<td>void</td>
<td>vec4</td>
</tr>
<tr>
<td>layout</td>
<td>bool</td>
<td>ivec2</td>
</tr>
<tr>
<td>centroid</td>
<td>true</td>
<td>ivec3</td>
</tr>
<tr>
<td>flat</td>
<td>false</td>
<td>ivec4</td>
</tr>
<tr>
<td>smooth</td>
<td>invariant</td>
<td>bvec2</td>
</tr>
<tr>
<td>perspective</td>
<td>discard</td>
<td>bvec3</td>
</tr>
<tr>
<td>break</td>
<td>return</td>
<td>bvec4</td>
</tr>
<tr>
<td>continue</td>
<td>mat2</td>
<td>uint</td>
</tr>
<tr>
<td>do</td>
<td>mat3</td>
<td>uvec2</td>
</tr>
<tr>
<td>for</td>
<td>mat4</td>
<td>uvec3</td>
</tr>
<tr>
<td>while</td>
<td>mat2x2</td>
<td>uvec4</td>
</tr>
<tr>
<td>switch</td>
<td>mat2x3</td>
<td>lowp</td>
</tr>
<tr>
<td>case</td>
<td>mat2x4</td>
<td>mediump</td>
</tr>
<tr>
<td>default</td>
<td>mat3x2</td>
<td>highp</td>
</tr>
<tr>
<td>if</td>
<td>mat3x3</td>
<td>precision</td>
</tr>
<tr>
<td>else</td>
<td>mat3x4</td>
<td>sampler1D</td>
</tr>
<tr>
<td>in</td>
<td>mat4x2</td>
<td>sampler2D</td>
</tr>
<tr>
<td>out</td>
<td>mat4x3</td>
<td>sampler3D</td>
</tr>
</tbody>
</table>
**Reserved Keywords (Continued)**

<table>
<thead>
<tr>
<th>Sampler</th>
<th>Unrestricted Sampler</th>
</tr>
</thead>
<tbody>
<tr>
<td>samplerCube</td>
<td>usamplerCube</td>
</tr>
<tr>
<td>sampler1DShadow</td>
<td>usampler1DArray</td>
</tr>
<tr>
<td>sampler2DShadow</td>
<td>usampler2DArray</td>
</tr>
<tr>
<td>samplerCubeShadow</td>
<td>sampler2DRect</td>
</tr>
<tr>
<td>sampler1DArray</td>
<td>sampler2DRectShadow</td>
</tr>
<tr>
<td>sampler2DArray</td>
<td>sampler2DRect</td>
</tr>
<tr>
<td>sampler1DArrayShadow</td>
<td>isampler2DRect</td>
</tr>
<tr>
<td>sampler2DArrayShadow</td>
<td>usampler2DRect</td>
</tr>
<tr>
<td>isampler1D</td>
<td>isamplerBuffer</td>
</tr>
<tr>
<td>isampler2D</td>
<td>usamplerBuffer</td>
</tr>
<tr>
<td>isampler3D</td>
<td>sampler2DMS</td>
</tr>
<tr>
<td>isamplerCube</td>
<td>isampler2DMS</td>
</tr>
<tr>
<td>isampler1DArray</td>
<td>usampler2DMS</td>
</tr>
<tr>
<td>isampler2DArray</td>
<td>sampler2DMSArray</td>
</tr>
<tr>
<td>usampler1D</td>
<td>isampler2DMSArray</td>
</tr>
<tr>
<td>usampler2D</td>
<td>usampler2DMSArray</td>
</tr>
<tr>
<td>usampler3D</td>
<td>struct</td>
</tr>
</tbody>
</table>

plus other keywords added since OpenGL 3.3
The `#version` Directive

- `#version` directive specifies which version of GLSL should be used to compile/link shader
- If `#version` directive specified, must be first statement in source
- If no `#version` directive given, version 1.10 is assumed
- `#version` directive takes two parameters (with second being optional):
  - 1. integer specifying GLSL version (scaled by a factor of 100)
  - 2. profile name, which can be either core or compatibility with core being default
- For OpenGL 3.3 and above, corresponding GLSL version matches OpenGL version (e.g., OpenGL 4.1 uses GLSL 4.1); for earlier OpenGL versions, relationship between OpenGL and GLSL versions as follows:

<table>
<thead>
<tr>
<th>OpenGL Version</th>
<th>GLSL Version</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>1.10</td>
</tr>
<tr>
<td>2.1</td>
<td>1.20</td>
</tr>
<tr>
<td>3.0</td>
<td>1.30</td>
</tr>
<tr>
<td>3.1</td>
<td>1.40</td>
</tr>
<tr>
<td>3.2</td>
<td>1.50</td>
</tr>
</tbody>
</table>

- For example, to specify use of GLSL 3.30 with core profile:
  
  `#version 330`
### Basic Types

#### Scalar and Void Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>void</code></td>
<td>dummy type for functions without return value</td>
</tr>
<tr>
<td><code>bool</code></td>
<td>boolean type</td>
</tr>
<tr>
<td><code>int</code></td>
<td>signed integer type</td>
</tr>
<tr>
<td><code>uint</code></td>
<td>unsigned integer type</td>
</tr>
<tr>
<td><code>float</code></td>
<td>single-precision floating-point type</td>
</tr>
</tbody>
</table>

#### Vector of `float` Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>vec2</code></td>
<td>two-component vector of <code>float</code></td>
</tr>
<tr>
<td><code>vec3</code></td>
<td>three-component vector of <code>float</code></td>
</tr>
<tr>
<td><code>vec4</code></td>
<td>four-component vector of <code>float</code></td>
</tr>
</tbody>
</table>

#### Vector of `bool` Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>bvec2</code></td>
<td>two-component vector of <code>bool</code></td>
</tr>
<tr>
<td><code>bvec3</code></td>
<td>three-component vector of <code>bool</code></td>
</tr>
<tr>
<td><code>bvec4</code></td>
<td>four-component vector of <code>bool</code></td>
</tr>
</tbody>
</table>
### Vector of `int` Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>ivec2</code></td>
<td>two-component vector of <code>int</code></td>
</tr>
<tr>
<td><code>ivec3</code></td>
<td>three-component vector of <code>int</code></td>
</tr>
<tr>
<td><code>ivec4</code></td>
<td>four-component vector of <code>int</code></td>
</tr>
</tbody>
</table>

### Vector of `uint` Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>uvec2</code></td>
<td>two-component vector of <code>uint</code></td>
</tr>
<tr>
<td><code>uvec3</code></td>
<td>three-component vector of <code>uint</code></td>
</tr>
<tr>
<td><code>uvec4</code></td>
<td>four-component vector of <code>uint</code></td>
</tr>
</tbody>
</table>

### Matrix of `float` Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>mat2</code></td>
<td>$2 \times 2$ matrix of <code>float</code></td>
<td><code>mat3x2</code></td>
<td>$3 \times 2$ matrix of <code>float</code></td>
</tr>
<tr>
<td><code>mat3</code></td>
<td>$3 \times 3$ matrix of <code>float</code></td>
<td><code>mat3x3</code></td>
<td>same as <code>mat3</code></td>
</tr>
<tr>
<td><code>mat4</code></td>
<td>$4 \times 4$ matrix of <code>float</code></td>
<td><code>mat3x4</code></td>
<td>$3 \times 4$ matrix of <code>float</code></td>
</tr>
<tr>
<td><code>mat2x2</code></td>
<td>same as <code>mat2</code></td>
<td><code>mat4x2</code></td>
<td>$4 \times 2$ matrix of <code>float</code></td>
</tr>
<tr>
<td><code>mat2x3</code></td>
<td>$2 \times 3$ matrix of <code>float</code></td>
<td><code>mat4x3</code></td>
<td>$4 \times 3$ matrix of <code>float</code></td>
</tr>
<tr>
<td><code>mat2x4</code></td>
<td>$2 \times 4$ matrix of <code>float</code></td>
<td><code>mat4x4</code></td>
<td>same as <code>mat4</code></td>
</tr>
</tbody>
</table>
- numerous sampler types
- numerous other types added since OpenGL 3.3
- matrix types stored in column-major order
- no pointer types
- `const` qualifier similar to C
- `struct` can be used to construct user-defined types
standard C/C++ arithmetic and logical operators

operators overloaded for matrix and vector types

for two operands of vector type, multiplication operator performs component-wise multiplication

for two operands of matrix type or one operand of matrix type and one of vector type, multiplication operator performs standard matrix/vector multiplication

example:

```cpp
mat4 a; mat4 b; mat4 c;
vec4 u; vec4 v; vec4 w;
// ...
v = a * u; // standard matrix-vector multiplication
c = a * b; // standard matrix-vector multiplication
w = u * v; // component-wise multiplication
```
first, second, third, and fourth components of vector (if they exist) can be selected by:

- subscripting operator with subscripts 0, 1, 2, and 3, respectively; or
- selection operator with $x$, $y$, $z$, and $w$, respectively; or
- selection operator with $r$, $g$, $b$, and $a$, respectively; or
- selection operator with $s$, $t$, $p$, and $q$, respectively

example:

```cpp
vec3 v;
// ...
float x = v.x;
float y = v.y;
float z = v.z;
```

components of matrices can be accessed by subscripting operator

single subscripting on matrix results in column of matrix

double subscripting on matrix results in element of matrix

example:

```cpp
mat2 a;
// ...
vec2 v = a[0];
float f = a[0][0];
```
can also form vectors by selecting multiple elements from vector (e.g., swizzling and smearing)

example:

```cpp
vec4 v; vec4 u;
vec3 a;
// ...
u = v.wzyx; // vec4(v.w, v.z, v.y, v.x)
u = v.xxxy; // vec4(v.x, v.x, v.y, v.y)
a = v.xyz; // vec3(v.x, v.y, v.z)
u = a.xxxx; // vec4(a.x, a.x, a.x, a.x)
```
Control Flow

- **selection statements**
  - `if`
  - `if-else`
  - ternary operator
  - `switch`

- **looping statements**
  - `for`
  - `while`
  - `do-while`

- also has **break** and **continue**

- **no goto statement**

- only in fragment shader: **discard** statement
- numerous built-in functions provided (e.g., abs, sin, cos, sqrt)
- user-defined functions are supported
- recursion not allowed
- function overloading supported (including for user-defined functions)
- `return` statement to return from function
constructor is function with same name as type
used to create value of type named by function
constructor parameters for matrix types specified in column-major order
example:

```cpp
vec3 v3 = vec3(1.0, 2.0, 3.0);
mat2 m2 = mat2(1.0, 2.0, 3.0, 4.0);
    // first column of m2 is 1.0, 2.0
    // second column of m2 is 3.0, 4.0
mat4 m4 = mat4(1.0);  // identity matrix
vec4 v4 = vec4(0.0);  // zero vector
const int lut[3] = int[3](1, 2, 4);
vec2 va[2] =
    vec2[](vec2(1.0, 2.0), vec2(3.0, 4.0));
bool b = bool(1);
```
number of implicit conversions allowed, some of which identified below

- integer types (e.g., `int` and `uint`) can be implicitly converted to `float`
- each integer vector type (e.g., `ivec4`) can be implicitly converted to floating-point vector type of same dimension (e.g., `vec4`)
- floating-point type *cannot* be implicitly converted to integer type
- unsigned integer type (e.g., `uint`) *cannot* be implicitly converted to signed integer type (e.g., `int`)

example:

```c++
int i; uint ui; float f; vec4 v4; ivec4 iv4;
// ...
f = i; // OK
// i = f; // ERROR: no implicit conversion
i = int(f); // OK
// iv4 = v4; // ERROR: no implicit conversion
iv4 = ivec4(v4); // OK
// i = 0u; // ERROR: no implicit conversion
// i = ui; // ERROR: no implicit conversion
i = int(ui); // OK
```
# Angle and Trigonometric Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>radians</td>
<td>convert from degrees to radians</td>
</tr>
<tr>
<td>degrees</td>
<td>convert from radians to degrees</td>
</tr>
<tr>
<td>sin</td>
<td>sine function</td>
</tr>
<tr>
<td>cos</td>
<td>cosine function</td>
</tr>
<tr>
<td>tan</td>
<td>tangent function</td>
</tr>
<tr>
<td>asin</td>
<td>arcsine function</td>
</tr>
<tr>
<td>acos</td>
<td>arccosine function</td>
</tr>
<tr>
<td>atan</td>
<td>arctangent function</td>
</tr>
</tbody>
</table>
## Exponential Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>pow</td>
<td>exponentiation function</td>
</tr>
<tr>
<td>exp</td>
<td>base-$e$ exponentiation function</td>
</tr>
<tr>
<td>log</td>
<td>natural logarithm function</td>
</tr>
<tr>
<td>exp2</td>
<td>base-2 exponentiation function</td>
</tr>
<tr>
<td>log2</td>
<td>base-2 logarithm function</td>
</tr>
<tr>
<td>sqrt</td>
<td>square-root function</td>
</tr>
<tr>
<td>inversesqrt</td>
<td>reciprocal of square-root function</td>
</tr>
</tbody>
</table>
## Common Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>abs</td>
<td>absolute-value function</td>
</tr>
<tr>
<td>sign</td>
<td>signum function</td>
</tr>
<tr>
<td>floor</td>
<td>floor function</td>
</tr>
<tr>
<td>ceil</td>
<td>ceiling function</td>
</tr>
<tr>
<td>fract</td>
<td>fractional-part function</td>
</tr>
<tr>
<td>mod</td>
<td>modulo function</td>
</tr>
<tr>
<td>min</td>
<td>minimum of two values</td>
</tr>
<tr>
<td>max</td>
<td>maximum of two values</td>
</tr>
<tr>
<td>clamp</td>
<td>clamp value to specified range</td>
</tr>
<tr>
<td>mix</td>
<td>affine combination of two values</td>
</tr>
<tr>
<td>step</td>
<td>step function</td>
</tr>
<tr>
<td>smoothstep</td>
<td>smooth step function</td>
</tr>
</tbody>
</table>
### Geometric Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td>length of vector</td>
</tr>
<tr>
<td>distance</td>
<td>distance between two points</td>
</tr>
<tr>
<td>dot</td>
<td>dot product</td>
</tr>
<tr>
<td>cross</td>
<td>cross product</td>
</tr>
<tr>
<td>normalize</td>
<td>get vector of unit length</td>
</tr>
<tr>
<td>faceforward</td>
<td>get vector that points in same direction as reference vector</td>
</tr>
<tr>
<td>reflect</td>
<td>get vector that points in direction of reflection</td>
</tr>
<tr>
<td>refract</td>
<td>get vector that points in direction of refraction</td>
</tr>
</tbody>
</table>
### Fragment Processing Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>dFdx</td>
<td>partial derivative of argument with respect to x</td>
</tr>
<tr>
<td>dFdy</td>
<td>partial derivative of argument with respect to y</td>
</tr>
<tr>
<td>fwidth</td>
<td>sum of absolute value of derivatives in x and y</td>
</tr>
</tbody>
</table>

### Matrix Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>matrixCompMult</td>
<td>multiply matrices component-wise</td>
</tr>
</tbody>
</table>

### Texture Lookup

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>texture2D</td>
<td>perform 2D texture lookup</td>
</tr>
<tr>
<td>textureCube</td>
<td>perform cubemap texture lookup</td>
</tr>
</tbody>
</table>
### Vector Relational Functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>lessThan</td>
<td>component-wise less-than comparison</td>
</tr>
<tr>
<td>lessThanEqual</td>
<td>component-wise less-than-or-equal comparison</td>
</tr>
<tr>
<td>greaterThan</td>
<td>component-wise greater-than comparison</td>
</tr>
<tr>
<td>greaterThanEqual</td>
<td>component-wise greater-than-or-equal comparison</td>
</tr>
<tr>
<td>equal</td>
<td>component-wise equality comparison</td>
</tr>
<tr>
<td>notEqual</td>
<td>component-wise inequality comparison</td>
</tr>
<tr>
<td>any</td>
<td>any component is true</td>
</tr>
<tr>
<td>all</td>
<td>all components are true</td>
</tr>
<tr>
<td>not</td>
<td>component-wise logical complement operation</td>
</tr>
</tbody>
</table>
shader parameters (i.e., input and output variables of shaders) and function parameters can be qualified with `in` and `out` qualifiers

- parameter declared `in`:
  - value given to parameter will be copied into parameter when function called
  - function may then modify parameter but changes will not affect caller
  - essentially pass-by-value semantics

- parameter declared `out`:
  - parameter will not have its value initialized by caller so initial value of parameter at start of function is undefined
  - function must modify parameter
  - after function’s execution is complete, value of parameter will be copied into variable that user specified when calling function

- default qualifier is `in` 

- example:

  ```cpp
  float foo(float x, int i, out int n);
  float calculate(in float x, in float y, in int n);
  ```
example:

```c
void calc(float x, int i, out float y, out int j) {
    // at this point, y and j are undefined
    y = ++x;
    j = ++i;
}

void func() {
    float a = 0.0;
    int b = 0;
    float c = 0.0;
    int d = 0;
    calc(a, b, c, d);
    // a and b are unchanged by function call
    // c is 1.0, d is 1
}
```
The **uniform** Qualifier

- Global variables and interface blocks can be declared with **uniform** qualifier.

- **Uniform** qualifier indicates that value of variable does not change across multiple shader invocations during rendering of single primitive (i.e., during `glDraw*` call).

- Uniform variables form linkage between shader and application program.

- Used to declare variables shared between shader and application program (e.g., projection matrix, light source position, material color).

- Uniform variable cannot be modified in shader.

- Uniform variable can only be modified by application program.

- Uniform variable can be used in multiple shaders (e.g., vertex and fragment shaders).

- If used in multiple shaders, must have identical declaration in each.

- Example:

  ```cpp
  uniform mat4 projectionMatrix;
  uniform mat4 modelViewMatrix;
  ```
outputs from and inputs to shader can be qualified with interpolation qualifier

interpolation qualifier controls how value of particular variable is interpolated

interpolation qualifiers: smooth, noperspective, flat

smooth qualifier: perspective-correct interpolation is performed

noperspective qualifier: linear interpolation is performed

flat qualifier: no interpolation is performed (i.e., value taken from provoking vertex of primitive)

default qualifier is smooth

example:

```
flat out vec4 color;
```
Interpolation Example

- single triangle rendered with vertices having color attributes of red, green, and blue, with provoking vertex being last vertex

Without Interpolation (I.e., Flat)  With Interpolation (E.g., Smooth)
Layout Qualifiers

- layout qualifiers used to specify how storage for variable allocated amongst other things
- layout qualifiers (e.g., location) provided by using `layout` keyword
- `location` layout qualifier can be used to specify location associated with variable
- vertex shaders allow input layout qualifiers on input variable declarations
- example: following will establish vertex shader input `vPosition` to be copied in from location number 1:
  ```cpp
  layout(location = 1) in vec4 vPosition;
  ```
- example: following will establish vertex shader input `colors` copied in from location numbers 6, 7, and 8:
  ```cpp
  layout(location = 6) in vec4 colors[3];
  ```
Configuration with Vertex and Fragment Shaders

Application Program

Shader Program

Uniform Variables

Vertex Shader

Input Variables

Output Variables

Fragment Shader

Input Variables

Output Variables

Vertex Attributes

Fragments

Input

Variables

Various Configurations of Shaders

Vertex and Fragment Shaders

Vertex, Geometry, and Fragment Shaders

Vertex, Tessellation, Geometry, and Fragment Shaders
Vertex Shaders

- vertex shader is programmable shader stage in rendering pipeline that handles processing of individual vertices

- vertex shader provided with vertex attribute data (e.g., position, normal, color, and texture coordinates) from VAO from drawing command

- for each vertex in input vertex stream, produces one vertex for output vertex stream

- must be one to one correspondence between input vertices and output vertices

- processes each vertex independently

- some uses of vertex shaders include:
  - vertex position transformation using modelview and projection matrices
  - normal transformation and (if needed) normalization
  - texture coordinate generation and transformation
  - per-vertex lighting
  - color computation
### Vertex Shader Inputs and Outputs

- **built-in input variables:**
  - `int gl_VertexID`: index of vertex currently being processed
  - `int gl_InstanceID`: index of current instance when doing some form of instanced rendering

- **other inputs associated with vertex attributes from VAO/VBO**

- **built-in output variables:**
  - `vec4 gl_Position`: clip-space output position of current vertex
  - `float gl_PointSize`: pixel width/height of point being rasterized; only has meaning for point primitives
  - `float gl_ClipDistance[]`: distance from vertex to each user-defined clipping half-space

- vertex shader must set `gl_Position`
// use version 3.30 of GLSL (core profile)

#version 330

// input attribute variable for vertex position
in vec4 aPosition;

// uniform variable for modelview-projection matrix
uniform mat4 uModelViewProjMatrix;

void main() {
    // set output position for vertex
    gl_Position = uModelViewProjMatrix * aPosition;
}

fragment shader is programmable shader stage that processes fragment generated by rasterization into set of colors and single depth value

for each sample of pixels covered by primitive, fragment is generated

each fragment has window space position, some other values, and all of interpolated per-vertex output values from last vertex processing stage

takes single fragment as input and produces single fragment as output

some uses of fragment shaders include:

- per-fragment lighting
- computing colors and texture coordinates per fragment
- texture application (texture and bump mapping)
- environment mapping
- fog computation
Fragment Shader Inputs and Outputs

- **built-in input variables:**
  - `vec4` `gl_FragCoord`: location of fragment in window space
  - `bool` `gl_FrontFacing`: indicates if fragment was generated by front face of primitive (only triangles can have back face)
  - `int vec2` `gl_PointCoord`: location within point primitive that defines position of fragment relative to side of point

- **other input variables** correspond to outputs of previous shader stage

- **built-in output variables:**
  - `float` `gl_fragDepth`: depth of fragment which defaults to `gl_FragCoord.z`

- **`vec4` output variable for fragment color**
// use version 3.30 of GLSL (core profile)

#version 330

// output variable for color
out vec4 fColor;

void main() {
    // set output color to white
    fColor = vec4(1.0, 1.0, 1.0, 1.0);
}

Geometry Shaders

- controls processing of primitives between vertex shader (or optional tessellation stage) and fixed-function vertex post-processing stage
- use of geometry shader optional
- takes single primitive as input and outputs zero or more primitives
- some uses of geometry shaders include:
  - layered rendering
  - transform feedback
Geometry Shader Inputs

- one input primitive per geometry shader invocation
- type of input primitives specified by layout qualifier, which is one of: points, lines, lines_adjacency, triangles, triangles_adjacency
- number of input vertices determined by input primitive type (e.g., three for triangles)
- per-vertex inputs available as members of elements in array gl_in:
  - `vec4 gl_Position`: vertex position
  - `float gl_PointSize`: pixel width/height of point being rasterized; only used for point primitive
  - `float gl_ClipDistance[]`: distance to clipping planes
- gl_in contains \( N \) elements (with indices starting from 0), where \( N \) is number of vertices in input primitive
- each shader input produced by previous pipeline stage is always array with one element per vertex
- per-primitive inputs:
  - `gl_PrimitiveIDIn`: current input primitive’s ID
  - `gl_InvocationID`: current instance
Geometry Shader Outputs

- type of output primitive generated specified by layout qualifier, which is one of: points, line_strip, triangle_strip
- can generate zero or more output primitives
- maximum number of vertices that can be generated specified by max_vertices layout qualifier
- per-vertex outputs:
  - `vec4 gl_Position`: vertex position
  - `float gl_PointSize`: pixel width/height of point being rasterized; only used for point primitive
  - `float gl_ClipDistance[]`: distance to clipping planes
- per-primitive outputs:
  - `vec4 gl_PrimitiveID`: primitive ID to pass to fragment shader
- `EmitVertex` called to process vertex outputs after all per-vertex outputs set
- after `EmitVertex` called, output variables have undefined values
- `EndPrimitive` called to signal end of primitive in order to start next output primitive
- not required to call `EndPrimitive` after last output primitive
Geometry Shader Example (Passthrough)

```cpp
// use version 3.30 of GLSL (core profile)
#version 330

// input primitives are triangles
layout(triangles) in;

// input variable for color
in vec3 vColor[];

// output primitives are triangle strips
// at most three vertices will be generated
layout(triangle_strip, max_vertices = 3) out;

// output variable for color
out vec3 gColor;

void main() {
    // for each vertex of input triangle...
    for (int i = 0; i < 3; ++i) {
        // set position and color of output vertex
        gl_Position = gl_in[i].gl_Position;
        gColor = vColor[i];
        // mark vertex as finished
        EmitVertex();
    }
    EndPrimitive(); // optional
}
```
Using Shader Programs

- Shaders need to be compiled and linked to yield executable shader program.
- OpenGL provides compiler and linker.
- Normally, a program should have vertex and fragment shaders.
- To generate an executable shader program:
  1. Create a program via `glCreateProgram`.
  2. For each shader in the program:
     1. Create a shader via `glCreateShader`.
     2. Load shader source via `glShaderSource`.
     3. Compile shader source to object code via `glCompileShader` and check status of compile via `glGetShaderiv`.
     4. Attach shader object code to program via `glAttachShader`.
  3. Link the program via `glLinkProgram` and check status of link via `glGetProgramiv`.

- Shader program currently in use selected via `glUseProgram`.
- Shader and program can be deleted when no longer needed via `glDeleteShader` and `glDeleteProgram`.

Copyright © 2015–2021 Michael D. Adams
Identifying Shader Variables in Application

- Application program needs means to refer to attribute and uniform variables in shaders (e.g., in order to associate data with such variables).

- Each attribute and uniform variable has integer identifier known as **location**.

- Location used as means to unambiguously name shader variable.

- GLSL provides mechanism to force variable to have particular location via **location layout** qualifier.

- Location of variable can be queried by name (which is most useful when **location layout** qualifier not employed).

- Can force attribute variable to use particular location via **glBindAttribLocation** prior to linking shader program.
get location of shader variable via `glGetAttribLocation`

example: query location of attribute variable `aPosition`:

```cpp
GLuint program; // shader program ID
// ...
GLint loc = glGetAttribLocation(program, "aPosition");
```

get location of uniform variable via `glGetUniformLocation`

example: query location of uniform variable `uModelViewProjMatrix`:

```cpp
GLuint program; // shader program ID
// ...
GLint loc = glGetUniformLocation(program, "uModelViewProjMatrix");
```
application program needs to be able to associate shader attribute variable with data source (namely, data in VBO of VAO)

to associate data in (VBO of) VAO with attribute variable in vertex shader, call `glVertexAttribPointer` when VAO/VBO containing attribute data is bound

**invocation of `glVertexAttribPointer` specifies:**
- location of vertex attribute variable
- number of components per vertex attribute (e.g., 1, 2, 3, or 4)
- type of each component (e.g., `GL_FLOAT` or `GL_DOUBLE`)
- whether fixed-point values should be normalized (e.g., to \([-1, 1]\) for signed values and \([0, 1]\) for unsigned values)
- stride (i.e., byte offset) between consecutive vertex attributes in array
- offset of first component of first vertex attribute in array

**to enable use of attribute data associated with VAO, call `glEnableVertexAttribArray` when VAO containing attribute data is bound**
Example: Associating Data in VAO with Attribute Variable

Part of Vertex Shader

```glsl
in vec3 aPosition;
```

Part of Application Program

```c
GLuint program; // program ID
GLuint vao; // VAO ID
GLuint vbo; // VBO ID
GLuint offset; // offset of data in VBO
GLsizei stride; // stride of data in VBO
// ...
GLint loc = glGetAttribLocation(program,
   "aPosition");
glBindVertexArray(vao);
glBindBuffer(GL_ARRAY_BUFFER, vbo);
glVertexAttribPointer(loc, 3, GL_FLOAT, GL_FALSE,
   stride,
   reinterpret_cast<GLvoid*>(offset));
 glEnableVertexAttribArray(loc);
```
Application program needs to be able to access uniform variables in shader.

Application can only write to uniform variables since data flows in one direction only (i.e., from application to shader).

Uniform variable identified by location.

To modify uniform variable, must know its location.

Modify uniform variable via `glUniform*` (which identifies variable to change by its location).

Example:

Part of Shader

```c
uniform float uTime;
```

Part of Application Program

```c
GLuint program; // shader program ID
// ...
GLint loc = glGetUniformLocation(program, "uTime");
glUniform1f(loc, 1.5f);
```
Section 5.6.3

Shader Examples
Simple: Shader Example

- vertex shader provided with two attributes per vertex (position and color)
- want smooth interpolation of color across faces
- rendering output shown below for mesh consisting of single triangle
Simple: Vertex and Fragment Shaders

### Vertex Shader
```
#version 330

in vec4 aPosition; // input vertex position attribute
in vec4 aColor; // input vertex color attribute

out vec4 vColor; // output vertex color (interpolated)

// uniform variable for modelview-projection
// matrix product
uniform mat4 uModelViewProjMatrix;

void main() {
    vColor = aColor;
    gl_Position = uModelViewProjMatrix * aPosition;
}
```

### Fragment Shader
```
#version 330

in vec4 vColor; // input color (interpolated)

out vec4 fColor; // output fragment color

void main() {
    fColor = vColor;
}
```
render triangles to cover entire drawing area and texture map Mandelbrot set onto triangles using fragment shader

some examples of rendering results shown below
Mandelbrot set: set of all complex numbers $c$ such that sequence $z_0, z_1, z_2, \ldots$ does not tend toward infinity, where

$$z_n = \begin{cases} \frac{z_{n-1}^2 + c}{c} & \text{if } n \geq 1 \\ c & \text{if } n = 0 \end{cases}$$

associate rectangular region in complex plane with graphics viewport

for point corresponding to each pixel in viewport, determine number of steps in above iterative process for which result does not become too large (i.e., tending towards infinity)

assign color to each pixel depending on obtained iteration count
Mandelbrot: Application Program

\[
\begin{align*}
v_0 &= (-1, -1) & v_1 &= (1, -1) \\
t_0 &= (-\frac{1}{2}, -\frac{1}{2}) & t_1 &= (\frac{1}{2}, -\frac{1}{2}) \\
v_3 &= (-1, 1) & v_2 &= (1, 1) \\
t_3 &= (-\frac{1}{2}, \frac{1}{2}) & t_2 &= (\frac{1}{2}, \frac{1}{2})
\end{align*}
\]

- application program simply renders two triangles that cover full extent of viewport (\( \{v_k\} \) are positional coordinates; \( \{t_k\} \) are texture coordinates)
- texture coordinate region \([\frac{-1}{2}, \frac{1}{2}] \times [\frac{-1}{2}, \frac{1}{2}]\) corresponds to full viewport
- square region in complex plane of width/height \(\text{scale}\) centered at point \text{center} is mapped onto region \([\frac{-1}{2}, \frac{1}{2}] \times [\frac{-1}{2}, \frac{1}{2}]\) in texture coordinates
Mandelbrot: Vertex Shader

```cpp
#version 330

in vec3 aPosition; // position vertex attribute
in vec3 aTexCoord; // texture-coordinate vertex attribute

out vec3 vTexCoord; // texture coordinate (interpolated)

void main() {
    vTexCoord = aTexCoord;
    gl_Position = vec4(aPosition, 1.0);
}
```
#version 330

in vec3 vTexCoord; // texture coordinates

out vec4 fColor; // vertex color

uniform vec2 center; // center of viewing region
uniform float scale; // width/height of viewing region
uniform int maxIters; // maximum iteration count

int mandelbrot(vec2 c) {
    vec2 z = vec2(0.0, 0.0);
    int i;
    for (i = 0; i < maxIters; ++i) {
        z = vec2(z.x * z.x - z.y * z.y + c.x, 2.0 * z.x * z.y + c.y);
        if (length(z) > 2.0) {break;}
    }
    return i;
}

float lookup(float x, float c) {return c * mod(x, 1.0 / c);}

void main() {
    int i = mandelbrot(vec2(scale * vTexCoord.x + center.x,
        scale * vTexCoord.y + center.y));
    float t = float(i) / maxIters;
    fColor = vec4(lookup(t, 2.0), lookup(t, 4.0), lookup(t, 8.0), 1.0);
}
ShrinkFace: Shader Example

- use geometry shader to shrink triangles sent to rendering pipeline
- triangles contracted towards their centroid so that triangles that were originally touching now have gap between them
- example rendering results are shown below

Rendered Normally

Rendered with Shrunken Faces
ShrinkFace: Triangle Shrinking

- Each vertex $v_k$ moved in direction of centroid $c$ to new position $v'_k = \frac{1}{2}(v_k + c)$ (i.e., midpoint of $v_k$ and $c$)
- Gap formed by shrinking of triangle is filled with new triangles drawn in black
ShrinkFace: Gap Filling

- gap can be filled with triangle strip with vertices: $v_2, v'_2, v_1, v'_1, v_0, v'_0, v_2, v'_2$
#version 330

in vec3 aPosition; // position vertex attribute
in vec3 aColor;  // color vertex attribute

out vec3 vColor; // color (interpolated)

void main() {
    gl_Position = vec4(aPosition, 1.0);
    vColor = aColor;
}
ShrinkFace: Geometry Shader

```
#version 330

layout(triangles) in;  // triangle primitives as input
in vec3 vColor[];     // input vertex colors

layout(triangle_strip, max_vertices=11) out;   // triangle strips as output; at most 11 vertices
out vec3 gColor;      // output color (interpolated)

uniform mat4 uModelViewProjMatrix;            // modelview-projection matrix product
```
void main() {
    vec3 v[6];
    for (int i = 0; i < 3; ++i) {v[i] = gl_in[i].gl_Position.xyz;}

    // compute centroid of triangle
    vec3 c = (v[0] + v[1] + v[2]) / 3.0;

    // compute vertices of shrunk triangle and generate
    // triangle strip consisting only of shrunk triangle
    for (int i = 0; i < 3; ++i) {
        v[i + 3] = c + 0.5 * (v[i] - c);
        gl_Position = uModelViewProjMatrix * vec4(v[i + 3], 1.0);
        gColor = vColor[i];
        EmitVertex();
    }
    EndPrimitive();

    // generate triangle strip to fill gap between triangles
    // introduced by shrinking
    const int lut[] = int[](2, 5, 1, 4, 0, 3, 2, 5);
    for (int i = 0; i < 8; ++i) {
        gl_Position = uModelViewProjMatrix * vec4(v[lut[i]], 1.0);
        gColor = vec3(0.0, 0.0, 0.0);
        EmitVertex();
    }
}
#version 330

in vec3 gColor; // input color

out vec4 fColor; // output color

void main() {
    fColor = vec4(gColor, 1.0);
}
use geometry shader to assist in superimposing wireframe on rendered surface

example rendering output shown below

Without Edges Shown

Edges Shown Using Shader
- Points on edge of triangle must have exactly one or two barycentric coordinates equal to zero, while points in the interior must have three nonzero coordinates.
- If at least one of barycentric coordinates is small, must be in vicinity of edge.
- If in vicinity of edge, use different color.
// Wireframe: Vertex Shader

#define version 330

in vec3 aPosition; // position vertex attribute
in vec3 aColor; // color vertex attribute

out vec3 vColor; // output color (interpolated)

uniform mat4 uModelViewProjMatrix;
    // modelview-projection matrix product

void main() {
    gl_Position = uModelViewProjMatrix * vec4(aPosition, 1.0);
    vColor = aColor;
}

#version 330

layout(triangles) in; // triangles as input
in vec3 vColor[]; // vertex colors

layout(triangle_strip, max_vertices=3) out;
// triangle strips as output; at most 3 vertices
out vec3 gColor; // output color

noperspective out vec3 gBaryCoord;
// output barycentric coordinates (interpolated)

void main() {
    const vec3 lut[3] = vec3[3](
        vec3(1.0, 0.0, 0.0),
        vec3(0.0, 1.0, 0.0),
        vec3(0.0, 0.0, 1.0));
    for (int i = 0; i < 3; ++i) {
        gl_Position = gl_in[i].gl_Position;
        gBaryCoord = lut[i];
        gColor = vColor[i];
        EmitVertex();
    }
}

Wireframe: Fragment Shader

```cpp
#version 330

in vec3 gColor; // input color
noperspective in vec3 gBaryCoord;
    // input barycentric coordinates

out vec4 fColor; // output color

void main() {
    const vec3 edgeColor = vec3(0.0, 0.0, 0.0);
    const float edgeWidth = 1.0;
    vec3 d = fwidth(gBaryCoord);
    vec3 a3 = smoothstep(vec3(0.0), d * edgeWidth, gBaryCoord);
    float v = min(min(a3.x, a3.y), a3.z);
    fColor = vec4(mix(edgeColor, gColor, v), 1.0);
}
```

- upper threshold for smoothstep chosen relative to approximate gradient magnitude so thickness of edges in wireframe same regardless of triangle size
- simpler code for calculating `a3` shown below would cause thickness of edges in wireframe to depend on triangle size, which would be less aesthetically pleasing:

  ```cpp
  vec3 a3 = smoothstep(vec3(0.0), vec3(0.02), gBaryCoord);
  ```
Ambient-Diffuse-Specular (ADS) Lighting Model

- **light properties:**
  - $\ell_a$: ambient component of light source
  - $\ell_d$: diffuse component of light source
  - $\ell_s$: specular component of light source

- **material properties:**
  - $k_a$: ambient reflection constant
  - $k_d$: diffuse reflection constant
  - $k_s$: specular reflection constant
  - $\alpha$: shininess constant

- **vectors:**
  - $\ell$: unit vector vector in direction from point on surface to light source
  - $n$: unit normal at point on surface
  - $v$: unit vector in direction from point on surface to viewer
  - $r$: unit vector in direction that perfectly reflected light ray would take from this point on surface (i.e., $r = 2(\ell \cdot n)n - \ell$)

- **illumination $i$ of point on surface given by:**

$$i = k_a \ell_a + \max \{(\ell \cdot n), 0\} k_d \ell_d + \max \{(r \cdot v)^\alpha, 0\} u(\ell \cdot n) k_s \ell_s$$

where $u$ is unit-step function
- $\ell$: unit vector vector in direction from point on surface to light source
- $n$: unit normal at point on surface
- $v$: unit vector in direction from point on surface to viewer
- $r$: unit vector in direction that perfectly reflected light ray would take from this point on surface
Per-Vertex Lighting: Shader Example

- per-vertex lighting using ambient-diffuse-specular (ADS) model
- example rendering result shown below
#version 330

in vec3 aPosition; // position vertex attribute
in vec3 aNormal; // normal vertex attribute

out vec3 vColor; // output color (interpolated)

uniform mat4 uModelViewMatrix; // modelview matrix
uniform mat3 uNormalMatrix; // normal transformation matrix
uniform mat4 uModelViewProjMatrix;
    // modelview-projection matrix product

struct LightSourceParams {
    vec4 position; // position
    vec3 ambient; // ambient component
    vec3 diffuse; // diffuse component
    vec3 specular; // specular component
};
uniform LightSourceParams uLight; // light parameters

struct MaterialParams {
    vec3 ambient; // ambient reflectance
    vec3 diffuse; // diffuse reflectance
    vec3 specular; // specular reflectance
    float shininess; // specular exponent
};
uniform MaterialParams uMaterial; // material parameters
vec3 ads(vec4 position, vec3 normal) {
    vec3 s = normalize(vec3(uLight.position - position));
    vec3 v = normalize(-position.xyz);
    vec3 r = reflect(-s, normal);
    float sn = dot(s, normal);
    vec3 ambient = uLight.ambient * uMaterial.ambient;
    vec3 diffuse = uLight.diffuse * uMaterial.diffuse * max(sn, 0.0);
    diffuse = clamp(diffuse, 0.0, 1.0);
    vec3 specular = (sn > 0.0) ? (uLight.specular * uMaterial.specular * pow(max(dot(r, v), 0.0), uMaterial.shininess)) : vec3(0.0);
    specular = clamp(specular, 0.0, 1.0);
    return clamp(ambient + diffuse + specular, 0.0, 1.0);
}

void main() {
    vec3 eyeNorm = normalize(uNormalMatrix * aNormal);
    vec4 eyePos = uModelViewMatrix * vec4(aPosition, 1.0);
    vColor = ads(eyePos, eyeNorm);
    gl_Position = uModelViewProjMatrix * vec4(aPosition, 1.0);
}
```glsl
#version 330

in vec3 vColor; // input color

out vec4 fColor; // output color

void main() {
    fColor = vec4(vColor, 1.0);
}
```
Per-Fragment Lighting: Shader Example

- per-fragment lighting using ambient-diffuse-specular (ADS) model
- example rendering result shown along with per-vertex lighting result for comparison
#version 330

in vec3 aPosition; // position vertex attribute
in vec3 aNormal; // normal vertex attribute

out vec3 vPosition; // output position (interpolated)
out vec3 vNormal; // output normal (interpolated)

uniform mat4 uModelViewMatrix; // modelview matrix
uniform mat3 uNormalMatrix; // normal transformation matrix
uniform mat4 uModelViewProjMatrix;
    // modelview-projection matrix product

void main() {
    vNormal = normalize(uNormalMatrix * aNormal);
    vPosition = vec3(uModelViewMatrix * vec4(aPosition, 1.0));
    gl_Position = uModelViewProjMatrix * vec4(aPosition, 1.0);
}
#version 330

in vec3 vNormal; // input normal
in vec3 vPosition; // input position

out vec4 fColor; // output color

struct LightSourceParams {
  vec4 position; // position
  vec3 ambient; // ambient component
  vec3 diffuse; // diffuse component
  vec3 specular; // specular component
};

uniform LightSourceParams uLight; // light parameters

struct MaterialParams {
  vec3 ambient; // ambient reflectance
  vec3 diffuse; // diffuse reflectance
  vec3 specular; // specular reflectance
  float shininess; // specular exponent
};

uniform MaterialParams uMaterial; // material parameters
```cpp
vec3 ads(vec4 position, vec3 normal) {
    vec3 s = normalize(vec3(uLight.position - position));
    vec3 v = normalize(-position.xyz);
    vec3 r = reflect(-s, normal);
    float sn = dot(s, normal);
    vec3 ambient = uLight.ambient * uMaterial.ambient;
    vec3 diffuse = uLight.diffuse * uMaterial.diffuse * max(sn, 0.0);
    diffuse = clamp(diffuse, 0.0, 1.0);
    vec3 specular = (sn > 0.0) ? uLight.specular * uMaterial.specular * pow(max(dot(r, v), 0.0), uMaterial.shininess) : vec3(0.0);
    specular = clamp(specular, 0.0, 1.0);
    return clamp(ambient + diffuse + specular, 0.0, 1.0);
}

void main() {
    fColor = vec4(ads(vec4(vPosition, 1.0), vNormal), 1.0);
}
```
Section 5.6.4

OpenGL Example Programs
simple 2-D graphics

draws points, lines, triangle, and quadrilateral
OpenGL Example Program: `simple_3d`

- simple 3-D graphics
- draws and animates several simple polyhedra
OpenGL Example Program: \textit{cube}

- 3-D graphics with lighting
- draws cube with lighting
- wireframe mesh viewer
- allows polygon mesh to viewed as wireframe
Section 5.6.5

References


10. OpenGL Software Development Kit (SDK),
    https://www.opengl.org/sdk (full documentation on each OpenGL function can be found at http://www.opengl.org/sdk/docs/man). 
11. Khronos Group on YouTube, 
    https://www.youtube.com/user/khronosgroup.
Software

- OpenGL Extension Wrangler Library (GLEW)
  http://glew.sourceforge.net
  http://www.opengl.org/sdk/libs/GLEW

- OpenGL FrameWork (GLFW) Library
  http://www.glfw.org

- OpenGL Utility Toolkit (GLUT) Library
  http://sourceforge.net/projects/freeglut

- OpenGL Mathematics (GLM) Library
  http://glm.g-truc.net

- Qt Library
  http://www.qt.io
  http://www.qt.io/developers
Section 5.7

Other Libraries
Numerical Libraries I

- **Eigen**
  - C++ library for linear algebra
  - web site: [http://eigen.tuxfamily.org](http://eigen.tuxfamily.org)

- **Lapack++**
  - C++ library for high-performance linear-algebra computations
  - C++ wrapper for LAPACK and BLAS
  - web site: [http://lapackpp.sourceforge.net](http://lapackpp.sourceforge.net)

- **Armadillo**
  - C++ library for linear algebra

- **GNU Scientific Library**
  - C library for numerical analysis

- **GNU Multiprecision Library**
  - C library for arbitrary-precision arithmetic
  - web site: [http://gmplib.org](http://gmplib.org)
Numerical Libraries II

- Boost.uBLAS
  - C++ library for numerical computation
  - web site: http://www.boost.org/doc/libs/release/libs/numeric/ublas

- Boost.Rational
  - C++ rational number library
  - web site: www.boost.org/doc/libs/release/libs/rational

- Boost.Interval
  - C++ interval arithmetic library

- Boost.Math
  - C++ library
  - provides math constants, GCD, LCM, quaternions, and more
  - web site: http://www.boost.org/doc/libs/release/libs/math

- Linear Algebra Package (LAPACK)
  - Fortran library for numerical computing
Basic Linear Algebra Subprograms (BLAS)

- de facto API for publishing libraries to perform basic linear algebra operations
- written in Fortran
- web site: http://www.netlib.org/blas
Part 6

Programming
Section 6.1

Good Programming Practices
Be consistent with the *formatting* of the source code (e.g., indentation strategy, tabs versus spaces, spacing, brackets/parentheses).

Avoid a formatting style that runs against common practices.

Be consistent in the *naming conventions* used for identifiers (e.g., names of objects, functions, namespaces, types) and files.

Avoid bizarre naming conventions that run against common practices.

*Comment* your code. If code is well documented, it should be possible to quickly ascertain what the code is doing without any prior knowledge of the code.

Use *meaningful names* for identifiers (e.g., names of objects, functions, types, etc.). This improves the readability of code.

Avoid *magic literal constants*. Define a constant object and give it a meaningful name.

```cpp
constexpr double miles_per_kilometer = 0.621371;
```
Error Handling

- If a program requires that certain *constraints on user input* be satisfied in order to work correctly, do not assume that these constraints will be satisfied. Instead, always check them.

- Always handle errors *gracefully*.

- Provide *useful* error messages.

- Always *check return codes*. Even if the operation/function theoretically cannot fail (under the assumption of bug-free code), in practice it may fail due to a bug.

- If an operation is performed that can fail, check the *status of the operation* to ensure that it did not fail (even if you think that it should not fail). For example, check for error conditions on streams.

- If a function can fail, always check its *return value*. 
Do not *unnecessarily complicate* code. Use the simplest solution that will meet the needs of the problem at hand.

Do not impose *bogus limitations*. If a more general case can be handled without complicating the code and this more general case is likely to be helpful to handle, then handle this case.

Do not *unnecessarily optimize* code. Highly optimized code is often much less readable. Also, highly optimized code is often more difficult to write correctly (i.e., without bugs). Do not write grossly inefficient code that is obviously going to cause performance problems, but do not optimize things beyond avoiding gross inefficiencies that you know will cause performance problems.
Avoid *duplication* of code. If similar code is needed in more than one place, put the code in a function. Also, utilize templates to avoid code duplication.

The avoidance of code duplication has many advantages.

1. It simplifies code understanding. (Understand once, instead of $n$ times.)
2. It simplifies testing. (Test once, instead of $n$ times.)
3. It simplifies debugging. (Fix bugs in one place, instead of $n$ places.)
4. It simplifies code maintenance. (Change code in one place, instead of $n$ places.)

Make good use of the available *libraries*. Do not reinvent the wheel. If a library provides code with the needed functionality, use the code in the library.
Avoid *multiple returns paths* (i.e., multiple points of exit) in functions when they serve to complicate (rather than simplify) code structure.

Whenever possible, avoid the use of *global state* (i.e., global variables).

Ensure that the code is *const correct*.

If an object does not need to change, make it const (or constexpr). This improves the readability of code. This also helps to ensure const correctness of code.

Whenever possible, avoid placing identifiers (such as the names of variables, functions, and types) in the global namespace.

Avoid bringing many unknown identifiers into scope. For example, avoid constructs like:

```cpp
using namespace std;
```

Only bring identifiers into scope if they are truly needed.
Whenever possible, avoid relying on behavior that is not promised by the language, as this can lead to brittle code. Avoid invoking undefined behavior. Whenever possible, avoid relying on unspecified or implementation-defined behavior.

Whenever possible, avoid relying on undocumented features of libraries, as this can lead to brittle code.

Enable compiler warning messages. Pay attention to warning messages issued by the compiler.

Learn how to use a source-level debugger. There will be times when you will absolutely need it.

Be careful to avoid using references, pointers, iterators that do not reference valid data. Always be clear about which operations invalidate references, pointers, and iterators.
- **precondition**: condition that must be true before function is called
  - for example, precondition for function that computes square root of $x$: $x \geq 0$
- **postcondition**: condition that must be true after function is called
  - for example, postcondition for function that removes entry from table of size $n$: new size of table $n - 1$
- whenever feasible, check for violations of preconditions and postconditions for functions
- if precondition or postcondition is violated at run time, terminate program immediately in order to help in localizing bug (e.g., by using `assert` or calling `std::abort` or `std::terminate`)
The single most important thing when writing code is that it does the job it was intended to do correctly. That is, there should not be any bugs.

Test your code. If you do not spend as much time testing your code as you do writing it, you are likely not doing enough testing.

Tests should exercise as much of the code as possible (i.e., provide good code coverage).

Design and structure your code so that it is easy to test. In other words, testing should be considered during design.

Your code will have bugs. Design your code so that it will help you to isolate bugs. Use assertions. Use preconditions and postconditions.

Design your code so that is modular and can be written and tested in pieces. The first testing of the software should never be testing the entire software as a whole.

Often in order to adequately test code, one has to write separate specialized test code.
**subscripting operator for 1-D array class:**

```cpp
template <class T>
const T& Array_1<T>::operator[](int i) const {
    // Precondition: index is in allowable range
    assert(i >= 0 && i < data_.size());
    return data_[i];
}
```

**function taking pointer parameter:**

```cpp
int stringLength(const char* ptr) {
    // Precondition: pointer is not null
    assert(ptr);
    // Code to compute and return string length.
    // ...
}
```

**function that modifies highly complicated data structure:**

```cpp
void modifyDataStructure(Type& dataStructure) {
    // Precondition: data structure is in valid state
    assert(isDataStructureValid(dataStructure));
    // Complicated code to update data structure.
    // ...
    // Postcondition: data structure is in valid state
    assert(isDataStructureValid(dataStructure));
}
```
Section 6.2

Algorithms
Software Performance

- two most basic performance measures, which are often of most interest:
  1. time complexity
  2. space complexity

- **time complexity**: amount of time required to execute code
- **space complexity**: amount of memory needed for code execution

- normally must consider both time and space complexities, since one type of complexity can often be traded off for other

- from practical standpoint, real-world time and memory usage are what matter most (as opposed to some approximate theoretical measures of code complexity)

- need techniques that can provide guidance when designing software so that more likely that later implementation (of design) will have acceptable performance

- many factors can potentially impact performance, including:
  - CPU instruction count
  - cache efficiency
  - degree of parallelism and concurrency
  - resource utilization (e.g., memory, disk, and network)
algorithms can be measured in machine-independent way using random-access machine (RAM) model

model assumes single processor

instructions executed sequentially with no concurrent operations

elementary types: integer and floating point numbers

each elementary operation takes one time unit

elementary operations include:

- arithmetic operations (e.g., addition, subtraction, multiplication, division) on elementary types
- loads and stores of elementary types
- branch operations (e.g., conditional branch, jump)
- subroutine call

loops and subroutines are not considered elementary operations, but rather as composition of numerous elementary operations

each memory access takes one time unit

unbounded amount of memory available
Worst-Case, Average, and Amortized Complexity

- complexity expressed as function of input problem size
- **worst-case complexity**: gives upper bound on complexity of algorithm for any input of given size
- **average complexity**: gives average complexity of algorithm in statistical sense if probability measure assigned to all inputs of given size
- often algorithm may only approach worst-case complexity for very small fraction of possible inputs, in which case average complexity might be more practically useful than worst-case complexity
- sometimes algorithm may be invoked many times and cost of single invocation difficult to determine in isolation (e.g., time complexity of `push_back` member function of `std::vector`)
- **amortized complexity**: complexity per invocation of algorithm evaluated over sequence of invocations
- amortized complexity makes guarantee about total expense of sequence of invocations of algorithm, rather than single invocation (e.g., `push_back` member function of `std::vector` takes amortized constant time)
Asymptotic analysis deals with behavior of algorithm as problem size becomes arbitrarily large.

**asymptotic complexity**: complexity of algorithm in limit as problem size becomes *arbitrarily large*.

Often interested in:
- asymptotic time complexity
- asymptotic space complexity

Asymptotic time and space complexities of algorithm often much easier to determine than exact running time and memory usage.

Often (but not always!) algorithm that is asymptotically more efficient will be best choice for all but very small inputs.

Asymptotic notation (to be discussed next) provides way to describe functions that is very useful for asymptotic analysis.
**Big-Theta (Θ) Notation**

- **big-theta (Θ) notation**: for function $g$, $\Theta(g)$ denotes the set of all functions $f$ for which positive constants $c_1$, $c_2$, and $n_0$ exist such that

\[ 0 \leq c_1 g(n) \leq f(n) \leq c_2 g(n) \quad \text{for all } n \geq n_0 \]

- Functions in $\Theta(g)$ grow asymptotically at *same* rate as $g$ (to within constant factor).

- Effectively, $f(n)$ is sandwiched between $c_1 g(n)$ and $c_2 g(n)$ for sufficiently large $n$ (i.e., $n \geq n_0$).

- Used to provide (asymptotic) *lower and upper bounds* on function, each to within constant factor (provides asymptotically tight bound).

- If $f \in \Theta(g)$, then for sufficiently large $n$, $f(n)$ equals $g(n)$ to within constant factor.

- Examples:
  - $f(n) = an^2 + bn + c$ where $a, b, c$ are constants and $a > 0$; $f \in \Theta(n^2)$ but $f \not\in \Theta(n)$ and $f \not\in \Theta(n^3)$
  - $f(n) = \sum_{i=0}^{d} a_i n^i$ where $\{a_i\}$ are constants and $a_d > 0$; $f \in \Theta(n^d)$ but $f \not\in \Theta(n^{d+1})$ and $f \not\in \Theta(n^{d-1})$
Big-Theta ($\Theta$) Notation (Continued)

- $f \in \Theta(g)$
- For $n \geq n_0$, $f(n)$ is **lower bounded** by $c_1g(n)$ and **upper bounded** by $c_2g(n)$
- Asymptotically, $f$ grows at **same** rate as $g$ to within constant factor
**Big-Oh (O) Notation**

- **big-oh (O) notation**: for function $g$, $O(g)$ denotes set of all functions $f$ for which positive constants $c$ and $n_0$ exist such that
  \[
  0 \leq f(n) \leq cg(n) \quad \text{for all } n \geq n_0
  \]

- Functions in $O(g)$ grow asymptotically at rate **at most** that of $g$ (to within constant factor)

- Used to provide (asymptotic) **upper bound** on function to within constant factor

- If $f \in O(g)$, then for sufficiently large $n$, $f(n)$ is less than or equal to $g(n)$ to within constant factor

- Since $\Theta(g(n)) \subset O(g(n))$, $f(n) \in \Theta(g(n))$ implies $f(n) \in O(g(n))$

- Often used to bound worst-case running time of algorithm

- Examples:
  - $f(n) = 3n^2 + 2n + 1$; $f \in O(n^2)$ and $f \in O(n^3)$ but $f \notin O(n)$
  - $f(n) = 5n + 42$; $f \in O(n)$ and $f \in O(n^2)$ but $f \notin O(1)$
  - $f(n) = \sum_{i=0}^{d} a_i n^i$ where $\{a_i\}$ are constants and $a_d > 0$;
    $f \in O(n^d)$ and $f \in O(n^{d+1})$ but $f \notin O(n^{d-1})$
\[ f \in O(g) \]

for \( n \geq n_0 \), \( f(n) \) is upper bounded by \( cg(n) \)

asymptotically, \( f \) grows at rate no greater than that of \( g \) to within constant factor
Big-Omega ($\Omega$) Notation

- **big-omega ($\Omega$) notation**: for function $g$, $\Omega(g)$ denotes set of all functions $f$ for which positive constants $c$ and $n_0$ exist such that
  \[ 0 \leq cg(n) \leq f(n) \quad \text{for all } n \geq n_0 \]

- Functions in $\Omega(g)$ grow asymptotically at rate *at least* that of $g$ (to within constant factor)

- Used to provide (asymptotic) *lower bound* on function to within constant factor

- If $f \in \Omega(g)$, then for sufficiently large $n$, $f(n)$ is greater than or equal to $g(n)$ to within constant factor

- Since $\Theta(g(n)) \subset \Omega(g(n))$, $f(n) \in \Theta(g(n))$ implies $f(n) \in \Omega(g(n))$

- Examples:
  - $f(n) = 5n^3 + n$; $f \in \Omega(n^3)$ and $f \in \Omega(n^2)$ but $f \not\in \Omega(n^4)$
  - $f(n) = an^2 + bn + c$ where $a, b, c$ are constants and $a > 0$;
    $f \in \Omega(n^2)$ and $f \in \Omega(n)$ but $f \not\in \Omega(n^3)$
  - $f(n) = \sum_{i=0}^{d} a_i n^i$ where $\{a_i\}$ are constants and $a_d > 0$;
    $f \in \Omega(n^d)$ and $f \in \Omega(n^{d-1})$ but $f \not\in \Omega(n^{d+1})$
Big-Omega ($\Omega$) Notation (Continued)

- $f \in \Omega(g)$
- for $n \geq n_0$, $f(n)$ lower bounded by $cg(n)$
- asymptotically, $f$ grows at rate no less than that of $g$ to within constant factor
Small-Oh ($o$) Notation

- **small-oh ($o$) notation**: for function $g$, $o(g)$ denotes set of all functions $f$ such that, for any positive constant $c$, positive constant $n_0$ exists such that

\[ 0 \leq f(n) < cg(n) \quad \text{for all } n \geq n_0 \]

- functions in $o(g)$ grow asymptotically at *strictly lesser* rate than $g$ (to within constant factor)

- used to provide *upper bound* on function that is *not asymptotically tight*

- $f \in o(g)$ implies that $f(n)$ becomes insignificant relative to $g(n)$ as $n$ becomes arbitrarily large (i.e., $\lim_{n \to \infty} \frac{f(n)}{g(n)} = 0$)

- examples:
  - $f(n) = 3n^3 + 2n + 1$; $f \in o(n^5)$ and $f \in o(n^4)$ but $f \not\in o(n^3)$
  - $f(n) = 2n^2$; $f \not\in o(n^2)$ but $f \in O(n^2)$
  - $f(n) = \sum_{i=0}^{d} a_i n^i$ where $\{a_i\}$ are constants and $a_d > 0$; $f \in o(n^{d+1})$ and $f \in o(n^{d+2})$ but $f \not\in o(n^d)$ and $f \not\in o(n^{d-1})$
**Small-Omega (ω) Notation**

- **small-omega (ω) notation**: for function $g$, $\omega(g)$ denotes set of all functions $f$ such that, for any positive constant $c$, positive constant $n_0$ exists such that

\[
0 \leq cg(n) < f(n) \quad \text{for all } n \geq n_0
\]

- functions in $\omega(g)$ grow asymptotically at **strictly greater** rate than $g$ (to within constant factor)

- used to provide **lower bound** on function that is not **asymptotically tight**

- $f \in \omega(g)$ implies that $f(n)$ becomes arbitrarily large relative to $g(n)$ as $n$ becomes arbitrarily large (i.e., $\lim_{n \to \infty} \frac{f(n)}{g(n)} = \infty$)

- examples:
  - $f(n) = 3n^2$; $f \in \omega(n)$ but $f \not\in \omega(n^2)$
  - $f(n) = an^2 + bn + c$ where $a, b, c$ are constants and $a > 0$; $f \in \omega(n)$ and $f \in \omega(1)$ but $f \not\in \omega(n^2)$ and $f \not\in \omega(n^3)$
  - $f(n) = \sum_{i=0}^{d} a_i n^i$ where $\{a_i\}$ are constants and $a_d > 0$; $f \in \omega(n^{d-1})$ but $f \not\in \omega(n^d)$ and $f \not\in \omega(n^{d+1})$
Asymptotic Notation in Equations and Inequalities

- when asymptotic notation stands alone on right-hand side of equation, equal sign means set membership
- for example:
  - $f(n) = \Theta(g(n))$ means $f(n) \in \Theta(g(n))$
- more generally, when asymptotic notation appears in formula, interpreted as placeholder for some anonymous function
- for example:
  - $3n^2 + 2n + 1 = 3n^2 + \Theta(n)$ means $3n^2 + 2n + 1 = 3n^2 + f(n)$ where $f(n)$ is some function in $\Theta(n)$ (i.e., $f(n) = 2n + 1 \in \Theta(n)$)
- using asymptotic notation in this way can help to reduce clutter in formulas
Properties of $\Theta$, $O$, and $\Omega$

- **Sum of functions:**
  - If $f_1 \in \Theta(g)$ and $f_2 \in \Theta(g)$, then $f_1 + f_2 \in \Theta(g)$
  - If $f_1 \in O(g)$ and $f_2 \in O(g)$, then $f_1 + f_2 \in O(g)$
  - If $f_1 \in \Omega(g)$ and $f_2 \in \Omega(g)$, then $f_1 + f_2 \in \Omega(g)$

- **Multiplication by constant:**
  - For all positive functions $f$ and all positive constants $a$, $af \in \Theta(f)$, $af \in O(f)$, and $af \in \Omega(f)$

- **Product of functions:**
  - For all positive functions $f_1, f_2, g_1, g_2$, if $f_1 \in \Theta(g_1)$ and $f_2 \in \Theta(g_2)$, then $f_1 f_2 \in \Theta(g_1 g_2)$
  - For all positive functions $f_1, f_2, g_1, g_2$, if $f_1 \in O(g_1)$ and $f_2 \in O(g_2)$, then $f_1 f_2 \in O(g_1 g_2)$
  - For all positive functions $f_1, f_2, g_1, g_2$, if $f_1 \in \Omega(g_1)$ and $f_2 \in \Omega(g_2)$, then $f_1 f_2 \in \Omega(g_1 g_2)$

- **Examples:**
  - If $f \in \Theta(n)$, then $nf(n) \in \Theta(n^2)$
  - If $f$ and $g$ are positive functions in $\Theta(1)$, then $f + g \in \Theta(1)$
Additional Remarks

- \( \log_2 n \in \Theta(\log_b n) \) for all \( b > 1 \) (i.e., base of logarithm does not impact asymptotic analysis)
Remarks on Asymptotic Complexity

- one must be careful in interpreting results of asymptotic complexity analysis
- asymptotic complexity only considers algorithm behavior when problem size becomes *arbitrarily large*
- for example: for problems of size \( n < 10^{10} \), algorithm \( A \) with time complexity \( f(n) = \left(\frac{1}{10^{10}}\right)n^2 \) will take less time than Algorithm \( B \) with time complexity \( g(n) = n \), in spite of fact that \( f(n) = \Theta(n^2) \) and \( g(n) = \Theta(n) \) (i.e., algorithm \( A \) has greater asymptotic complexity than algorithm \( B \))
- asymptotic complexity *hides constant factors*
- for example: for problems of size \( n \), algorithm \( A \) with time complexity \( f(n) = n \) is clearly preferable to algorithm \( B \) with time complexity \( g(n) = 1000n \), but both \( f \) and \( g \) are in \( \Theta(n) \) (i.e., both algorithms have same asymptotic complexity)
- asymptotic complexities can be used for guidance but should not be followed blindly
# Some Common Complexities

<table>
<thead>
<tr>
<th>Name</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>constant</td>
<td>$O(1)$</td>
</tr>
<tr>
<td>logarithmic</td>
<td>$O(\log n)$</td>
</tr>
<tr>
<td>fractional power</td>
<td>$O(n^c)$, $c \in (0, 1)$</td>
</tr>
<tr>
<td>linear</td>
<td>$O(n)$</td>
</tr>
<tr>
<td>log-linear</td>
<td>$O(n \log n)$</td>
</tr>
<tr>
<td>quadratic</td>
<td>$O(n^2)$</td>
</tr>
<tr>
<td>cubic</td>
<td>$O(n^3)$</td>
</tr>
<tr>
<td>exponential</td>
<td>$O(a^n)$</td>
</tr>
<tr>
<td>factorial</td>
<td>$O(n!)$</td>
</tr>
<tr>
<td>double exponential</td>
<td>$O(a^{b^n})$</td>
</tr>
</tbody>
</table>

- above complexities listed in order of *increasing* (asymptotic) growth rate
- that is, for sufficiently large $n$,
  
  $1 < \log n < \sqrt{n} < n < n \log n < n^2 < n^3 < \ldots < 2^n < n! < 2^{2^n}$
Recurrence Relations

- **recurrence relation** is equation that implicitly defines sequence in terms of itself
- for example, Fibonacci number sequence $f$ is solution to recurrence relation:
  \[
  f(n) = \begin{cases} 
  f(n-1) + f(n-2) & n \geq 2 \\
  1 & n \in \{0, 1\}
  \end{cases}
  \]
- recurrence relations often arise when trying to determine complexity of algorithm that employs recursion
- for example, consider time complexity of recursive Fibonacci algorithm:

```cpp
1  unsigned long long fibonacci(unsigned int n) {
2      if (n <= 2) {
3          return 1;
4      } else {
5          return fibonacci(n - 1) + fibonacci(n - 2);
6      }
7  }
```

- time complexity $T$ of above algorithm leads to recurrence relation
  \[
  T(n) = c + T(n-1) + T(n-2)
  \]
Solving Recurrence Relations

- no known general technique for solving recurrence relations
- solving recurrence relations somewhat of an art
- linear constant coefficient difference equations can be solved using $z$ transform
- Master theorem can be used to solve some recurrence relations of form:
  \[ f(n) = g(n) + af(n/b) \]
- Akra-Bazzi theorem can be used to solve some recurrence relations of form:
  \[ f(n) = g(n) + \sum_{i=0}^{L-1} a_i f(b_in + h_i(n)) \]
- need to be careful about non-integer sequence indices arising in recurrence relations like:
  \[ T(n) = \sum_{i=0}^{L-1} a_i T(n/b_i) + f(n) \]
- preceding formula does not make sense if $n/b_i$ is not integer
- in many cases, if this issue ignored, correct asymptotic bound still obtained, although without being correctly justified
- numerous software tools available for solving recurrence relations, such as WolframAlpha and PURRS
<table>
<thead>
<tr>
<th>Recurrence Relation</th>
<th>Solution</th>
</tr>
</thead>
</table>
| \( f(n) = \begin{cases} 
  b + f(n-1) & n \geq 2 \\
  a & n = 1 
\end{cases} \) | \( f(n) = b(n-1) + a \in \Theta(n) \) |
| \( f(n) = \begin{cases} 
  bn + f(n-1) & n \geq 2 \\
  a & n = 1 
\end{cases} \) | \( f(n) = \frac{1}{2}bn(n+1) + b - a \in \Theta(n^2) \) |
| \( f(n) = \begin{cases} 
  b + f(\lfloor n/2 \rfloor) & n \geq 2 \\
  a & n = 1 
\end{cases} \) | \( f(n) \in \Theta(\log n) \) |
| \( f(n) = \begin{cases} 
  b + f(\lceil n/2 \rceil) & n \geq 2 \\
  a & n = 1 
\end{cases} \) | \( f(n) \in \Theta(\log n) \) |
| \( f(n) = \begin{cases} 
  b + f(\lfloor n/2 \rfloor) + f(\lceil n/2 \rceil) & n \geq 2 \\
  a & n = 1 
\end{cases} \) | \( f(n) \in \Theta(n) \) |
| \( f(n) = \begin{cases} 
  bn + f(\lfloor n/2 \rfloor) + f(\lceil n/2 \rceil) & n \geq 2 \\
  a & n = 1 
\end{cases} \) | \( f(n) \in \Theta(n \log n) \) |
| \( f(n) = \begin{cases} 
  c + f(n-1) + f(n-2) & n \geq 3 \\
  b & n = 2 \\
  a & n = 1 
\end{cases} \) | \( f \in \Theta(2^n) \) |
consider algorithm for multiplying $m \times n$ matrix by $n \times p$ matrix:

```cpp
template <class T, int m, int n, int p>
void multiply(const T (&a)[m][n], const T (&b)[n][p],
             T (&c)[m][p]) {
    for (int i = 0; i < m; ++i) {
        for (int j = 0; j < p; ++j) {
            T sum = T(0);
            for (int k = 0; k < n; ++k) {
                sum += a[i][k] * b[k][j];
            }
            c[i][j] = sum;
        }
    }
}
```

total time cost per line (assuming basic operations on $T$ are $O(1)$):

<table>
<thead>
<tr>
<th>Line</th>
<th>Total Time Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>$c_{4,1}m + c_{4,2}$</td>
</tr>
<tr>
<td>5</td>
<td>$m(c_{5,1}p + c_{5,2})$</td>
</tr>
<tr>
<td>6</td>
<td>$mp(c_6)$</td>
</tr>
<tr>
<td>7</td>
<td>$mp(c_{7,1}n + c_{7,2})$</td>
</tr>
<tr>
<td>8</td>
<td>$mpn(c_8)$</td>
</tr>
<tr>
<td>10</td>
<td>$mp(c_{10})$</td>
</tr>
</tbody>
</table>

asymptotic time complexity is $a_1 mnp + a_2 mp + a_3 m + a_4 = \Theta(mnp)$
again, consider algorithm for multiplying $m \times n$ matrix by $n \times p$ matrix:

```cpp
template <class T, int m, int n, int p>
void multiply(const T (&a)[m][n], const T (&b)[n][p],
              T (&c)[m][p]) {
  for (int i = 0; i < m; ++i) {
    for (int j = 0; j < p; ++j) {
      T sum = T(0);
      for (int k = 0; k < n; ++k) {
        sum += a[i][k] * b[k][j];
      }
      c[i][j] = sum;
    }
  }
}
```

- $a$, $b$, and $c$ are references and each effectively incur memory cost of pointer
- $m$, $n$, and $p$ are constant expressions are require no storage
- assuming object of type $T$ requires $O(1)$ space, each of $a$, $b$, $c$, $i$, $j$, $k$, and $sum$, requires $\Theta(1)$ space
- asymptotic space complexity is $\Theta(1)$
Iterative Fibonacci Algorithm: Time Complexity

- consider iterative algorithm for computing \( n \)th Fibonacci number:

```c
unsigned long long fibonacci(unsigned int n) {
    unsigned long long a[3] = {1, 1, 1};
    for (int i = 3; i <= n; ++i) {
        a[0] = a[1];
        a[1] = a[2];
        a[2] = a[0] + a[1];
    }
    return a[2];
}
```

- total time cost per line (assuming \( n \geq 2 \)):

<table>
<thead>
<tr>
<th>Line</th>
<th>Total Time Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>( c_1 )</td>
</tr>
<tr>
<td>3</td>
<td>( (n - 2)c_{3,1} + c_{3,2} )</td>
</tr>
<tr>
<td>4</td>
<td>( (n - 2)c_4 )</td>
</tr>
<tr>
<td>5</td>
<td>( (n - 2)c_5 )</td>
</tr>
<tr>
<td>6</td>
<td>( (n - 2)c_6 )</td>
</tr>
<tr>
<td>8</td>
<td>( c_8 )</td>
</tr>
</tbody>
</table>

- asymptotic time complexity is

\[
(c_{3,1} + c_4 + c_5 + c_6) n + (c_1 - 2c_{3,1} + c_{3,2} - 2c_4 - 2c_5 - 2c_6 + c_8) = a_1 n + a_2 = \Theta(n)
\]
Iterative Fibonacci Algorithm: Space Complexity

- again, consider iterative algorithm for computing \( n \)th Fibonacci number:

```c
unsigned long long fibonacci(unsigned int n) {
    unsigned long long a[3] = {1, 1, 1};
    for (int i = 3; i <= n; ++i) {
        a[0] = a[1];
        a[1] = a[2];
        a[2] = a[0] + a[1];
    }
    return a[2];
}
```

- storage cost per variable:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Storage Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n )</td>
<td>( c_1 )</td>
</tr>
<tr>
<td>( a )</td>
<td>( c_2 )</td>
</tr>
<tr>
<td>( i )</td>
<td>( c_3 )</td>
</tr>
</tbody>
</table>

- asymptotic space complexity is \( c_1 + c_2 + c_3 = a_1 = \Theta(1) \)
consider recursive algorithm for computing $n$th Fibonacci number:

```c++
unsigned long long fibonacci(unsigned int n) {
    if (n <= 2) {
        return 1;
    } else {
        return fibonacci(n - 1) + fibonacci(n - 2);
    }
}
```

time cost $T(n)$ satisfies recurrence relation:

$$T(n) = \begin{cases} 
T(n - 1) + T(n - 2) + c_1 & n \geq 3 \\
c_2 & n \in \{1, 2\}
\end{cases}$$

asymptotic time complexity is $\Theta(2^n)$
again, consider recursive algorithm for computing $n$th Fibonacci number:

```c
unsigned long long fibonacci(unsigned int n) {
    if (n <= 2) {
        return 1;
    } else {
        return fibonacci(n - 1) + fibonacci(n - 2);
    }
}
```

during recursion, function calls nest to depth of at most $n - 2 = \Theta(n)$
each invocation of function incurs memory cost for local variable $n$
each function call also incurs space on stack for return address and possibly other saved state
asymptotic space complexity is $\ (n - 2)c_1 + c_0 = a_1n + a_0 = \Theta(n)$
may want to determine overall speedup that can be achieved by introducing speedup into some part of task

overall speedup $s_o$ of whole task given by

$$s_o = \frac{1}{(1 - f_e) + \frac{f_e}{s_e}},$$

where $s_e$ is speedup of part of task that benefits from enhancement and $f_e$ is fraction of time consumed by part of task benefitting from enhancement

preceding result known as Amdahl’s law

overall speedup is limited by fraction of time that enhancement can be exploited:

$$s_o \leq \frac{1}{1 - f_e} \quad \text{and} \quad \lim_{s_e \to \infty} s_o = \frac{1}{1 - f_e}$$

for example, if $f_e = 25\%$ and $s_e = 2$, then $s_o = 1.1429$
Section 6.2.1

References


Section 6.3

Data Structures
Abstract Data Types (ADTs)

- **abstract data type (ADT)** is model for data type where behavior specified from point of view of user of type (i.e., with implementation details hidden)

- ADT specifies:
  - general nature of entity represented by type
  - set of allowable states/values that type can assume
  - set of operations that can be performed on type
  - any preconditions or postconditions for operations

- often, ADT also provides complexity guarantees (e.g., time or space complexity guarantees for various operations)

- for example, (generic) integer type is ADT:
  - can assume integer values
  - provides basic arithmetic operations, relational operations, and so on
  - particular representation used for integers not specified by ADT

- in contrast to ADT, concrete (i.e., non-abstract) data type provides very specific details as to how type is implemented
Container ADTs

- **container ADT** (also called **collection ADT**): stores collection of objects, organized in way that follows some specific access rules

- operations for container ADT often include:
  - clear: remove all elements from container
  - is empty: test if container is empty (i.e., contains no elements)
  - size: query number of elements in container
  - insert: insert element in container
  - remove: remove element from container
  - find: locate element in container if present

- often container ADT provides means to traverse elements in container (e.g., via iterator ADT)

- if elements in container consist of key-value pairs where key used to find corresponding value in container, container said to be **associative**

- if elements in container have well-defined order, container said to be **ordered**; otherwise, **unordered**

- if all elements stored in container of same type, container said to be **homogeneous**; otherwise, **heterogeneous**
examples of realizations of container ADTs:
- std::array, std::vector, std::list, std::forward_list
- std::set, std::multiset, std::map, std::multimap
- std::unordered_set, std::unordered_multiset, std::unordered_map, std::unordered_multimap
- boost::intrusive::slist, boost::intrusive::list

container ADTs can differ in many ways:
- number of elements container can store (e.g., one versus multiple)
- whether values stored by container must be unique
- associative versus non-associative
- ordered versus unordered
- homogeneous versus heterogeneous
- intrusive versus nonintrusive
- concurrency properties (e.g., not thread safe, thread safe, lock free)
iterator ADT is ADT used to traverse collection of elements, which are often stored in container

typically iterator ADT provided as part of container ADT

operations provided by iterator ADT may include:
  - dereference: access element to which iterator refers
  - next: go to next element
  - previous: go to previous element
  - advance: advance by $n$ elements (where $n$ can be negative for backwards direction)

iterator specifies order in which elements can be accessed; for example:
  - forward, bidirectional (i.e., forward and backward), random access

iterator may only permit certain types of element access; for example:
  - read only (const), read and write (non-const), write only (output)
  - one dereference per element or multiple dereferences per element

examples of realizations of iterator ADT:
  - iterator and const_iterator types in numerous C++ standard library containers, such as std::vector and std::set
are elements in container stored contiguously in memory?
what is fixed storage overhead of container (if any)?
what is per-element storage overhead of container (if any)?
is container limited in size (e.g., container based on fixed size array)?
is container dynamic (i.e., can it be changed once created) or static?
can element be inserted at start, end, or arbitrary position in container in worst-case or amortized $O(1)$ time?
can element be removed at start, end, or arbitrary position in container in $O(1)$ time?
can element be accessed at start, end, or arbitrary position in $O(1)$ time?
can element be located in container efficiently (e.g., $O(\log n)$ time or better)?
- can container be traversed (e.g., via iterator) efficiently?
- what is storage cost of iterator (e.g., 1 pointer)?
- in what order can iterator access elements (e.g., forward, bidirectional, random access)?
- what circumstances result in element references being invalidated?
- what circumstances result in iterators being invalidated?
- what is per-element and amortized time cost of traversing elements in container?
Section 6.3.1

Lists, Stacks, and Queues
**List ADT**

- **List ADT** is ADT that stores countable number of ordered values, where same value may occur more than once.

