Lecture Slides for Programming in C++
(Version: 2017-02-24)

Current with the C++14 Standard

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For additional information and resources related to these lecture slides (including errata and lecture videos covering the material on many of these slides), please visit: http://www.ece.uvic.ca/~mdadams/cppbook

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Part 0

Preface
This document constitutes a detailed set of lecture slides on the C++ programming language and is current with the C++14 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.
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; and
4. engaging 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 in a font like this.

To emphasize particular words, the words are typeset in a font like this.
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)
Which Language to Learn?

C, C++, Fortran, Java, MATLAB, C#, Objective C

programming language popularity

http://www.tiobe.com/ TIOBE Software Programming Community Index Jan 2011 all in top four: Java, C, C++ MATLAB (23rd) Fortran (27th)

Programming Language Popularity Normalized Comparison http://www.langpop.com/ top three languages: C, Java, C++

international standard

vendor neutral
C

- created by Dennis Ritchie, AT&T Bell Labs in 1970s
- international standard ISO/IEC 9899:2011 (informally known as “C11”)
- 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
- most recent specification of language in ISO/IEC 14882:2014 (informally known as “C++14”)
- 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
- 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
designed by John Backus, IBM, in 1950s

international standard ISO/IEC 1539-1:2010 (informally known as ”Fortran 2008”)

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
developed by Microsoft, team led by Anders Hejlsberg

ECMA-334 and ISO/IEC 23270:2006

most recent language specifications not standardized by ECMA or ISO/IEC

intellectual property concerns over Microsoft patents

object oriented
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
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++
Part 2
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:

B. Stroustrup. *Communication and Control in Distributed Computer Systems.*

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)
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)

B. Stroustrup. Classes: An abstract data type facility for the C language.
Bell Laboratories Computer Science Technical Report
CSTR-84, Apr. 1980.
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
B. Stroustrup. Classes: An abstract data type facility for the C language.


Feb 1983 more detailed paper on C with Classes published

B. Stroustrup. Adding classes to the C language: An exercise in language evolution.


- 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

B. Stroustrup. Data abstraction in C. 
(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
B. Stroustrup. Operator overloading in C++.  

1984 stream I/O library first implemented and later presented in  
B. Stroustrup. *An extensible I/O facility for C++*.  

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  
B. Stroustrup. *The C++ Programming Language*.  
Addison Wesley, 1986.
(Cfront Release 1.0 corresponded to language as defined in this book)

Oct 1985  tutorial paper on C++

B. Stroustrup.  *A C++ tutorial.*

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)

B. Stroustrup.  *What is object-oriented programming?*
Timeline for C84 to C++98 (1982–1998) V

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:

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 \(\to\)
pointers to members (first provided in release 1.2)

1989 main features of Cfront 2.0 summarized in

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

Addison Wesley, May 1990.
(formed basis for ANSI standardization)

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

B. Stroustrup. *The C++ Programming Language*.

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 C++*.
(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

A. Stepanov and M. Lee. The standard template library. 

Aug 1996  export accepted (Stockholm, Sweden)
1997   third edition of C++PL published

B. Stroustrup. The C++ Programming Language. 
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

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)
Timeline After C++98 (1998–Present) II

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
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
### C++ User Population

<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)
- entertainment (games)
- GUI
- 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)

B. Stroustrup. *The Design and Evolution of C++.*


(See [http://www.softwarepreservation.org/projects/c_plus_plus/cfront](http://www.softwarepreservation.org/projects/c_plus_plus/cfront)).

Section 2.2

Getting Started
```cpp
#include <iostream>

int main ()
{
    std::cout << "Hello, world!\n";
}
```

- 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
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:

```
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`:

```
g++ -c file.cpp
```

link object files `file_1.o, file_2.o, ...` to produce executable file `executable`:

```
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

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-c</td>
<td>compile only (i.e., do not link)</td>
</tr>
<tr>
<td>-o <code>file</code></td>
<td>use file <code>file</code> for output</td>
</tr>
<tr>
<td>-g</td>
<td>include debugging information</td>
</tr>
<tr>
<td>-O<code>n</code></td>
<td>set optimization level to <code>n</code> (0 almost none; 3 full)</td>
</tr>
<tr>
<td>-std=c++14</td>
<td>conform to C++14 standard</td>
</tr>
<tr>
<td>-pthread</td>
<td>enable concurrency support (via pthreads library)</td>
</tr>
<tr>
<td>-I <code>dir</code></td>
<td>specify additional directory <code>dir</code> to search for include files</td>
</tr>
<tr>
<td>-L <code>dir</code></td>
<td>specify additional directory <code>dir</code> to search for libraries</td>
</tr>
<tr>
<td>-l <code>lib</code></td>
<td>link with library <code>lib</code></td>
</tr>
<tr>
<td>-pedantic-errors</td>
<td>strictly enforce compliance with standard</td>
</tr>
<tr>
<td>-Wall</td>
<td>enable most warning messages</td>
</tr>
<tr>
<td>-Wextra</td>
<td>enable some extra warning messages not enabled by -Wall</td>
</tr>
<tr>
<td>-Wpedantic</td>
<td>warn about deviations from strict standard compliance</td>
</tr>
<tr>
<td>-Werror</td>
<td>treat all warnings as errors</td>
</tr>
</tbody>
</table>
Clang C++ Compiler