  - Operations for list ADT include:
    - clear: remove all elements from list
    - is empty: test if list empty
    - size: query number of elements in list
    - insert: insert element in list
    - remove: remove element from list

  - Operations for traversing elements in list (which are often provided via iterator ADT) include:
    - successor: get next element in list
    - predecessor (optional): get previous element in list

- Examples of realizations of list ADT:
  - `std::vector`, `std::forward_list`, and `std::list`
  - `boost::intrusive::slist` and `boost::intrusive::list`
Array-Based Lists

- can represent list with array

- code example:

```cpp
template <class T> class Iterator {
  // ...
  T* ptr_;  // pointer to referenced element
};

template <class T> class List {
  // ...
  T* start_;  // pointer to start of element data
  T* finish_;  // pointer to end of element data
  T* end_;  // pointer to end of allocated storage
};
```

- array capacity (i.e., allocated size) is `end_ - start_`
- array size (i.e., number of elements) is `finish_ - start_`
Array-Based Lists: Diagram

List

start_

finish_

end_

Array of T

x_0

x_1

\vdots

x_{n-1}

x_n

x_{n+1}

\vdots

x_{m-1}

Iterator

ptr_
Remarks on Array-Based Lists

- **advantages:**
  - elements stored contiguously in memory (which is cache friendly)
  - no per-element storage overhead
  - can insert at end of list in amortized $O(1)$ time
  - can remove at end of list in $O(1)$ time
  - can access element in any position in $O(1)$ time
  - (random-access) iterator has storage cost of one pointer

- **disadvantages:**
  - cannot insert or remove at start or arbitrary position in $O(1)$ time
  - if capacity of array exceeded, memory reallocation and copying required
  - if array can be reallocated, insert at end can only at best guarantee amortized (not worst-case) $O(1)$ time
  - if array reallocated, element references invalidated

- **useful when insertion and removal only performed at end of list and stable references to elements not needed**
- **singly-linked list** is node-based implementation of list where each node tracks its successor (but not predecessor)
- null pointer used as sentinel value to denote “no such node”; for example, null pointer used to indicate:
  - no successor node for last node in list
  - no head (i.e., first) node for empty list
- for singly-linked list, insertion and removal normally defined to take place at position after that specified by iterator
- to specify insertion or removal at start of list requires “before-begin” iterator
// list node

```cpp
template <class T> struct Node {
    Node* next_; // pointer to next node in list
    T elem_; // element data
};
```

// list

```cpp
template <class T> class List {
    // ...
    Node<T>* head_; // pointer to first node in list
    std::size_t size_; // number of elements in list
};
```

// iterator

```cpp
template <class T> class Iterator {
    // ...
    Node<T>* node_; // pointer to node with referenced element
    Node<T>** head_; // pointer to list head pointer
    // one of three possibilities:
    // 1) iterator refers to before-begin position:
    //    head_ points to list head pointer and node_ is null
    // 2) iterator refers to end position:
    //    head_ and node_ both null
    // 3) iterator refers to element in list:
    //    head_ is null and node_ points to referenced node
};
```
Remarks on Singly-Linked Lists

- **advantages:**
  - can insert element after (but not before) particular position in $O(1)$ time
  - can remove element at start of list in $O(1)$ time
  - no capacity exceeded problem like with array
  - reduced memory cost relative to doubly-linked list as consequence of node not tracking predecessor
  - element references are stable
  - can find successor in list in $O(1)$ time

- **disadvantages:**
  - element data not contiguous in memory
  - has per-element storage overhead (1 pointer for successor)
  - cannot insert element before particular position in $O(1)$ time
  - cannot remove element at arbitrary position in $O(1)$ time
  - cannot efficiently iterate backwards over elements in list
  - cannot find predecessor in list in $O(1)$ time
  - (forward) iterator requires two pointers for state (due to need for “before-begin” iterator)

- typically useful when insertions and removals always performed at start of list
Singly-Linked List With Header Node

- **singly-linked list with header node** is node-based implementation of list where each node tracks its successor (but not predecessor).
- null pointer used as sentinel value to denote “no such node”; for example, null pointer used to indicate:
  - no successor for last node in list
  - no head node for empty list
- header node used as placeholder for one-before start of list (i.e., “before-begin” position)
```cpp
// list node base class
struct node_base {
    // ...
    node_base* next_;  
}

// list node derived class (with list element)
template <class T> struct node : public node_base {
    T elem_; 
};

// list iterator class
template <class T> class slist_iter {
    // ...
    node_base* node_; 
    // one of three possibilities:
    // 1) iterator refers to before-begin position:
    //      node_ points to header node
    // 2) iterator refers to end position:
    //      node_ is null
    // 3) iterator refers to element in list:
    //      node_ points to referenced element’s node
};

// list class
template <class T> class list {
    // ...
    node_base node_; 
    std::size_t size_; 
};
```
Singly-Linked List With Header Node: Diagram

List

node_

next_

size_
3

Node

next_

Node

next_

elem_

Node

next_ 0

elem_

Node

next_ 0

elem_

Iterator (before-begin position)

node_

Iterator (element)

node_

Iterator (end position)

node_ 0
- advantages and disadvantages mostly similar to those of classic singly-linked list
- effectively *no memory cost* for header node over standard singly-linked list
- in absence of header node, special representation of before-begin iterator needed, which causes problems for efficient implementation of forward iterator
- use of header node *facilitates more efficient iterator type*
- (forward) iterator can be implemented with single pointer as state
- typically, singly-linked list with header node used to implement `std::forward_list`
**doubly-linked list**: node-based implementation of list where each node tracks both its successor and predecessor

null pointer used as sentinel value to indicate “no such node”; for example, null pointer used to indicate:
- no successor for last node in list
- no predecessor for first node in list
- no head or tail node for empty list

normally, for doubly-linked list, insertion defined to take place at position **before** that specified by iterator and removal defined to take place **at** position specified by iterator
// list node class

```cpp
template <class T> struct Node {
    Node* next_; // pointer to next node in list
    Node* prev_; // pointer to previous node in list
    T elem_; // element
};
```

// iterator class

```cpp
template <class T> class Iterator {
    // ...
    Node<T>* node_; // node of referenced element
    Node<T>** tail_; // pointer to tail pointer of list
    // tail_ always points to tail_ pointer in list object
    // one of two possibilities:
    // 1) iterator refers to end position:
    //     node_ is null
    // 2) iterator refers to element in list:
    //     node_ points to referenced element’s node
};
```

// list class

```cpp
template <class T> class List {
    // ...
    Node<T>* head__; // pointer to first node in list
    Node<T>* tail_; // pointer to last node in list
    std::size_t size_; // number of elements in list
};
```
Remarks on Doubly-Linked Lists

- **advantages:**
  - no capacity-exceeded problem like in array case
  - stable references to elements
  - can insert or remove at arbitrary position in $O(1)$ time
  - can find successor and predecessor in $O(1)$ time
  - can efficiently iterate both forwards and backwards over elements in list

- **disadvantages:**
  - elements not stored contiguously in memory
  - per-element storage overhead (2 pointers)
  - relative to singly-linked list, has greater per-element storage overhead (1 additional pointer for predecessor)
  - iterator storage cost is more than single pointer (i.e., 2 pointers)

- most useful for lists where insertion and removal can happen anywhere in list
Doubly-Linked List With Sentinel Node

- list has one dummy node called **sentinel node** and zero or more regular (i.e., non-sentinel) nodes
- list object itself has sentinel node as member
- each regular node is associated with list element
- sentinel node is not associated with any list element
- each (regular and sentinel) node has pointer to its successor and predecessor
- if list not empty, successor of sentinel node is node corresponding to first element in list; otherwise, successor is sentinel node itself
- if list not empty, predecessor of sentinel node is node corresponding to last element in list; otherwise, predecessor is sentinel node itself
- thus, sentinel and regular nodes effectively form augmented list that is **circular**
- augmented list never empty, since always contains sentinel node
- augmented list has no beginning or end, since circular
- using sentinel node eliminates many special cases for insertion and removal, which leads to simpler and more efficient code
Doubly-Linked List With Sentinel Node: Code

```cpp
// list node base class (which does not have element data)
struct Node_base {
    Node_base* next_; // pointer to next node in list
    Node_base* prev_; // pointer to previous node in list
};

// list node (which has element data)
template <class T> struct Node : public Node_base {
    T elem_; // element data
};

// list
template <class T> class List {
    Node_base node_; // sentinel node
};

// list iterator
template <class T> class Iterator {
    Node_base* node_; // pointer to referenced node
    // one of two possibilities:
    // 1) iterator refers to end position:
    //     node_ points to sentinel node
    // 2) iterator refers to element in list:
    //     node_ points to referenced element’s node
};
```
Remarks on Doubly-Linked Lists With Sentinel Node

- advantages and disadvantages mostly similar to those of classic doubly-linked list
- effectively *no memory cost* for sentinel node over standard doubly-linked list
- sentinel node effectively makes list circular and always nonempty
- sentinel node *eliminates special cases* caused by empty list and insertion and removal at start and end of list (simplifying code)
- in absence of sentinel node, special representation needed for end iterator, which causes problems for efficient implementation of bidirectional iterator (namely, consider predecessor operation for iterator that refers to end of list)
- use of sentinel node *facilitates more efficient iterator type*
- (bidirectional) iterator can be implemented with single pointer as state
- typically, doubly-linked list with sentinel node used to implement `std::list`
- **stack ADT** is ADT for container where elements can only be inserted or removed in last-in first-out (LIFO) order
- can only insert and remove elements at top of stack
- operations provided by stack ADT:
  - clear: remove all elements from stack
  - is empty: test if stack is empty
  - top: access element at top of stack (without removing)
  - push: add element to top of stack
  - pop: remove element from top of stack
- **stack overflow**: attempting to perform push operation when insufficient space available for element being added
- **stack underflow**: attempting to perform pop operation when stack empty
- example realizations of stack ADT:
  - `std::stack`
  - `boost::lockfree::stack`
Array Implementation of Stack

- stack can be efficiently implemented using array
- code example:

```cpp
template <class T> class Stack {
  // ...
  T* start_; // pointer to start of element storage
  T* end_; // pointer to end of element storage
  T* ptr_; // pointer to next free slot on stack
};
```

- stack empty if `ptr_` equals `start_`
- stack has reached capacity if `ptr_` equals `end_`
- push operation stores element at `*ptr_` and then increments `ptr_`
- pop operation decrements `ptr_`
- top operation provides access to `ptr_[-1]`
- due to possibility of exceeding array capacity, cannot guarantee each push operation takes constant time; can only hope for amortized (not worst-case) $O(1)$ time
- memory efficient: only per-element storage cost is element data itself
- cache-efficient: element data is contiguous in memory
Array Implementation of Stack: Diagram

Stack

- start_
- end_
- ptr_

Array of T

- $x_0$
- $x_1$
- $\ldots$
- $x_{n-1}$
Remarks on Array Implementation of Stack

■ advantages:
  - elements stored contiguously in memory
  - no per-element storage overhead

■ disadvantages:
  - if capacity of array exceeded, must reallocate and copy
  - if array grown, can only guarantee amortized (not worst-case) $O(1)$ time for push
  - if array reallocated, elements references are invalidated
stack can be efficiently implemented using node-based *singly-linked* list

code example:

```cpp
// stack node
template <class T> struct Node {
    Node* next_; // pointer to next node in stack
    T elem_; // element data
};

// stack
template <class T> class Stack {
    // ...
    Node<T>* top_; // pointer to node at top of stack
};
```

only need list to be singly linked (as opposed to doubly linked), since all
insertions and removals performed at start of list (i.e., top of stack)
Node-Based Implementation of Stack: Diagram
Remarks on Node-Based Implementation of Stack

- **advantages:**
  - no capacity-exceeded problem as in array case
  - can perform push operation in $O(1)$ time in worst case
  - element references are stable

- **disadvantages:**
  - element data not contiguous in memory
  - has per-element storage overhead (i.e., 1 pointer for successor)
  - relative to array-based implementation, requires more space
Queue ADT

- **queue ADT** is a container where elements can only be inserted and removed in first-in first-out (FIFO) order.
- Elements are removed from the front (a.k.a. head) of the queue.
- Elements are inserted at the back (a.k.a. tail) of the queue.
- Operations for the queue ADT include:
  - `clear`: remove all elements from the queue.
  - `is empty`: test if the queue is empty.
  - `front`: access the element at the front of the queue (without removing).
  - `enqueue`: insert an element at the back of the queue.
  - `dequeue`: remove an element from the front of the queue.
- Examples of realizations of the queue ADT:
  - `std::queue`
  - `boost::lockfree::queue`
- Double-ended queue ADT is similar to the queue ADT except it allows elements to be inserted or removed at either the front or back.
Array Implementation of Queue

- array implementation of bounded queue
- code example:

```cpp
// bounded queue
template <class T> class Queue {
    // ...
    T* start_; // start of array for queue elements
    T* end_; // end of array for queue elements
    T* head_; // pointer to element at front of queue
    T* tail_; // pointer to back of queue
    std::size_t size_; // number of entries in queue
};
```
- array used in circular fashion
- queue is empty if `size_` is zero
- queue is full if `size_` equals `max_size`
- if queue not full, enqueue operation places element at `tail_` and then increments `tail_` with wraparound and increments `size_`
- if queue not empty, dequeue operation increments `head_` with wraparound and decrements `size_`
- front operation provides access to `*head_`
Array Implementation of Queue: Diagram

Queue

- start_
- end_
- head_
- tail_
- size_ \( n \)

Array of \( T \)

- \( x_0 \)
- \( x_1 \)
- \( x_{n-1} \)
- \( \ldots \)
Remarks on Array Implementation of Queue

- although only consider queue of bounded size, could extend to unbounded case by using dynamically-resizable array

- advantages:
  - elements stored in contiguous buffer, occupying at most two contiguous regions of memory (i.e., contiguous region with potential hole in middle)
  - can insert and remove in $O(1)$ time
  - can access front element in $O(1)$ time

- disadvantages:
  - queue must be of bounded size
  - relaxing restriction of bounded size raises other issues associated with reallocation of array when capacity exceeded (e.g., worst case enqueue time not $O(1)$, element references not stable)
array of arrays can be used to implement (unbounded) queue

code example:

```cpp
// how many Ts held in each block?

```template <class T> constexpr std::size_t block_size
 = sizeof(T) < 512 ? 512 / sizeof(T) : 1;

```template <class T> class Iterator {
  // ...
  T* cur_; // pointer to referenced element
  T* first_; // pointer to first element in block
  T* last_; // pointer to end element in block
  T** node_; // pointer to current block
};

```template <class T> class Queue {
  // ...
  T** map_; // array of block pointers
  std::size_t size_; // size of map array
  Iterator start_; // iterator for first element in queue
  Iterator finish_; // iterator for end element in queue
};
```
Remarks on Array of Arrays Implementation of Queue

- **advantages:**
  - elements never change their location so pointers and references to elements are stable

- **disadvantages:**
  - although each individual block holding element data is contiguous, blocks not contiguous
  - although elements are never relocated by insertions and removals, iterators can be invalidated

- similar data structure used in some implementations of `std::deque`
doubly-linked list implementation of queue

code example:

```cpp
// queue node
template <class T> struct Node {
  Node* next_; // pointer to next entry in queue
  Node* prev_; // pointer to previous entry in queue
  T elem_; // element data
};

template <class T> class Queue {
  // ...
  Node<T>* first_; // first entry in queue
  Node<T>* last_; // last entry in queue
  std::size_t size_; // number of queued elements
};
```

enqueue operation uses insert operation of linked list to insert element at end of list

dequeue operation uses remove operation of linked list to remove element at head of list

front operation provides access to element at head of list
Remarks on Node-Based Implementation of Queue

■ advantages:
  - enqueue and dequeue operations can be performed in $O(1)$ time
  - stable element references

■ disadvantages:
  - elements not stored contiguously in memory

■ could use doubly-linked list with sentinel node in order to facilitate more efficient iterator
Section 6.3.2

Multiway and Binary Trees
- tree is non-linear hierarchical data type
- tree consists of zero or more nodes
- except root, each node has parent
- each node has zero or more children
- tree containing no nodes is empty
- node $q$ said to be **parent** of node $n$ if $n$ is child of $q$
- **root node**: node in tree with no parent
- node $q$ said to be **sibling** of node $n$ if $q$ and $n$ have same parent
- tree said to be **ordered** if linear ordering of children of each node

**example:**

![Tree Diagram]

- $A$ is root node
- $B$ is child of $A$
- $A$ is parent of $B$
- $C$ and $D$ are siblings of $B$
- **path** of length $k$ in a tree is a sequence of $k + 1$ nodes $n_0, n_1, \ldots, n_k$ where $n_i$ is parent of $n_{i+1}$
- Node $q$ is said to be an **ancestor** of node $n$ if $q$ is on the path from the root node to $n$
- Node $q$ is said to be a **descendant** of node $n$ if $q$ is on the path from $n$ to a leaf
- Every node is both an ancestor and descendant of itself
- Node $q$ is said to be a **proper ancestor** of $n$ if $q$ is an ancestor of, and distinct from, $n$
- Node $q$ is said to be a **proper descendant** of $n$ if $q$ is a descendant of, and distinct from, $n$

**Example:**

```
    A
   /|
  B  C  D
 / \   / \
E   F  G  H
```

- $A, B, F$ is a path of length 2
- $A$ and $B$ are proper ancestors of $E$
- $E$ and $F$ are proper descendants of $B$
- $B$ is an ancestor and descendant of $B$
Tree Terminology (Continued 1)

- **subtree** rooted at node \( n \) is a tree that consists of \( n \) and all of its descendants (e.g., subtree of root is the entire tree)

- **degree** of a node is the number of its children

- **degree** of a tree is the maximum node degree taken over all nodes in the tree

- **internal node** is a node that has at least one child

- **external node** (also called leaf node) is a node that does not have any children

---

**example:**

- **example:**

  - tree consisting of nodes \( B, E, \) and \( F \)
    - is subtree associated with node \( B \)
    - degree of node \( B \) is 2

  - degree of tree is 3

  - \( A, B, \) and \( D \) are internal nodes

  - \( C, E, F, G, \) and \( H \) are leaf nodes
Tree Terminology (Continued 2)

- **depth** of node (also called **level**) is length of path from root to node (or equivalently, number of proper ancestors of node) (e.g., root node has depth of zero)
- **$d$th level** of tree is all nodes at depth $d$ in tree
- **height** of node is length of longest path from node to any leaf (e.g., leaf node has height of zero)
- **height** of tree is maximum node height taken over all nodes in tree (i.e., height of root) if tree is nonempty; otherwise, defined to be $-1$

example:

```
  A
 /   \
B     C
   / |
  E   F
 /   |
G   H
```

- depths of nodes $C$ and $E$ are 1 and 2, respectively
- nodes $B$, $C$, and $D$ are at level 1
- height of node $D$ is 1
- height of tree is 2
- **weight** of node \( n \) is number of descendant leaf nodes possessed by \( n \)
- **weight** of tree is number of leaf nodes in tree (i.e., weight of root node)

**example:**

```
  A
 /   \\
B     C
|     |
E     F
|     |
G     H
```

- weights of nodes \( B \) and \( C \) are 2 and 0, respectively
- weight of tree is 5
- **preorder traversal**: node visited before its descendants (i.e., parent before children)

- **postorder traversal**: node visited after its descendants (i.e., children before parent)

- preorder traversal might be used, for example, to print hierarchical document, where nodes correspond to sections in document

- postorder traversal might be used, for example, to compute space used by files in directory and its subdirectories

**example:**

- preorder traversal visits nodes in order: A, B, E, F, C, D, G, H

- postorder traversal visits nodes in order: E, F, B, C, G, H, D, A
Applications of Trees

- representing directory tree in hierarchical file system
  - each internal node corresponds to directory
  - each leaf node corresponds to file (or empty directory)

- representing arithmetic expressions
  - each internal node corresponds to operator
  - each leaf node corresponds to operand

- representing decision-making process
  - each internal node corresponds to question with yes/no answer
  - each leaf node corresponds to final outcome of decision-making process

- searching for elements in collection
  - nodes correspond to elements in collection
  - nodes positioned in tree based on element keys
Tree ADT

- **tree ADT** provides abstraction of tree data type
- operations provided by tree ADT include:
  - clear: remove all nodes from tree
  - size: get number of nodes in tree
  - is empty: test if tree is empty (i.e., contains no nodes)
  - root: get root node of tree
  - parent: get parent of node (which is not root)
  - children: get children of node
  - is internal: test if node is internal node
  - is external: test if node is external node
  - is root: test if node is root
  - replace: replace element in node

- may provide iterator ADT for traversing tree
- often tree ADT by itself is not particularly useful
- instead, tree ADT typically used to build other more task-specific ADTs (e.g., set ADT, multiset ADT, and so on)
Node-Based Tree Implementation

- node-based implementation of tree
- each node has pointer to first child and next sibling
- subsequent children can be accessed by following sibling pointers from first child
- allows size of node data structure to be constant (i.e., independent of maximum number of children)

Code example:

```cpp
template <class T> struct Node {
    Node* parent_; // pointer to parent
    Node* child_; // pointer to first child
    Node* sibling_; // pointer to next sibling
    T elem_;  
};

template <class T> class Tree {
    // ...
    Node<T>* root_; // pointer to root node
    std::size_t size_; // number of nodes in tree
};
```
Binary Trees

- each internal node has at most two children
- each node, excluding root node, labelled as either left or right child
- **left subtree** is tree rooted at left child
- **right subtree** is tree rooted at right child

**example:**

```
    A
   / \  
  B   C
 / \   \ 
D   E   F
```

- root node is A
- left child of A is B
- right child of A is C
- left subtree of A is tree consisting of nodes B, D, and E
- right subtree of A is tree consisting of nodes C and F
- binary tree said to be **perfect** (or **full**) if each internal node has exactly two children (which results in all leaves being at the same level)
- binary tree said to be **complete** if perfect except possibly for the deepest level which must be filled from left to right
- perfect implies complete
- balanced binary tree said to be **perfectly balanced** if left and right subtrees of each (interior) node contain same number of nodes (i.e., perfect tree)
- balanced binary tree said to be **strictly balanced** if can be formed by discarding zero or more leaf nodes from perfect tree
- balanced binary tree said to be **height balanced** if height of left and right subtrees of each (interior) node differ by at most one

perfectly balanced implies strictly balanced (but converse does not hold)
strictly balanced implies height balanced (but converse does not hold)
Binary Tree Traversal

- **preorder traversal**: visit node, then left subtree, then right subtree
- **postorder traversal**: visit left subtree, then right subtree, then node
- **level-order traversal**: visit nodes from left to right within level from top downwards
- one additional traversal order for binary trees: in order
- **in-order traversal**: visit left subtree, then node, then right subtree

example:

```
          A
         / \
        B   C
       /   /\n      D   E  F
```

- preorder traversal order: \( A, B, D, E, C, F \)
- postorder traversal order: \( D, E, B, F, C, A \)
- inorder traversal order: \( D, B, E, A, C, F \)
- level order traversal order: \( A, B, C, D, E, F \)
- **binary tree ADT** provides abstraction of binary tree
- operations provided by binary tree ADT that are common to general (i.e., \(m\)-ary) tree ADT include:
  - create: make empty tree
  - root: get root node
  - parent: get parent of node
  - is internal: test if node is internal (i.e., non-leaf)
  - is external: test if node is external (i.e., leaf)
  - is root: test if node is root of tree
  - is empty: test if binary tree is empty (i.e., contains no nodes)
  - size: get number of nodes in tree
  - clear: remove all nodes from tree
  - replace: replace element in node
  - add root: add root node (to empty tree)
other operations provided by binary tree ADT include:

- left child: get left child of node
- right child: get right child of node
- has left child: test if node has left child
- has right child: test if node has right child
- insert left: insert node as left child of node (which must be leaf)
- insert right: insert node as right child of node (which must be leaf)
- remove: remove node (which must be leaf)

may provide iterator ADT for traversing tree
Node-Based Binary Tree

- node-based implementation of binary tree
- node data structure and tree data structure
- null pointer used as sentinel to indicate “no such node” (e.g., child of leaf, parent of root, etc.)
- code example:

  ```cpp
  template <class T> struct Node {
    Node* parent_; // pointer to parent
    Node* left_; // pointer to left child
    Node* right_; // pointer to right child
    T elem_; // element data
  };

  template <class T> class Tree {
    // ...
    Node<T>* root_; // pointer to root node
    std::size_t size_; // number of nodes in tree
  };

- node-based implementation preferred for trees that are not complete
- in practice, sentinel node often preferred when iterator functionality must be provided
Remarks on Node-Based Binary Tree

- **advantages:**
  - can handle case of tree that is not complete without gross memory inefficiency
  - can provide stable element references

- **disadvantages:**
  - has per-element storage overhead (3 pointers: 1 for parent, 1 for first child, and 1 for second child or next sibling)
  - element data not contiguous
Array-Based Binary Tree

- complete binary tree can be implemented using array
- position in array determines position in tree
- let index(n) denote index of node n
- let parent(n), left(n), and right(n) denote parent, left child, and right child of node n
- root node has index 0; and
  \[
  \begin{align*}
  \text{index}(\text{left}(n)) &= 2 \cdot \text{index}(n) + 1 \\
  \text{index}(\text{right}(n)) &= 2 \cdot \text{index}(n) + 2 \\
  \text{index}(\text{parent}(n)) &= \left\lfloor \frac{\text{index}(n) - 1}{2} \right\rfloor
  \end{align*}
  \]

- code example:
  ```cpp
  template <class T> class Tree {
    // ...
    T* start_; // start of element data
    T* end_; // end of element data
    std::size_t size_; // allocated size of data
  };
  ```
example of complete tree with nodes labelled with corresponding array indices:
Remarks on Array-Based Binary Tree

- **advantages:**
  - memory efficient: no per-element storage overhead (i.e., no memory cost for representing connectivity of nodes in tree)
  - cache efficient: element data stored contiguously in memory

- **disadvantages:**
  - can only handle complete trees
  - although could generalize this approach to handle non-complete tree, would be grossly inefficient in terms of memory usage
  - if array capacity exceeded, costly reallocation and copy required
  - if array reallocation occurs, cannot provide stable references to elements

- array implementation should be preferred for complete trees (unless inability to guarantee stable element references is problematic)
Binary Search Trees

- Binary tree is said to have **binary search tree** property if, for each node node $n$ with key $k$, following holds:
  - every key in left subtree of $n$ is less than or equal to $k$; and
  - every key in right subtree of $n$ is greater than or equal to $k$

- For tree of height $h$, can find element in $O(h)$ time

- Example of binary search tree:

```
  40
 /   \
20   60
 /   /   \
10  30  50  70
 /   /   /   \
 5  25  35  45  80
```
- tree said to have **heap property** if, for each node \( n \) in tree, following holds:
  - key of \( n \) is greater than or equal to key of each descendant of \( n \)
- **heap** is tree that satisfies heap property
- inserting or removing node can be done in \( O(\log n) \) time without breaking heap property (but may need rearrangement of some nodes)
- example of heap:

```
     80
   /   \
  70    60
 /     /     \
55  45   35  42
|     |     \
10 20  30  15 16
```
Section 6.3.3

Hash Tables
Basic Idea Behind Hash Tables

- rather than navigating through search tree comparing search key to element key, hashing tries to reference element directly in table based on key
- effectively, hashing transforms key into address in table
- basic operations provided by hash table:
  - insert: add element to hash table
  - remove: remove element from hash table
  - find: search for element in hash table based on key
- want above operations to take $O(1)$ time on average
- order of elements in table unimportant
hash table of size $m$ consists of $m$ slots (also called buckets) numbered from 0 to $m - 1$ (inclusive)

each element stored in hash table has key and possibly some associated value

each slot can be empty or contain element data

slot in which element stored determined by applying hash function to key

load factor is ratio of number of elements in hash table to hash table size

collision said to occur when two distinct keys map to same index in hash table

often, choosing table size as prime number helps to ensure more uniform distribution of elements over slots
Hash Table Example

- collection of 10-digit employee numbers
- employee number is key
- hash function yields last four digits of employee number

<table>
<thead>
<tr>
<th>Index</th>
<th>Slot</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td></td>
</tr>
<tr>
<td>0001</td>
<td>0019910001</td>
</tr>
<tr>
<td>0002</td>
<td>5919870002</td>
</tr>
<tr>
<td>0003</td>
<td></td>
</tr>
<tr>
<td></td>
<td>...</td>
</tr>
<tr>
<td>9997</td>
<td>1212009997</td>
</tr>
<tr>
<td>9998</td>
<td></td>
</tr>
<tr>
<td>9999</td>
<td>1122339999</td>
</tr>
</tbody>
</table>
Hash Functions

- **hash function**: maps key \( k \) of given type to integer in \( \{0, 1, \ldots, m - 1\} \)
- hash function usually specified as composition of two functions:
  1. hash code map
  2. compression map

- **hash code map**: maps key to integer
- **compression map**: maps integer to integer in \( \{0, 1, \ldots, m - 1\} \)
- first hash-code map \( h_1 \) applied to key \( k \) and then compression map \( h_2 \) applied to result to yield hash function \( h(k) = h_2(h_1(k)) \)
- hash function is typically many-to-one mapping (which can therefore result in collisions)
- goal of hash function is to distribute keys uniformly across elements of \( \{0, 1, \ldots, m - 1\} \), which will reduce likelihood of collisions
- hash function should be fast to compute
various strategies can be used to generate hash-code map

integer cast:
- reinterpret bits of key as integer

component sum:
- partition key into integers of fixed size
- then, sum these integers ignoring overflow

polynomial accumulation:
- partition bits of key into sequence of components of fixed length $a_0, a_1, \ldots, a_{n-1}$
- then, evaluate polynomial $p(z) = \sum_{i=0}^{n-1} a_i z^i$ for some fixed value of $z$, ignoring overflow
Remarks on Compression Maps

- various strategies can be used to generate compression map
- let $m$ denote size of hash table
- $m$ usually chosen to be prime in order to better distribute keys over hash values
- division:
  - $h_2(i) = i \mod m$
- multiply, add, and divide:
  - $h_2(i) = (ai + b) \mod m$, where $a$ and $b$ nonnegative integers and $a \mod m \neq 0$
Collision Resolution by Chaining

- **Chaining** also called closed addressing
- With chaining, collisions handled by allowing multiple elements to be placed in single slot
- Elements in slot stored in linked list
- **Simple uniform hashing**: keys equally likely to hash into any of slots
- For load factor $\alpha$, successful and unsuccessful searches take average-case time $\Theta(1 + \alpha)$ under assumption of simple uniform hashing
- If insertion of elements already in hash table not allowed, insert operation has worst-case $O(1)$ time
- Removal of element has worst-case $O(1)$ time
- Can support insert, remove, and search all in $O(1)$ time on average (under assumption of simple uniform hashing)
- Hash table cannot fill since each slot can potentially hold any number of elements
Collision Resolution by Open Addressing

- with open addressing, only one element allowed to be stored per slot in table so in case of collision alternate choice must be made for slot to store element
- sequence of indices to consider (in order) when inserting (or searching for) element with given key called **probe sequence**
- examine table at each position in probe sequence until slot for element is found (e.g., empty slot for insertion)
- for each possible key $k$, probe sequence should be permutation of $\{0, 1, \ldots, m - 1\}$ so that all slots are reachable
- many possible choices for probe sequence (e.g., linear, quadratic, double hashing, and random hashing)
- load factor $\alpha$ must satisfy $\alpha \leq 1$ (since only one element stored per slot)
- **uniform hashing**: probe sequence of each key equally likely to be any of $m!$ permutations of $\{0, 1, \ldots, m - 1\}$
- number of probes in unsuccessful search is at most $\frac{1}{1-\alpha}$, assuming uniform hashing
■ with linear probing, probe sequence starts at hash value of key and then proceeds as necessary sequentially, wrapping around to beginning of table when end of table reached

■ $i$th value in probe sequence for key $k$ given by $h(k, i) = (h'(k) + i) \mod m$, where $h'$ is hash function

■ suffers from primary clustering, where colliding elements clump together causing future collisions to generate longer sequence of probes

■ expected number of probes for insertion or unsuccessful search is

$$\frac{1}{2} \left( 1 + \frac{1}{(1-\alpha)^2} \right)$$

■ expected number of probes for successful search is $\frac{1}{2} \left( 1 + \frac{1}{1-\alpha} \right)$
Linear Probing Example

- integer key; hash function $h(k) = k \mod 13$
- insert 18, 15, 23, 31, 44, and 9 (in order):

```
0  1  2  3  4  5  6  7  8  9  10  11  12
  |   |   |   |   |   |   |   |   |   |   |   |   |
  +---+---+---+---+---+---+---+---+---+---+---+---+
      18
```

```
0  1  2  3  4  5  6  7  8  9  10  11  12
  15  |   |   |   |   |   |   |   |   |   |   |   |   |
       +---+---+---+---+---+---+---+---+---+---+---+---+
            18
```

```
0  1  2  3  4  5  6  7  8  9  10  11  12
  15  18  |   |   |   |   |   |   |   |   |   |   |   |
        +---+---+---+---+---+---+---+---+---+---+---+---+
              23
```

```
0  1  2  3  4  5  6  7  8  9  10  11  12
  15  18  31  |   |   |   |   |   |   |   |   |   |   |   |
        +---+---+---+---+---+---+---+---+---+---+---+---+
              23
```

```
0  1  2  3  4  5  6  7  8  9  10  11  12
  15  18  31  44  |   |   |   |   |   |   |   |   |   |   |   |
        +---+---+---+---+---+---+---+---+---+---+---+---+
                  23
```

```
0  1  2  3  4  5  6  7  8  9  10  11  12
  15  18  31  44  9  23  |   |   |   |   |   |   |   |   |   |   |   |
        +---+---+---+---+---+---+---+---+---+---+---+---+
```

<table>
<thead>
<tr>
<th>$k$</th>
<th>$h(k)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>5</td>
</tr>
<tr>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>23</td>
<td>10</td>
</tr>
<tr>
<td>31</td>
<td>5</td>
</tr>
<tr>
<td>44</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>
with quadratic probing, distance between probes is determined by quadratic polynomial

\[ h(k, i) = (h'(k) + c_1 i + c_2 i^2) \mod m, \]
where \( h' \) is hash function and \( c_1 \) and \( c_2 \) are nonnegative integer constants

\( c_1, c_2, \) and \( m \) must be carefully chosen to guarantee successful insertion is possible

most often \( c_1 = 0 \) and \( c_2 = 1 \) and \( m \) prime

must ensure that loading factor \( \alpha \leq \frac{1}{2} \) in order to guarantee successful insertion

eliminates primary clustering, but suffers from secondary clustering
Quadratic Probing Example

- Integer key; hash function $h(k) = k \mod 13$; $c_1 = 0$ and $c_2 = 1$
- Insert 18, 15, 23, 31, 44, and 9 (in order):

```
0 1 2 3 4 5 6 7 8 9 10 11 12
  18

0 1 2 3 4 5 6 7 8 9 10 11 12
  15 18

0 1 2 3 4 5 6 7 8 9 10 11 12
  15 18 23

0 1 2 3 4 5 6 7 8 9 10 11 12
  15 18 31 23

0 1 2 3 4 5 6 7 8 9 10 11 12
  15 18 31 44 23

0 1 2 3 4 5 6 7 8 9 10 11 12
  9 15 18 31 44 23
```

<table>
<thead>
<tr>
<th>$k$</th>
<th>$h(k)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>5</td>
</tr>
<tr>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>23</td>
<td>10</td>
</tr>
<tr>
<td>31</td>
<td>5</td>
</tr>
<tr>
<td>44</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>
with double hashing, distance between successive probes determined by secondary hash function

ith value in probe sequence for key \( k \) given by

\[
h(k, i) = (h_1(k) + ih_2(k)) \mod m,
\]
where \( h_1 \) is (primary) hash function and \( h_2 \) is secondary hash function

\( h_2 \) must never be zero

\( h_2 \) must be coprime with \( m \) for entire hash table to be searched

for example, could let \( m \) be prime and have \( h_2 \) always yield strictly positive integer less than \( m \)
Double Hashing Example

- integer key; hash function \( h(k) = k \mod 13 \); secondary hash function \( d(k) = 7 - k \mod 7 \)

- insert 18, 15, 23, 31, 44, and 9 (in order):

```
0 1 2 3 4 5 6 7 8 9 10 11 12
  18
0 1 2 3 4 5 6 7 8 9 10 11 12
  15 18
0 1 2 3 4 5 6 7 8 9 10 11 12
  15 18 23
0 1 2 3 4 5 6 7 8 9 10 11 12
  15 18 31 23
0 1 2 3 4 5 6 7 8 9 10 11 12
  15 18 44 31 23
0 1 2 3 4 5 6 7 8 9 10 11 12
   9 15 18 44 31 23
```

<table>
<thead>
<tr>
<th>k</th>
<th>h(k)</th>
<th>d(k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>15</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>23</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>31</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>44</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>5</td>
</tr>
</tbody>
</table>
with random hashing, probe sequence generated by output of pseudorandom number generator seeded by key
random number generation is relatively expensive
in practice, double hashing tends to work about as well
with open addressing, removal of elements can be problematic; in earlier linear probing example, consider removal of element with key 31 followed by search for element with key 44

simplest solution is to distinguish between slot that has always been empty and slot from which element was deleted

to perform search:
- probe until:
  - element with query key is found; or
  - empty slot is found; or
  - all slots have been unsuccessfully probed

to insert element (assuming not already in table):
- examine successive slots in probe sequence until
  - slot found that is empty or “deleted”
- if all slots have been unsuccessfully probed, error
- store element in located slot

to remove element:
- remove element and mark occupied slot with special “deleted” marker
- If keep adding elements to hash table, eventually size of table will need to be increased, due to loading factor becoming too large (for good performance or correct behavior)

- **Rehashing**: rebuilding hash table with different number of slots

- Typical threshold for load factor $\alpha$ for rehashing:
  - 1 for chaining
  - $\frac{1}{2}$ for open addressing
Some Applications of Hash Tables

- dictionary searches (e.g., spelling checkers, natural language understanding)
- accessing tree or graph nodes by name (e.g., city names on geographical maps)
- symbol tables in compilers
- transposition tables used in some games (e.g., chess)
Section 6.3.4

Sets, Multisets, Maps, and Multimaps
Set and Multiset ADTs

- **set ADT** is a container that stores a collection of *unique* values.
- A set can be ordered (i.e., elements have a well-defined order) or unordered.
- Operations provided by the set ADT include:
  - `clear`: remove all elements from the set.
  - `is empty`: test if the set is empty.
  - `size`: query the cardinality of the set (i.e., number of elements in the set).
  - `insert`: insert a value into the set.
  - `remove`: remove a value from the set.
  - `find`: locate a value in the set if present (i.e., for testing set membership).

- **multiset ADT** is similar to the set ADT except that *duplicate values are allowed*.

- Example realizations of set/multiset ADT:
  - `std::set` and `std::multiset`
  - `std::unordered_set` and `std::unordered_multiset`
  - `boost::intrusive::unordered_set` and `boost::intrusive::unordered_multiset`
  - `boost::intrusive::set` and `boost::intrusive::multiset`
Map and Multimap ADTs

- **map (or associative array) ADT** is container that stores pairs each consisting of key and value, where keys are *unique*
- each element in map consists of key and value
- operations provided by map ADT include:
  - clear: remove all elements from map
  - is empty: test if map is empty
  - size: query number of elements in map
  - insert: insert element in map
  - remove: remove element from map
  - find: locate element in map if present based on its key

- **multimap ADT** similar to map ADT except that keys *need not be unique*
- example realizations of map/multimap ADT:
  - `std::map` and `std::multimap`
  - `std::unordered_map` and `std::unordered_multimap`
  - `boost::intrusive::set` and `boost::intrusive::multiset`
Remarks on Implementation of Sets and Maps

- ordered sets, multisets, maps, and multimaps typically implemented using balanced binary search tree [see \texttt{binary.search.trees}]
- unordered sets, multisets, maps, and multimaps typically implemented using hash table
Red-Black Trees

- red-black trees first proposed by Bayer (1972)
- red-black tree is approximately height-balanced binary search tree
- requires one additional field per node, namely, color (i.e., red or black)
- binary search tree with following invariants:
  - each node is either red or black
  - root node is black
  - if node is red, then both of its children are black
  - every path from given node to any of its descendant nil nodes (i.e., null pointer) contains same number of black nodes
- invariants guarantee approximate height balancing
- path from root to farthest leaf no more than twice as long as path from root to nearest leaf
- height $h$ of tree with $n$ nodes is bounded by $h \leq 2 \log_2(n + 1)$
- invariants maintained by rotation and color flipping operations
- memory cost only 1 additional bit per node (for color), relative to classic binary tree
some C++ standard library implementations use red-black trees for types that provide binary search tree functionality (e.g., `std::set` and `std::map`)

example realizations of red-black trees:
- `boost::intrusive::rbtree`, `boost::intrusive::set`, and `boost::intrusive::multiset`

example of red-black tree (where red nodes are shaded gray):

```
40
  /    /
20  60
 /   /
10  30 50
     /   /   
    5   45 65
   /   /   /   
   42  55 65 75
```
AVL Trees

- AVL trees first proposed by Adelson-Velsky and Landis (1962)
- AVL tree is height-balanced binary search tree
- balance factor \( b \) of node \( n \) is defined as \( b = r - \ell \), where \( \ell \) and \( r \) are heights of left and right subtrees of \( n \), respectively
- AVL tree is binary search tree such that, for every node \( n \), balance factor \( b \) of \( n \) satisfies \( b \in \{-1, 0, 1\} \) (i.e., for each node in tree, height of left and right subtrees differ by at most one)
- need to store balance factor in each node
- AVL trees more rigidly balanced than red-black trees
- height \( h \) of tree with \( n \) nodes is bounded by
  \[
  h \leq c \log_2(n + d) + b \approx 1.440 \log_2(n + 1.065) - 0.328,
  \]
  where \( c = \frac{1}{\log_2 \phi} \), \( b = \frac{c}{2} \log_2 5 - 2 \), \( d = 1 + \frac{1}{\phi^4 \sqrt{5}} \), and \( \phi = \frac{1+\sqrt{5}}{2} \)
- memory cost is 2 bits per node (for balance factor), relative to classic binary tree
- rebalancing achieved by rotation operations
AVL Trees (Continued)

- since AVL trees more rigidly balanced than red-black trees, search operations typically faster in AVL tree
- insertion and removal operations typically slower in AVL tree than in red-black tree, due to more work being required for tree re-balancing
- example realizations of AVL trees:
  - `boost::intrusive::avltree`, `boost::intrusive::avl_set`, and `boost::intrusive::avl_multiset`
- example of AVL tree:
treap is combination of binary search tree and heap
- each node has key and priority
- nodes arranged to form binary search tree with respect to key
- nodes also arranged to form heap with respect to priority
- if priorities chosen randomly, tree will be well balanced with high probability
- treaps provide benefits of balanced search trees, but rebalancing (which is driven by heap property) is less complicated than with some other types of balanced search trees
- example realizations of treaps:
  - `boost::intrusive::treap`, `boost::intrusive::treap_set`, and `boost::intrusive::treap_multiset`
Splay Trees

- splay tree is self-adjusting binary search tree with property that searches for more frequently accessed elements can be performed more quickly
- splay tree keeps more recently accessed elements closer to root
- caching effect comes at cost of tree rebalancing being required each time search is performed
- significant disadvantage of splay tree is that height of tree can become linear in number of elements
- in worst case, insertion, removal, and search operations take amortized $O(\log n)$ time
- example realizations of splay trees:
  - `boost::intrusive::splay_tree`, `boost::intrusive::splay_set`, and `boost::intrusive::splay_multiset`
Scapegoat Trees

- scapegoat tree is self-balancing binary search tree
- provides worst-case $O(\log n)$ search time
- provides insertion and removal in amortized $O(\log n)$ time
- unlike other self-balancing binary search trees that provide worst-case $O(\log n)$ search time, scapegoat trees have no additional per-node overhead compared to regular binary search tree
- rebalancing can potentially be very expensive, although only infrequently
- consequently, insertion and removal operations have worst-case $O(n)$ time
- example realizations of scapegoat trees:
  - `boost::intrusive::sgtree`, `boost::intrusive::sg_set`, and `boost::intrusive::sg_multiset`
Section 6.3.5

Priority Queues
priority queue ADT is ADT similar to queue except that each element on queue also has corresponding priority

element at front of queue is always element with highest priority

operations provided by priority queue ADT include:

- front: access element at front of queue (i.e., element with highest priority)
- insert: insert element in queue with specified priority
- remove: remove element from front of queue (i.e., element with highest priority)
- update priority (optional): update priority of element in queue

if priority queue has stability property, elements with equal priority will be removed in FIFO order

elements of realization of priority queue ADT:

- std::priority_queue,
- boost::heap::priority_queue and boost::heap::fibonacci_heap
Remarks on Priority Queue Implementations

- Priority queues typically implemented with heaps [see heaps]
- Heaps can always be constructed to be complete trees
- Consequently, can reasonably choose to implement priority queue with either array-based or node-based tree
- In practice, stability often ensured by augmenting priority with integer sequence number, which is incremented with each insertion
- Array-based implementation more memory efficient but does not have stable element references (if underlying array can be reallocated)
- Node-based implementation can offer stable element references
Section 6.3.6

Graphs
Graphs

- graph is concept from discrete mathematics
- collection of nodes and edges
- nodes can be connected by edges
- directed graph: edges are directed (i.e., have direction)
- undirected graph: edges are undirected
- examples of graphs:
Graph ADTs

- **graph ADT** is abstraction of mathematical notion of graph

- operations for graph ADT include:
  - adjacent: tests if edge from one vertex to another
  - neighbours: list all vertices that have edge to another vertex
  - insert vertex: add vertex to graph
  - remove vertex: remove vertex from graph
  - insert edge: add edge from one vertex to another
  - remove edge: remove edge from one vertex to another
  - get vertex value: get value associated with vertex
  - set vertex value: set value associated with vertex
  - get edge value: get value associated with edge
  - set edge value: set value associated with edge

- examples of realization of graph ADT:
  - `boost::adjacency_list` and `boost::adjacency_matrix`
adjacency (i.e., connectivity) of \( n \) nodes can be represented using \( n \times n \) binary matrix called **adjacency matrix**

\((i, j)\)th element of adjacency matrix is 1 if graph has edge from node \( i \) to node \( j \) and 0 otherwise

if graph is undirected, adjacency matrix is symmetric and only lower triangular part of matrix need be stored

if graph is directed, adjacency matrix is not necessarily symmetric, and entire matrix must be stored

can test adjacency of two nodes (which requires examining element in matrix) in \( O(1) \) time

identifying all neighbours of given node takes \( O(n) \) time

iterating over all edges is slow

storage cost of adjacency matrix is \( \Theta(n^2) \)

high storage cost easier to justify if graph has large number of edges
Adjacency List Implementation of Graph

- adjacency (i.e., connectivity) of \( v \) nodes can be represented using \( v \) linked lists
- \( i \)th list contains node \( j \) if and only if graph has edge from node \( i \) to node \( j \)
- can test adjacency of two nodes (which requires traversing linked list) in worst-case \( O(d) \) time, where \( d \) is largest valence of nodes in graph
- identifying all neighbours of given node very cheap
- storage cost of adjacency list is \( O(v + e) \), where \( v \) and \( e \) is number of node and edges, respectively
Section 6.3.7

Data Structures and File Formats for Polygon Meshes
struct Face {
    int vertexIndexes[3]; // indexes of vertices of triangle
};

Vertex vertices[numVertices]; // vertex array
Face triangles[numTriangles]; // triangle array

- edges not explicitly represented
- some adjacency information not readily accessible
- to find neighboring face, must scan through face array looking for face with two vertices in common, which takes $O(n)$ time (where $n$ is number of vertices)
- need data structures that allow efficient access to adjacency information
Naive Triangle-Mesh Data Structure Example

\[
\begin{align*}
  v_0 &= (−1, 1, −1) \\
  v_1 &= (1, −1, −1) \\
  v_2 &= (−1, −1, 1) \\
  v_3 &= (1, 1, 1)
\end{align*}
\]

\[
\begin{align*}
  f_0 &= \{v_0, v_1, v_3\} \\
  f_1 &= \{v_1, v_2, v_3\} \\
  f_2 &= \{v_0, v_2, v_3\}
\end{align*}
\]

---

**Vertices**

<table>
<thead>
<tr>
<th>Array Index</th>
<th>Array Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>(-1,-1,1)</td>
</tr>
<tr>
<td>1</td>
<td>(1,-1,-1)</td>
</tr>
<tr>
<td>2</td>
<td>(-1,1,-1)</td>
</tr>
<tr>
<td>3</td>
<td>(1,1,1)</td>
</tr>
</tbody>
</table>

**Faces**

<table>
<thead>
<tr>
<th>Array Index</th>
<th>Array Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0, 1, 3</td>
</tr>
<tr>
<td>1</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>2</td>
<td>0, 3, 2</td>
</tr>
</tbody>
</table>
Half-Edge Data Structure

- every edge represented as pair of directed edges, each called half-edge
- 6 pointers plus 2 bits (i.e., 2 one-bit integers) per edge
- used in Computational Geometry Algorithms Library (CGAL)
- representing edges in terms of directed line segments often advantageous in algorithms
**struct** HalfEdge {
    **int** index;  // index of half-edge in parent edge
    HalfEdge* next;  // next CCW half-edge around left face
    Vertex* term;  // terminal vertex
    Face* left;  // left face
};

**struct** Edge {
    HalfEdge e[2];  // pair of symmetric half-edges
};
Quad-Edge Data Structure

- proposed in:
- simultaneously represents graph and its dual
- each edge belongs to four circular singly-linked lists corresponding to two vertices and two faces incident to edge
- vertex/face represented by ring of quad-edges
- 8 pointers plus 4 two-bit integers per edge
- used in various research software available on Internet (e.g., Scape terrain-simplification software, Dani Lischinski’s constrained DT software)
quad-edge data structure (continued)

```c
struct QuadEdge {
    int index; // index of quad-edge in parent edge
    QuadEdge* next; // next CCW quad-edge with same origin
    void* data; // face or vertex
};

struct Edge {
    QuadEdge* e[4]; // four quad-edges of edge
};
```
- simple scheme for encoding the geometry and topology of a polygon mesh
- also has provisions for including color and normal information
OFF Example (Triangle Mesh)

\[ v_0 = (-1, -1, 0), \quad v_1 = (1, -1, 0), \quad v_2 = (1, 1, 0), \quad v_3 = (-1, 1, 0) \]

Corresponding OFF File:

```
OFF
5 4 0
-1 -1 0
1 -1 0
1 1 0
-1 1 0
0 0 1
3 0 1 4
3 1 2 4
3 2 3 4
3 0 4 3
```
OFF Example (Quad Mesh)

\[
\begin{align*}
\mathbf{v}_0 &= (-1, -1, -1) \\
\mathbf{v}_1 &= (0, -1, 0) \\
\mathbf{v}_2 &= (1, -1, -1) \\
\mathbf{v}_3 &= (1, 0, 0) \\
\mathbf{v}_4 &= (1, 1, -1) \\
\mathbf{v}_5 &= (0, 1, 0) \\
\mathbf{v}_6 &= (-1, 1, -1) \\
\mathbf{v}_7 &= (-1, 0, 0) \\
\mathbf{v}_8 &= (0, 0, 1)
\end{align*}
\]

Corresponding OFF File

```
OFF
9 4 0
-1 -1 -1
0 -1 0
1 -1 -1
1 0 0
1 1 -1
0 1 0
-1 1 -1
-1 0 0
0 0 1
4 0 1 8 7
4 1 2 3 8
4 8 3 4 5
4 7 8 5 6
```
Section 6.3.8

Intrusive Containers
container said to be **intrusive** if it requires help from elements it intends to store in order to store them

intrusive container *directly* places user’s objects in container (*not copies* of user’s objects)

node pointers exposed to user of container, which allows some operations to be performed more efficiently

intrusive container *does not own* elements it stores

lifetime of stored object not bound to or managed by container (i.e., lifetime of stored objects managed by user)

can store element in multiple intrusive containers simultaneously (which is not possible with nonintrusive containers)

more coupling between code for container and code using container
Shortcomings of Non-Intrusive Containers

- object can only belong to one container
- only copies of objects stored in nonintrusive containers
- creating copies of values can become bottleneck (due to memory allocation and copying)
- noncopyable and nonmovable objects cannot be stored in nonintrusive containers (unless objects can be directly constructed inside container and are guaranteed not to be copied/moved subsequently)
- cannot store derived object in nonintrusive container and retain original type (i.e., copying derived object into container would result in slicing)
Advantages of Intrusive Containers

- Same object can be placed in multiple intrusive containers simultaneously.
- Intrusive containers do not invoke memory management operations since they do not own stored elements.
- Complexity of inserting and removing elements in intrusive containers is more predictable since no memory allocation involved.
- Intrusive containers tend to allow stronger complexity guarantees (since no memory allocation or copying performed).
- Intrusive containers offer better exception safety guarantees (since do not need to make copy of element to place in container).
- For intrusive container, computation of iterator from pointer or reference to element is $O(1)$ time operation, which is often not true for nonintrusive containers (e.g., for nonintrusive list std::list, this operation takes $O(n)$ time).
Disadvantages of Intrusive Containers

- In order to use type with intrusive container, must change definition of type.
- Each type stored in intrusive container needs additional memory to hold information for container.
- Intrusive containers unavoidably expose some implementation details of container to user.
- Since some implementation details are exposed, easier to break invariants of container; for example:
  - Changing key of element in map.
  - Corrupting pointers used to link nodes in container.
- User must assume responsibility for memory management (since container does not).
- User must manage lifetime of objects placed in container independent from lifetime of container itself, which can be error prone:
  - When destroying container before object, must be careful to avoid resource leaks.
  - Destroying object while in container, likely to be disastrous since container uses part of object to implement container.
- typically, intrusive containers not copyable (and often not movable as well) since such containers do not directly perform memory allocation
- analyzing thread safety of program using intrusive containers often more difficult since container contents can be modified without going through container interface
node-based implementation of list where each node tracks both its successor and predecessor

value type (which stores user data) and node type (which is used to maintain list) are same

null pointer used as sentinel value to indicate “no such node” (e.g., no successor/predecessor node or no head/tail node)

in order for elements of type $T$ to be used with container, $T$ must include special type as data member (which encapsulates next/previous pointers for linked list)

uses pointer to member to identify member that holds list node state [see pointers to members]
// type encapsulating links for list
// (i.e., part of list node)
template <class T> struct list_hook {
    // ...
    T* next_; // pointer to next node in list
    T* prev_; // pointer to previous node in list
};

// iterator class
// (constness of T determines if const_iterator)
template <class T, list_hook<T> T::* P> class list_iterator {
    // ...
    // node_ptr is T* (where T may be const qualified)
    node_ptr node_; // pointer to node of referenced element
    node_ptr const* tail_; // pointer to list tail node pointer
};

template <class T, list_hook<T> T::* P> class list {
    // ...
    T* head_; // pointer to first node in list
    T* tail_; // pointer to last node in list
    std::size_t size_; // number of elements in list
};
// list node with user data
struct Widget {
    // ...
    list_hook<Widget> hook; // public
    // ...
};

// type for list of Widget objects
using Widget_list = list<Widget, &Widget::hook>;

// list node with user data
// (which can be placed on two lists simultaneously)
struct Gadget {
    // ...
    list_hook<Gadget> first_hook; // public
    list_hook<Gadget> second_hook; // public
    // ...
};

// type for list of Gadget objects using first_hook
using First_gadget_list = list<Gadget, &Gadget::first_hook>;

// type for list of Gadget objects using second_hook
using Second_gadget_list = list<Gadget, &Gadget::second_hook>;
Intrusive Doubly-Linked List: Diagram

List

head_

.tail_

size_ 3

Widget

:: hook

next_

prev_ 0

... Widget

:: hook

next_

prev_

... Widget

:: hook

next_ 0

prev_

... Iterator

node_

tail_

Copyright © 2015–2021 Michael D. Adams
Programming in C++ Version 2021-04-01
Remarks on Intrusive Doubly-Linked List

- node pointer and value pointer are equivalent (i.e., pointers to next and previous nodes have type \( T^* \))
- storage cost of iterator is two pointers (but one pointer would be more desirable)
- iterator state requires pointer to list tail pointer in order to handle case of decrementing end iterator (which has null node pointer)
- implementation does not require any non-portable constructs
- **intrusive doubly-linked list with sentinel node** is circular doubly-linked list with dummy node that serves as sentinel (instead of using null pointer)
- value type (which stores user data) and node type (which is used to maintain list) are *distinct*
- in particular, value type contains node type as data member
- effectively sentinel node makes list circular
- in order for elements of type $\mathbb{T}$ to be used with container, $\mathbb{T}$ must include special type as data member (which encapsulates next/previous pointers for linked list)
// list node class
struct list_hook {
    // ...
    list_hook* next_; // pointer to next node in list
    list_hook* prev_; // pointer to previous node in list
};

// list traits class (no data members)
template <class T, list_hook<T> T::* P> class list_traits {
    // functions for mapping between object and node pointers
};

// list iterator class
// (constness of T determines if const_iterator)
template <class T, list_hook<T> T::* P> class list_iterator :
    list_traits<T, P>{
    // ...
    list_hook* node_; // pointer to node of referenced element
};

// list
template <class T, list_hook<T> T::* P> class list :
    list_traits<T, P> {
    // ...
    list_hook node_; // sentinel node
    std::size_t size_; // number of elements in list
};
// list node with user data
// (which can be placed on two lists simultaneously)
struct Gadget {
    // ...
    list_hook first_hook; // public
    list_hook second_hook; // public
    // ...
};

// type for list of Gadget objects using first_hook
using First_gadget_list = list<Gadget, &Gadget::first_hook>;

// type for list of Gadget objects using second_hook
using Second_gadget_list = list<Gadget, &Gadget::second_hook>;
Intrusive Doubly-Linked List With Sentinel Node: Diagram
circular list avoids many special cases in implementation of list class (since circular list never empty and list has no beginning or end)

node and value types are distinct (i.e., node pointers are of type list_hook, not T)

storage cost of iterator is one pointer

implementation requires non-portable construct to determine value pointer from node pointer

determining value pointer from node pointer cannot work in all cases (in particular, if value type uses virtual inheritance)

limitations on what types can be placed in container

another variation on this intrusive list approach can be obtained by using inheritance to add required list state to user’s type (instead of adding by data members), which has some advantages
Examples of Intrusive Containers

- as of C++20, all container classes in standard library are nonintrusive
- Boost library has good selection of intrusive containers, which includes (amongst others):
  - `boost::intrusive::slist` (intrusive singly-linked list)
  - `boost::intrusive::list` (intrusive doubly-linked list)
  - `boost::intrusive::set` (intrusive set/map)
  - `boost::intrusive::multiset` (intrusive multiset/multimap)
  - `boost::intrusive::unordered_set` (intrusive unordered set/map)
  - `boost::intrusive::unordered_multiset` (intrusive unordered multiset/multimap)
  - `boost::intrusive::ptr` (intrusive reference-counted smart pointer)
Section 6.3.9

Miscellany
for reasons of efficiency or functionality (or even correctness), often necessary to:
- separate memory allocation from construction
- separate memory deallocation from destruction

operator new can be used to perform only memory allocation (without construction)

placement new can be used to perform only construction (without memory allocation)

operator delete can be used to perform only memory deallocation (without destruction)

direct invocation of destructor can be used to perform only destruction (without memory deallocation)

allocator type provides interface that decouples allocation/deallocation and construction/destruction

numerous convenience functions provided by standard library for dealing with uninitialized storage
Row-Major Versus Column-Major Order

Row-Major Order

Column-Major Order
Section 6.3.10

References


What do each of the following functions output when executed?

```cpp
void func1() {
    double x = 0.1;
    double y = 0.3;
    double z = 0.4;
    if (x + y == z)
        {std::cout << "true\n";}
    else
        {std::cout << "false\n";}
}

void func2() {
    double x = 1e50;
    double y = -1e50;
    double z = 1.0;
    if (x + y + z == z + y + x)
        {std::cout << "true\n";}
    else
        {std::cout << "false\n";}
}

void func3() {
    for (double x = 0.0; x != 1.0; x += 0.1)
        {std::cout << "hello\n";}
}
```
Example: Controlling Precision of Output

```cpp
#include <iostream>
#include <iomanip>
#include <limits>
#include <boost/io/ios_state.hpp>

template <class T> void func(T x) {
    boost::io::ios_flags_saver saver(std::cout);
    std::cout << x << ' ' << 
    std::setprecision(std::numeric_limits<T>::digits10) << x << ' ' <<
    std::setprecision(std::numeric_limits<T>::max_digits10) << x << ' ' <<
    std::hexfloat << x << '\n';
}

int main() {
    func(0.1f);
    func(0.1);
    func(0.1L);
}

/* example output:
0.1 0.1 0.100000001 0x1.99999ap-4
0.1 0.1 0.10000000000000001 0x1.999999999999ap-4
0.1 0.1 0.1000000000000000000001 0xc.ccccccddpp-7
*/
```
Example: Determining Next/Previous Representable Value

```cpp
#include <cmath>
#include <iostream>
#include <limits>
#include <boost/io/ios_state.hpp>

// template class
template <class T>
void func(T x) {
    boost::ios_flags_saver saver(std::cout);
    T prev = std::nextafter(x, -INFINITY);
    T next = std::nextafter(x, INFINITY);
    std::cout.precision(std::numeric_limits<T>::max_digits10);
    std::cout << prev << ' ' << x << ' ' << next << '
';
    std::cout << std::hexfloat;
    std::cout << prev << ' ' << x << ' ' << next << '
';
}

int main() {
    func(0.0f);
    func(0.0);
    func(0.0L);
}

/* example output:
-1.40129846e-45  0  1.40129846e-45
-0x1p-149  0x0p-0  0x1p-149
-4.9406564584124655e-324  0  4.9406564584124655e-324
-0x0.00000000000001p-1022  0x0p+0  0x0.00000000000001p-1022
-3.6451995318827460253e-4951  0  3.6451995318827460253e-4951
-0x0.000000000000001p-16385  0x0p+0  0x0.000000000000001p-16385
*/
```

Copyright © 2015–2021 Michael D. Adams

Programming in C++

Version 2021-04-01
Note: All numbers are base 10, unless explicitly indicated otherwise.

What is the representation of \( \frac{1}{3} \) in base 3?
\[
\frac{1}{3} = 0.\overline{3} = 0.1_3
\]

What is the representation of \( \frac{1}{10} \) in base 2?
\[
\frac{1}{10} = 0.1 = 0.00011_2
\]

A number may have a representation with a finite number of non-zero digits in one particular number base but not in another.

Therefore, when a value must be represented with a limited number of significant digits, the number base matters (i.e., affects the approximation error).

For example, in base 2, \( \frac{1}{10} \) cannot be represented exactly using only a finite number of significant digits.

\[
0.00011_2 = 0.09375
\]
\[
0.000110011_2 = 0.099609375
\]
\[
\ldots
\]
finite-precision number representation only capable of representing small fixed number of digits

due to limited number of digits, many values cannot be represented exactly

in cases that desired value cannot be represented exactly, choose nearest representable value (i.e., round to nearest representable value)

finite-precision representations can suffer from error due to roundoff, underflow, and overflow

two general classes of finite-precision representations:

1. fixed-point representations
2. floating-point representations
Fixed-Point Number Representations

- **fixed-point representation**: radix point remains fixed at same position in number

- if radix point fixed to right of least significant digit position, integer format results

  | Integer Format | $a_{n-1} \ a_{n-2} \cdots \ a_1 \ a_0$ |

- if radix point fixed to left of most significant digit position, purely fractional format results

  | Fractional Format | $^*a_{n-1} \ a_{n-2} \cdots \ a_1 \ a_0$ |

- fixed-point representations **quite limited in range** of values that can be represented

- numbers that vary greatly in magnitude cannot be represented easily using fixed-point representations

- one solution to range problem would be for programmer to maintain scaling factor for each fixed-point number, but this is clumsy and error prone
Floating-Point Number Representations

- **floating-point representation**: radix point is not fixed at particular position within number; instead radix point allowed to move and scaling factor automatically maintained to track position of radix point
- in general, floating-point value represents number $x$ of form
  \[ x = sr^e, \]
  - $s$ is signed integer with fixed number of digits, and called **significand**
  - $e$ is signed integer with fixed number of digits, and called **exponent**
  - $r$ is integer satisfying $r \geq 2$, and called **radix**
- in practice, $r$ typically 2
- for fixed $r$, representation of particular $x$ not unique if no constraints placed on $s$ and $e$ (e.g., $5 \cdot 10^0 = 0.5 \cdot 10^1 = 0.05 \cdot 10^2$)
to maximize number of significant digits in significand, $s$ and $e$ usually chosen such that first nonzero digit in significand is to immediate left of radix point (i.e., $1 \leq |s| < r$); number in this form called **normalized**; otherwise called **denormalized**

other definitions of normalized/denormalized sometimes used but above one consistent with IEEE 754 standard

Example:

$$0.75 = 0.11_2 = 1.1_2 \cdot 2^{-1}$$
$$1.25 = 1.01_2 = 1.01_2 \cdot 2^0$$
$$-0.5 = -0.1_2 = -1.0_2 \cdot 2^{-1}$$
IEEE 754 Standard (IEEE Std. 754-1985)

- most widely used standard for (binary) floating-point arithmetic
- specifies four floating-point formats: single, double, single extended, and double extended
- single and double formats called basic formats
- radix 2
- three integer parameters determine values representable in given format:
  - number $p$ of significand bits (i.e., precision)
  - maximum exponent $E_{\text{max}}$
  - minimum exponent $E_{\text{min}}$
- parameters for four formats are as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Single</th>
<th>Single Extended</th>
<th>Double</th>
<th>Double Extended</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>24</td>
<td>$\geq 32$</td>
<td>53</td>
<td>$\geq 64$</td>
</tr>
<tr>
<td>$E_{\text{max}}$</td>
<td>127</td>
<td>$&gt; 1023$</td>
<td>1023</td>
<td>$\geq 16383$</td>
</tr>
<tr>
<td>$E_{\text{min}}$</td>
<td>$-126$</td>
<td>$\leq -1022$</td>
<td>$-1022$</td>
<td>$\leq -16382$</td>
</tr>
<tr>
<td>Exponent bias</td>
<td>127</td>
<td>unspecified</td>
<td>1023</td>
<td>unspecified</td>
</tr>
</tbody>
</table>
with each format, numbers of following form can be represented

\[ (-1)^s 2^E (b_0.b_1 b_2 \cdots b_{p-1}) \]

where \( s \in \{0, 1\} \), \( E \) is integer satisfying \( E_{\text{min}} \leq E \leq E_{\text{max}} \), and \( b_i \in \{0, 1\} \)

in addition, can represent four special values: \(+\infty\), \(-\infty\), signaling NaN, and quiet NaN

NaNs produced by:

- operations with at least one NaN operand
- operations yielding indeterminate forms, such as \(0/0\), \((\pm\infty)/(\pm\infty)\), \(0 \cdot (\pm\infty)\), \((\pm\infty) \cdot 0\), \((+\infty) + (-\infty)\), and \((-\infty) + (\infty)\)
- real operations that yield complex results, such as square root of negative number, logarithm of negative number, inverse sine/cosine of number that lies outside \([-1, 1]\)
IEEE 754 Basic Formats

- always represent number in normalized form whenever possible; in such cases, $b_0 = 1$ and $b_0$ need not be stored explicitly as part of significand.
- bit patterns with reserved exponent values (i.e., exponent values that lie outside the range $E_{\text{min}} \leq E \leq E_{\text{max}}$) used to represent $\pm 0$, $\pm \infty$, denormalized numbers, and NaNs.
- each of (basic) formats consist of three fields:
  - a sign bit, $s$
  - a biased exponent, $e = E + \text{bias}$
  - a fraction, $f = .b_1 b_2 \cdots b_{p-1}$
- only difference between formats is size of biased exponent and fraction fields.
- value represented by basic format number related to its sign, exponent, and fraction field, but relationship is complicated by the presence of zeros, infinities, and NaNs.
- “strange” combination of biased and sign-magnitude formats used to encode floating-point value chosen so that nonnegative floating-point values ordered in same way as integers, allowing integer comparison to compare floating-point numbers.
single format:

![Binary representation of single format](image)

- **Normalized:**
  - Exponent: $E_{\text{min}} \leq E \leq E_{\text{max}}$
  - Fraction: $f \neq 0$
  - Value: $(-1)^s 2^E (1 + f)$

- **Denormalized:**
  - Exponent: $E = E_{\text{min}} - 1$
  - Fraction: $f = 0$
  - Value: $(-1)^s 2^{E_{\text{min}}} f$

- **Zero:**
  - Exponent: $E = E_{\text{min}} - 1$
  - Fraction: $f = 0$
  - Value: $(-1)^s 0$

- **Infinity:**
  - Exponent: $E = E_{\text{max}} + 1$
  - Fraction: $f = 0$
  - Value: $(-1)^s \infty$

- **Not-a-Number (NaN):**
  - Exponent: $E = E_{\text{max}} + 1$
  - Fraction: $f \neq 0$
  - Value: NaN

double format:

![Binary representation of double format](image)

- **Normalized:**
  - Exponent: $E_{\text{min}} \leq E \leq E_{\text{max}}$
  - Fraction: $f \neq 0$
  - Value: $(-1)^s 2^E (1 + f)$

- **Denormalized:**
  - Exponent: $E = E_{\text{min}} - 1$
  - Fraction: $f = 0$
  - Value: $(-1)^s 2^{E_{\text{min}}} f$

- **Zero:**
  - Exponent: $E = E_{\text{min}} - 1$
  - Fraction: $f = 0$
  - Value: $(-1)^s 0$

- **Infinity:**
  - Exponent: $E = E_{\text{max}} + 1$
  - Fraction: $f = 0$
  - Value: $(-1)^s \infty$

- **Not-a-Number (NaN):**
  - Exponent: $E = E_{\text{max}} + 1$
  - Fraction: $f \neq 0$
  - Value: NaN
IEEE 754 Encoding Examples

- How would the number $5.25_{10}$ be represented in single format?
- $5.25_{10} = 101.01_2 \cdot 2^0 = 1.0101_2 \cdot 2^2$
- Therefore, $s = 0$, $e = 2_{10} + 127_{10} = 129_{10} = 10000001_2$, and $f = 0101000 \cdots 0$, resulting in the word:

```
+-----------------+-----------------+-----------------+
|     s           |     e           |     f           |
| 0 | 100000001 | 01010000000000000000000000000000 |
```

- How would the number $-9.125_{10}$ be represented in double format?
- $-9.125_{10} = -1001.001_2 \cdot 2^0 = -1.001001_2 \cdot 2^3$
- Therefore, $s = 1$, $e = 3_{10} + 1023_{10} = 1026_{10} = 10000000010_2$, and $f = 001001000 \cdots 0$, resulting in the word:

```
+-----------------+-----------------+-----------------+
|     s           |     e           |     f           |
| 1 | 100000000010 | 0010010000000000000000000000000000000000000000000000 |
```
Understand the impact of using finite-precision arithmetic.

Do not make invalid assumptions about the set of values that can be represented by a particular fixed-point or floating-point type.

Integer arithmetic can *overflow*. Be careful to avoid overflow.

Floating-point arithmetic can *overflow and underflow*.

Perhaps, more importantly, however, floating-point arithmetic has *roundoff error*. If you are not deeply troubled by the presence of roundoff error, you should be as it can cause major problems in many situations.

2 IEEE Std. 754-1985 — IEEE standard for binary floating-point arithmetic, 1985

3 IEEE Std. 754-2008 — IEEE standard for floating-point arithmetic, 2008
Section 6.5

Interval Arithmetic
interval arithmetic is technique for placing bounds on error in numerical computation

often values provided as input to numerical computation not known exactly, rather only known to within certain tolerance

uncertainty may be due to measurement error or other factors

consider numerous measured quantities that are provided as input to some numerical computation

since measured quantity never known exactly (as measurement always introduces uncertainty), more natural to represent quantity by range

therefore, would be convenient to have form of arithmetic that operates on values that correspond to ranges

this is essentially what interval arithmetic does

interval arithmetic represents each value as range of possibilities and defines set of rules for performing arithmetic on these ranges
Applications of Interval Arithmetic

- rounding error analysis in numerical algorithms
- filtered robust geometric predicates
- robustly finding intersection of curves and surfaces
- more robust root finding in ray tracing
- computing optimal solutions to geometric matching problems under bounded error
- finding polygonal approximations of implicit curves
- computer-assisted mathematical proofs
in real interval arithmetic, each value is represented as real interval:

\[ [a_1, a_2] = \{ x \in \mathbb{R} \mid a_1 \leq x \leq a_2 \} \]

addition, subtraction, and multiplication defined as:

\[
A + B = \{ a + b \mid a \in A \land b \in B \}
\]
\[
A - B = \{ a - b \mid a \in A \land b \in B \}
\]
\[
A \cdot B = \{ a \cdot b \mid a \in A \land b \in B \}
\]

assuming division by interval containing 0 is not allowed, division defined as:

\[
A / B = \{ a/b \mid a \in A \land b \in B \}
\]
Addition and Subtraction

- addition:

\[ A + B = [a_1, a_2] + [b_1, b_2] = [a_1 + b_1, a_2 + b_2] \]

- negation:

\[ -B = -[b_1, b_2] = [-b_2, -b_1] \]

- formula for negation follows from fact that:
  - \( x \geq b_1 \Rightarrow -x \leq -b_1 \) and
  - \( x \leq b_2 \Rightarrow -x \geq -b_2 \)

- subtraction:

\[ A - B = [a_1, a_2] - [b_1, b_2] = [a_1 - b_2, a_2 - b_1] \]

- formula for subtraction follows from combining addition and negation
Multiplication and Division

- **multiplication:**

  \[ A \cdot B = [a_1, a_2] \cdot [b_1, b_2] = \{ \min\{a_1b_1, a_1b_2, a_2b_1, a_2b_2\}, \\max\{a_1b_1, a_1b_2, a_2b_1, a_2b_2\} \} \]

  (e.g., \([a_1, a_2] \cdot [b_1, b_2] = [a_1b_1, a_2b_2]\) if \(0 \leq a_1 \leq a_2\) and \(0 \leq b_1 \leq b_2\))

- **reciprocal** (assuming division by interval containing 0 not allowed):

  \[ 1/B = 1/[b_1, b_2] = [1/b_2, 1/b_1] \]

  formula for reciprocal follows from fact that, since \(0 \notin [b_1, b_2]\), \(x \in [b_1, b_2]\), \(b_1, b_2\) all have same sign (implying \(b_1x > 0\) and \(b_2x > 0\)) and consequently:

  - \(x \geq b_1 \Rightarrow \frac{x}{b_1x} \geq \frac{b_1}{b_1x} \Rightarrow 1/b_1 \geq 1/x \Rightarrow 1/x \leq 1/b_1\)
  - \(x \leq b_2 \Rightarrow \frac{x}{b_2x} \leq \frac{b_2}{b_2x} \Rightarrow 1/b_2 \leq 1/x \Rightarrow 1/x \geq 1/b_2\)

- **division** (assuming division by interval containing 0 not allowed):

  \[ A/B = [a_1, a_2]/[b_1, b_2] = \{ \min\{a_1/b_1, a_1/b_2, a_2/b_1, a_2/b_2\}, \\max\{a_1/b_1, a_1/b_2, a_2/b_1, a_2/b_2\} \} \]

  formula for division follows from fact that division is simply multiplication by reciprocal
Allowing Division By Interval Containing Zero

- consider implications of allowing division by interval containing zero
- reciprocal, if \( 0 \in [b_1, b_2] \):

\[
1/B = 1/[b_1, b_2] = \begin{cases} 
(-\infty, 1/b_1] & b_1 \neq 0, b_2 = 0 \\
[1/b_2, +\infty) & b_1 = 0, b_2 \neq 0 \\
(-\infty, 1/b_1] \cup [1/b_2, +\infty) & b_1 \neq 0, b_2 \neq 0 \\
0 & b_1 = b_2 = 0
\end{cases}
\]

- thus, if division by interval containing 0 is allowed, result cannot always be represented by interval of form

\[
[a_1, a_2] = \{ x \in \mathbb{R} \mid a_1 \leq x \leq a_2 \}
\]

- in particular, arithmetic can yield result that corresponds to:
  - interval unbounded at one end
  - empty set
  - union of two separate intervals
to accommodate division by interval containing zero, represent sets of following forms:

\[
\begin{align*}
[a_1, a_2] &= \{ x \in \mathbb{R} \mid a_1 \leq x \leq a_2 \} \\
[a_1, +\infty) &= \{ x \in \mathbb{R} \mid x \geq a_1 \} \\
(-\infty, a_2] &= \{ x \in \mathbb{R} \mid x \leq a_2 \} \\
(-\infty, +\infty) &= \emptyset
\end{align*}
\]

for sake of simplicity, result of form \(( -\infty, \beta_1 ] \cup [ \beta_2, +\infty )\) (where \(\beta_1 < \beta_2\)) is mapped to \(( -\infty, +\infty )\)
in case of floating-point interval arithmetic, interval bounds are floating-point values

that is, represent intervals of following form, where $F$ is set of machine-representable real numbers:

$$ [a_1, a_2] = \{ x \in F \mid a_1 \leq x \leq a_2 \} $$

since floating-point value can only represent finite number of real numbers, some real numbers cannot be represented exactly

when arithmetic operation performed, result must always be rounded to machine-representable value

processor typically allows for control over how rounding performed by supporting several rounding modes, such as:

- round to nearest
- round towards zero (i.e., truncate)
- round upwards (i.e., towards $+\infty$)
- round downwards (i.e., towards $-\infty$)
must ensure that rounding does not cause interval to no longer bracket result that would be obtained by (exact) real interval arithmetic

need to select shortest interval that contains result that would be obtained from (exact) real interval arithmetic

lower bound of result must be computed with rounding downwards

upper bound of result must be computed with rounding upwards

using rounding in this way ensures that resulting interval will bracket idealized (exact real) interval
Floating-Point Interval Arithmetic Operations

\[ A + B = [a_1, a_2] + [b_1, b_2] = [a_1 \nabla b_1, a_2 \triangle b_2] \]

\[ A - B = [a_1, a_2] - [b_1, b_2] = [a_1 \nabla b_2, a_2 \triangle b_1] \]

\[ A \cdot B = [a_1, a_2] \cdot [b_1, b_2] \]

\[ \frac{A}{B} = [a_1, a_2] / [b_1, b_2] \text{ where } 0 \notin [b_1, b_2] \]
to accommodate division by intervals containing zero, represent intervals of form

\[
[a_1, a_2] = \{ x \in \mathbb{R} \mid a_1 \leq x \leq a_2 \} \\
[a_1, +\infty) = \{ x \in \mathbb{R} \mid x \geq a_1 \} \\
(-\infty, a_2] = \{ x \in \mathbb{R} \mid x \leq a_2 \} \\
(-\infty, +\infty) \quad \emptyset
\]

arithmetic operations as defined on subsequent slides

if any operand is \( \emptyset \), result of operation is also \( \emptyset \)
### Addition and Subtraction

#### $A + B$

<table>
<thead>
<tr>
<th></th>
<th>$(-\infty, b_2]$</th>
<th>$[b_1, b_2]$</th>
<th>$[b_1, +\infty)$</th>
<th>$(-\infty, +\infty)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(-\infty, a_2]$</td>
<td>$(-\infty, a_2 \triangledown b_2]$</td>
<td>$(-\infty, a_2 \triangledown b_2]$</td>
<td>$(-\infty, +\infty)$</td>
<td>$(-\infty, +\infty)$</td>
</tr>
<tr>
<td>$[a_1, a_2]$</td>
<td>$(-\infty, a_2 \triangledown b_2]$</td>
<td>$[a_1 \triangledown b_1, a_2 \triangledown b_2]$</td>
<td>$[a_1 \triangledown b_1, +\infty)$</td>
<td>$(-\infty, +\infty)$</td>
</tr>
<tr>
<td>$[a_1, +\infty)$</td>
<td>$(-\infty, +\infty)$</td>
<td>$[a_1 \triangledown b_1, +\infty)$</td>
<td>$[a_1 \triangledown b_1, +\infty)$</td>
<td>$(-\infty, +\infty)$</td>
</tr>
<tr>
<td>$(-\infty, +\infty)$</td>
<td>$(-\infty, +\infty)$</td>
<td>$(-\infty, +\infty)$</td>
<td>$(-\infty, +\infty)$</td>
<td>$(-\infty, +\infty)$</td>
</tr>
</tbody>
</table>

#### $A - B$

<table>
<thead>
<tr>
<th></th>
<th>$(-\infty, b_2]$</th>
<th>$[b_1, b_2]$</th>
<th>$[b_1, +\infty)$</th>
<th>$(-\infty, +\infty)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(-\infty, a_2]$</td>
<td>$(-\infty, +\infty)$</td>
<td>$(-\infty, a_2 \triangledown b_1]$</td>
<td>$(-\infty, a_2 \triangledown b_1]$</td>
<td>$(-\infty, +\infty)$</td>
</tr>
<tr>
<td>$[a_1, a_2]$</td>
<td>$[a_1 \triangledown b_2, +\infty)$</td>
<td>$[a_1 \triangledown b_2, a_2 \triangledown b_1]$</td>
<td>$(-\infty, a_2 \triangledown b_1]$</td>
<td>$(-\infty, +\infty)$</td>
</tr>
<tr>
<td>$[a_1, +\infty)$</td>
<td>$[a_1 \triangledown b_2, +\infty)$</td>
<td>$[a_1 \triangledown b_2, +\infty)$</td>
<td>$(-\infty, +\infty)$</td>
<td>$(-\infty, +\infty)$</td>
</tr>
<tr>
<td>$(-\infty, +\infty)$</td>
<td>$(-\infty, +\infty)$</td>
<td>$(-\infty, +\infty)$</td>
<td>$(-\infty, +\infty)$</td>
<td>$(-\infty, +\infty)$</td>
</tr>
</tbody>
</table>
### Multiplication

\[ A \cdot B \]

<table>
<thead>
<tr>
<th>([a_1, a_2] )</th>
<th>([b_1, b_2] )</th>
<th>([b_1, b_2] )</th>
<th>([b_1, b_2] )</th>
<th>([0, 0] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_2 \leq 0)</td>
<td>([a_2 \bowtie b_2, a_1 \triangle b_1])</td>
<td>([a_1 \bowtie b_2, a_1 \triangle b_1])</td>
<td>([a_1 \bowtie b_2, a_2 \triangle b_1])</td>
<td>([0, 0])</td>
</tr>
<tr>
<td>(a_1 &lt; 0 &lt; a_2)</td>
<td>([a_2 \bowtie b_1, a_1 \triangle b_1])</td>
<td>([\min{a_1 \bowtie b_2, a_2 \bowtie b_1}, \max{a_1 \triangle b_1, a_2 \triangle b_2}]</td>
<td>([a_1 \bowtie b_2, a_2 \triangle b_2])</td>
<td>([0, 0])</td>
</tr>
<tr>
<td>(a_1 \geq 0)</td>
<td>([a_2 \bowtie b_1, a_1 \triangle b_2])</td>
<td>([a_2 \bowtie b_1, a_2 \triangle b_2])</td>
<td>([a_1 \bowtie b_1, a_2 \triangle b_2])</td>
<td>([0, 0])</td>
</tr>
<tr>
<td>([0, 0] )</td>
<td>([0, 0] )</td>
<td>([0, 0] )</td>
<td>([0, 0] )</td>
<td>([0, 0] )</td>
</tr>
<tr>
<td>((−\infty, a_2])</td>
<td>([a_2 \bowtie b_2, +\infty))</td>
<td>((−\infty, +\infty))</td>
<td>((−\infty, a_2 \triangle b_1])</td>
<td>([0, 0])</td>
</tr>
<tr>
<td>((−\infty, a_2])</td>
<td>([a_2 \bowtie b_1, +\infty))</td>
<td>((−\infty, +\infty))</td>
<td>((−\infty, a_2 \triangle b_2])</td>
<td>([0, 0])</td>
</tr>
<tr>
<td>([a_1, +\infty))</td>
<td>((−\infty, a_1 \triangle b_1])</td>
<td>((−\infty, +\infty))</td>
<td>([a_1 \bowtie b_2, +\infty))</td>
<td>([0, 0])</td>
</tr>
<tr>
<td>([a_1, +\infty))</td>
<td>((−\infty, a_1 \triangle b_2])</td>
<td>((−\infty, +\infty))</td>
<td>([a_1 \bowtie b_1, +\infty))</td>
<td>([0, 0])</td>
</tr>
<tr>
<td>((−\infty, +\infty))</td>
<td>((−\infty, +\infty))</td>
<td>((−\infty, +\infty))</td>
<td>((−\infty, +\infty))</td>
<td>([0, 0])</td>
</tr>
</tbody>
</table>
### Multiplication (Continued)

**A · B**

<table>
<thead>
<tr>
<th></th>
<th>$(-\infty, b_2]$</th>
<th>$(-\infty, b_2]$</th>
<th>$[b_1, +\infty)$</th>
<th>$[b_1, +\infty)$</th>
<th>$(\infty, +\infty)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[a_1, a_2]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_2 \leq 0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$[a_1, a_2]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_1 &lt; 0 &lt; a_2$</td>
<td>$(-\infty, +\infty)$</td>
<td>$(-\infty, +\infty)$</td>
<td>$(-\infty, +\infty)$</td>
<td>$(-\infty, +\infty)$</td>
<td>$(-\infty, +\infty)$</td>
</tr>
<tr>
<td>$[a_1, a_2]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_1 \geq 0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$[0, 0]$</td>
<td>$[0, 0]$</td>
<td>$[0, 0]$</td>
<td>$[0, 0]$</td>
<td>$[0, 0]$</td>
<td>$[0, 0]$</td>
</tr>
<tr>
<td>$(-\infty, a_2]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_2 \leq 0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(-\infty, a_2]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_2 \geq 0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$[a_1, +\infty)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_1 \leq 0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$[a_1, +\infty)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_1 \geq 0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(\infty, +\infty)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Copyright © 2015–2021 Michael D. Adams  
Programming in C++  
Version 2021-04-01
### Division

\[ A / B, \; 0 \not\in B \]

<table>
<thead>
<tr>
<th>( [a_1, a_2] ) ( a_2 \leq 0 )</th>
<th>( [a_2 \searrow b_1, a_1 \swarrow b_2] )</th>
<th>( [a_2 \searrow b_1, a_2 \swarrow b_2] )</th>
<th>( [0, a_1 \swarrow b_2] )</th>
<th>( [a_1 \searrow b_1, 0] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( [a_1, a_2] ) ( a_1 &lt; 0 &lt; a_2 )</td>
<td>( [a_2 \searrow b_2, a_1 \swarrow b_2] )</td>
<td>( [a_1 \searrow b_1, a_2 \swarrow b_1] )</td>
<td>( [a_2 \searrow b_2, a_1 \swarrow b_2] )</td>
<td>( [a_1 \searrow b_1, a_2 \swarrow b_1] )</td>
</tr>
<tr>
<td>( [a_1, a_2] ) ( a_1 \geq 0 )</td>
<td>( [a_2 \searrow b_2, a_1 \swarrow b_2] )</td>
<td>( [a_1 \searrow b_2, a_2 \swarrow b_1] )</td>
<td>( [a_2 \searrow b_2, 0] )</td>
<td>( [0, a_2 \swarrow b_1] )</td>
</tr>
<tr>
<td>( [0, 0] )</td>
<td>( [0, 0] )</td>
<td>( [0, 0] )</td>
<td>( [0, 0] )</td>
<td>( [0, 0] )</td>
</tr>
<tr>
<td>( (\infty, a_2] ) ( a_2 \leq 0 )</td>
<td>( [a_2 \searrow b_1, +\infty) )</td>
<td>( (\infty, a_2 \swarrow b_2] )</td>
<td>( [0, +\infty) )</td>
<td>( (\infty, 0] )</td>
</tr>
<tr>
<td>( (\infty, a_2] ) ( a_2 \geq 0 )</td>
<td>( [a_2 \searrow b_2, +\infty) )</td>
<td>( (\infty, a_2 \swarrow b_1] )</td>
<td>( [a_2 \searrow b_2, +\infty) )</td>
<td>( (\infty, a_2 \swarrow b_1] )</td>
</tr>
<tr>
<td>( [a_1, +\infty) ) ( a_1 \leq 0 )</td>
<td>( (\infty, a_1 \swarrow b_2] )</td>
<td>( [a_1 \searrow b_1, +\infty) )</td>
<td>( (\infty, a_1 \swarrow b_2] )</td>
<td>( [a_1 \searrow b_1, +\infty) )</td>
</tr>
<tr>
<td>( [a_1, +\infty) ) ( a_1 \geq 0 )</td>
<td>( (\infty, a_1 \swarrow b_1] )</td>
<td>( [a_1 \searrow b_2, +\infty) )</td>
<td>( (\infty, 0] )</td>
<td>( [0, +\infty) )</td>
</tr>
<tr>
<td>( (\infty, +\infty) )</td>
<td>( (\infty, +\infty) )</td>
<td>( (\infty, +\infty) )</td>
<td>( (\infty, +\infty) )</td>
<td>( (\infty, +\infty) )</td>
</tr>
</tbody>
</table>
### Division (Continued)

\( A/B, 0 \in B \)

<table>
<thead>
<tr>
<th>( [a_1, a_2] )</th>
<th>( [0, 0] )</th>
<th>( [b_1, b_2] ) ( b_1 &lt; b_2 = 0 )</th>
<th>( [b_1, b_2] ) ( 0 = b_1 &lt; b_2 )</th>
<th>( (\neg\infty, b_2] ) ( b_2 = 0 )</th>
<th>( [b_1, +\infty) ) ( b_1 = 0 )</th>
<th>( (\neg\infty, +\infty) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_2 &lt; 0 )</td>
<td>( 0 )</td>
<td>( [a_2 \triangledown b_1, +\infty) )</td>
<td>( (\neg\infty, a_2 \triangledown b_2] )</td>
<td>( [0, +\infty) )</td>
<td>( (\neg\infty, 0] )</td>
<td>( (\neg\infty, +\infty) )</td>
</tr>
<tr>
<td>( a_1 \leq 0 \leq a_2 )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
</tr>
<tr>
<td>( a_1 &gt; 0 )</td>
<td>( 0 )</td>
<td>( (\neg\infty, a_1 \triangledown b_1] )</td>
<td>( [a_1 \triangledown b_2, +\infty) )</td>
<td>( (\neg\infty, 0] )</td>
<td>( [0, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
</tr>
<tr>
<td>( (\neg\infty, a_2] ) ( a_2 &lt; 0 )</td>
<td>( 0 )</td>
<td>( [a_2 \triangledown b_1, +\infty) )</td>
<td>( (\neg\infty, a_2 \triangledown b_2] )</td>
<td>( [0, +\infty) )</td>
<td>( (\neg\infty, 0] )</td>
<td>( (\neg\infty, +\infty) )</td>
</tr>
<tr>
<td>( (\neg\infty, a_2] ) ( a_2 &gt; 0 )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
</tr>
<tr>
<td>( [a_1, +\infty) ) ( a_1 &lt; 0 )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
</tr>
<tr>
<td>( (a_1, +\infty) ) ( a_1 &gt; 0 )</td>
<td>( 0 )</td>
<td>( (\neg\infty, a_1 \triangledown b_1] )</td>
<td>( [a_1 \triangledown b_2, +\infty) )</td>
<td>( (\neg\infty, 0] )</td>
<td>( [0, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
</tr>
<tr>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
<td>( (\neg\infty, +\infty) )</td>
</tr>
</tbody>
</table>

\[ a_1, b_1, b_2 \in \mathbb{R} \]
definition of comparison operations introduces some complications

many ways in which comparison operations might be defined

for comparison operator \( \circ \) (i.e., equality, inequality, less than, greater than, less than or equal, greater than or equal), one possible way to define \([a_1, a_2] \circ [b_1, b_2]\) would be as follows:

- yields true if \( x \circ y \) is satisfied for all \( x \in [a_1, a_2] \) and all \( y \in [b_1, b_2] \),
- yields false if \( x \circ y \) is violated for all \( x \in [a_1, a_2] \) and all \( y \in [b_1, b_2] \),
- yields indeterminate (or throws exception) otherwise

for example, with preceding definition:

- \([0, 1] \leq [1, 2]\) would be true
- \([0, 1] \leq [-2, -1]\) would be false
- \([0, 2] \leq [1, 3]\) would be indeterminate
- \([0, 1] = [0, 0]\) would be indeterminate

above definition of comparison operations is particularly useful in number applications
Setting and Querying Rounding Mode

- header file `cfenv` contains various information relevant to floating-point environment
- defines macros (which expand to nonnegative integral constants) for following rounding modes:
  - `FE_TOWARDZERO`: round towards zero
  - `FE_TONEAREST`: round to nearest representable value
  - `FE_UPWARD`: round towards positive infinity
  - `FE_DOWNWARD`: round towards negative infinity
- current rounding mode can be set with `std::fesetround`
  ```
  int fesetround(int round)
  ```
  - attempts to set current rounding mode to `round`
  - returns 0 upon success non-zero value otherwise
- current rounding mode can be queried with `std::fegetround`
  ```
  int fegetround()
  ```
  - returns value of current rounding mode
- floating-point environment access and modification only meaningful when #pragma STDC FENV_ACCESS is supported and set to ON
Impact of Current Rounding Mode

- **current rounding mode** affects:
  - results of floating-point arithmetic operations outside of constant expressions
  - results of standard library mathematical functions (e.g., `sin`, `cos`, `tan`, `exp`, `log`, and `sqrt`)
  - floating-point to floating-point implicit conversion and casts
  - string conversions (e.g., `strtod`)
  - library rounding functions `nearbyint`, `rint`, and `lrint`

- **current rounding mode** does not affect:
  - floating-point to integer implicit conversions and casts (which are always towards zero)
  - results of floating-point arithmetic operations in constant expressions (which are always to nearest)
  - library functions `round`, `lround`, `ceil`, `floor`, and `trunc`

- behavior of many things affected by current rounding mode
- since some algorithms may rely on use of particular rounding mode, one must be careful to always restore previous rounding mode
```cpp
#include <iostream>
#include <cmath>
#include <cfenv>
#include <limits>

#pragma STDC FENV_ACCESS ON

int main() {
    std::cout.precision(std::numeric_limits<double>::max_digits10);
    int old_mode = std::fegetround();
    int modes[] = {FE_TONEAREST, FE_TOWARDZERO, FE_UPWARD, FE_DOWNWARD};
    for (auto mode : modes) {
        if (std::fesetround(mode)) {abort();}
        std::cout << std::sqrt(2.0) << '
';
    }
    if (std::fesetround(old_mode)) {abort();}
    std::cout << std::sqrt(2.0) << '
';
}

/* Example output:
1.4142135623730951
1.4142135623730951
1.4142135623730952
1.4142135623730951
1.4142135623730951
*/
```
Section 6.5.1

Applications in Geometry Processing
Geometric Predicates

- interval arithmetic frequently employed in geometry processing
- one application of interval arithmetic is for efficient implementation of exact geometric predicates
- geometric predicate tests for one of small number of possibilities involving geometric objects such as points, lines, and planes
- some basic geometric predicates include tests for such things as:
  - on which side of oriented line point located (i.e., 2-dimensional orientation test)
  - on which side of oriented plane point located (i.e., 3-dimensional orientation test)
  - on which side of circle point located (i.e., in-circle test)
  - on which side of sphere point located (i.e., in-sphere test)
- geometric predicates like those above essential in many geometric algorithms
- exact predicate is one that must always yield correct result
determining result of geometric predicate involves arithmetic computation
if arithmetic used for computation not exact, predicate may yield incorrect result
vast majority of algorithms cannot tolerate incorrect results from predicates
unfortunately, using exact arithmetic extremely costly
use interval arithmetic to quickly determine bound on numerical results of interest
if bound obtained from interval arithmetic sufficient to make determination of predicate result, high cost of using exact arithmetic avoided
only if bound insufficient, recompute result using exact arithmetic
in practice, interval arithmetic often sufficient to determine predicate result, leading to great increase in efficiency
Two-Dimensional Orientation Test

given three points \( a = (a_x, a_y), \ b = (b_x, b_y), \) and \( c = (c_x, c_y) \) in \( \mathbb{R}^2 \), determine to which side of directed line through \( a \) and \( b \) point \( c \) lies

can be determined from sign of determinant of \( 2 \times 2 \) matrix

\[
\text{orient2d}(a, b, c) = \det \begin{bmatrix} a_x & b_x & c_x \\ a_y & b_y & c_y \\ 1 & 1 & 1 \end{bmatrix} = \det \begin{bmatrix} a_x - c_x & b_x - c_x \\ a_y - c_y & b_y - c_y \end{bmatrix}
\]

if \( \text{orient2d}(a, b, c) \) is positive, negative, or zero, then \( c \) is respectively to left of, to right of, or collinear with directed line through \( a \) and \( b \)
Example: Two-Dimensional Orientation Test

orient2d(a, b, c) = det \[
\begin{bmatrix}
0 & 2 & 2 \\
0 & 2 & 0 \\
1 & 1 & 1 \\
\end{bmatrix}
\] = det \[
\begin{bmatrix}
-2 & 0 \\
0 & 2 \\
\end{bmatrix}
\] = -4 < 0; c is right of oriented line through a and b

orient2d(a, b, d) = det \[
\begin{bmatrix}
0 & 2 & 1 \\
0 & 2 & 1 \\
1 & 1 & 1 \\
\end{bmatrix}
\] = det \[
\begin{bmatrix}
-1 & 1 \\
-1 & 1 \\
\end{bmatrix}
\] = 0; d is on oriented line through a and b

orient2d(a, b, e) = det \[
\begin{bmatrix}
0 & 2 & 0 \\
0 & 2 & 2 \\
1 & 1 & 1 \\
\end{bmatrix}
\] = det \[
\begin{bmatrix}
0 & 2 \\
-2 & 0 \\
\end{bmatrix}
\] = 4 > 0; e is left of oriented line through a and b
Convex Polygons

A polygon is said to be **convex** if every line segment between two points on the polygon’s boundary is contained strictly inside or on the boundary of the polygon.

A polygon is said to be **strictly convex** if it is convex and all of its interior angles are strictly less than 180 degrees.
let $a$, $b$, and $c$ be three consecutive vertices of polygon in counterclockwise (CCW) order

polygon is **strictly convex** if and only if, for every choice of $a, b, c$, $c$ is to left of directed line through $ab$ (i.e., $\text{orient2d}(a, b, c) > 0$)

polygon is **convex** if and only if, for every choice of $a$, $b$, and $c$, $c$ is to left of or collinear with directed line through $ab$ (i.e., $\text{orient2d}(a, b, c) \geq 0$)
given four points $a = (a_x, a_y, a_z)$, $b = (b_x, b_y, b_z)$, $c = (c_x, c_y, c_z)$, and $d = (d_x, d_y, d_z)$ in $\mathbb{R}^3$, determine to which side of oriented plane through $a$, $b$, and $c$ point $d$ lies; above side of oriented plane is side from which $a$, $b$, and $c$ appear in CCW order

can be determined from sign of determinant of $3 \times 3$ matrix

orient3d($a$, $b$, $c$, $d$) = \[ \begin{vmatrix} a_x & b_x & c_x & d_x \\ a_y & b_y & c_y & d_y \\ a_z & b_z & c_z & d_z \\ 1 & 1 & 1 & 1 \end{vmatrix} = \begin{vmatrix} a_x - d_x & b_x - d_x & c_x - d_x \\ a_y - d_y & b_y - d_y & c_y - d_y \\ a_z - d_z & b_z - d_z & c_z - d_z \end{vmatrix} \]

if orient3d($a$, $b$, $c$, $d$) is positive, negative, or zero, then $d$ is respectively below, above, or on oriented plane through $a$, $b$, and $c$
Example: Three-Dimensional Orientation Test

\[ d = (1, 1, 2) \]
\[ c = (2, 2, 0) \]
\[ e = (1, 1, 0) \]
\[ b = (2, 0, 0) \]
\[ a = (0, 0, 0) \]
\[ f = (1, 1, -2) \]

- \( \text{orient3d}(a, b, c, d) = \text{det} \begin{bmatrix} 0 & 2 & 2 & 1 \\ 0 & 0 & 2 & 1 \\ 0 & 0 & 0 & 2 \\ 1 & 1 & 1 & 1 \end{bmatrix} = \text{det} \begin{bmatrix} -1 & 1 & 1 \\ -1 & -1 & 1 \\ -2 & -2 & -2 \end{bmatrix} = -8 < 0; \) \( d \) above oriented plane through \( a, b, \) and \( c \)
- \( \text{orient3d}(a, b, c, e) = \text{det} \begin{bmatrix} 0 & 2 & 2 & 1 \\ 0 & 0 & 2 & 1 \\ 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 \end{bmatrix} = \text{det} \begin{bmatrix} -1 & 1 & 1 \\ -1 & -1 & 1 \\ 0 & 0 & 0 \end{bmatrix} = 0; \) \( e \) lies in oriented plane through \( a, b, \) and \( c \)
- \( \text{orient3d}(a, b, c, f) = \text{det} \begin{bmatrix} 0 & 2 & 2 & 1 \\ 0 & 0 & 2 & 1 \\ 0 & 0 & 0 & -2 \\ 1 & 1 & 1 & 1 \end{bmatrix} = \text{det} \begin{bmatrix} -1 & 1 & 1 \\ -1 & -1 & 1 \\ -1 & -2 & -2 \end{bmatrix} = 8 > 0; \) \( f \) below oriented plane through \( a, b, \) and \( c \)
given four points \( a = (a_x, a_y), b = (b_x, b_y), c = (c_x, c_y), \) and \( d = (d_x, d_y) \) in \( \mathbb{R}^2 \), determine whether \( d \) is on positive side, negative side, or boundary of oriented circle through \( a, b, \) and \( c \); positive side is side to left of oriented path through \( a, b, \) and \( c \)

can be determined from result of 3-dimensional orientation test

project \( a, b, c, \) and \( d \) (in third dimension) onto paraboloid \( f(x, y) = x^2 + y^2 \) and perform orientation test on resulting four points

\[
\text{inCircle}(a, b, c, d) = \text{orient3d}(a', b', c', d'), \text{ where } a' = (a_x, a_y, a_x^2 + a_y^2),
\]
\[
b' = (b_x, b_y, b_x^2 + b_y^2), \text{ c' = (c_x, c_y, c_x^2 + c_y^2), and } d' = (d_x, d_y, d_x^2 + d_y^2)
\]

if \( \text{inCircle}(a, b, c, d) \) is positive, negative, or zero, then \( d \) lies respectively on positive side, negative side, or boundary of oriented circle through \( a, b, \) and \( c \)
**Example: Side-of-Oriented-Circle Test**

- \[ \text{inCircle}(a, b, c, d) = \det \begin{bmatrix} 0 & 2 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix} = 8 > 0; \ d \text{ on positive side of oriented circle through } a, b, \text{ and } c \ (i.e., \ d \text{ inside circle}) \]

- \[ \text{inCircle}(a, b, c, e) = \det \begin{bmatrix} 0 & 2 & 0 & 2 \\ 0 & 0 & 0 & 2 \\ 1 & 1 & 2 & 2 \\ 1 & 1 & 2 & 2 \end{bmatrix} = 0; \ e \text{ on oriented circle through } a, b, \text{ and } c \]

- \[ \text{inCircle}(a, b, c, f) = \det \begin{bmatrix} 0 & 2 & 0 & 3 \\ 0 & 0 & 0 & 3 \\ 1 & 1 & 3 & 3 \\ 1 & 1 & 3 & 3 \end{bmatrix} = -24 < 0; \ f \text{ on negative side of oriented circle through } a, b, \text{ and } c \ (i.e., \ f \text{ outside circle}) \]
Preferred-Direction Test

Given two line segments $ab$ and $cd$ and vector $v$, determine if, compared to orientation of $cd$, orientation of $ab$ is more close, less close, or equally close to the orientation of $v$.

Can be determined from result of computation involving dot products:

$$\text{prefDir}(a, b, c, d, v) = |d - c|^2 ((b - a) \cdot v)^2 - |b - a|^2 ((d - c) \cdot v)^2$$

If $\text{prefDir}(a, b, c, d, v)$ is positive, negative, or zero, then compared to orientation of $cd$, orientation of $ab$ is more close, less close, or equally close to orientation of $v$, respectively.
Example: Preferred-Direction Test

\[ \text{prefDir}(a, b, c, d, u) = |(-2, 2)|^2 [(2, 2) \cdot (2, 1)]^2 - |(2, 2)|^2 [(-2, 2) \cdot (2, 1)]^2 = 256 > 0; \text{ ab closer than } cd \text{ to direction of } u \]

\[ \text{prefDir}(a, b, c, d, v) = |(-2, 2)|^2 [(2, 2) \cdot (1, 0)]^2 - |(2, 2)|^2 [(-2, 2) \cdot (1, 0)]^2 = 0; \text{ ab and } cd \text{ equally close to direction of } v \]

\[ \text{prefDir}(a, b, c, d, w) = |(-2, 2)|^2 [(2, 2) \cdot (-1, 2)]^2 - |(2, 2)|^2 [(-2, 2) \cdot (-1, 2)]^2 = -256 < 0; \text{ cd closer than } ab \text{ to direction of } w \]
A **triangulation** of a set $V$ of vertices is a set $T$ of triangles such that:

- the union of the vertices of all triangles in $T$ is $V$;
- the interiors of any two triangles in $T$ are disjoint; and
- the union of the triangles in $T$ is the convex hull of $V$.
A triangulation is said to be **Delaunay** if each triangle in the triangulation is such that the interior of its *circumcircle contains no vertices*.
Nonuniqueness of Delaunay Triangulations
Delaunay triangulation maximizes minimum interior angle of all triangles in triangulation.

avoids long-thin triangles to whatever extent is possible.

long-thin triangles often undesirable for interpolation purposes; can lead to large discretization error and large errors in derivatives.

Delaunay triangulation only guaranteed to be unique if no four points are cocircular.

when not unique, schemes exist for making unique choice from set of all possible Delaunay triangulations, such as one proposed in:


dual graph of Delaunay triangulation is Voronoi diagram (circumcircle centers become vertices, original vertices become faces).
Edge Flips

- edge $e$ in triangulation said to be **flippable** if $e$ has two incident faces (i.e., is not on triangulation boundary) and union of these two faces is strictly convex quadrilateral $q$.

- if $e$ is flippable, valid triangulation obtained if $e$ deleted from triangulation and replaced by other diagonal $e'$ of quadrilateral $q$

- such transformation known as **edge flip**

- edge-flip example:

```
\[ v_\ell \quad e \quad v_j \quad \rightarrow \quad v_\ell \quad e' \quad v_j \]
```

- number of different triangulations of $n$ vertices upper bounded by $\binom{n}{2} = \frac{n^2 - n}{2}$, which is $O(n^2)$

- all triangulations of set of vertices have same number of edges

- every triangulation reachable from every other triangulation by edge flips
Locally-Delaunay Test

- given flippable edge $e$ in triangulation with incident faces $abc$ and $acd$ whose vertices are specified in CCW order (and whose union is strictly convex quadrilateral), determine if $e$ is locally Delaunay
- result can be determined using side-of-oriented-circle test
- $\text{localDelaunay}(a, b, c, d) = \begin{cases} 1 & \text{inCircle}(a, b, c, d) \leq 0 \\ 0 & \text{inCircle}(a, b, c, d) > 0 \end{cases}$
- if $\text{localDelaunay}(a, b, c, d) \neq 0$, edge $e$ is locally Delaunay
- if every flippable edge in triangulation is locally Delaunay, triangulation is Delaunay
Locally Preferred-Directions Delaunay Test

- Given flippable edge $e$ in triangulation with incident faces $abc$ and $acd$ whose vertices are specified in CCW order (and whose union is strictly convex quadrilateral), determine if $e$ is locally preferred-directions Delaunay with first and second direction vectors $u$ and $v$, respectively (where $u$ and $v$ are nonzero and neither parallel nor orthogonal).

- Result can be determined using side-of-oriented-circle and preferred-direction tests.

\[
\alpha(a, b, c, d, u, v) = \begin{cases} 
1 & \text{prefDir}(a, c, b, d, u) > 0 \\
1 & \text{prefDir}(a, c, b, d, u) = 0 \text{ and } \text{prefDir}(a, c, b, d, v) > 0 \\
0 & \text{otherwise}
\end{cases}
\]
Locally Preferred-Directions Delaunay Test (Continued)

- \( \text{localPrefDirDelaunay}(a, b, c, d, u, v) \)
  
  \[
  = \begin{cases} 
  1 & \text{inCircle}(a, b, c, d) < 0 \\
  0 & \text{inCircle}(a, b, c, d) > 0 \\
  \alpha(a, b, c, d, u, v) & \text{otherwise}
  \end{cases}
  \]

- If (and only if) \( \text{localPrefDirDelaunay}(a, b, c, d, u, v) \neq 0 \), edge \( e \) is locally preferred-directions Delaunay with first and second direction vectors \( u \) and \( v \), respectively.

- If every flippable edge in triangulation is locally preferred-directions Delaunay, triangulation is preferred-directions Delaunay.
Lawson Local Optimization Procedure (LOP)

- Lawson local optimization procedure (LOP) finds optimal triangulation of set of points via edge flips

- Flippable edge said to be **optimal** if:
  1. It is not flippable; or
  2. It is flippable and satisfies some optimality criterion, such as the locally-Delaunay or preferred-directions locally-Delaunay condition

- Edge said to be **suspect** if its optimality is currently uncertain

- Initially, all flippable edges are marked as suspect

- While at least one suspect edge remains, perform following:
  - Select suspect edge $e$
  - If edge $e$ is optimal, mark $e$ as not suspect; otherwise, flip $e$ to obtain edge $e'$, mark $e'$ as not suspect, and mark any edges whose optimality might be affected by flip of $e$ as suspect

- Essentially, LOP simply keeps flipping (flippable) edges that are not optimal until all edges are optimal
given any triangulation of set $P$ of points, can compute Delaunay triangulation of $P$ using Lawson LOP

select optimality criterion as locally-Delaunay or preferred-directions
locally-Delaunay condition

when edge flipped, which edges can have their optimality affected?

let $e$ denote edge being flipped

let $q$ denote quadrilateral formed by union of two faces incident on $e$

let $e'$ denote edge obtained by applying edge flip to $e$

edges that should be marked as suspect are all flippable edges belonging to $q$

for example, if edge $e'$ was produced by flipping edge $e$, would need to mark all edges drawn with thicker line (as shown below) as suspect
Preferred-Directions Delaunay Triangulation Example

Point Set

Non-Delaunay Triangulation

Delaunay Triangulation With Preferred Directions \((1, 0)\) and \((1, 1)\)

\[
d_0 = (1, 0)
\]

\[
d_1 = (1, 1)
\]

Delaunay Triangulation With Preferred Directions \((0, 1)\) and \((1, -1)\)

\[
d_0 = (0, 1)
\]

\[
d_1 = (1, -1)
\]
Section 6.5.2

References


Section 6.6

Cache-Efficient Code
The Memory Latency Problem

- over time, processors have continued to become faster
- speed improvements in memory, however, have not kept pace with processors
- compared to speed of processor, main memory is very slow
- consequently, bottlenecks in algorithms can often be due to memory speed
- very substantial amount of complexity in modern processors devoted to reducing impact of memory latency
- particularly important feature for hiding memory latency is cache
- effective utilization of cache often critical to writing high-performance code
Section 6.6.1

Memory Hierarchy and Caches
**Principle of Locality**

- **locality of reference**: programs do not access all code or data uniformly

  Two basic types of locality:

  1. **temporal**
  2. **spatial**

- **temporal locality**: tendency to reuse same information stored in memory within relatively small time interval (e.g., code in loops, top of stack)

  Example (where accesses to `i` and `sum` have good temporal locality, due to their repeated use in loop):

    ```
    int func(int);
    int sum = 0;
    for (int i = 0; i < 10000; ++i) {sum += func(i);}
    ```

- **spatial locality**: tendency to use information stored in nearby locations in memory together (e.g., sequential code, neighbouring elements in array)

  Example (where accesses to neighbouring elements of `a` have good spatial locality):

    ```
    int a[1024];
    // ...
    a[42] = a[43] * a[44] + a[45];
    ```

- To exploit locality, memory hierarchy is employed
Memory Hierarchy

Registers

Cache (E.g., L1, L2, L3)

Memory (E.g., DRAM)

Secondary Storage (E.g., Disk)

Tertiary Storage (E.g., Tape)

Increasing Latency
Increasing Capacity
Decreasing Cost Per Byte
Section Title: Caches

- **cache**: fast (but relatively small) memory
- **data cache** (a.k.a. D cache): cache that holds only data
- **instruction cache** (a.k.a., I cache): cache that holds only instructions
- **unified cache**: cache that holds both instructions and data
- **translation lookaside buffer (TLB)**: memory cache that stores recent translations of virtual to physical addresses
- May be several levels to cache hierarchy
- **level-1 (L1) cache** closest to processor, while **last-level (LL) cache** farthest
- When processor needs to read or write location, checks cache
- When data needed is available in cache, **cache hit** said to occur
- When data needed cannot be supplied by cache, **cache miss** said to occur
- Cache may be local to single core or shared between multiple cores
- L1 cache usually on core and local to core, while higher-level caches often shared between some or all cores
### Memory and Cache

<table>
<thead>
<tr>
<th>Memory Address</th>
<th>$B$ bytes</th>
<th>Block Number</th>
<th>Memory Cache</th>
<th>$B$ bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0B$</td>
<td>$b_0$</td>
<td>0</td>
<td></td>
<td>$b_0$</td>
</tr>
<tr>
<td>$1B$</td>
<td></td>
<td>1</td>
<td></td>
<td>$b_5$</td>
</tr>
<tr>
<td>$2B$</td>
<td></td>
<td>2</td>
<td></td>
<td>$b_3$</td>
</tr>
<tr>
<td>$3B$</td>
<td>$b_3$</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$4B$</td>
<td></td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$5B$</td>
<td>$b_5$</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$6B$</td>
<td></td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$7B$</td>
<td></td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
<td>...</td>
<td></td>
<td>...</td>
</tr>
<tr>
<td>$(M - 1)B$</td>
<td></td>
<td>$M - 1$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Memory partitioned into blocks of $B$ bytes (where $B$ is typically power of two)
- Memory comprised of $M$ blocks for total memory size of $BM$ bytes
- Cache can hold $N$ blocks for total cache size of $BN$ bytes
- Size of cache much less than size of memory (i.e., $BN \ll BM$)
**Block Placement**

- **block placement policy**: strategy used to determine where block can be placed in cache
  - three basic block placement policies:
    1. **direct mapped**: each block has only one place it can appear in cache
      - typically, memory block \(i\) mapped to cache block \(\mod(i,n)\), where \(n\) is number of blocks in cache
    2. **set associative**: block can be placed in restricted number of places in cache; block first mapped to group of blocks in cache called set, and then block can be placed anywhere within that set
      - typically, memory block \(i\) can be placed in any cache block in set \(\mod(i,S)\), where \(S\) is number of sets in cache
      - if each set contains \(k\) blocks, called **\(k\)-way set associative**
    3. **fully associative**: block can be placed anywhere in cache
strictly speaking, set associative includes direct mapped and fully associative as special cases

direct mapped equivalent to 1-way set associative

fully associative equivalent to $N$-way set associative, where $N$ is total number of blocks in cache

block placement policies typically employ expressions of form $\text{mod}(n, m)$ where $m = 2^k$, since result is simply given by $k$ least significant bits (LSBs) of $n$

for example:

- $\text{mod}(10, 4) = \text{mod}(1010_2, 2^2) = 10_2 = 2$
- $\text{mod}(42, 16) = \text{mod}(101010_2, 2^4) = 1010_2 = 10$
memory block $i$ can only be placed in cache block $\text{mod}(i, N)$, where $N$ is number of blocks in cache

for example, if $N = 8$ (as above), memory block 10 can only be placed in cache block $\text{mod}(10, 8) = 2$ [recall: $\text{mod}(1010_2, 2^3) = 010_2 = 2$]
memory block $i$ can be placed in any of $K$ cache blocks in set $\text{mod}(i, S)$, where $S$ is number of sets

for example, if $S = 4$ and $K = 2$ (as above), memory block 10 can be placed in any of cache blocks in set $\text{mod}(10, 4) = 2$ [recall: $\text{mod}(10_{10}, 2^2) = 10_2 = 2$]
any memory block can be placed in any cache block

for example, memory block 10 could be placed in any cache block
**block identification strategy**: method used to find block if in cache

when address is referenced, need to determine if associated data in cache, and if it is, find it

without loss of generality, we can consider case of $K$-way set associative cache

memory block $i$ can be mapped to any block in set $s = \text{mod}(i, S)$, where $S$ is number of sets in cache

each cache entry is associated with one particular set in cache and contains:

- valid bit to indicate if cache entry in use
- tag to identify which block is in cache entry (if block is valid)
- data for block (if block is valid)
Decomposition of Memory Address

- $B$ is cache block size, $N$ is number of blocks in cache, $K$ is cache associativity, and $S$ is number of sets (where $S = N/K$)
- memory address decomposed into block address and block offset
- block address then decomposed into tag and index
- in fully associative case (i.e., $S = 1$), index not present
- index $s$ identifies set in which block $i$ can be placed (i.e., $s = \text{mod}(i, S)$)
Cache Entries for $i$th Set (for $K$-Way Set Associative Cache)

<table>
<thead>
<tr>
<th></th>
<th>Tag</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_{i,0}$</td>
<td>$t_{i,0}$</td>
<td>$d_{i,0}$</td>
</tr>
<tr>
<td>$v_{i,1}$</td>
<td>$t_{i,1}$</td>
<td>$d_{i,1}$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>$v_{i,K-1}$</td>
<td>$t_{i,K-1}$</td>
<td>$d_{i,K-1}$</td>
</tr>
</tbody>
</table>

- Need to determine if any entry matches tag and (if not fully associative) index
- First determine set in which block can be placed:
  - If not fully associative, determined by index
  - Otherwise, cache only has one set
- Then look in this set for matching tag
- If match found, cache hit; otherwise, cache miss
**block replacement policy**: strategy used to determine which block should be replaced (i.e., evicted) upon miss when no unused cache entry available

in case of direct mapped cache, only one choice for block to replace so no freedom in choice of replacement policy

in case of set-associative or fully-associative cache, have some choice in block to replace

some commonly-used replacement policies include:

1. random
2. least recently used (LRU)
3. first-in first-out (FIFO)
4. approximate LRU

**random**: block to be replaced is randomly chosen (often using pseudorandom number generator)

**least-recently used (LRU)**: block that has not been used for longest time is replaced

**first-in first-out (FIFO)**: block that has been in cache longest is replaced
Write Policy

- **write policy**: strategy used to handle writes to memory
- two aspects to write policy:
  1. cache-hit policy (i.e., how to handle cache hit)
  2. cache-miss policy (i.e., how to handle cache miss)
- two basic write-hit policies:
  1. write through: information written to both block in cache and block in lower-level memory
  2. write back: information written only to block in cache; modified cache block written to main memory only when replaced
- two basic write-miss policies:
  1. write allocate (a.k.a. fetch on write): write miss brings block into cache, followed by write-hit action
  2. no write allocate (a.k.a. write around): write miss only updates lower-level memory, leaving cache unchanged
- usually, write through used with no write allocate, and write back used with write allocate
- write through always combined with write buffer to avoid always having to wait for lower-level memory
Cache Misses

- **compulsory miss** (a.k.a. cold miss): miss due to address being accessed for first time (impossible to avoid; misses even with infinite sized cache)

- **capacity miss**: miss due to cache not being large enough (i.e., program working set is much larger than cache capacity resulting in block being evicted from cache and later accessed again)

- **conflict miss**: miss due to limited associativity (i.e., miss that would have been avoided with fully associative cache); occurs when too many blocks mapped to same set resulting in memory locations being mapped to same cache entry

- **coherence miss**: miss due to cache flushes to keep multiple caches consistent (i.e., coherent) in multiprocessor system

- **true sharing miss**: coherence miss that is due to multiple threads sharing same data in cache block

- **false sharing miss**: coherence miss that is due to threads accessing different data that happens to reside in same cache block (i.e., cache block is shared between threads but not data within cache block)
virtual memory is a memory management technique that maps addresses called virtual address into physical addresses in computer memory.

- Allows the amount of memory used by the system to exceed what is physically available.
- Allows processes to share memory.
- Provides memory protection.
- Each process has its own virtual address space.
- Programs access memory using virtual addresses.
- Memory management unit (MMU) translates virtual addresses to physical addresses.
- memory partitioned into pages of size $P$ bytes (where $P$ is typically power of two)
- physical address space comprised of $M$ pages
- virtual address space comprised of $N$ pages
- virtual address space typically at least as large as physical address space (i.e., $PN \geq PM$)
- can arbitrarily map pages in virtual address space to physical pages
# Address Translation

<table>
<thead>
<tr>
<th>(\eta_{VPN}) bits</th>
<th>(\log_2 P) bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virtual Page Number</td>
<td>Page Offset</td>
</tr>
</tbody>
</table>

Virtual Address

<table>
<thead>
<tr>
<th>(\eta_{PPN}) bits</th>
<th>(\log_2 P) bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical Page Number</td>
<td>Page Offset</td>
</tr>
</tbody>
</table>

Physical Address

- \(P\) is page size
- virtual address and physical address both decomposed into page number and page offset
- address translation only changes page number part of address
- when virtual address translated to physical address, page offset does not change
- address translation is slow process
- to reduce translation time, use cache called translation lookaside buffer (TLB)
- TLB caches information for address-translation mappings
if virtual memory employed, question arises as to whether memory caches should use virtual or physical addressing

- cache that employs physical addressing called **physical cache** (or physically-addressed cache)
- cache that employs virtual addressing called **virtual cache** (or virtually-addressed cache)

key difference between use of virtual and physical cache is where address translation takes place:

- in case of accessing physical cache, always require address translation
- in case of accessing virtual cache, only need address translation on cache miss
virtual cache has advantage of eliminating address translation time for cache hit

virtual cache has disadvantage of introducing numerous complications:

- same virtual address (in different processes) can refer to distinct physical addresses (which is typically resolved by adding process ID to virtual address instead of flushing cache on each context switch)
- two distinct virtual addresses can refer to same physical address, which is called aliasing (aliasing typically resolved, in case of direct-mapped cache, by restricting address mapping such that aliases map to same cache set)
Virtually-Indexed Physically-Tagged (VIPT) Caches

- cache accesses require tag and index
- in case of virtually-indexed physically-tagged cache, index derived from virtual address and tag derived from physical address
- virtually-indexed physically-tagged cache tries to achieve simplicity of physical cache with speed closer to that of virtual cache
- recall that page offset is unaffected by address translation
- use page offset part of virtual address (which is unaffected by address translation) to determine index for cache (i.e., select set in cache)
- doing this allow us to overlap reading of tags and performing address translation
- this approach faster, but imposes some restrictions on cache parameters
- in particular, number of sets in cache cannot exceed number of cache blocks per page (without additional complications)
- L1 cache often virtually indexed and physically tagged
VIPT Cache Example

**Virtual Address (48 bits)**

<table>
<thead>
<tr>
<th>Virtual Page Number (36 bits)</th>
<th>Virtual Page Offset (12 bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cache Tag (36 bits)</td>
<td>Cache Index (6 bits)</td>
</tr>
<tr>
<td></td>
<td>Cache Block Offset (6 bits)</td>
</tr>
</tbody>
</table>

**TLB**

**Physical Page Number (24 bit)**

**Physical Page Offset (12 bits)**

**Cache**

**Cache Tags**

**Cache Tag Comparison**

**Cache Result**

- 48-bit virtual address, 36-bit physical address
- 64-byte cache block
- 4 KB page size
- L1 data cache: 32 KB, 8-way set associative, 64 entries per set
- **hit rate**: fraction of memory access that hit in cache
- **miss rate**: fraction of memory access that miss in cache (1 - hit rate)
- **miss penalty**: time to replace block from lower level in memory hierarchy to cache
- **hit time**: time to access cache memory (including tag comparison)
- **average memory access time (AMAT)**:
  - $\text{AMAT} = \text{hit time} + \text{miss rate} \cdot \text{miss penalty}$
Intel Core i7

- 64-bit processor, x86-64 instruction set
- 36-bit physical addresses and 48-bit virtual addresses
- three-level cache hierarchy; all levels use 64-byte block size; two-level TLB
  - L1 cache:
    - I cache: 32 KB 4-way set associative; D cache: 32 KB 8-way set associative; per core, pseudo LRU replacement, virtually indexed and physically tagged
  - L2 cache:
    - 256 KB, 8-way set associative, per core, pseudo-LRU replacement, physically indexed (and tagged)
  - L3 cache:
    - 2 MB per core, 16-way set associative, pseudo-LRU replacement (with ordered selection algorithm), physically indexed (and tagged)
- first-level TLB:
  - I TLB: 128 entries, 4-way set associative, pseudo-LRU replacement; D TLB: 64 entries, 4-way set associative, pseudo-LRU replacement
- second-level TLB:
  - 512 entries, 4-way set associative, pseudo-LRU replacement, 4 KB page size
ARM Cortex A8

- 32-bit processor, ARM v7 instruction set
- 32-bit physical and virtual addresses
- Two-level cache hierarchy; both levels use 64-byte block size
- L1 cache:
  - Separate I and D caches; 16 KB or 32 KB 4-way set associative using way prediction and random replacement; virtually indexed and physically tagged
- Optional L2 cache:
  - 8-way set associative, 128 KB to 1 MB; physically indexed and physically tagged
- TLB:
  - Pair of TLBs (I and D), each of which fully associative with 32 entries and variable page size (4 KB, 16 KB, 64 KB, 1 MB, 16 MB); replacements done by round robin
  - TLB misses handled in hardware, which walks page table structure in memory
Section 6.6.2

Cache-Efficient Algorithms
to effectively exploit cache, need to maximize locality

various transformations can be applied to code in order to increase locality

algorithm may be either cache aware or cache oblivious

**Cache aware**: has knowledge of memory hierarchy such as cache parameters (e.g., cache size, cache block size)

**Cache oblivious**: has no knowledge of particulars of memory hierarchy
numerous transformations can be applied to code in order to improve spatial and/or temporal locality

**merging arrays**: improve spatial locality by using array of aggregate type instead of multiple arrays

**loop interchange**: change nesting of loops to access data in order stored in memory

**loop fusion**: combine two or more independent loops that have same looping and some variables overlap

**blocking**: improve temporal locality by accessing blocks of data repeatedly
before array merging:

```cpp
constexpr int num_points = 32'768;
static double x[num_points]; // x coordinates
static double y[num_points]; // y coordinates
static double z[num_points]; // z coordinates
```

after array merging:

```cpp
constexpr int num_points = 32'768;
struct Point {
    double x; // x coordinate
    double y; // y coordinate
    double z; // z coordinate
};
static Point p[num_points];
```

- x, y, and z coordinates of particular point likely to be accessed together
- use array of aggregate type instead of three separate arrays in order to improve spatial locality and reduce potential conflicts
Loop Interchange Example

- before loop interchange:
  ```cpp
  constexpr int n = 2'048;
  static double a[n][n];
  // ...
  for (int j = 0; j < n; ++j) {
    for (int i = 0; i < n; ++i) {
      a[i][j] *= 2.0;
    }
  }
  ```

- after loop interchange:
  ```cpp
  constexpr int n = 2'048;
  static double a[n][n];
  // ...
  for (int i = 0; i < n; ++i) {
    for (int j = 0; j < n; ++j) {
      a[i][j] *= 2.0;
    }
  }
  ```

- interchange loops so that array elements accessed consecutively instead of with large stride in order to improve locality and reduce potential conflicts
Loop Fusion Example

- **before loop fusion:**
  ```cpp
cconstexpr int n = 2'048;
static float a[n][n], b[n][n], c[n][n], d[n][n];
// ...
for (int i = 0; i < n; ++i) {
  for (int j = 0; j < n; ++j) {
    a[i][j] = b[i][j] * c[i][j];
  }
}
for (int i = 0; i < n; ++i) {
  for (int j = 0; j < n; ++j) {
    d[i][j] = a[i][j] + c[i][j];
  }
}
```

- **after loop fusion:**
  ```cpp
cconstexpr int n = 2'048;
static float a[n][n], b[n][n], c[n][n], d[n][n];
// ...
for (int i = 0; i < n; ++i) {
  for (int j = 0; j < n; ++j) {
    a[i][j] = b[i][j] * c[i][j];
    d[i][j] = a[i][j] + c[i][j];
  }
}
```

- **merge loops in order to improve temporal locality (due to reuse of a[i][j] and c[i][j] in each innermost loop iteration)**
before blocking:

```cpp
1 // compute c := c + a b, where a, b, c are N-by-N
2 // matrices
3 template <class T, int N>
4 void naive_multiply(const T (&a)[N][N], const T (&b)[N][N],
5     T (&c)[N][N]) {
6     for (int i = 0; i < N; ++i) {
7         for (int j = 0; j < N; ++j) {
8             double s = 0;
9             for (int k = 0; k < N; ++k)
10                 {s += a[i][k] * b[k][j];}
11                 c[i][j] += s;
12         }
13     }
14 }
```

want to partition computation into blocks of size \(B \times B\), where \(B\) chosen so that each block fits in cache
use each row of \( a \) \( N \) times (once for each column of \( b \))

for each row of \( a \), use each of \( N \) columns of \( b \) in succession

update elements in \( c \) in left-to-right top-to-bottom order
after blocking (with blocking factor $B$):

```cpp
// compute $c := c + a \cdot b$, where $a$, $b$, $c$ are $N$-by-$N$
// matrices

template <int B, class T, int N>
void blocked_multiply(const T (&a)[N][N], const T (&b)[N][N],
                     T (&c)[N][N]) {
  for (int kk = 0; kk < N; kk += B) {
    for (int jj = 0; jj < N; jj += B) {
      for (int i = 0; i < N; ++i) {
        for (int j = jj; j < std::min(jj + B, N); ++j) {
          double s = 0;
          for (int k = kk; k < std::min(kk + B, N); ++k) {
            s += a[i][k] * b[k][j];
          }
          c[i][j] += s;
        }
      }
    }
  }
}
```

- performing computation using blocking significantly improves locality
- potentially many fewer cache misses
- unfortunately, code using blocking much less readable (i.e., more difficult to understand)
■ key idea is that block of \( b \) brought into cache, fully utilized, then discarded

■ innermost loop pair (i.e., for \( j \) and \( k \)) multiplies \( 1 \times B \) sliver of \( a \) by \( B \times B \) block of \( b \) and accumulates result in \( 1 \times B \) sliver of \( c \)

■ references to \( a \) have: good spatial locality, since elements accessed consecutively in loop for \( k \); and good temporal locality, since each sliver accessed \( B \) times in succession in loop for \( j \)

■ references to \( b \) have good temporal locality, since entire block accessed \( N \) times in succession in loop for \( i \)

■ references to \( c \) have good spatial locality since each element of sliver written in succession in loop for \( j \)
cache-aware approaches require knowledge of memory hierarchy and caches (e.g., cache size and cache block size for each level of cache) in order to choose key tuning parameters

often, such knowledge of memory hierarchy difficult to obtain in reliable manner

furthermore, effective cache size may differ significantly from true cache size, if multiple threads using cache (which reduces effective cache size)

if tuning parameters not well chosen, performance can potentially be very poor

in contrast, cache oblivious approaches:
  - require no knowledge of memory hierarchy and caches
  - require no “magical” tuning parameters
  - effectively autotune
  - handle multilevel caches automatically
  - well accommodate multiprogrammed environments
Section 6.6.3

Cache-Oblivious Algorithms
suppose that cache has size $M$ with block size $B$ and $N = M/B$ entries

- cache is said to be **tall** if $N > c'B$ for some sufficiently large constant $c' \geq 1$; otherwise, said to be **short**

- essentially, tall property ensures that $N$ exceeds $B$ by large enough margin that any (possibly non-contiguous) data of size $D$ is guaranteed to fit in cache if $D \leq M$

- that is, if size of some data does not exceed cache size, then that data must fit in cache

- this is not the case for short caches

- for example, $n \times n$ block of elements inside larger array stored in **row-major order** with $n^2 < M$ will not necessarily fit in cache if cache is short
idealized cache model employs two-level memory hierarchy (i.e., cache and main memory)

assumptions of idealized cache model:
- fully associative
- optimal replacement policy (i.e., evict cache block whose next access will be furthest in future)
- tall cache

idealized model only crude approximation to real-world caches

real-world caches usually not fully associative and never employ optimal replacement policy (which requires noncausal hardware)

real-world caches, however, usually tend to be tall
Remarks on Assumption of Optimal-Replacement Policy

- reasonable to question validity of assumption of optimal-replacement policy in idealized cache model
- Sleator and Tarjan (1985) have shown that amortized cost of LRU replacement policy within constant factor of optimal replacement policy
- suppose that algorithm that incurs $Q$ cache misses on ideal cache of size $M$
- then, on fully-associative cache of size $2M$ that uses LRU replacement policy, at most $2Q$ cache misses
- therefore, *to within constant factor, LRU replacement as good as optimal replacement (for fully-associative cache)*
- implication is that for asymptotic analysis can assume optimal or LRU replacement as convenient
- in this sense, assumption of optimal-replacement policy is quite reasonable
Cache-Oblivious Algorithms

- when analyzing algorithms with respect to idealized cache model typically we are interested in
  - amount of work $W$ (ordinary running time)
  - number of cache misses $Q$
- cache oblivious algorithms often based on divide and conquer
- cache block holds $B$ array elements
- consider scanning $N$ elements of array in order (e.g., to compute sum or minimum/maximum)
- requires $\Theta(N)$ work (assuming work per element is $O(1)$)
- scanning $N$ elements stored contiguously in memory incurs either $\lceil N/B \rceil + 1$ or $\lceil N/B \rceil$ cache misses (i.e., $\Theta(N/B)$ cache misses)
- may require one more than $\lceil N/B \rceil$ cache misses due to arbitrary alignment
- cache oblivious and optimal (i.e., incurs only minimum number of cache misses)
Array Reversal

- cache block holds $B$ array elements
- consider reversing elements of $N$-element array $a$
- use two parallel scans, one from each end of array, and each step swaps two corresponding elements
- for $i$ in $0, 1, \ldots, \lfloor N/2 \rfloor - 1$, swap $a[i]$ and $a[N - 1 - i]$
- requires $\Theta(N)$ work (i.e., $\lfloor N/2 \rfloor$ swap operations)
- assuming at least two blocks fit in cache, incurs either $\lceil N/B \rceil + 1$ or $\lceil N/B \rceil$ cache misses (i.e., $\Theta(N/B)$ cache misses)
- cache oblivious and optimal
naive matrix transpose code has following form:

```cpp
template <class T, int m, int n>
void transpose(const T (&a)[m][n], T (&b)[n][m]) {
    for (int i = 0; i < m; ++i) {
        for (int j = 0; j < n; ++j) {
            b[j][i] = a[i][j];
        }
    }
}
```

arrays stored in row-major order

although data in `a` being accessed sequentially, data in `b` being accessed with large stride

many unnecessary cache misses on accesses to `b` if number of rows in `b` sufficiently large
Naive Matrix Transposition: Performance

- cache block holds $L$ matrix elements
- requires $\Theta(mn)$ work (which is optimal)
- in innermost loop, accesses to $b$ use potentially large stride
- strided access to $b$ can potentially result in large number of cache misses
- if all blocks for entire column of $b$ cannot be kept resident in cache simultaneously, every access to $b$ will miss
- in this case, at most $\lceil mn/L \rceil + 1 + mn$ cache misses
- any matrix-transpose algorithm must access all $mn$ elements of $a$ and all $mn$ elements of $b$, which incurs at most $2(\lceil mn/L \rceil + 1)$ cache misses
- naive approach incurs about $\left(\frac{L-1}{L}\right)mn$ more cache misses than this
consider Rec-Transpose algorithm for matrix transposition from page 4:7 of:


given $m \times n$ matrix $A$ and $n \times m$ matrix $B$, place $A^T$ into $B$

$A$ and $B$ assumed to correspond to distinct objects (i.e., not in-place transposition)

based on divide and conquer strategy

algorithm halves largest of dimensions $m$ and $n$, and recurs

two cases to consider (i.e., $m$ or $n$ largest)

if more than one case applies (i.e., $m = n$), choose one case arbitrarily
case 1. if $n = \max\{m, n\}$ (i.e., number of columns in $A$ and rows in $B$ largest):

- decompose problem as follows:

  \[
  \begin{align*}
  &\text{let } A = \begin{bmatrix} A_1 & A_2 \end{bmatrix} \quad \text{and } B = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix}; \quad \text{so } \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = \begin{bmatrix} A_1^T & A_2^T \end{bmatrix} \\
  &\text{recurse to solve } B_1 = A_1^T \quad \text{and } B_2 = A_2^T
  \end{align*}
  \]

case 2. if $m = \max\{m, n\}$ (i.e., number of rows in $A$ and columns in $B$ largest):

- decompose problem as follows:

  \[
  \begin{align*}
  &\text{let } A = \begin{bmatrix} A_1 \\ A_2 \end{bmatrix} \quad \text{and } B = \begin{bmatrix} B_1 & B_2 \end{bmatrix}; \quad \text{so } \begin{bmatrix} B_1 & B_2 \end{bmatrix} = \begin{bmatrix} A_1^T \\ A_2^T \end{bmatrix} \\
  &\text{recurse to solve } B_1 = A_1^T \quad \text{and } B_2 = A_2^T
  \end{align*}
  \]

conceptually, base case for recursion occurs when $m = n = 1$

in practice, stop recursion earlier
Cache-Oblivious Matrix Transposition Example 1A

\[
\begin{bmatrix}
  b_{11} & b_{12} \\
  b_{21} & b_{22}
\end{bmatrix} = 
\begin{bmatrix}
  a_{11} & a_{12} \\
  a_{21} & a_{22}
\end{bmatrix}^T
\]

\[
\begin{bmatrix}
  b_{11} \\
  b_{12}
\end{bmatrix} = 
\begin{bmatrix}
  a_{11} \\
  a_{21}
\end{bmatrix}^T
\]

\[
\begin{bmatrix}
  b_{21} \\
  b_{22}
\end{bmatrix} = 
\begin{bmatrix}
  a_{12} \\
  a_{22}
\end{bmatrix}^T
\]

\[
\begin{bmatrix}
  b_{11}
\end{bmatrix} = 
\begin{bmatrix}
  a_{11}
\end{bmatrix}^T
\]

\[
\begin{bmatrix}
  b_{12}
\end{bmatrix} = 
\begin{bmatrix}
  a_{21}
\end{bmatrix}^T
\]

\[
\begin{bmatrix}
  b_{21}
\end{bmatrix} = 
\begin{bmatrix}
  a_{12}
\end{bmatrix}^T
\]

\[
\begin{bmatrix}
  b_{22}
\end{bmatrix} = 
\begin{bmatrix}
  a_{22}
\end{bmatrix}^T
\]
Cache-Oblivious Matrix Transposition Example 1B

\[
\begin{bmatrix}
  b_{11} & b_{12} \\
  b_{21} & b_{22}
\end{bmatrix}
= \begin{bmatrix}
  a_{11} & a_{12} \\
  a_{21} & a_{22}
\end{bmatrix}^T
\]

\[
\begin{bmatrix}
  b_{11} \\
  b_{21}
\end{bmatrix}
= \begin{bmatrix}
  a_{11} \\
  a_{12}
\end{bmatrix}^T
\]

\[
\begin{bmatrix}
  b_{12} \\
  b_{22}
\end{bmatrix}
= \begin{bmatrix}
  a_{21} \\
  a_{22}
\end{bmatrix}^T
\]

\[
\begin{bmatrix}
  b_{11} \\
  b_{21}
\end{bmatrix}
= \begin{bmatrix}
  a_{11} \\
  a_{12}
\end{bmatrix}^T
\]

\[
\begin{bmatrix}
  b_{12} \\
  b_{22}
\end{bmatrix}
= \begin{bmatrix}
  a_{21} \\
  a_{22}
\end{bmatrix}^T
\]
Cache-Oblivious Matrix Transposition Example 2

\[
\begin{bmatrix}
 b_{11} & b_{12} \\
 b_{21} & b_{22} \\
 b_{31} & b_{32}
\end{bmatrix}
= \begin{bmatrix}
 a_{11} & a_{12} & a_{13}^T \\
 a_{21} & a_{22} & a_{23}
\end{bmatrix}
\]

\[
\begin{bmatrix}
 b_{11} & b_{12} \\
 b_{21} & b_{22}
\end{bmatrix}
= \begin{bmatrix}
 a_{11} & a_{12}^T \\
 a_{21} & a_{22}
\end{bmatrix}
\]

\[
\begin{bmatrix}
 b_{31} & b_{32}
\end{bmatrix}
= \begin{bmatrix}
 a_{13}^T \\
 a_{23}
\end{bmatrix}
\]

\[
[b_{11}] = [a_{11}]^T \\
[b_{12}] = [a_{21}]^T \\
[b_{21}] = [a_{12}]^T \\
[b_{22}] = [a_{22}]^T \\
[b_{31}] = [a_{13}]^T \\
[b_{32}] = [a_{23}]^T
\]
let $L$ denote number of array elements per cache block

for $m \times n$ matrix, cache-oblivious matrix-transposition algorithm:
- requires $\Theta(mn)$ work
- incurs $\Theta(1 + mn/L)$ cache misses, assuming idealized cache model

any matrix-transposition algorithm must write to $mn$ distinct elements, which occupy at least $\lceil mn/L \rceil = \Omega(1 + mn/L)$ cache lines

therefore, cache-oblivious algorithm is asymptotically optimal
Naive Matrix Multiplication

naive matrix multiply code has following form:

```cpp
template <class T, int m, int n, int p>
void multiply(const T (&a)[m][n], const T (&b)[n][p],
              T (&c)[m][p]) {
    for (int i = 0; i < m; ++i) {
        for (int j = 0; j < p; ++j) {
            T sum = T(0);
            for (int k = 0; k < n; ++k) {
                sum += a[i][k] * b[k][j];
            }
            c[i][j] = sum;
        }
    }
}
```

arrays stored in **row-major order**

in innermost loop, \(b\) accessed with potentially large stride, which is problematic

in second innermost loop, row of \(a\) is accessed \(p\) times in succession, which is problematic if row does not fit in cache

many unnecessary cache misses likely to result in case of larger matrices
cache block holds $L$ matrix elements

innermost loop (in which $k$ varies) computes dot product of $i$th row of $a$ with $k$th column of $b$ to yield $(i, j)$th element of $c$

second innermost loop (over $j$) changes column of $b$ to use in dot product with $i$th row of $a$ (reusing $i$th row of $a$ $p$ times)

requires $\Theta(mnp)$ work, which is $\Theta(n^3)$ in case of square matrices

assuming that row of $a$ and column of $b$ do not fit in cache simultaneously, algorithm incurs $\Theta(mnp/L + mnp + mp/L)$ cache misses, which is $\Theta(n^3)$ in case of square matrices
consider Rec-Mult algorithm for matrix multiplication from pages 4:4–4:5 of:


given $m \times n$ matrix $A$ and $n \times p$ matrix $B$, compute $m \times p$ matrix $C$, where $C := C + AB$

if $C$ initialized to 0, computation $C := C + AB$ yields $C = AB$

based on divide and conquer strategy

algorithm halves largest of three dimensions $m$, $n$, and $p$, and recurs

three cases to consider (i.e., $m$, $n$, or $p$ largest)

if more than one of three cases applies (e.g., if $m = n = p$), choose one case arbitrarily
Cache-Oblivious Matrix Multiplication (Continued 1)

- **case 1.** if $m = \max\{m, n, p\}$ (i.e., number of rows in $A$ and $C$ largest):
  - decompose problem as follows:
    
    $$C = \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} \text{ and } A = \begin{bmatrix} A_1 \\ A_2 \end{bmatrix}; \quad \text{so } AB = \begin{bmatrix} A_1 \\ A_2 \end{bmatrix} B = \begin{bmatrix} A_1 B \\ A_2 B \end{bmatrix}$$
    
    - recurse to compute $C_1 := C_1 + A_1 B$ and $C_2 := C_2 + A_2 B$

- **case 2.** if $n = \max\{m, n, p\}$ (i.e., number of columns in $A$ and rows in $B$ largest):
  - decompose problem as follows:
    
    $$A = \begin{bmatrix} A_1 & A_2 \end{bmatrix} \text{ and } B = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix}; \quad \text{so } AB = \begin{bmatrix} A_1 & A_2 \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = A_1 B_1 + A_2 B_2$$
    
    - recurse to compute $C := C + A_1 B_1$ and then $C := C + A_2 B_2$

- **case 3.** if $p = \max\{m, n, p\}$ (i.e., number of columns in $B$ and $C$ largest):
  - decompose problem as follows:
    
    $$C = \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} \text{ and } B = \begin{bmatrix} B_1 & B_2 \end{bmatrix}; \quad \text{so } AB = A \begin{bmatrix} B_1 & B_2 \end{bmatrix} = \begin{bmatrix} AB_1 & AB_2 \end{bmatrix}$$
    
    - recurse to compute $C_1 := C_1 + AB_1$ and $C_2 := C_2 + AB_2$
conceptually, base case for recursion occurs when \( m = n = p = 1 \), in which case two elements multiplied and added into result matrix

in practice, however, stop recursion earlier
Cache-Oblivious Matrix Multiplication Example 1

\[
\begin{bmatrix}
c_{11} & c_{12} \\
c_{21} & c_{22}
\end{bmatrix} =
\begin{bmatrix}
a_{11} & a_{12} \\
a_{21} & a_{22}
\end{bmatrix}
\begin{bmatrix}
b_{11} & b_{12} \\
b_{21} & b_{22}
\end{bmatrix}
\]
Cache-Oblivious Matrix Multiplication Example 2
Cache block holds $L$ matrix elements

- cache size $M$ (in matrix elements)

To multiply $m \times n$ matrix by $n \times p$ matrix:
- requires $\Theta(mnp)$ work
- incurs $\Theta\left(m + n + p + \frac{1}{L}(mn + np + mp) + \frac{1}{LM^{1/2}}mnp\right)$ cache misses, assuming idealized cache model

To multiply two square matrices (i.e., $m = n = p$):
- requires $\Theta(n^3)$ work
- incurs $\Theta\left(\frac{1}{LM^{1/2}}n^3\right)$ cache misses, assuming idealized cache model

Hong and Kung (1981) have shown this to be optimal bound for cache misses for matrix multiplication

Therefore, cache-oblivious algorithm is optimal
strictly speaking, Rec-Mult algorithm performs matrix multiply and accumulate

can zero matrix that holds result to achieve effect of matrix multiply alone

alternatively, can use additional state during recursion to handle whether accumulation done

add accumulate flag to recursion

when accumulate flag is set, result is added to destination; otherwise, result overwrites destination

always perform call for left child in recursion tree first; then perform call for right child

at start of recursion, accumulate flag set to false

for cases 1 and 3, accumulate flag passed unmodified in call for both children in recursion tree

for case 2, accumulate flag passed unmodified in call for left child in recursion tree and set to true in call for right child in recursion tree
Cache-Oblivious Matrix Multiplication Revisited Example 1

\[
\begin{bmatrix}
  c_{11} & c_{12} \\
  c_{21} & c_{22}
\end{bmatrix} =
\begin{bmatrix}
  a_{11} & a_{12} \\
  a_{21} & a_{22}
\end{bmatrix}
\begin{bmatrix}
  b_{11} & b_{12} \\
  b_{21} & b_{22}
\end{bmatrix}
\]

\[
\begin{bmatrix}
  c_{11} | c_{12}
\end{bmatrix} =
\begin{bmatrix}
  a_{11} | a_{12}
\end{bmatrix}
\begin{bmatrix}
  b_{11} | b_{12}
\end{bmatrix}
\]

\[
\begin{bmatrix}
  c_{21} | c_{22}
\end{bmatrix} =
\begin{bmatrix}
  a_{21} | a_{22}
\end{bmatrix}
\begin{bmatrix}
  b_{11} | b_{12}
\end{bmatrix}
\]
Cache-Oblivious Matrix Multiplication Revisited Example 2

\[
\begin{align*}
\begin{bmatrix}
c_{11} & c_{12} \\
c_{21} & c_{22}
\end{bmatrix} &=
\begin{bmatrix}
a_{11} & a_{12} \\
a_{21} & a_{22}
\end{bmatrix} \\
\begin{bmatrix}
b_{11} & b_{12} \\
b_{21} & b_{22}
\end{bmatrix}
\end{align*}
\]

Copyright © 2015–2021 Michael D. Adams

Programming in C++  
Version 2021-04-01
Strassen’s Algorithm for Matrix Multiplication

- given two $n \times n$ matrices $A$ and $B$ where $n$ is power of two, compute $C = AB$
- approach based on divide and conquer
- partition $A$, $B$, and $C$ into equally sized block matrices:

\[
A = \begin{bmatrix}
A_{1,1} & A_{1,2} \\
A_{2,1} & A_{2,2}
\end{bmatrix}, \quad
B = \begin{bmatrix}
B_{1,1} & B_{1,2} \\
B_{2,1} & B_{2,2}
\end{bmatrix}, \quad
C = \begin{bmatrix}
C_{1,1} & C_{1,2} \\
C_{2,1} & C_{2,2}
\end{bmatrix}
\]

- define (using only 7 matrix multiplications instead of 8):

\[
M_1 = (A_{1,1} + A_{2,2})(B_{1,1} + B_{2,2}), \quad M_2 = (A_{2,1} + A_{2,2})B_{1,1},
\]
\[
M_3 = A_{1,1}(B_{1,2} - B_{2,2}), \quad M_4 = A_{2,2}(B_{2,1} - B_{1,1}),
\]
\[
M_5 = (A_{1,1} + A_{1,2})B_{2,2}, \quad M_6 = (A_{2,1} - A_{1,1})(B_{1,1} + B_{1,2}),
\]
\[
M_7 = (A_{1,2} - A_{2,2})(B_{2,1} + B_{2,2})
\]

- can compute $C$ as follows:

\[
C_{1,1} = M_1 + M_4 - M_5 + M_7, \quad C_{1,2} = M_3 + M_5,
\]
\[
C_{2,1} = M_2 + M_4, \quad C_{2,2} = M_1 - M_2 + M_3 + M_6
\]

- Strassen’s matrix multiplication algorithm optimal in cache-oblivious sense
Discrete Fourier Transform (DFT)

- The discrete Fourier transform (DFT) of vector \( x \) of \( n \) complex numbers is
  vector \( y \) (of \( n \) complex numbers) given by
  \[
  y(i) = \sum_{j=0}^{n-1} x(j) \omega_n^{-ij}
  \]
  where \( \omega_n = e^{2\pi \sqrt{-1}/n} \)

- For any factorization \( n = n_1 n_2 \) of \( n \), we have
  \[
  y(i_1 + i_2 n_1) = \sum_{j_2=0}^{n_2-1} \left[ \left( \sum_{j_1=0}^{n_1-1} x(j_1 n_2 + j_2) \omega_n^{-i_1 j_1} \right) \omega_n^{-i_1 j_2} \right] \omega_n^{-i_2 j_2}
  \]

- In preceding equation, inner and outer summations are DFTs

- Operationally, computation specified in above equation can be performed by:
  1. Computing \( n_2 \) DFTs of size \( n_1 \) (i.e., inner summation)
  2. Multiplying result by factors \( \omega_n^{-i_1 j_2} \) (called twiddle factors)
  3. Computing \( n_1 \) DFTs of size \( n_2 \) (i.e., outer summation)
Cache-Oblivious Fast Fourier Transform (FFT)

- “six-step” variant of Cooley-Tukey FFT algorithm
- want to compute (one-dimensional) FFT of $n$ element array $x$, where $n$ is composite and preferably power of two
- FFT is computed in place (i.e., output in $x$)
- algorithm consists of following steps (in order):
  1. factor $n$ as $n = n_1 n_2$, where $n_1$ is as close to $\sqrt{n}$ as possible
  2. treat input vector $x$ as row-major $n_1 \times n_2$ matrix $A$, and use cache-oblivious transpose algorithm to transpose $A$ in place (by writing transpose of $A$ to auxiliary array $B$ and then copying $B$ back to $A$)
  3. for each of $n_2$ rows of $A$, replace row with its $n_1$-point DFT, where each DFT is computed recursively
  4. multiply $A$ by twiddle factors
  5. transpose $A$ in place (so that inputs to next stage placed in contiguous locations)
  6. for each of $n_1$ rows of $A$, replace row with its $n_2$-point DFT, where each DFT is computed recursively
  7. transpose $A$ in place to yield output array $x$ with elements in correct order
Example: Four-Point DFT

- Note: The DFT of \([x_0 \ x_1]\) is easily shown to be \([x_0 + x_1 \ x_0 - x_1]\).
- Consider computing the DFT of the following sequence of length \(n = 4\):
  \[
  \begin{bmatrix}
  x_0 & x_1 & x_2 & x_3 \\
  \end{bmatrix}.
  \]
- Factor \(n\) as \(n_1n_2\), where \(n_1 = n_2 = 2\).
- Treat the one-dimensional array of size 4 as the following \(2 \times 2\) array stored in row-major order:
  \[
  \begin{bmatrix}
  x_0 & x_1 \\
  x_2 & x_3 \\
  \end{bmatrix}.
  \]
- Transpose the matrix to obtain:
  \[
  \begin{bmatrix}
  x_0 & x_2 \\
  x_1 & x_3 \\
  \end{bmatrix}.
  \]
- Replace each row of the matrix by its two-point DFT to yield:
  \[
  \begin{bmatrix}
  x_0 + x_2 & x_0 - x_2 \\
  x_1 + x_3 & x_1 - x_3 \\
  \end{bmatrix}.
  \]
Apply the twiddle factors to the matrix to obtain (where $\omega_4 = e^{2\pi\sqrt{-1}/4} = \sqrt{-1}$):

$$
\begin{bmatrix}
\omega_4^{(0.0)}(x_0 + x_2) & \omega_4^{(1.0)}(x_0 - x_2) \\
\omega_4^{(0.1)}(x_1 + x_3) & \omega_4^{(1.1)}(x_1 - x_3)
\end{bmatrix}
= \begin{bmatrix}
x_0 + x_2 & x_0 - x_2 \\
x_1 + x_3 & \sqrt{-1}(-x_1 + x_3)
\end{bmatrix}.
$$

Transpose the matrix to yield:

$$
\begin{bmatrix}
x_0 + x_2 & x_1 + x_3 \\
x_0 - x_2 & \sqrt{-1}(-x_1 + x_3)
\end{bmatrix}.
$$

Replace each row of the matrix by its two-point DFT to yield:

$$
\begin{bmatrix}
x_0 + x_1 + x_2 + x_3 & x_0 - x_1 + x_2 - x_3 \\
x_0 - x_2 + \sqrt{-1}(-x_1 + x_3) & x_0 - x_2 + \sqrt{-1}(x_1 - x_3)
\end{bmatrix}.
$$

Transpose the matrix to obtain:

$$
\begin{bmatrix}
x_0 + x_1 + x_2 + x_3 & x_0 - x_2 + \sqrt{-1}(-x_1 + x_3) \\
x_0 - x_1 + x_2 - x_3 & x_0 - x_2 + \sqrt{-1}(x_1 - x_3)
\end{bmatrix}.
$$
Treat the $2 \times 2$ matrix stored in row-major order as a one-dimensional array to yield:

$$
\begin{bmatrix}
  x_0 + x_1 + x_2 + x_3 \\
  x_0 - x_2 + \sqrt{-1}(-x_1 + x_3) \\
  x_0 - x_1 + x_2 - x_3 \\
  x_0 - x_2 + \sqrt{-1}(x_1 - x_3)
\end{bmatrix}^T.
$$
can be proven by induction that algorithm requires $O(n \log_2 n)$ work

- cache block holds $L$ elements of array
- $Z$ cache size in units of array element size

- can be shown that algorithm incurs $O(1 + (n/L)(1 + \log_Z n))$ cache misses

- preceding cache miss result asymptotically optimal for Cooley-Tukey algorithm, matching lower bound by Hong and Kung when $n$ is exact power of two
Section 6.6.4

References


Section 6.7

Vectorization
Section 6.7.1

Vector Processing
Vector processor has instruction set that can operate on one-dimensional arrays of data called vectors.