- `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`
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:
   
   ```bash
   g++ -c hello.cpp
   ```

2. link object file hello.o to produce executable program hello:
   
   ```bash
   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

C++ Basics
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 14882:2014 (informally known as “C++14”)
- next version of standard expected in 2017
- 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
two styles of comments provided

comment starts with // and proceeds to end of line

comment starts with /* and proceeds to first */

    // 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

    /*
      /* 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
- Identifiers that begin with underscore (in many cases) or contain double underscores are reserved for use by C++ implementation and should be avoided
- 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)
<table>
<thead>
<tr>
<th>Reserved Keywords</th>
</tr>
</thead>
<tbody>
<tr>
<td>alignas</td>
</tr>
<tr>
<td>alignof</td>
</tr>
<tr>
<td>and</td>
</tr>
<tr>
<td>and_eq</td>
</tr>
<tr>
<td>asm</td>
</tr>
<tr>
<td>auto</td>
</tr>
<tr>
<td>bitand</td>
</tr>
<tr>
<td>bitor</td>
</tr>
<tr>
<td>bool</td>
</tr>
<tr>
<td>break</td>
</tr>
<tr>
<td>case</td>
</tr>
<tr>
<td>catch</td>
</tr>
<tr>
<td>char</td>
</tr>
<tr>
<td>char16_t</td>
</tr>
<tr>
<td>char32_t</td>
</tr>
<tr>
<td>class</td>
</tr>
<tr>
<td>compl</td>
</tr>
<tr>
<td>const</td>
</tr>
<tr>
<td>constexpr</td>
</tr>
<tr>
<td>const_cast</td>
</tr>
<tr>
<td>continue</td>
</tr>
<tr>
<td>decltype</td>
</tr>
</tbody>
</table>

*Note: context sensitive*
Section 2.3.1

Objects, Types, and Values
Fundamental Types

- boolean type: `bool`
- character types:
  - `char` (may be signed or unsigned)
  - `signed char`
  - `unsigned char`
  - `char16_t`
  - `char32_t`
  - `wchar_t`
- `char` is distinct type from `signed char` and `unsigned char`
- standard signed integer types:
  - `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

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 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 char (in special cases int)</td>
</tr>
<tr>
<td>u8 [since C++17]</td>
<td>UTF-8</td>
<td>char</td>
</tr>
<tr>
<td>u</td>
<td>UCS-2</td>
<td>char16_t</td>
</tr>
<tr>
<td>U</td>
<td>UCS-4</td>
<td>char32_t</td>
</tr>
<tr>
<td>L</td>
<td>wide</td>
<td>wchar_t</td>
</tr>
</tbody>
</table>

special characters can be represented by escape sequence:

<table>
<thead>
<tr>
<th>Character</th>
<th>Escape Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>newline (LF)</td>
<td>\n</td>
</tr>
<tr>
<td>horizontal tab (HT)</td>
<td>\t</td>
</tr>
<tr>
<td>vertical tab (VT)</td>
<td>\v</td>
</tr>
<tr>
<td>backspace (BS)</td>
<td>\b</td>
</tr>
<tr>
<td>carriage return (CR)</td>
<td>\r</td>
</tr>
<tr>
<td>form feed (FF)</td>
<td>\f</td>
</tr>
<tr>
<td>alert (BEL)</td>
<td>\a</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Character</th>
<th>Escape Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>backslash ()</td>
<td>\ \</td>
</tr>
<tr>
<td>question mark (?)</td>
<td>?</td>
</tr>
<tr>
<td>single quote (‘)</td>
<td>‘</td>
</tr>
<tr>
<td>double quote (&quot;)</td>
<td>&quot;</td>
</tr>
<tr>
<td>octal number ooo</td>
<td>\ooo</td>
</tr>
<tr>
<td>hex number hhh</td>
<td>\xhhh</td>
</tr>
</tbody>
</table>

eamples of character literals:

'a' '1' '!' '\n' u'a' U'a' L'a' u8'a'
decimal digit characters guaranteed to be consecutive in value (e.g., ‘1’ must equal ‘0’ + 1)

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

- 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 char[]</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!"
  "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’
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:

```cpp
42
1’000’000’000’000ULL
0xdeadU
```

integer literal always nonnegative; so, for example, \(-1\) is integer literal 1 with negation operation applied
### 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>unsigned long int</td>
<td>unsinged 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>1 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>unsigned long int</td>
<td>unsinged long int</td>
</tr>
<tr>
<td></td>
<td>unsigned long long int</td>
<td>unsigned long long int</td>
</tr>
<tr>
<td>Both u or U and 1 or L</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>1l or LL</td>
<td>long long int</td>
<td>long long int</td>
</tr>
<tr>
<td></td>
<td>unsigned long long int</td>
<td>unsigned long long int</td>
</tr>
<tr>
<td>Both u or U and 1l or LL</td>
<td>unsigned long long int</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:
  
  - 1.414
  - 1.25e-8

- Examples of `float` literals:
  
  - 1.414f
  - 1.25e-8f

- Examples of `long double` literals:
  
  - 1.5L
  - 1.25e-20L

- Floating-point literals always nonnegative; so, for example, \(-1.0\) is literal 1.0 with negation operator applied.
*boolean literals:*
  
  `true`
  `false`

*pointer literal:*
  
  `nullptr`
Declarations and Definitions

- **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
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 a collection of one or more objects of *same* type that are stored *contiguously* in memory.
- Each element in an array is identified by (unique) integer index, with indices starting from *zero*.
- Arrays are denoted by `[]`.
- Example:
  ```
  double x[10];  // array of 10 doubles
  int data[512][512];  // 512 by 512 array of ints
  ```
- Elements of an array are accessed using the subscripting operator `[]`.
- Example:
  ```
  int x[10];
  // elements of arrays are x[0], x[1], ..., x[9]
  ```
- In C++ rarely ever need to use arrays.
- Use `std::array` or `std::vector` type instead (as this has many practical advantages over array).
- Will revisit `std::array` and `std::vector` types later.
Array Example

- **Code:**
  ```cpp
  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>
Points

- **pointer** is an object whose value is the address in memory where another object is stored.

- Pointer to an object of type `T` is denoted by `T*`.

- **null pointer** is a special pointer value that does not refer to any valid memory location.

- Null pointer value provided by **nullptr** keyword.

- Accessing the object to which the pointer refers is called **dereferencing**.

- Dereferencing a pointer is performed by the *indirection operator* (i.e., `*`).

- If `p` is a pointer, `*p` is the object to which the pointer `p` refers.

- If `x` is an object of type `T`, and `&x` is the address of the object (which has type `T*`).

- **Example:**
  ```
  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>
**References**

- **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
  ```
code:

```cpp
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>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>42</td>
</tr>
</tbody>
</table>
Assume: sizeof(int) is 4, sizeof(int*) is 4

\[
\begin{align*}
\text{int } i &= 0; \\
\text{int } j &= 1; \\
\text{int } k &= 2;
\end{align*}
\]

\[
\begin{align*}
\text{int } i &= 0; \\
\text{int* } j &= \& i; \\
\text{int } k &= 1;
\end{align*}
\]

\[
\begin{align*}
\text{int } i &= 0; \\
\text{int* } j &= \& i;
\end{align*}
\]

\[
\begin{align*}
i &= 3; \text{ vs. } j &= 3; ? \\
i &= 3; \text{ vs. } j &= 3; ? \\
i &= 3; \text{ vs. } *j &= 3; ?
\end{align*}
\]
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 referred to

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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 to 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:

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

desc
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:**

```
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*
  ```
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
  ```
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 \texttt{const} Qualifier and Pointer Types