Vector processing has its roots in early supercomputers.

Approach has been refined significantly over the years.

Attempts to exploit data-level parallelism.

Most modern processors provide some level of vector processing functionality.
Scalar Versus Vector Instructions

Scalar Operation
With Two Operands

- first operand $a$
- second operand $b$
- result $a \text{ op } b$

Vector Operation
With Two Operands

- first operand $a_0, a_1, \ldots, a_{L-1}$
- second operand $b_0, b_1, \ldots, b_{L-1}$
- result $a_0 \text{ op } b_0, a_1 \text{ op } b_1, \ldots, a_{L-1} \text{ op } b_{L-1}$

- each operand of scalar instruction is single value
- each operand of vector instruction is set of $L$ values known as **vector**
- $L$ called **vector length**
- same operation applied to each of $L$ elements of vector
- operation might, for example, be: load/store, arithmetic operation, logical operation, comparison, conversion operation, or shuffle operation
two basic approaches to vector processing:

1. vector-memory architecture
2. vector-register architecture

vector-memory architecture:
- for all vector operations, operands fetched from main memory and results written back to main memory
- includes early vector machines through mid 1980s
- no longer used much (if at all) in modern processors
- large startup time for vector operations

vector-register architecture:
- for all vector operations except loads and stores, operands read from and written to vector registers
- used by most modern processors that support vector operations
Vector register is collection of $N$ elements of same type, where each element is $M$ bits in size.

- $N$ called vector length
- Vector register size $NM$ typically 128 to 512
- Advantages of vector processing:
  - Potential speedup by factor of $N$
  - Often more energy efficient relative to other approaches for increasing performance (such as wider superscalar or higher clock rate)
  - Potentially smaller code size, since single instruction can perform multiple operations
modern high-performance CPU architectures have specialized instructions to exploit parallelism in loops
commonly referred as single-instruction multiple-data (SIMD) extensions
operate on multiple elements of wide vector register simultaneously
reduces runtime trip count of loop by vectorization factor
requires sophisticated analysis and heuristics in order to make good decisions about vectorization safety and profitability
widen each operation in loop from scalar type to vector type
applies same operation in parallel to number of data items packed into large register (e.g., 64, 128, 256, 512 bits)
particularly useful for algorithms with high degree of data-level parallelism, such as those often found in multimedia systems, graphics, and image/video/audio processing
Streaming SIMD Extensions (SSE) is family of vector extensions to Intel x86/x86-64 instruction set architecture (namely, SSE, SSE2, SSE3, SSSE3, SSE4.1, and SSE 4.2).

Collectively, SSE family added:
- In case of x86: **8 128-bit vector registers**, known as XMM0 to XMM7
- In case of x86-64: **16 128-bit vector registers**, known as XMM0 through XMM15

Each vector register can be used to hold:
- 16 8-bit bytes
- 8 16-bit integers
- 4 32-bit integers
- 2 64-bit integers
- 4 32-bit single-precision floating-point numbers
- 2 64-bit double-precision floating-point numbers
Advanced Vector Extensions (AVX) is a family of vector extensions to Intel x86/x86-64 instruction set architecture (namely, AVX, AVX2, and AVX-512) that builds upon SSE.

- AVX extends 16 vector registers of SSE from 128 to **256 bits**.
- It renames vector registers as YMM0 to YMM7 for x86 and YMM0 to YMM15 for x86-64.
- Each 256-bit vector register can be used to hold:
  - 32 8-bit bytes
  - 16 16-bit integers
  - 8 32-bit integers
  - 4 64-bit integers
  - 8 32-bit single-precision floating-point numbers
  - 4 64-bit double-precision floating-point numbers
  - 8 32-bit single-precision floating-point numbers
  - 4 64-bit double-precision floating-point numbers

- AVX-512 extends vector registers to **512 bits**.
NEON is vector extension to ARM Cortex-A series and Cortex-R52 processors

**16 128-bit vector registers**

NEON instructions perform same operations in all lanes of vectors

Vector registers can hold:

- 16 8-bit character
- 8 16-bit integer
- 4 32-bit integer
- 2 64-bit integer
- 8 16-bit floating-point (only in Armv8.2-A)
- 4 32-bit floating-point
- 2 64-bit floating-point (only in Armv8-A/R)
on Linux systems, information on processor can be found in 
/proc/cpuinfo

level of processor support for vector operations can be determined by checking for various processor flags/features in this file

on Intel x86/x86-64 systems, look for flags/features:
  - mmx, sse, sse2, ssse3, sse4_1, sse4_2, avx, avx2

on ARM systems, look for flags/features:
  - neon
Section 6.7.2

Code Vectorization
Vectorization

- Consider loop in function:
  
  ```c
  void axpy(float a, float* x, float y, int n) {
    for (int i = 0; i < n; ++i) {
      x[i] = a * x[i] + y;
    }
  }
  ```

- Loop vectorization: scalar computations in body of above loop could be grouped to allow use of vector operations.

- Consider code in basic block:
  
  ```c
  a = b + c * d;
  e = f + g * h;
  i = j + k * l;
  m = n + o * p;
  ```

- Basic-block vectorization: four statements in preceding code follow similar pattern and could be grouped together to allow vector operations to be used.
Conceptualizing Loop Vectorization

- can think of loop vectorization in terms of loop unrolling

- consider following loop where, for simplicity, we assume $n$ multiple of 4:
  
  ```cpp
  for (int i = 0; i < n; ++i) {c[i] = a[i] + b[i];}
  ```

- can partially unroll loop to obtain following, where each iteration of new loop corresponds to 4 iterations of original loop:
  
  ```cpp
  for (int i = 0; i < n; i += 4) {
    c[i + 0] = a[i + 0] + b[i + 0]; // iteration i
    c[i + 1] = a[i + 1] + b[i + 1]; // iteration i + 1
    c[i + 2] = a[i + 2] + b[i + 2]; // iteration i + 2
    c[i + 3] = a[i + 3] + b[i + 3]; // iteration i + 3
  }
  ```

- code in body of new loop can be mapped to vector operations of length 4 on vector registers v0, v1, and v2:
  
  1. load $a[i]$ to $a[i + 3]$ into v0
  2. load $b[i]$ to $b[i + 3]$ into v1
  3. add v0 and v1, writing result into v2
  4. store v2 into $c[i]$ to $c[i + 3]$

- using non-standard C++ syntax, vectorized loop can be expressed as:
  
  ```cpp
  for (int i = 0; i < n; i += 4)
  {c[i : i + 3] = a[i : i + 3] + b[i : i + 3];}
  ```
Approaches to Vectorization

- several approaches to vectorization can be taken:
  1. auto-vectorization
     - compiler automatically vectorizes code when deemed both safe and profitable
  2. auto-vectorization with compiler hints
     - annotations added to source code to guide auto-vectorization
  3. explicit directives
     - special directives added to source code to exercise control over vectorization (e.g., OpenMP, Cilk Plus)
  4. computation using vector data types
     - use special vector types provided by compiler (e.g., __m128 for GCC on x86, int8x8_t for GCC on ARM, __m128 for MSVC on x86)
  5. compiler intrinsics
     - use special low-level functions provided by compiler (e.g., __mm_add_epi16 for GCC on x86, vaddq_s16 for GCC on ARM, _arm_sadd16 for MSVC on ARM)
  6. inline assembly language
     - use SIMD instructions directly by using assembly language

- above approaches listed in order of decreasing ease of use and increasing degree of programmer control
Auto-Vectorization

- easiest way to vectorize code is to have compiler do this automatically called auto-vectorization
- most compilers have support for auto-vectorization
- advantages of auto-vectorization:
  - easy to use
  - less error prone (no bugs, unless compiler has bug)
  - sometimes compiler may be able to make better judgement as to whether vectorization would be beneficial
- compiler, however, must be very conservative when vectorizing code
- compiler cannot transform code in way that changes its behavior
- unfortunately, compiler often does not have sufficient knowledge of code behavior to perform vectorization well (or at all)
GCC supports auto-vectorization

GCC has two vectorizers:
1. loop vectorizer
2. basic-block vectorizer

both vectorizers enabled by default for optimization level of at least 3 (where optimization level specified with \texttt{-O} option)

GCC fully supports OpenMP 4.5 for C/C++ (but not Fortran) as of GCC 6.1 and fully supports OpenMP 4.0 as of GCC 4.9.1
GCC Compiler Options Related to Vectorization

- **-ftree-vectorize** and **-fno-tree-vectorize**
  - enable and disable all vectorization, respectively
- **-ftree-loop-vectorize** and **-fno-tree-loop-vectorize**
  - enable and disable loop vectorizer, respectively
- **-ftree-slp-vectorize** and **-fno-tree-slp-vectorize**
  - enable and disable basic-block vectorizer, respectively
- **-fopt-info-vec-optimized**
  - enable remarks that identify places in code where vectorization successfully applied
- **-fopt-info-vec-missed**
  - enable remarks that identify places in code where vectorization could not be applied
- **-march=native**
  - use instructions supported by local CPU
  - to see which flags are enabled with -march=native, use:
    ```
    g++ -march=native -Q --help=target
    ```
-fopenmp
  - enable OpenMP support (which requires GOMP library)

-fopenmp-simd
  - enable OpenMP SIMD support (which does not require run-time library)

-S
  - produce assembly language output only (instead of object code)

-fverbose-asm
  - enable generation of more verbose assembly language output (e.g., compiler version and command-line options, source-code lines associated with assembly instructions, hints on which high-level expressions correspond to various assembly instruction operands)
Clang supports auto-vectorization

Clang has two vectorizers:
1. loop vectorizer
2. superword-level parallelism (SLP) vectorizer

loop vectorizer widens instructions in loops to operate on multiple consecutive iterations (i.e., performs loop vectorization)

SLP vectorizer combines similar independent scalar instructions into vector instructions

both loop and SLP vectorizers enabled by default for optimization level of at least 1 (where optimization level specified by \(-O\) option)

Clang supports all non-offloading features of OpenMP 4.5 as of Clang 3.9
Clang Compiler Options Related to Vectorization

- `-fvectorize` and `-fno-vectorize`
  - enable and disable loop vectorizer, respectively

- `-fslp-vectorize` and `-no-fslp-vectorize`
  - enable and disable SLP vectorizer, respectively

- `-fslp-vectorize-aggressive`
  - enable more aggressive vectorization in SLP vectorizer

- `-Rpass=loop-vectorize`
  - enable remarks that identify loops that were successfully vectorized

- `-Rpass-missed=loop-vectorize`
  - enable remarks that identify loops that failed vectorization and indicate if vectorization specified

- `-Rpass-analysis=loop-vectorize`
  - enable remarks that identify statements that caused vectorization to fail

- `-fopenmp`
  - enable OpenMP support (which requires OMP library)

- `-S`
  - produce assembly language output only (instead of object code)
Assessing Quality of Vectorized Code

- to assess quality of vectorized code generated by compiler, often very helpful to view assembly code generated by compiler
- quick inspection of assembly code can often give clear indication as to how well particular part of code was vectorized
- most compilers provide option to generate assembly source as compilation output (instead of object code)
- to assist in locating assembly source corresponding to particular part of C++/C source code (such as loop) can inject comments into assembly code using `asm`

**Example:**

```c++
float innerprod(float* a, float* b, int n) {
  float result = 0.0f;
  asm volatile ("# loop start");
  for (int i = 0; i < n; ++i) {result += a[i] * b[i];}
  asm volatile ("# loop end");
  return result;
}
```
Assessing Quality of Vectorized Code (Continued)

1 .file "inner_product_1.cpp"
2 .text
3 .globl _Z9innerprodPfS_i
4 .type _Z9innerprodPfS_i, @function
5 _Z9innerprodPfS_i:
6 .LFB0:
7 .cfi_startproc
8  #APP
9  # 3 "inner_product_1.cpp" 1
10     # loop start
11  # 0 "" 2
12  #NO_APP
13     xorl %eax, %eax
14     vxorps %xmm0, %xmm0, %xmm0
15 .L3:
16     cmpl %eax, %edx
17     jle .L2
18     vmovss (%rdi,%rax,4), %xmm1
19     vfmadd231ss (%rsi,%rax,4), %xmm1, %xmm0
20     incq %rax
21     jmp .L3
22 .L2:
23  #APP
24  # 5 "inner_product_1.cpp" 1
25     # loop end
26  # 0 "" 2
27  #NO_APP
28     ret
29 .cfi_endproc
in order to allow compiler to perform auto-vectorization more effectively, can provide hints to compiler
place annotations in code to provide compiler with additional information to guide vectorization
annotations typically provide information that compiler could not reasonably deduce on its own but is important in making decisions regarding vectorization
approach is relatively easy to use since compiler still does most of work
must be careful to provide correct information to compiler, however; otherwise, compiler may generate incorrect code
numerous obstacles to vectorization:
- data dependencies
- control-flow dependencies
- aliasing
- noncontiguous memory accesses
- misaligned data

by eliminating such obstacles, compiler can perform auto-vectorization more effectively
Data Dependencies and Vectorization

- vectorization changes order of computation compared to sequential case
- changing order of computation may yield different result
- cannot replace sequential loop with vectorized version if this would change result of computation
- need to consider independence of unrolled loop operations, which depends on vectorization factor
- three types of data dependencies:
  1. flow dependency (read after write)
  2. output dependency (write after write)
  3. antidependency (write after read)
- flow and output dependencies are of most concern for vectorization
■ flow dependency (also called read-after-write dependency) is type of data dependency that occurs when variable is written in one iteration of loop and read in subsequent iteration

■ dependency distance is difference in iteration number in which read and write of variable occur

■ example of flow dependency with dependency distance of 1:

```c
for (int i = 1; i < n; ++i)
    {a[i] = a[i - 1] + 1;}
```

■ if dependency distance less than vectorization factor, vectorized loop cannot be guaranteed to yield same result as sequential version
consider vectorization of following loop with vectorization factor of 4:

```cpp
for (int i = 1; i < n; ++i)
    {a[i] = a[i - 1] + b[i];}
```

loop exhibits flow dependence (i.e., read after write) on $a[i-1]$  
(dependence distance 1)

loop in partially unrolled form (assuming number of iterations multiple of 4):

```cpp
for (int i = 1; i < n; i += 4) {
    a[i + 0] = a[i - 1] + b[i + 0];
    a[i + 1] = a[i + 0] + b[i + 1];
    a[i + 2] = a[i + 1] + b[i + 2];
    a[i + 3] = a[i + 2] + b[i + 3];
}
```

loop in vectorized form (assuming number of iterations multiple of 4):

```cpp
for (int i = 1; i < n; i += 4)
    {a[i : i + 3] = a[i - 1 : i + 2] + b[i : i + 3];}
```

vectorized loop will not always produce same results as sequential loop  
(due to flow dependence with dependence distance 1)

therefore, with vectorization factor of 4, loop not legal to vectorize
suppose that:

```cpp
constexpr int n = 5;
int a_data[n] = {-1, -2, -3, -4, -5};
int b_data[n] = {0, 1, 2, 3, 4};
int* a = a_data;
int* b = b_data;
```

sequential loop:
```
for (int i = 1; i < n; ++i) {
    a[i] = a[i - 1] + b[i]
}
```

computation for loop iteration:

<table>
<thead>
<tr>
<th>i</th>
<th>a[i - 1]</th>
<th>b[i]</th>
<th>a[i]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>4</td>
<td>9</td>
</tr>
</tbody>
</table>

upon loop termination, array pointed to by `a` contains:

```
{-1, 0, 2, 5, 9}
```
again, suppose that:

```cpp
constexpr int n = 5;
int a_data[n] = {-1, -2, -3, -4, -5};
int b_data[n] = {0, 1, 2, 3, 4};
int* a = a_data;
int* b = b_data;
```

vectorized loop:

```cpp
for (int i = 1; i < n; i += 4) {
    a[i : i + 3] = a[i - 1 : i + 2] + b[i : i + 3];
}
```

computation for loop iteration:

<table>
<thead>
<tr>
<th>i</th>
<th>a[i - 1 : i + 2]</th>
<th>b[i : i + 3]</th>
<th>a[i : i + 3]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>{-1, -2, -3, -4}</td>
<td>{1, 2, 3, 4}</td>
<td>{0, 0, 0, 0}</td>
</tr>
</tbody>
</table>

upon loop termination, array pointed to by a contains:

\{-1, 0, 0, 0, 0\}
consider vectorizing following loop using vectorization factor of 4:

```c
for (int i = 5; i < n; ++i)
    {a[i] = a[i - 5] + b[i];}
```

loop exhibits flow dependence (i.e., read after write) on `a[i-5]` (dependence distance 5)

loop in partially unrolled form (assuming number of iterations multiple of 4):

```c
for (int i = 5; i < n; i += 4) {
    a[i + 0] = a[i - 5] + b[i + 0];
    a[i + 1] = a[i - 4] + b[i + 1];
    a[i + 2] = a[i - 3] + b[i + 2];
    a[i + 3] = a[i - 2] + b[i + 3];
}
```

loop in vectorized form (assuming number of iterations multiple of 4):

```c
for (int i = 5; i < n; i += 4)
    {a[i : i + 3] = a[i - 5 : i - 2] + b[i : i + 3];}
```

vectorized loop will always yield same result as sequential loop since no flow dependence occurs within single iteration of vectorized loop

with vectorization factor of 4, loop legal to vectorize
- **output dependency** (also called **write-after-write dependency**) is a type of data dependency that occurs when the same variable is written in more than one iteration.

- Example of output dependency:
  ```cpp
  for (int i = 0; i < n; ++i)
  {a[i % 2] = b[i] + c[i];}
  ```

- Generally unsafe to perform vectorization of loops with output dependencies.
control-flow dependencies can lead to different operations for elements in vector

consider loop in following function:

```c
void func(float* a, float* b, int n) {
    for (int i = 0; i < n; ++i) {
        a[i] = (a[i] > 1.0) ? a[i] / b[i] : a[i];
    }
}
```

code has control-flow dependence on `a[i]` (code behavior depends on condition `a[i] > 1.0`)

good compiler might be able to vectorize above function

when control-flow dependencies become more complex, however, vectorization extremely difficult or impossible to perform

therefore, control-flow dependencies are best avoided
when same memory location can be accessed through different names, **aliasing** said to occur

example of aliasing:

- code:
  ```
  float v[64];
  float* p = &v[0];
  float* q = &v[1];
  // p and q can be used to access same memory
  // e.g., p[1] and q[0] refer to same object
  ```

- memory layout:
  ```
  p     q
  ```

aliasing often limits ability of compiler to perform optimization

in effect, aliasing can introduce new data dependencies that would not otherwise exist

failing to take aliasing into account could lead to illegal optimizations (i.e., optimizations that change code behavior)
consider code:

```c
void func(int* a, int* b, int* c) {
  *a = 42;
  *b = 0;
  *c = *a;
}
```

at first glance, might seem that code can be optimized to yield:

```c
void func(int* a, int* b, int* c) {
  *a = 42;
  *b = 0;
  *c = 42;
}
```

above optimized code is incorrect, since \(a\) might equal \(b\), in which case \(*c\) should be assigned 0, not 42
consider code:

```c
void add(float* a, float* b, float* c) {
    for (int i = 0; i < 1024; ++i) {
        a[i] = b[i] + c[i];
    }
}
```

if only this code visible to compiler, simply vectorizing loop in this function is not legal

a could be aliased to b or c (i.e., storage pointed to by a, b, and c could overlap); for example, if a equals b + 1, then b[i] same as a[i - 1]

in this case, sequential and parallel execution of loop would yield different results

best compiler could do might be to:

- generate two different versions of code for loop, one without vectorization for aliasing case and one with vectorization for case of no aliasing
- emit runtime aliasing check that decides which version of code for loop to execute

this solution less than ideal as it incurs cost of runtime check and results in increased code size
The `__restrict__` Keyword

- sometimes highly beneficial to have means to indicate to compiler that aliasing cannot occur (so that compiler can better optimize code)
- although not part of C++ standard, some compilers support special keyword for this purpose; for example:
  - GCC and Clang support `__restrict__` keyword
  - MSVC supports `__restrict__` keyword
- keyword can be applied to pointer or reference
- during execution of block in which restricted pointer/reference `p` is declared, if some object that is accessible through `p` (directly or indirectly) is modified by any means, then all access to that object in that block must occur through `p` (directly or indirectly)
- important only to use `__restrict__` if certain that no aliasing can occur; otherwise, code behavior likely to be incorrect
- example:

```c
void func(int* __restrict__ p, int* __restrict__ q) {
    // compiler can safely assume that any data modified though p
    // will only be accessed through p; and similarly for q
    // thus, data pointed to by p and q cannot overlap
    // ... (code modifies data pointed to by p and q)
}
```
Noncontiguous Memory Accesses

- Vector load/store operation typically reads/writes contiguous block of memory (that is appropriately aligned)
- Noncontiguous data typically needs multiple instructions to be read/written
- Example of code with noncontiguous memory accesses:
  ```c
  // in loop, array elements accesses with stride 2
  for (int i = 0; i < n; i += 2) {
    c[i] = a[i] + b[i];
  }
  ```
- Sometimes noncontiguous memory access problem can be addressed by choosing different layout for data in memory (e.g., struct of arrays instead of array of structs)
- Other times, problem may be resolvable by restructuring code to perform computations in different order
- for reasons of performance, vector load and store operations often impose restrictions on data alignment
- typically, target address for vector load or store of $n$-byte register needs to be aligned on $n$-byte boundary
- for some architectures, such alignment is strict requirement (i.e., code will not work if data misaligned)
- for other architectures, such alignment is not strictly required, but substantial performance penalty may be incurred in case of misaligned data
- for this reason, important to align data appropriately whenever possible
- also, to allow compiler to vectorize in most effective manner possible, important to let compiler know when data is appropriately aligned
Handling Misaligned Data

- sometimes not possible or practical to avoid misaligned data
- in such cases, can still partially vectorize
- peel first few iterations of loop where data is misaligned and process data using scalar operations
- peel last few iterations (as necessary) where insufficient data to fill vector register and process data using scalar operations
- use vector operations for remainder of iterations
- compared to case of properly aligned data that is multiple of vector size, above approach likely to be slower and have larger code size
- alternatively, could add padding before and/or after data to ensure data with padding is appropriately aligned and multiple of vector length, but this approach often not practical
Controlling Alignment of Data

- for non-heap allocation, can use `alignas` qualifier to control alignment of object
- for heap allocation, can use `std::aligned_alloc` to allocate memory with particular alignment
- `std::free` can be used to free memory allocated by `std::aligned_alloc`

Example:
```cpp
#include <cassert>
#include <cstdlib>
#include <cstdint>

int main() {
    alignas(4096) static char buffer[65536];
    static_assert(alignof(buffer) == 4096);
    float* fp = static_cast<float*>(
        std::aligned_alloc(4096, sizeof(float)));
    if (!fp) { return 1; }
    assert(!((reinterpret_cast<intptr_t>(fp) % 4096)));
    std::free(fp);
}
```
to facilitate more effective vectorization by compiler, important to be able to indicate data alignment in code

\texttt{std::assumed\_aligned} template function can be used to indicate alignment

\texttt{std::assumed\_aligned} declared as:

\begin{verbatim}
template <\texttt{std::size\_t} Align, \texttt{class} T>
\texttt{constexpr} T* assume\_aligned(T* p);
\end{verbatim}

this function simply returns its argument \texttt{p} and allows compiler to assume that returned pointer is at least \texttt{align} bytes aligned

example:

\begin{verbatim}
void func(float* a, float* b, int n) {
    // *a and *b can be assumed aligned to 64-byte boundary
    a = std::assume\_aligned<64>(a);
    b = std::assume\_aligned<64>(b);
    for (int i = 0; i < n; ++i) {/* ... */}
}
\end{verbatim}
Profitability of Vectorization

- Vectorization can often provide significant speedup (in some cases linear with vectorization factor), but costs need to be considered.
- Vector loop bodies can be larger than their scalar forms, as more complex operations may be needed, increasing code size.
- Vector loop may have increased startup costs to prepare for vectorized execution.
- If aliasing is potential problem, require overhead of runtime aliasing check.
- Vector instructions may take more cycles.
source code:

```cpp
#include <cstddef>

template <std::size_t n, class T>
void add(const T (&a)[n], T (&b)[n]) {
    for (int i = 0; i < n; ++i) {
        b[i] += a[i];
    }
}
```

since `a` and `b` may be aliased, compiler must generate code that correctly handles aliased case (as well as non-aliased case)

often, will generate code that tests for aliasing at run time and uses result to decide between code for aliased case or non aliased case

since compiler does not know alignment of `a` and `b`, must generate code that handles any valid alignment
source code:

```cpp
#include <cstddef>

template <std::size_t n, class T>
void add(const T (&__restrict__ a)[n],
         T (&__restrict__ b)[n]) {
    for (int i = 0; i < n; ++i) {
        b[i] += a[i];
    }
}
```

- compiler can assume no aliasing (due to use of `__restrict__`)  
- since compiler does not know alignment of `a` and `b`, must generate code that handles any valid alignment
# Vectorization Example: Version 3

**source code:**
```
#include <cstdint>
#include <memory>

template <std::size_t n, std::size_t align, class T>
void add(const T (& __restrict__ a)[n],
          T (& __restrict__ b)[n]) {
    const T* ap = std::assume_aligned<align>(&a[0]);
    T* bp = std::assume_aligned<align>(&b[0]);
    for (int i = 0; i < n; ++i) {bp[i] += ap[i];}
}
```

**compiler can assume no aliasing (due to use of __restrict__) and align-byte alignment (due to use of std::assume_aligned)**

**code generated for vectorized loop in case of**
```
add<65536, 16 * alignof(float), float>:
```
```
.L2:
    vmovaps (%rsi,%rax), %ymm0
    vaddps (%rdi,%rax), %ymm0, %ymm0
    vmovaps %ymm0, (%rsi,%rax)
    addq $32, %rax
    cmpq $262144, %rax
    jne .L2
```
when calling add function, must be careful to ensure that assumptions about aliasing and data alignment are not violated

source code:

```cpp
#include <cstdint>
#include <iostream>
#include <algorithm>
#include <numeric>
#include "example4_util.hpp"

int main() {
    constexpr std::size_t n = 65536;
    constexpr std::size_t align = 16 * alignof(float);
    alignas(align) static float a[n];
    alignas(align) static float b[n];
    std::iota(&a[0], &a[n], 1);
    std::fill(&b[0], &b[n], -1);
    add<n, align>(a, b);
    for (auto i : b) {std::cout << i << 'n';}
}
```

if add function invoked in manner that violates assumptions about aliasing or data alignment, code not guaranteed to work correctly (e.g., may crash or yield incorrect results)
Basic Requirements for Vectorizable Loops

- requirements imposed on vectorizable loops vary from compiler to compiler
- so whether given loop can be vectorized will in many cases depend on particular compiler being used
- consult compiler documentation for specific requirements
- some typical examples of requirements imposed on vectorizable loops include:
  - loop is countable (i.e., number of loop iterations known at run time upon entry to loop); this implies, for example, no conditional termination of loop
  - straight-line code in loop body (i.e., no control flow); no switch statements; if statements only allowable when can be implemented as masked assignments
  - must be innermost loop if nested
  - no function calls, except some basic math functions (such as `std::pow`, `std::sqrt`, and `std::sin`) and some inline functions
OpenMP is industry standard API for parallel computing

- supports C++, C, and Fortran
- OpenMP 4.0 added constructs for expressing SIMD data-level parallelism
- although OpenMP offers large amount of functionality, we only focus on SIMD-related functionality here

- use pragmas to control vectorization

- **simd** pragma allows explicit control of vectorization of for loops
- **declare simd** pragma instructs compiler to generate vectorized version of function (which can be used to vectorize loops containing function calls)
vectorized loop can be achieved with OpenMP `simd` pragma

**syntax:**

```cpp
#pragma omp simd [clause...] /* for statement in canonical form */
```

`simd` pragma must be immediately followed by for loop in canonical form

optional clauses may be specified to affect behavior of pragma (i.e., safelen, linear, aligned, private, lastprivate, reduction, and collapse)

amongst other things, canonical form of for loop implies:
   - induction variable has integer, pointer, or random-access iterator type
   - limited test and increment/decrement for induction variable
   - iteration count known before execution of loop

can target inner or outer loops

loop must be suitable for vectorization (e.g., no data-dependence problems)

**example:**

```cpp
#pragma omp simd
for (int i = 0; i < n; ++i) {c[i] = a[i] + b[i];}
```
- can generate vectorized versions of functions with `declare simd` pragma

- syntax:
  ```c
  #pragma omp declare simd [clause...] /* function declaration/definition */
  ```

- optional clauses may be specified to affect behavior of pragma (i.e., `simdlen`, `linear`, `aligned`, `uniform`, `inbranch`, and `notinbranch`)

- example:
  ```c
  #pragma omp declare simd
  float foo(float a, float b, float c) {
    return a * b + c;
  }
  ```
OpenMP SIMD-Related Pragma Clauses

- **safelen**(length)
  - specifies length as maximum number of iterations that can be run concurrently in a safe manner (i.e., without data-dependence problems)

- **collapse**(n)
  - specifies how many (nested) loops to associate with loop construct (i.e., how many nested loops to combine)

- **simdlen**(length)
  - specifies length as preferred length of vector registers used

- **aligned**(argument-list[[:alignment]])
  - specifies items in argument-list as having given alignment (e.g., alignment)

- **uniform**(argument-list)
  - indicates each argument in argument-list has constant value between iterations of given loop (i.e., constant value across all SIMD lanes)

- **inbranch**
  - specifies that function will always be called from inside conditional statement of SIMD loop

- **notininbranch**
  - specifies that function will never be called from inside conditional statement of SIMD loop
OpenMP SIMD-RelatedPragma Clauses (Continued)

- **linear** \((list[:linear-step])\)
  - Specifies that, for every iteration of original scalar loop, each variable in \(list\) is incremented by particular step \(step\) (i.e., variable is incremented by \(step\) times vector length for vectorized loop)

- **private** \((list)\)
  - Declares variables in \(list\) to be private to each iteration

- **lastprivate** \((list)\)
  - Declares variables in \(list\) to be private to each iteration, and last value is copied out from last iteration instance

- **reduction** \((operator:list)\)
  - Specifies variables in \(list\) are reduction variables for operator \(operator\)
```cpp
#include <cstdlib>
#include <iostream>
#include <numeric>

//template <std::size_t align, std::size_t n, class T>
[[ gnu::noinline ]]
void multiply(const T (&a)[n], const T (&b)[n], T (&c)[n]) {
    #pragma omp simd aligned(a, b, c : align)
    for (int i = 0; i < n; ++i) {
        c[i] = a[i] * b[i];
    }
}

int main() {
    constexpr std::size_t n = 65536;
    constexpr std::size_t align = 16 * alignof(float);
    alignas(align) static float a[n];
    alignas(align) static float b[n];
    alignas(align) static float c[n];
    std::iota(a, &a[n], 0);
    std::iota(b, &b[n], 0);
    multiply<align>(a, b, c);
    for (auto x : c) {
        std::cout << x << '
';
    }
}
```
Example: Vectorized Loop and Function

```cpp
#include <cstdint>
#include <iostream>
#include <numeric>

#pragma omp declare simd notinbranch
float func(float a, float b) {
    return a * a + b * b;
}

int main() {
    constexpr std::size_t n = 65536;
    constexpr std::size_t align = 16 * alignof(float);
    alignas(align) static float a[n];
    alignas(align) static float b[n];
    alignas(align) static float c[n];
    std::iota(a, &a[n], 0);
    std::iota(b, &b[n], 0);
    #pragma omp simd aligned(a, b, c : align)
    for (int i = 0; i < n; ++i) {
        c[i] = func(a[i], b[i]);
    }
    for (auto x : c) {
        std::cout << x << '
';
    }
}
```
Section 6.7.3

References

Section 6.8

Documentation for Software Development
documentation plays essential role in software development process

many benefits to formalizing in writing various aspects of software at different points in development process

consider two types of documents:

1. software requirements specification
2. software design description

software requirements specification (SRS): describes what software should do (from external viewpoint)

software design description (SDD): describes how software works internally
Software Requirements Specification (SRS)

- establishes agreement between consumer and contractors on what software is expected to do as well as what it is not expected to do
- can be thought of as contract between customer and contractor
- functionality: what does software do? (what problem does it solve?)
- external interfaces: how does software interact with external agents, such as humans, hardware, and software (e.g., command-line interface, graphical user interface, application program interface)
- performance: speed, availability, response time, recovery time of various functions
- attributes: considerations regarding reliability, availability, maintainability, portability, security
- design constraints imposed on implementation: implementation language, resource limits, operating environments
- assumptions upon which requirements are based
distinguish classes of requirements:
  - essential: software will be unacceptable unless requirement met
  - conditional: would enhance software if requirement met, but not unacceptable if requirement not met
  - optional: class of functionality that may or may not be worthwhile

should not leave details of software requirements to be determined

only focus on what the software needs to do, not how done (i.e., should not describe any design or implementation details)

typical use cases

constraints imposed on software:
  - time constraints
  - memory constraints

software limitations:
  - restrictions on input data
  - allowable ranges for parameters of methods
  - dependencies on other software (e.g., other programs needed to function)
External Interfaces

- external interfaces: how software interacts with external agents, such as humans, hardware, and software

- command line interface (CLI) (for program)
  - options (e.g., required versus optional, default settings)
  - standard input, output, error
  - exit status

- graphical user interface (GUI) (for program)
  - window layout
  - user interaction (e.g., mouse/keyboard actions)

- application program interface (API) (for library)
  - constants
  - types, classes/methods
  - functions
  - namespaces

- format of all data used by software
Benefits of SRS

- establishes basis for agreement between customer and contractors
- reduces development effort by thoroughly considering all requirements before starting design
- provides basis for estimating costs and schedules
- provides baseline for validation and verification
- facilitates transfer of software product to new users or machines
- serves as basis for enhancement
SRS Example: Sorting Program

- single program that performs sorting
- given records as input, program sorts records and outputs records in sorted order
- record data format (for input and output):
  - records delimited by single newline character
  - each record consists of one or more fields, separated by one or more whitespace characters
- restrictions/constraints:
  - may assume sufficient memory to buffer all records
  - software must work without any modification to source code on any platform with C++ compiler compliant with C++11 standard
- records read from standard input
- sorted records written to standard output
- any error/warning messages written to standard error
- sorts records using $n$th field in record as key
- can sort in ascending or descending order
- sort key may be numeric or string
command-line interface:

```
sort [-r] [-k $n] [-n]
```

supported command-line options:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-k $n</td>
<td>Sort using $n$th field in record; if not specified, $n$ defaults to 1.</td>
</tr>
<tr>
<td>-n</td>
<td>Treat key as real number (instead of string) for sorting purposes; if not specified, key treated as string.</td>
</tr>
<tr>
<td>-r</td>
<td>Sort in descending (instead of ascending) order; if not specified, defaults to ascending order.</td>
</tr>
</tbody>
</table>

give examples illustrating expected use cases
high-level design: overview of entire system, identifying all its components at some level of abstraction (i.e., overall software architecture)

detailed design (a.k.a. low-level design): full details of system and its components (e.g., types, functions, APIs, pseudocode, etc.)

describes high-level and detailed design of software

some context regarding functionality provided by software

how design is recursively structured into constituent parts and role of those parts

types and interfaces (e.g., classes and public members)

data structures used to represent information to be processed

internal interfaces (and external interfaces not described in SRS)

interaction amongst entities

algorithms
- describe overall structure of software
- carefully consider choice of data structures used to represent information being processed, as choice will almost always have performance implications
- specify any data formats used internally by software
- provide pseudocode for key parts of software
- state any potentially limiting assumptions made
Benefits of SDD

- encourages better planning by forcing design ideas to be more carefully considered and organized
- allows greater scrutiny of design
- captures important design decisions, such as rationale for particular design choices
- allows newcomers to development team to become acquainted with software more easily
- provides point of reference to be used throughout project
- promotes reuse of code (since well documented code more likely to be reused)
- facilitates better software testing (since certain types of testing benefit from understanding of software design)
SDD Example: Sorting Program

- **Key** alias for type that represents sort key (alias for `std::string`)
- **Compare** functor class for comparing Key objects
- **Dataset** class represents collection of all records
- specify all class interfaces (i.e., public members)
- **Dataset** class provides:
  - constructor that creates dataset by reading all records from input stream
  - function to output all records in sorted order to output stream
- **Dataset class to use** `std::multimap<Key, std::string, Compare>`
- allows $n$ records to be sorted in $O(n \log n)$ time [$n$ insertions, each requiring $O(\log n)$ time]
- handling $n$ records requires $O(n)$ memory
- only uses C++ standard library
document is combination of SRS and SDD with some added information about testing strategies
briefly introduce problem being addressed by software
describe each program and library to be developed
identify parts of any external software (e.g., programs or libraries) that will be used
describe user interface (e.g., CLI, GUI) for each program
fully specify all data formats used
describe overall structure of each program and library
identify all key data structures and algorithms to be used
provide pseudocode for key parts of the software
state any potentially limiting assumptions made by software
indicate how programs and library code will be tested
offer any other information that may be helpful (since above list is not exhaustive)
provide sufficient detail for other people to understand how software is to be structured and how it will be implemented and tested

Section 6.9

Software Testing
Software testing is process of checking to ensure that software (e.g., program, library, or system):

- meets formal requirements (e.g., functional specification)
- works as expected

This involves such things as checking that software:

- responds correctly to all inputs
- has acceptable resource consumption (e.g., time and memory)
- is sufficiently usable
- works properly in all intended environments
- does what is supposed to do
- does not have undesired side effects (i.e., does not do things that it is not supposed to do)
Examples of Well-Known Software Failures

- **Therac-25 Radiation Overdoses**
  - from 1985 to 1987, at least six incidents in which patients being treated with Therac-25 radiation-therapy machine received massive overdoses of radiation (as much as 100 times intended dosage); at least three patients died
  - failure due to race condition in control software

- **Northeast Blackout of 2003**
  - in 2003, widespread blackout occurred affecting several states/provinces in USA and Canada (i.e., New York, New Jersey, Maryland, Connecticut, Massachusetts, Ohio, and Ontario) with outage lasting from hours to days
  - at time, world’s second most widespread blackout in history
  - blackout contributed to almost 100 deaths
  - triggered by local outage that went undetected due to race condition in monitoring software

- **Ariane 5 Rocket Explosion**
  - in 1996, unmanned Ariane 5 launched by European Space Agency exploded 37 seconds after lift off
  - cause of failure was numerical overflow in inertial guidance system software
Example of Well-Known Software Failures (Continued)

- **Toyota Electronic Throttle Control System**
  - in some 2009–2011 Toyota vehicles, electronic throttle control system (ETCS) caused sudden unintended acceleration
  - at least 89 people were killed as result
  - problem likely caused by stack overflow in control software

- **NASA Mars Climate Orbiter**
  - in 1998, NASA Mars Climate Orbiter approached Mars at wrong angle entering upper atmosphere and disintegrating
  - failure due to software using incorrect units in calculations controlling thrusters

- **NASA Mars Polar Lander**
  - in 1999, when attempting to land on Mars, NASA Mars Polar Lander prematurely terminated firing of engine causing spacecraft to crash into planet’s surface
  - flight-control software mistook vibrations of stowed legs as surface touchdown
- **error**: mistake made by programmer when coding

- **defect** (also known as **fault** or **bug**): flaw in source code resulting from error

- **failure**: occurs when code corresponding to defect executes (i.e., defect causes system to behave incorrectly)

- not all defects result in failures, since code corresponding to defect might not execute (e.g., defect may be in unreachable code)

- **incident**: instance in which code does not behave as expected

- **test case**: specification of set of inputs and expected results associated with checking particular program behavior

- **test**: act of exercising software with test cases
Some Types of Faults

- input/output faults
  - correct input not accepted; incorrect input accepted; wrong format; cosmetic; incomplete or missing result
- interface faults
  - parameter mismatch; incompatible types; call to wrong procedure; call to nonexistent procedure
- logic faults
  - missing or duplicate cases; missing or extraneous conditions; incorrect loop iteration; incorrect operator; infinite recursion
- data faults
  - using uninitialized variable; dereferencing null pointer; incorrect initialization; wrong variable used; wrong data reference; incorrect subscript; incorrect data scope; inconsistent data; scaling or units error
- computation faults
  - incorrect algorithm; missing computation; incorrect operation; arithmetic overflow or underflow; insufficient precision
- multithreading faults
  - race condition; deadlock
testing methods can be classified into two categories:

1. **static**: testing without executing code
2. **dynamic**: testing by executing code

examples of static testing methods:
- code reviews
- static analysis tools

examples of dynamic testing methods:
- black box
- white box
- gray box
- dynamic analysis tools
Code Reviews

- **Code review** is process whereby source code examined by one or more people in effort to identify bugs or other problems.
- Variety of terms used to refer to code reviews (e.g., code inspections and code walkthroughs) but no widely accepted meaning for such terms.
- Code reviews can be applied at almost any stage of software development.
- Code review typically has several participants with original author often being one.
- Code review meeting might last couple of hours.
- May involve some preparatory work prior to meeting (e.g., examining source code).
- Code review process can take many forms, such as:
  - Read code line by line looking for errors.
  - Select some test cases and then, for each test case, step through code as if being executed by computer.
- May be formal written documentation to complete as part of review.
- Code reviews often find actual bug as opposed to failure resulting from bug.
- Code reviews can be effective at finding certain types of errors.
static analysis tools examine code without executing it
most frequently analyze source code
can be used to find certain types of code defects
examples of types of defects that can be found by static analysis tools include:
- use of uninitialized variable
- unused variable
- unreachable code (i.e., code that never executes) or dead code (i.e., code that has no effect)
- coding standards violation
- security vulnerability
- syntax violation
- inconsistent interfaces between modules and components
Examples of Static Analysis Tools

- **Clang Tidy**
- **Clang Static Analyzer**
- **CppCheck** ([http://cppcheck.sourceforge.net](http://cppcheck.sourceforge.net))
- **Cpplint** ([http://github.com/cpplint/cpplint](http://github.com/cpplint/cpplint))

- many commercial products also available, such as:
  - Coverity Scan ([http://scan.coverity.com](http://scan.coverity.com)), which is free for use in open-source projects
  - CppDepend ([http://www.cppdepend.com](http://www.cppdepend.com))
**Black-Box Testing (a.k.a. Functional Testing)**

- **black-box testing** (also known as **functional testing**) is testing method that checks if software meets its specifications *without using knowledge of its internal structure*

  - concentrates on finding circumstances in which software does not behave according to its specifications
  - test cases derived solely from specifications

**advantages:**

- tester does not need to know internal structure of program
- test cases can be created as soon as functional specifications complete
- tester needs no knowledge of implementation, including specific programming languages
- tests will be performed from user’s point of view
- testing can help to expose ambiguities or inconsistencies in specifications
- as tester and developer are independent of each other, testing balanced and unprejudiced

**disadvantages:**

- may leave many program paths untested
- high probability of repeating tests already performed by developer
White-Box Testing (a.k.a. Structural Testing)

- **white-box testing** (also known as **structural testing**) is a testing method that employs *knowledge of internal structure of software* under test.
- The tester has access to source code and possibly documentation describing software internals, such as data structures and algorithms used.
- Derive testing strategy based on examination of internal structure of software.
- Typically choose tests to exercise as much of code and control flow as possible.

**Advantages:**
- More thorough testing possible than with black-box testing.
- Forces developer to reason more carefully about implementation.

**Disadvantages:**
- As details of code are considered, skilled testers required with knowledge of programming.
- Tests more sensitive to changes in underlying implementation (and may be rendered useless due to implementation changes).
Gray-Box Testing

- **gray-box testing** is combination of black-box (i.e., functional) and white-box (i.e., structural) testing
- in gray-box testing, tester has partial knowledge of internal structure of code to be tested
- for example, tester may have access to documentation describing internal data structures and algorithms used
- tester does not have access to source code
- advantages:
  - testing performed from point of view of users rather than developer
  - allows tester to prioritize tests based on partial knowledge of underlying program structure
- disadvantages:
  - some tests may be redundant since developer may have performed some similar tests
Equivalence-Class Testing (a.k.a. Equivalence Partitioning)

- **equivalence-class testing** is testing method in which input domain (i.e., set of all possible inputs) for software being tested partitioned into equivalence classes, which then drive testing process.

- particular partitioning of input domain determined by equivalence relation (i.e., elements in same equivalence class if and only if equivalent as determined by equivalence relation).

- each possible input appears in exactly one equivalence class.

- union of all equivalence classes yields set of all possible inputs.

- equivalence relation chosen so that inputs in same equivalence class expected to cause software to behave similarly.

- consequently, if testing one input in equivalence class would detect defect, testing all other inputs in same equivalence class would be expected to find same defect.

- challenge in equivalence-class testing is making good choice of equivalence relation (which determines equivalence classes) and good choice is crucial.
often equivalence relation chosen based on:
  - ranges of input variables
  - expected output
  - type of computation needed

with regard to type of inputs considered, equivalence-class testing said to be:
  - normal if considers only valid inputs
  - robust if considers both valid and invalid inputs

robust testing only possible in situations where invalid inputs required to yield well-defined behavior
advantages:

- equivalence classes allow many inputs to be tested using one representative element from equivalence class, greatly reducing number of test cases
- since equivalence classes are disjoint, can eliminate/reduce redundancy in tests

disadvantages:

- just because members of equivalence class should in theory behave similarly does not mean that they actually will in practice (e.g., due to unanticipated bugs)
consider program that calculates volume discount, where customer can order from 1 to 299 units:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>1–9</th>
<th>10–49</th>
<th>50–99</th>
<th>100–199</th>
<th>200–299</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discount (%)</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

suppose that we partition into equivalence classes on basis of type of calculation performed (i.e., type of discount calculation)

for normal testing, leads to 5 equivalence classes:

<table>
<thead>
<tr>
<th>Class</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>1–9</td>
<td>10–49</td>
<td>50–99</td>
<td>100–199</td>
<td>200–299</td>
</tr>
</tbody>
</table>

for robust testing, add 2 equivalence classes:

<table>
<thead>
<tr>
<th>Class</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>0 or less</td>
<td>300 or greater</td>
</tr>
</tbody>
</table>

select one test case for each equivalence class
consider function that computes sum of two integers safely (i.e., ensuring that overflow does not occur) and has declaration:
\[
\text{std::pair<int, bool> safe_add(int x, int y);}
\]

one possible choice for equivalence classes:
1. overflow in positive direction: \( x \geq 0 \) and \( y \geq 0 \) and \( y > \text{INT_MAX} - x \)
2. overflow in negative direction: \( x < 0 \) and \( y < 0 \) and \( y < \text{INT_MIN} - x \)
3. no overflow:
   - \( x \geq 0 \) and \( y < 0 \); or \( x < 0 \) and \( y \geq 0 \); or
   - \( x \geq 0 \) and \( y \geq 0 \) and \( y \leq \text{INT_MAX} - x \); or
   - \( x < 0 \) and \( y < 0 \) and \( y \geq \text{INT_MIN} - x \)

could then use three test cases, one from each equivalence class
boundary-value testing is testing method that involves testing inputs at boundaries of equivalence classes.

The rationale behind boundary-value testing is that errors tend to occur near extreme values of inputs (which typically correspond to boundaries of equivalence classes).

For example, off-by-one errors are common (e.g., iterate one too many or few times or array index one too great or little).

With regard to types of inputs allowed, boundary-value testing is said to be:

- **normal** if only valid inputs considered
- **robust** if considers both valid and invalid inputs

Robust testing is only possible in situations where invalid inputs are required to yield well-defined behavior.
again, consider program that calculates volume discount, where customer can order from 1 to 299 units:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Discount (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–9</td>
<td>0</td>
</tr>
<tr>
<td>10–49</td>
<td>1</td>
</tr>
<tr>
<td>50–99</td>
<td>2</td>
</tr>
<tr>
<td>100–199</td>
<td>3</td>
</tr>
<tr>
<td>200–299</td>
<td>5</td>
</tr>
</tbody>
</table>

for normal testing, could use values:

- 1, 2, 8, 9
- 10, 11, 48, 49
- 50, 51, 98, 99
- 100, 101, 198, 199
- 200, 201, 298, 299

for robust testing, could add additional values:

- -1, 0
- 300, 301
again, consider function that computes sum of two integers safely (i.e., ensuring that overflow does not occur) and has declaration:

```cpp
std::pair<int, bool> safe_add(int x, int y);
```
as shown in figure, can partition input domain into three equivalence classes (i.e., overflow in positive direction, overflow in negative direction, and no overflow):

![Diagram showing partitioning of input domain into three equivalence classes.]

could choose test cases to correspond to points at or near boundaries between equivalence classes:

- $x \geq 0$ and $y \geq 0$ and $y = \text{INT\_MAX} - x + \Delta$, where $\Delta \in \{-1, 0, 1, 2\}$
- $x < 0$ and $y < 0$ and $y = \text{INT\_MIN} - x - \Delta$, where $\Delta \in \{-1, 0, 1, 2\}$
Special-Value Testing

- **special-value testing** is type of testing where tester uses domain knowledge, experience with similar programs, and information about soft spots to devise test cases.
- Effectively tester guesses likely errors and tests for them.
- Form of experience-based testing.
- Perhaps most widely used form of functional testing.
- Most intuitive and probably least uniform (i.e., most ad hoc).
- Effectiveness of special-value testing heavily dependent on skill of tester.

Example: some test cases for sorting subroutine might include:

- Input list is empty.
- Input list contains exactly one element.
- All entries in list have same value.
- Input list is already sorted.
example: some test cases for binary search in container (e.g., array) might include:
- exactly one element in container being searched
- container size is power of 2
- container size is one greater and one less than power of 2
- query element in container
- query element not in container

example: to test algorithm that calculates sinc function, might use knowledge that handling cases of computing $\text{sinc}(x) = \sin(x)/x$ for $x = 0$ and $x \neq 0$ likely to be performed differently, leading to at least two test cases:
- test for both zero and nonzero values
Random Testing

- instead of choosing input variables deterministically, generate values randomly
- black-box testing technique
- has advantage of avoiding possible bias in testing
- may be difficult to determine how much testing is sufficient
- can be quite beneficial, for example, in testing algorithms that have very many possible edge/corner cases, which may be impossible to reliably identify and enumerate (in full)
- for example, might use random testing for algorithm that inserts point in triangulation (since certain bugs may only manifest themselves for very particular inputs that would be difficult to identify manually in reliable manner)
- particular test case that fails during random testing might also be codified as non-random test to ensure that failed test case always included in future testing; in this sense, random testing can also be used as means to generate non-random tests
Control-Flow Graphs

- control-flow graph is directed graph that shows paths of execution in code
- nodes correspond to statement fragments or statements
- given two nodes $i$ and $j$ in control-flow graph, edge from $i$ to $j$ exists if and only if statement fragment corresponding to node $j$ can be executed immediately after statement fragment corresponding to node $i$
- program can be viewed in terms of control-flow graph
- control-flow graphs are particularly useful for purposes of considering structural coverage in software testing
Control-Flow Graph Examples: If-Else and Switch

declarations:

```c++
bool c; double x; double y;
```

```c++
1 if (c) {
2     y = x * x;
3 } else {
4     y = x;
5 }
6 // ...
```

declarations:

```c++
int n; double x; double y;
```

```c++
1 switch (n) {
2    case 0:
3        y = 0.0;
4        break;
5    case 1:
6        y = 2.0 * x;
7        break;
8    case 2:
9        y = 0.5 * x * x;
10       break;
11 }
12 // ...
```
Control-Flow Graph Examples: While and Do-While Loops

declarations:

```c
int n;
1 while (n > 0) {
2    --n;
3 } // ...
```

declarations:

```c
int n;
1 do {
2    --n;
3 while (n > 0);
4 } // ...
```
Control-Flow Graph Examples: For Loop

declarations:

```cpp
int a[1024];

1 for (int i = 0; i < 1024; ++i) {
2    a[i] = 0;
3 } // ...
```
structural coverage analysis used to determine which code structure exercised by test procedures

such analysis can be helpful in order to:
- create additional test cases to increase coverage
- eliminate redundant test cases
- detect unreachable code
- determine quantitative measure of coverage, which can serve as indirect measure of quality

structural coverage criteria can be classified into one of two types:
1. control flow
2. data flow

control flow criteria measure flow of control between statements and sequences of statements

data flow criteria measure flow of data between variable assignments and references to variables
Examples of Structural-Coverage Criteria

- some examples of coverage criteria based on control flow include:
  - function coverage
  - statement coverage
  - decision coverage
  - condition coverage
  - condition/decision coverage
  - modified condition/decision coverage
  - multiple condition coverage
  - all paths coverage

- some examples of coverage criteria based on data flow include:
  - all-definitions coverage
  - all C-uses coverage
  - all P-uses coverage
  - all-uses coverage
  - all DU-paths coverage
- **function coverage** ensures that every function invoked at least once
- level of function coverage can be measured as number of functions invoked divided by total number of functions in program
- function coverage does not imply that all statements execute
- with only function coverage, very large fraction of code may never be executed
- function coverage is extremely weak coverage criterion and therefore not very useful by itself
statement coverage ensures that every statement executed at least once.

Statement coverage ensures that each node in control-flow graph visited during testing (consequently, also called node coverage).

Level of statement coverage can be measured as number of (distinct) statements executed divided by total number of (distinct) statements in program.

Statement coverage alone not particularly strong coverage criterion.

Some weaknesses of statement coverage include:
- Does not usually test all branch outcomes.
- Predicates may be tested for only one value.
- Loop bodies may only be executed once.

Statement coverage for following code fragment can be achieved with single test case (e.g., \((a, b) = (1, 1)\)):

```cpp
if (a > 0)
  ++x;
if (b > 0)
  --x;
```

In above example, statement coverage achieved with single test case does not exercise all possible branch outcomes.
Conditions and Decisions

- **condition**: boolean expression containing no boolean operators (i.e., boolean expression that cannot be decomposed into boolean subexpressions)

- **decision**: boolean expression composed of conditions and zero or more boolean operators (or integral expression in case of `switch` statement)

- decisions associated with branching (i.e., control-flow) constructs (e.g., `if`, `switch`, `for`, `while`, `do`, and ternary operator)

- example:

  - consider code fragment:
    ```cpp
    if (x > 0 && x < 1024) {
        /* ... */
    }
    ```
  - `x > 0` is condition
  - `x < 1024` is condition
  - `x > 0 && x < 1024` is decision but not condition since can be decomposed further

- short-circuit evaluation of boolean expressions has implications in terms of what constitutes decision, as **short-circuit evaluation** introduces additional control flow
**Decision Coverage (a.k.a. Branch Coverage)**

- **decision coverage** (also known as **branch coverage**) ensures that:
  1. every point of entry invoked at least once
  2. every decision assumes every possible outcome (e.g., true or false) at least once (i.e., every branch direction traversed at least once)

- decision coverage ensures that each edge in control-flow graph traversed during testing (consequently, also called **edge coverage**)

- decision coverage includes statement coverage (so decision coverage is a stronger criterion than statement coverage)

- some weaknesses of decision coverage include:
  - does not necessarily ensure that each condition upon which decision based assumes all possible values (e.g., true and false)

- decision coverage for following code fragment requires at least two test cases (e.g., \((a, b) \in \{(0, 0), (1, 1)\}\)):
  
  ```
  if (a > 0) 
  ++x;
  if (b > 0) 
  --x;
  ```
consider following code fragment (with partial control-flow graph shown earlier):

```c
if ((a || b) && c) ++x;
```

assuming no short-circuiting logic:

- **one decision** \((a || b) && c\) with three conditions, namely, \(a\), \(b\), and \(c\)
- decision coverage requires at least two test cases (i.e., one test case for each possible outcome of single binary decision), such as:

| # | a | b | c | \((a || b) && c\) |
|---|---|---|---|-------------------|
| 1 | F | F | F | F                 |
| 2 | T | T | T | T                 |

assuming short-circuiting logic:

- effectively, **three decisions**: one with condition \(a\), one with condition \(b\), and one with condition \(c\)
- decision coverage requires at least three test cases, such as:

| # | a | b | c | \((a || b) && c\) |
|---|---|---|---|-------------------|
| 1 | F | F | X | F                 |
| 2 | F | T | F | F                 |
| 3 | T | X | T | T                 |
Condition Coverage

- **condition coverage** ensures that:
  1. every point of entry invoked at least once
  2. every condition in every decision assumes each possible outcome at least once

- condition coverage often does not yield decision coverage

- condition coverage alone is very weak criterion so only useful when combined with other criteria

- for following code fragment, condition coverage can be achieved (without statement or decision coverage) with only two test cases (e.g., \( (a,b) \in \{(0,1),(1,0)\} \)):
  ```
  if (a > 0 && b > 0)
      ++x;
  ```

- in above example, note that condition coverage is achieved without achieving either decision or statement coverage
Condition/Decision Coverage

- **condition/decision coverage** ensures that:
  1. every point of entry in program invoked at least once
  2. every decision assumes each possible outcome (e.g., true or false) at least once
  3. every condition in each decision assumes each possible outcome at least once

- that is, condition/decision coverage simply combines requirements for decision coverage with those for condition coverage

- condition/decision coverage includes statement, decision, and condition coverages

- for following code fragment, condition/decision coverage can be achieved with two test cases (e.g., \((a, b) \in \{(0, 0), (1, 1)\}\)):

  ```
  if (a > 0 && b > 0)
      ++x;
  ```
consider following code fragment (with partial control-flow graph shown earlier):

```c
if ((a || b) && c)
    ++x;
```

assuming no short-circuiting logic:

- **one decision** \((a || b) && c\) with three conditions, namely, \(a\), \(b\), and \(c\)
- condition/decision coverage requires at least two test cases, such as:

| #  | a | b | c | \((a || b) && c\) |
|----|---|---|---|-----------------|
| 1  | F | F | F | F               |
| 2  | T | T | T | T               |

assuming short-circuiting logic:

- effectively, **three decisions**: one with condition \(a\), one with condition \(b\), and one with condition \(c\)
- condition/decision coverage requires at least three test cases, such as:

| #  | a | b | c | \((a || b) && c\) |
|----|---|---|---|-----------------|
| 1  | F | F | X | F               |
| 2  | F | T | F | F               |
| 3  | T | X | T | T               |
Modified Condition/Decision Coverage (MCDC)

- **modified condition/decision coverage (MCDC)** ensures that:
  - every point of entry invoked at least once
  - every condition in each decision in program assumes each possible outcome at least once
  - each condition in decision shown to independently affect that decision’s outcome

- several different variants of MCDC, each differing in how independence shown (i.e., last condition above)

- **unique-cause MCDC**: condition shown to independently affect decision’s outcome by varying just that condition while holding fixed all other possible conditions

- **masking MCDC**: condition is shown to independently affect decision’s outcome by applying principle of boolean logic to assure that no other condition influences output (even though more than one condition in decision may change value)
- unique-cause MCDC cannot handle decisions with strongly coupled conditions
- for decision with $n$ uncoupled (i.e., independent) conditions, need at least $n + 1$ test cases
- MCDC includes statement, decision, condition, and condition/decision coverages
consider following code fragment:

```c
if (a || b)
    x = 42;
else
    x = 0;
```

assuming no short-circuiting logic, unique-cause MCDC requires at least 3 test cases, such as:

| # | a  | b  | (a || b) | Independence Pairs |
|---|----|----|----------|--------------------|
| 1 | F  | F  | F        |                    |
| 2 | T  | F  | T        | a (1, 2)           |
| 3 | F  | T  | T        | b (1, 3)           |

assuming short-circuiting logic, masking MCDC requires at least 3 test cases, such as:

| # | a  | b  | (a || b) | Independence Pairs |
|---|----|----|----------|--------------------|
| 1 | F  | F  | F        |                    |
| 2 | T  | X  | T        | a (1, 2)           |
| 3 | F  | T  | T        | b (1, 3)           |
consider following code fragment:

```cpp
if (a && b && c && d)
    x = 42;
else
    x = 0;
```

assuming no short-circuiting logic, unique-cause MCDC requires at least 5 test cases, such as:

<table>
<thead>
<tr>
<th>#</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>a &amp;&amp; b &amp;&amp; c &amp;&amp; d</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>F</td>
</tr>
<tr>
<td>3</td>
<td>T</td>
<td>F</td>
<td>T</td>
<td>T</td>
<td>F</td>
</tr>
<tr>
<td>4</td>
<td>T</td>
<td>T</td>
<td>F</td>
<td>T</td>
<td>F</td>
</tr>
<tr>
<td>5</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>

Independence Pairs

- a (1, 2)
- b (1, 3)
- c (1, 4)
- d (1, 5)

assuming short-circuiting logic, masking MCDC requires at least 5 test cases, such as:

<table>
<thead>
<tr>
<th>#</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>a &amp;&amp; b &amp;&amp; c &amp;&amp; d</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>T</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>F</td>
</tr>
<tr>
<td>3</td>
<td>T</td>
<td>F</td>
<td>X</td>
<td>X</td>
<td>F</td>
</tr>
<tr>
<td>4</td>
<td>T</td>
<td>T</td>
<td>F</td>
<td>X</td>
<td>F</td>
</tr>
<tr>
<td>5</td>
<td>T</td>
<td>T</td>
<td>T</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>

Independence Pairs

- a (1, 2)
- b (1, 3)
- c (1, 4)
- d (1, 5)
consider following code fragment (with partial control-flow graph shown earlier):

```c
if ((a || b) && c)
    ++x;
```

assuming no short-circuiting logic, unique-cause MCDC requires at least 4 test cases, such as:

| #  | a | b | c | (a || b) && c |
|----|---|---|---|---------------|
| 1  | F | F | T | F             |
| 2  | T | F | T | T             |
| 3  | F | T | T | T             |
| 4  | T | F | F | F             |

Independence Pairs

<table>
<thead>
<tr>
<th></th>
<th>Independence Pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>(1, 2)</td>
</tr>
<tr>
<td>b</td>
<td>(1, 3)</td>
</tr>
<tr>
<td>c</td>
<td>(2, 4)</td>
</tr>
</tbody>
</table>

assuming short-circuiting logic, masking MCDC requires at least 4 test cases, such as:

| #  | a | b | c | (a || b) && c |
|----|---|---|---|---------------|
| 1  | F | F | X | F             |
| 2  | T | X | T | T             |
| 3  | F | T | T | T             |
| 4  | T | X | F | F             |

Independence Pairs

<table>
<thead>
<tr>
<th></th>
<th>Independence Pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>(1, 2)</td>
</tr>
<tr>
<td>b</td>
<td>(1, 3)</td>
</tr>
<tr>
<td>c</td>
<td>(2, 4)</td>
</tr>
</tbody>
</table>

as seen earlier, condition/decision coverage only requires 3 test cases
multiple-condition coverage ensures that:

1. every point of entry invoked at least once
2. each possible combination of condition outcomes in each decision occurs at least once

that is, multiple-condition coverage requires exhaustive testing of all possible combinations of condition outcomes

multiple-condition coverage is very strong criterion as it includes statement, decision, condition, and condition/decision, and MCDC coverages

for decision with \( n \) uncoupled (i.e., independent) conditions and no short-circuiting logic, need at least \( 2^n \) test cases

often, multiple-condition coverage is impractical as it can result in very large number of test cases being required
consider following code fragment (with partial control-flow graph shown earlier):

```cpp
if ((a || b) && c)
    ++x;
```

assuming no short-circuiting logic, multiple-condition coverage requires at least $2^3 = 8$ test cases (i.e., 1 test case for each possible combination of outcomes from 3 conditions):

| # | a | b | c | (a || b) && c |
|---|---|---|---|-------------|
| 1 | F | F | F | F           |
| 2 | T | F | F | F           |
| 3 | F | T | F | F           |
| 4 | T | T | F | F           |
| 5 | F | F | T | F           |
| 6 | T | F | T | T           |
| 7 | F | T | T | T           |
| 8 | T | T | T | T           |

assuming short-circuiting logic, multiple-condition coverage requires at least 5 test cases, such as:

| # | a | b | c | (a || b) && c |
|---|---|---|---|-------------|
| 1 | F | F | X | F           |
| 2 | T | X | F | F           |
| 3 | F | T | F | F           |
| 4 | T | X | T | T           |
| 5 | F | T | T | T           |
**All-Paths Coverage**

- **all-paths coverage** ensures that every path in program taken at least once.
- In other words, all-paths coverage ensures that every possible path from source node to sink node in control-flow graph is taken during testing.
- All-paths coverage includes function, statement, decision, condition, condition/decision, MCDC, and multiple-condition coverages.
- Except in case of trivial programs, number of possible paths astronomically large.
- Testing every path infeasible except in very trivial programs.
- Consequently, all-paths coverage of little practical utility.
- Moreover, even if every path could be tested, not sufficient to test every path through code, since:
  - Testing every path may not guarantee that program meets all specifications.
  - Defects in code could be due to missing paths and non-existent paths cannot be tested.
  - Whether bug manifests itself on particular path through code may depend on program state at each step (i.e., data sensitivity).
consider following code fragment:

```cpp
if (a)
    x = 42;
if (b)
    y = 42;
```

all-paths coverage would require at least 4 test cases, such as:

<table>
<thead>
<tr>
<th>#</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>2</td>
<td>T</td>
<td>F</td>
</tr>
<tr>
<td>3</td>
<td>F</td>
<td>T</td>
</tr>
<tr>
<td>4</td>
<td>T</td>
<td>T</td>
</tr>
</tbody>
</table>

consider following code fragment, where \( n \) is of type `unsigned int` and `unsigned int` is 64-bit integer:

```cpp
for (unsigned int i = 0; i < n; ++i)
    sum += a[i];
```

all-paths coverage would require at least \( 2^{64} \approx 1.84 \cdot 10^{19} \) (i.e., about 18.4 quintillion) test cases
## Comparison of Various Structural-Coverage Types

<table>
<thead>
<tr>
<th>Coverage Criterion</th>
<th>Statement Coverage</th>
<th>Decision Coverage</th>
<th>Condition Coverage</th>
<th>Condition/Decision Coverage</th>
<th>MCDC Coverage</th>
<th>Multiple Condition Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>every point of entry and exit invoked at least once</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>every statement executed at least once</td>
<td>✓</td>
<td>✓*</td>
<td>✓*</td>
<td>✓*</td>
<td>✓*</td>
<td>✓*</td>
</tr>
<tr>
<td>every decision has taken all possible outcomes at least once</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>every condition in each decision has taken all possible outcomes at least once</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>every condition in each decision shown to independently affect that decision’s outcome</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>every combination of condition outcomes within each decision invoked at least once</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

*not explicitly required in coverage definition but always implicitly satisfied*
Data-Flow Coverage

- Data-flow coverage considers how data modified and accessed (i.e., writes to and reads from variables)
- Data-flow analysis particularly well suited to detecting problems such as:
  - Variable used before being initialized
  - Variable initialized but never used
  - Variable initialized more than once before its use
- Data-flow coverage criteria not used as much in practice as control-flow counterparts
Variable Definitions and Uses

- each occurrence of variable in program classified as being either definition or use

- **definition**: occurrence of variable where its value is set (i.e., written)
  - `std::string s;` // definition of s (via construction)
  - `i = 0;` // definition of i
  - `*p = 42;` // definition of *p

- **use**: occurrence of variable where its value is used (i.e., read)

- each use can be classified as either being predicate use or computation use

- **predicate use (P-use)**: use of variable in predicate (i.e., condition) of branch statement; for example:
  - `if (x > 0) {/* ... */} // P-use of x`
  - `while (n != 0) {/* ... */} // P-use of n`

- **computation use (C-use)**: use of variable that is not P-use; for example:
  - `y = x + 1;` // C-use of x
  - `y = sin(x);` // C-use of x (pass by value parameter)

- variable can be both used and re-defined in same statement; for example:
  - `x = 3 * x + 2;` // x read and then written
  - `increment(x);` // x incremented (via pass by reference)
Definition-Clear and Definition-Use Paths

- C-use associated with \textit{node} in graph
- P-use associated with \textit{edge} in graph

\textbf{definition-clear (DC) path} with respect to variable \(x\) from node \(i\) to \textit{node} \(j\) is path \((i,n_1,\ldots,n_m,j)\), where \(m \geq 0\), that contains no definitions of \(x\) in nodes \(n_1,\ldots,n_m\)

\textbf{definition-clear (DC) path} with respect to variable \(x\) from node \(i\) to \textit{edge} \((j,k)\) is path \((i,n_1,\ldots,n_m,j,k)\), where \(m \geq 0\), that contains no definitions of \(x\) in nodes \(n_1,\ldots,n_m,j\)

\textbf{definition-use (DU) path} with respect to variable \(x\) is path \((n_1,\ldots,n_j,n_k)\) such that \(n_1\) has definition of \(x\) and either:

- node \(n_k\) has C-use of \(x\) and \((n_1,\ldots,n_j,n_k)\) is DC simple path with respect to \(x\); or
- edge \((n_j,n_k)\) has P-use of \(x\) and \((n_1,\ldots,n_j)\) is DC loop-free path with respect to \(x\)
Define/Use Coverage Criteria

- **all definitions coverage**: for every program variable \( x \), at least one DC path from every definition of \( x \) to at least one C-use or one P-use of \( x \) must be covered

- **all C-uses coverage**: for every program variable \( x \), at least one DC path from every definition of \( x \) to every C-use of \( x \) must be covered

- **all P-uses coverage**: for every program variable \( x \), at least one DC path from every definition of \( x \) to every P-use (including all outgoing edges of predicate statement) of \( x \) must be covered

- **all uses coverage**: for every program variable \( x \), at least one DC path from every definition of \( x \) to every C-use and P-use (including all outgoing edges of predicate statement) of \( x \) must be covered

- **all DU-paths coverage**: for every program variable \( x \), every DU path from every definition of \( x \) to every C-use and P-use of \( x \) must be covered

- all-definitions coverage subsumed by all-uses coverage subsumed by all DU-paths coverage
```c++
double power(double x, int y) {
    int p;
    if (y >= 0) {
        p = y;
    } else {
        p = -y;
    }
    double z = 1.0;
    while (p > 0) {
        z *= x;
        --p;
    }
    if (y < 0) {
        z = 1.0 / z;
    }
    return z;
}
```
initialize x, y; if (y >= 0)

Node | Definitions | C Uses
--- | --- | ---
1 | x, y |  
2 | p | y 
3 | p | y 
4 | z |  
5 |  |  
6 | z, p | x, z, p 
7 |  |  
8 | z | z 
9 |  | z 

Edge | P Uses
--- | ---
(1, 2) | y 
(1, 3) | y 
(5, 6) | p 
(5, 7) | p 
(7, 8) | y 
(7, 9) | y 

Copyright © 2015–2021 Michael D. Adams
Difficulties With Data-Flow Coverage

- often does not scale well to large real-world programs
- how to handle arrays
- aliasing poses challenges
- underestimation of aliases may fail to consider some definitions or uses
- overestimation of aliases may introduce infeasible test obligations
- can be more difficult to design test cases
Structural Coverage in Various Standards

- **DO-178C — Software Considerations in Airborne Systems and Equipment Certification**
  - primary document used by certification authorities (such as FAA, EASA, and Transport Canada) to approve all commercial software-based aerospace systems.
  - code that could result in catastrophic failure (e.g., crash) must have statement, decision, and MCDC coverages.
  - code that could result in hazardous failure (e.g., passenger fatality) must have decision and statement coverages.
  - code that could result in major failure (e.g., passenger injury) must have statement coverage.

- **ISO 26262 — Road vehicles — Functional safety**
  - standard for functional safety of electrical and electronic systems in production automobiles.
  - for most critical systems, highly recommends decision and MCDC coverages and recommends statement coverage.
  - for least critical systems, highly recommends statement coverage and recommends decision and MCDC coverages.
IEC 61508 — Functional Safety of Electrical/Electronic/Programmable Electronic Safety-Related Systems
- safety standard that applies to many industries
- for most critical systems, highly recommends statement, decision, and MCDC coverages
- for least critical systems, recommends statement, decision, and MCDC coverages

EN 50128 — Railway Applications — Communication, Signalling and Processing Systems (a.k.a. IEC 62279)
- pertains to programmable electronic systems used in railway control and protection applications
- for most critical systems, highly recommends statement, decision, and MCDC coverage

- defines integrated approach to systematic and documented unit testing
- specifies statement coverage as completeness requirement
- recommends decision coverage for code that is critical or has inadequate requirements specification
for software in safety-critical systems (i.e., systems in which failures could result in death or serious injury), desirable to have 100% coverage with respect to statement, decision, condition/decision, and MCDC criteria

for software that is not safety/mission critical, probably want to achieve 80% coverage or better with respect to each of statement, decision, and condition/decision coverage,

many organizations require at least 85% statement coverage for all projects

some people believe that anything less than 100% statement, decision, or condition/decision coverage does not ensure sufficient quality, but achieving 100% coverage often requires very substantial effort
Dynamic Analysis Tools

- Dynamic analysis tools examine code by executing it.
- Dynamic analysis tools can be used to:
  - find certain types of code defects
  - measure structural coverage
- Some types of code defects that can be found by dynamic analysis tools include:
  - invalid memory accesses
  - memory leaks
  - data races
  - use of uninitialized variable
  - signed integer overflow
  - use of memory after deallocation
  - double deallocation
Examples of Dynamic Analysis Tools

- Address Sanitizer (ASan)
- Undefined-Behavior Sanitizer (UBSan)
- Thread Sanitizer (TSan)
- Memory Sanitizer (MSan)
- Leak Sanitizer (LSan)
- Valgrind (Callgrind, CacheGrind, Helgrind, Memcheck, and Massif) and KCacheGrind
- Gcov, Lcov, Gcovr, and LLVM Cov
- Kcov

- Control Flow Integrity (CFI) Sanitizer (https://clang.llvm.org/docs/ControlFlowIntegrity.html)

- many commercial products also available, such as:
  - Testwell CTC++ (http://www.testwell.fi/ctcdesc.html)
  - Bullseye Coverage (http://www.bullseye.com)
  - PurifyPlus (http://teamblue.unicomsi.com/products/purifyplus)
- software testing levels are stages of testing performed as part of software-development lifecycle
- four levels of testing (in order performed) are:
  1. unit testing
  2. integration testing
  3. system testing
  4. acceptance testing
Unit Testing

- **unit testing** is stage of software testing in which individual components (i.e., units) tested
- first level of software testing; happens before integration testing
- unit being tested typically corresponds to:
  - class or class method
  - function
- goal is to isolate unit and validate its correctness
- only ensures that unit works correctly in isolation
- conducted by developer
- usually uses white-box testing but may also employ gray-box and black-box testing
- can be done manually but is usually automated
- unit testing allows problems to be found early in development cycle
- unit testing might include (amongst other things): static code analysis, running test cases in conjunction with structural-coverage analysis, and code reviews
Integration testing is stage of software testing in which individual components combined and tested as group

Second level of testing; occurs after unit testing and before system testing

Components may be combined together incrementally or all at once (i.e., big bang)

Usually prefer to combine components incrementally as this typically allows bugs to be isolated more quickly

Purpose is to expose defects in interfaces and interaction between integrated components

Progressively larger groups of components integrated until software works as system

Employs black-box or white-box testing

Performed by tester (or in some cases developer)
**System Testing**

- **system testing** is testing of complete software product (i.e., consisting of all integrated components) against specifications.
- Third level of testing; occurs after integration testing and before acceptance testing.
- Performed before completed software product introduced to market.
- Goal is to ensure that system meets its requirements.
- Conducted by tester.
- Employed black-box testing.
- Examples of different types of testing that may be included in system testing:
  - Graphical user interface testing
  - Usability testing
  - Compatibility testing
  - Performance testing
  - Regression testing
  - Installation testing
  - Recovery testing
Acceptance testing is stage of testing that evaluates compliance with business requirements and assesses whether acceptable for delivery.

- fourth (and last) level of testing; after system testing
- usually uses black-box testing and often ad hoc
- internal acceptance testing performed by members of organization that developed software but are not directly involved in project
- external acceptance testing performed by people outside organization that developed software
Regression testing involves re-running tests to ensure that software still works correctly after change or addition.

**Regression**: defect (where software has reverted to exhibiting incorrect behavior) due to code change.

Changes that may require regression testing include:
- applying bug fixes
- adding enhancements or new features
- making configuration changes (e.g., changes to configuration files)

May re-run full test suite or subset thereof, depending on particular situation.
Performance Testing

- **performance testing** checks how software will behave and perform under various workloads
- may consider such factors as:
  - speed
  - resource usage (e.g., memory, disk, and network)
  - reliability
  - scalability
  - responsiveness
  - throughput

- **load testing** checks how software behaves under anticipated workloads
- **stress testing** checks how software behaves under extreme workloads
- **soak testing** (also known as **endurance testing**) checks how well software can handle expected workload over long periods of time
Fuzz Testing

- **fuzz testing** (also known as **fuzzing**) is an automated technique used to find bugs in code by providing massive amounts of random data as input to the test subject in an effort to induce failure.
- Tool used to perform fuzz testing called **fuzzer**.
- Particularly effective for code that processes streams of characters (e.g., file-format processing and parsers).
- Often exploit genetic algorithms in order to mutate input data.
- May be aware of input structure.
- May be aware of program structure (e.g., coverage-guided fuzzing).
Fuzzing Tools

- American Fuzzy Lop (AFL)
  - security-oriented fuzzer that uses compiler-time instrumentation and genetic algorithms
  - web site: http://lcamtuf.coredump.cx/afl

- libFuzzer
  - coverage-guided fuzzer in LLVM
  - web site: https://llvm.org/docs/LibFuzzer.html

- OSS-Fuzz
  - service provided by Google for continuous fuzzing of open-source software with large user base
  - employs libFuzzer fuzzing engine
  - web site: https://github.com/google/oss-fuzz
unit-test framework is a tool that provides infrastructure for facilitating unit testing.

By using a unit-test framework, you can avoid developing code that runs tests and instead focus on code for tests themselves.

test fixture: provides a properly initialized context in which to run tests (which is typically used by multiple tests).

mock object: a simulated object that mimics the behavior of real objects in controlled ways.

Unit-test frameworks vary greatly in the features they offer, and may include support for things such as:

- test fixtures (to reduce duplication of boiler-plate code)
- mock objects
- mechanisms for performing floating-point comparisons with tolerances
- variety of output formats for reporting test results
- multithreaded code
Examples of Unit-Test Frameworks

- **Catch2**
- Google Test ([http://github.com/google/googletest](http://github.com/google/googletest))
- Boost Test ([http://www.boost.org](http://www.boost.org))
- many commercial products also available, such as:
  - Testwell CTA++ ([http://www.testwell.fi/ctadesc.html](http://www.testwell.fi/ctadesc.html))
multi-threaded programs can have all same types of bugs as single-threaded programs plus many more

some types of bugs specific to multi-threaded programs include:
- race conditions
- data races
- deadlocks
- livelocks
- starvation
- atomicity violation (i.e., assumption that code block executes atomically is violated)
- ordering violation (i.e., assumption regarding relative order in which operations performed is violated)
- unintended sharing
Strategies for Testing Concurrent Programs

- conduct detailed code inspections, looking for problems such as:
  - accessing shared data without taking lock
  - taking multiple locks in inconsistent orders
  - making invalid assumptions about happens-before relationships

- test code in manner that varies code timing as much as possible, since many bugs will only show with very particular code timing (as many bugs caused by race conditions)

- as in testing of any code, ensure:
  - good code coverage
  - boundary conditions encountered

- perform load (i.e., stress) testing, since many types of bugs more likely to show themselves under extreme conditions

- allow test code to run for longer periods of time in hopes that less frequently occurring timings that may expose bugs will eventually be encountered
Strategies for Testing Concurrent Programs (Continued)

- utilize data-race detection tools such as:
  - Thread Sanitizer (TSan)
  - Valgrind/Helgrind

- test code on all platforms of interest (e.g., different processor architectures and operating systems)

- since implementations of synchronization primitives may differ across operating systems, some bugs may show themselves only under certain operating systems

- some implementations of synchronization primitives (particularly those on processor architectures with relatively strong memory models) may provide more guarantees than what is requested by code, which can mask bugs

- suppose, for example, that code requires particular aligned 32-bit memory access to be atomic in order to work correctly, but does not specifically request access to be atomic, which is bug

- preceding bug would never show itself on processor architecture where all aligned 32-bit memory accesses are atomic
Section 6.9.1

References


Section 7.1

Set Theory
A binary relation $\diamond$ on a set $S$ is said to be **reflexive** if
\[
\text{for all } a \in S, \quad a \diamond a.
\]

A relation that is not reflexive is called irreflexive.

For example, the usual equality relation ($=$) on the real numbers is reflexive and the usual less-than relation ($<$) on the same set is irreflexive.

A binary relation $\diamond$ on a set $S$ is said to be **symmetric** if
\[
\text{for all } a, b \in S, \quad a \diamond b \iff b \diamond a.
\]

For example, the usual equality relation ($=$) on the real numbers is symmetric.

A binary relation $\diamond$ on a set $S$ is said to be **asymmetric** if
\[
\text{for all } a, b \in S, \quad \text{if } a \diamond b \text{ then not } (b \diamond a).
\]

For example, the usual less-than relation ($<$) on the real numbers is asymmetric.
A binary relation $\diamond$ on a set $S$ is said to be **antisymmetric** if

for all $a, b \in S$, if $a \diamond b$ and $b \diamond a$ then $a = b$.

For example, the usual less-than-or-equal relation ($\leq$) on the real numbers is antisymmetric.

A binary relation $\diamond$ on a set $S$ is said to be **transitive** if

for all $a, b, c \in S$, if $a \diamond b$ and $b \diamond c$ then $a \diamond c$.

For example, the usual equality relation ($=$) on the real numbers is transitive.

A relation that is not transitive is called intransitive.
A binary relation $\Diamond$ on a set $S$ is said to be **connex** if

for all $a, b \in S$, $a \Diamond b$ or $b \Diamond a$.

For example, the usual less-than-or-equal relation ($\leq$) on the real numbers is connex.

A binary relation $\Diamond$ on a set $S$ is said to be **semiconnex** if

for all $a, b \in S$, $a \Diamond b$ or $b \Diamond a$ or $a = b$.

For example, the usual less-than relation ($<$) on the real numbers is semiconnex.

Asymmetry implies irreflexivity.

Irreflexivity and transitivity together imply asymmetry.

Connexity implies reflexivity (since reflexivity is special case of connexity with $a = b$).
A relation \( \leq \) is said to be a **(non-strict) total order** on a set \( S \) if the relation is:

- antisymmetric (i.e., for all \( a, b \in S \), if \( a \leq b \) and \( b \leq a \) then \( a = b \));
- transitive (i.e., for all \( a, b, c \in S \), if \( a \leq b \) and \( b \leq c \) then \( a \leq c \)); and
- connex (i.e., for all \( a, b \in S \), \( a \leq b \) or \( b \leq a \)).

A relation \( < \) is said to be a **strict total order** on a set \( S \) if the relation is:

- asymmetric (i.e., for all \( a, b \in S \), if \( a < b \) then not \( (b < a) \));
- irreflexive (i.e., for all \( a \in S \), not \( (a < a) \)); and
- semiconnexit (i.e., for all \( a, b \in S \), \( a < b \) or \( b < a \) or \( a = b \)).

Informally, each element in the set **has a rank** (from least to greatest) and this rank is **unique**.

Connexity/semiconnexitery ensures that every two elements in the set are comparable.

Given \( a, b \in S \), exactly one of the following must be true:

1. \( a \) is less than \( b \)
2. \( a \) is greater than \( b \)
3. \( a \) is equal to \( b \)
The usual definition of the less-than-or-equal ($\leq$) and greater-than-or-equal ($\geq$) relations for the set of integers are each a total order.

The usual definition of the less-than ($<$) and greater-than ($>$) relations for the set of integers are each a strict total order.
Each non-strict total order has an associated strict total order and vice versa.

A non-strict total order \( \leq \) on the set \( S \) has the associated strict total order \( < \) defined by:

\[
\text{for all } a, b \in S, \quad a < b \text{ if not } b \leq a.
\]

A strict total order \( < \) on \( S \) has the associated non-strict total order \( \leq \) defined by:

\[
\text{for all } a, b \in S, \quad a \leq b \text{ if not } b < a.
\]

Furthermore, each corresponding pair of non-strict and strict total orders \( \leq \) and \( < \) on the set \( S \) has the associated corresponding complements \( > \) and \( \geq \) given by:

\[
\text{for } a, b \in S, \quad a \geq b \text{ if not } a < b \quad \text{and} \quad a > b \text{ if not } a \leq b.
\]

So, any one of the strict/non-strict total orders \( \leq, \geq, <, \text{ and } > \), completely determines the others.
A relation $\leq$ is said to be a **total preorder** on a set $S$ if the relation is:
- transitive (i.e., for all $a, b \in S$, if $a \leq b$ and $b \leq c$ then $a \leq c$); and
- connex (i.e., for all $a, b \in S$, $a \leq b$ or $b \leq a$).

Relative to a total order, a total preorder drops the antisymmetry property.

Informally, each element in the set *has a rank* (from least to greatest) but this rank is *not necessarily unique*.

Connexity ensures that every two elements in the set are comparable.

Given $a, b \in S$, exactly one of the following must be true:
- 1. $a$ is less than $b$
- 2. $a$ is greater than $b$
- 3. $a$ is equivalent (but not necessarily equal) to $b$

A relation on the set of integer vectors that compares the vectors by their length is a total preorder.
A relation $\leq$ is said to be a **preorder** on a set $S$ if the relation is:

- reflexive (i.e., for all $a \in S$, $a \leq a$); and
- transitive (i.e., for all $a, b, c \in S$, if $a \leq b$ and $b \leq c$ then $a \leq c$).

Relative to a total preorder, a preorder drops the connex property.

Given $a, b \in S$, exactly one of the following must be true:

1. $a$ is less than $b$
2. $a$ is greater than $b$
3. $a$ is equivalent (but not necessarily equal) to $b$
4. $a$ and $b$ are incomparable

The usual less-than-or-equal relation on the set of real intervals is a preorder, since nontrivial overlapping intervals are incomparable (e.g., $[0, 2]$ and $[1, 3]$).
Basic Operations of Boolean Algebra

- **conjunction (AND)** of two booleans \( x \) and \( y \), denoted \( x \land y \), is defined as
  \[
  x \land y = \begin{cases} 
  1 & x = 1 \text{ and } y = 1 \\ 
  0 & \text{otherwise}
  \end{cases}
  \]

- **disjunction (OR)** of two booleans \( x \) and \( y \), denoted \( x \lor y \), is defined as
  \[
  x \lor y = \begin{cases} 
  1 & x = 1 \text{ or } y = 1 \\ 
  0 & \text{otherwise}
  \end{cases}
  \]

- **negation (NOT)** of boolean \( x \), denoted \( \neg x \), is defined as
  \[
  \neg x = \begin{cases} 
  1 & x \neq 1 \\ 
  0 & \text{otherwise}
  \end{cases}
  \]

- Operator precedence from highest to lowest is as follows:
  1. negation
  2. conjunction
  3. disjunction

- For example, \( \neg a \land b \lor c \land d \) means \( \((\neg a) \land b) \lor (c \land d)\)
# Laws of Boolean Algebra

<table>
<thead>
<tr>
<th>Property</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Associativity of Conjunction</td>
<td>$(x \land y) \land z = x \land (y \land z)$</td>
</tr>
<tr>
<td>Associativity of Disjunction</td>
<td>$(x \lor y) \lor z = x \lor (y \lor z)$</td>
</tr>
<tr>
<td>Commutativity of Conjunction</td>
<td>$x \land y = y \land x$</td>
</tr>
<tr>
<td>Commutativity of Disjunction</td>
<td>$x \lor y = y \lor x$</td>
</tr>
<tr>
<td>Distributivity of Conjunction over Disjunction</td>
<td>$x \land (y \lor z) = (x \land y) \lor (x \land z)$</td>
</tr>
<tr>
<td>Distributivity of Disjunction over Conjunction</td>
<td>$x \lor (y \land z) = (x \lor y) \land (x \lor z)$</td>
</tr>
<tr>
<td>Identity of Disjunction</td>
<td>$x \lor 0 = x$</td>
</tr>
<tr>
<td>Identity of Conjunction</td>
<td>$x \land 1 = x$</td>
</tr>
<tr>
<td>Annihilator for Conjunction</td>
<td>$x \land 0 = 0$</td>
</tr>
<tr>
<td>Annihilator for Disjunction</td>
<td>$x \lor 1 = 1$</td>
</tr>
<tr>
<td>Idempotence of Disjunction</td>
<td>$x \lor x = x$</td>
</tr>
<tr>
<td>Idempotence of Conjunction</td>
<td>$x \land x = x$</td>
</tr>
<tr>
<td>Absorption 1</td>
<td>$x \land (x \lor y) = x$</td>
</tr>
<tr>
<td>Absorption 2</td>
<td>$x \lor (x \land y) = x$</td>
</tr>
<tr>
<td>Complementation 1</td>
<td>$x \land \neg x = 0$</td>
</tr>
<tr>
<td>Complementation 2</td>
<td>$x \lor \neg x = 1$</td>
</tr>
<tr>
<td>Double Negation</td>
<td>$\neg \neg x = x$</td>
</tr>
<tr>
<td>De Morgan 1</td>
<td>$\neg x \land \neg y = \neg (x \lor y)$</td>
</tr>
<tr>
<td>De Morgan 2</td>
<td>$\neg x \lor \neg y = \neg (x \land y)$</td>
</tr>
</tbody>
</table>
Conjunctive Normal Form (CNF)

- boolean expressions can be written in numerous forms
- one key form known as conjunctive normal form
- boolean expression written in manner meeting following requirements is said to be in **conjunctive normal form (CNF)**:
  - each clause allowed to contain *only disjunction and negation* operations
  - if more than one clause, clauses joined by *conjunctions*
- examples of expressions in CNF:
  - $a$, which consists of single clause
  - $a \lor b$, which consists of single clause
  - $\neg a \lor b$, which consists of single clause
  - $(a \lor b) \land (c \lor d)$, which consists of two clauses joined by conjunction
  - $a \land (b \lor \neg c \lor d) \land (e \lor f)$, which consists of three clauses joined by conjunctions
- as alternative to computing by hand, Wolfram Alpha can be used to find CNF: [https://www.wolframalpha.com/input/?i=CNF+x](https://www.wolframalpha.com/input/?i=CNF+x)
Disjunctive Normal Form (DNF)

- another key form for boolean expression known as disjunctive normal form
- boolean expression written in manner that meets following requirements

  said to be in **disjunctive normal form (DNF):**
  - each clause allowed to contain *only* conjunction and negation operations
  - if more than one clause, clauses joined by *disjunctions*

- examples of expressions in DNF:
  - $a$, which consists of single clause
  - $a \land b$, which consists of single clause
  - $\neg a \land b$, which consists of single clause
  - $(a \land b) \lor (c \land d)$, which consists of two clauses joined by disjunction
  - $a \lor (b \land \neg c \land d) \lor (e \land f)$, which consists of three clauses joined by disjunctions

- as alternative to computing by hand, Wolfram Alpha can be used to find DNF: [https://www.wolframalpha.com/input/?i=DNF+x](https://www.wolframalpha.com/input/?i=DNF+x)
for two boolean expressions \(x\) and \(y\), \(x\) is said to \textbf{subsume} \(y\) if

\[
x = 1 \text{ implies } y = 1
\]

by definition, boolean expression always subsumes itself (i.e., \(x\) subsumes \(x\) for any expression \(x\)).

subsumption relationships can be used to determine if one boolean condition is \textit{more constraining} (i.e., more difficult to satisfy) than another.

consider expressions \(a\) and \(a \land b\):

- \(a \land b\) subsumes \(a\), since \(a \land b = 1\) implies \(a = 1\)
- \(a\) does not subsume \(a \land b\), since \(a = 1\) does not necessarily imply \(a \land b = 1\)

consider expressions \(a\) and \(a \lor b\):

- \(a\) subsumes \(a \lor b\), since \(a = 1\) implies \(a \lor b = 1\)
- \(a \lor b\) does not subsume \(a\), since \(a \lor b = 1\) does not necessarily imply \(a = 1\)

consider expressions \(a \land b\) and \(a \land c\):

- \(a \land b\) does not subsume \(a \land c\)
- \(a \land c\) does not subsume \(a \land b\)
Part 8

Debugging and Testing Tools
Section 8.1

Debuggers
unfortunately, software does not always work as intended due to errors in code (i.e., bugs)

how does one go about fixing bugs in time-efficient manner?

source-level debugger is essential tool

single stepping: step through execution of code, one source-code line at a time

breakpoints: pause execution at particular points in code

watchpoints: pause execution when the value of variable is changed

print values of variables
GNU Debugger (GDB)

- GNU Debugger (GDB) is powerful source-level debugger
- home page: http://www.gnu.org/software/gdb
- available on most platforms (e.g., Unix, Microsoft Windows)
- most popular source-level debugger on Unix systems
- allows one to see what is happening inside program as it executes or what a program was doing at the moment it crashed
- has all of the standard functionality of a source-level debugger (e.g., breakpoints, watchpoints, single-stepping)

- `gdb` command

- command-line usage:
  
  ```
  gdb [options] executable
  ```
help
    Print help information.

quit
    Exit debugger.

run [arglist]
    Start the program (with arglist if specified).

print expr
    Display the value of the expression expr.

bt
    Display a stack backtrace.

list
    Type the source code lines in the vicinity of where the program is currently stopped.
break function
  Set a breakpoint at the function function.

watch expr
  Set a watchpoint for the expression expr.

c
  Continue running the program (e.g., after stopping at a breakpoint).

next
  Execute the next program line, stepping over any function calls in the line.

step
  Execute the next program line, stepping into any function calls in the line.
- graphical front-end to command-line debuggers such as GDB
- has some fancy graphical data display functionality
- *all* `gdb` commands available in text window, but can use graphical interface to enter commands as well
- home page: http://www.gnu.org/software/ddd
- `ddd` command
Section 8.2

Code Sanitizers
- **code sanitizer**: tool for automatically performing variety of run-time checks on code
- typically requires compiler to instrument code
- may also need library for run-time support
- several code sanitizers supported by Clang and/or GCC, including:
  - Address Sanitizer (**ASan**)
  - Thread Sanitizer (**TSan**)
  - Memory Sanitizer (**MSan**)
  - Undefined-Behavior Sanitizer (**UBSan**)
  - Leak Sanitizer (**LSan**)
- sanitizers easy to use
- can easily catch many bugs
- overhead of code sanitizer typically much less than that of other competing approaches for detecting similar types of bugs
Address Sanitizer (ASan) can be used to detect numerous errors related to memory addressing, such as:

- out of bounds accesses to heap, stack, and globals
- heap use after free
- stack use after return
- stack use after scope
- double or invalid free
- memory leaks
- initialization order problems

- supported by both Clang and GCC
- compiler instruments all loads/stores and inserts redzones around stack and global variables
- run-time library provides malloc replacement (with redzone and quarantine functionality) and bookkeeping for error messages
- typically introduces about 2 times slowdown
- about 1.5 to 3 times memory overhead
need to enable address sanitizer at compile and link time using 
-fsanitize=address option for Clang and GCC

environment variable ASAN_OPTIONS can be set to whitespace-separated 
list of options to control some sanitizer behavior at run time

some sanitizer options include:
  • strip_path_prefix
  • verbosity
  • detect_leaks
  • allocator_may_return_null
  • check_initialization_order
  • detect_stack_use_after_return
  • new_delete_type_mismatch
  • exitcode

to enable checking for initialization order problems, use
ASAN_OPTIONS="check_initialization_order=1"
global_buffer_overflow.cpp

```cpp
#include <iostream>

int a[4] = {1, 2, 3, 4};

int main() {
    for (int i = 0; i <= 4; ++i) {
        std::cout << a[i] << '
';
    }
}
```

program output (truncated):

```
=================================================================
==3359==ERROR: AddressSanitizer: global-buffer-overflow on address 0
  x00000006020d0 at pc 0x000000400d31 bp 0x7ffeb78d2350 sp 0
  x7ffeb78d2348
READ of size 4 at 0x0000006020d0 thread T0
  #0 0x400d30 in main global_buffer_overflow.cpp:5
  #1 0x7f83da8d4fdf in __libc_start_main (/lib64/libc.so.6+0x1ffdf)
  #2 0x400bf8 (global_buffer_overflow+0x400bf8)
0x00000006020d0 is located 0 bytes to the right of global variable 'a'
  defined in 'global_buffer_overflow.cpp:2:5' (0x6020c0) of size 16
SUMMARY: AddressSanitizer: global-buffer-overflow
  global_buffer_overflow.cpp:5 in main
Shadow bytes around the buggy address:
```

Out-of-Bounds Access to Stack

stack_buffer_overflow.cpp

```cpp
#include <iostream>

int main() {
    int a[4] = {1, 2, 3, 4};
    for (int i = 0; i <= 4; ++i)
        {std::cout << a[i] << '\n';}
}
```

program output (truncated):

```
=================================================================
==3364==ERROR: AddressSanitizer: stack-buffer-overflow on address 0x7ffc3e811cf0
at pc 0x000000400e53 bp 0x7ffc3e811c70 sp 0x7ffc3e811c68
READ of size 4 at 0x7ffc3e811cf0 thread T0
#0 0x400e52 in main stack_buffer_overflow.cpp:5
#1 0x7f10c1c7afdf in __libc_start_main (/lib64/libc.so.6+0x1ffdf)
#2 0x400c48 (stack_buffer_overflow+0x400c48)
Address 0x7ffc3e811cf0 is located in stack of thread T0 at offset 112 in frame
#0 0x400d06 in main stack_buffer_overflow.cpp:2
This frame has 2 object(s):
[32, 33) '__c'
[96, 112) 'a' <= Memory access at offset 112 overflows this variable
HINT: this may be a false positive if your program uses some custom stack unwind
mechanism or swapcontext
(longjmp and C++ exceptions *are* supported)
SUMMARY: AddressSanitizer: stack-buffer-overflow stack_buffer_overflow.cpp:5 in
main
Shadow bytes around the buggy address:
```

Out-of-Bounds Access to Heap

heap_buffer_overflow.cpp

```cpp
#include <iostream>
#include <cstring>

int main() {
    char* p = new char[5];
    std::strcpy(p, "Hello");
    std::cout << p << 'n';
    delete[] p;
}
```

program output (truncated):

```
=================================================================
==3360==ERROR: AddressSanitizer: heap-buffer-overflow on address 0x602000000015
  at pc 0x7f7497932399 bp 0x7ffd8defc240 sp 0x7ffd8defb9f0
WRITE of size 6 at 0x602000000015 thread T0
  #0 0x7f7497932398 in __interceptor_memcpy ../../../../src/libsanitizer/asan/
      asan_interceptors.cc:456
  #1 0x400dd4 in main heap_buffer_overflow.cpp:5
  #2 0x7f7496c7dfdf in __libc_start_main (/lib64/libc.so.6+0x1ffdf)
  #3 0x400ca8 (heap_buffer_overflow+0x400ca8)
0x602000000015 is located 0 bytes to the right of 5-byte region [0x602000000010,0x602000000015)
allocated by thread T0 here:
  #0 0x7f7497997170 in operator new[](unsigned long) ../../ ../src/
      libsanitizer/asan/asan_new_delete.cc:82
  #1 0x400dbf in main heap_buffer_overflow.cpp:4
SUMMARY: AddressSanitizer: heap-buffer-overflow ../../ ../src/libsanitizer/asan/
      asan_interceptors.cc:456 in __interceptor_memcpy
Shadow bytes around the buggy address:
```
use_after_free.cpp

```cpp
int main() {
    int* p = new int[16];
    delete[] p;
    *p = 42;
}
```

program output (truncated):

```
=================================================================
==3366==ERROR: AddressSanitizer: heap-use-after-free on address 0x606000000020 at pc 0x000000400836 bp 0x7ffc752b5c20 sp 0x7ffc752b5c18
WRITE of size 4 at 0x606000000020 thread T0
 #0 0x400835 in main use_after_free.cpp:4
 #1 0x7f0b6dab5fdf in __libc_start_main (/lib64/libc.so.6+0x1ffdf)
 #2 0x400738 (use_after_free+0x400738)
0x606000000020 is located 0 bytes inside of 64-byte region [0x606000000020,0 x606000000060)
freed by thread T0 here:
 #0 0x7f0b6e7cfe70 in operator delete[](void*) ..../..../src/libsanitizer/asan/asan_new_delete.cc:128
 #1 0x400801 in main use_after_free.cpp:3
previously allocated by thread T0 here:
 #0 0x7f0b6e7cf170 in operator new[](unsigned long) ..../..../src/libsanitizer/asan/asan_new_delete.cc:82
 #1 0x4007f1 in main use_after_free.cpp:2
SUMMARY: AddressSanitizer: heap-use-after-free use_after_free.cpp:4 in main
Shadow bytes around the buggy address:
```

Stack Use After Return

Stack Use After Return

stack_use_after_return.cpp

```cpp
1    int* g = nullptr;
2    void foobar() {int i = 42; g = &i;}
3    int main() {
4        foobar();
5            return *g;
6    }
```

Program output (truncated) (with ASAN_OPTIONS=detect_stack_use_after_return=1):

```
==========
==3365==ERROR: AddressSanitizer: stack-use-after-return on address 0x7f74e7500020
    at pc 0x000000400a88 bp 0x7ffdbd534e20 sp 0x7ffdbd534e18
READ of size 4 at 0x7f74e7500020 thread T0
    #0 0x400a87 in main stack_use_after_return.cpp:5
    #1 0x7f74eb1dffdf in __libc_start_main (/lib64/libc.so.6+0x1ffdf)
    #2 0x4008b8 (stack_use_after_return+0x4008b8)
Address 0x7f74e7500020 is located in stack of thread T0 at offset 32 in frame
    #0 0x400976 in foobar() stack_use_after_return.cpp:2
This frame has 1 object(s):
    [32, 36) 'i' <= Memory access at offset 32 is inside this variable
HINT: this may be a false positive if your program uses some custom stack unwind
    mechanism or swapcontext
    (longjmp and C++ exceptions *are* supported)
SUMMARY: AddressSanitizer: stack-use-after-return stack_use_after_return.cpp:5 in
    main
Shadow bytes around the buggy address:
```

# Stack Use After Scope

**use_after_scope.cpp**

```cpp
#include <iostream>

int main() {
    int* p;
    { int x = 0; p = &x; }
    std::cout << *p << '\n';
}
```

**program output (truncated):**

```
==3367==ERROR: AddressSanitizer: stack-use-after-scope on address 0x7ffe1d6a6c40
    at pc 0x000000400b6b bp 0x7ffe1d6a6c10 sp 0x7ffe1d6a6c08
READ of size 4 at 0x7ffe1d6a6c40 thread T0
 #0 0x400b6a in main use_after_scope.cpp:5
 #1 0x7fea2e596fdf in __libc_start_main (/lib64/libc.so.6+0x1ffdf)
 #2 0x400a58 (use_after_scope+0x400a58)
Address 0x7ffe1d6a6c40 is located in stack of thread T0 at offset 32 in frame
 #0 0x400b16 in main use_after_scope.cpp:2
This frame has 1 object(s):
 [32, 36) 'x' <= Memory access at offset 32 is inside this variable
HINT: this may be a false positive if your program uses some custom stack unwind
    mechanism or swapcontext
    (longjmp and C++ exceptions *are* supported)
SUMMARY: AddressSanitizer: stack-use-after-scope use_after_scope.cpp:5 in main
Shadow bytes around the buggy address:
```
double_free.cpp

```cpp
int main() {
    int* p = new int[16];
    delete[] p;
    delete[] p;
}
```

program output (truncated):

```
=================================================================
==3358==ERROR: AddressSanitizer: attempting double-free on 0x606000000020 in thread T0:
    #0 0x7fdc05ed8e70 in operator delete[](void*) ../../../../src/libsanitizer/asan/asan_new_delete.cc:128
    #1 0x4007b9 in main double_free.cpp:4
    #2 0x7fdc051befdf in __libc_start_main (/lib64/libc.so.6+0x1ffdf)
    #3 0x4006e8 (double_free+0x4006e8)
0x606000000020 is located 0 bytes inside of 64-byte region [0x606000000020,0x606000000060)
freed by thread T0 here:
    #0 0x7fdc05ed8e70 in operator delete[](void*) ../../../../src/libsanitizer/asan/asan_new_delete.cc:128
    #1 0x40007b1 in main double_free.cpp:3
previously allocated by thread T0 here:
    #0 0x7fdc05ed8170 in operator new[](unsigned long) ../../../../src//libsanitizer/asan/asan_new_delete.cc:82
    #1 0x4007a1 in main double_free.cpp:2
SUMMARY: AddressSanitizer: double-free ../../../../src/libsanitizer/asan/asan_new_delete.cc:128 in operator delete[](void*)
```

---

Memory Leaks

memory_leak.cpp

```cpp
#include <iostream>
#include <cstring>

int main() {
    char* p = new char[1024];
    std::strcpy(p, "Hello, World!\n");
    std::cout << p;
}
```

program output (truncated):

```text
Hello, World!
=================================================================
==3362==ERROR: LeakSanitizer: detected memory leaks
Direct leak of 1024 byte(s) in 1 object(s) allocated from:
  #0 0x7f7413651170 in operator new[](unsigned long) ../../../../src/asan/asan_new_delete.cc:82
  #1 0x400b51 in main memory_leak.cpp:4
SUMMARY: AddressSanitizer: 1024 byte(s) leaked in 1 allocation(s).
```
Initialization Order Problems

**init_order_main.cpp**
```
#include <iostream>
extern int B;
int A = B;
int main()
{
    std::cout << A << '
';
}
```

**init_order_other.cpp**
```
#include <cstdlib>
int B = std::atoi("42");
```

**program output (truncated)** (with `ASAN_OPTIONS=check_initialization_order=1`):
```
=================================================================
==3361==ERROR: AddressSanitizer: initialization-order-fiasco on address 0
  x000000602440 at pc 0x0000000400f14 bp 0x7fff92151540 sp 0x7fff92151538
READ of size 4 at 0x000000602440 thread T0
  #0 0x400f13 in __static_initialization_and_destruction_0 init_order_main.cpp
  :3
  #1 0x400f13 in _GLOBAL__sub_I_A init_order_main.cpp:5
  #2 0x40103c in __libc_csu_init (init_order+0x40103c)
  #3 0x7f933e2e7f6e in __libc_start_main (/lib64/libc.so.6+0x1ff6e)
  #4 0x400c98 (init_order+0x400c98)
0x000000602440 is located 0 bytes inside of global variable 'B' defined in '
  init_order_other.cpp:2:5' (0x602440) of size 4
registered at:
  #0 0x7f933ef5b7c8 in __asan_register_globals ../../../../src/libsanitizer/
asan/asan_globals.cc:317
  #1 0x400fe9 in _GLOBAL__sub_I_00099_1_B (init_order+0x400fe9)
SUMMARY: AddressSanitizer: initialization-order-fiasco init_order_main.cpp:3 in
  __static_initialization_and_destruction_0
Shadow bytes around the buggy address:
```
Thread Sanitizer (TSan)

- Thread Sanitizer (TSan) detects data races and deadlocks
- supported by Clang and GCC
- compiler instruments code to intercept all loads/stores
- run-time library provides malloc replacement, intercepts all synchronization, and handles loads/stores
- does not instrument prebuilt libraries and inline assembly
- about 4 to 10 times slower
- about 5 to 8 times more memory
- only supported on 64-bit Linux
need to enable sanitizer at compile and link time using
-fsanitize=thread option for Clang and GCC

environment variable TSAN_OPTIONS can be set to whitespace-separated
list of options to control some sanitizer behavior at run time

some sanitizer options include:

- strip_path_prefix
- verbosity
- report_bugs
- history_size
- suppressions
- exitcode

for example, to set per-thread history size value to 7, use
TSAN_OPTIONS="history_size=7"

at least some versions of TSan do not detect potential deadlock if it
actually happens (although arguably if deadlock happens, probably it will
be noticed)
#include <thread>

int x = 0;

int main() {
    std::thread t([&]{x = 42;});
    x = 43;
    t.join();
}

program output (truncated):

WARNING: ThreadSanitizer: data race (pid=10305)
Write of size 4 at 0x000001553848 by thread T1:
#0 main::$_0::operator()() const data_race.cpp:4:22 (data_race+0x4bfc81)
#1 void std::__Bind_simple<main::$_0 ()>::_M_invoke<> (std::__Index_tuple<> ) /usr/lib/gcc/x86_64-redhat-linux/4.9.2/../../../../include/c++/4.9.2/functional:1699:18 (data_race+0x4bfbf8)
#2 std::__Bind_simple<main::$_0 ()>::operator()() /usr/lib/gcc/x86_64-redhat-linux/4.9.2/../../../../include/c++/4.9.2/functional:1688:16 (data_race+0x4bfb98)
#3 std::thread::Impl<std::__Bind_simple<main::$_0 ()> >::_M_run() /usr/lib/gcc/x86_64-redhat-linux/4.9.2/../../../../include/c++/4.9.2/thread:115:13 (data_race+0x4bf94c)
#4 execute_native_thread_routine_compat /gcc-7.1.0/build/x86_64-pc-linux-gnu/libstdc++-v3/src/c++/../../../../src/libstdc++-v3/src/c++11/thread.cc:110 (libstdc++.so.6+0xb46f)
Previous write of size 4 at 0x000001553848 by main thread:
#0 main data_race.cpp:5:4 (data_race+0x4be2ce)
Location is global 'x' of size 4 at 0x000001553848 (data_race+0x000001553848)
Thread T1 (tid=10310, running) created by main thread at:
#0 pthread_create /llvm-clang-4.0.0/src/projects/compiler-rt/lib/tsan/rtl/tsan_interceptors.cc:897 (data_race+0x44f89b)
#1 __gthread_create /gcc-7.1.0/build/x86_64-pc-linux-gnu/libstdc++-v3/include/x86_64-pc-linux-gnu/bits/gthr-default.h:662 (libstdc++.so.6+0xba5b2)
#2 std::thread::_M_start_thread (std::shared_ptr<std::thread::Impl_base> , void () ) /gcc-7.1.0/build/x86_64-pc-linux-gnu/libstdc++-v3/src/c++11/thread.cc:191 (libstdc++.so.6+0xba5b2)
#3 main data_race.cpp:4:14 (data_race+0x4be2bd)
SUMMARY: ThreadSanitizer: data race data_race.cpp:4:22 in main::$_0::operator()() const
deadlock.cpp

```cpp
#include <iostream>
#include <thread>
#include <mutex>

std::mutex m0;
std::mutex m1;

void func1(int n) {
    for (auto i = n; i > 0; --i) {
        std::scoped_lock<std::mutex> l0(m0);
        std::scoped_lock<std::mutex> l1(m1);
        std::cout << "a\n";
    }
}

void func2(int n) {
    for (auto i = n; i > 0; --i) {
        std::scoped_lock<std::mutex> l1(m1);
        std::scoped_lock<std::mutex> l0(m0);
        std::cout << "b\n";
    }
}

int main() {
    std::thread t1([]{func1(10'000);});
    std::thread t2([]{func2(10'000);});
    t1.join(); t2.join();
}
```
program output (truncated):

```
WARNING: ThreadSanitizer: lock-order-inversion (potential deadlock) (pid=29188)
Cycle in lock order graph: M9 (0x00000040404240) => M10 (0x00000040404200) => M9
Mutex M10 acquired here while holding mutex M9 in thread T1:
  #0 pthread_mutex_lock ../../../../src/libsanitizer/sanitizer_common/sanitizer_common_interceptors.inc
      :3799 (libtsan.so.0+0x407ab)
  #1 __gthread_mutex_lock /include/c++/8.2.0/x86_64-pc-linux-gnu/bits/gthr-default.h:748 (deadlock+0x40166e)
  #2 std::mutex::lock() /include/c++/8.2.0/bits/std_mutex.h:103 (deadlock+0x40166e)
  #3 std::scoped_lock<std::mutex>::scoped_lock(std::mutex&) /include/c++/8.2.0/mutex:610 (deadlock+0x40166e)
  #4 func1(int) deadlock.cpp:9 (deadlock+0x4016e6)
[text deleted]
  Hint: use TSAN_OPTIONS=second_deadlock_stack=1 to get more informative warning message
Mutex M9 acquired here while holding mutex M10 in thread T2:
  #0 pthread_mutex_lock ../../../../src/libsanitizer/sanitizer_common/sanitizer_common_interceptors.inc
      :3799 (libtsan.so.0+0x407ab)
  #1 __gthread_mutex_lock /include/c++/8.2.0/x86_64-pc-linux-gnu/bits/gthr-default.h:748 (deadlock+0x401786)
  #2 std::mutex::lock() /include/c++/8.2.0/bits/std_mutex.h:103 (deadlock+0x401786)
  #3 std::scoped_lock<std::mutex>::scoped_lock(std::mutex&) /include/c++/8.2.0/mutex:610 (deadlock+0x401786)
  #4 func2(int) deadlock.cpp:16 (deadlock+0x401786)
[text deleted]
SUMMARY: ThreadSanitizer: lock-order-inversion (potential deadlock) /include/c++/8.2.0/x86_64-pc-linux-gnu/
  bits/gthr-default.h:748 in __gthread_mutex_lock
=
```
- Memory Sanitizer (MSan) detects reads from uninitialized memory
- In contrast, ASan cannot detect uninitialized reads
- Currently, MSan only supported by Clang (not GCC)
- Compiler instruments all loads/stores
- Uses bit to bit shadow mapping
- If not all code instrumented (so that not all stores are observed), false positives can result
- About 3 to 6 times slowdown
- About 2 to 3 times memory overhead
- need to enable sanitizer at compile and link time using `-fsanitize=memory` option for Clang
- environment variable `MSAN_OPTIONS` can be set to whitespace-separated list of options to control some sanitizer behavior at run time
- some sanitizer options include:
  - `strip_path_prefix`
  - `verbosity`
- for example, to set verbosity level to 2, use `MSAN_OPTIONS="verbosity=2"`
uninitialized_1.cpp

```cpp
int main(int argc, char** argv) {
    int x[2];
    x[0] = 1;
    if (x[argc % 2]) {
        return 1;
    }
}
```

program output (truncated):

```
==22595==WARNING: MemorySanitizer: use-of-uninitialized-value
    #0 0x4a46c3 in main uninitialized_1.cpp:4:6
    #1 0x7f5d3908ffdf in __libc_start_main (/lib64/libc.so.6+0x1ffdf)
    #2 0x41a77e in _start (uninitialized_1+0x41a77e)
SUMMARY: MemorySanitizer: use-of-uninitialized-value uninitialized_1.cpp:4:6 in main
Exiting
```
Undefined-Behavior Sanitizer (UBSan) detects code that results in various types of undefined behavior

some types of problems detected include:

- using misaligned or null pointer
- signed integer overflow
- conversion to, from, or between floating-point types which would overflow destination
- reaching end of value-returning function with returning value
- out of bounds array indexing where array bound can be statically determined

compiler instruments code with extra checks

supported by Clang and GCC

slowdown varies between 0% and 50%
need to enable sanitizer at compile and link time using 
\texttt{-fsanitize=undefined} option for Clang and GCC

environment variable \texttt{UBSAN\_OPTIONS} can be set to 
whitespace-separated list of options to control some sanitizer behavior at 
run time

some sanitizer options include:

- suppressions
- \texttt{strip\_path\_prefix}
- verbosity
signed_integer_overflow.cpp

```cpp
#include <iostream>
#include <limits>

int main() {
    int x = std::numeric_limits<int>::max();
    int y = x + 1;
    std::cout << y << '
';
}
```

program output:

```
signed_integer_overflow.cpp:5:14: runtime error: signed integer overflow: 2147483647 + 1 cannot be represented in type 'int'
        -2147483648
```
invalid_shift.cpp

```cpp
#include <iostream>

int main() {
    int x = 32678;
    int y = 1 << x;
    std::cout << y << '
';
}
```

**program output:**

```
invalid_shift.cpp:4:12: runtime error: shift exponent 32678 is too large for 32-bit type 'int'
0
```
Leak Sanitizer (LSan) detects memory leaks

supported by Clang and GCC

adds almost no performance overhead until end of program, at which point extra leak-detection checks performed

need to enable sanitizer at compile and link time using `-fsanitize=leak` option for Clang and GCC (or by using ASan, which includes LSan functionality)

environment variable `LSAN_OPTIONS` can be set to whitespace-separated list of options to control some sanitizer behavior at run time

some sanitizer options include:

- `strip_path_prefix`
- `verbosity`
#include <iostream>
#include <cstring>

int main() {
    char* p = new char[1024];
    std::strcpy(p, "Hello, World!\n");
    std::cout << p;
}

program output:
Hello, World!
=================================================================
==10786==ERROR: LeakSanitizer: detected memory leaks
Direct leak of 1024 byte(s) in 1 object(s) allocated from:
 #0 0x7faa5e0a7436 in operator new[](unsigned long) ../../../../src/lsan/libsanitizer/lsan/lsan_interceptors.cc:164
 #1 0x400894 in main_memory_leak.cpp:4
SUMMARY: LeakSanitizer: 1024 byte(s) leaked in 1 allocation(s).
Section 8.2.1

References

Section 8.3

Clang Static Analyzer
Clang Static Analyzer is a static analysis tool for C/C++, which is part of Clang. It supports many checks (e.g., new-delete mismatch, assigning uninitialized values, and so on). The interface is provided mainly through two programs: scan-build, which is used to invoke the static analyzer when building code, and scan-view, which is used to view results from the static analyzer. It can be used with most build processes (e.g., CMake, Make, or direct compiler invocation). There is an incurs cost of processing code with the static analyzer in addition to compilation. Static analysis can be much slower than compilation since detailed analysis of code can incur significant computational cost. The static analyzer can sometimes yield false positives. The website is https://clang-analyzer.llvm.org.
Some Supported Checks

- uninitialized arguments
- dereferencing null pointers
- division by zero
- address of stack memory that escapes function
- undefined result of binary operator
- uninitialized array subscript
- assigning uninitialized values
- uninitialized branch condition
- blocks that capture uninitialized values
- uninitialized value being returned from function
- new-delete mismatch
scan-build program allows user to run static analyzer over codebase as part of performing regular build

during project build, as source files compiled, also processed by static analyzer

upon completion of build, results can be viewed in web browser

scan-build is used to invoke command that builds code (typically CMake or Make)

only files that are compiled are analyzed

command line has following form:

```
scan-build [options] command [command_options]
```

some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-h</td>
<td>print help information and exit</td>
</tr>
<tr>
<td>-v</td>
<td>increase verbosity of output</td>
</tr>
<tr>
<td>-o target_dir</td>
<td>set output directory to <code>target_dir</code></td>
</tr>
<tr>
<td>-V</td>
<td>view analysis results in web browser</td>
</tr>
<tr>
<td>--force-analyze-debug-code</td>
<td>force assertions to be enabled</td>
</tr>
</tbody>
</table>
enabling assertions can help to reduce false positives

so advisable to either analyze project in its debug configuration or use
--force-analyze-debug-code flag of scan-build to force assertions
to be enabled

can use verbose output to debug scan-build
scan-build sets CXX and CC environment variables to Clang Static Analyzer program and then invokes user-specified command

when Clang Static Analyzer invoked, performs static analysis and then invokes real compiler to compile code

internally, uses CCC_CXX and CCC_CC environment variables (set by scan-build) to determine real compiler programs to use

can enable verbosity of static analyzer with environment variable CCC_ANALYZER_VERBOSE
Using `scan-build` With CMake

- must run CMake configure operation and build operation with `scan-build`
- all should work fine as long as `CMAKE_CXX_COMPILER` not set by CMakeLists file or on command line
- for example:
  ```
  scan-build cmake -S$SOURCE_DIR -B$BINARY_DIR
  scan-build cmake --build $BINARY_DIR
  ```
#include <iostream>

void func(int i) {
    for (int j; j < i; ++j) {
        std::cout << "hello\n";
    }
}

in above code, variable j is not initialized
**Summary** > Report 1dae28

**Bug Summary**

**File:** uninitialized_value.cpp  
**Warning:** line 4, column 16  
The left operand of '<' is a garbage value

[Report Bug]

**Annotated Source Code**

```cpp
#include <iostream>

void func(int i) {
    for (int j; j < i; ++j) {
        // 'j' declared without an initial value
        std::cout << "hello\n";
    }
}
```
void func() {
    int *ip = new int[1024];
    // ...
    delete ip;
}

- in above code, array new not paired with array delete
Summary > Report 131b66

Bug Summary

File: new_delete_mismatch.cpp
Warning: line 4, column 2
Memory allocated by 'new[]' should be deallocated by 'delete[]', not 'delete'

Report Bug

Annotated Source Code

```cpp
void func() {
    int *ip = new int[1024];

    // ...
    delete ip;
}
```

1 Memory is allocated
2 Memory allocated by 'new[]' should be deallocated by 'delete[]', not 'delete'
Section 8.3.1

References
Section 8.4

Clang-Tidy
Clang-Tidy is static analysis tool for C/C++, which is part of Clang

- supports many checks, which consider such things as:
  - correctness
  - efficiency
  - readability
  - modern style

- can automatically fix code in many cases
- by default, only small subset of checks enabled
- probably not advisable to enable all checks, since many benign warnings may result, obscuring warnings that indicate serious problems

- web site: https://clang.llvm.org/extra/clang-tidy
The `clang-tidy` Command

- command line has following form:
  ```
  clang-tidy [options] [$source_file]...
  ```

- some options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>-checks=string</code></td>
<td>specify check to include/exclude</td>
</tr>
<tr>
<td><code>-p build_path</code></td>
<td>set build path to <code>build_path</code></td>
</tr>
<tr>
<td><code>-version</code></td>
<td>print version information and exit</td>
</tr>
<tr>
<td><code>-help</code></td>
<td>print help information and exit</td>
</tr>
<tr>
<td><code>-list-checks</code></td>
<td>list all enabled checks and exit</td>
</tr>
<tr>
<td><code>-fix</code></td>
<td>apply suggested fixes</td>
</tr>
<tr>
<td><code>-fix-errors</code></td>
<td>apply suggested fixes even if compilation errors found</td>
</tr>
<tr>
<td><code>-warnings-as-errors=string</code></td>
<td>treat specified warnings as errors</td>
</tr>
</tbody>
</table>
```cpp
int func(int x) {
    if (!x) {
        return 1024 / x;
    } else {
        return x;
    }
}
```

clang-tidy output:
```
divide_by_zero.cpp:3:15: warning: Division by zero [clang-analyzer-core.DivideZero]
    return 1024 / x;
     ^
divide_by_zero.cpp:2:6: note: Assuming 'x' is 0
    if (!x) {
     ^
divide_by_zero.cpp:2:2: note: Taking true branch
    if (!x) {
     ^
divide_by_zero.cpp:3:15: note: Division by zero
    return 1024 / x;
     ^
```
New-Delete Mismatch

new_delete_mismatch.cpp

```cpp
int main() {
    char* p = new char[1024];
    delete p;
}
```

clang-tidy output:

```
new_delete_mismatch.cpp:3:2: warning: 'delete' applied to a pointer that was allocated with 'new[]'; did you mean 'delete[]'? [clang-diagnostic-mismatched-new-delete]
    delete p;
   ^
new_delete_mismatch.cpp:2:12: note: allocated with 'new[]' here
    char* p = new char[1024];
       ^
new_delete_mismatch.cpp:3:2: warning: Memory allocated by 'new[]' should be deallocated by 'delete[]', not 'delete' [clang-analyzer-unix.MismatchedDeallocator]
    delete p;
   ^
new_delete_mismatch.cpp:2:12: note: Memory is allocated
    char* p = new char[1024];
       ^
new_delete_mismatch.cpp:3:2: note: Memory allocated by 'new[]' should be deallocated by 'delete[]', not 'delete'
    delete p;
   ^
```
no_return.cpp

```cpp
int func(int x) {
    if (x >= 0) {
        return 1;
    }
}
```

clang-tidy output:

```
no_return.cpp:5:1: warning: control may reach end of non-void function
      [clang-diagnostic-return-type]
    }
^`

Copyright © 2015–2021 Michael D. Adams
Programming in C++
Version 2021-04-01
Stack Address Escapes Function

stack_address_escape.cpp

```cpp
int* p;

void test() {
    int x = 42;
    p = &x;
}
```

clang-tidy output:

```
stack_address_escape.cpp:6:1: warning: Address of stack memory associated with local variable 'x' is still referred to by the global variable 'p' upon returning to the caller. This will be a dangling reference [clang-analyzer-core.StackAddressEscape]
```

```
stack_address_escape.cpp:6:1: note: Address of stack memory associated with local variable 'x' is still referred to by the global variable 'p' upon returning to the caller. This will be a dangling reference
```
**Undefined Operand**

```cpp
int test() {
    int x;
    return x + 1;
}
```

**clang-tidy output:**

```
undefined_operand.cpp:3:11: warning: The left operand of '+' is a garbage value [clang-analyzer-core.UndefindefBinaryOperatorResult]
    return x + 1;
    ^

undefined_operand.cpp:2:2: note: 'x' declared without an initial value
    int x;
    ^

undefined_operand.cpp:3:11: note: The left operand of '+' is a garbage value
    return x + 1;
    ^
```

---

Clang Tidy With CMake

- Clang Tidy relatively easy to use with CMake
- CMake provides `CXX_CLANG_TIDY` property for targets that can be set to command to invoke for performing code checking with Clang Tidy
- Consider example to illustrate use of Clang Tidy with CMake
- Want each source file to be processed by Clang Tidy in addition to being compiled
- Project consists of three files:
  1. `CMakeLists.txt`
  2. `app.cpp`
  3. `lib.cpp`
CMakeLists.txt

```cmake
# CMakeLists File

# Clang Tidy CMake Example

# Languages
project(clang_tidy LANGUAGES CXX)

# Find clang-tidy
find_program(CLANG_TIDY_PROGRAM NAMES "clang-tidy"
             DOC "Path to clang-tidy executable")

if (CLANG_TIDY_PROGRAM)
    set(CLANG_TIDY_OPTIONS "--warnings-as-errors=*")
    set(RUN_CLANG_TIDY "${CLANG_TIDY_PROGRAM}" "${CLANG_TIDY_OPTIONS}")
endif()

# Compile and link
add_library(lib lib.cpp)
add_executable(app app.cpp lib)
set(targets lib app)

if (CLANG_TIDY_PROGRAM)
    set_target_properties(${targets} PROPERTIES CXX_CLANG_TIDY
                         "${RUN_CLANG_TIDY}")
endif()
```

lib.cpp

```c
int func() {}
char* foobar() {
    char c;
    return &c;
}
```

app.cpp

```c
int func();
char* foobar();

int main() {
    auto x = 1 / 2;
    double y = 1 / x;
    char* cp = new char[1024];
    delete cp;
    func();
    foobar();
    int i;
    return i + 1;
}
```
Section 8.4.1

References
Section 8.5

Valgrind
Valgrind is software framework that provides number of tools for dynamic analysis

- tools provided by Valgrind include:
  - Memcheck (memory error detector)
  - CacheGrind (cache and branch-prediction profiler)
  - CallGrind (call-graph generating cache and branch-prediction profiler)
  - Helgrind (thread error detector)
  - DRD (thread error detector)
  - Massif (heap profiler)
  - DHAT (dynamic heap analysis tool)

- above tools can be used to:
  - detect many memory management and threading bugs
  - profile programs in detail

- access to various Valgrind tools provided via valgrind program

Valgrind software is open source

web site: http://www.valgrind.org
Valgrind works by simulating processor in software

Valgrind does not fully support IEEE 754 (floating-point arithmetic standard)

consequently, code that uses floating-point arithmetic in particular ways may not behave correctly

do not use Valgrind with ASan, TSan, or MSan code sanitizers
unfortunately, Valgrind does not fully support IEEE 754 floating-point standard (at time of this writing, at least)

lacks support for floating-point exceptions

lacks full support for floating-point rounding modes (e.g., some instructions always use round to nearest)

consequently, code that relies on control over rounding mode will not behave correctly (e.g., code using interval arithmetic)

code using CGAL library, for example, is often problematic, due to heavy use of interval arithmetic (which needs rounding-mode control) for efficient exact geometric predicates

does not support extended floating-point formats used by some architectures

consequently, can sometimes obtain less accurate results from floating-point arithmetic (which in extreme cases might cause numerical instability)
Helgrind is Valgrind tool for detecting synchronization errors in programs that use POSIX pthreads threading primitives.

Helgrind can detect:
- misuses of POSIX pthreads API (e.g., thread exits while holding locks, recursively locking non-recursive mutex, and so on)
- potential deadlocks arising from lock ordering problems
- data races (i.e., accessing memory without adequate locking or synchronization)

Run-time overhead of Helgrind can be quite significant (e.g., slowdown of 100 times not unusual).

To run program *program* using Helgrind, use command like:
```
valgrind --tool=helgrind program
```

Helgrind described in Valgrind documentation:
#include <thread>
#include <iostream>

unsigned long count = 0;

void func() {
    for (unsigned long i = 0; i < 1’000’000; ++i) {
        ++count;
    }
}

int main() {
    std::thread t1(func);
    std::thread t2(func);
    t1.join();
    t2.join();
    std::cout << count << '\n';
}
output for command: `valgrind --tool=helgrind ./data_race_1_0`

```
[...]
==5517== Thread #3 was created
[...]
==5517== by 0x400D1E: main (data_race_1_0.cpp:14)
[...]
==5517== Thread #2 was created
[...]
==5517== by 0x400D0D: main (data_race_1_0.cpp:13)
[...]
==5517== Possible data race during read of size 8 at 0x603250 by thread #3
==5517== Locks held: none
==5517== at 0x400CD8: func() (data_race_1_0.cpp:8)
[...]
==5517== This conflicts with a previous write of size 8 by thread #2
==5517== Locks held: none
==5517== at 0x400CE3: func() (data_race_1_0.cpp:8)
[...]
==5517== Address 0x603250 is 0 bytes inside data symbol "count"
[...]
==5517== Possible data race during write of size 8 at 0x603250 by thread #3
==5517== Locks held: none
==5517== at 0x400CE3: func() (data_race_1_0.cpp:8)
[...]
==5517== This conflicts with a previous write of size 8 by thread #2
==5517== Locks held: none
==5517== at 0x400CE3: func() (data_race_1_0.cpp:8)
[...]
==5517== Address 0x603250 is 0 bytes inside data symbol "count"
[...]
==5517== For counts of detected and suppressed errors, rerun with: -v
==5517== Use --history-level=approx or =none to gain increased speed, at
==5517== the cost of reduced accuracy of conflicting-access information
==5517== ERROR SUMMARY: 2 errors from 2 contexts (suppressed: 0 from 0)
```
Memcheck is a Valgrind tool for memory error detection. It can detect certain types of invalid memory accesses:

- overrunning/underrunning heap blocks
- overrunning top of stack
- accessing memory after being freed

It can also detect certain other types of memory-related problems, such as:

- using uninitialized variables
- incorrect freeing of heap memory (e.g., double freeing heap blocks and mismatched use of `malloc/new/new[]` and `free/delete/delete[]`)
- overlapping source and destination buffers in `memcpy` and other related functions
- passing suspicious (e.g., excessively large) value to size parameter of memory allocation function
- memory leaks

The valgrind Program With Memcheck

- command line interface has following form:
  
  ```
  valgrind [options] program [program_options]
  ```

- to use Memcheck tool, must specify `--tool=memcheck` option

- some Memcheck-specific options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>--leak-check=mode</code></td>
<td>specifies mode for checking for memory leaks, where <code>mode</code> is no (disabled), summary (summary information), or yes/full (detailed information)</td>
</tr>
</tbody>
</table>
memory_leak.cpp

```cpp
int main() {
    char* buf = new char[1024];
    double* dp = new double;
    // ... (no delete or delete[])
}
```

new_delete_mismatch.cpp

```cpp
int main() {
    char* buf = new char[1024];
    // ...
    delete buf;
}
```

uninitialized_memory.cpp

```cpp
#include <iostream>

int main() {
    int i;
    std::cout << i << '
';
}
```
command:

valgrind --tool=memcheck -q --leak-check=yes ./memory_leak

output:

==15265== 8 bytes in 1 blocks are definitely lost in loss record 1 of 2
==15265== at 0x4C2E1FC: operator new(unsigned long) (vg_replace_malloc.c:334)
==15265== by 0x400611: main (memory_leak.cpp:3)
==15265==
==15265== 1,024 bytes in 1 blocks are definitely lost in loss record 2 of 2
==15265== at 0x4C2E8E9: operator new[](unsigned long) (vg_replace_malloc.c:423)
==15265== by 0x400603: main (memory_leak.cpp:2)
==15265==
Memcheck Output for new_delete_mismatch Program

command:

valgrind -q --tool=memcheck ./new_delete_mismatch

output:

==15267== Mismatched free() / delete / delete []
==15267== at 0x4C2F21A: operator delete(void*) (vg_replace_malloc.c:576)
==15267== by 0x400638: main (new_delete_mismatch.cpp:4)
==15267== Address 0x5ab4c80 is 0 bytes inside a block of size 1,024 alloc’d
==15267== at 0x4C2E8E9: operator new[](unsigned long) (vg_replace_malloc.c:423)
==15267== by 0x400623: main (new_delete_mismatch.cpp:2)
==15267==
Memcheck Output for uninitialized_memory Program

command:

```
valgrind -q --tool=memcheck ./uninitialized_memory
```

output (truncated):

```
==15266== Conditional jump or move depends on uninitialised value(s)
==15266==  at 0x4F3B8CB: std::ostreambuf_iterator<char, std::char_traits<char> > std::num_put<char, std::
  ostreambuf_iterator<char, std::char_traits<char> > >::M_insert_int<long>(std::ostreambuf_iterator<char,
  std::char_traits<char> >, std::ios_base&, char, long) const (locale_facets.tcc:874)
==15266==  by 0x4F47234: put (locale_facets.h:2371)
==15266==  by 0x4F47234: std::ostream& std::ostream::M_insert<long>(long) (ostream.tcc:73)
==15266==  by 0x400798: main (uninitialized_memory.cpp:5)
==15266==
==15266== Use of uninitialised value of size 8
==15266==  at 0x4F3B3DE: int std::__int_to_char<char, unsigned long>(char*, unsigned long, char const*, std::
  _Ios_Fmtflags, bool) (locale_facets.tcc:803)
==15266==  by 0x4F3B8F4: std::ostreambuf_iterator<char, std::char_traits<char> > std::num_put<char, std::
  ostreambuf_iterator<char, std::char_traits<char> > >::M_insert_int<long>(std::ostreambuf_iterator<char,
  std::char_traits<char> >, std::ios_base&, char, long) const (locale_facets.tcc:876)
==15266==  by 0x4F47234: put (locale_facets.h:2371)
==15266==  by 0x4F47234: std::ostream& std::ostream::M_insert<long>(long) (ostream.tcc:73)
==15266==  by 0x400798: main (uninitialized_memory.cpp:5)
==15266==
==15266== Conditional jump or move depends on uninitialised value(s)
==15266==  at 0x4F3B3DE: int std::__int_to_char<char, unsigned long>(char*, unsigned long, char const*, std::
  _Ios_Fmtflags, bool) (locale_facets.tcc:806)
==15266==  by 0x4F3B8F4: std::ostreambuf_iterator<char, std::char_traits<char> > std::num_put<char, std::
  ostreambuf_iterator<char, std::char_traits<char> > >::M_insert_int<long>(std::ostreambuf_iterator<char,
  std::char_traits<char> >, std::ios_base&, char, long) const (locale_facets.tcc:876)
==15266==  by 0x4F47234: put (locale_facets.h:2371)
==15266==  by 0x4F47234: std::ostream& std::ostream::M_insert<long>(long) (ostream.tcc:73)
==15266==  by 0x400798: main (uninitialized_memory.cpp:5)
==15266==
```
Massif is Valgrind tool for performing heap profiling
measures how much heap memory program uses, including both useful space and extra bytes allocated for bookkeeping and alignment
can optionally measure size of program stack
can use to determine how memory consumption evolves over lifetime of program as well as peak memory usage
Massif tool of Valgrind accessed via valgrind program
running program with Massif tool generates output file containing heap profiling information
output file can be analyzed with various tools, such as ms_print and Massif Visualizer
The valgrind Command with Massif

- command line interface has following form:
  
  valgrind [options] program [program_options]

- to use Massif tool, must specify --tool=massif option

- some Massif-specific options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>--massif-out-file=file</td>
<td>sets output file to file; defaults to massif.out-$pid where $pid is process ID</td>
</tr>
<tr>
<td>--stacks=flag</td>
<td>specifies whether stack profiling should be performed, where flag is true or false</td>
</tr>
<tr>
<td>--time-unit=unit</td>
<td>specifies time unit for profiling, where unit is i (instructions), ms (time), or B (bytes)</td>
</tr>
</tbody>
</table>
Valgrind software includes program called `ms_print` for analyzing Massif data files

`ms_print` output is text based

GUI-based tools also available for analyzing Massif data files, such as Massif Visualizer

Massif Visualizer is accessible via `massif-visualizer` program

Massif Visualizer web site:

[https://github.com/KDE/massif-visualizer](https://github.com/KDE/massif-visualizer)
source code for `heap_1` program:

```cpp
#include <algorithm>
#include <cstdlib>
#include <iostream>
#include <numeric>
#include <vector>

int main() {
    std::size_t size = 1;
    while (size < 1’000’000) {
        std::vector<float> v;
        v.reserve(size);
        std::generate_n(std::back_inserter(v), size,
                        []() -> float {return drand48();});
        auto sum = std::accumulate(v.begin(), v.end(), 0.0f);
        std::cout << sum / size << '
';
        size <<= 1;
    }
}
```

command to invoke Massif tool for `heap_1` program:

```
valgrind --tool=massif --massif-out-file=profile.massif --stacks=yes ./heap_1
```
Massif Example: \texttt{ms\_print} Output

command:
\begin{verbatim}
ms_print --x=70 --y=10 profile.massif
\end{verbatim}

output (truncated):

\begin{verbatim}
Command:  ./heap_1
Massif arguments:  --massif-out-file=profile.massif --stacks=yes
ms_print arguments:  --x=70 --y=10 profile.massif

MB
2.071^ ##
| # :::::::::::::::::::::: @ :::::: @:::
| # :: : ::::::::::::::::: @ :::::: @:::
| # :: : ::::::::::::::::: @ :::::: @:::
| # :: : ::::::::::::::::: @ :::::: @:::
| @:::@::::@ :::::::# :: : ::::::::::::::::: @ :::::: @:::
| @: :@::::@::: :: # :: : ::::::::::::::::: @ :::::: @:::
| @: :@::::@::: :: # :: : ::::::::::::::::: @ :::::: @:::
| @ :::::: @:@: :@::::@::: :: # :: : ::::::::::::::::: @ :::::: @:::
| ::::@:::: :@:@: :@::::@::: :: # :: : ::::::::::::::::: @ :::::: @:::
\end{verbatim}

0 +--------------------------------------------------------------------->Mi
0 312.7

Number of snapshots: 71
Detailed snapshots: [8, 14, 16, 19, 24, 31 (peak), 55, 65]

\begin{verbatim}
\begin{tabular}{rrrrrr}
 n & time(i) & total(B) & useful-heap(B) & extra-heap(B) & stacks(B) \\
 0 & 0 & 0 & 0 & 0 & 0 \\
 1 & 5,653,795 & 90,704 & 90,112 & 24 & 568 \\
 2 & 9,989,271 & 139,760 & 139,264 & 24 & 472 \\
 3 & 15,104,837 & 205,296 & 204,800 & 24 & 472 \\
 4 & 19,380,693 & 205,296 & 204,800 & 24 & 472 \\
 5 & 25,946,699 & 335,296 & 335,872 & 24 & 400 \\
 6 & 30,435,811 & 335,296 & 335,872 & 24 & 400 \\
\end{tabular}
\end{verbatim}
Massif-Visualizer Example: Tool Output

command:

massif-visualizer profile.massif

output:

```
Total Memory Heap Consumption
in 1 place, below massif's threshold
_GLOBAL__sub_I_eh_alloc.cc
-gnu_cxx::new_allocator<float>::allo...
```
Section 8.5.1

References
Section 8.6

Gcov and LLVM Cov
Gcov is code coverage analysis tool, which is part of GCC software intended to be used in conjunction with GCC compiler. It supports measurement of function, statement, and decision (i.e., branch) coverage. It can be used to assess test coverage and possibly as a guide for improving efficiency of code. In order to generate data for Gcov, the program being run must be properly instrumented. The compiler instruments code to count the number of times each basic block (i.e., node in control-flow graph) and each branch (i.e., edge in control-flow graph) executes. When the program runs, coverage data files are generated. Coverage data files can then be processed and displayed with Gcov. The web site is: https://gcc.gnu.org/onlinedocs/gcc/Gcov.html.
- The `gcov` Program
  - can examine data files produced by execution of compiler-instrumented code by using `gcov` program
  - command line interface for `gcov` has following form:
    ```
    gcov [options] [$file]...
    ```
  - `$file` is source file for which coverage information desired or corresponding object file
  - some commonly-used options include:
    | Option | Description |
    |--------|-------------|
    | `-a`   | write individual execution counts for every basic block |
    | `-b`   | write branch frequencies/counts to output file |
    | `-c`   | use branch counts instead of frequencies |
    | `-m`   | use demangled function names in output |
    | `-h`   | print help information and exit |
Using Gcov

1. build each program for which code coverage information is desired
   - must compile and link with `--coverage` option with GCC
   - one block-graph description file (with `.gcno` extension) generated for each object file produced during compilation and placed in same directory as corresponding object file

2. run each program for which coverage information is desired one or more times
   - when program exits, one count file (with `.gcda` extension) generated for each object file associated with program
   - if output file does not yet exist, file created
   - if output file already exists, statistics are added to those already there
   - that is, statistics maintained in data files are cumulative

3. run `gcov` program to format data for display
   - for each source file with corresponding coverage data file, `gcov` generates `source_file.gcov` (or transformed version of this name) for `source_file.cpp`
optimization and inline functions can cause strange behaviors in coverage statistics

for example, optimization can cause multiple lines of code to be merged together, which will lead to unusual results for affected lines

for above reasons, desirable to disable optimization (including function inlining) when performing coverage analysis

exceptions can introduce many additional conditional branches, which may be undesirable when performing branch-coverage analysis

consequently, when performing branch-coverage analysis, may be desirable to disable exceptions if not used
```cpp
#include <cstdlib>
#include <iostream>
#include "utility.hpp"

int main(int argc, char** argv) {
    if (argc < 2) {
        return 1;
    }
    double x = std::atof(argv[1]);
    std::cout << signum(x) << '\n';
}
```

utility.hpp

```cpp
int signum(double x);
```

signum.cpp

```cpp
#include "utility.hpp"
int signum(double x) {
    if (x > 0) {
        return 1;
    } else if (x < 0) {
        return -1;
    } else {
        return 0;
    }
}
```
Signum Example: Using Gcov

- build program app using GCC, ensuring that --coverage option is used for both compiling and linking; for example, use command sequence like:
  ```
g++ -O0 --coverage -c app.cpp
  g++ -O0 --coverage -c signum.cpp
  g++ -O0 --coverage -o app app.o signum.o
  ```

- run app program twice as follows:
  ```
  ./app 0
  ./app 1
  ```

- since app program run twice, statistics are accumulated from both runs of program

- run Gcov; for example, use command like:
  ```
gcov -b -c -m app.o signum.o
  ```

- view resulting .gcov files (examples of which are given on following slides)
Signum Example: Gcov Output [app.cpp.gcov]

```cpp
#include <cstdlib>
#include <iostream>
#include "utility.hpp"

int main(int argc, char** argv) {
  if (argc < 2) {
    return 1;
  }
  double x = std::atof(argv[1]);
  std::cout << signum(x) << 'n';
}

main: function main called 2 returned 100% blocks executed 86%
main: function main called 2 returned 100% blocks executed 86%
```
function signum(double) called 2 returned 100% blocks executed 83%

2: int signum(double x) {
  3:   if (x > 0) {
    branch 0 taken 1 (fallthrough)
  4:     return 1;
    branch 1 taken 1
  5:   } else if (x < 0) {
    branch 0 taken 0 (fallthrough)
  6:     return -1;
    branch 1 taken 1
  7:   } else {
    8:     return 0;
  9:   }
LLVM Cov is code coverage analysis tool, which is part of LLVM software, intended for use with Clang compiler

supports measurement of function, statement, and decision (i.e., branch) coverage

manner in which coverage information collected similar to case of Gcov

LLVM Cov provided as program called `llvm-cov`

coverage data files produced by compiler and program execution processed with `gcov subcommand of llvm-cov`

`gcov subcommand of llvm-cov` has very similar interface as `gcov` program (of Gcov)

build program app using Clang, ensuring that --coverage option is used for both compiling and linking; for example, use command sequence like:

```
clang++ -O0 --coverage -c app.cpp
clang++ -O0 --coverage -c signum.cpp
clang++ -O0 --coverage -o app app.o signum.o
```

run app program twice as follows:

```
./app 0
./app 1
```

since app program run twice, statistics are accumulated from both runs of program

run LLVM Cov; for example, use command like:

```
llvm-cov gcov -b -c app.o signum.o
```

view resulting .gcov files (which look similar to ones produced by Gcov; see earlier Gcov example)
Lcov is graphical front end for Gcov
collects Gcov data from multiple source files and creates HTML pages containing source code annotated with coverage information
also provides overview pages for easy navigation
Lcov supports statement, function, and decision (i.e., branch) coverage measurement
web site: http://ltp.sourceforge.net/coverage/lcov.php
The `lcov` Program: Capture

- to capture (i.e., import) coverage data from data files generated by executing instrumented code, `lcov` has following command-line interface:
  ```
  lcov -c [options]
  ```

- some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>--gcov-tool path</code></td>
<td>set location of Gcov program to <code>path</code></td>
</tr>
<tr>
<td><code>--rc keyword=value</code></td>
<td>set configuration parameter <code>keyword</code> to <code>value</code></td>
</tr>
<tr>
<td><code>-o file</code></td>
<td>write trace data to file <code>file</code></td>
</tr>
<tr>
<td><code>--no-external</code></td>
<td>do not capture coverage data from external source files</td>
</tr>
<tr>
<td><code>-d dir</code></td>
<td>search for <code>.da</code> files in directory <code>dir</code></td>
</tr>
<tr>
<td><code>-h</code></td>
<td>print help information and exit</td>
</tr>
<tr>
<td><code>-q</code></td>
<td>do not print progress messages</td>
</tr>
</tbody>
</table>
Lcov relies on external program to process information in coverage data files

external program must have similar command-line interface and behavior as gcov

external program used for above functionality controlled by --gcov-tool option of lcov

if using GCC, external program can simply be gcov

if using Clang, however, need to invoke gcov subcommand of llvm-cov through wrapper program to provide expected interface

this can be accomplished by creating file containing following shell script and then specifying this file to lcov via --gcov-tool option:

```
#!/usr/bin/env bash
exec llvm-cov gcov "$@
```
to display summary information from tracefile, `lcov` has following command-line interface:

```
lcov --summary [options]
```

some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>--rc keyword=value</code></td>
<td>set configuration parameter <code>keyword</code> to <code>value</code></td>
</tr>
</tbody>
</table>
coverage report can be generated in HTML format from one or more trace files with \texttt{genhtml} program, which has following command-line interface:

\begin{verbatim}
genhtml [options] $trace_file...
\end{verbatim}

some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>--legend</td>
<td>include legend in report</td>
</tr>
<tr>
<td>--branch-coverage</td>
<td>include branch coverage information in report</td>
</tr>
<tr>
<td>-o \textit{dir}</td>
<td>set output directory for HTML document to \textit{dir}</td>
</tr>
<tr>
<td>-h</td>
<td>print help information and exit</td>
</tr>
</tbody>
</table>
Using Lcov

1. build project with GCC or Clang, ensuring that --coverage option is used for compiling and linking (as in earlier Gcov example)

2. run program (one or more times) to collect coverage data (e.g., as in earlier Gcov or LLVM Cov examples)

3. process coverage data with Lcov; for example, use command like following (where coverage data files under current directory):

   ```bash
   lcov -c --gcov-tool $gcov_tool -d . -o coverage.lcov \ 
   --rc lcov_branch_coverage=1
   ```

   where $gcov_tool is gcov for GCC or pathname of wrapper script shown earlier for Clang

4. if HTML output desired, generate output using genhtml; for example, use command like following:

   ```bash
   genhtml --branch-coverage --legend -o output coverage.lcov
   ```

   (main HTML document accessible via output/index.html)

5. if plaintext output desired, brief summary can be generated from tracefile using command like:

   ```bash
   lcov --summary coverage.lcov --rc lcov_branch_coverage=1
   ```
Reading tracefile coverage.lcov
Summary coverage rate:
  lines.......: 83.3% (10 of 12 lines)
  functions...: 100.0% (2 of 2 functions)
  branches....: 66.7% (4 of 6 branches)
## LCOV - code coverage report

Current view: **top level - signum**

<table>
<thead>
<tr>
<th>Test</th>
<th>coverage.info</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>2018-09-19 14:58:31</td>
</tr>
</tbody>
</table>

Legend: Rating: low: < 75 %  medium: >= 75 %  high: >= 90 %

<table>
<thead>
<tr>
<th></th>
<th>Hit</th>
<th>Total</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lines</td>
<td>10</td>
<td>12</td>
<td>83.3 %</td>
</tr>
<tr>
<td>Functions</td>
<td>2</td>
<td>2</td>
<td>100.0 %</td>
</tr>
<tr>
<td>Branches</td>
<td>4</td>
<td>6</td>
<td>66.7 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Filename</th>
<th>Line Coverage</th>
<th>Functions</th>
<th>Branches</th>
</tr>
</thead>
<tbody>
<tr>
<td>app.cpp</td>
<td>83.3 %</td>
<td>100.0 %</td>
<td>50.0 %</td>
</tr>
<tr>
<td>signum.cpp</td>
<td>83.3 %</td>
<td>100.0 %</td>
<td>75.0 %</td>
</tr>
</tbody>
</table>

Generated by: **LCOV version 1.13-15-g94eac0e**
### LCOV - code coverage report

Current view: **top level - signum - app.cpp (source / functions)**

**Test:** coverage.info  
**Date:** 2018-09-19 14:58:31  
**Legend:** Lines: hit | not hit | Branches: + taken | - not taken | # not executed

<table>
<thead>
<tr>
<th>Branch data</th>
<th>Line data</th>
<th>Source code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>: #include &lt;cstdlib&gt;</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>: #include &lt;iostream&gt;</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>: #include &quot;utility.hpp&quot;</td>
</tr>
<tr>
<td>4</td>
<td>2 :</td>
<td>: int main(int argc, char** argv) {</td>
</tr>
<tr>
<td></td>
<td>[ - + ]</td>
<td>2 : if (argc &lt; 2) {</td>
</tr>
<tr>
<td>5</td>
<td>0 :</td>
<td>0 : return 1;</td>
</tr>
<tr>
<td>6</td>
<td>:</td>
<td>}</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>2 : double x = std::atof(argv[1]);</td>
</tr>
<tr>
<td>8</td>
<td>2 :</td>
<td>2 : std::cout &lt;&lt; signum(x) &lt;&lt; '\n';</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>2 : }</td>
</tr>
</tbody>
</table>

**Lines:** 5 / 6 | **Coverage:** 83.3 %  
**Functions:** 1 / 1 | **Coverage:** 100.0 %  
**Branches:** 1 / 2 | **Coverage:** 50.0 %

*Generated by:* LCOV version 1.13-15-g94eac0e*
LCOV - code coverage report

Current view: top level - signum - signum.cpp (source / functions)

Test: coverage.info
Date: 2018-09-19 14:58:31

Legend: Lines: hit not hit | Branches: + taken - not taken # not executed

<table>
<thead>
<tr>
<th>Branch data</th>
<th>Line data</th>
<th>Source code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>: #include &quot;utility.hpp&quot;</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>: 2: int signum(double x) {</td>
</tr>
<tr>
<td>[ + + ]</td>
<td>3</td>
<td>2: if (x &gt; 0) {</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>1: return 1;</td>
</tr>
<tr>
<td>[ - + ]</td>
<td>5</td>
<td>1: } else if (x &lt; 0) {</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>0: return -1;</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>} else {</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>1: return 0;</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>}</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>}</td>
</tr>
</tbody>
</table>

Generated by: LCOV version 1.13-15-g94eac0e
some potentially unexpected behaviors may be observed when using Lcov

branches may be shown to be present at what might be unexpected places in code, due to implicit control flow associated with *short-circuit evaluation* or exception handling

constructors or destructors that have been called may be reported as never having been called, due to compiler implementing *constructors* and *destructors* in manner similar to that specified in Itanium C++ ABI

counts for different instantiations of same template are aggregated

some functions associated with static initialization that have been called are reported as never having been called (probably due to bug)
main.cpp

```cpp
#include "utility.hpp"

int main() {
  Widget<int> wi(42);
  wi.get();
  Widget<double> wd(42.0);
  wd.get();
  abs(42);
  abs(42.0);
}
```

utility.hpp

```cpp
template <class T> class Widget {
public:
  Widget (T x) : x_(x) {}  
  T get() const {
    return x_;  
  }  
private:
  T x_;  
};

template <class T> T abs(T x) {
  if (x < 0) {
    return -x;
  } else {
    return x;
  }
}  
```
function main called 1 returned 100% blocks executed 100%
function main called 1 returned 100% blocks executed 100%
function main called 1 returned 100% blocks executed 100%
function main called 1 returned 100% blocks executed 100%

1: 3: int main() {
1: 4: Widget<int> wi(42);
call 0 returned 1
1: 5: wi.get();
call 0 returned 1
1: 6: Widget<double> wd(42.0);
call 0 returned 1
1: 7: wd.get();
call 0 returned 1
1: 8: abs(42);
call 0 returned 1
1: 9: abs(42.0);
call 0 returned 1
1: 10:}
```cpp
template <class T> class Widget {
  public:
    Widget (T x) : x_(x) {}------------------
  Widget <double>:: Widget (double);
  function Widget <double>:: Widget (double) called 1 returned 100% blocks executed 100%
  1: 3: Widget (T x) : x_(x) {}
    Widget <int>:: Widget (int);
  function Widget <int>:: Widget (int) called 1 returned 100% blocks executed 100%
  1: 3: Widget (T x) : x_(x) {}
    2: 4: T get () const {
      2: 5: return x_;
      }------------------
    Widget <double>:: get () const:
  function Widget <double>:: get () const called 1 returned 100% blocks executed 100%
  1: 4: T get () const {
    1: 5: return x_;
    }------------------
  Widget <int>:: get () const:
  function Widget <int>:: get () const called 1 returned 100% blocks executed 100%
  1: 4: T get () const {
    1: 5: return x_;
    }------------------
  private:
    T x_;}
```