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

```cpp
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

- \texttt{1000} (`&p`)
- \texttt{2000} (`&i`)

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// 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
*pci = 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 pointee
*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: `const` Qualifier and Reference Types

// 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 il = 0; const int cil = 0;

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

// reference to const int
const int& rci = ci;
rci = i; // ERROR: cannot modify const referee
const int& rci = cil;
    // 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
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 place holder 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
Section 2.3.2

Operators and Expressions
## Operators

### 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>

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### Logical/Relational Operators

<table>
<thead>
<tr>
<th>Operator Name</th>
<th>Syntax</th>
</tr>
</thead>
<tbody>
<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-&gt;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>Operator Name</td>
<td>Syntax</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>----------------------</td>
</tr>
<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>
</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>postfix increment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>--</td>
<td>postfix 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>prefix increment</td>
<td></td>
</tr>
<tr>
<td></td>
<td><code>--</code></td>
<td>prefix 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>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>-&gt;*</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;</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>9</td>
<td>==</td>
<td>equality</td>
<td>left to right</td>
</tr>
<tr>
<td></td>
<td>!=</td>
<td>inequality</td>
<td></td>
</tr>
</tbody>
</table>
## Operator Precedence (Continued 3)

<table>
<thead>
<tr>
<th>Precedence</th>
<th>Operator</th>
<th>Name</th>
<th>Associativity</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>&amp;</td>
<td>bitwise AND</td>
<td>left to right</td>
</tr>
<tr>
<td>11</td>
<td>^</td>
<td>bitwise XOR</td>
<td>left to right</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td>bitwise OR</td>
</tr>
<tr>
<td>13</td>
<td>&amp;&amp;</td>
<td>logical AND</td>
<td>left to right</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>? :</td>
<td>ternary conditional</td>
<td>right to left</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>assignment</td>
<td>right to left</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><strong>throw</strong></td>
<td>throw exception</td>
<td>right to left</td>
</tr>
<tr>
<td>18</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><code>and</code></td>
<td><code>&amp;&amp;</code></td>
</tr>
<tr>
<td><code>bitor</code></td>
<td>`</td>
</tr>
<tr>
<td><code>or</code></td>
<td>`</td>
</tr>
<tr>
<td><code>xor</code></td>
<td><code>^</code></td>
</tr>
<tr>
<td><code>compl</code></td>
<td><code>~</code></td>
</tr>
<tr>
<td><code>bitand</code></td>
<td><code>&amp;</code></td>
</tr>
<tr>
<td><code>and_eq</code></td>
<td><code>&amp;=</code></td>
</tr>
<tr>
<td><code>or_eq</code></td>
<td>`</td>
</tr>
<tr>
<td><code>xor_eq</code></td>
<td><code>^=</code></td>
</tr>
<tr>
<td><code>not</code></td>
<td><code>!</code></td>
</tr>
<tr>
<td><code>not_eq</code></td>
<td><code>!=</code></td>
</tr>
</tbody>
</table>

Alternative tokens above probably best avoided as they lead to more verbose code.
An expression is a sequence of operators and operands that specifies a computation.

An expression has a type and, if the type is not void, a value.

A constant expression is an expression that can be evaluated at compile time (e.g., 1 + 1).

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</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>true</td>
</tr>
<tr>
<td>p == &amp;x</td>
<td>int&amp;</td>
<td>false</td>
</tr>
<tr>
<td>x &gt; 2 * y</td>
<td>bool</td>
<td>reference to x</td>
</tr>
<tr>
<td>std::sin(d)</td>
<td>double</td>
<td>0.0</td>
</tr>
</tbody>
</table>

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## Operator Precedence/Associativity Example

<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>
</tbody>
</table>
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
**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 \texttt{alignof} Operator

- object type can have restriction on address at which object of type can start called \textit{alignment requirement}
- for given object type \( T \), starting address for objects of type \( T \) must be integer multiple of \( N \) bytes, where integer \( N \) is called \textit{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
- \texttt{alignof} operator is used to query alignment of type
- for object type \( T \), \texttt{alignof}(T) \) yields alignment used for objects of this type
- \texttt{alignof(char)}, \texttt{alignof(signed char)}, and \texttt{alignof(unsigned char)} guaranteed to be 1
- fundamental types of size greater than 1 often have alignment greater than 1
**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
cconstexpr 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 `static_assert` Statement

- `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
- as of C++17, 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");
  ```
Section 2.3.3

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
  ```

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to include multiple statements in branch of `if`, must group statements into single statement using brace brackets

```cpp
if (expression) {
    statement_1,1
    statement_1,2
    statement_1,3
...
} else {
    statement_2,1
    statement_2,2
    statement_2,3
...
}
```

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`
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";
}
```

eexample 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";
}
```
The `switch` Statement

- allows conditional execution of code based on value of integer expression
- syntax has form:
  ```
  switch (expression) {
    case const_expr1:
      statements1
    case const_expr2:
      statements2
    ...
    case const_exprn:
      statementsn
    default:
      statements
  }
  ```

- `expression` is integer expression; `const_expr_i` is constant integer expression (e.g., 2, 5+3, 3*5−11)
- 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
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;
}
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;
    }
}
```
example with single statement in loop body:

    // Print the integers from 0 to 9 inclusive.
    for (int i = 0; i < 10; ++i)
        std::cout << i << '
';

example with multiple statements in loop body:

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

example with error in assumption about scoping rules:

    for (int i = 0; i < 10; ++i) {
        std::cout << i << '
';
    }
    ++i; // ERROR: i no longer exists
variant of for loop for iterating over elements in range

example:

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

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

- looping construct
- has following general syntax:

```cpp
    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

```cpp
    do {
      statement_1
      statement_2
      ...
    } while (expression);
```

- advisable to *always use brace brackets*, even when loop body consists of only one statement
example with single statement in loop body:

```cpp
// delay by looping 10000 times
int n = 0;
do
    ++n;
while (n < 10000);
```

eexample with multiple statements in loop body:

```cpp
// print integers from 0 to 9 inclusive
int n = 0;
do {
    std::cout << n << '
';
    ++n;
} while (n < 10);
```
**break** statement causes enclosing loop or switch to be terminated immediately

**example:**

```cpp
#include <iostream>

int main() {
    int x;
    while (std::cin >> x) {
        if (x < 0) {
            break;
        }
        std::cout << x << '
';
    }
    return 0;
}
```

// Read integers from standard input until an error or end-of-file is encountered or a negative integer is read.
The `continue` Statement

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

- example:

```cpp
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] << '
';
}
```
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 << '
';
      ++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 2.3.4

Functions
argument (a.k.a. actual parameter): argument is value supplied to function by caller; appears in parentheses of function-call operator

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

although abuse of terminology, parameter and argument often used interchangeably

return value: result passed from function back to caller

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

basic syntax for function declaration:

\[
\text{return\_type \ function\_name (parameter\_declarations)};
\]

examples of function declarations:

\[
\begin{align*}
\text{int } \ & \text{min} (\text{int, int}); \\
\text{double } \ & \text{square} (\text{double});
\end{align*}
\]

basic syntax for function definition:

\[
\begin{align*}
\text{return\_type \ function\_name (parameter\_declarations)} \\
\{ \\
\qquad \text{statements} \\
\}
\]

examples of function definitions:

\[
\begin{align*}
\text{int } \ & \text{min} (\text{int } x, \text{int } y) \ \{ \text{return } x < y \ ? \ x : \ y; \} \\
\text{double } \ & \text{square} (\text{double } x) \ \{ \text{return } x * x; \}
\end{align*}
\]
Trailing Return-Type Syntax

- 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;
  ```

- examples 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
  }
  ```

- examples 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 no parameter
- 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
class一门 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):
  ```
  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:

```
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:

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

double square(double x)
    // x is passed by value
{
    return x * x;
}
```
if object being passed to function is *expensive to copy* (e.g., a very large data type), always faster to pass by reference

if function needs to *change value of object in caller*, must pass by reference

example:

```cpp
void increment0(int x) {
    ++x; // Increment x by one.
}

void increment(int& x) {
    ++x; // Increment x by one.
}

void func() {
    int i = 0;
    increment0(i); // i is passed by value
                    // i still equals 0 (i was not incremented)
    increment(i);  // i is passed by reference
                    // i equals 1 (i was incremented)
}
```
void func() {
    int i = ∅;
    increment ∅(i); // i unchanged
}

void increment ∅(int x) {
    ++x;
}
```cpp
void func() {
    int i = \emptyset;
    increment(i);  // i is incremented
}

void increment(int &x) {
    ++x;
}
```
void func() {
    double a;
    RealVector v = getvector();
    a = average(v);
}

double average(RealVector & x) {
    double a;
    // initialize a here
    return a;
}

• above code is incorrect
void func() {
    double a;
    const RealVector v = getvector();
    a = average(v);
}

double average(RealVector & x) {
    double a;
    // initialize a here
    return a;
}

• code will not compile
// ERROR: parameter type should be const char*

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
}

// 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
```cpp
#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
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;
}
**inline function**: 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

- can request function be made inline by including `inline` qualifier along with function return type

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

- inline function definition must be visible at point of use

- example:

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

- inlining of `isEven` function transforms code fragment 1 into code fragment 2

**Code fragment 1:**

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

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

**Code fragment 2:**

```cpp
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
- `constexpr` function very restricted in what it can do (e.g., no external state, can only call `constexpr` functions, variables must be initialized)
- Example:

```cpp
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
#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 << '
';
}
```
```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 << '
';
```
#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;}
    const double c = power_int(x, 2);
    // must be computed at run time
    std::cout << a << ' ' << b << ' ' << c << '\n';
    return 0;
}
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: multiple functions can have same name as long as they differ in number/type of their arguments

example:

```cpp
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

equal:

```cpp
// 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 x, double b = 10.0);
```

```cpp
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 \texttt{const} and/or \texttt{volatile}); of these, those that do not add \texttt{const} and/or \texttt{volatile} to pointer/reference better than those that do
  2. match with promotions (e.g., \texttt{int} to \texttt{long}, \texttt{float} to \texttt{double})
  3. match with standard conversions (e.g., \texttt{float} to \texttt{int}, \texttt{double} to \texttt{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

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

int i, j, k;
double a, b, c;

// ...
k = max(i, j);
// best match on first argument: max(int, int)
// best match on second argument: max(int, int)
// best match: max(int, int)
// OK: calls max(int, int)
c = max(a, b);
// best match on first argument: max(double, double)
// best match on second argument: max(double, double)
// best match: max(double, double)
// OK: calls max(double, double)
c = max(i, b);
// best match on first argument: max(int, int)
// best match on second argument: max(double, double)
// best match: empty set
// 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)
- Example:
  ```cpp
  #include <cassert>

  double sqrt(double x) {
    assert(x >= 0);
    // ...
  }
  ```
Section 2.3.5

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";
    }
}
```
manipulators provide way to control 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 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)
## I/O Manipulators (Continued)

<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 << ' ' << 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 123456789.000000
   3.14  123456789.00
   xxxxx3.14 xxxxxxxxx123456789.00
   */
```
Section 2.3.6

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:
  ```cpp
  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
}
```
```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';
}
```
#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);
}
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
cchar* 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
cchar* buffer = new char[64]; // allocate
delete buffer; // ERROR: nonarray delete to
  // delete array
  // may compile fine, but crash
  ```
```cpp
#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 << '
';
}