```cpp
2: 11: template <class T> T abs(T x) {
2: 12: if (x < 0) {
    13: return -x;
2: 14: } else {
    15: return x;
    }------------------
    16: }
    17:}
```
## LCOV - code coverage report

**Current view:** top_level - templates_1 - main.cpp (source / functions)

**Test:** total.lcov  
**Date:** 2018-11-22 19:18:28  
**Legend:** Lines: hit not hit

<table>
<thead>
<tr>
<th>Line data</th>
<th>Source code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>#include &quot;utility.hpp&quot;</td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1: int main() {</td>
</tr>
<tr>
<td>4</td>
<td>1: Widget&lt;int&gt; wi(42);</td>
</tr>
<tr>
<td>5</td>
<td>1: wi.get();</td>
</tr>
<tr>
<td>6</td>
<td>1: Widget&lt;double&gt; wd(42.0);</td>
</tr>
<tr>
<td>7</td>
<td>1: wd.get();</td>
</tr>
<tr>
<td>8</td>
<td>1: abs(42);</td>
</tr>
<tr>
<td>9</td>
<td>1: abs(42.0);</td>
</tr>
<tr>
<td>10</td>
<td>1: }</td>
</tr>
</tbody>
</table>

Generated by: LCOV version 1.13-16-ge675080
LCOV - code coverage report

Current view: top level - templates_1 - utility.hpp (source / functions)

Test: total.lcov
Date: 2018-11-22 19:18:28

Legend: Lines: hit not hit

<table>
<thead>
<tr>
<th>Line data</th>
<th>Source code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>: template &lt;class T&gt; class Widget {</td>
</tr>
<tr>
<td>2</td>
<td>: public:</td>
</tr>
<tr>
<td>3</td>
<td>2 : Widget (T x) : x_(x) {}</td>
</tr>
<tr>
<td>4</td>
<td>2 : T get() const {</td>
</tr>
<tr>
<td>5</td>
<td>2 : return x_;</td>
</tr>
<tr>
<td>6</td>
<td>: }</td>
</tr>
<tr>
<td>7</td>
<td>1 : private:</td>
</tr>
<tr>
<td>8</td>
<td>1 : T x_;</td>
</tr>
<tr>
<td>9</td>
<td>: }</td>
</tr>
<tr>
<td>10</td>
<td>1 :</td>
</tr>
<tr>
<td>11</td>
<td>1 : template &lt;class T&gt; T abs(T x) {</td>
</tr>
<tr>
<td>12</td>
<td>: if (x &lt; 0) {</td>
</tr>
<tr>
<td>13</td>
<td>: return -x;</td>
</tr>
<tr>
<td>14</td>
<td>: } else {</td>
</tr>
<tr>
<td>15</td>
<td>: return x;</td>
</tr>
<tr>
<td>16</td>
<td>: }</td>
</tr>
<tr>
<td>17</td>
<td>2 : }</td>
</tr>
</tbody>
</table>

Generated by: LCOV version 1.13-16-ge675080

Exceptions Example: Source Code

main.cpp

```cpp
#include <vector>
#include "utility.hpp"

void increment_3(int& i) noexcept { ++i; }
void increment_4(int& i) { ++i; }

int main() {
    std::vector<int> u;
    std::vector<int> v{1, 2, 3, 4};
    u = v;
    increment_1(u[0]);
    increment_2(u[0]);
    increment_3(u[0]);
    increment_4(u[0]);
}
```

utility.hpp

```cpp
void increment_1(int&) noexcept;
void increment_2(int&);
```

utility.cpp

```cpp
#include "utility.hpp"

void increment_1(int& i) noexcept { ++i; }
void increment_2(int& i) { ++i; }
```
Exceptions Example: Gcov Output

```
-: 0:Source:main.cpp
-: 0:Programs:2
-: 1:#include <vector>
-: 2:#include "utility.hpp"
-: 3:
-: 4: void increment_3(int i) noexcept {++i;}
--------------
increment_3(int):
function increment_3(int) called 1 returned 100% blocks executed 100%
--------------
increment_3(int):
function increment_3(int) called 1 returned 100% blocks executed 100%
--------------
increment_3(int):
function increment_3(int) called 1 returned 100% blocks executed 100%
--------------
increment_3(int):
function increment_3(int) called 1 returned 100% blocks executed 100%
--------------
increment_4(int): 5: void increment_4(int i) {++i;}
increment_4(int):
function increment_4(int) called 1 returned 100% blocks executed 100%
--------------
increment_4(int):
function increment_4(int) called 1 returned 100% blocks executed 100%
--------------
-: 6:
-: 7: int main() {
-: 8:    std::vector<int> u;
-: call 0 returned 1
-: call 1 returned 1
-: call 2 never executed
-: call 0 returned 1
-: call 1 returned 1
-: branch 2 taken 1 (fallthrough)
-: branch 3 taken 0 (throw)
-: call 4 returned 1
-: call 5 never executed
-: branch 10: u = v;
-: call 0 returned 1
-: branch 1 taken 1 (fallthrough)
-: branch 2 taken 0 (throw)
-: branch 11: increment_1(u[0]);
-: call 0 returned 1
-: call 1 returned 1
-: call 0 returned 1
-: call 1 returned 1
-: branch 2 taken 1 (fallthrough)
-: branch 3 taken 0 (throw)
-: branch 12: increment_2(u[0]);
-: call 0 returned 1
-: call 1 returned 1
-: call 0 returned 1
-: call 1 returned 1
-: branch 13: increment_3(u[0]);
-: call 0 returned 1
-: call 1 returned 1
-: call 0 returned 1
-: call 1 returned 1
-: branch 14: increment_4(u[0]);
-: call 0 returned 1
-: call 1 returned 1
-: branch 15:
--------------
main:
function main called 1 returned 100% blocks executed 72%
main:
function main called 1 returned 100% blocks executed 72%
```
Exceptions Example: Gcov Output

utility.cpp.gcov

-: 0:Source:utility.cpp
-: 0:Programs:2
-: 1:#include "utility.hpp"
-: 2:
function increment_1(int&) called 1 returned 100% blocks executed 100%
1: 3:void increment_1(int& i) noexcept {++i;}
function increment_2(int&) called 1 returned 100% blocks executed 100%
1: 4:void increment_2(int& i) {++i;}

Copyright © 2015–2021 Michael D. Adams
Programming in C++
Version 2021-04-01
## LCOV - code coverage report

**Current view:** top level - exceptions_1  
**Test:** coverage.info  
**Date:** 2018-09-20 18:48:59  
**Legend:** Rating: low: < 75 % | medium: >= 75 % | high: >= 90 %  

<table>
<thead>
<tr>
<th>Filename</th>
<th>Line Coverage</th>
<th>Functions</th>
<th>Branches</th>
</tr>
</thead>
<tbody>
<tr>
<td>main.cpp</td>
<td>100.0 %</td>
<td>100.0 %</td>
<td>50.0 %</td>
</tr>
<tr>
<td>utility.cpp</td>
<td>100.0 %</td>
<td>100.0 %</td>
<td>-</td>
</tr>
</tbody>
</table>

**Generated by:** LCOV version 1.13-15-g94eac0e
## LCOV - code coverage report

**Current view:** top level - exceptions_1 - main.cpp (source / functions)

**Test:** coverage.info

**Date:** 2018-09-20 18:48:59

**Legend:**
- Lines: hit not hit
- Branches: + taken - not taken # not executed

<table>
<thead>
<tr>
<th>Branch data</th>
<th>Line data</th>
<th>Source code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>: #include <code>&lt;vector&gt;</code></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>: #include &quot;utility.hpp&quot;</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>:</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>: void increment_3(int&amp; i) noexcept {++i;}</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>: void increment_4(int&amp; i) {++i;}</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>:</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>: int main() {</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>: std::vector&lt;int&gt; u;</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>: std::vector&lt;int&gt; v{1, 2, 3, 4};</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>: u = v;</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>: increment_1(u[0]);</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>: increment_2(u[0]);</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>: increment_3(u[0]);</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>: increment_4(u[0]);</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>: }</td>
</tr>
</tbody>
</table>

**Lines:** 11/11 (100.0 %)

**Functions:** 3/3 (100.0 %)

**Branches:** 3/6 (50.0 %)

Generated by: LCOV version 1.13-15-g94eac0e
### LCOV - code coverage report

**Current view:** top level - exceptions_1 - utility.cpp (source / functions)

<table>
<thead>
<tr>
<th>Test</th>
<th>coverage.info</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>2018-09-20 18:48:59</td>
</tr>
</tbody>
</table>

#### Legend:
- Lines: hit | not hit
- Branches: + taken | - not taken | # not executed

<table>
<thead>
<tr>
<th>Branch data</th>
<th>Line data</th>
<th>Source code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>: #include &quot;utility.hpp&quot;</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>:</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>: 1 : void increment_1(int&amp; i) noexcept {++i;}</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>: 1 : void increment_2(int&amp; i) {++i;}</td>
</tr>
</tbody>
</table>

**Generated by:** LCOV version 1.13-15-g94eac0e

---

**Copyright © 2015–2021 Michael D. Adams**

**Programming in C++**

**Version 2021-04-01**

---
```cpp
class Flag {
public:
  explicit Flag(bool b = false) noexcept : b_(b) {}
  explicit operator bool() const noexcept { return b_;

  Flag operator&&(const Flag& other) noexcept {
    return Flag(b_ && other.b_);
  }

  Flag operator||(const Flag& other) noexcept {
    return Flag(b_ || other.b_);
  }

private:
  bool b_;}
```
**Short-Circuiting Example: Source Code**

```cpp
#include <tuple>
#include "utility.hpp"

bool func(bool a, bool b, bool c) noexcept {
    return (a || b) && c;
}

Flag func(Flag a, Flag b, Flag c) noexcept {
    return (a || b) && c;
}

int main() {
    std::tuple<bool, bool, bool> tests[] = {{0, 0, 0}, {1, 1, 1}};
    for (auto&& [a, b, c] : tests) {
        func(a, b, c);
        func(Flag(a), Flag(b), Flag(c));
    }
}
```
LCOV - code coverage report

Current view: top level - decision - main.cpp (source / functions)

Test: coverage.info

Date: 2018-09-20 20:16:20

Legend: Lines: hit not hit | Branches: + taken - not taken # not executed

Lines: 10 10 100.0 %
Functions: 3 3 100.0 %
Branches: 6 8 75.0 %

1: #include <tuple>
2: #include "utility.hpp"
4: 2: bool func(bool a, bool b, bool c) noexcept {
5: [ + ++ ] [ - + ]:
6: [ + - ]:
7:
8: 2: Flag func(Flag a, Flag b, Flag c) noexcept {
9: 2: return (a || b) && c;
10:
11:
12: 1: int main() {
13: 1: std::tuple<bool, bool, bool> tests[] = {{0, 0, 0}, {1, 1, 1}};
14: [ + ++ ]:
15: 3: for (auto& [a, b, c] : tests) {
16: 2:
17: 2: func(a, b, c);
18: 2: func(Flag(a), Flag(b), Flag(c));
19: 1: }

Generated by: LCOV version 1.13-15-g94eac0e
# LCOV - code coverage report

**Current view:** top level - decision - utility.hpp (source / functions)

**Test:** coverage.info  
**Date:** 2018-09-20 20:16:20

<table>
<thead>
<tr>
<th>Lines:</th>
<th>Hit</th>
<th>Total</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5</td>
<td>5</td>
<td>100.0 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Functions:</th>
<th>Hit</th>
<th>Total</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>3</td>
<td>3</td>
<td>100.0 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Branches:</th>
<th>Hit</th>
<th>Total</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>8</td>
<td>8</td>
<td>75.0 %</td>
</tr>
</tbody>
</table>

```cpp
1  : class Flag {
2  :
3  :   explicit Flag(bool b = false) noexcept : b_(b) {}  
4  :
5  :   explicit operator bool() const noexcept {return b_;}
6  :  [ + + ][ + - ]:
7  :   2 : Flag operator||(const Flag& other) noexcept {
8  :  [ + + ][ - + ]:
9  :   2 : Flag operator&&(const Flag& other) noexcept {
10 :  [ + + ][ - + ]:
11 :   2 : return Flag(b_ || other.b_);  
12 :  :
13 :   2 : return Flag(b_ && other.b_);  
14 :  :
15 :   2 : private:
16 :   2 :   bool b_;  
17 :   2 :};
```

*Generated by: LCOV version 1.13-15-g94eac0e*
example_1_1.cpp

```cpp
struct Gadget {
    Gadget();
    virtual ~Gadget();
};
Gadget::Gadget() {}
Gadget::~Gadget() {}

struct Widget : Gadget {
    Widget();
    virtual ~Widget();
};
Widget::Widget() {}
Widget::~Widget() {}

int main() {
    Widget w;
}
```
**Virtual Destructor Example 1A: Lcov Output**

**LCOV - code coverage report**

<table>
<thead>
<tr>
<th>Function Name</th>
<th>Hit count</th>
</tr>
</thead>
<tbody>
<tr>
<td>_ZN6GadgetD0Ev</td>
<td>0</td>
</tr>
<tr>
<td>ZN6WidgetD0Ev</td>
<td>0</td>
</tr>
<tr>
<td>_ZN6GadgetC2Ev</td>
<td>1</td>
</tr>
<tr>
<td>_ZN6GadgetD2Ev</td>
<td>1</td>
</tr>
<tr>
<td>_ZN6WidgetC2Ev</td>
<td>1</td>
</tr>
<tr>
<td>_ZN6WidgetD2Ev</td>
<td>1</td>
</tr>
<tr>
<td>main</td>
<td>1</td>
</tr>
</tbody>
</table>

*Generated by: LCOV version 1.13-16-ge675080*

- **_ZN6GadgetD0Ev** is mangled name for deleting destructor variant (in Itanium C++ ABI) of Gagdet::~Gagdet()
- **_ZN6WidgetD0Ev** is mangled name for deleting destructor variant (in Itanium C++ ABI) of Widget::~Widget()
struct Gadget {
    Gadget();
    virtual ~Gadget();
};
Gadget::Gadget() {}
Gadget::~Gadget() {}

struct Widget : Gadget {
    Widget();
    virtual ~Widget();
};
Widget::Widget() {}
Widget::~Widget() {}

int main() {
    Widget w;
    Widget* wp = new Widget;
    delete wp;
    // invoke deleting destructor (Itanium C++ ABI)
    Gadget* gp = new Gadget;
    delete gp;
    // invoke deleting destructor (Itanium C++ ABI)
}
## LCOV - code coverage report

Current view: **top level - example_1 - example_1_2.cpp** (source / functions)

<table>
<thead>
<tr>
<th>Test</th>
<th>total.lcov</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>2018-11-22 15:23:27</td>
</tr>
</tbody>
</table>

**Legend:** Lines: hit  not hit

<table>
<thead>
<tr>
<th>Function Name</th>
<th>Hit count</th>
</tr>
</thead>
<tbody>
<tr>
<td>_ZN6GadgetD0Ev</td>
<td>1</td>
</tr>
<tr>
<td>_ZN6WidgetD0Ev</td>
<td>1</td>
</tr>
<tr>
<td>main</td>
<td>1</td>
</tr>
<tr>
<td>_ZN6WidgetC2Ev</td>
<td>2</td>
</tr>
<tr>
<td>_ZN6WidgetD2Ev</td>
<td>2</td>
</tr>
<tr>
<td>_ZN6GadgetC2Ev</td>
<td>3</td>
</tr>
<tr>
<td>_ZN6GadgetD2Ev</td>
<td>3</td>
</tr>
</tbody>
</table>

Generated by: **LCOV version 1.13-16-ge675080**

- **_ZN6GagdetD0Ev** is now called (unlike previously)
- **_ZN6WidgetD0Ev** is now called (unlike previously)
Gcov and Lcov somewhat tricky to use with CMake

one very convenient way to collect coverage information with CMake is by using CodeCoverage module developed by Lars Bilke, which can be obtained from:


slightly modified version of above module can be found at:

```cmake
# Gcov/Lcov CMake Example: CMakeLists File

CMakeLists.txt

1 cmake_minimum_required(VERSION 3.1 FATAL_ERROR)
2 project(coverage_example LANGUAGES CXX C)
3 option(ENABLE_COVERAGE "Enable coverage" false)
4 set(CMAKE_VERBOSE_MAKEFILE true)
5 set(CMAKE_EXPORT_COMPILE_COMMANDS true)

6 if (ENABLE_COVERAGE)
7   set(CMAKE_BUILD_TYPE "Debug" CACHE STRING "Set the build type." FORCE)
8   include(CodeCoverage.cmake)
9   append_coverage_compiler_flags()
10 endif()

11 add_executable(app app.cpp)

12 if (ENABLE_COVERAGE)
13   setup_target_for_coverage_lcov(
14     NAME coverage
15     EXECUTABLE ${CMAKE_CURRENT_SOURCE_DIR}/run_tests
16     EXECUTABLE_ARGS ${CMAKE_CURRENT_BINARY_DIR}
17     LCOV_ARGS -rc lcov_branch_coverage=1
18     GENHTML_ARGS --branch-coverage
19     DEPENDENCIES app)
20 endif()
```
app.cpp

```cpp
#include <iostream>

void func(int x) {
    if (x % 2) {
        std::cout << "odd\n";
    } else {
        std::cout << "even\n";
    }
}

int main() {
    for (int i = 0; i < 100; ++i) {
        func(i);
    }
}
```

run_tests

```bash
#!/usr/bin/env bash

BINARY_DIR="$1"

$BINARY_DIR/app
```
- Gcovr is another tool for processing GCC coverage data
- similar in functionality to Lcov
- can generate XML output that can be used with Cobertura plugin of Jenkins continuous integration server
- web site: https://gcovr.com
- GitHub web page: https://github.com/gcovr/gcovr
Section 8.6.1

References


Section 8.7

LLVM XRay
LLVM XRay

- LLVM XRay is a function call tracing system that combines compiler-inserted instrumentation points and a run-time library that can enable and disable instrumentation.
- XRay is part of LLVM software and needs to be used in conjunction with Clang compiler.
- Allows the collection of a trace of function calls and information about stack frames for those calls.
- Very minimal overhead when collection disabled.
- Moderate overhead when collection enabled.
- Consists of three main parts:
  1. Compiler-inserted instrumentation points
  2. Runtime library for enabling/disabling tracing at runtime
  3. Suite of tools for analyzing traces
- Website: https://llvm.org/docs/XRay.html
Instrumenting Application

- when compiling with Clang, must enable instrumentation of code
- Clang has several options that relate to instrumentation of code for XRay:
  - `-fxray-instrument`
    - enable instrumentation for XRay
  - `-fxray-instruction-threshold n`
    - specify that functions with at least \( n \) instructions should be instrumented
  - `-fxray-always-instrument`
    - treat each function as if marked with always-instrument attribute
  - `-fxray-never-instrument`
    - treat each function as if marked with never-instrument attribute
- in order to allow any instrumentation to be performed by compiler, must provide `-fxray-instrument` option
- other options may also be used to assert greater control over how instrumentation performed
- must link with XRay Runtime Library (to be discussed shortly)
- providing `-fxray-instrument` option to Clang when linking, will automatically link with XRay Runtime Library
Clang compiler attributes for XRay include:

- `clang::xray_always_instrument` force (free or member) function to always be instrumented for XRay
- `clang::xray_never_instrument` inhibit (free or member) function from being instrumented for XRay
- `clang::xray_log_args(n)` preserve $n$ arguments of function in logging (as of Clang 7.0.0, only $n = 1$ is supported)

above attributes can be used to assert finer control over XRay instrumentation (if necessary)

some examples of using attributes follow:

```cpp
[[clang::xray_always_instrument]] void func_1() { /* ... */}
[[clang::xray_never_instrument]] void func_2() { /* ... */}
```
XRay Runtime Library is part of LLVM compiler-rt project

environment variable XRAY_OPTIONS contains whitespace-delimited list of options that control behavior of runtime library at application start up

some supported options include:

- patch_premain
  - if instrumentation points should be enabled prior to entering main
  - valid values: true and false; default value: false

- xray_mode
  - default mode to install and initialize before main
  - valid values: xray-basic (basic) and xray-fdr (flight data recorder)

- xray_logfile_base
  - base name of XRay log file
  - default value: xray-log.

- verbosity
  - runtime verbosity level
  - integer value; default value: 0

application can also control settings of XRay Runtime Library via API
XRay supports two modes of operation:

1. basic
2. flight data recorder

in basic mode, traces of application’s execution periodically appended to single log file

environment variable XRAY_BASIC_OPTIONS can be used to provide additional options for basic mode

in flight data recorder (FDR) mode, tracing events written to fixed-size circular buffer in memory and traces can be dumped on demand through triggering API

environment variable XRAY_FDR_OPTIONS can be used to provide additional options for FDR mode
LLVM XRay Tool

- trace log files can be analyzed with `llvm-xray` program
- command-line interface for `llvm-xray`:
  ```
  llvm-xray [options] subcommand [subcommand_options]
  ```
- supports several subcommands:
  - account
    - performs basic function call accounting statistics with various options for sorting and output formats
  - convert
    - converts XRay log file from one format to another
  - extract
    - extracts instrumentation map from binary and returns as YAML
  - graph
    - generates DOT graph of function call relationships between functions in XRay trace
  - stack
    - reconstructs function call stacks from timeline of function calls in XRay trace
```cpp
#include <iostream>
#include <thread>
#include <chrono>

[[gnu::noinline, clang::xray_always_instrument]]
void delay() {
    using namespace std::chrono_literals;
    std::this_thread::sleep_for(1ms);
}

[[gnu::noinline, clang::xray_always_instrument, 
  clang::xray_log_args(1)]]
void func(int i, std::size_t n) {
    for (std::size_t j = 0; j < n; ++j) {
        std::cout << (i ? 'X' : 'O') << std::flush;
        delay();
    }
}

[[clang::xray_never_instrument]]
int main() {
    std::thread t1([](){func(0, 500);});
    std::thread t2([](){func(1, 500);});
    t1.join(); t2.join();
    std::cout << '\n';
}
```
build instrumented code with command:

```
clang++ -std=c++20 -fxray-instrument -O1 example_1.cpp -o example_1
```

run application with command:

```
XRAY_OPTIONS="patch_premain=true xray_mode=xray-basic" ./example_1
```
command:

```bash
llvm-xray account -k -m ./example_1 xray-log.example_1.5fNAQv
```

output produced:

```
Functions with latencies: 3

<table>
<thead>
<tr>
<th>funcid</th>
<th>count</th>
<th>[ min, med, 90p, 99p, max ]</th>
<th>sum</th>
<th>function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1000</td>
<td>[ 0.000782, 0.000827, 0.000835, 0.000899, 0.000919 ]</td>
<td>0.825670</td>
<td>&lt;invalid&gt;:0:0: delay()</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>[ 0.420710, 0.420710, 0.420710, 0.420710, 0.420710 ]</td>
<td>0.420710</td>
<td>&lt;invalid&gt;:0:0: func(int, unsigned long)</td>
</tr>
<tr>
<td>3</td>
<td>1000</td>
<td>[ 0.000781, 0.000825, 0.000831, 0.000896, 0.000917 ]</td>
<td>0.822853</td>
<td>&lt;invalid&gt;:0:0: void std::this_thread::sleep_for&lt;long, std::ratio&lt;1l, 1000l&gt; &gt;(std::chrono::duration&lt;long, std::ratio&lt;1l, 1000l&gt; &gt; const&amp;)</td>
</tr>
</tbody>
</table>
```
command:

```bash
llvm-xray stack -m ./example_1 xray-log.example_1.5fNAQv
```

output produced:

Unique Stacks: 2

Top 10 Stacks by leaf sum:

```
Sum: 1439155104
lvl function     count    sum
#0 func(int, unsigned long) 1 1475472614
#1 delay()          500 1446943616
#2 void std::this_thread::sleep_for<long, std::ratio<1l, 100... 499 1439155104
```

Sum: 1437712794

```
lvl function     count    sum
#0 func(int, unsigned long) 1 1472486054
#1 delay()          500 1442899912
#2 void std::this_thread::sleep_for<long, std::ratio<1l, 100... 500 1437712794
```

Top 10 Stacks by leaf count:

```
Count: 500
lvl function     count    sum
#0 func(int, unsigned long) 1 1472486054
#1 delay()          500 1442899912
#2 void std::this_thread::sleep_for<long, std::ratio<1l, 100... 500 1437712794
```

Count: 499

```
lvl function     count    sum
#0 func(int, unsigned long) 1 1475472614
#1 delay()          500 1446943616
#2 void std::this_thread::sleep_for<long, std::ratio<1l, 100... 499 1439155104
```
Trace Subcommand Example

command:

```
llvm-xray convert -f yaml -y -m ./example_1 xray-log.example_1.5fNAQv
```

output produced:

```yaml
---
header:
  version: 3
  type: 0
  constant-tsc: true
  nonstop-tsc: true
  cycle-frequency: 350000000
records:
- { type: 0, func-id: 2, function: 'func(int, unsigned long)', args: [ 0 ], cpu: 5, thread: 29992, 
  process: 29991, kind: function-enter-arg, tsc: 1027021087397834 }
- { type: 0, func-id: 2, function: 'func(int, unsigned long)', args: [ 1 ], cpu: 4, thread: 29993, 
  process: 29991, kind: function-enter-arg, tsc: 1027021087460270 }
- { type: 0, func-id: 1, function: 'delay()', cpu: 5, thread: 29992, process: 29991, kind: function-enter, 
  tsc: 1027021087525002 }
- { type: 0, func-id: 3, function: 'void std::this_thread::sleep_for<long, std::ratio<1l, 1000l> >(std::chrono::duration<long, std::ratio<1l, 1000l> > const&)', cpu: 5, thread: 29992, process: 29991, 
  kind: function-enter, tsc: 1027021087526060 }
- { type: 0, func-id: 1, function: 'delay()', cpu: 4, thread: 29993, process: 29991, kind: function-enter, 
  tsc: 1027021087535002 }
- { type: 0, func-id: 3, function: 'void std::this_thread::sleep_for<long, std::ratio<1l, 1000l> >(std::chrono::duration<long, std::ratio<1l, 1000l> > const&)', cpu: 4, thread: 29993, process: 29991, 
  kind: function-enter, tsc: 102702108753716 }
- { type: 0, func-id: 3, function: 'void std::this_thread::sleep_for<long, std::ratio<1l, 1000l> >(std::chrono::duration<long, std::ratio<1l, 1000l> > const&)', cpu: 4, thread: 29993, process: 29991, 
  kind: function-exit, tsc: 102702109028388 }
```
1  Dean Berris. Debugging With LLVM XRay. Pacific++, Christchurch, NZ, Oct. 26, 2017. Available online at https://youtu.be/cBc_MxbzqhY. [This talk gives an introduction to the LLVM XRay tool, including what it is, what it does, and how it works.]

Section 8.8

Miscellaneous Tools
Kcov is a tool for measuring code coverage. Unlike Gcov/Lcov, Kcov does not require instrumentation of code. Kcov only supports measurement of statement coverage based on breakpoints. It can generate HTML reports similar in appearance to Lcov. The web site is [https://github.com/SimonKagstrom/kcov](https://github.com/SimonKagstrom/kcov).
Section 8.9

Catch2
Catch2 (originally known as Catch) is multiparadigm test framework for C++

Catch2 stands for “C++ automated test cases in a header”

primarily distributed as single header library

open source; released under Boost Software License

written by Phil Nash

official Git repository: http://github.com/catchorg/Catch2

Google group: http://groups.google.com/group/catch-forum
```cpp
#include <limits>
#include <stdexcept>

class counter {
public:
    using count_type = std::size_t;
    static constexpr count_type max_count() {
        return std::numeric_limits<count_type>::max();
    }
    counter(count_type count = 0) : count_(count) {}
    count_type get_count() const {
        return count_;
    }
    void increment() {
        if (count_ == max_count()) {
            throw std::overflow_error("counter overflow");
        }
        ++count_;
    }
private:
    count_type count_;}
```
```cpp
#include <catch2/catch.hpp>
#include "counter.hpp"

TEST_CASE("constructor", "[counter]") {
    counter x;
    CHECK(x.get_count() == 0);
    counter y(1);
    CHECK(y.get_count() == 1);
}

TEST_CASE("maximum count", "[counter]") {
    CHECK(counter::max_count() == std::numeric_limits<
        counter::count_type>::max());
}

TEST_CASE("increment (no overflow)", "[counter]") {
    counter x(0);
    REQUIRE(x.get_count() == 0);
    x.increment();
    CHECK(x.get_count() == 1);
}

TEST_CASE("increment (overflow)", "[counter]") {
    counter x(counter::max_count());
    CHECK_THROWS_AS(x.increment(), std::overflow_error);
}
```

Copyright © 2015–2021 Michael D. Adams
Programming in C++
Version 2021-04-01
2537
#define CATCH_CONFIG_MAIN

#include <catch2/catch.hpp>
#include <cstdint>
#include <vector>

TEST_CASE("Check resize", "[vector]") {
    constexpr std::size_t size = 128;
    std::vector<int> x(size);
    REQUIRE(x.size() == size);
    REQUIRE(x.capacity() >= size);
    SECTION("Increase size") {
        std::size_t n = size * 16;
        x.resize(n);
        CHECK(x.size() == n);
        CHECK(x.capacity() >= n);
    }
    SECTION("Decrease size") {
        std::size_t n = size / 16;
        x.resize(n);
        CHECK(x.size() == n);
        CHECK(x.capacity() >= n);
    }
    SECTION("Zero size") {
        x.resize(0);
        CHECK(x.size() == 0);
        CHECK(x.capacity() >= size);
    }
}
#define CATCH_CONFIG_MAIN

#include <catch2/catch.hpp>

TEST_CASE("addition") {
    float x = 0.0f;
    for (int i = 0; i < 10; ++i) {x += 0.1f;}
    CHECK_NOFAIL(x == 1.0f);
    // condition may be false due to roundoff error
    CHECK(x == Approx(1.0f));
    // should pass
    CHECK(x == Approx(1.0f).margin(0.01f));
    // should pass (absolute tolerance 0.01)
    CHECK(x == Approx(1.0f).epsilon(0.01f));
    // should pass (relative tolerance 1%)
}
#include <cstdlib>
#include <vector>

// Note: T is not allowed to be bool.

template <class T>
class Stack {
public:
    bool empty() const {return s_.empty();}
    std::size_t size() const {return s_.size();}
    const T& top() const {return s_.back();}
    void push(const T& x) {s_.push_back(x);}
    void pop() {s_.pop_back();}
private:
    std::vector<T> s_; 
};
#define CATCH_CONFIG_MAIN

#include <catch2/catch.hpp>
#include <complex>
#include "stack.hpp"

TEMPLATE_TEST_CASE("Check default constructor", "[constructors]", int, double, std::complex<double>) {
    Stack<TestType> s;
    CHECK(s.empty());
    CHECK(s.size() == 0);
}

TEMPLATE_TEST_CASE("Check push and pop", "[modifiers]", int, double, std::complex<double>) {
    std::size_t size = 0;
    Stack<TestType> s;
    REQUIRE(s.size() == size);
    while (size < 3) {
        ++size; s.push(TestType(size));
        REQUIRE(s.size() == size);
        REQUIRE(s.top() == TestType(size));
    }
    while (size > 0) {
        s.pop(); --size;
        REQUIRE(s.size() == size);
    }
}
```cpp
#define CATCH_CONFIG_MAIN
#include <catch2/catch.hpp>
#include <deque>
#include <stdexcept>

class TestFixture {
public:
    TestFixture() : q0(), q1{1, 2, 3} {
    }

protected:
    std::deque<int> q0;
    std::deque<int> q1;
};

TEST_CASE_METHOD(TestFixture, "Check deque at", "[deque]") {
    CHECK_THROWS_AS(q0.at(0), std::out_of_range);
    CHECK(q1.at(0) == 1);
    CHECK_THROWS_AS(q1.at(3), std::out_of_range);
}

TEST_CASE_METHOD(TestFixture, "Check deque clear", "[deque]") {
    q0.clear();
    CHECK(q0.size() == 0);
    q1.clear();
    CHECK(q1.size() == 0);
}


Part 9

Performance Analysis Tools
Linux kernel provides Perf Event (i.e., \texttt{perf_event}) interface for performance monitoring

\texttt{perf_event_open} system call returns file descriptor that can then be used to collect performance information

collection of performance data started and stopped with \texttt{ioctl} system call

performance data accessed either via \texttt{read} or \texttt{mmap} system call

Perf Event interface used by numerous performance analysis tools and libraries on Linux systems (e.g., Perf and PAPI)

supports many profiling/tracing features, including:
  - CPU performance monitoring counters
  - statically defined tracepoints
  - user and kernel dynamic tracepoints

good documentation on Perf Event interface is scarce
- open-source profiling tool
- can collect aggregated counts of events during code execution
- can perform event-driven sample-based profiling
- uses Perf Event interface of Linux kernel
- noninvasive (i.e., no code instrumentation required)
- low overhead (i.e., code runs close to native speed)
- sample-based profiling can collect stack traces in addition to instruction pointer
- does not provide call counts for functions
- web site: https://perf.wiki.kernel.org
Events

- **hardware event:**
  - event measurable by performance monitoring unit (PMU) of processor
  - examples: CPU cycles (cycles) and cache misses (cache-misses)

- **hardware cache event:**
  - event measurable by PMU of processor
  - examples: L1 data cache load misses (L1-dcache-load-misses) and data translation-lookaside-buffer load misses (dTLB-load-misses)

- **software event:**
  - low-level events based on kernel counters
  - examples: CPU clock (cpu-clock) and page fault (page-faults)

- **kernel tracepoint event:**
  - predefined static instrumentation points in kernel code where trace information can be collected
  - examples: entering open system call (syscalls:sys_enter_open) and context switch (sched:sched_switch)

- **probe event:**
  - user-defined events dynamically inserted into kernel
  - created using uprobes or kprobes
# Some Events

<table>
<thead>
<tr>
<th>Event</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>cache-misses</td>
<td>cache misses</td>
</tr>
<tr>
<td>cache-references</td>
<td>cache accesses</td>
</tr>
<tr>
<td>cycles</td>
<td>CPU cycles</td>
</tr>
<tr>
<td>cpu-clock</td>
<td>CPU wall-time clock</td>
</tr>
<tr>
<td>instructions</td>
<td>CPU instructions</td>
</tr>
<tr>
<td>cs</td>
<td>context switches</td>
</tr>
<tr>
<td>faults</td>
<td>page faults</td>
</tr>
</tbody>
</table>
stack trace is list of stack frames
with event-based sampling, sampling process driven by one or more types of events

sample is taken upon occurrence of every \( n \)th event, where \( n \) is either:
- directly specified by user; or
- dynamically chosen by kernel in order to (approximately) meet average sampling rate specified by user

default sampling event is cycles with average sampling rate that depends on Perf version (typically 1000 Hz to 4000 Hz)
cycles event does not necessarily have constant relationship with time, due to CPU frequency scaling
each sample captures:
- timestamp
- CPU number, process ID (PID), and thread ID (TID)
- instruction pointer
- stack trace (optional)
can perform sampling:
- system wide, per processor, per program, or per thread
Event Specifiers

- event specifier consists of event name, optionally followed by colon and then one of more event modifiers

- list of event modifiers as follows:

<table>
<thead>
<tr>
<th>Modifier</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>user-space counting</td>
</tr>
<tr>
<td>k</td>
<td>kernel counting</td>
</tr>
<tr>
<td>h</td>
<td>hypervisor counting</td>
</tr>
<tr>
<td>i</td>
<td>non-idle counting</td>
</tr>
<tr>
<td>G</td>
<td>guest counting (in KVM guests)</td>
</tr>
<tr>
<td>H</td>
<td>host counting (not in KVM guests)</td>
</tr>
<tr>
<td>p</td>
<td>preciseness level (i.e., amount of skid)</td>
</tr>
<tr>
<td>S</td>
<td>read sample value</td>
</tr>
<tr>
<td>D</td>
<td>pin event to PMU</td>
</tr>
</tbody>
</table>
number \( n \) of \( \_p \)'s in modifier influences preciseness of event measurement as follows:

<table>
<thead>
<tr>
<th>( n )</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>can have arbitrary skid</td>
</tr>
<tr>
<td>1</td>
<td>must have constant skid</td>
</tr>
<tr>
<td>2</td>
<td>requested (but not required) to have zero skid</td>
</tr>
<tr>
<td>3</td>
<td>must have zero skid</td>
</tr>
</tbody>
</table>

if zero skid required but not supported, error will be generated

some examples of event specifiers are as follows:

<table>
<thead>
<tr>
<th>Event Specifier</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>cycles:( u )</td>
<td>clock cycles in user space</td>
</tr>
<tr>
<td>cache-misses:( u )</td>
<td>cache misses in user space</td>
</tr>
<tr>
<td>cache-misses:( k )</td>
<td>cache misses in kernel</td>
</tr>
<tr>
<td>cache-misses:( uppp )</td>
<td>cache misses in user space with zero skid</td>
</tr>
</tbody>
</table>
measurements involving hardware counters typically employ interrupts
when hardware counter for event overflows, interrupt occurs
when overflow interrupt occurs, takes CPU some amount of time to stop processor and pinpoint exactly which instruction was active at time of overflow
due to this delay, can often be offset in execution flow between instruction claimed to be active at time of overflow and instruction that actually was active
this offset known as **skid**
in some cases, for example, skid could result in caller function event being recorded in callee function
due to skid, some care must be taken when interpreting profiling results
The perf Program

- functionality of Perf software provided by `perf` program
- command line interface has following form:
  ```bash
  perf [options] command [args]
  ```
- some common commands include:

<table>
<thead>
<tr>
<th>Command</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>list</td>
<td>list all symbolic event types</td>
</tr>
<tr>
<td>stat</td>
<td>run command and gather performance count statistics</td>
</tr>
<tr>
<td>record</td>
<td>run command and record its profile into Perf data file</td>
</tr>
<tr>
<td>report</td>
<td>read Perf data (created by Perf record) and display profile</td>
</tr>
<tr>
<td>script</td>
<td>read Perf data (created by Perf record) and display trace output</td>
</tr>
<tr>
<td>annotate</td>
<td>read Perf data (created by Perf record) and display annotated code</td>
</tr>
</tbody>
</table>

- some common options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>--help</td>
<td>print help information and exit</td>
</tr>
<tr>
<td>--version</td>
<td>print version information and exit</td>
</tr>
</tbody>
</table>
list all symbolic event types

command line interface has following form:

```bash
perf list [event_type]
```

event types include:

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>hw</td>
<td>hardware</td>
</tr>
<tr>
<td>sw</td>
<td>software</td>
</tr>
<tr>
<td>cache</td>
<td>cache</td>
</tr>
<tr>
<td>tracepoint</td>
<td>tracepoint</td>
</tr>
<tr>
<td>pmu</td>
<td>PMU</td>
</tr>
<tr>
<td><code>glob_expr</code></td>
<td>any event matching glob expression <code>glob_expr</code></td>
</tr>
</tbody>
</table>

only lists event types available to invoking user

some events only available to root user
$ perf list
List of pre-defined events (to be used in -e):
  branch-instructions OR branches [Hardware event]
  branch-misses [Hardware event]
  bus-cycles [Hardware event]
  cache-misses [Hardware event]
  cache-references [Hardware event]
  cpu-cycles OR cycles [Hardware event]
  instructions [Hardware event]
  ref-cycles [Hardware event]
  alignment-faults [Software event]
  context-switches OR cs [Software event]
  cpu-clock [Software event]
  cpu-migrations OR migrations [Software event]
  L1-dcache-load-misses [Hardware cache event]
  L1-dcache-loads [Hardware cache event]
  L1-dcache-prefetch-misses [Hardware cache event]
  L1-dcache-store-misses [Hardware cache event]
  L1-dcache-stores [Hardware cache event]
  L1-icache-load-misses [Hardware cache event]
  cache-misses OR cpu/cache-misses/ [Kernel PMU event]
  cache-references OR cpu/cache-references/ [Kernel PMU event]
  cpu-cycles OR cpu/cpu-cycles/ [Kernel PMU event]
  instructions OR cpu/instructions/ [Kernel PMU event]
  mem-loads OR cpu/mem-loads/ [Kernel PMU event]
  mem-stores OR cpu/mem-stores/ [Kernel PMU event]
[Text deleted]
run command and gather performance count statistics

command line interface has following form:

```
perf stat [options] command [args]
```

some common options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-e event</td>
<td>specify event for which to gather statistics</td>
</tr>
<tr>
<td>-p pid</td>
<td>consider events on existing process ID</td>
</tr>
<tr>
<td>-t tid</td>
<td>consider events on existing thread ID</td>
</tr>
<tr>
<td>-a</td>
<td>consider all processors (i.e., system wide)</td>
</tr>
<tr>
<td>-r n</td>
<td>repeat command n times and print averages and standard deviations</td>
</tr>
<tr>
<td>-C cpu</td>
<td>consider only CPUs specified by cpu</td>
</tr>
</tbody>
</table>
$ perf stat dd if=/dev/urandom of=/dev/null bs=1K count=32K status=none

Performance counter stats for
'dd if=/dev/urandom of=/dev/null bs=1K count=32K status=none'

1727.055828 task-clock (msec)  # 0.999 CPUs utilized
  1 context-switches  # 0.001 K/sec
  13 cpu-migrations  # 0.008 K/sec
  60 page-faults  # 0.035 K/sec
5,805,261,702 cycles  # 3.361 GHz
2,115,865,103 stalled-cycles-frontend  # 36.45% frontend
  cycles idle

<not supported> stalled-cycles-backend
12,108,757,065 instructions  # 2.09 insns per cycle
  # 0.17 stalled cycles per insn

254,471,634 branches  # 147.344 M/sec
  257,282 branch-misses  # 0.10% of all branches

1.728232622 seconds time elapsed
Perf Record Command

- run command and record its profile into Perf data file
- command line interface has following form:
  ```
  perf record [options] command [args]
  ```
- some common options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-e event</td>
<td>specify event name</td>
</tr>
<tr>
<td>-a</td>
<td>collect data from all processors</td>
</tr>
<tr>
<td>-p pid</td>
<td>collect data from existing process ID pid</td>
</tr>
<tr>
<td>-t tid</td>
<td>collect data from existing thread ID tid</td>
</tr>
<tr>
<td>-C cpu</td>
<td>collect data from CPUs cpu</td>
</tr>
<tr>
<td>-c count</td>
<td>set event count between samples to count</td>
</tr>
<tr>
<td>-o file</td>
<td>set output file to file</td>
</tr>
<tr>
<td>-F freq</td>
<td>set sampling frequency to approximately freq</td>
</tr>
<tr>
<td>-g</td>
<td>enable call graph (i.e., stack trace) recording</td>
</tr>
</tbody>
</table>

- output file defaults to `perf.data`
- by default, uses `cycles` event with sampling frequency set to version-dependent value (typically, 1000 Hz to 4000 Hz)
$ perf record -g -F 99 -o perf.data dd if=/dev/urandom of=/dev/null bs=1K count=3200K status=none
[ perf record: Woken up 9 times to write data ]
[ perf record: Captured and wrote 2.121 MB perf.data (16246 samples) ]
$ ls
perf.data
Perf Report Command

- read Perf data (created by Perf record) and display profile
- command line interface has following form:
  ```
  perf report [options]
  ```
- some common options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-i file</td>
<td>set input file to file</td>
</tr>
<tr>
<td>-v</td>
<td>increase verbosity level</td>
</tr>
<tr>
<td>-n</td>
<td>show number of samples for each symbol</td>
</tr>
<tr>
<td>-C cpu</td>
<td>only show events for CPU cpu</td>
</tr>
<tr>
<td>--pid pid</td>
<td>only show events for process ID pid</td>
</tr>
<tr>
<td>--tid tid</td>
<td>only show events for thread ID tid</td>
</tr>
<tr>
<td>-d dsos</td>
<td>only consider symbols in DSO/object files dsos</td>
</tr>
<tr>
<td>-S syms</td>
<td>only consider symbols syms</td>
</tr>
<tr>
<td>-s key</td>
<td>sort data by key key (such as PID)</td>
</tr>
<tr>
<td>--stdio</td>
<td>use stdio interface</td>
</tr>
<tr>
<td>-U</td>
<td>only display entries that resolve to symbol</td>
</tr>
<tr>
<td>-D</td>
<td>dump raw trace data</td>
</tr>
</tbody>
</table>

- input file defaults to `perf.data`
Perf Report Example

```bash
$ perf record -g -e cycles:u -F 13000 -o perf.data ./array_sum
$ perf report -i perf.data -d array_sum --stdio
# To display the perf.data header info, please use --header/--header-only options.
# dso: array_sum
# Samples: 1K of event 'cycles:u'
# Event count (approx.): 158559166
# Children  Self  Command  Symbol
# ..........  ..........  ................
# 79.94%  79.94%  array_sum  [.]  naive_sum
#    |---naive_sum
#    |    main
#    |    __libc_start_main
#    |    0x48e258d4c544155
# 7.56%  7.56%  array_sum  [.]  improved_sum
#    |---improved_sum
#    |    main
#    |    __libc_start_main
#    |    0x48e258d4c544155

# (For a higher level overview, try: perf report --sort comm,dso)
#```
read Perf data (created by Perf record) and display trace output

command line interface has following form:

```
perf script [options]
```

some common options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-i file</td>
<td>set input file to file</td>
</tr>
<tr>
<td>--pid pid</td>
<td>only show events for process ID pid</td>
</tr>
<tr>
<td>--tid tid</td>
<td>only show events for thread ID tid</td>
</tr>
<tr>
<td>-C cpu</td>
<td>only show events for CPU cpu</td>
</tr>
</tbody>
</table>

input file defaults to `perf.data`
$ perf record -g -e cycles:u -F 13000 -o perf.data ./array_sum
1
1
$ perf script -i perf.data
array_sum 15602 2408817.214222: 1 cycles:u:  
cf0  _start (/usr/lib64/ld-2.20.so)
array_sum 15602 2408817.214230: 1 cycles:u:  
cf0  _start (/usr/lib64/ld-2.20.so)
array_sum 15602 2408817.214234: 2 cycles:u:  
cf0  _start (/usr/lib64/ld-2.20.so)
array_sum 15602 2408817.214237: 7 cycles:u:  
cf0  _start (/usr/lib64/ld-2.20.so)
array_sum 15602 2408817.214241: 25 cycles:u:  
cf0  _start (/usr/lib64/ld-2.20.so)
array_sum 15602 2408817.214245: 88 cycles:u:  
cf0  _start (/usr/lib64/ld-2.20.so)
array_sum 15602 2408817.214248: 308 cycles:u:  
cf0  _start (/usr/lib64/ld-2.20.so)
array_sum 15602 2408817.214253: 1081 cycles:u:  
ffffff8179bef0  page_fault ([kernel.kallsyms])  
cf0  _start (/usr/lib64/ld-2.20.so)
array_sum 15602 2408817.214270: 3147 cycles:u:  
4980  _dl_start (/usr/lib64/ld-2.20.so)
array_sum 15602 2408817.214274: 4536 cycles:u:  
4b8f  _dl_start (/usr/lib64/ld-2.20.so)  
cf8  _dl_start_user (/usr/lib64/ld-2.20.so)
[tex...
Perf Annotate Command

- read Perf data (created by Perf record) and display annotated code
- command line interface has following form:
  
  ```bash
  perf annotate [options]
  ```
- some common options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-i file</td>
<td>set input file to file</td>
</tr>
<tr>
<td>-s sym</td>
<td>annotate symbol sym</td>
</tr>
<tr>
<td>-d dsos</td>
<td>only consider symbols in DSO/object files dsos</td>
</tr>
<tr>
<td>-v</td>
<td>increase verbosity level</td>
</tr>
<tr>
<td>-l</td>
<td>print matching source lines</td>
</tr>
<tr>
<td>-P</td>
<td>do not shorten displayed pathnames</td>
</tr>
<tr>
<td>-k file</td>
<td>set vmlinux pathname to file</td>
</tr>
<tr>
<td>--stdio</td>
<td>use stdio interface</td>
</tr>
<tr>
<td>--no-source</td>
<td>disable displaying of source code</td>
</tr>
</tbody>
</table>

- input file defaults to `perf.data`
$ perf record -g -e cycles:u -F 13000 -o perf.data ./array_sum
$ perf annotate -i perf.data -s naive_sum -l --stdio

```c
double naive_sum(const double a[][N]) {
    double sum = 0.0;
    for (int j = 0; j < N; ++j) {
        for (int i = 0; i < M; ++i) {
            sum += a[i][j];
        }
    }
    return sum;
}
```

array_sum.cpp:11 100.00 : 400824: add $0x4000,%rax

#include <iostream>
#include <algorithm>

constexpr int M = 4096;
constexpr int N = 4096;

[[gnu::noinline]]
double naive_sum(const double a[][N]) {
    double sum = 0.0;
    for (int j = 0; j < N; ++j) {
        for (int i = 0; i < M; ++i) {
            sum += a[i][j];
        }
    }
    return sum;
}

[[gnu::noinline]]
double improved_sum(const double a[][N]) {
    double sum = 0.0;
    for (int i = 0; i < M; ++i) {
        for (int j = 0; j < N; ++j) {
            sum += a[i][j];
        }
    }
    return sum;
}
```cpp
int main() {
    for (int i = 0; i < 16; ++i) {
        static double a[M][N];
        static double b[M][N];
        std::fill_n(&a[0][0], M * N, 1.0 / (M * N));
        std::fill_n(&b[0][0], M * N, 1.0 / (M * N));
        std::cout << naive_sum(a) << ' ';
        std::cout << improved_sum(b) << '
';
    }
}
```
Profile of Cycles

To display the perf.data header info, please use --header/--header-only options.

dso: array_sum
Samples: 16K of event 'cycles:u'
Event count (approx.): 14049539983

Children Self Command Symbol
---------- ---------- ---------- ---------------
99.97% 0.00% array_sum [.] __libc_start_main

99.97% 10.92% array_sum [.] main

82.97% 82.97% array_sum [.] naive_sum

5.90% 5.90% array_sum [.] improved_sum

[text deleted]
Cycles for $\text{naive\_sum}$

: $0000000000400807 \ <\text{naive\_sum}(\text{double const (*) [4096]})>$:
: $\_Z9\text{naive\_sum}\_PA4096\_Kd()$:

[Text deleted]
: $[[\text{gnu::noinline}]]$
: $\text{double naive\_sum(const double a[][N])}$ {
0.00 : 400807: push %rbp
0.00 : 400808: mov %rsp,%rbp
0.00 : 40080b: lea 0x8000(%rdi),%rcx
: double sum = 0.0;
0.00 : 400812: pxor %xmm0,%xmm0
0.00 : 400816: lea 0x8000000(%rdi),%rdx
0.00 : 40081d: mov %rdi,%rax
: for (int j = 0; j < N; ++j) {
 : for (int i = 0; i < M; ++i) {
 : sum += a[i][j];
[Text deleted]
: for (int j = 0; j < N; ++j) {
 : for (int i = 0; i < M; ++i) {

array_sum.cpp:12 99.93 : 400824: add $0x8000,%rax
[Text deleted]
: for (int j = 0; j < N; ++j) {
 : for (int i = 0; i < M; ++i) {
0.07 : 40082a: cmp %rdx,%rax
0.00 : 40082d: jne 400820 <\text{naive\_sum}(\text{double const (*) [4096]})+0x19>
0.00 : 40082f: add $0x8,%rdi
[Text deleted]
: $[[\text{gnu::noinline}]]$
: $\text{double naive\_sum(const double a[][N])}$ {
 : double sum = 0.0;
 : for (int j = 0; j < N; ++j) {
0.00 : 400833: cmp %rcx,%rdi
0.00 : 400836: jne 400816 <\text{naive\_sum}(\text{double const (*) [4096]})+0xf>
: for (int i = 0; i < M; ++i) {
 : sum += a[i][j];
 : }
: return sum;
: }
0.00 : 400838: pop %rbp
0.00 : 400839: retq
Cycles for improved_sum

```c
: 00000000004083a <improved_sum(double const (*) [4096])>: 
: __Z12improved_sumPA4096_Kd():

[...text deleted...]
: [[gnu::noinline]]
: double improved_sum(const double a[][N]) {
  0.00 : 40083a:  push %rbp
  0.00 : 40083b:  mov %rsp,%rbp
  0.00 : 40083e:  lea 0x8000000(%rdi),%rdx
    : double sum = 0.0;
  0.00 : 400845:  pxor %xmm0,%xmm0
  0.00 : 400849:  lea 0x8000(%rdi),%rax
    : for (int i = 0; i < M; ++i) {
      0.00 : 400850:  addsd (%rdi),%xmm0
    array_sum.cpp:23 99.70 : 400854:  add $0x8,%rdi
    [text deleted...]
      : for (int j = 0; j < N; ++j) {
        0.30 : 400858:  cmp %rax,%rdi
      0.00 : 40085b:  jne 400850 <improved_sum(double const (*) [4096])+0x16>
      : }
    : }
  : [[gnu::noinline]]
  : double improved_sum(const double a[][N]) {
    0.00 : 40085d:  cmp %rdx,%rdi
    : double sum = 0.0;
    : for (int i = 0; i < M; ++i) {
      0.00 : 400860:  jne 400849 <improved_sum(double const (*) [4096])+0xf>
    : for (int j = 0; j < N; ++j) {
      0.00 : 400866:  sum += a[i][j];
        : }
    : }
    : return sum;
  : }
  0.00 : 400862:  pop %rbp
  0.00 : 400863:  retq
```

Copyright © 2015–2021 Michael D. Adams
Profile of Cache Misses

To display the perf.data header info, please use --header/--header-only options.

dso: array_sum
Samples: 25K of event 'cache-misses:u'
Event count (approx.): 256620000

<table>
<thead>
<tr>
<th>Children</th>
<th>Self</th>
<th>Command</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>99.99%</td>
<td>0.00%</td>
<td>array_sum</td>
<td>.] __libc_start_main</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>---__libc_start_main</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0x46e258d4c544155</td>
</tr>
<tr>
<td>99.99%</td>
<td>3.67%</td>
<td>array_sum</td>
<td>.] main</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>---main</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>__libc_start_main</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0x46e258d4c544155</td>
</tr>
<tr>
<td>93.74%</td>
<td>93.73%</td>
<td>array_sum</td>
<td>.] naive_sum</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>---naive_sum</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>main</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>__libc_start_main</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0x46e258d4c544155</td>
</tr>
<tr>
<td>2.58%</td>
<td>2.58%</td>
<td>array_sum</td>
<td>.] improved_sum</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>---improved_sum</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>main</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>__libc_start_main</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0x46e258d4c544155</td>
</tr>
</tbody>
</table>

$text deleted$
Cache Misses for `naive_sum`

```plaintext
0000000000400807 <naive_sum(double const (*) [4096])>:
  _Z9naive_sumPA4096_Kd():
  [[gnu::noinline]]
  double naive_sum(const double a[][N]) {
    double sum = 0.0;
    for (int j = 0; j < N; ++j) {
      for (int i = 0; i < M; ++i) {
        sum += a[i][j];
      }
    }
    return sum;
  }
array_sum.cpp:12  99.93:  400824: add $0x8000,%rax
  [text deleted]
```
Cache Misses for **improved_sum**

```cpp
000000000040083a <improved_sum(double const (*) [4096])>:
  _Z12improved_sumPA4096_Kd():

[[gnu::noinline]]
  double improved_sum(const double a[][N]) {
    double sum = 0.0;
    for (int i = 0; i < M; ++i) {
      for (int j = 0; j < N; ++j) {
        sum += a[i][j];
      }
    }
    return sum;
  }
```

```
array_sum.cpp:23  99.70  400854:  add $0x8,%rdi
```

```
Copyright © 2015–2021 Michael D. Adams
Programming in C++  Version 2021-04-01  2575
```
- Avoid sampling in lockstep with periodic behavior exhibited by programs (e.g., caused by timeouts or loops).
- Since programmers often choose timeout (and other timing related) values to be “nice” numbers, such as integer multiples of 0.01 s, may be beneficial to choose sampling frequency of 99 Hz instead of 100 Hz or 999 Hz instead of 1000 Hz.
- Sample-based profiling only provides meaningful results if sufficient number of samples collected.
- Can use `taskset` command to pin process for particular CPU.
- Might want to force single-threaded program to run on fixed CPU so that migration does not impact measurements (e.g., due to caching effects).
Flame Graphs

- flame graph provides way to visualize collection of stack traces
- useful for visualizing output of profiler that collects stack traces using sampling (e.g., Perf)
- stack trace represented as column of boxes, with each box corresponding to function in stack trace
- function executing at time of stack trace shown at top of column
- vertical direction corresponds to stack depth
- horizontal direction spans stack trace collection (does not represent time)
- left to right ordering has no special meaning
- when identical function boxes horizontally adjacent, merged
- width of each function box shows frequency with which function present in part of stack trace ancestry
- functions with wider boxes more frequent in stack traces than those with narrower boxes
Flame Graph Example
- can generate flamegraphs from Perf data by using software available from
  - https://github.com/brendangregg/FlameGraph
- need to use `stackcollapse-perf.pl` and `flamegraph.pl` programs
- convert Perf data from binary to text format via Perf script command; for example:
  ```bash
  perf script -i perf.data > tmp.perf
  ```
- fold stack samples into single lines via
  `stackcollapse-perf.pl` command; for example:
  ```bash
  stackcollapse-perf.pl tmp.perf > tmp.folded
  ```
- generate flame graph in SVG format via `flamegraph.pl` command; for example:
  ```bash
  flamegraph.pl tmp.folded > flamegraph.svg
  ```
Section 9.1.1

References


Section 9.2

Performance API (PAPI) Software
Motivation

- often easy to identify in general terms which parts of code are slow
- sometimes more difficult to pinpoint precise reason why code is slow (i.e., what is precise cause of bottleneck)
- often need to consider factors such as:
  - cache behavior
  - memory and resource contention
  - floating-point efficiency
  - branch behavior
- often, processor itself in best position to provide information related to above factors
Hardware Performance Counters

- hardware performance counters are specialized registers used to measure various aspects of processor performance

- hardware counters can provide insight into:
  - timing
  - cache behaviors (e.g., cache misses and cache coherence protocol events)
  - branch behaviors (e.g., incorrect branch predictions)
  - pipeline behavior (e.g., stalls)
  - memory and resource access patterns
  - floating-point efficiency
  - instructions per cycle

- hardware counter information can be obtained with:
  - subroutine or basic block resolution
  - process or thread attribution

- provide low-level information that often cannot be obtained easily through other means

- useful for performance analysis and tuning (e.g., identifying bottlenecks in code)

- use of hardware performance counters has no or little overhead
Performance API (PAPI) software provides portable and efficient API for accessing hardware performance counters found on modern processors.

- more generally allows monitoring of system information on range of components, such as CPUs, network interface cards, and power monitors.
- consists of library and several utility programs.
- open source.
- written in C.
- supports most mainstream Unix-based operating systems (e.g., Linux, OS X, and other Unix variants); older versions support Microsoft Windows.
- supports most modern processors (e.g., Intel and AMD 32- and 64-bit x86, ARM, MIPS, Intel Itanium II, UltraSparc I, II, and III, and IBM Power 4, 5, 6, and 7).
- web site: http://icl.utk.edu/papi
• event is simply some action that can be counted

• **native event**: event that is specified in platform-dependent manner and directly corresponds to particular hardware counter

• which native events are available will depend on underlying hardware

• **preset event**: event that is specified in platform-independent manner, which is then mapped to appropriate native event(s) (e.g., `PAPI_TOT_INS`)

• **derived event**: preset event derived from multiple native events

• if hardware does not directly support counting of particular event, event count can sometimes be computed by using combination of native events

• for example, `PAPI_L1_TCM` might be derived from L1 data misses plus L1 instruction misses

• preset events usually available for most processors, where derived events used in cases where no corresponding native event exists
Events (Continued)

- which events supported and which combinations of supported events can be used together depends on hardware
- hardware will typically have some upper limit on number of events that can be monitored simultaneously
- some events often cannot be used with others (even if upper limit on number of events not exceeded)
- `papi_avail` or `papi_native_avail` utility (discussed later) can be used to determine number of hardware counters available
- `papi_avail` utility (discussed later) can be used to determine which preset events are supported
- `papi_native_avail` utility (discussed later) can be used to determine which native events are supported
- `papi_event_chooser` utility (discussed later) can be used to determine which events can be used with which other events
- must include header file `papi.h`
- library initialized with function `PAPI_library_init`
- depending on which functions used, may need to explicitly initialize library
- calls low-level API
- easier to use than low-level API
- usually enough for more basic measurements
- for preset events only
- high-level interface functions will initialize library if needed (so `PAPI_library_init` need not be explicitly called)
## Functions in PAPI High-Level Interface

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAPI_accum_counters</td>
<td>add current counts to array and reset counters</td>
</tr>
<tr>
<td>PAPI_flips</td>
<td>get floating-point instruction rate and real and processor time</td>
</tr>
<tr>
<td>PAPI_flops</td>
<td>get floating-point operation rate and real and processor time</td>
</tr>
<tr>
<td>PAPI_ipc</td>
<td>get instructions per cycle and real and processor time</td>
</tr>
<tr>
<td>PAPI_num_counters</td>
<td>get number of hardware counters available on system</td>
</tr>
<tr>
<td>PAPI_read_counters</td>
<td>copy current counts to array and reset counters</td>
</tr>
<tr>
<td>PAPI_start_counters</td>
<td>start counting hardware events</td>
</tr>
<tr>
<td>PAPI_stop_counters</td>
<td>stop counters and return current counts</td>
</tr>
</tbody>
</table>
### Some Commonly-Used Preset Events

#### Instruction Mix

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAPI_LD_INS</td>
<td>number of load instructions</td>
</tr>
<tr>
<td>PAPI_SR_INS</td>
<td>number of store instructions</td>
</tr>
<tr>
<td>PAPI_LST_INS</td>
<td>number of load/store instructions</td>
</tr>
<tr>
<td>PAPI_BR_INS</td>
<td>number of branch instructions</td>
</tr>
<tr>
<td>PAPI_INT_INS</td>
<td>number of integer instructions</td>
</tr>
<tr>
<td>PAPI_FP_INS</td>
<td>number of floating-point instructions</td>
</tr>
<tr>
<td>PAPI_VEC_INS</td>
<td>number of vector/SIMD instructions</td>
</tr>
<tr>
<td>PAPI_VEC_SP</td>
<td>number of single-precision vector/SIMD instructions</td>
</tr>
<tr>
<td>PAPI_VEC_DP</td>
<td>number of double-precision vector/SIMD instructions</td>
</tr>
<tr>
<td>PAPI_TOT_INS</td>
<td>number of instructions in total</td>
</tr>
</tbody>
</table>
### Clock Cycles

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAPI_TOT_CYC</td>
<td>total number of clock cycles</td>
</tr>
</tbody>
</table>

### FLOPS

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAPI_FP_OPS</td>
<td>number of floating-point operations</td>
</tr>
<tr>
<td>PAPI_SP_OPS</td>
<td>number of floating-point operations executed, optimized to count scaled single-precision vector operations</td>
</tr>
<tr>
<td>PAPI_DP_OPS</td>
<td>number of floating-point operations executed, optimized to count scaled double-precision vector operations</td>
</tr>
</tbody>
</table>

### Translation Lookaside Buffer (TLB)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAPI_TLB_DM</td>
<td>number of data TLB misses</td>
</tr>
<tr>
<td>PAPI_TLB_IM</td>
<td>number of instruction TLB misses</td>
</tr>
<tr>
<td>PAPI_TLB_TL</td>
<td>number of TLB misses (in total)</td>
</tr>
</tbody>
</table>
### L1 Cache Behavior

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAPI_L1_DCA</td>
<td>number of L1 data cache accesses</td>
</tr>
<tr>
<td>PAPI_L1_DCH</td>
<td>number of L1 data cache hits</td>
</tr>
<tr>
<td>PAPI_L1_DCM</td>
<td>number of L1 data cache misses</td>
</tr>
<tr>
<td>PAPI_L1_DCR</td>
<td>number of L1 data cache reads</td>
</tr>
<tr>
<td>PAPI_L1_DCW</td>
<td>number of L1 data cache writes</td>
</tr>
<tr>
<td>PAPI_L1_ICA</td>
<td>number of L1 instruction cache accesses</td>
</tr>
<tr>
<td>PAPI_L1_ICH</td>
<td>number of L1 instruction cache hits</td>
</tr>
<tr>
<td>PAPI_L1_ICM</td>
<td>number of L1 instruction cache misses</td>
</tr>
<tr>
<td>PAPI_L1_ICR</td>
<td>number of L1 instruction cache reads</td>
</tr>
<tr>
<td>PAPI_L1_ICW</td>
<td>number of L1 instruction cache writes</td>
</tr>
<tr>
<td>PAPI_L1_LDM</td>
<td>number of L1 load misses</td>
</tr>
<tr>
<td>PAPI_L1_STM</td>
<td>number of L1 store misses</td>
</tr>
<tr>
<td>PAPI_L1_TCA</td>
<td>number of L1 cache accesses (in total)</td>
</tr>
<tr>
<td>PAPI_L1_TCH</td>
<td>number of L1 cache hits (in total)</td>
</tr>
<tr>
<td>PAPI_L1_TCM</td>
<td>number of L1 cache misses (in total)</td>
</tr>
<tr>
<td>PAPI_L1_TCR</td>
<td>number of L1 cache reads (in total)</td>
</tr>
<tr>
<td>PAPI_L1_TCW</td>
<td>number of L1 cache writes (in total)</td>
</tr>
</tbody>
</table>
## L2 and L3 Cache Behavior

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAPI_L2_LDM</td>
<td>number of L2 load misses</td>
</tr>
<tr>
<td>PAPI_L2_STM</td>
<td>number of L2 store misses</td>
</tr>
<tr>
<td>PAPI_L2_TCA</td>
<td>number of L2 cache accesses (in total)</td>
</tr>
<tr>
<td>PAPI_L2_TCH</td>
<td>number of L2 cache hits (in total)</td>
</tr>
<tr>
<td>PAPI_L2_TCM</td>
<td>number of L2 cache misses (in total)</td>
</tr>
<tr>
<td>PAPI_L2_TCR</td>
<td>number of L2 cache reads (in total)</td>
</tr>
<tr>
<td>PAPI_L2_TCW</td>
<td>number of L2 cache writes (in total)</td>
</tr>
<tr>
<td>PAPI_L3_LDM</td>
<td>number of L3 load misses</td>
</tr>
<tr>
<td>PAPI_L3_STM</td>
<td>number of L3 store misses</td>
</tr>
<tr>
<td>PAPI_L3_TCA</td>
<td>number of L3 cache accesses (in total)</td>
</tr>
<tr>
<td>PAPI_L3_TCH</td>
<td>number of L3 cache hits (in total)</td>
</tr>
<tr>
<td>PAPI_L3_TCM</td>
<td>number of L3 cache misses (in total)</td>
</tr>
<tr>
<td>PAPI_L3_TCR</td>
<td>number of L3 cache reads (in total)</td>
</tr>
<tr>
<td>PAPI_L3_TCW</td>
<td>number of L3 cache writes (in total)</td>
</tr>
</tbody>
</table>
most frequently used events are often those related to cache behavior

instructions per cycle could be computed from events:

- \texttt{PAPI\_TOT\_CYC and PAPI\_TOT\_INS}

L1 cache data miss rate could be computed from events:

- \texttt{PAPI\_L1\_DCM and PAPI\_L1\_DCA; or}
- \texttt{PAPI\_L1\_DCM and PAPI\_L1\_DCH; or}
- \texttt{PAPI\_L1\_DCM, PAPI\_LD\_INS, and PAPI\_SR\_INS}

L2 cache (total) miss rate could be computed from events:

- \texttt{PAPI\_L2\_TCM and PAPI\_L2\_TCA; or}
- \texttt{PAPI\_L2\_TCM and PAPI\_L2\_TCH; or}
- \texttt{PAPI\_L2\_TCM, PAPI\_LD\_INS, and PAPI\_SR\_INS}
```cpp
#include <iostream>
#include <papi.h>

void do_work() {
    for (volatile auto i = 1'000'000; i > 0; --i) {}
}

int main() {
    constexpr int num_events = 2;
    int events[num_events] = {PAPI_TOT_INS, PAPI_TOT_CYC};
    long long values[num_events];
    if (PAPI_start_counters(events, num_events) != PAPI_OK)
        {std::cerr << "cannot start counters\n"; return 1;}
    do_work();
    if (PAPI_stop_counters(values, num_events) != PAPI_OK)
        {std::cerr << "cannot stop counters\n"; return 1;}
    for (auto i : values) {std::cout << i << '\n';}
}
```
PAPI Low-Level Interface

- several dozen functions available in low-level API
- provides increased efficiency and functionality
- can obtain more detailed information about hardware
- low-level interface works with event sets
  - **event set**: set of events to be monitored
- some low-level API functions listed on next slide
- low-level interface functions do not initialize library (so `PAPI_library_init` must be called explicitly)
Some Functions in PAPI Low-Level Interface

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAPI_library_init</td>
<td>initialize PAPI library</td>
</tr>
<tr>
<td>PAPI_shutdown</td>
<td>cleanup PAPI library</td>
</tr>
<tr>
<td>PAPI_create_eventset</td>
<td>create event set</td>
</tr>
<tr>
<td>PAPI_destroy_eventset</td>
<td>destroys empty event set</td>
</tr>
<tr>
<td>PAPI_cleanup_eventset</td>
<td>removes all events from event set</td>
</tr>
<tr>
<td>PAPI_add_event</td>
<td>add preset or native hardware event to event set</td>
</tr>
<tr>
<td>PAPI_add_events</td>
<td>add multiple preset or native hardware events to event set</td>
</tr>
<tr>
<td>PAPI_start</td>
<td>start counting hardware events in event set</td>
</tr>
<tr>
<td>PAPI_read</td>
<td>read hardware counters from event set</td>
</tr>
<tr>
<td>PAPI_reset</td>
<td>reset hardware event counts in event set</td>
</tr>
<tr>
<td>PAPI_accum</td>
<td>adds hardware counters from event set to elements in array and resets counters</td>
</tr>
<tr>
<td>PAPI_stop</td>
<td>stop counting hardware events in event set</td>
</tr>
</tbody>
</table>
#include <iostream>
#include <papi.h>

void do_work() {for (volatile auto i = 1’000’000; i > 0; --i) {}}

int main() {
  constexpr int num_events = 2;
  int event_set = PAPI_NULL;
  int events[num_events] = {PAPI_TOT_INS, PAPI_TOT_CYC};
  long long values[num_events];
  if (PAPI_library_init(PAPI_VER_CURRENT) != PAPI_VER_CURRENT)
    {std::cerr << "cannot initialize\n"; return 1;}
  if (PAPI_create_eventset(&event_set) != PAPI_OK)
    {std::cerr << "cannot create event set\n"; return 1;}
  if (PAPI_add_events(event_set, events, num_events) != PAPI_OK)
    {std::cerr << "cannot add events\n"; return 1;}
  if (PAPI_start(event_set) != PAPI_OK)
    {std::cerr << "cannot start\n"; return 1;}
  do_work();
  if (PAPI_stop(event_set, values) != PAPI_OK)
    {std::cerr << "cannot stop\n"; return 1;}
  if (PAPI_cleanup_eventset(event_set) != PAPI_OK)
    {std::cerr << "cannot cleanup event set\n"; return 1;}
  if (PAPI_destroy_eventset(&event_set) != PAPI_OK)
    {std::cerr << "cannot destroy event set\n"; return 1;}
  for (auto i : values) {std::cout << i << 'n';}
}
# PAPI Utilities

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>papi_avail</td>
<td>provides availability and detail information for PAPI preset events</td>
</tr>
<tr>
<td>papi_clockres</td>
<td>measures and reports clock latency and resolution for PAPI timers</td>
</tr>
<tr>
<td>papi_cost</td>
<td>computes execution time costs for basic PAPI operations</td>
</tr>
<tr>
<td>papi_command_line</td>
<td>executes PAPI preset or native events from command line</td>
</tr>
<tr>
<td>papi_decode</td>
<td>provides availability and detail information for PAPI preset events</td>
</tr>
<tr>
<td>papi_event_chooser</td>
<td>given list of named events, lists other events that can be counted with them</td>
</tr>
<tr>
<td>papi_mem_info</td>
<td>provides information on memory architecture of current processor</td>
</tr>
<tr>
<td>papi_native_avail</td>
<td>provides detailed information for PAPI native events</td>
</tr>
<tr>
<td>papi_version</td>
<td>provides version information for PAPI</td>
</tr>
</tbody>
</table>
Available events and hardware information.

<table>
<thead>
<tr>
<th>Name</th>
<th>Code</th>
<th>Avail</th>
<th>Deriv</th>
<th>Description (Note)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAPI_L1_DCM</td>
<td>0x80000000</td>
<td>Yes</td>
<td>No</td>
<td>Level 1 data cache misses</td>
</tr>
<tr>
<td>PAPI_L1_ICM</td>
<td>0x80000001</td>
<td>Yes</td>
<td>No</td>
<td>Level 1 instruction cache misses</td>
</tr>
<tr>
<td>PAPI_L2_DCM</td>
<td>0x80000002</td>
<td>Yes</td>
<td>Yes</td>
<td>Level 2 data cache misses</td>
</tr>
<tr>
<td>PAPI_L2_ICM</td>
<td>0x80000003</td>
<td>Yes</td>
<td>No</td>
<td>Level 2 instruction cache misses</td>
</tr>
<tr>
<td>PAPI_L3_DCM</td>
<td>0x80000004</td>
<td>No</td>
<td>No</td>
<td>Level 3 data cache misses</td>
</tr>
<tr>
<td>PAPI_L3_ICM</td>
<td>0x80000005</td>
<td>No</td>
<td>No</td>
<td>Level 3 instruction cache misses</td>
</tr>
<tr>
<td>PAPI_L1_TCM</td>
<td>0x80000006</td>
<td>No</td>
<td>Yes</td>
<td>Level 1 cache misses</td>
</tr>
<tr>
<td>PAPI_L2_TCM</td>
<td>0x80000007</td>
<td>Yes</td>
<td>No</td>
<td>Level 2 cache misses</td>
</tr>
<tr>
<td>PAPI_L3_TCM</td>
<td>0x80000008</td>
<td>Yes</td>
<td>No</td>
<td>Level 3 cache misses</td>
</tr>
</tbody>
</table>

[99 lines deleted]

Of 108 possible events, 43 are available, of which 14 are derived.

avail.c

PASSED
Memory Cache and TLB Hierarchy Information.

---

TLB Information.
There may be multiple descriptors for each level of TLB if multiple page sizes are supported.

L1 Data TLB:
- Page Size: 4 KB
- Number of Entries: 64
- Associativity: 4

Cache Information.

L1 Data Cache:
- Total size: 32 KB
- Line size: 64 B
- Number of Lines: 512
- Associativity: 8

L1 Instruction Cache:
- Total size: 32 KB
- Line size: 64 B
- Number of Lines: 512
- Associativity: 8

L2 Unified Cache:
- Total size: 256 KB
- Line size: 64 B
- Number of Lines: 4096
- Associativity: 8

[information for L3 Unified Cache deleted]
Available native events and hardware information.

PAPI Version : 5.3.2.0
Vendor string and code : GenuineIntel (1)
Model string and code : Intel(R) Core(TM) i7-3820QM CPU @ 2.70GHz (58)
CPU Revision : 9.000000
CPUID Info : Family: 6 Model: 58 Stepping: 9
CPU Max Megahertz : 3700
CPU Min Megahertz : 1200
Hdw Threads per core : 2
Cores per Socket : 4
Sockets : 1
NUMA Nodes : 1
CPUs per Node : 8
Total CPUs : 8
Running in a VM : no
Number Hardware Counters : 11
Max Multiplex Counters : 64

===============================================================================
Native Events in Component : perf_event
===============================================================================
<table>
<thead>
<tr>
<th>perf::L1-DCACHE-LOADS</th>
<th>L1 cache load accesses</th>
</tr>
</thead>
</table>

===============================================================================
Native Events in Component : coretemp
===============================================================================
| coretemp::hwmon0:temp1_input | degrees C, acpitz module, label ? |

Total events reported: 322
native_avail.c PASSED
Section 9.2.1

References

Section 9.3

Gprof
Gprof

- open-source tool for code-execution profiling
- can be used to collect statistics from program run, including:
  - amount of time spent in each function
  - how many times each function called
  - callers and callees of each function (i.e., call graph information)
- based on compiler instrumentation of code and sampling
- works with GCC and Clang compilers
- instrumentation added to code gathers function call information used to generate call graphs and function call counts
- timing of code execution accomplished by statistical sampling at run time
- program counter probed at regular intervals by interrupting program
- typical sampling period 100 or 1000 samples/second
Comments on Gprof

- since sampling is a statistical process, timing measurements are not exact (i.e., only a statistical approximation)
- if too few samples are taken (e.g., in case of a short-running program), timing measurements are very inaccurate
- overhead caused by instrumentation can be quite high (about 30% to 260%)
- overhead distorts timing measurements (e.g., instrumentation added to code changes code timing) so timing of code with and without profiling can potentially be quite different
- may not correctly handle multi-threaded applications
- cannot profile shared libraries
- cannot measure time spent in kernel mode (e.g., system calls); only user-space code profiled
- has difficulties with call graphs containing non-trivial cycles (e.g., mutual recursion)
command line interface has following form:

```
gprof [options] [executable_file] [profile_file...]```

- `executable_file` defaults to `a.out`
- `profile_file` defaults to `gmon.out`

some common options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-b</td>
<td>omit explanations of meaning of all fields in output</td>
</tr>
<tr>
<td>-I dirs</td>
<td>add directories <code>dirs</code> to search path for source files</td>
</tr>
<tr>
<td>-p</td>
<td>show flat profile</td>
</tr>
<tr>
<td>-q</td>
<td>show call graph</td>
</tr>
<tr>
<td>-h</td>
<td>print help information and exit</td>
</tr>
<tr>
<td>-s</td>
<td>summarize information in profile data files and write to <code>gmon.sum</code></td>
</tr>
</tbody>
</table>
Using Gprof

- compile and link program with `-pg` option; for example:
  
  ```
g++ -c -pg -g -O example_1.cpp  
g++ -c -pg -g -O example_2.cpp  
g++ -pg -g -O -o example example_1.o example_2.o
  ```

- run program which will produce profiling data file `gmon.out`; for example:
  ```example
  ```

- run `gprof` to analyze profiling data; for example:
  ```
gprof example
  ```

- several `gmon` files can be combined with `gprof -s` to accumulate data over several runs of program

- `gprof2dot` can be used to convert call graph to graphical form
output can be generated in following forms:
- flat profile
- call graph

flat profile reports:
- how much of total execution time spent in each function
- how many times each function called
- output sorted by percentage

call graph reports:
- for each function, which functions called it, which other functions it called, and how many times
- estimate of how much time spent in subroutines of each function

flat profile useful to identify most expensive functions

call graph useful to identify places where function calls could be eliminated
#include <algorithm>

constexpr int M = 1024;
constexpr int N = 1024;
constexpr int P = 1024;

// c += a * b
void naive_matmul(const double a[][N], const double b[][P], double c[][P]) {
    for (int i = 0; i < M; ++i) {
        for (int j = 0; j < N; ++j) {
            for (int k = 0; k < P; ++k) {
                c[i][j] += a[i][k] * b[k][j];
            }
        }
    }
}

// c += a * b
void improved_matmul(const double a[][N], const double b[][P], double c[][P]) {
    for (int i = 0; i < M; ++i) {
        for (int k = 0; k < P; ++k) {
            for (int j = 0; j < N; ++j) {
                c[i][j] += a[i][k] * b[k][j];
            }
        }
    }
}
```cpp
int main(int argc, char** argv) {
    static double a[M][N];
    static double b[N][P];
    static double c0[M][P];
    static double c1[M][P];
    std::fill_n(&a[0][0], M * N, 1.0);
    std::fill_n(&b[0][0], N * P, 1.0);
    std::fill_n(&c0[0][0], M * P, 0.0);
    naive_matmul(a, b, c0);
    std::fill_n(&a[0][0], M * N, 1.0);
    std::fill_n(&b[0][0], N * P, 1.0);
    std::fill_n(&c1[0][0], M * P, 0.0);
    improved_matmul(a, b, c1);
}
```
Flat Profile Information

- each row in table corresponds to function
- columns in table have following meanings:
  - % time: percentage of total running time of program used by this function
  - cumulative seconds: running sum of number of seconds accounted for by this function and those listed above it
  - self seconds: number of seconds accounted for by this function alone (i.e., excluding descendants)
  - calls: number of times this function was invoked if function is profiled, blank otherwise
  - self ms/call: average number of milliseconds spent in this function per call (excluding descendants) if function is profiled, blank otherwise
  - total ms/call: average number of milliseconds spent in this function and its descendants per call if function is profiled, blank otherwise
  - name: name of function
- entries in table sorted first by self seconds and then by function name
Flat profile:

Each sample counts as 0.01 seconds.