// Program output:
// (0,3.14)
```
Section 2.3.7

References
D. Saks. Placing const in declarations. 

D. Saks. What const really means. 

D. Saks. const T vs. T const. 

D. Saks. Top-level cv-qualifiers in function parameters. 
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
Access Specifiers

- can control *level of access* that users of class have to its members
- three levels of access:
  1. public
  2. protected
  3. private
- **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
};
```
class members are private by default

two code examples below are exactly equivalent:

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

```cpp
class Widget {
    private:
        // ...
};
```
The **struct** Keyword

- **struct** is class where members public by default
- two code examples below are exactly equivalent:

```c++
struct Widget {
    // ...
};
```

```c++
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;
};
```

```cpp
void func() {
    Widget x;
    x.updateValue(5); // in Widget::updateValue, variable this equals &x
}
```
member function has reference to object of class as implicit parameter (i.e., object pointed to by `this`)

need way to indicate if member function can change value of object

`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 be const!
}
```
member function whose definition is provided in body of class is automatically **inline**

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;
};

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

```cpp
class Point_2 {  // Two-dimensional point class.
  public:
    typedef double Coordinate;  // 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., `::`)
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

eexample:

```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

    // ...

};
```
```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 \textit{without modifying the source object}.

**Moving** propagates the value of the source object to the destination object and is \textit{permitted to modify the source object}.

Moving is always at least as efficient as copying, and for many types, moving is \textit{more efficient} than copying.

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

Before Copy

<table>
<thead>
<tr>
<th>source</th>
<th>destination</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>b</td>
</tr>
</tbody>
</table>

After Copy

<table>
<thead>
<tr>
<th>source</th>
<th>destination</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
</tr>
</tbody>
</table>

A copy operation *does not modify* the value of the source object.

**Move operation.** Propagating the value of the source object `source` to the destination object `destination` by moving.

Before Move

<table>
<thead>
<tr>
<th>source</th>
<th>destination</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>b</td>
</tr>
</tbody>
</table>

After Move

<table>
<thead>
<tr>
<th>source</th>
<th>destination</th>
</tr>
</thead>
<tbody>
<tr>
<td>?</td>
<td>a</td>
</tr>
</tbody>
</table>

A move operation is *not guaranteed to preserve* the value of the source object. After the move operation, the value of the source object is *unknown.*
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 \( \text{void} \))
- 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 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**

if *no constructors* specified, default constructor *automatically provided* that calls default constructor for each data member of class type (does nothing for data member of built-in type)

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
Copy Constructor

- for class \( T \), constructor taking lvalue reference to \( T \) as first parameter that can be called with one argument known as **copy constructor**
- used to *create* object by *copying* from already-existing object
- copy constructor for class \( T \) typically is of form \( T(const \ T&) \)
- if *no copy constructor* specified (and no move constructor or move assignment operator specified), copy constructor is *automatically provided* that copies each data member (using copy constructor for class and bitwise copy for built-in type)

```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&)
```

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Move Constructor

- for class `T`, constructor taking rvalue reference to `T` as first parameter that can be called with one argument known as **move constructor**
- used to *create* object by *moving* from already-existing object
- move constructor for class `T` typically is of form `T(T&&)`
- if *no move constructor* specified (and no destructor, copy constructor, or copy/move assignment operator operator specified), move constructor is **automatically provided** that moves each data member (using move for class and bitwise copy for built-in type)

```cpp
class Vector { // Two-dimensional vector class.
public:
    // ...
    Vector(Vector&& v) // Move 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 f(); // declares function f that returns Vector
Vector v = f(); // calls Vector::Vector(Vector&&) if move not elided
```
class Vector { // Two-dimensional vector class.
public:
    Vector() // Default constructor.
    { x_ = 0.0; y_ = 0.0;}
    Vector(const Vector & v) // Copy constructor.
    { x_ = v.x_; y_ = v.y_;}
    Vector(Vector&& v) // Move constructor.
    { x_ = v.x_; y_ = v.y_;}
    Vector(double x, double y) // Another constructor.
    { x_ = x; y_ = y;}
    // ...
private:
    double x_; // The x component of the vector.
    double y_; // The y component of the vector.
};
Vector u; // calls Vector::Vector(); u set to (0,0)
Vector v(1.0, 2.0); // calls Vector::Vector(double, double)
Vector w(v); // calls Vector::Vector(const Vector&) 
Vector z = u; // calls Vector::Vector(const Vector&) 
Vector f(); // declares function f that returns Vector 
Vector y = f(); // calls Vector::Vector(Vector&&) if move not elided

- four constructors provided
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
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
};
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 T always has name T::\texttt{\~}T
- destructor has no return type (not even void)
- destructor cannot be overloaded
- destructor always takes no parameters
- if no destructor is specified, destructor automatically provided that calls destructor for each data member of class type
- sometimes, automatically provided destructor will not have 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
};
```

without explicitly-provided destructor (i.e., with destructor automatically provided by compiler), memory associated with `bufferPtr_` would not be freed
Section 2.4.3