<table>
<thead>
<tr>
<th>time</th>
<th>cumulative</th>
<th>self</th>
<th>seconds</th>
<th>seconds</th>
<th>calls</th>
<th>s/call</th>
<th>s/call</th>
<th>name</th>
</tr>
</thead>
<tbody>
<tr>
<td>89.48</td>
<td>7.55</td>
<td>7.55</td>
<td></td>
<td></td>
<td>1</td>
<td>7.55</td>
<td>7.55</td>
<td>naive_matmul( double const (<em>) [1024], double const (</em>) [1024], double (*) [1024])</td>
</tr>
<tr>
<td>11.23</td>
<td>8.50</td>
<td>0.95</td>
<td></td>
<td></td>
<td>1</td>
<td>0.95</td>
<td>0.95</td>
<td>improved_matmul( double const (<em>) [1024], double const (</em>) [1024], double (*) [1024])</td>
</tr>
<tr>
<td>0.12</td>
<td>8.51</td>
<td>0.01</td>
<td></td>
<td></td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>main</td>
</tr>
<tr>
<td>0.00</td>
<td>8.51</td>
<td>0.00</td>
<td></td>
<td></td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>_GLOBAL__sub_I__Z12naive_matmulPA1024_KdS1_PA1024_d</td>
</tr>
</tbody>
</table>
Call Graph Information

- Table describes call graph of program.
- One multi-line entry in table per function, with each entry containing information for function and its callers and callees.
- Line with index number in left margin lists current function.
- Lines above current function list its callers.
- Lines below current function list its callees.
- For current function, fields have following meanings:
  - index: unique integer index for this function.
  - % time: percentage of total time spent in this function and its children.
  - self: total amount of time spent in this function.
  - children: total amount of time propagated into this function by its children.
  - called: number of times this function called nonrecursively (possibly followed by “+” and number of recursive calls).
  - name: name of this function (with index printed after it).
for each parent of current function, fields have following meanings:
- self: amount of time propagated directly from function into this parent
- children: amount of time propagated from function’s children into this parent
- called: number of times parent called function, followed by “/”, followed by total number of times function called
- name: name of this parent (with its index printed after name)

if parents of current function cannot be determined, “<spontaneous>” is printed in name field

for each child of current function, fields have following meanings:
- self: amount of time propagated directly from child to current function
- children: amount of time propagated from child’s children to current function
- called: number of times current function called child, followed by “/”, followed by total number of times child called
- name: name of function (followed by its index)
Example: Call Graph

Call graph

**granularity:** each sample hit covers 2 byte(s) for 0.12% of 8.51 seconds

<table>
<thead>
<tr>
<th>index</th>
<th>% time</th>
<th>self</th>
<th>children</th>
<th>called</th>
<th>name</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1]</td>
<td>100.0</td>
<td>0.01</td>
<td>8.50</td>
<td></td>
<td>main</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.55</td>
<td>0.00</td>
<td>1/1</td>
<td>naive_matmul(double const (<em>)[1024], double const (</em>)[1024], double (*)[1024]) [2]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.95</td>
<td>0.00</td>
<td>1/1</td>
<td>improved_matmul(double const (<em>)[1024], double const (</em>)[1024], double (*)[1024]) [3]</td>
</tr>
<tr>
<td>[2]</td>
<td>88.7</td>
<td>7.55</td>
<td>0.00</td>
<td>1</td>
<td>main</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>naive_matmul(double const (<em>)[1024], double const (</em>)[1024], double (*)[1024]) [2]</td>
<td></td>
</tr>
<tr>
<td>[3]</td>
<td>11.1</td>
<td>0.95</td>
<td>0.00</td>
<td>1</td>
<td>main</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>improved_matmul(double const (<em>)[1024], double const (</em>)[1024], double (*)[1024]) [3]</td>
<td></td>
</tr>
<tr>
<td>[10]</td>
<td>0.0</td>
<td>0.00</td>
<td>0.00</td>
<td>1</td>
<td>__libc_csu_init</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>__GLOBAL__sub_I__Z12naive_matmulPA1024_KdS1_PA1024_d</td>
<td></td>
</tr>
</tbody>
</table>

Index by function name

```
[10] __GLOBAL__sub_I__Z12naive_matmulPA1024_KdS1_PA1024_d (matmul_array.cpp) [3]
    improved_matmul(double const (*)[1024], double const (*)[1024], double (*)[1024])
[2] naive_matmul(double const (*)[1024], double const (*)[1024], double (*)[1024])
[1] main
```
Section 9.3.1

References

Callgrind is a Valgrind tool that collects function call graph information and measures the number of instructions executed and cache behavior for a program. It does not measure execution time per se, but provides sufficient information to make clock cycle estimates (as is done in KCachegrind). It can be used to determine cache hit/miss counts and miss rate on a program-wide, per function, and per source-code line basis. It simulates L1 instruction/data cache and L2 cache. Parameters for each cache can be specified (i.e., size, associativity, and line size) but default to values taken from the machine’s cache. The simplistic cache model only approximates real cache. It handles code in shared libraries and typically 15 to 100 times slower (depending on whether cache and branch simulation enabled).
The valgrind Command with Callgrind Tool

- command line interface has following form:
  
  valgrind [options] program [program_options]

- to use Callgrind tool, must specify --tool=callgrind option

- some tool-independent options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>--help</td>
<td>print help information and exit</td>
</tr>
<tr>
<td>--log-file=file</td>
<td>set file for log information to file</td>
</tr>
</tbody>
</table>

- some Callgrind-specific options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>--callgrind-out-file=file</td>
<td>sets output file to file; defaults to callgrind.out-$pid where $pid is process ID</td>
</tr>
<tr>
<td>--cache-sim=b</td>
<td>specifies if information on cache use should be collected, where $b is yes or no</td>
</tr>
<tr>
<td>--branch-sim=b</td>
<td>specifies if branching information should be collected, where $b is yes or no</td>
</tr>
</tbody>
</table>
command line interface has following form:

```
callgrind_annotate [options] $callgrind_out_file
```

some options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>--help</code></td>
<td>print help information and exit</td>
</tr>
<tr>
<td><code>--auto=b</code></td>
<td>specifies if all source files should be annotated, where $b$ is yes or no</td>
</tr>
</tbody>
</table>
Using Callgrind

- build code as one would normally (no compile-time instrumentation is needed); for example:
  ```
g++ -g -O -o array_sum array_sum.cpp
  ```

- run program using `valgrind` with Callgrind tool; for example:
  ```
  valgrind --tool=callgrind --cache-sim=yes \ 
  --log-file=callgrind.log \ 
  --callgrind-out-file=callgrind.out \ 
  ./array_sum
  ```

- display results with `callgrind_annotate`; for example:
  ```
callgrind_annotate --auto=yes callgrind.out
  ```

- alternatively, display results in graphical form with tool like KCachegrind (discussed later)
```cpp
#include <iostream>
#include <algorithm>

constexpr int M = 2048;
constexpr int N = 2048;

double naive_sum(const double a[][N]) {
    double sum = 0.0;
    for (int j = 0; j < N; ++j) {
        for (int i = 0; i < M; ++i)
            {sum += a[i][j];}
    }
    return sum;
}

double improved_sum(const double a[][N]) {
    double sum = 0.0;
    for (int i = 0; i < M; ++i) {
        for (int j = 0; j < N; ++j)
            {sum += a[i][j];}
    }
    return sum;
}
```
int main() {
    static double a[M][N];
    std::fill_n(&a[0][0], M * N, 1.0 / (M * N));
    std::cout << naive_sum(a) << '\n';
    static double b[M][N];
    std::fill_n(&b[0][0], M * N, 1.0 / (M * N));
    std::cout << improved_sum(b) << '\n';
}
Example: Callgrind

$ valgrind --tool=callgrind --cache-sim=yes --branch-sim=yes --log-file=callgrind.log --callgrind-out-file=callgrind.out ./array_sum

$ cat callgrind.log
==23469== Callgrind, a call-graph generating cache profiler
==23469== Copyright (C) 2002-2013, and GNU GPL'd, by Josef Weidendorfer et al.
==23469== Using Valgrind-3.10.1 and LibVEX; rerun with -h for copyright info
==23469== Command: ./array_sum
==23469== Parent PID: 23449
==23469== warning: L3 cache found, using its data for the LL simulation.
==23469== For interactive control, run 'callgrind_control -h'.
==23469== Events: Ir Dr Dw I1mr D1mr D1mw ILmr DLmr DLmw Bc Bcm Bi Bim
==23469== Collected: 70339139 9142838 8663373 1601 4738282 1051026 1585 4728422 1050172 17247597 30398 4923 423
==23469== I refs: 70,339,139
==23469== I1 misses: 1,601
==23469== LLi misses: 1,585
==23469== I1 miss rate: 0.0%
==23469== LLi miss rate: 0.0%
==23469== D refs: 17,806,211 (9,142,838 rd + 8,663,373 wr)
==23469== D1 misses: 5,789,308 (4,738,282 rd + 1,051,026 wr)
==23469== LLd misses: 5,778,594 (4,728,422 rd + 1,050,172 wr)
==23469== D1 miss rate: 32.5% (51.8% + 12.1% )
==23469== LLd miss rate: 32.4% (51.7% + 12.1% )
==23469== LL refs: 5,790,909 (4,739,883 rd + 1,051,026 wr)
==23469== LL misses: 5,780,179 (4,730,007 rd + 1,050,172 wr)
==23469== LL miss rate: 6.5% (5.9% + 12.1% )
==23469== Branches: 17,252,520 (17,247,597 cond + 4,923 ind)
==23469== Mispredicts: 30,821 (30,398 cond + 423 ind)
==23469== Mispred rate: 0.1% (0.1% + 8.5% )
Example: callgrind_annotate

$ callgrind_annotate callgrind.out array_sum.cpp

[Text deleted]

Ir Dr Dw Ilmr Dlmr Dlmw Ilmr Dlmr Dlmw Bc Bcm Bi Bim

| 4,097 | . | . | . | . | . | . | . | . | . | . | . |
| 4,096 | . | . | . | . | . | . | . | . | . | . | . |
| 8,390,656 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2,048 |
| 8,388,608 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4,194,304 | 2,063 |
| 8,388,608 | 4,194,304 | 0 | 0 | 4,194,304 | 0 | 0 | 4,194,304 | . | . | . | . |
| 4,096 | . | . | . | . | . | . | . | . | . | . | . |
| 8,388,608 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4,194,304 | 2,058 |
| 8,388,608 | 4,194,304 | 0 | 0 | 524,288 | 0 | 0 | 524,288 | . | . | . | . |
| 4,096 | . | . | . | . | . | . | . | . | . | . | . |
| 8,388,608 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4,194,304 | 2,058 |
| 8,388,608 | 4,194,304 | 0 | 0 | 524,288 | 0 | 0 | 524,288 | . | . | . | . |
| 4,096 | . | . | . | . | . | . | . | . | . | . | . |
| 8,378,459 | 4,194,305 | 0 | 1 | 4,194,305 | 0 | 1 | 4,194,305 | 0 | 4,196,352 | 2,066 |
| 8,378,366 | 4,194,305 | 0 | 0 | 524,289 | 0 | 0 | 524,289 | 0 | 4,196,352 | 2,061 |
| 4,096 | . | . | . | . | . | . | . | . | . | . | . |

Ir Dr Dw Ilmr Dlmr Dlmw Ilmr Dlmr Dlmw Bc Bcm Bi Bim

| 48 | 92 | 0 | 0 | 100 | 0 | 0 | 100 | 49 | 14 | 0 | 0 |

Percentage of events annotated

open-source call-graph profiling-data visualization tool
part of K Desktop Environment (KDE)
supports Callgrind data
allows graphical visualization of:
- call-graph relationships between functions (e.g., callers and callees)
- function costs/counts
- annotated source/assembly with costs/counts
allows much easier interpretation of Callgrind data (relative to callgrind_annotate)
to allow annotation of assembly, add \texttt{--dump-instr=yes} option to valgrind command for Callgrind
use command of form:
\texttt{kcachegrind $callgrind\_out\_file}
web site: \url{https://kcachegrind.github.io}
### KCachegrind Example: Source/Assembly Annotation

#### Copyright © 2015–2021 Michael D. Adams

#### Programming in C++

#### Version 2021-04-01

#### Callgrind Output

<table>
<thead>
<tr>
<th>Incl.</th>
<th>Self</th>
<th>Called</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.00</td>
<td>0.00</td>
<td></td>
<td>(0) 0x0000000000000000</td>
</tr>
<tr>
<td>99.35</td>
<td>0.00</td>
<td>1</td>
<td>0x0000000000000000</td>
</tr>
<tr>
<td>99.35</td>
<td>0.00</td>
<td>1</td>
<td>(below main)</td>
</tr>
<tr>
<td>99.31</td>
<td>218.07</td>
<td>4</td>
<td>main</td>
</tr>
</tbody>
</table>

#### Source Code

```c
int main() {
    static double a[M][N];
    std::fill_n(&a[0][0], M * N, 1.0 / (M * N));
    std::cout << "naive_sum(a) = \n";
    static double b[M][N];
    std::fill_n(&b[0][0], M * N, 1.0 / (M * N));
    std::cout << "improved_sum(b) = \n";
    return sum;
}
```

#### Assembly Instructions

<table>
<thead>
<tr>
<th>CESt</th>
<th>Hex</th>
<th>Assembly Instructions</th>
<th>Source Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 0853</td>
<td>75 f3</td>
<td>jne 400848 &lt;improved_sum(...)</td>
<td></td>
</tr>
<tr>
<td>40 0855</td>
<td>48 39 d7</td>
<td>cmp %rdx,%rdi</td>
<td></td>
</tr>
<tr>
<td>40 0858</td>
<td>75 e7</td>
<td>jne 400841 &lt;improved_sum(...)</td>
<td></td>
</tr>
<tr>
<td>40 085a</td>
<td>f3 c3</td>
<td>repz retq</td>
<td></td>
</tr>
<tr>
<td>40 085c</td>
<td>00 48 83 ec 18</td>
<td>sub $0x18,%rsp</td>
<td>array_sum.cpp:25</td>
</tr>
<tr>
<td>40 0860</td>
<td>00 b8 80 11 60 02</td>
<td>mov $0x2601180,%eax</td>
<td>array_sum.cpp:25</td>
</tr>
<tr>
<td>40 0865</td>
<td>00 f2 0f 10 05 4b 01 00</td>
<td>movsd $0x14b(%rip),%xmm0</td>
<td>array_sum.cpp:25</td>
</tr>
<tr>
<td>40 0866</td>
<td>00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 086d</td>
<td>00 48 8d 90 00 00 00 00 02</td>
<td>lea 0x2000000(%rax),%rdx</td>
<td>array_sum.cpp:25</td>
</tr>
<tr>
<td>40 0874</td>
<td>87 f2 0f 11 00</td>
<td>movsd %xmm0,(%rax)</td>
<td>stl_algobase.h:753</td>
</tr>
<tr>
<td>40 0878</td>
<td>0.59 48 83 c0 08</td>
<td>add $0x8,%rax</td>
<td>stl_algobase.h:752</td>
</tr>
<tr>
<td>40 087c</td>
<td>0.59 48 39 d0</td>
<td>cmp %rdx,%rax</td>
<td>stl_algobase.h:753</td>
</tr>
<tr>
<td>40 087f</td>
<td>0.59 7f f3</td>
<td>jne 400874 &lt;main+0x18&gt;</td>
<td>stl_algobase.h:753</td>
</tr>
<tr>
<td>40 0881</td>
<td>0.00 bf 80 11 60 02</td>
<td>mov $0x2601180,%edi</td>
<td>array_sum.cpp:25</td>
</tr>
<tr>
<td>40 0886</td>
<td>0.00 e8 7cf fi ff</td>
<td>callq 400807 &lt;naive_sum(...&gt; array_sum.cpp:20</td>
<td></td>
</tr>
</tbody>
</table>
```


---

### Call Graph

- callgrind.out
- naive_sum(double)
- array_sum.cpp
- stl_algobase.h
- Heap
- Stack

---

### Machine Code

- 0x00 7cf
- 0x00 61 06 20

---

### Source Code

```c
#include <iostream>

int main() {
    double a[M][N];
    std::fill_n(&a[0][0], M * N, 1.0 / (M * N));
    std::cout << "naive_sum(a) = \n";
    double b[M][N];
    std::fill_n(&b[0][0], M * N, 1.0 / (M * N));
    std::cout << "improved_sum(b) = \n";
    return sum;
}
```

---

### Machine Code

- 0x00 7cf
- 0x00 61 06 20

---

### Call Graph

- callgrind.out
- naive_sum(double)
- array_sum.cpp
- stl_algobase.h
- Heap
- Stack

---

### Machine Code

- 0x00 7cf
- 0x00 61 06 20
### KCachegrind Example

**Version 2021-04-01**

**callgrind.out [array_sum]**

#### Flat Profile

<table>
<thead>
<tr>
<th>Incl.</th>
<th>Self</th>
<th>Called</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.00</td>
<td>0.00</td>
<td>0.00</td>
<td>(0) 0x0000000000000000</td>
</tr>
<tr>
<td>99.35</td>
<td>0.00</td>
<td>1.00</td>
<td>0x00000000000040</td>
</tr>
<tr>
<td>99.35</td>
<td>0.00</td>
<td>1.00</td>
<td>(below main)</td>
</tr>
<tr>
<td>99.31</td>
<td>21.07</td>
<td>1.00</td>
<td>main</td>
</tr>
<tr>
<td>67.68</td>
<td>67.68</td>
<td>1.00</td>
<td>naive_sum(double)</td>
</tr>
<tr>
<td>10.54</td>
<td>10.54</td>
<td>1.00</td>
<td>improved_sum(double)</td>
</tr>
<tr>
<td>0.62</td>
<td>0.00</td>
<td>1.00</td>
<td>_dl_start</td>
</tr>
<tr>
<td>0.62</td>
<td>0.00</td>
<td>1.00</td>
<td>_dl_sysdep_start</td>
</tr>
<tr>
<td>0.62</td>
<td>0.00</td>
<td>1.00</td>
<td>_dl_main</td>
</tr>
<tr>
<td>0.39</td>
<td>0.11</td>
<td>1.00</td>
<td>_dl_relocate_object</td>
</tr>
<tr>
<td>0.50</td>
<td>0.13</td>
<td>1.808</td>
<td>_dl_lookup_symbol</td>
</tr>
<tr>
<td>0.37</td>
<td>0.23</td>
<td>1.808</td>
<td>do_lookup_x</td>
</tr>
<tr>
<td>0.14</td>
<td>0.07</td>
<td>10.732</td>
<td>check_match.isra</td>
</tr>
<tr>
<td>0.07</td>
<td>0.02</td>
<td>6.221</td>
<td>strncmp</td>
</tr>
<tr>
<td>0.04</td>
<td>0.04</td>
<td>32.594</td>
<td>strncmp</td>
</tr>
<tr>
<td>0.04</td>
<td>0.00</td>
<td>92.00</td>
<td>_dl_runtime_resolve</td>
</tr>
<tr>
<td>0.04</td>
<td>0.00</td>
<td>92.00</td>
<td>_dl_fixup</td>
</tr>
<tr>
<td>0.03</td>
<td>0.00</td>
<td>1.00</td>
<td>__libc_csu_init</td>
</tr>
<tr>
<td>0.03</td>
<td>0.00</td>
<td>1.00</td>
<td>GLOBAL_sub_1</td>
</tr>
<tr>
<td>0.03</td>
<td>0.00</td>
<td>1.00</td>
<td>std::ios_base::Init</td>
</tr>
<tr>
<td>0.03</td>
<td>0.00</td>
<td>1.00</td>
<td>_dl_init</td>
</tr>
<tr>
<td>0.03</td>
<td>0.00</td>
<td>1.00</td>
<td>call_init.part.0</td>
</tr>
<tr>
<td>0.03</td>
<td>0.00</td>
<td>1.00</td>
<td>GLOBAL_sub_1</td>
</tr>
<tr>
<td>0.03</td>
<td>0.00</td>
<td>1.00</td>
<td>malloc</td>
</tr>
<tr>
<td>0.03</td>
<td>0.00</td>
<td>1.00</td>
<td>malloc_hook_init</td>
</tr>
<tr>
<td>0.03</td>
<td>0.00</td>
<td>1.00</td>
<td>ptmalloc_init.part.0</td>
</tr>
<tr>
<td>0.02</td>
<td>0.02</td>
<td>22.00</td>
<td>std::locale::locale</td>
</tr>
<tr>
<td>0.02</td>
<td>0.02</td>
<td>22.00</td>
<td>std::locale::S_in</td>
</tr>
<tr>
<td>0.02</td>
<td>0.00</td>
<td>1.00</td>
<td>std::locale::S_in</td>
</tr>
<tr>
<td>0.02</td>
<td>0.00</td>
<td>1.00</td>
<td>std::locale::impl</td>
</tr>
<tr>
<td>0.01</td>
<td>0.00</td>
<td>2.00</td>
<td>std::ostream &amp; str</td>
</tr>
<tr>
<td>0.01</td>
<td>0.00</td>
<td>12.00</td>
<td>_dl_catch_error</td>
</tr>
<tr>
<td>0.01</td>
<td>0.00</td>
<td>12.00</td>
<td>_dl_map_object</td>
</tr>
</tbody>
</table>

#### Event Type

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Incl.</th>
<th>Self</th>
<th>Short</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Write Access</td>
<td>96.87</td>
<td>96.83</td>
<td>Dw</td>
<td></td>
</tr>
<tr>
<td>L1 Instr. Fetch Miss</td>
<td>14.80</td>
<td>0.37</td>
<td>L1mr</td>
<td></td>
</tr>
<tr>
<td>L1 Data Read Miss</td>
<td>99.59</td>
<td>0.00</td>
<td>D1mr</td>
<td></td>
</tr>
<tr>
<td>L1 Data Write Miss</td>
<td>99.77</td>
<td>0.00</td>
<td>D1mw</td>
<td></td>
</tr>
<tr>
<td>L1 Instr. Fetch Miss</td>
<td>14.89</td>
<td>0.32</td>
<td>L1mr</td>
<td></td>
</tr>
<tr>
<td>L1 Data Read Miss</td>
<td>99.80</td>
<td>0.00</td>
<td>D1mr</td>
<td></td>
</tr>
<tr>
<td>L1 Data Write Miss</td>
<td>99.86</td>
<td>99.85</td>
<td>D1mw</td>
<td></td>
</tr>
<tr>
<td>Conditional Branch</td>
<td>97.32</td>
<td>48.64</td>
<td>Bc</td>
<td></td>
</tr>
<tr>
<td>Mispredicted Cond. Branch</td>
<td>15.17</td>
<td>0.04</td>
<td>Bcm</td>
<td></td>
</tr>
<tr>
<td>Indirect Branch</td>
<td>1.91</td>
<td>0.12</td>
<td>Bi</td>
<td></td>
</tr>
<tr>
<td>Mispredicted Ind. Branch</td>
<td>13.48</td>
<td>0.95</td>
<td>Bim</td>
<td></td>
</tr>
<tr>
<td>L1 Miss Sum</td>
<td>99.60</td>
<td>18.11</td>
<td>L1m = L1mr + D1mr + D1mw</td>
<td></td>
</tr>
<tr>
<td>Last-level Miss Sum</td>
<td>99.79</td>
<td>18.14</td>
<td>LLM = L1mr + D1mr + D1mw</td>
<td></td>
</tr>
<tr>
<td>Mispredicted Branch</td>
<td>15.15</td>
<td>0.06</td>
<td>Bm = Bim + Bcm</td>
<td></td>
</tr>
</tbody>
</table>

#### Cycle Estimation

- **Main**
  - **Incl.** 99.31%
  - **Self** 99.31%
  - **Short** 67.68%
  - **Function** naive_sum(double const *) [2048]
  - **Incl.** 99.31%
  - **Self** 99.31%

---

**callgrind.out [array_sum] - Total Cycle Estimation Cost: 706 574 339**
Section 9.4.1

References
Part 10

Build Tools
Section 10.1

Build Tools
Build tools are programs that automate the creation of executable programs, libraries, and other artifacts from source code. Build tools also typically provide some basic facilities for testing and packaging the artifacts generated by the build process.

Building software requires careful tracking of:
- what items need to be built, and
- the dependencies between these items.

Dependency tracking is necessary to:
- determine the order in which items must be built, and
- minimize the number of items that need to be re-built when a change is made to the code.

In the case of very small projects, it may be feasible to perform the build process manually.

For larger projects, however, the build process is far too complex to manage by hand, and build tools are therefore needed.
Some examples of build tools include:

- CMake (a cross-platform tool)
- GNU Build System (also known as Autotools) (for Unix)
- Make (for Unix)
- MSBuild (for Microsoft Visual Studio under Microsoft Windows)
- Xcodebuild (for Apple Xcode)
Section 10.2

Make
make command

controls generation of executables and/or other non-source files from program’s source files

ever extremely popular tool for automating build process

available on many platforms (e.g., Unix, Microsoft Windows, Mac OS X); used extensively on Unix systems

very flexible

can handle building multiple programs consisting of hundreds of source files or single program consisting of only one source file

can be used to build almost anything (i.e., need not be a program)

for example, all materials for this course typeset using \LaTeX\ (e.g., coursepack, slides, handouts, exams), and make utility used to compile \LaTeX\ source code into PDF documents

one of most popular implementations of make is GNU Make

GNU Make web site: http://www.gnu.org/software/make
The `make` Command

- target is something that can be built, typically (but not necessarily) file such as executable file or object file
- `make` command driven by data file called makefile
- makefile usually named `Makefile` or `makefile`
- command-line usage:
  ```make [options] [targets]```
  - `targets`: zero or more targets to be built
  - `options`: zero or more options
- by default, looks for makefile called `makefile` and then `Makefile`
- if no targets are specified, will build first target specified in makefile
- only builds files that are out of date
- most common command-line options include:
  - `-n` show commands that would be executed but do not actually execute them
  - `-f makefile` use makefile `makefile`
Makefiles

- comment starts at hash character (i.e., “#”) and continues until end of line; example:
  
  # This comment continues until the end of the line.

- supports variables

- some important variables used by built-in rules:

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CXX</td>
<td>C++ compiler command</td>
</tr>
<tr>
<td>CXXFLAGS</td>
<td>C++ compiler options</td>
</tr>
<tr>
<td>LDFLAGS</td>
<td>linker options</td>
</tr>
</tbody>
</table>

- to assign value to variable, use equal sign; example:

  CXX = g++

- to substitute value of variable, use dollar sign followed by variable name in parentheses; example:

  $(CXX)
makefile specifies targets and rules for building targets.

Each rule in makefile has the following form:

```
targets : prerequisites
  commands
  ...
```

Indentation shown above must be with tab character and not spaces.

- `targets`: list of one or more targets.
- `prerequisites`: files on which targets depend (i.e., files used to produce targets).
- `commands`: actions that must be carried out to produce target from its prerequisites.
■ normally, each target associated with file of same name (and building target will create this file)

■ phony target: target that is not associated with any file

■ to identify target as phony make it prerequisite of special target called “. PHONY”; example (specify all as phony target):

  .PHONY: all

■ some special built-in variables that can be used in rules:

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$@$</td>
<td>target</td>
</tr>
<tr>
<td>$&lt;$</td>
<td>name of first prerequisite</td>
</tr>
<tr>
<td>$^$</td>
<td>names of all of prerequisites separated by spaces</td>
</tr>
</tbody>
</table>
CXX = g++    # The C++ compiler command.
CXXFLAGS = -g -O  # The C++ compiler options.
LDFLAGS =        # The linker options (if any).

# The all target builds all of the programs handled by
# the makefile.
# This target has the dependency chain:
#    all -> hello -> hello.o -> hello.cpp
all: hello

# The clean target removes all of the executable files
# and object files produced by the build process.
clean:
  rm -f hello *.

# The hello target builds the hello executable.
hello: hello.o
  $(CXX) $(CXXFLAGS) -o $@ $^ $(LDFLAGS)

# Indicate that the all and clean targets do not
# correspond to actual files.
.PHONY: all clean

# The following rule is effectively built into make and
# therefore need not be explicitly specified:
# hello.o: hello.cpp
# __$(CXX) $(CXXFLAGS) -c <$
all target: builds all of the programs handled by the makefile (e.g., hello)

clean target: removes all of the executable files and object files produced by build process (e.g., hello, hello.o)

although all and clean have no special meaning to make, very common practice to provide targets with these particular names in all makefiles

hello target: compiles and links the hello program

chain of dependencies for all target:
    all → hello → hello.o → hello.cpp

all and clean examples of phony targets
Section 10.2.1

References
Section 10.3

CMake
CMake is open-source cross-platform family of tools designed to build, test, and package software
controls software build process (e.g., compiling and linking) using simple platform- and compiler-independent configuration files
used in conjunction with native build environments
generates files appropriate for whatever build environment being used
supports native build environments such as Unix Make, Apple Xcode, and Microsoft Visual Studio
automatically generates dependency information for source files
supports parallel builds
created by Kitware (http://www.kitware.com)
web site: https://cmake.org
CMake has very large user base and is employed in many open-source and commercial projects.

Some users of CMake include:

- Blender (https://www.blender.org)
- Clang (http://clang.llvm.org)
- Computational Geometry Algorithms Library (CGAL) (http://www.cgal.org)
- JasPer Image Processing/Coding Tool Kit (http://www.ece.uvic.ca/~mdadams/jasper)
- K Desktop Environment (KDE) (https://www.kde.org)
- MySQL (https://www.mysql.com)
- Netflix (https://www.netflix.com)
- OpenCV (http://opencv.org)
- Qt (https://www.qt.io)
- Second Life (http://secondlife.com)
CMake build files: files used by CMake to describe build process for software project (i.e., `CMakeLists.txt` and other build files it references)

native build tool: program used to build code for particular software development environment being employed (e.g., `make` for Unix, `MSBuild` for Microsoft Visual Studio, and `xcodebuild` for Apple Xcode)

native build files: files used by native build tool to control build process (e.g., makefiles for Unix, project/solution files for Microsoft Visual Studio, and project files for Apple Xcode)

build process consists of two steps:

1. CMake used, with CMake build files as input, to produce native build files
2. native build tool invoked to build code using native build files generated by CMake

strictly speaking, CMake does not itself build code, but rather produces build files that can be used by native build tool to build code
- **source directory**: top-level directory of source tree for code to be built
- **binary directory**: directory under which all files generated by build process will be placed
- source directory must contain `CMakeLists.txt` file which is used to describe build process
- **cache**: file where CMake stores values of variables used for configuration of build process (i.e., `CMakeCache.txt` in binary directory)
- **build-system generator**: entity within CMake that produces native build files (i.e., build files targeting particular native build tool)
- CMake provides numerous generators (e.g., generators for Unix Make, Apple Xcode, and Microsoft Visual Studio)
- **build configuration**: description of build to be performed with particular set of parameters (e.g., optimized or debug version)
- some generators support multiple configurations using single build
- for generators that support only single configuration, need to specify which configuration to build
**In-Source Versus Out-of-Source Builds**

- **in-source build**: when binary directory chosen to be inside source tree (e.g., same as source directory)
- **out-of-source build**: when binary directory chosen to be outside source tree

When out-of-source build used, contents of source directory not modified in any way by build process.

In contrast, when in-source build used, build process can generate many new files under source directory.

Out-of-source builds have numerous advantages over in-source builds; in particular, out-of-source builds:

- Avoid cluttering source tree with many files generated by build process, which can cause numerous difficulties (e.g., interacting poorly with version control systems).
- Facilitate easy removal of all files generated by build process without risk of accidentally removing source files.
- Allow for multiple builds from single source tree (e.g., debug and release builds).

For above reasons, in-source builds should generally be avoided.
The `cmake` Command for Configuring

- To generate build files for a native build tool (i.e., configure), use a command of the form:

  ```
  cmake [options] [$srcdir]
  ```

- The source directory `$srcdir` may be optionally specified.

- The source and binary directories default to the current directory (resulting in an in-source build), but may both be set by using the `–S` and `–B` options.

- Some options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>–S srcdir</code></td>
<td>Set the source directory to <code>srcdir</code>.</td>
</tr>
<tr>
<td><code>–B bindir</code></td>
<td>Set the binary directory to <code>bindir</code>.</td>
</tr>
<tr>
<td><code>–D var=val</code></td>
<td>Set the CMake variable <code>var</code> to <code>val</code>.</td>
</tr>
<tr>
<td><code>–G gen</code></td>
<td>Set the build-system generator to <code>gen</code>.</td>
</tr>
<tr>
<td><code>--version</code></td>
<td>Print name/version banner and exit.</td>
</tr>
<tr>
<td><code>--help</code></td>
<td>Print usage information and exit.</td>
</tr>
<tr>
<td><code>--debug-output</code></td>
<td>Enable debugging output.</td>
</tr>
<tr>
<td><code>--trace</code></td>
<td>Enable tracing output.</td>
</tr>
</tbody>
</table>
Some supported generators include:

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unix_Makefiles</td>
<td>makefiles for Unix Make</td>
</tr>
<tr>
<td>Xcode</td>
<td>project files for Apple Xcode</td>
</tr>
<tr>
<td>Visual_Studio_15_2017</td>
<td>project files for Microsoft Visual Studio 15</td>
</tr>
<tr>
<td>Ninja</td>
<td>build files for Ninja build system</td>
</tr>
</tbody>
</table>

Some environment variables used by `cmake` include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMAKE_CONFIG_TYPE</td>
<td>The default build configuration.</td>
</tr>
<tr>
<td>CMAKE_BUILD_PARALLEL_LEVEL</td>
<td>The maximum number of concurrent processes to use when building.</td>
</tr>
<tr>
<td>CC</td>
<td>The command for compiling C source.</td>
</tr>
<tr>
<td>CFLAGS</td>
<td>The default compilation flags for compiling C source.</td>
</tr>
<tr>
<td>CXX</td>
<td>The command for compiling C++ source.</td>
</tr>
<tr>
<td>CXXFLAGS</td>
<td>The default compilation flags for compiling C++ source.</td>
</tr>
<tr>
<td>LDFLAGS</td>
<td>The default linker flags.</td>
</tr>
</tbody>
</table>
To invoke the native build tool in a platform-independent manner for the build files in the binary directory `$bindir`, use a command of the form:

```
cmake --build $bindir [$options]
```

Some options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>--target target</code></td>
<td>Build the target <code>target</code> instead of the default targets.</td>
</tr>
<tr>
<td><code>--config config</code></td>
<td>For a multi-configuration generator, select the build configuration <code>config</code>. For a single-configuration generator, this option is ignored.</td>
</tr>
<tr>
<td><code>--clean-first</code></td>
<td>Build the “clean” target first.</td>
</tr>
<tr>
<td><code>-j n</code></td>
<td>Set the maximum number of concurrent processes to <code>n</code>.</td>
</tr>
<tr>
<td><code>--</code></td>
<td>Pass the remaining options to the native build tool.</td>
</tr>
</tbody>
</table>
source directory \$SOURCE_DIR contains two files:

1. CMakeLists.txt
2. hello.cpp

commands to build with binary directory \$BINARY_DIR:

cmake -S\$SOURCE_DIR -B\$BINARY_DIR

cmake --build \$BINARY_DIR

\$SOURCE_DIR/hello.cpp

```cpp
#include <iostream>

int main() {std::cout << "Hello, World!\n";}
```

\$SOURCE_DIR/CMakeLists.txt

```cpp
# Specify minimum required version of CMake.
cmake_minimum_required(VERSION 3.1 FATAL_ERROR)

# Specify project and identify languages used.
project(hello LANGUAGES CXX)

# Add program target called hello.
add_executable(hello hello.cpp)
```

Copyright © 2015–2021 Michael D. Adams

Programming in C++

Version 2021-04-01

2659
Section 10.3.1

CMakeLists Files
- **project**: collection of source code to be built using CMake
- **target**: something to be built by build process, such as executable or library
- target typically associated with one or more source files
- target has numerous properties (e.g., compiler flags and linker flags)
- target names cannot contain whitespace
- by default, following build configurations are supported:

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Debug</td>
<td>basic debugging code/information enabled</td>
</tr>
<tr>
<td>Release</td>
<td>basic optimization enabled</td>
</tr>
<tr>
<td>RelWithDebInfo</td>
<td>optimized build with debugging code/information enabled as well</td>
</tr>
<tr>
<td>MinSizeRel</td>
<td>smallest (but not necessarily fastest) code</td>
</tr>
</tbody>
</table>
Comments and Commands

- comment starts with hash character (i.e., “#”) and continues until end of line
- file consists of sequence of commands
- command consists of following (in order):
  1. command name
  2. opening parenthesis
  3. whitespace-separated arguments
  4. closing parenthesis

- command example:
  cmake_minimum_required(VERSION 3.1)

- command names are case insensitive

- anything in double quotes treated as single argument; for example, as in:
  message("Hello World")

- backslash character can be used to escape character such as double quote; for example, as in:
  message("\${X} is not a variable expansion")
Variables

- variable name is sequence of one or more letters, digits, and underscore characters that does not begin with digit (e.g., `MATH_LIBRARY`, `i`)
- variable names are case sensitive
- value of variable can be treated as string or list of strings
- value of variable $X$ is accessed as `${X}`
- boolean tests are case insensitive
  - all of following considered false: `OFF`, `0`, `NO`, `FALSE`, `NOTFOUND`, `*NOTFOUND`, `IGNORE`
- variable can be internal or cache
- cache variable persists across separate invocations of `cmake` while internal variable does not
- internal variable take precedence over cache variable
Modules

- module is file containing re-usable piece of CMakeLists code
- normally use “.cmake” file name extension
- most modules can be classified into one of following categories:
  - find
  - system introspection
  - utility
- find module:
  - determines location of software elements such as header files and libraries
  - often module name starts with prefix “Find”
  - examples: FindBoost and FindOpenGL
- system introspection module:
  - provides information about target system or compiler (e.g., size of various types, availability of header files, compiler version)
  - often module name starts with prefix “Test” or “Check”
  - examples: CheckCXXSourceCompiles and CheckIncludeFile
- utility module:
  - provides additional functions/macros for convenience
  - example: ExternalProject
- module can be accessed via `include` command
- find module normally accessed via `find_package` command (instead of directly using `include` command)
Commonly-Used Variables

- **Source and binary directories:**
  - **CMAKE_BINARY_DIR.** The full path to the top-level directory of the current CMake build tree. For an in-source build, this is the same as CMAKE_SOURCE_DIR.
  - **CMAKE_SOURCE_DIR.** The full path to the top-level directory of the current CMake source tree. For an in-source build, this is the same as CMAKE_BINARY_DIR.
  - **CMAKE_CURRENT_SOURCE_DIR.** The full path to the source directory that is currently being processed by cmake.
  - **CMAKE_CURRENT_BINARY_DIR.** The full path to the binary directory that is currently being processed by cmake.

- **Build type:**
  - **CMAKE_BUILD_TYPE.** In the case of single-configuration generators, specifies the build type (e.g., Release, Debug, RelWithDebInfo, MinSizeRel). In the case of multi-configuration generators, unused.
  - **BUILD_SHARED_LIBS.** Specifies if all libraries created should default to shared (instead of static).
  - **BUILD_TESTING.** Specifies if testing is enabled (when the CTest module is used).
Commonly-Used Variables (Continued 1)

- **C++ compiler:**
  - **CMAKE_CXX_COMPILER_ID.** The C++ compiler in use (e.g., Clang, GNU, Intel, MSVC).
  - **CMAKE_CXX_STANDARD.** Used to initialize the `CXX_STANDARD` property on all targets, which selects version of C++ standard (e.g., 98, 11, and 14).
  - **CMAKE_CXX_STANDARD_REQUIRED.** Used to initialize the `CXX_STANDARD_REQUIRED` property of all targets. This property determines whether the specified version of C++ standard is required.
  - **CMAKE_CXX_COMPILER.** The compiler command used for C++ source code.
  - **CMAKE_CXX_FLAGS.** The compiler flags for compiling C++ source code.
  - **CMAKE_CXX_FLAGS_DEBUG.** The compiler flags for compiling C++ source code for a debug build.
  - **CMAKE_CXX_FLAGS_RELEASE.** The compiler flags for compiling C++ source code for a release build.
  - **CMAKE_CXX_FLAGS_RELWITHDEBINFO.** The compiler flags for compiling C++ source code for a release build with debug flags.
  - **CMAKE_CXX_FLAGS_MINSIZEREL.** The compiler flags for compiling C++ source code for a release build with minimum code size.
Linker:

- **CMAKE_EXE_LINKER_FLAGS.** The linker flags used to create executables. This variable also has configuration-specific variants, such as `CMAKE_EXE_LINKER_FLAGS_RELEASE`.
- **CMAKE_SHARED_LINKER_FLAGS.** The linker flags used to create shared libraries. This variable also has configuration-specific variants, such as `CMAKE_SHARED_LINKER_FLAGS_RELEASE`.
- **CMAKE_STATIC_LINKER_FLAGS.** The linker flags used to create static libraries. This variable also has configuration-specific variants, such as `CMAKE_STATIC_LINKER_FLAGS_RELEASE`.

Target OS:

- **CMAKE_SYSTEM_NAME.** The name of the target system’s OS (e.g., Linux, Windows, Darwin).
- **UNIX.** Specifies if the target system’s OS is UNIX (or UNIX-like).
- **APPLE.** Specifies if the target system’s OS is Mac OS X.
- **WIN32.** Specifies if the target system’s OS is Microsoft Windows (32- or 64-bit).
Commonly-Used Variables (Continued 3)

- Makefile builds:
  - CMAKE_VERBOSE_MAKEFILE. Enable/disable verbose output from Makefile builds.
  - CMAKE_RULE_MESSAGES. Specify if a progress message should be reported by each makefile rule.

- Other:
  - CMAKE_MODULE_PATH. The list of directories to search for CMake modules. (This is used by commands like include and find_package.)
  - CMAKE_PREFIX_PATH. The list of directories specifying installation prefixes to be searched by the find_package, find_program, find_library, and find_file commands.
  - CMAKE_PROJECT_NAME. The name of the current project.
  - CMAKE_CURRENT_LIST_DIR. The directory of the listfile currently being processed. (The values of CMAKE_CURRENT_SOURCE_DIR and CMAKE_CURRENT_LIST_DIR can differ, for example, when a listfile outside the current source directory is included.)
  - CMAKE_EXPORT_COMPILE_COMMANDS. Enable/disable output of compile commands during generation in file compile_commands.json.
Commonly-Used Commands

- **Initialization:**
  - `cmake_minimum_required`. Set the minimum required version of Cmake for a project.
  - `cmake_policy`. Manage CMake policy settings. (This is used to select between old and new behaviors in CMake.)
  - `project`. Set a name, version, and enable languages for the entire project. (If no languages specified, defaults to C and C++.)
  - `option`. Provide an option that the user can (optionally) select.

- **Adding targets:**
  - `add_executable`. Add a program target.
  - `add_library`. Add a library target.
  - `add_test`. Add a test target. (This is used in conjunction with the module CTest.)
  - `add_custom_target`. Add a target with no output file that is always out of date.
  - `add_custom_command`. Add a custom build rule to the generated build system.
Setting properties for a specific target:

- `target_compile_definitions`. Add compile definitions to a target.
- `target_compile_options`. Add compile options to a target.
- `target_include_directories`. Add include directories to a target.
- `target_link_libraries`. Add libraries to the list of libraries to be used for linking a target. (May be used multiple times for the same target.)
- `set_target_properties`. Set properties for a target. (Some properties include: `OUTPUT_NAME`, `SOVERSION`, and `VERSION`.)
Setting properties for all targets (which is usually best avoided):

- `add_compile_options`. Adds options to the compilation of source files in the current directory and below. (This command should precede an `add_executable` or `add_library` command.)
- `add_definitions`. Adds `-D` define flags to the compilation of source files in the current directory and below.
- `include_directories`. Add directories to the list of include directories used for compiling programs.
- `link_libraries`. Add libraries to the list of libraries used for linking programs. (This command appends to the list, each time it is invoked.)
- `link_directories`. Specify directories in which the linker is to look for libraries.

Processing other files or directories:

- `add_subdirectory`. Add a subdirectory to the build.
- `include`. Load and run CMake code from a file or module.
Querying external packages and programs:
- `find_package`. Load settings for an external software package (e.g., Doxygen, Threads, Boost, OpenGL, GLEW, GLUT, CGAL, PkgConfig).
- `find_library`. Find an external library.
- `find_program`. Find an external program.

Assignment, control flow, functions, and macros:
- `set`. Set a CMake, cache, or environment variable to a given value.
- `if`, `elseif`, `else`, and `endif`. Conditionally execute a group of commands.
- `foreach` and `endforeach`. Evaluate a group of commands for each value in a list.
- `while` and `endwhile`. Evaluate a group of commands while a condition is true.
- `function` and `endfunction`. Record a function for later invocation as a command.
- `macro` and `endmacro`. Record a macro for later invocation as a command.
■ String and list processing:
  - list. Perform operations on lists.
  - string. Perform operations on strings.

■ Other:
  - message. Display a message to the user.
  - configure_file. Copy a file to another location and modify its contents.
  - install. Specify rules to run at install time (e.g., rules to install programs, libraries, and header files).
  - math. Evaluate mathematical expressions.
  - file. Manipulate files.
  - enable_language. Enable a language.
Commonly-Used Modules

- **CheckIncludeFiles** module, which provides:
  - `check_include_files`. Check if the specified files can be included.

- **CheckCXXSourceCompiles** module, which provides:
  - `check_cxx_source_compiles`. Check if the specified C++ source code compiles and links to produce an executable.

- **CheckFunctionExists** module, which provides:
  - `check_function_exists`. Check if the specified C function is provided by libraries on the system.

- **CTest** module:
  - Configure a project for testing with CTest/CDash.

- **CPack** module:
  - Configure a project to use CPack to build binary and source package installers.

- **PkgConfig** module, which requires `pkg-config` tool to be available and provides:
  - `pkg_search_module`. Finds a package via `pkg-config`. 

Commonly-Used Modules (Continued 1)

- **ExternalProject module**, which provides:
  - `externalproject_add`. Create custom targets to build projects in external trees.

- **GNUInstallDirs module**:
  - Define GNU standard installation directories (e.g., `CMAKE_INSTALL_INCLUDEDIR`, `CMAKE_INSTALL_LIBDIR`, and `CMAKE_INSTALL_MANDIR`).

- **GenerateExportHeader module**, which provides:
  - `generate_export_header`. Generate a header file containing export macros to be used for a shared library.

- **CMakePackageConfigHelpers module**, which provides:
  - `configure_package_config_file`. Create a package configuration file for installing a project or library. (This should be used instead of `configure_file`.)
  - `write_basic_package_version_file`. Write a package version file.
Some Find and Pkg-Config Modules

- Boost
  - [https://cmake.org/cmake/help/v3.10/module/FindBoost.html](https://cmake.org/cmake/help/v3.10/module/FindBoost.html)
  - variables: Boost_FOUND, Boost_INCLUDE_DIRS, Boost_LIBRARY_DIRS, Boost_LIBRARIES
  - imported targets: Boost::boost, Boost::component

- CGAL (Computational Geometry Algorithms Library)
  - variables: CGAL_INCLUDE_DIRS, CGAL_LIBRARY, GMP_LIBRARIES

- Doxygen
  - [https://cmake.org/cmake/help/v3.10/module/FindDoxygen.html](https://cmake.org/cmake/help/v3.10/module/FindDoxygen.html)
  - variables: DOXYGEN_FOUND, DOXYGEN_EXECUTABLE
  - imported targets: Doxygen::doxygen, Doxygen::dot

- GLEW (OpenGL Extension Wrangler Library)
  - [https://cmake.org/cmake/help/v3.10/module/FindGLEW.html](https://cmake.org/cmake/help/v3.10/module/FindGLEW.html)
  - variables: GLEW_FOUND, GLEW_INCLUDE_DIRS, GLEW_LIBRARIES
  - imported targets: GLEW::GLEW

- GLFW (OpenGL Helper Library) [pkg-config module]
  - variables: GLFW_FOUND, GLFW_INCLUDE_DIRS, GLFW_LIBRARIES
Some Find and Pkg-Config Modules (Continued 1)

- GLUT (OpenGL Utility Toolkit)
  - [Link](https://cmake.org/cmake/help/v3.10/module/FindGLUT.html)
  - variables: GLUT_FOUND, GLUT_INCLUDE_DIR, GLUT_LIBRARIES
  - imported targets: GLUT::GLUT

- OpenGL (Open Graphics Library)
  - [Link](https://cmake.org/cmake/help/v3.10/module/FindOpenGL.html)
  - variables: OPENGL_FOUND, OPENGL_INCLUDE_DIR, OPENGL_LIBRARIES
  - imported targets: OpenGL::GL, OpenGL::GLU, OpenGL::GLX

- SPL (Signal/Geometry Processing Library)
  - variables: SPL_FOUND, SPL_INCLUDE_DIRS, SPL_LIBRARY_DIRS, SPL_LIBRARIES, SNDFILE_INCLUDE_DIRS, SNDFILE_LIBRARIES

- Threads
  - [Link](https://cmake.org/cmake/help/v3.10/module/FindThreads.html)
  - variables: CMAKE_THREAD_LIBS_INIT
  - imported targets: Threads::Threads
can set compiler options, compiler definitions, include directories, and link libraries in two ways:

1. **per target** (e.g., using `target_compile_options`, `target_compile_definitions`, `target_include_directories`, and `target_link_libraries`)
2. **globally** (e.g., using `add_compile_options`, `add_definitions`, `include_directories`, and `link_libraries`)

- per-target approach allows properties to be specified with finer granularity than global approach
- finer-granularity control over properties often necessary, especially when building more complex projects
- if executable targets in project do not all use same set of libraries, global specification of include directories and link libraries can introduce artificial dependencies on some libraries
- per-target specification of link libraries allows automatic propagation of library dependencies when hierarchies of libraries used (which, for example, may avoid need to link against same library multiple times)
Section 10.3.2

Examples
Hello World Example Revisited

**hello.cpp**

```cpp
#include <iostream>

int main() {std::cout << "Hello, World!\n";}
```

**CMakeLists.txt**

```cmake
# Specify minimum required version of CMake.
cmake_minimum_required(VERSION 3.1 FATAL_ERROR)

# Specify project and identify languages used.
project(hello LANGUAGES CXX)

# Print message indicating detected OS.
if (UNIX)
  set(platform "Unix")
elseif (WIN32)
  set(platform "Microsoft Windows")
else()
  set(platform "Unknown")
endif()
message("OS is \${platform}\")

# Add program target called hello.
add_executable(hello hello.cpp)
```
want to build and test hello-world program

code written in C++

files in project:
- CMakeLists.txt
- hello.cpp
- test_wrapper.in
- run_test

project has:
- executable target hello
- test target run_test
hello.cpp

```cpp
#include <iostream>

int main() { std::cout << "Hello, World!\n"; }
```

test_wrapper.in (with execute permission set)

```sh
#!/bin/sh
# Initialize the environment for the command being invoked.
export CMAKE_SOURCE_DIR="@CMAKE_SOURCE_DIR@"
export CMAKE_BINARY_DIR="@CMAKE_BINARY_DIR@"
"$@"
```

run_test

```sh
#!/bin/sh
# Test if the hello program produces the desired output.
($CMAKE_BINARY_DIR/hello | grep "^Hello, World!$") || \
exit 1
```
CMakeLists.txt

1    # Specify minimum required version of CMake.
2    cmake_minimum_required(VERSION 3.1 FATAL_ERROR)

# Specify project and identify languages used.
project(hello LANGUAGES CXX)

# Include the CTest module for testing.
include(CTest)

# Find the Bourne shell.
find_program(sh SH_COMMAND)

# Add program target called hello.
add_executable(hello hello.cpp)

# Create a wrapper script that initializes the environment
# for any test scripts.
configure_file(${CMAKE_SOURCE_DIR}/test_wrapper.in
    ${CMAKE_BINARY_DIR}/test_wrapper @ONLY)

# Add a test that invokes run_test via a wrapper script.
add_test(run_test ${SH_COMMAND}
    ${CMAKE_BINARY_DIR}/test_wrapper
    ${CMAKE_BINARY_DIR}/run_test)
want to build simple multithreaded program using pthread library

code written in C++

files in project:
  - CMakeLists.txt
  - hello.cpp

project has:
  - executable target hello
hello.cpp

```cpp
#include <iostream>
#include <thread>

int main() {
  std::thread t1([](){std::cout << "Hello, World!\n";});
  t1.join();
}
```

CMakeLists.txt

```cmake
cmake_minimum_required(VERSION 3.4 FATAL_ERROR)
project(threads_example LANGUAGES CXX)

# Require compliance with C++11 standard.
set(CMAKE_CXX_STANDARD 11)
set(CMAKE_CXX_STANDARD_REQUIRED TRUE)

# Find the threads library, indicating a preference for the # pthread library.
set(THREADS_PREFER_PTHREAD_FLAG ON)
find_package(Threads REQUIRED)

# Define a program target called hello.
add_executable(hello hello.cpp)

# Set the libraries for the hello target.
target_link_libraries(hello Threads::Threads)
```
Boost Log Example

- want to build simple program using Boost Log
- code written in C++
- uses Log component of Boost library
- files in project:
  - CMakeLists.txt
  - main.cpp
- project has:
  - executable target my_app
main.cpp

```cpp
#include <boost/log/trivial.hpp>

int main() {
    BOOST_LOG_TRIVIAL(warning) << "A warning severity message";
    BOOST_LOG_TRIVIAL(error) << "An error severity message";
    BOOST_LOG_TRIVIAL(fatal) << "A fatal severity message";
}
```
CMakeLists.txt

1  cmake_minimum_required(VERSION 3.4 FATAL_ERROR)
2  project(boost_example LANGUAGES CXX)
3
4  # Find the required libraries (i.e., POSIX threads and Boost).
5  set(Boost_USE_MULTITHREADED ON)
6  find_package(Threads REQUIRED)
7  find_package(Boost 1.54.0 REQUIRED COMPONENTS log)
8
9  # Define a program target called my_app.
10  add_executable(my_app main.cpp)
11
12  # Set the includes, defines, and libraries for the my_app target.
13  target_include_directories(my_app PUBLIC ${Boost_INCLUDE_DIRS})
14  target_compile_definitions(my_app PUBLIC "-DBOOST_LOG_DYN_LINK")
15  target_link_libraries(my_app ${Boost_LIBRARIES}
16     ${CMAKE_THREAD_LIBS_INIT})
CMakeLists.txt

1    cmake_minimum_required(VERSION 3.5 FATAL_ERROR)
2    project(boost_example LANGUAGES CXX)
3
4    # Find the required libraries (i.e., POSIX threads and Boost).
5    set(Boost_USE_MULTITHREADED ON)
6    find_package(Threads REQUIRED)
7    find_package(Boost 1.54.0 REQUIRED COMPONENTS log)
8
9    # Define a program target called my_app.
10   add_executable(my_app main.cpp)
11
12   # Set the defines, includes, and libraries for the my_app target.
13   target_compile_definitions(my_app PUBLIC "-DBOOST_LOG_DYN_LINK")
14   target_link_libraries(my_app Boost::log Threads::Threads)
want to build simple OpenGL/GLFW application

code written in C++

uses OpenGL and GLFW libraries (as well as GLEW library)

files in project:

- CMakeLists.txt
- trivial.cpp

project has:

- executable target trivial
trivial.cpp

```c
#include <cstdlib>
#include <GLFW/glfw3.h>

void display(GLFWwindow* window) {
    glfwMakeContextCurrent(window);
    glClearColor(0.0, 1.0, 1.0, 0.0);
    glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
    glfwSwapBuffers(window);
}

int main(int argc, char** argv) {
    if (!glfwInit()) {return EXIT_FAILURE;}
    glfwSwapInterval(1);
    GLFWwindow* window = glfwCreateWindow(512, 512, argv[0], nullptr, nullptr);
    if (!window) {
        glfwTerminate();
        return EXIT_FAILURE;
    }
    glfwSetWindowRefreshCallback(window, display);
    while (!glfwWindowShouldClose(window)) {
        glfwWaitEvents();
    }
    glfwTerminate();
    return EXIT_SUCCESS;
}
```
CMakeLists.txt

1  cmake_minimum_required(VERSION 3.2 FATAL_ERROR)
2  project(opengl_example LANGUAGES CXX)
3  set(CMAKE_CXX_STANDARD 11)
4  set(CMAKE_CXX_STANDARD_REQUIRED TRUE)

5  # Find the required libraries (i.e., OpenGL, GLEW, and GLFW).
6  find_package(OpenGL REQUIRED)
7  find_package(GLEW REQUIRED)
8  find_package(PkgConfig REQUIRED)
9  pkg_search_module(GLFW REQUIRED glfw3)
10
11  # Define a program target called trivial.
12  add_executable(trivial trivial.cpp)

13  # Set the includes and libraries for the trivial target.
14  target_include_directories(trivial PUBLIC ${GLFW_INCLUDE_DIRS}
15     ${GLEW_INCLUDE_DIRS} ${OPENGL_INCLUDE_DIR})
16  target_link_libraries(trivial ${GLFW_LIBRARIES} ${GLEW_LIBRARIES}
17     ${OPENGL_LIBRARIES})
CMakeLists.txt

```cmake
# Find the required libraries (i.e., OpenGL, GLEW, and GLFW).
foundation(OpenGL REQUIRED)
foundation(GLEW REQUIRED)
foundation(PkgConfig REQUIRED)
pkg_search_module(GLFW REQUIRED glfw3)

# Define a program target called trivial.
add_executable(trivial trivial.cpp)

# Set the includes and libraries for the trivial target.
target_include_directories(trivial PUBLIC ${GLFW_INCLUDE_DIRS})
target_link_libraries(trivial ${GLFW_LIBRARIES} GLEW::GLEW OpenGL::GL)
```
want to build simple OpenGL/GLUT application

code written in C++

uses OpenGL and GLUT libraries

files in project:

- CMakeLists.txt
- trivial.cpp

project has:

- executable target trivial
trivial.cpp

```cpp
#include <GL/glut.h>

void display() {
    glClearColor(0.0, 1.0, 1.0, 0.0);
    glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
    glutSwapBuffers();
}

int main(int argc, char** argv) {
    glutInit(&argc, argv);
    glutInitDisplayMode(GLUT_DOUBLE | GLUT_RGB);
    glutInitWindowSize(512, 512);
    glutCreateWindow(argv[0]);
    glutDisplayFunc(display);
    glutMainLoop();
}
```
CMakeLists.txt

```cmake
1 cmake_minimum_required(VERSION 3.9 FATAL_ERROR)
2 project(opengl_example LANGUAGES CXX)

# Find the required libraries (i.e., OpenGL and GLUT).
3 find_package(OpenGL REQUIRED)
4 find_package(GLUT REQUIRED)

# Define a program target called trivial.
5 add_executable(trivial trivial.cpp)

# Set the includes and libraries for the trivial target.
6 target_include_directories(trivial PUBLIC ${GLUT_INCLUDE_DIR}
7   ${OPENGL_INCLUDE_DIR})
8 target_link_libraries(trivial ${GLUT_LIBRARIES} ${OPENGL_LIBRARIES})
```
CMakeLists.txt

1  cmake_minimum_required(VERSION 3.8 FATAL_ERROR)
2  project(opengl_example LANGUAGES CXX)

4  # Find the required libraries (i.e., OpenGL and GLUT).
5  find_package(OpenGL REQUIRED)
6  find_package(GLUT REQUIRED)

7  # Define a program target called trivial.
8  add_executable(trivial trivial.cpp)

11  # Set the includes and libraries for the trivial target.
12  target_link_libraries(trivial GLUT::GLUT OpenGL::GL)
want to build simple CGAL application

code written in C++

uses CGAL library (as well as GMP library)

files in project:

- CMakeLists.txt
- orient_test.cpp

project has:

- executable target orient_test
#orient_test.cpp

```cpp
#include <iostream>
#include <string>
#include <CGAL/Cartesian.h>
#include <CGAL/Filtered_kernel.h>

std::string toString(CGAL::Orientation orient) {
    switch (orient) {
    case CGAL::LEFT_TURN:
        return "left turn";
    case CGAL::RIGHT_TURN:
        return "right turn";
    case CGAL::COLLINEAR:
        return "collinear";
    }
}

int main(int argc, char** argv) {
    using Point = CGAL::Point_2<
        CGAL::Filtered_kernel<
            CGAL::Cartesian<double>>
    >;
    Point a, b, q;
    while (std::cin >> a >> b >> q) {
        auto orient = CGAL::orientation(a, b, q);
        std::cout << toString(orient) << '\n';
    }
}
```
# Specify minimum required version of CMake.
cmake_minimum_required(VERSION 3.1 FATAL_ERROR)

# Specify project and enable the C++ language.
project(cgal_demo LANGUAGES CXX)

# Find the required CGAL package.
find_package(CGAL REQUIRED)

# On some systems, GCC may need the -frounding-math option.
if (CMAKE_CXX_COMPILER_ID MATCHES GNU)
    add_compile_options("-frounding-math")
endif()

# Add a program target called orient_test.
add_executable(orient_test orient_test.cpp)

# Specify the includes and libraries for the orient_test target.
target_include_directories(orient_test PUBLIC ${CGAL_INCLUDE_DIRS})
target_link_libraries(orient_test ${CGAL_LIBRARY} ${GMP_LIBRARIES})
want to be able to build and install HG2G library and application that uses library

code written in C++

files in project:

- CMakeLists.txt
- app/CMakeLists.txt
- app/answer.cpp
- hg2g/CMakeLists.txt
- hg2g/answer.cpp
- hg2g/question.cpp
- hg2g/include/hg2g/answer.hpp
- hg2g/include/hg2g/config.hpp.in

project has:

- library target hg2g
- executable target answer
- option HG2G_ZAPHOD (which takes a boolean value)
HG2G Example: Library Source Code

hg2g/include/hg2g/config.hpp.in

```c
#ifndef HG2G_CONFIG_H
#define HG2G_CONFIG_H
#define HG2G_VERSION "@HG2G_VERSION@"
cmakedefine HG2G_ZAPHOD
#endif
```

hg2g/include/hg2g/answer.hpp

```c
#include <string>
namespace hg2g {
std::string answer_to_ultimate_question();
std::string ultimate_question();
}
```

hg2g/answer.cpp

```c
#include "hg2g/answer.hpp"
namespace hg2g {
std::string answer_to_ultimate_question() {return "42";}
}
```

hg2g/question.cpp

```c
#include "hg2g/answer.hpp"
namespace hg2g {
std::string ultimate_question() {throw 42;}
}
```
```cpp
#include <iostream>
#include <hg2g/config.hpp>
#include <hg2g/answer.hpp>

int main() {
    #ifdef HG2G_ZAPHOD
        std::cout << "HG2G_ZAPHOD is defined\n";
    #endif

    std::cout << "According to version " << HG2G_VERSION << " of the HG2G library:\n";
    std::cout << "The answer to the ultimate question is " <<
    hg2g::answer_to_ultimate_question() << ".\n";
}
```
CMakeLists.txt

1  cmake_minimum_required(VERSION 3.1 FATAL_ERROR)
2  project(hg2g_example LANGUAGES CXX)
3  option(HG2G_ZAPHOD "Define HG2G_ZAPHOD" FALSE)
4  
5  # Set the version number and name.
6  set(HG2G_VERSION_MAJOR 1)
7  set(HG2G_VERSION_MINOR 42)
8  set(HG2G_VERSION_PATCH 0)
9  string(CONCAT HG2G_VERSION "${HG2G_VERSION_MAJOR}"
10     ".${HG2G_VERSION_MINOR}" ".${HG2G_VERSION_PATCH}")
11  
12  # Process the subdirectories hg2g and app.
13  add_subdirectory(hg2g)
14  add_subdirectory(app)

app/CMakeLists.txt

1  # Add a program target called answer.
2  add_executable(answer answer.cpp)
3  
4  # Link the answer program against the hg2g library.
5  target_link_libraries(answer hg2g)
6  
7  # Install the answer program in the bin directory.
8  install(TARGETS answer DESTINATION bin)
# Place the names of the header and source files into variables (for convenience).
set(hg2g_headers include/hg2g/answer.hpp
 "${CMAKE_CURRENT_BINARY_DIR}/include/hg2g/config.hpp")
set(hg2g_sources answer.cpp question.cpp)

# Add a library target called hg2g.
add_library(hg2g ${hg2g_sources} ${hg2g_headers})

# Specify the include directories for library.
target_include_directories(hg2g PUBLIC
 include
 "${CMAKE_CURRENT_BINARY_DIR}/include")

# Create a header file containing the config information.
configure_file(
   include/hg2g/config.hpp.in
   "${CMAKE_CURRENT_BINARY_DIR}/include/hg2g/config.hpp")

# Install the library in the lib directory.
install(TARGETS hg2g DESTINATION lib)

# Install the header files in the include/hg2g directory.
install(FILES ${hg2g_headers} DESTINATION include/hg2g)
hello, hg2g, and example_100 are subdirectories containing CMake projects

CMakeLists.txt

```cmake
1 cmake_minimum_required(VERSION 3.1 FATAL_ERROR)
2 # Specify the project and do not enable any languages.
3 project(examples LANGUAGES CXX)
4 # Include the module for external project functionality.
5 include(ExternalProject)
6 # Create a list of the subdirectories containing
7 # CMake projects to be built.
8 list(APPEND dirs hello hg2g "example 100")
9 # Add each project as an external project.
10 foreach(dir IN LISTS dirs)
11   # Set target name to directory name with any
12   # spaces changed to underscores.
13   string(REPLACE " " "_" target "${dir}")
14   # Add external project.
15   externalproject_add("${target}"
16       SOURCE_DIR "${CMAKE_SOURCE_DIR}/${dir}"
17       BINARY_DIR "${CMAKE_BINARY_DIR}/${dir}"
18       CMAKE_ARGS
19       "-DCMAKE_CXX_COMPILER=${CMAKE_CXX_COMPILER}"
20       INSTALL_COMMAND "")
21 endforeach()
```
want to build \LaTeX{} document (i.e., produce PDF document from \LaTeX{} source)

files in project:

- CMakeLists.txt
- main.tex
- bib.bib
- cmake_modules/UseLATEX.cmake


```latex
\documentclass{article}
\usepackage{graphicx}
\author{John Doe}
\title{Why I Like C++}
\begin{document}
\maketitle
\section{Why I Like C++}
What can I say?
\cite{TCPL4} is a great language!
\includegraphics[width=1in, height=1in, keepaspectratio]{cpp.png}
\bibliographystyle{plain}
\bibliography{bib}
\end{document}
```

```bib
@book{TCPL4,
author = "B. Stroustrup",
title = "The \{C++\} Programming Language",
edition = "4th",
publisher = "Addison Wesley",
year = 2013
}
```
CMakeLists.txt

```cmake
# Specify the project name and indicate that no languages
# should be enabled.
project(my_doc NONE)

# Add the cmake_modules directory to the module search path.
set(CMAKE_MODULE_PATH ${CMAKE_MODULE_PATH}
    ${CMAKE_SOURCE_DIR}/cmake_modules)

# Include the UseLATEX module.
include(UseLATEX)

# Specify the properties of the LaTeX document such as its
# constituent source files (e.g., LaTeX, BibTeX, images,
# figures, etc.)
add_latex_document(main.tex IMAGES cpp.png BIBFILES bib.bib)
```

cmake_modules/UseLATEX.cmake

This file is taken from https://cmake.org/Wiki/images/8/80/UseLATEX.cmake.
want to provide file that can be included in CMakeLists file that defines option called \texttt{ENABLE_PROFILING} for building code with profiling enabled.

for sake of simplicity, only consider cases of using GCC and Clang C++ compilers.

place definition of option in file named \texttt{profiling.cmake}.

include \texttt{profiling.cmake} in \texttt{CMakeLists.txt}.
profiling.cmake

# Define an option for enabling code profiling, which is disabled
# by default.
option(ENABLE_PROFILING "Enable code profiling with gprof." false)

if (ENABLE_PROFILING)
  if (CMAKE_CXX_COMPILER_ID MATCHES GNU OR
      CMAKE_CXX_COMPILER_ID MATCHES Clang)
    # The GCC or Clang C++ compiler is being used.
    # Add the -pg option to the flags used for compiling.
    set(CMAKE_CXX_FLAGS "${CMAKE_CXX_FLAGS} -pg")
    # Add the -pg option to the linker flags used for creating
    # executables.
    set(CMAKE_EXE_LINKER_FLAGS "${CMAKE_EXE_LINKER_FLAGS} -pg")
    # Add the -pg option to the linker flags used for creating
    # shared libraries.
    set(CMAKE_SHARED_LINKER_FLAGS "${CMAKE_SHARED_LINKER_FLAGS} -pg")
  else()
    # Handle the case of unsupported compilers.
    message(FATAL_ERROR "Only GCC and Clang are currently supported.")
  endif()
endif()
CMakeLists.txt (showing how one might use profiling.cmake)

```cmake
1 cmake_minimum_required(VERSION 3.1 FATAL_ERROR)
2 project(gprof LANGUAGES CXX)
3
4 # Include the file containing the profiling option definition.
5 # Note: To enable profiling, one can add the command line option
6 # -DENABLE_PROFILING=true to cmake.
7 include(profiling.cmake)
8
9 add_executable(app app.cpp)
```
References

3. CMake FAQ, https://cmake.org/Wiki/CMake_FAQ.
6. CMakeUserUseLATEX
   https://cmake.org/Wiki/CMakeUserUseLATEX
7. UseLATEX GitHub Site https://github.com/kmorel/UseLATEX


Part 11

Version Control Systems
Section 11.1

Version Control Systems
Version control (also known as revision control) is the management of changes to programs, documents, and other collections of information.

In practice, multiple versions of the same software will often be in existence at any given time.

For the purposes of locating and fixing a bug, it is critically important to be able to access different versions of the software, since only certain versions of the software may have the bug.

When concurrently developing multiple versions of some software, it is necessary to be able to keep track of what information belongs to which versions.

Having developers manually maintain version information themselves is impractical, as this would be very error prone.

Therefore, a version control system (VCS) is used to manage changes in a systematic manner.

Some examples of VCSes include: Source Code Control System (SCCS), Revision Control System (RCS), Concurrent Versions System (CVS), Subversion, Mercurial, and Git.
Centralized Version Control

- repository resides only on server
- users do not have their own local copy of repository
- examples: CVS and Subversion
- each user has their own local copy of repository
- examples: Git and Mercurial
Pros and Cons of Distributed Version Control

- **advantages of distributed (over centralized) version control:**
  - most operations (namely, ones that do not synchronize with other repositories) are local and extremely fast
  - all operations, except those that synchronize with other repositories, can be performed without network connection
  - more robust (e.g., data loss less likely due to replication of information across repositories, less reliance on network/server connectivity)
  - committing new changesets can be done locally without anyone else seeing them
  - easier to share changes with only, say, one or two people before showing changes to everyone

- **disadvantages of distributed (relative to centralized) version control:**
  - since repository is stored locally, more local disk space is required
  - if repository becomes large, downloading it can require considerable amount of time
Section 11.2

Git
Git is open-source distributed (i.e., decentralized) version control system
created by Linus Torvalds
development started in 2005 with first release made later in same year
designed to support projects varying in size from very small to very large
with speed and efficiency
can efficiently handle very large numbers of files
can efficiently handle large numbers of parallel branches
revision history of file modelled as directed acyclic graph (DAG)
official web site: https://git-scm.com
Users of Git

- Git has a very large user base and is employed heavily in industry
- some organizations using Git include:
  - Apple (https://github.com/apple)
  - eBay (https://github.com/eBay)
  - Facebook (https://github.com/facebook)
  - Google (https://github.com/google)
  - Intel (https://github.com/intel)
  - Microsoft (https://github.com/Microsoft)
  - NVIDIA (https://github.com/NVIDIA)
  - Twitter (https://github.com/twitter)
- some projects using Git include:
  - Linux Kernel (https://github.com/torvalds/linux)
  - Android (https://android-review.googlesource.com)
  - Qt (http://code.qt.io)
  - Gnome (https://git.gnome.org)
  - Eclipse (https://git.eclipse.org)
  - KDE (https://github.com/KDE)
  - FreeDesktop (https://cgit.freedesktop.org)
A repository is effectively a database that records the information for all of the versions of all of the files in the directory tree under version control.

A commit is simply a record (i.e., snapshot) of all of the files that comprise a particular version in the repository.

This record includes, for each file, the location of the file in the directory tree as well as the contents of the file.

For each version of the directory tree, the repository has a corresponding commit (i.e., snapshot).
The revision history can be represented as a directed acyclic graph (DAG).

Each node in the graph corresponds to a commit in the repository.

Each edge in the graph points to the immediately preceding commit in the revision history.

Example of DAG:

- $C_1$ based on changing content from $C_0$;
- $C_2$ based on changing content from $C_1$;
- $C_4$ based on changing content from $C_2$;
- $C_6$ based on *merging* content from $C_4$ and $C_5$;
- $C_7$ based on...
Branching Workflows

- single (master) branch:

  ![Diagram of a single (master) branch]

  - $M_1 \rightarrow M_2 \rightarrow M_3 \rightarrow M_4 \rightarrow M_5 \rightarrow M_6$

- master, development, and topic branches:

  ![Diagram of master, development, and topic branches]

  - $M_1 \rightarrow M_2 \leftarrow D_1 \rightarrow D_2 \rightarrow D_3 \rightarrow T_1 \rightarrow T_2$

  - master branch: used for releases (highly stable, well tested)
  - development branch: used for development work (possibly unstable)
  - topic branch: used for highly experimental work

Copyright © 2015–2021 Michael D. Adams
Programming in C++   Version 2021-04-01
three distinct types of data:

- **working tree**: directory hierarchy containing files on which user is working
- **index** (also known as **staging area**): place where changes that are tentatively marked to be committed are stored
- **repository**: database used to store all versions of data and associated metadata

three basic local operations on data:

- **checking out**: populates working tree with particular version of data from repository
- **staging**: applies changes in working tree to index
- **committing**: applies changes in index to repository
- **clone**: creates local repository that is copy of remote repository

- three basic operations for propagating changes between repositories:
  - **push**: propagate changes from local repository to remote repository
  - **fetch**: propagate changes from remote repository to local repository without merging changes
  - **pull**: propagate changes from remote repository to local repository and merge changes
- The name **HEAD** is a reference to the current working revision (i.e., a branch or commit) in the repository.

- Normally (i.e., except in the case of a detached **HEAD**), **HEAD** refers to the current branch.

- In the case of a detached **HEAD**, **HEAD** refers to a specific commit (not a branch).

- Consider a repository having a single **master** branch and three commits $C_1$, $C_2$, and $C_3$ (with $C_3$ being the most recent), where the current branch is **master**. This would appear as follows:
Consider a remote repository whose commit history is as shown below, with a single branch *master*.

Cloning the above repository will produce a new local repository whose commit history is as shown below, with a (local) branch *master* and a remote-tracking branch *origin/master*.

A branch fetched from a remote repository is called a **remote-tracking branch**.

A remote-tracking branch is a reference to a commit in the remote repository and is used for operations like pushing and fetching/pulling.
1. Consider the following remote repository with a single branch `master`:

```
HEAD -> master

C_1 <- C_2
```

2. Cloning the remote repository yields a new local repository that is identical to the remote repository but with a remote-tracking branch `origin/master` added as follows:

```
HEAD -> master

C_1 <- C_2

origin/master
```
3 Committing change $A_1$ to the master branch of the local repository transforms the local repository as follows:

4 Committing change $A_2$ to the master branch of the local repository transforms the local repository as follows:
5 Another user committing changes $B_1$ and $B_2$ to the remote repository transforms the remote repository as follows:

6 Fetching (to the local repository) from the remote repository transforms the local repository as follows:
7. Merging the `origin/master` branch into the `master` branch (in the local repository) transforms the local repository as follows:

```
Commit History Example IV

7. Merging the `origin/master` branch into the `master` branch (in the local repository) transforms the local repository as follows:

8. Pushing (from the local repository) to the remote repository transforms the remote and local repositories, respectively, as follows:

Copyright © 2015–2021 Michael D. Adams
Program in C++  Version 2021-04-01

Commit History Example: Commands to Setup Remote

1. TOP_DIR=`pwd`
2. cd $TOP_DIR
3. mkdir remote
4. cd remote
5. git init
6. printf "apple\n" >> fruits.txt
7. git add fruits.txt
8. git commit -m "Added file fruits.txt" # Commit C1
9. printf "banana\n" >> fruits.txt
10. git add fruits.txt
11. git commit -m "Added banana to fruits.txt" # Commit C2
12. git init --bare .git
13. mv .git $TOP_DIR/remote.git
14. cd $TOP_DIR
15. rm -rf remote
Commit History Example: Remaining Commands

1. cd $TOP_DIR
2. git clone remote.git local-1
3. cd $TOP_DIR/local-1
4. printf "grape\n" >> fruits.txt
5. git add fruits.txt
6. git commit -m "Added grape to fruits.txt" # Commit A1
7. printf "orange\n" >> fruits.txt
8. git add fruits.txt
9. git commit -m "Added orange to fruits.txt" # Commit A2
10. cd $TOP_DIR
11. git clone remote.git local-2
12. cd local-2
13. printf "red\n" >> colors.txt
14. git add colors.txt
15. git commit -m "Added file colors.txt" # Commit B1
16. printf "green\n" >> colors.txt
17. git add colors.txt
18. git commit -m "Added green to colors.txt" # Commit B2
19. git push
20. cd $TOP_DIR/local-1
21. git push # ERROR: local repository not up to date
22. git fetch
23. git merge -m "Merged changes." # Commit A3
24. git push
Git employs three levels of configuration settings, which in order of decreasing priority are as follows:

1. local (i.e., per repository)
2. global (i.e., per user)
3. system (i.e., system wide)

Configuring system settings may require administrator privileges.

On Linux systems, the global settings are typically stored in the file 
$HOME/.gitconfig.
Git on One Slide

- Configure user information and clone the repository:
  - `git config --global user.name "John Doe"`
  - `git config --global user.email jdoe@gmail.com`
  - `git clone $repository $directory`

- Edit the working tree and stage changes as appropriate for the local repository:
  - `git add $path_to_add`
  - `git mv $source_path $destination_path`
  - `git rm $file_to_remove`
  - `git rm -r $directory_to_remove`

- Check what changes are staged and then commit these changes to the local repository:
  - `git status`
  - `git commit`

- Push changes from the local repository to the remote repository:
  - `git push`

- As needed, retrieve changes from the remote repository and merge them locally (e.g., if a push failed due to being out of date):
  - `git pull`
Section 11.2.1

Basic Commands
Determining the Version of Git

To query the version of the Git software, type:

```
git --version
```

The original release dates for a few versions of Git are as follows:

<table>
<thead>
<tr>
<th>Version</th>
<th>Original Release Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>2005-12-21</td>
</tr>
<tr>
<td>1.7</td>
<td>2010-02-13</td>
</tr>
<tr>
<td>1.8</td>
<td>2012-10-21</td>
</tr>
<tr>
<td>1.9</td>
<td>2014-02-14</td>
</tr>
<tr>
<td>2.0</td>
<td>2014-05-28</td>
</tr>
<tr>
<td>2.3</td>
<td>2015-02-05</td>
</tr>
<tr>
<td>2.8</td>
<td>2016-03-28</td>
</tr>
<tr>
<td>2.12</td>
<td>2017-02-24</td>
</tr>
<tr>
<td>2.16</td>
<td>2018-01-17</td>
</tr>
<tr>
<td>2.21</td>
<td>2019-02-24</td>
</tr>
<tr>
<td>2.25</td>
<td>2020-01-13</td>
</tr>
</tbody>
</table>

As of 2021-03-22, the most recent version of Git is 2.30.2.
Obtaining Help on the *git* Command

- To obtain general help for the *git* command, use a command of the form:
  ```
git help [options]
  ```

- To obtain detailed information for the *git* command or guide `$item`, use a command of the form:
  ```
git help [options] $item
  ```

- Some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-a</td>
<td>list all commands for which help available</td>
</tr>
<tr>
<td>-g</td>
<td>list all available help guides</td>
</tr>
<tr>
<td>-w</td>
<td>display in HTML format using a web browser</td>
</tr>
<tr>
<td>-m</td>
<td>display in man (i.e., manual page) format</td>
</tr>
</tbody>
</table>

- To obtain detailed help on the `commit` command with the information displayed in HTML format in a web browser, type:
  ```
git help -w commit
  ```

- To list all of the help guides available, type:
  ```
git help -g
  ```
### Configuring Git

- To set the variable `$name` to the value `$value`, use a command of the form:
  ```
git config [options] $name $value
  ```
- To unset the variable `$name`, use a command of the form:
  ```
git config [options] --unset $name
  ```
- To list all of the current variables settings, use a command of the form:
  ```
git config [options] -l
  ```
- Some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>--system</code></td>
<td>consider only the system-wide settings</td>
</tr>
<tr>
<td><code>--global</code></td>
<td>consider only the global (i.e., per-user) settings</td>
</tr>
<tr>
<td><code>--local</code></td>
<td>consider only the local (i.e., per-repository) settings</td>
</tr>
</tbody>
</table>
### Some Commonly-Used Git Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>core.askPass</td>
<td>program for entering user name and password credentials</td>
</tr>
<tr>
<td>core.editor</td>
<td>program for editing</td>
</tr>
<tr>
<td>core.pager</td>
<td>program for paging output</td>
</tr>
<tr>
<td>credential.helper</td>
<td>external program to be called when a user name or password credential is needed</td>
</tr>
<tr>
<td>user.name</td>
<td>user’s full name</td>
</tr>
<tr>
<td>user.email</td>
<td>user’s email address</td>
</tr>
<tr>
<td>web.browser</td>
<td>program for browsing web</td>
</tr>
</tbody>
</table>
To globally set the user name to “John Doe”, type:
   `git config --global user.name "John Doe"`

To globally set the email address to “jdoe@gmail.com”, type:
   `git config --global user.email jdoe@gmail.com`

To list all system, global, and local variables, type:
   `git config -l`

To list only the global variables, type:
   `git config --global -l`

To list only the local (i.e., per-repository) variables for the current repository, type:
   `git config --local -l`
Configuring User-Credential-Related Information

■ To enable the global caching of user credentials for 1 hour (i.e., 3600 seconds), type:
  
  ```bash
  git config --global \
  credential.helper 'cache --timeout=3600'
  ```

■ To disable all caching of user credentials (i.e., at the system, global, and repository levels) and purge any cached values, type:
  
  ```bash
  git config --unset credential.helper
  git config --global --unset credential.helper
  git config --system --unset credential.helper
  git credential-cache exit
  ```

■ To ensure that prompting for user credentials employs standard input/output (as opposed to, say, a pop-up window), type:
  
  ```bash
  git config --unset core.askPass
  git config --global --unset core.askPass
  git config --system --unset core.askPass
  unset GIT_ASKPASS
  unset SSH_ASKPASS
  ```
To create an empty repository, use a command of the form:

```
git init [$directory]
```

If `$directory` is not specified, it defaults to the current directory.

The repository is created in the directory `$directory`.

If `$directory` already contains a repository, the repository is re-initialized (in a non-destructive manner).

All of the information used internally by Git to maintain the state of the repository is stored in a directory named `.git` at the top-level directory in the working tree.

To create a new repository in the directory `hello` (which does not currently exist), type:

```
git init hello
```
To clone a repository $repository, use a command of the form:

```
git clone [options] $repository [directory]
```

If $directory is not specified, it defaults to a value derived from $repository.

The cloned repository is placed in the directory $directory.

The repository specifier $repository can be a URL (for a repository accessed through a network server) or a directory (for a repository accessed through the local file system).

Some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-b $branch</td>
<td>after cloning, checkout the branch $branch</td>
</tr>
</tbody>
</table>

To clone the repository associated with the URL

```
https://github.com/uvic-aurora/hello-world.git
```
to the directory hello-world, type:

```
git clone \\nhttps://github.com/uvic-aurora/hello-world.git \\nhello-world
```
Adding Files/Directories to the Index

- To add the files/directories $\text{path}\ldots$ to the index (i.e., mark for committing later), use a command of the form::
  
  ```bash
  git add $\text{path}\ldots
  ```

- The contents of $\text{path}\ldots$ \textit{at the time that the} \texttt{git add} \texttt{command is run} are staged; subsequent changes to these contents are not automatically staged.

- When a directory is staged, all directories and files that are contained under it are staged (i.e., staging is recursive).

- To prevent certain files/directories in a directory from being staged, they can be listed in a .\texttt{gitignore} file in that directory.

- To add the files README and LICENSE to the index, type:
  
  ```bash
  git add README LICENSE
  ```

- To add the directory src (and everything contained under it) to the index, type:
  
  ```bash
  git add src
  ```
To remove all changes from the index, type:

```bash
git reset
```

To remove the files/directories `$path...` from the index, use a command of the form:

```bash
git reset $path...
```

To undo the effects of the command “git add README LICENSE”, type:

```bash
git reset README LICENSE
```

To undo the effects of the command “git add README”, type:

```bash
git reset README
```
To move the file/directory \$source to \$destination, use a command of the form:

\texttt{git mv [options] \$source \$destination}

To move multiple files \$s_1, \$s_2, ..., \$s_n to the directory \$destination_directory, use a command of the form:

\texttt{git mv [options] \$s_1 \$s_2 ... \$s_n \slash \$destination_directory}

Some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-f</td>
<td>force moving even if the target exists</td>
</tr>
</tbody>
</table>

To rename the file README to README.old, type:

\texttt{git mv README README.old}

To move the files hello.cpp and goodbye.cpp to the directory src, type:

\texttt{git mv hello.cpp goodbye.cpp src}
To remove the files/directories $\text{path...}$ from the working tree and the index, use a command of the form:

```
    git rm [options] $\text{path...}
```

Some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-f</td>
<td>override the up-to-date check</td>
</tr>
<tr>
<td>-r</td>
<td>if the given path is a directory, recursively remove files below it</td>
</tr>
</tbody>
</table>

To remove the directory `src` and all files and directories beneath it from the working tree and index, type:

```
    git rm -r src
```

To remove the files `README` and `LICENSE` from the working tree and index, type:

```
    git rm README LICENSE
```
Committing Changes

- To commit all staged changes, use a command of the form:
  
  `git commit [options]`

- Some commonly-used options include:
  
<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-a</td>
<td>automatically stage any files that have been modified or deleted</td>
</tr>
<tr>
<td>-m $message</td>
<td>set message to $message</td>
</tr>
</tbody>
</table>

- To commit all staged changes with the message “Fixed overflow bug”, type:
  
  `git commit -m "Fixed overflow bug"`

- To commit all staged changes with the message “Fixed overflow bug”, automatically staging any files that have been modified or deleted, type:
  
  `git commit -a -m "Fixed overflow bug"`
To display the status of the working tree, use a command of the form:

```
git [options] status
```

Some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>--long</td>
<td>give the output in long format (default)</td>
</tr>
<tr>
<td>--short</td>
<td>give the output in short format</td>
</tr>
</tbody>
</table>

The information displayed by this command includes:

- paths (i.e., files and directories) that have differences between the index and the current HEAD commit, (i.e., what would be committed by running `git commit`)
- paths that have differences between the working tree and index as well as paths that are not tracked by Git (i.e., what could by committed by running `git add` before `git commit`)

To display the status of the working tree in long form, type:

```
git status
```
To show the commit history (which can be limited to a particular revision range $\texttt{revision\_range}$ or files/directories $\texttt{path}...$), use a command of the form:

```
git log [options] [$\texttt{revision\_range}] [[--] $\texttt{path}...]
```

Some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>--since $\texttt{date}$</td>
<td>select commits more recent than date $\texttt{date}$</td>
</tr>
<tr>
<td>--until $\texttt{date}$</td>
<td>select commits older than date $\texttt{date}$</td>
</tr>
<tr>
<td>-$n$</td>
<td>select last $n$ commits</td>
</tr>
<tr>
<td>-S $\texttt{pattern}$</td>
<td>select commits adding/removing string matching pattern $\texttt{pattern}$</td>
</tr>
<tr>
<td>--graph</td>
<td>draw text-based graph of commit history</td>
</tr>
<tr>
<td>--all</td>
<td>consider all branches/remotes/tags</td>
</tr>
<tr>
<td>--grep $\texttt{pattern}$</td>
<td>select only commits with message matching $\texttt{pattern}$</td>
</tr>
</tbody>
</table>
■ To show the commit history for the file README since 2016-01-01, type:
  git log --since 2016-01-01 README

■ To show the commit history for all files between 2014-01-01 and 2014-12-31, type:
  git log --since 2014-01-01 --until 2014-12-31

■ To show the commit history for all files in all branches with a text-based graph, type:
  git log --all --graph

■ To show the commit history for all commits made since v1.0 until and including v2.0 (assuming that v1.0 and v2.0 exist), type:
  git log v1.0..v2.0
To show changes between the working tree and the index (i.e., what could be staged but has not yet been) for files/directories `$path...` (which defaults to all files/directories), use a command of the form:

```
git diff [options] [$path...]
```

To show changes between the index and the named commit `$commit` (which defaults to HEAD) for the files/directories `$path...` (which defaults to all files/directories), use a command of the form:

```
git diff [options] --cached [$commit] -- \[$path...]
```

To show changes between the working tree and the named commit `$commit` (which defaults to HEAD) for the files/directories `$path...` (which defaults to all files/directories), use a command of the form:

```
git diff [options] [$commit] -- [$path...]
```

To show changes between two arbitrary commits `$commit1` and `$commit2` for the files/directories `$path...`, use a command of the form:

```
git diff [options] $commit1 $commit2 -- \[$path...]
```
Some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-b</td>
<td>ignore changes in amount of whitespace</td>
</tr>
<tr>
<td>-w</td>
<td>ignore all whitespace</td>
</tr>
<tr>
<td>--ignore-blank-lines</td>
<td>ignore blank lines</td>
</tr>
</tbody>
</table>

To show all changes between the working tree and the index for all files/directories, type:

```
 git diff
```

To show all differences between the working tree and the index for the file `README`, ignoring changes in amount of whitespace, type:

```
 git diff -b README
```
Finding Lines Matching a Pattern

To find all lines of text in the files $path...$ (which defaults to all files) in the working tree that satisfy the condition specified by the $p_options$, use a command of the form:

```
git grep [options] [p_options] -- [$path...]```

Some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>-l</code></td>
<td>print only names of files with matches</td>
</tr>
<tr>
<td><code>-i</code></td>
<td>ignore case</td>
</tr>
<tr>
<td><code>--max-depth $depth</code></td>
<td>descend at most $depth levels of directories</td>
</tr>
<tr>
<td><code>-v</code></td>
<td>select non-matching lines</td>
</tr>
<tr>
<td><code>-F</code></td>
<td>patterns are fixed strings</td>
</tr>
<tr>
<td><code>-E</code></td>
<td>patterns are extended POSIX regular expressions</td>
</tr>
<tr>
<td><code>-e $pattern</code></td>
<td>specify pattern $pattern</td>
</tr>
<tr>
<td><code>--and</code></td>
<td>logical and</td>
</tr>
<tr>
<td><code>--or</code></td>
<td>logical or</td>
</tr>
<tr>
<td><code>--not</code></td>
<td>logical not</td>
</tr>
<tr>
<td><code>(</code></td>
<td>for grouping logical operations</td>
</tr>
<tr>
<td><code>)</code></td>
<td>for grouping logical operations</td>
</tr>
<tr>
<td><code>--cache</code></td>
<td>search in the index instead of the working tree</td>
</tr>
</tbody>
</table>
To search for the text "hello" in a case insensitive manner in all of the files in the working tree, type:

```bash
git grep -i -e hello
```

To print only the names of the files that match the pattern specified in the preceding example, type:

```bash
git grep -i -e hello -l
```

To find all of the files in the working tree with suffixes "cpp" or "hpp" that have lines containing either "#include <vector>" or "#include <list>", type:

```bash
git grep -e '#include <vector>' --or -e '#include <list>' -- '*.cpp' '*.hpp'
```

To perform the same search as the preceding example but in the index rather than the working tree, type:

```bash
git grep --cache -e '#include <vector>' --or -e '#include <list>' -- '*.cpp' '*.hpp'
```
Removing Untracked Files and Directories

To remove all untracked files in the working tree, use a command of the form:

```bash
git clean [options]
```

Some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-d</td>
<td>remove untracked directories in addition to untracked files</td>
</tr>
<tr>
<td>-f</td>
<td>force removal of files</td>
</tr>
<tr>
<td>-i</td>
<td>enable interactive mode</td>
</tr>
<tr>
<td>-n</td>
<td>show what would be done without actually doing anything</td>
</tr>
<tr>
<td>-x</td>
<td>do not use standard ignore rules (such as those specified in <code>.gitignore</code> files)</td>
</tr>
</tbody>
</table>

To remove all untracked files and directories in the working tree excluding those ignored by Git, type:

```bash
git clean -d -f
```

To remove all untracked files and directories in the working tree including those ignored by Git, type:

```bash
git clean -d -f -x
```
A `.gitignore` file specifies which files and directories are intentionally untracked and should be ignored by Git.

The purpose of a `.gitignore` file is to ensure that certain files not tracked by Git remain untracked.

The `.gitignore` file lists patterns specifying files that should be ignored by Git.

A “!” prefix negates a pattern.

A leading slash matches the directory containing the `.gitignore` file. For example, `/hello.cpp` matches `hello.cpp` but not `some/subdirectory/hello.cpp`.

The patterns in a `.gitignore` file apply to the directory containing the file as well as all directories below the file in the working tree.

The patterns in a `.gitignore` file at a higher level in the tree are overridden by patterns in a `.gitignore` file at a lower level.

A `.gitignore` file in the root directory of the working tree can be used to establish ignore defaults for the whole tree.
# ignore all object files
*.o

# ignore all library files
*.a

# ignore foobaz only in this directory
/foobaz

# ignore foo only in directory example
/example/foo
A `.gitattributes` file is used to specify attributes for files/directories.

For example, the determination of whether a file employs a binary or text format can be controlled via a `.gitattributes` file.

An example of a `.gitattributes` file is as follows:

```
# Consider all PNM files to be binary.
*.pnm binary
```

The settings in a `.gitattributes` file apply to the directory containing the file as well as all directories below the file in the working tree.

The settings in a `.gitattributes` file at a higher level in the tree are overridden by settings in a `.gitattributes` file at a lower level.

A `.gitattributes` file in the root directory of the working tree can be used to establish attribute defaults for the whole tree.
The current implementation of git does not allow empty directories to be tracked.

The best workaround for this problem is to create a .gitignore file in the directory that ignores all files except the .gitignore file itself.

Such a .gitignore file might look like the following:

```plaintext
# First, ignore everything in this directory.
*

# Now, override the preceding rule and force
# the .gitignore file not to be ignored.
! .gitignore
```

This is not a perfect solution as it requires that the “empty” directory contain one file (namely, a .gitignore file) and this file be committed to the repository.
Section 11.2.2

Remote-Related Commands
To list the remotes, use a command of the form:
```
git remote [general_options]
```

Some general options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-v</td>
<td>enable verbose mode</td>
</tr>
</tbody>
</table>

To add the remote `$remote` with the associated URL `$url`, use a command of the form:
```
git remote add $remote $url
```

To remove the remote `$remote`, use a command of the form:
```
git remote rm $remote
```

To rename a remote from `$old` to `$new`, use a command of the form:
```
git remote rename $old $new
```

To show detailed information on the remote `$remote`, use a command of the form:
```
git remote [general_options] show $remote
```
To fetch changes from the remote $\text{remote}$ (which normally defaults to \text{origin}), use a command of the form:

\begin{verbatim}
git fetch [$\text{remote}$]
\end{verbatim}

A fetch operation gathers any commits from the target branch that do not exist in current branch, and stores them in the local repository.

It is always safe to perform a fetch in sense that no conflicts can arise, since no merge is attempted.

By fetching frequently, one can keep their local repository up to date without being forced to merge.
Pushing Changes to Another Repository

- To push changes to the branch \$branch (which normally defaults to the current branch) of the remote \$remote (which normally defaults to origin), use a command of the form:
  
  ```
  git push [options] \[$remote \[$branch]\]
  ```

- When pushing a new local branch to a remote, the `-u` option should be specified.

- To delete the branch \$branch on the remote \$remote only, use a command of the form:
  
  ```
  git push --delete origin \$branch
  ```

- The preceding command is useful if one wants to delete a branch that exists on the remote but not in the local repository.

- To delete the tag \$tag on the remote \$remote only, use a command of the form:
  
  ```
  git push --delete origin \$tag
  ```

- To push to the default remote and branch, type:
  
  ```
  git push
  ```
To pull changes from the branch $branch of the remote $remote, use a command of the form:

\texttt{git pull \{[$remote \{[$branch]\}]\}}

To pull from the default remote and branch, type:

\texttt{git pull}

A pull is approximately a fetch followed by merge.

A pull automatically merges commits without letting them be reviewed first.

For this reason, some people suggest that it is better to use fetch and merge separately instead of performing a pull.

Also, the use of pull operations can, in some cases, result in unnecessary merge commits.
To merge changes from the branch \$branch (which normally defaults to the upstream branch for the current branch) into the current branch, use a command of the form:

```bash
git merge \$branch
```

To merge from the default branch, type:

```bash
git merge
```

Note that the merge direction is from the branch \$branch into the current branch.

It is advisable to ensure that any outstanding changes are committed before running `git merge` in order to reduce the likelihood of major difficulties in the case of a conflict.

If a conflict arises, no commit will be performed and manual intervention is required to resolve the conflict.
Section 11.2.3

Branch-Related Commands
To list all of the branches, use a command of the form:
   `git branch [options]`

To create a branch `$branch`, use a command of the form:
   `git branch [options] $branch`

To delete the (local) branch `$branch`, use a command of the form:
   `git branch [options] -d $branch`

Some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-a</td>
<td>list both remote and local branches</td>
</tr>
<tr>
<td>-r</td>
<td>list or delete remote branches</td>
</tr>
<tr>
<td>-v</td>
<td>enable verbose mode for listing (use twice for extra verbose)</td>
</tr>
</tbody>
</table>

When a new branch is created with `git branch`, this does not automatically checkout (i.e., switch to using) the new branch.
To checkout (i.e., switch to) the branch \texttt{$\text{branch}$}, use a command of the form:

\begin{verbatim}
git checkout $\text{branch}$
\end{verbatim}

Checking out a branch changes the files/directories of the working tree to match that branch.

If you have local modifications to one or more files that are different between the current branch and the branch to which you are switching, the command refuses to switch branches in order to preserve your modifications in context.
Section 11.2.4

Tag-Related Commands
To list all tags, type:

```
git tag
```

To tag a commit $commit (which defaults to HEAD) with the name $name, use a command of the form:

```
git tag [options] $name [$commit]
```

To delete the (local) tags with names $name..., use a command of the form:

```
git tag -d $name...
```

Some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-a</td>
<td>make an unsigned annotated tag</td>
</tr>
</tbody>
</table>

To create an annotated tag version-1.0 for the most recent commit on the master branch, type:

```
git tag -a version-1.0 master
```

To delete the tag version-1.0, type:

```
git tag -d version-1.0
```
To push a tag $tag \textit{to the remote} \ $remote, use a command of the form:

```
git push \$remote \$tag
```

To push the tag \texttt{v1.0} \textit{to the remote} origin, \textit{type}:

```
git push origin v1.0
```
Section 11.2.5

Miscellany
can create exact duplicate of entire Git repository (including all tags and local branches) by using bare-clone and mirror-push operations

to copy repository $source_repo to (already existing) remote repository $destination_repo (overwriting contents of repository), use command sequence:

  # Create a bare clone of the repository.
  git clone --bare $source_repo $bare_dir
  # Mirror push to the destination repository.
  git -C $bare_dir push --mirror $destination_repo
  # Remove the temporary local bare repository.
  rm -rf $bare_dir

   to copy repository $source_repo to local repository directory $destination_dir, simply perform bare clone operation using command:

    git clone --bare $source_repo $destination_dir
if SSH used to access repository, SSH passphrase often needs to be provided

to avoid having to enter SSH passphrase every time it is needed, can use SSH Agent to cache passphrase and provide it as required

to start SSH Agent and provide it with passphrase to cache for private key file $key_file, use command sequence:

```
# Start SSH Agent
eval `ssh-agent`
# Provide passphrase for particular key.
ssh-add $key_file
```

on Unix systems, SSH key information typically stored in directory $HOME/.ssh
A file is said to be derived if it is generated from one or more other files (e.g., an object file is derived from its corresponding source code file, a PDF or PostScript file is derived from its corresponding LaTeX source files).

Do not place derived files under version control, as such files are completely redundant and can often lead to a significant increase in repository size.

Do not place large unchanging datasets under version control, as this will greatly increase repository size without any tangible benefit (i.e., since the datasets are not changing, there will never be multiple versions of them to manage).

Avoid placing sensitive information (e.g., passwords) under version control.

Remember that deleting a file from a particular commit does not delete that file from the repository, since the file will still exist in other commits.
Git-Related Software

- Gitg. A GNOME GUI client for viewing Git repositories.  


- Hub. A command-line wrapper for Git that facilitates easier use of GitHub.  
Section 11.2.6

References
References

1. **Official Git Web Site.** [https://git-scm.com](https://git-scm.com), August 2016. This web site has many excellent resources related to Git, including:
   1. **Git Downloads:** [https://git-scm.com/downloads](https://git-scm.com/downloads). This web page has the Git software for various platforms, including Linux, Mac OS X, and Windows.
   2. **Git Book:** Scott Chacon and Ben Straub, *Pro Git*, [http://git-scm.com/book](http://git-scm.com/book). This online book can also be downloaded in several formats (including PDF).
   3. **Git Videos:** [https://git-scm.com/videos](https://git-scm.com/videos). This web page has several short videos on various aspects of Git.

2. **Good Resources for Learning Git and GitHub,** [https://help.github.com/articles/good-resources-for-learning-git-and-github](https://help.github.com/articles/good-resources-for-learning-git-and-github), August 2016. This web page has a list of many excellent resources for learning both Git and GitHub.
3. TryGit Tutorial, https://try.github.com, August 2016. This online Git tutorial allows the user to try Git in their web browser.

Talks

Linus Torvalds shares his thoughts on Git, the source control management system he created.

This is an excellent introduction to using Git.

This is another popular introduction to using Git.

This is a very good more advanced talk on Git.
Part 12

Miscellaneous Tools
Section 12.1

Online C++ Compilers
Online C++ Compilers

- numerous online (i.e., web-based) C++ compilers available
- typically provide means to upload, edit, build, and run code
- usually provide some control over compiler options and libraries
- often support multiple compilers and/or compiler versions
- some examples of online C++ compilers include:
  - Wandbox
    - http://melpon.org/wandbox
  - Ideone
    - https://ideone.com
  - Coliru
    - http://coliru.stacked-crooked.com
  - Repl.It
    - https://repl.it/repls/SmallIvorySyntax
  - Compiler Explorer (discussed in more detail shortly)
  - C++ Insights (discussed in more detail shortly)
```cpp
#include <iostream>
#include <string>
#include <vector>

template<typename T>
std::ostream& operator<<(std::ostream& os, const std::vector<T>& vec)
{
    for (auto& el : vec)
    {
        os << el << ' ';
    }
    return os;
}

int main()
{
    std::vector<std::string> vec = {
        "Hello", "from", "GCC", __VERSION__, "!"
    };
    std::cout << vec << std::endl;
}
```

```
g++ -std=c++17 -02 -Wall -pedantic -pthread main.cpp && ./a.out
```
Compiler Explorer

- Compiler Explorer is interactive web-based compiler that supports C++, C, and numerous other languages
- can load, save, and edit source code
- source code is automatically compiled as edited
- can simultaneously display source code and corresponding assembly code
- can select language, compiler, and compiler options
- source code can utilize numerous libraries (such as Boost)
- extremely useful for understanding what assembly code is generated by compiler
- also helpful for quickly testing compilation of small code snippets with variety of compilers
- created by Matt Godbolt
- web site running Compiler Explorer: https://godbolt.org
- GitHub page: https://github.com/mattgodbolt/compiler-explorer
Some Compiler Explorer Functionalities

- uses color coding to show correspondence between lines of source and assembly code
- can hover over instruction name in assembly code for information on instruction
- display of assembly code can be controlled in various ways:
  - show or hide machine op codes
  - use mangled versus demangled names
  - show or hide debugging information
  - trim extra whitespace
  - filter unused labels or extra assembler directives
- can display assembly code from multiple compilers at same time
- can draw control flow graph corresponding to assembly code
- can be used to test whether different compilers can successfully compile particular source code
- can share code and Compiler Explorer session via URL
- does not support execution of code (at least as of October 2018)
```cpp
#include <iostream>

int get_answer() {
    return 42;
}

int main() {
    std::cout << get_answer() << '\n';
}
```

Compiler Explorer Example
```cpp
#include <iostream>

int get_answer() {
    return 42;
}

int main() {
    std::cout << get_answer() << '\n';
}
```

Transfers program control to a return address located on the top of the stack. The address is usually placed on the stack by a CALL instruction, and the return is made to the instruction that follows the CALL instruction.

More information available in the context menu.
Example Showing GCC Code-Coverage Instrumentation

```cpp
double unitstep(double x) {
    if (x >= 0.0) {
        return 1.0;
    } else {
        return 0.0;
    }
}
```

```
unitstep(double):
  pushq %rbp
  movq %rsp, %rbp
  movsd %xmm0, -8(%rbp)
  movsd -8(%rbp), %xmm0
  pxor %xmm1, %xmm1
  comisd %xmm1, %xmm0
  jb .L6
  movsd .LC1(%rip), %xmm0
  jmp .L4
  .L6:
  pxor %xmm0, %xmm0
  .L4:
  popq %rbp
  ret

__gcov_.unitstep(double):
  pushq %rbp
  movq %rsp, %rbp
  movsd %xmm0, -8(%rbp)
  movq __gcov0.unitstep(double)(%rip), %rax
  movq %rax, __gcov0.unitstep(double)(%rip)
  movsd -8(%rbp), %xmm0
  pxor %xmm1, %xmm1
  comisd %xmm1, %xmm0
  jmp .L6
  movq __gcov0.unitstep(double)+8(%rip), %rax
  addq $1, %rax
  movq %rax, __gcov0.unitstep(double)+8(%rip)
  movq .LC1(%rip), %xmm0
  jmp .L4
  .L6:
  pxor %xmm0, %xmm0
  .L4:
  popq %rbp
  ret

__gcov0.unitstep(double):
  .quad .LPBX0
  .long 273018497
  .long 559119906
  .long -1032603044
  .zero 4
  .long 2
  .zero 4
  .quad __gcov0.unitstep(double)
  .LC2:
  .string "/tmp/comp..."
Example Showing Short-Circuit Evaluation

```cpp
bool func(bool a, bool b, bool c) {
    if ((a || b) && c) {
        return true;
    } else {
        return false;
    }
}
```

```assembly
func(bool, bool, bool):
    pushq %rbp  #
    movq %rsp, %rbp  #, a, tmp89
    movl %edi, %eax  # b, tmp91
    movl %esi, %ecx  # b, tmp91, tmp92
    movb %al, -4(%rbp)  # tmp90, a
    movl %ecx, %eax  # tmp92, b
    movb %al, -8(%rbp)  # tmp93, tmp94
    movb %al, -12(%rbp)  # tmp94, c
    cmpb $0, -4(%rbp)  #, a
    jne .L2  #
    cmpb $0, -8(%rbp)  #, b
    je .L3  #,
    .L2:
    cmpb $0, -12(%rbp)  #, c
    je .L3  #,
    movl $1, %eax  #, _1
    jmp .L4  #
    .L3:
    movl $0, %eax  #, _1
    .L4:
    popq %rbp  #
    ret
```
C++ Insights is a Clang-based tool that makes visible numerous code transformations performed by the compiler.

- Created by Andreas Fertig.
- For example, the tool allows for things such as following to be seen:
  - Operator invocations
  - Expansion of range-based for loop into “classic” for loop
  - Classes generated from lambda expressions
  - Code generation associated with structured bindings

- C++ Insights page (which allows the tool to be accessed via a web browser):
  - https://cppinsights.io

- GitHub repository page:
  - https://github.com/andreasfertig/cppinsights
```cpp
#include <iostream>

struct Point {
    int x;
    int y;
};

Point get_point() {
    return {1, 2};
}

int main() {
    Point p;
    auto [a, b] = get_point();
    std::cout << a << 'n';
    std::cout << b << 'n';
}
```

---

```cpp
#include <iostream>

struct Point {
    int x;
    int y;

    /* public: inline Point() noexcept; */
    /* public: inline constexpr Point(const Point &); */
    /* public: inline constexpr Point(Point &); */
    /* public: inline ~Point() noexcept; */
};

Point get_point() {
    return {1, 2};
}

int main() {
    Point p = Point();
    Point __get_point16 = get_point();
    int& a = __get_point16.x;
    int& b = __get_point16.y;
    std::operator<<(std::cout.operator<<(a), 'n');
    std::operator<<(std::cout.operator<<(b), 'n');
}
```
Example: Lambda Expressions

Source:

```cpp
#include <iostream>

int main() {
    auto f = [](){std::cout << "Hello, World!\n";};
    f();
}
```

Insight:

```cpp
#include <iostream>

int main()
{
    class __lambda_4_14
    {
        public: inline /*constexpr*/ void operator()() const
        {
            std::operator<<(std::cout, "Hello, World!\n");
        }
    };

    __lambda_4_14 f = __lambda_4_14{};
    f.operator()();
}
```

Console:

Insights exited with result code: 0

Section 12.2

Clang Format
Clang Format is a tool for performing automatic formatting of source code for C++ (and other languages in the C family).

It is accessible via the `clang-format` program and has a command-line interface:
```
clang-format [options] $file...
```

Some common options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-help</td>
<td>print usage information and exit</td>
</tr>
<tr>
<td>-i</td>
<td>perform formatting in place</td>
</tr>
<tr>
<td>-style style</td>
<td>use coding style <em>style</em> (supported styles include: LLVM, Google, Chromium, Mozilla, WebKit)</td>
</tr>
</tbody>
</table>

It can be used as a standalone tool or integrated with various editors (e.g., Vim or Emacs) or IDEs.

Online documentation can be found at:
- [http://clang.llvm.org/docs/ClangFormat.html](http://clang.llvm.org/docs/ClangFormat.html)

Section 12.3

Language Server Protocol (LSP) Clients and Servers
Language Server Protocol (LSP) is a protocol used between an editor or IDE and a server to provide language features such as completion, identifier queries (e.g., go to definition and find all references), formatting, and identifier renaming.

LSP is language agnostic; servers are available for many languages including C++ and C.

It was originally proposed by Microsoft.

It allows language-aware components of software to be separated from the editing component.

The server has intimate knowledge of the particular programming language.

The client is typically an editor or IDE.

The base protocol consists of a header and content part (similar to HTTP).

The content part of messages uses JSON-RPC to describe requests, responses, and notifications.

The website is: [https://microsoft.github.io/language-server-protocol/specification](https://microsoft.github.io/language-server-protocol/specification)
Clangd is LSP server developed as part of LLVM project
supports C++ and C languages
has basic LSP support (e.g., completion, diagnostics, fix-its, signature help, local rename, go to definition, and formatting)
has support for global completion (e.g., completion still knows about std::vector even if vector header not included in translation unit)
has support for project-wide index
LSP server provided by clangd program
clangd not normally run directly by user; instead, invoked indirectly by editor or IDE
web site: https://clang.llvm.org extra/clangd.html
Cquery is highly-scalable low-latency LSP server for C, C++ and Objective C

designed for large code bases

fast but has large memory overhead for caching

web site: https://github.com/cquery-project/cquery
LSP Clients

- growing number of IDEs and editors providing support for LSP
- some editors and IDEs with LSP support include:
  - Microsoft Visual Studio IDE ([https://visualstudio.microsoft.com/vs](https://visualstudio.microsoft.com/vs))
  - Eclipse IDE ([https://www.eclipse.org/ide](https://www.eclipse.org/ide))
  - Vim ([https://www.vim.org](https://www.vim.org)) and Neovim ([https://neovim.io](https://neovim.io))
    - Vim LSP ([https://github.com/prabirshrestha/vim-lsp](https://github.com/prabirshrestha/vim-lsp))
    - LanguageClient-Neovim ([https://github.com/autozimu/LanguageClient-neovim](https://github.com/autozimu/LanguageClient-neovim))
    - Asynchronous Lint Engine (ALE) ([https://github.com/w0rp/ale](https://github.com/w0rp/ale))
  - Emacs ([https://www.gnu.org/software/emacs](https://www.gnu.org/software/emacs))
    - Emacs LSP Mode ([https://github.com/emacs-lsp/lsp-mode](https://github.com/emacs-lsp/lsp-mode))
    - Emacs Polyglot ([https://github.com/joaotavora/eglot](https://github.com/joaotavora/eglot))


Section 12.4

YouCompleteMe (YCM)
YouCompleteMe (YCM) is code completion engine for Vim editor

Some features of YCM include:

- semantic code completion
- real-time diagnostic display for fast syntax checking
- find declaration, definitions, usages of identifiers
- display type information for classes, variables, functions
- fix coding errors by applying fix-it hints
- display documentation for identifiers

YCM supports C++, C, and other languages.

YCM uses libclang to perform semantic analysis of code.

Web site: http://ycm-core.github.io/YouCompleteMe
```cpp
#include <iostream>

int main() {
  std::cout << "Hello, World!\n";
  return std::cin
}~
cin
cend( const _Container &__cont )
cerr
clog
copy( _II __first, _II __last, _OI __result )
cout
crend( const _Container &__cont )
c<type> _CharT>
calloc( size_t __nmemb, size_t __size )
cbegin( const _Container &__cont )
codecvt<typename _InternT, typename _ExternT, typename _StateT>
collate<typename _CharT>
crbegin( const _Container &__cont )
clearerr( FILE *__stream )
conditional<bool, typename, typename>
c<type> _base
char_traits<class _CharT>
c<common_type<typename _Tp>

-- INSERT --
```
to perform semantic analysis, YCM uses library interface to Clang compiler (libclang)

libclang must be provided with set of compile flags in order to parse code

YCM allows compile flags to be specified in two ways:

1. via compilation database (i.e., compile_commands.json file)
2. via (user-provided) Python script (i.e., .ycm_extra_conf.py)

use of compilation database is preferred approach, since database can often be automatically generated by build tools

YCM searches for file named compile_commands.json, starting in directory of opened file and then moving up directory hierarchy

YCM also searches for file name .ycm_extra_conf.py, starting in directory of opened file and then moving up directory hierarchy

full functionality of YCM requires that compile-flag information be specified
if using CMake, compile_commands.json file can be automatically generated (in build directory) by setting CMAKE_EXPORT_COMPILE_COMMANDS to true when configuring with CMake

then, symlink (or copy) compile_commands.json in build directory to directory searched by YCM (if needed)

can set CMAKE_EXPORT_COMPILE_COMMANDS when configuring with cmake command via command line option “-DCMAKE_EXPORT_COMPILE_COMMANDS=ON”

alternatively, can set CMAKE_EXPORT_COMPILE_COMMANDS via line in CMakeLists.txt like:

```plaintext
set(CMAKEEXPORTCOMPILECOMMANDSON)```
YCM Commands

- :YcmRestartServer
  - restarts ycmd completion server (e.g., if server exits for some reason)
- :YcmForceCompileAndDiagnostics
  - forces YCM to immediately recompile file and display any new diagnostics encountered
- :YcmDiags
  - populates Vim’s locationlist with errors or warnings if any were detected in file and then opens locationlist
- :YcmShowDetailedDiagnostic
  - shows full diagnostic text when user’s cursor is on line with diagnostic
- :YcmDebugInfo
  - displays various debug information for current file
- :YcmToggleLogs
  - shows list of logfiles created by YCM, ycmd server, and semantic engine server for current filetype, if any
- :YcmCompleter
  - gives access to numerous additional IDE-like features like go to definition and apply fix-it
Some YcmCompleter Subcommands

- **GoTo**
  - performs context-sensitive goto operation based on current cursor position (e.g., GoToInclude, GoToDeclaration, GoToDefinition, etc.)

- **GoToInclude**
  - looks for header file on current line and jumps to it

- **GoToDeclaration**
  - looks up identifier at current cursor position and jumps to its declaration

- **GoToDefinition**
  - looks up identifier at current cursor position and jumps to its definition

- **GoToType**
  - looks up identifier at current cursor position and jumps to definition of its type

- **GetType**
  - displays type of identifier at current cursor position

- **FixIt**
  - attempts to make changes to buffer to correct diagnostics on current line
- enable file type detection in `.vimrc` file with ``:filetype on``
- typically choose to map commonly used YCM commands to Vim keyboard shortcuts
- to map ``:YcmForceCompileAndDiagnostics`` to F5 key, add line like following to `.vimrc` file:
  
  ```vim
  nnoremap <F5> :YcmForceCompileAndDiagnostics<CR>
  ```
- to map ``:YcmCompleter GoTo`` to key sequence `<leader>jd`, add line like following to `.vimrc` file:
  
  ```vim
  nnoremap <leader>jd :YcmCompleter GoTo<CR>
  ```
- leader key (i.e., `<leader>`) can be queried with ``:let mapleader`` (often set to comma on Linux systems)
- leader key can be set to comma with ``:let mapleader="","
- for more information on Vim, refer to Vim web site:
  
  ```html
  http://www.vim.org
  ```
Part 13

Miscellany
Section 13.1

Miscellany
Consider a program with the following source listing:

```cpp
#include <iostream>
#include <cstdlib>
int main() {std::cout << abs(-1.5) << '\n';}
```

The C++ implementation is permitted (but not required) to place the C \texttt{abs} function in the global namespace.

If the implementation does not do this, the above program will fail to compile (avoiding the more troubling problem discussed next).

If, however, the C++ implementation does do this (which is not uncommon in practice), the above program will compile successfully, but behave unexpectedly when run.

In particular, the program will output a value of 1, instead of the value of 1.5 that was likely expected by the programmer.

Since the C \texttt{abs} function is declared as \texttt{int abs(int)}, the use of this function will introduce a conversion from \texttt{double} to \texttt{int}, leading to the unexpected result.
The problems of the previous slide can be easily avoided as follows.

First, include the header `cmath`, which provides overloads of `std::abs` for various built-in types, including `double`.

Then, invoke the function `std::abs` (instead of `::abs`).

For example, the following code will behave as expected, outputting the value of 1.5:

```cpp
#include <iostream>
#include <cmath>
int main() {std::cout << std::abs(-1.5) << '\n';}
```
sizeof Class Versus Sum of Member Sizes

- compilers can (and do) add padding to classes/structs

- Example:

```cpp
#include <iostream>

class Widget {
    // ...
    private:
    char c;
    int i;
};

int main() {
    // two numbers printed not necessarily the same
    std::cout << sizeof(char) + sizeof(int) << " " <<
               sizeof(Widget) << "\n";
    std::cout << alignof(int) << " " <<
               alignof(Widget) << "\n";
}
```

- many processors place alignment restrictions on data (e.g., data type of size $n$ must be aligned to start on address that is multiple of $n$)

- other factors can also add to size of class/struct (e.g., virtual function table pointer)
consider following type:

```cpp
struct Widget {
    char c;
    int i;
};
```

suppose that `sizeof(int)` is 4 and `alignof(int)` is 4

compiler adds padding to structure so that `int` data member is suitably aligned (i.e., offset is multiple of 4)

memory layout for `Widget` object:
Returning an rvalue reference to an rvalue reference parameter can potentially lead to very subtle bugs.

Example:

```cpp
std::string&& join(std::string&& s, const char* p) {
    return std::move(s.append(",").append(p));
}

std::string getMessage() { return "Hello"; }

void func() {
    const string& r = join(getMessage(), " World");
    // lifetime of temporary returned by getMessage
    // not extended to lifetime of r since not
    // directly bound to r
    // r now refers to destroyed temporary
}
```

Fix:

```cpp
std::string join(std::string&& s, const char* p) {
    return std::move(s.append(",").append(p));
}
```

Returning by rvalue reference should probably be avoided, except in very special circumstances (such as `std::forward` and `std::move`).
Be Careful When Mixing Signed and Unsigned Types

```cpp
#include <cassert>

int main() {
    short ss = -1;
    int si = -1;
    long sl = -1;
    long long sll = -1;
    unsigned short us = 0;
    unsigned int ui = 0;
    unsigned long ul = 0;
    unsigned long long ull = 0;

    // comparison between signed and unsigned types
    assert(ss < ui); // FAILS: ss becomes UINT_MAX
    // comparison between signed and unsigned types
    assert(si < ui); // FAILS: si becomes UINT_MAX
    // comparison between signed and unsigned types
    assert(sl < ul); // FAILS: sl becomes ULONG_MAX
    // comparison between signed and unsigned types
    assert(sll < ull); // FAILS: sll becomes ULONGLONG_MAX
}
```

- be aware of rules for promotions and conversions involving integral types
- if these rules not considered, code may not behave in manner expected
#include <initializer_list>
#include <iostream>
#include <string>
#include <vector>

class Widget {
public:
    Widget(const std::vector<std::string>& v) : v_(v) {}
    const std::string& get(std::size_t i) const { return v_[i]; }

private:
    std::vector<std::string> v_;
};

int main() {
    Widget w({"zero", "one", "two", "three"});

    for (auto&& i : w.get(0)) {
        std::cout << i;
    }
    std::cout << '\n';

    // ERROR: dangling reference
    for (auto&& i : Widget(w).get(0)) {
        std::cout << i;
    }
    std::cout << '\n';
}
Section 13.2

Exercises
main.cpp

```cpp
#include <complex>
#include <iostream>
#include <vector>

std::complex<long double>
square(std::complex<long double>& x) {
    return x * x;
}

void do_stuff(std::vector<int>& v) {
    int* ip = v.data();
    std::cout << ip << '
';
    for (std::vector<int>::iterator i = v.begin();
        i != v.end(); ++i) {
        std::cout << (i - v.begin()) << ' ' << *i << '
';
    }
}

int main() {
    std::vector<int> v{1, 2, 4, 8};
    do_stuff(v);
    std::complex<long double> fortytwo{42};
    std::cout << square(fortytwo) << '
';
}```
main.cpp

```cpp
#include <complex>
#include <iostream>
#include <vector>

std::complex<long double>
square(const std::complex<long double>& x) {
    return x * x;
}

void do_stuff(const std::vector<int>& v) {
    const int* ip = v.data();
    std::cout << ip << '
';
    for (std::vector<int>::const_iterator i = v.begin();
        i != v.end(); ++i) {
        std::cout << (i - v.begin()) << ' ' << *i << '
';
    }
}

int main() {
    const std::vector<int> v{1, 2, 4, 8};
    do_stuff(v);
    const std::complex<long double> fortytwo{42};
    std::cout << square(fortytwo) << '
';
}
```
What Is Wrong With This Code?

main.cpp

```
#include <iostream>

class Counter {
public:
  Counter(unsigned c = 0) : c_(c) {}
  Counter(Counter& other) : c_(other.c_) {}
  Counter(const Counter&& other) : c_(other.c_) {}
  ~Counter() {}
  Counter& operator=(Counter& other) {
    c_ = other.c_; return *this;
  }
  Counter& operator=(const Counter&& other) {
    c_ = other.c_; return *this;
  }
  void clear() {c_ = 0;}
  const unsigned get_count() {return c_;}
  const Counter& operator++() {++c_; return *this;}
  operator bool() {return c_ != 0;}
private:
  unsigned c_; // counter value
};

int main() {
  Counter zero;
  Counter c{zero};
  ++c;
  std::cout << c.get_count() << 'n';
  std::cout << zero.get_count() << 'n';
}
```
#include <iostream>

class Counter {
public:
    Counter(unsigned c = 0) : c_(c) {}
    Counter(const Counter& other) : c_(other.c_) {}
    Counter(Counter&& other) : c_(other.c_) {}
    ~Counter() {}
    Counter& operator=(const Counter& other)
    { c_ = other.c_; return *this; }
    Counter& operator=(Counter&& other)
    { c_ = other.c_; return *this; }
    void clear() {c_ = 0;}
    unsigned get_count() const {return c_;}
    Counter& operator++() {++c_; return *this;}
    operator bool() const {return c_ != 0;}
private:
    unsigned c_; // counter value
};

int main() {
    const Counter zero;
    Counter c{zero};
    ++c;
    std::cout << c.get_count() << 'n';
    std::cout << zero.get_count() << 'n';
}
What Is Wrong With This Code?

foo.hpp

```cpp
#ifndef foo_hpp
#define foo_hpp
namespace foo {
    bool is_odd(int x) { return (x % 2) != 0; }
    bool is_even(int x) { return (x % 2) == 0; }
}
#endif
```

main.cpp

```cpp
#include <iostream>
#include "foo.hpp"
int main() {
    std::cout << foo::is_odd(42) << ' ' << foo::is_even(42) << '
';
}
```

other.cpp

```cpp
#include "foo.hpp"
// ...
```
foo.hpp

```cpp
#ifndef foo_hpp
#define foo_hpp
namespace foo {
inline bool is_odd(int x) { return (x % 2) != 0; }
inline bool is_even(int x) { return (x % 2) == 0; }
}
#endif
```

main.cpp

```cpp
#include <iostream>
#include "foo.hpp"
int main() {
    std::cout << foo::is_odd(42) << ' ' << foo::is_even(42) << '
';
}
```

other.cpp

```cpp
#include "foo.hpp"
// ...
```
[Q.4] What Is Wrong With This Code?

foo.hpp

```cpp
#ifndef foo_hpp
#define foo_hpp
namespace foo {
inline bool is_odd(int x);
inline bool is_even(int x);
}
#endif
```

foo.cpp

```cpp
#include "foo.hpp"
namespace foo {
bool is_odd(int x) {return (x % 2) != 0;}
bool is_even(int x) {return (x % 2) == 0;}
}
```

app.cpp

```cpp
#include <iostream>
#include "foo.hpp"
int main() {
    std::cout << foo::is_odd(42) << ' ' << foo::is_even(42) << '
';
}
```
foo.hpp

1   #ifndef foo_hpp
2   #define foo_hpp
3   namespace foo {
4   inline bool is_odd(int x) {return (x % 2) != 0;}
5   inline bool is_even(int x) {return (x % 2) == 0;}
6   }
7   #endif

app.cpp

1   #include <iostream>
2   #include "foo.hpp"
3   int main() {
4       std::cout << foo::is_odd(42) << ' ' <<
5       foo::is_even(42) << '
';
6   }

**What Is Wrong With This Code?**

### foo.hpp
```cpp
#ifndef foo_hpp
#define foo_hpp
namespace foo {
  template <typename T> T abs(const T& x);
}
#endif
```

### foo.cpp
```cpp
#include "foo.hpp"
namespace foo {
  template <typename T> T abs(const T& x) {
    return (x < 0) ? (-x) : x;
  }
}
```

### app.cpp
```cpp
#include <iostream>
#include "foo.hpp"
int main() {
  std::cout << foo::abs(-42) << ' ' << foo::abs(-3.14) << '
';
}
```
Solution 1: Explicit Template Instantiation

foo.hpp

```cpp
#ifndef foo_hpp
#define foo_hpp
namespace foo {
    template <typename T> T abs(const T& x);
}
#endif
```

foo.cpp

```cpp
#include "foo.hpp"
namespace foo {
    template <typename T> T abs(const T& x)
    {
        return (x < 0) ? (-x) : x;
    }
    template int abs<int>(const int&);
    template double abs<double>(const double&);
}
```

app.cpp

```cpp
#include <iostream>
#include "foo.hpp"
int main() {
    std::cout << foo::abs(-42) << ' ' <<
    foo::abs(-3.14) << '
';
}
```
Solution 2: Define Function Template in Header File

**foo.hpp**

```cpp
#ifndef foo_hpp
#define foo_hpp
namespace foo {
  template<typename T> T abs(const T& x) {
    return (x < 0) ? (-x) : x;
  }
}
#endif
```

**app.cpp**

```cpp
#include <iostream>
#include "foo.hpp"
int main() {
  std::cout << foo::abs(-42) << ' ' << foo::abs(-3.14) << '
;}
```
Remarks on Headers Files and Function Declarations

- Every function (whether it be inline or non-inline, or template or non-template) must be *declared* before being used.

- Consequently, functions that are part of an interface should normally be declared in a *header file* so that users of the interface can obtain the declarations needed for the interface by simply including the header file.

- An inline function should always be *defined* before being used.

- Consequently, an inline function that is declared in a header file should normally also be *defined* in the file.

- A template function must be *defined* at its point of use in order for the template to be implicitly instantiated.

- Consequently, a template function that is declared in a header file should normally also be *defined* in the file.

- A function must not be defined more than once.

- Consequently, unless a function is inline or a template, it should not be defined in a header file, as this will result in multiple definitions if the header file is included by more than one source file.
[Q.6] What Is Wrong With This Code?

foo.hpp

```cpp
#ifndef foo_hpp
#define foo_hpp
#include <cmath>
namespace foo {
    double log(double x, double b);
}
#endif
```

foo.cpp

```cpp
#include <cmath>
#include "foo.hpp"
namespace foo {
    double log(double x, double b = 10.0) {
        return std::log(x) / std::log(b);
    }
}
```

app.cpp

```cpp
#include <iostream>
#include "foo.hpp"
int main() {
    std::cout << foo::log(16.0, 2.0) << " " <<
              foo::log(10.0) << "\n";
}
```
foo.hpp

```cpp
#ifndef foo_hpp
#define foo_hpp
#include <cmath>
namespace foo {
    double log(double x, double b = 10.0);
}
#endif
```

foo.cpp

```cpp
#include <cmath>
#include "foo.hpp"
namespace foo {
    double log(double x, double b) {
        return std::log(x) / std::log(b);
    }
}
```

app.cpp

```cpp
#include <iostream>
#include "foo.hpp"
int main() {
    std::cout << foo::log(16.0, 2.0) << ' ' << foo::log(10.0) << '
';
}
```
What Is Wrong With This Code?

foo.hpp

```cpp
namespace foo {
    constexpr int abs(int x);
}
```

foo.cpp

```cpp
#include "foo.hpp"

namespace foo {
    constexpr int abs(int x) { return (x < 0) ? (-x) : x; }
}
```

app.cpp

```cpp
#include <iostream>
#include "foo.hpp"

int main() {
    constexpr auto a = foo::abs(-42);
    std::cout << a << '
';
}
```
foo.hpp

```cpp
namespace foo {
  constexpr int abs(int x) { return (x < 0) ? (-x) : x; }
}
```

app.cpp

```cpp
#include <iostream>
#include "foo.hpp"

int main() {
  constexpr auto a = foo::abs(-42);
  std::cout << a << '\n';
}
```
What Is Wrong With This Code?

```cpp
#include <cmath>
#include <cassert>

constexpr double func(double x) {
    assert(x >= 0.0);
    return std::sqrt(x) + std::sin(x) * std::cos(x);
}
```
std::sqrt, std::sin, and std::cos are not constexpr functions (at least, in fully compliant C++20 implementation) \[\text{[C++17 §20.5.5.6/1]}\]

consequently, \texttt{func} is invalid constexpr function, since no arguments exist for which function can be evaluated as constant expression

invocation of \texttt{assert} is okay, since \texttt{assert} can be used in constant expression
What Is Wrong With This Code?

```cpp
#include <list>
#include <iostream>

constexpr std::list<int> get_values() {
    return {1, 2, 3};
}

int main() {
    for (auto x : get_values()) {
        std::cout << x << '
';
    }
}
```
#include <list>
#include <iostream>

// ERROR: std::list<int> is not literal type
// could instead use return type of std::array<int, 3>
constexpr std::list<int> get_values() {
    return {1, 2, 3};
}

int main() {
    for (auto x : get_values()) {
        std::cout << x << '
';
    }
}
#include <vector>
#include <iostream>

constexpr std::vector<int> get_values(int a, int b, int c) {
    return {a, b, c};
}

int main() {
    constexpr auto v = get_values(1, 2, 3);
    for (auto x : v) {
        std::cout << x << 'n';
    }
}
```cpp
#include <vector>
#include <iostream>

constexpr std::vector<int> get_values(int a, int b, int c) {
    return {a, b, c};
}

int main() {
    // ERROR: initializer for v is not constant expression due to constructor of std::vector<int> allocating memory (via new) that is not freed during evaluation of initializer expression; to fix this problem, could change return type of get_values to std::array<int, 3> or remove constexpr from declaration of v
    constexpr auto v = get_values(1, 2, 3);
    for (auto x : v) {
        std::cout << x << ' ' << '
';
    }
}
```
What Is Wrong With This Code?

```cpp
#include <algorithm>
#include <cstddef>

template <class T>
void in_place_transpose(T* a, std::size_t m, std::size_t n) {
    T tmp[m][n];
    std::copy_n(a, m * n, &tmp[0][0]);
    for (std::size_t i = 0; i < m; ++i) {
        for (std::size_t j = 0; j < n; ++j) {
            a[j * m + i] = tmp[i][j];
        }
    }
}
```

- Ignore possibility of integer overflow
- Ignore potential cache-efficiency issues
The code has at least two serious problems:

- **code uses variable length array (VLA) (i.e., `tmp`)**
- **VLAs are forbidden in (standard-compliant) C++ (i.e., array sizes must be constant expressions)**
- **even with compilers that allow VLAs in violation of C++ standard (such as GCC), object of unknown (and potentially very large) size being created on stack**
- **can easily result in stack overflow**
Solution: Avoid VLAs and Creating Large Stack Objects

```cpp
#include <algorithm>
#include <vector>
#include <cstddef>

template <class T>
void in_place_transpose(T* a, std::size_t m, std::size_t n) {
    std::vector<T> tmp(a, a + m * n);
    for (std::size_t i = 0; i < m; ++i) {
        for (std::size_t j = 0; j < n; ++j) {
            a[j * m + i] = tmp[i * n + j];
        }
    }
}
```

- use of `std::vector` for temporary array avoids need for VLA
- since `std::vector` allocates its underlying array storage from heap, potential stack overflow problem avoided
How to Invoke `func` at Compile Time?

```cpp
int func() {
    int i = 0;
    // ... (valid code for constexpr function)
    return i;
}

int main() { return func();
}
```
```cpp
constexpr int func() {
    int i = 0;
    // ... (valid code for constexpr function)
    return i;
}

int main() {
    constexpr int i = func();
    return i;
}
```
How to Invoke `func` at Compile Time?

```cpp
void func() {
    // ... (valid code for constexpr function)
}

int main() {
    func();
    func();
}
```


```cpp
constexpr void func() {
    // ... (valid code for constexpr function)
}

static_assert((func(), true));

int main() {
}
```
Cache Exercise

- memory and cache parameters:
  - maximum memory size is 1024 bytes
  - cache size is 64 bytes
  - 4-byte cache block size
  - 4-way set associative cache

- determine:
  1. number of bits in address
     - \( \log_2 1024 = 10 \) (i.e., log base 2 of number of addresses)
  2. number of blocks in memory
     - \( 1024/4 = 256 \) (i.e., memory size divided by block size)
  3. number of blocks in cache
     - \( 64/4 = 16 \) (i.e., cache size divided by block size)
  4. number of sets in cache
     - \( 16/4 = 4 \) (i.e., number of cache blocks divided by set associativity)
  5. number of bits in block offset
     - \( \log_2 4 = 2 \) (i.e., log base 2 of cache block size)
  6. number of bits in cache index
     - \( \log_2 4 = 2 \) (i.e., log base 2 of number of sets)
  7. number of bits in cache tag
     - \( 10 - (2 + 2) = 6 \) (i.e., number of address bits minus number of cache index and block offset bits)
same memory and cache parameters as on previous slide

valid entries in cache:

<table>
<thead>
<tr>
<th>Tag</th>
<th>Index</th>
<th>Byte 0</th>
<th>Byte 1</th>
<th>Byte 2</th>
<th>Byte 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>001010_2</td>
<td>10_2</td>
<td>11_{16}</td>
<td>12_{16}</td>
<td>13_{16}</td>
<td>14_{16}</td>
</tr>
<tr>
<td>001010_2</td>
<td>11_2</td>
<td>21_{16}</td>
<td>22_{16}</td>
<td>23_{16}</td>
<td>24_{16}</td>
</tr>
<tr>
<td>001001_2</td>
<td>00_2</td>
<td>31_{16}</td>
<td>32_{16}</td>
<td>33_{16}</td>
<td>34_{16}</td>
</tr>
<tr>
<td>001111_2</td>
<td>01_2</td>
<td>41_{16}</td>
<td>42_{16}</td>
<td>43_{16}</td>
<td>44_{16}</td>
</tr>
</tbody>
</table>

does memory access to each of following addresses result in cache hit or miss, and if hit what value for address in cache?

1. 0010100011_2
   - tag 001010_2, index 00_2, block offset 11_2; cache miss

2. 0010101101_2
   - tag 001010_2, index 11_2, block offset 01_2; cache hit; data 22_{16}
Virtual Memory Exercise

- virtual and physical memory parameters:
  - 16-bit virtual address
  - 12-bit physical address
  - page size is 256 bytes

- determine:
  1. number of virtual pages
     - \( 2^{16}/2^8 = 2^8 = 256 \) (i.e., number of virtual addresses divided by page size)
  2. number of physical pages
     - \( 2^{12}/2^8 = 2^4 = 16 \) (i.e., number of physical addresses divided by page size)
  3. number of bits in page offset (PO)
     - \( \log_2 256 = 8 \) (i.e., log base 2 of page size)
  4. number of bits in virtual page number (VPN)
     - \( 16 - 8 = 8 \) (i.e., virtual address size in bits minus number of bits in PO)
  5. number of bits in physical page number (PPN)
     - \( 12 - 8 = 4 \) (i.e., physical address size in bits minus number of bits in PO)
Virtual Memory Exercise (Continued)

- same virtual memory parameters as on previous slide
- page table contains following address translation information:

<table>
<thead>
<tr>
<th>VPN</th>
<th>PPN</th>
<th>Flags</th>
</tr>
</thead>
<tbody>
<tr>
<td>00000000₂</td>
<td>1111₂</td>
<td>present, readable, writable, not executable</td>
</tr>
<tr>
<td>00000001₂</td>
<td>1010₂</td>
<td>present, readable, writable, not executable</td>
</tr>
<tr>
<td>10000000₂</td>
<td>0000₂</td>
<td>present, readable, not writable, executable</td>
</tr>
</tbody>
</table>

- determine result of translation and protection check for accesses to following addresses:
  1. data read 1111111100000000₂
     - VPN 11111111₂, PO 00000000₂ access violation (no address mapping)
  2. instruction fetch 0000000000000000₂
     - VPN 00000000₂, PO 00000000₂; access violation (physical address 111100000000₂)
  3. data write 0000000100000000₂
     - VPN 00000001₂, PO 00000000₂; physical address 101000000000₂
- could virtual address xxxxxxxx00000000₂ map to physical address yyyyy00001111₂?
  - no (page offsets differ)
```cpp
#include <cstddef>

// write elements of source array src to destination
// array dst in reverse order

template <class T, std::size_t N>
void reverse(const T (&src)[N], T (&dst)[N]) {
    for (std::size_t i = 0; i < N; ++i) {
        dst[N - 1 - i] = src[i];
    }
}
```
#include <iostream>

// include definition of reverse
#include "aliasing_1_1.hpp"

int main() {
    int a[4] = {1, 2, 3, 4};
    reverse(a, a);
    for (auto&& x : a) {
        std::cout << x << '\n';
    }
}

- reverse will not work correctly if src and dst parameters refer to same array
- consider above usage of reverse, which is problematic
```cpp
#include <cstddef>

template <class T, std::size_t N>
void reverse(const T (&src)[N], T (&dst)[N]) {
    // Check for aliasing case.
    if (src == dst) {
        for (std::size_t i = 0; i < N / 2; ++i) {
            using std::swap;
            swap(dst[i], dst[N - 1 - i]);
        }
    } else {
        for (std::size_t i = 0; i < N; ++i) {
            dst[N - 1 - i] = src[i];
        }
    }
}
```
What is wrong with this code?

```
// Append the string pointed to by src to the string pointed to by dst.
// Suppose that no restrictions are placed on src and dst.
// What is wrong with this code?
char* string_concat(char* dst, const char* src) {
    while (*dst != '\0') {
        ++dst;
    }
    while (*src != '\0') {
        *dst++ = *src++;
    }
    *dst = '\0';
}
```
```cpp
#include <iostream>

char* string_concat(char *, const char*);

int main() {
    char a[1024] = "bye";
    string_concat(a, a);
    std::cout << a << '\n';
}
```

- **string_concat** will not work correctly if source and destination strings overlap
- Consider above code, which will not work correctly (and probably result in segmentation fault)
- Best solution is to change interface so that overlap of source and destination forbidden (since detecting aliasing cannot be done efficiently)
class Complex {
public:
    Complex(double r, double i) : r_(r), i_(i) {}
    double real() const {return r_;}
    double imag() const {return i_;}
    // What is wrong with the following function?
    Complex& operator*=(const Complex& other) {
        auto r = r_;  
        auto i = i_;  
        r_ = r * other.r_ - i * other.i_;   
        i_ = r * other.i_ + i * other.r_;   
        return *this;
    }
    // ...
private:
    double r_; // real part
    double i_; // imaginary part
};
#include <iostream>
#include "aliasing_3_1.hpp"

int main() {
    Complex a(1.0, 1.0);
    Complex b(a);
    b *= a;
    a *= a;
    // The value of b is correct.
    std::cout << b.real() << ' ' << b.imag() << '
';
    // The value of a is not correct.
    std::cout << a.real() << ' ' << a.imag() << '
';
}

- Complex::operator* will not correctly handle case that *this and other are aliased
- above code will not work correctly
```cpp
class Complex {
public:
    Complex(double r, double i) : r_(r), i_(i) {} 
    double real() const {return r_;}
    double imag() const {return i_;}
    Complex& operator*=(const Complex& other) {
        auto r = r_; 
        auto i = i_; 
        auto other_r = other.r_; 
        auto other_i = other.i_; 
        r_ = r * other_r - i * other_i; 
        i_ = r * other_i + i * other_r; 
        return *this;
    }
    // ...
private:
    double r_; // real part 
    double i_; // imaginary part
};
```
Triangle Program

- consider simple triangle classification program

- program performs following:
  1. read (from standard input stream) three integers \(a\), \(b\), and \(c\) that represent lengths of sides of triangle
  2. classify triangle with sides of lengths \(a\), \(b\), and \(c\) as one of:
     1. equilateral (i.e., all three sides equal in length)
     2. isosceles (i.e., exactly two sides equal in length)
     3. scalene (i.e., all sides have distinct lengths)
  3. write (to standard output stream) triangle classification

- what set of test cases would be effective for testing above program?
problem somewhat ill-posed in sense that following important information not stated:
  □ how critical is correct program function
  □ what assumptions can be made about input data

as starting point, might consider test cases that cover:
  □ equilateral case (e.g., (2, 2, 2))
  □ isosceles case, considering all permutations of edge lengths (e.g., (1, 1, 2), (1, 2, 1), (2, 1, 1))
  □ scalene case, considering all possible permutations of edge lengths (e.g., (3, 4, 5), (3, 5, 4), (4, 3, 5), (4, 5, 3), (5, 3, 4), (5, 4, 3))
  □ incorrectly formatted data (e.g., “1 2 apple”)
  □ insufficient data (i.e., less than three integers provided)
  □ superfluous data (i.e., more than three integers provided)
  □ lengths correspond to invalid triangle (e.g.: lengths not all strictly positive; or sum of any two lengths less than or equal to remaining length)
  □ lengths chosen in attempt to induce overflow (i.e., very large lengths)

if mission critical, we might perform more exhaustive testing
```cpp
#include <iostream>
#include <string>
#include <utility>

std::string&& func1(std::string& x) {
    return std::move(x);
    // x? std::move(x)?
}

int main() {
    const std::string hello("Hello");
    std::string a;
    std::string b;

    a = hello + "!";
    // hello? hello + "!"? a = hello + "!"?
    std::cout << a << ' ';
    // std::cout? std::cout << a?

    a = std::string(""");
    // std::string("")? a = std::string("")?
    ((a += hello) += "!");
    // a += hello?
    b = func1(a);
    // func1(a)? b = func1(a)?
    std::cout << b << ' ';
}
```
What Is the Behavior of This Code?

class Widget {
  public:
    Widget() {}
    int i() const {return i_;}  // Note the const
  private:
    int i_;  // Notice the private
};

int main() {
  Widget w;
  return w.i();
}
class Widget {
public:
    Widget() : i_() {}
    int i() const { return i_; }
private:
    int i_;  
};

int main() {
    Widget w;
    return w.i();
}
class Widget {
public:
    Widget() {}
    int i() const {return i_;}
private:
    int i_{};
};

int main() {
    Widget w;
    return w.i();
}
What Is the Behavior of This Code?

```
#include <iostream>

// aggregate
struct Widget {
    int i = 0;
    int j = 0;
};

std::ostream& operator<<(std::ostream& out, const Widget& w) {
    return out << w.i << ',' << w.j;
}

int main() {
    Widget a;
    Widget b{};
    Widget c{1};
    Widget d{1, 2};
    std::cout << a << ' ' << b << ' ' << c << ' ' << d << '\n';
}
```
#include <utility>

class Gadget {
public:
    Gadget();
    Gadget(const Gadget&);
    Gadget(Gadget&&);
    Gadget& operator=(const Gadget&);
    Gadget& operator=(Gadget&&);
    // ...
};

Gadget func_1() {return Gadget();}
Gadget func_2() {Gadget g; return g;}
void func_3(Gadget g) { /* ... */}

int main() {
    Gadget s = Gadget();
    Gadget t(std::move(s));
    Gadget u(func_1());
    Gadget v(func_2());
    Gadget w(v);
    s = std::move(t);
    t = s;
    s = func_1();
    s = func_2();
    func_3(s);
    func_3(std::move(s));
    func_3(func_1());
}
```cpp
#include <utility>

class Gadget {
public:
    Gadget();
    Gadget(const Gadget&);
    Gadget(Gadget&&);
    Gadget& operator=(const Gadget&);
    Gadget& operator=(Gadget&&);
    // ...
};

Gadget func_1() {return Gadget();}
Gadget func_2() {Gadget g; return g;}
void func_3(Gadget g) {/* ... */}

int main() {
    Gadget s = Gadget(); // default ctor, elided copy
    Gadget t(std::move(s)); // move ctor
    Gadget u(func_1()); // default ctor, elided copy
    Gadget v(func_2()); // default ctor, maybe move ctor
    Gadget w(v); // copy ctor
    s = std::move(t); // move assign
    t = s; // copy assign
    s = func_1(); // default ctor, elided copy, move assign
    s = func_2(); // default ctor, maybe move ctor, move assign
    func_3(s); // copy ctor
    func_3(std::move(s)); // move ctor
    func_3(func_1()); // default ctor, elided copy
    func_3(std::move(func_1())); // move ctor
    return 0;
}
```
#include <utility>

class Gadget {
public:
    Gadget();
    Gadget(const Gadget&);
    Gadget(Gadget&&);
    Gadget& operator=(const Gadget&);
    Gadget& operator=(Gadget&&);
    // ...
};

Gadget func_1() {return std::move(Gadget());} // BAD IDEA
Gadget func_2() {Gadget g; return std::move(g);} // BAD IDEA
const Gadget func_3() {return Gadget();} // BAD IDEA
const Gadget func_4() {Gadget g; return g;} // BAD IDEA

int main() {
    Gadget s(func_1());
    Gadget u(func_2());
    Gadget t(func_3());
    Gadget w(func_4());
    s = func_1();
    s = func_2();
    s = func_3();
    s = func_4();
}
```cpp
#include <utility>

class Gadget {
public:
    Gadget();
    Gadget(const Gadget&);
    Gadget(Gadget&&);
    Gadget& operator=(const Gadget&);
    Gadget& operator=(Gadget&&);
    // ...
};

Gadget func_1() {return std::move(Gadget());} // BAD IDEA
Gadget func_2() {Gadget g; return std::move(g);} // BAD IDEA
const Gadget func_3() {return Gadget();} // BAD IDEA
const Gadget func_4() {Gadget g; return g;} // BAD IDEA

int main() {
    Gadget s(func_1()); // default ctor, move ctor
    Gadget u(func_2()); // default ctor, move ctor
    Gadget t(func_3()); // default ctor, copy elided
    Gadget w(func_4()); // default ctor, maybe move ctor
    s = func_1(); // default ctor, move ctor, move assign
    s = func_2(); // default ctor, move ctor, move assign
    s = func_3(); // default ctor, copy elided, copy assign
    s = func_4(); // default ctor, maybe move ctor, copy assign
}
```
What is wrong with the following code?

```cpp
void func(const std::string&);
std::string s("one");
const char* p = "two";
func(std::string(s) + std::string(",
") + std::string(p));
func(std::string(p) + std::string(",
") + std::string(s));
```

**Unnecessary temporaries!**

**Fix:**

```cpp
func(s + ", "+ p);
func(p + ", "+ s);
```
What is wrong with the following code?

```cpp
std::vector<std::string> v;
std::string s("one");
v.push_back(std::string(s));
v.push_back(std::string(s + ", two");
v.push_back(std::string("three");
v.push_back(std::string());
```

Again, unnecessary temporaries.

Fix:

```cpp
v.push_back(s);
v.push_back(s + ", two")
v.emplace_back("three");
v.emplace_back();
```
What is wrong with this code?

```cpp
class TwoResources {
public:
    TwoResources() : x_(nullptr) : y_(nullptr) {
        x_ = new X;
        y_ = new Y;
    }
    ~TwoResources() {
        delete x_; 
        delete y_; 
    }
private:
    X* x_; 
    Y* y_; 
};
```

If an exception is thrown in a constructor, the object being constructed is deemed not to have started its lifetime and no destructor will ever be called for the object.

So, for example, if `new Y` throws, `x_` will be leaked.

Fix:

```cpp
class TwoResources {
public:
    TwoResources() : x_(make_unique<X>()) , y_(make_unique<Y>()) {} 
private:
    unique_ptr<X> x_; 
    unique_ptr<Y> y_; 
};
```
What is wrong with the following code?

```cpp
const std::string getMessage() {
    return "Hello";
}
```

The const return value will *interact poorly with move semantics*, as the returned object cannot be used as the source for a move operation (since the source for a move operation must be modifiable).

Fix:

```cpp
std::string getMessage() {
    return "Hello";
}
```
When specifying a literal, be careful to use a literal of the correct type, as the type can often be quite important.

For example, what value will be printed by the following code and (more importantly) why:

```cpp
std::vector<double> values;
values.push_back(0.5);
values.push_back(0.5);
// Compute the sum of the elements in the vector values.
double sum = std::accumulate(values.begin(),
    values.end(), 0);
std::cout << sum << '\n';
```

Hint: The value printed for `sum` is not 1.

In order to determine what values will be printed, look carefully at the definition of `std::accumulate`.

Answer: The value printed for `sum` is 0.
This slide is a placeholder and has been intentionally left blank.
Part 14

Additional Learning Resources
Know what you do not know.

Ask questions when you are uncertain about something and be sure that the person whom you ask is knowledgeable enough to give a correct answer.

Know what information resources can be trusted.

Learn to use reference materials effectively (e.g., documentation on libraries, standards).
Some good references on various topics related to the C++ programming language, C++ standard library, and other C++ libraries (such as Boost) are listed on the slides that follow.
This is the definitive specification of the C++ language and standard library. This is an essential reference for any advanced programmer.

This is the classic book on the C++ programming language and standard library, written by the creator of the language. This is one of the best references for first learning C++.

This is the web site of a non-profit organization whose purpose is to support the C++ software development community and promote the understanding and use of modern standard C++ on all compilers and platforms. This is an absolutely outstanding source of information on C++. 


This book covers a list of 50 topics on how to better utilize the Standard Template Library (STL), an essential component of the C++ standard library.


This is a very comprehensive book on the C++ standard library. This is arguably the best reference on the standard library (other than the C++ standard).


This is a very comprehensive book on template programming in C++. It is arguably one of the best books on templates in C++.


This is a fairly comprehensive book on concurrency and multithreaded programming in C++. It is arguably the best book available for those who want to learn how to write multithreaded code using C++.
This book covers topics including (but not limited to): proper resource management, exception safety, RAII, and good class design.

This book covers topics including (but not limited to): exception safety, effective object-oriented programming, and correct use of STL.

This book covers topics including (but not limited to): generic programming, optimization, resource management, and how to write modular code.

This book presents 101 best practices, idioms, and common pitfalls in C++ in order to allow the reader to become a more effective C++ programmer.

This book provides a very detailed look at C++ I/O streams and locales.


This is a detailed tutorial on how to interpret complex C/C++ type declarations. This tutorial explains how type declarations are parsed in the language, which is essential for all programmers to understand clearly.


   An introduction to programming using C++ by the creator of the language.


1. Herb Sutter’s Web Site: http://herbsutter.com
4. ISO C++ Working Group web site:
   http://www.open-std.org/jtc1/sc22/wg21/
5. ISO C++ Standards Committee GitHub site:
   https://github.com/cplusplus
10. Stackoverflow: http://stackoverflow.com
11 Cpp Reddit (C++ discussions, articles, and news):
   https://www.reddit.com/r/cpp

12 Cplusplus Reddit (C++ questions, answers, and discussion):
   https://www.reddit.com/r/cplusplus

13 ACCU Overload Journal:
   http://accu.org/index.php/journals/c78/

14 The C++ Source: http://www.artima.com/cppsource
1. CppCon, [https://cppcon.org](https://cppcon.org)
2. C++ Now, [http://cppnow.org](http://cppnow.org)
3. Meeting C++, [https://meetingcpp.com](https://meetingcpp.com)
4. code::dive, [https://codedive.pl](https://codedive.pl)
5. ACCU Conference, [https://conference.accu.org](https://conference.accu.org)
6. Pacific++, [https://pacificplusplus.com](https://pacificplusplus.com)
7. NDC Conferences, [https://ndcconferences.com](https://ndcconferences.com)
   - NDC TechTown, [https://ndctechtown.com](https://ndctechtown.com)
Google Code Jam

https://code.google.com/codejam/

Topcoder

https://www.topcoder.com/

IEEEExtreme 24-Hour Programming Competition

http://www.ieee.org/xtreme

ACM International Collegiate Programming Contest (ICPC)

http://icpcnews.com/

CodeChef

https://www.codechef.com/
Use as many information resources as you can to learn as much as you can about C++.

Read books, articles, and other documents.

Watch videos.

Attend lectures and seminars.

Participate in programming competitions.

But most importantly:

Write code!
Write lots and lots and lots and lots of code!

The only way to truly learn a programming language well is to use it heavily (i.e., write lots of code using the language).