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>arithmetic</th>
<th>+  −  *  /  %</th>
</tr>
</thead>
<tbody>
<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>=  +=  -=  *= /= %=  ^= &amp;=</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;  *</td>
</tr>
<tr>
<td>others</td>
<td>-&gt;*  ,  -&gt; 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 @ 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>a@b</td>
<td>Member Function: <code>a.operator@(b)</code> Nonmember Function: <code>operator@(a, b)</code></td>
</tr>
<tr>
<td>Prefix unary</td>
<td>@a</td>
<td>Member Function: <code>a.operator@()</code> Nonmember Function: <code>operator@(a)</code></td>
</tr>
<tr>
<td>Postfix unary</td>
<td>a@</td>
<td>Member Function: <code>a.operator@(i)</code> 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>
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
}
**Operator Overloading: Member vs. Nonmember Functions**

- some considerations: access to private members; whether first operand has class type

```cpp
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 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
}
```
Copy Assignment Operator

- for class \( T \), \( T::\text{operator}= \) having exactly one parameter that is lvalue reference to \( T \) known as **copy assignment operator**
- used to assign, to already-existing object, value of another object by **copying**
- if no copy assignment operator specified (and no move constructor or move assignment operator specified), copy assignment operator **automatically provided** that copy assigns to each data member (using data member's copy assignment operator for class and bitwise copy for built-in type)

- copy assignment operator for class \( T \) typically is of form
  \[ T& \ \text{operator}=(\text{const } T&) \] (returning reference to \(*\text{this}\))
- copy assignment operator returns (nonconstant) reference in order to allow for statements like following to be valid (where \( x, y, \) and \( z \) are of type \( T \) and \( T::\text{modify} \) is a non-const member function):
  \[
  x = y = z; \quad // \quad x.\text{operator}=(y.\text{operator}=(z)) \\
  (x = y) = z; \quad // \quad (x.\text{operator}=(y)).\text{operator}=(z) \\
  (x = y).\text{modify}(); \quad // \quad (x.\text{operator}=(y)).\text{modify}()
  \]

- be careful to correctly consider case of self-assignment
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

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

if no move assignment operator specified (and no destructor, copy/move constructor, or copy assignment operator specified), move assignment operator automatically provided that move assigns to each data member (using move for class and bitwise copy for built-in type)

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

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

self-assignment should probably not occur in move case (but might be prudent to protect against “insane” code with assertion) (library effectively forbids self-assignment for move)
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))
without explicitly-provided assignment operator (i.e., with assignment operator automatically provided by compiler), memory leaks and memory corruption would result
Section 2.4.4

Miscellany
#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();
}
constructor callable with *single* argument can be used in implicit conversions (e.g., when attempting to obtain matching type for function parameter in function call)

often, desirable to prevent constructor from being used for implicit conversions

to accommodate this, constructor can be marked as explicit

**explicit constructor** is constructor that cannot be used to perform implicit conversions

prefixing constructor declaration with *explicit* keyword makes constructor explicit

example:

```cpp
class Widget {
public:
    explicit Widget (int); // explicit constructor
    // ...
};
```
Example Without Explicit Constructor

```cpp
#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
}
```
Explicitly Deleted/Defaulted Special Member Functions

- 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
- example:

```cpp
class Thing {
public:
    Thing() = default;

    // 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.
```

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

int main() {
    Widget w('A', 42);
    Widget v(42);
}
```
Static Data Members

- 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

e.g.,

```
class Widget {
  public:
    // ...
    // convert degrees to radians
    static double degToRad(double deg) {
      return (M_PI / 180.0) * deg;
    }
  private:
    // ...
};
```

```
void func() {
  Widget x; double rad;
  rad = Widget::degToRad(45.0);
  rad = x.degToRad(45.0); // x is ignored
}
```
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 (e.g., cannot be virtual)
- `constexpr` member function \textit{implicitly inline}
- `constexpr` member function \textit{not implicitly const} (as of C++14)
constructors can also be qualified as `constexpr` to indicate object construction can be performed *at compile time* provided that all arguments to constructor are constant expressions

`constexpr` constructor *implicitly inline*
// 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(Vector&& v) : x_(v.x_), y_(v.y_) {}  
  Vector& operator=(const Vector& v) {
    if (this != &v) {
      x_ = v.x_; y_ = v.y_;  
    }
    return *this;
  }
constexpr double x() const {return x_;}  
constexpr double y() const {return y_;}  
constexpr double squaredLength() const {
  return x_ * x_ + y_ * y_;  
}
 private:
  double x_; // The x component of the vector.
  double y_; // The y component of the vector.
};
The **mutable** Qualifier

- Type for data member can be qualified as **mutable** meaning that member does not affect externally visible state of class.
- `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.
```cpp
#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
};
```
stream inserters write data to output stream

overload `operator<<`

have general form

```cpp
std::ostream& operator<<(std::ostream&, T) where type T is typically const lvalue reference type
```

equation:

```cpp
std::ostream& operator<<(std::ostream& outStream, const Complex& a)
{
    outStream << a.real() << ' ' << a.imag();
    return 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
  \[
  \text{std::istream}& \ \text{operator}>> (\text{std::istream}&, \ T) \ \text{where type} \ T \ \text{is typically non-const lvalue reference type}
  \]
- example:
  ```cpp
  \text{std::istream}& \ \text{operator}>> (\text{std::istream}& \ \text{inStream}, \ \text{Complex}& \ a) \\
  \{ \\
  \text{double} \ \text{real} = 0.0; \\
  \text{double} \ \text{imag} = 0.0; \\
  \text{inStream} >> \ \text{real} >> \ \text{imag}; \\
  a = \text{Complex}(\ \text{real}, \ \text{imag}); \\
  \text{return} \ \text{inStream}; \\
  \}
  ```
Section 2.4.5

Temporary Objects
Temporary Objects

- A **temporary object** is an unnamed object introduced by the compiler.
- Temporary objects are 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.
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(a + a);
    b = a + b;
}
**Temporary Objects Example (Continued)**

**Original code:**
```cpp
int main() {
    Complex a(1.0, 2.0);
    Complex b(a + a);
    b = a + b;
}
```

**Code showing temporaries (assuming no optimization):**
```cpp
int main() {
    Complex a(1.0, 2.0);
    Complex _tmp1(a + a);
    Complex b(_tmp1);
    Complex _tmp2(a + b);
    b = _tmp2;
}
```

**Original code:**
```cpp
Complex operator+(const Complex& a, const Complex& b) {
    return Complex(a.real() + b.real(), a.imag() + b.imag());
}
```

**Code showing temporaries:**
```cpp
Complex operator+(const Complex& a, const Complex& b) {
    Complex _tmp(a.real() + b.real(), a.imag() + b.imag());
    return _tmp;
}
```
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=
    }

```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.

- First exception: When a default constructor with one or more default arguments is called to initialize an element of an array.

- 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:
  - 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?
}
```
Return Value Optimization (RVO)

- **Return value optimization (RVO)** is compiler optimization technique that eliminates copy of return value from local object in function to object in caller.

  **Example:**

  ```cpp
  SomeType function() {
    return SomeType(); // returns temporary object
  }

  void caller() {
    SomeType x = function(); // copy construction
  }
  ```

  - Without RVO: return value of function (which is local to function) is copied to new temporary object (so return value not lost when function returns); then, value of new temporary object copied to object that is to hold return value.
  - With RVO: return value of function is placed directly in object (in caller) that is to hold return value.
  - By avoiding need for temporary object to hold return value, eliminates one copy constructor and destructor call.
  - Any good compiler should support RVO, although RVO cannot always be applied in all circumstances.
Named Return Value Optimization (NRVO) is a variation on RVO where the return value is a named object (i.e., not a temporary object).

Example:

```cpp
SomeType function () {  
    SomeType result;  
    // ...  
    return result;  // returns named object
}

void caller () {  
    SomeType x = function();  // copy construction
}
```

The compiler optimizes away `result` in the function and the return value constructed directly in `x`.

Effectively, `result` becomes a reference to `x`.

Code with NRVO is more efficient (i.e., move/copy constructor and destructor calls are eliminated).
Section 2.4.6

Functors
**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
- 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) {
        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
Section 2.5

Templates
**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:

  ```
  int max(int x, int y) {
    return x > y ? x : y;}
  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:

  ```
  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 Templates**

- **function template** is a 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:
  
  \[
  \text{template} \ <\text{parameter\_list}> \ \text{function\_declaration}
  \]

- **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.
- Template template parameter must use **class** keyword.
- Non-type parameter designated by its type (e.g., **bool**, **int**).
- Example:
  
  ```cpp
  // declaration of function template
  template <\text{class} \ T> \ T \ \text{max}(\ T \ x, \ T \ y);
  
  // definition of function template
  template <\text{class} \ T> \ T \ \text{max}(\ T \ x, \ T \ y)
  \{ \text{return} \ x > y \ ? \ x : y; \}
  ```
to explicitly identify particular instance of template, use syntax:

```
function<parameters>
```

element:

for function template declaration:

```
template <class T> T max(T x, T y);
```

max<int> refers to int max(int, int)

max<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
template <class T>
T min(T x, T y) {
    return x < y ? x : y;
}

// compute square of value
template <typename T>
T sqr(T x) {
    return x * x;
}

// swap two values
template <class T>
void swap(T& x, T& y) {
    T tmp = x;
    x = y;
    y = tmp;
}

// invoke function/functor multiple times
template <int N = 1, typename F, typename T>
void invoke(F func, const T& value) {
    for (int i = 0; i < N; ++i) {
        func(value);
    }
}
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 name** is 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 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

e.g.,

```cpp
template <class T>
void func(const T& x) {
    int i = T::magicValue;
    // ...
}
```

name `T::magicValue` is dependent
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
  // std::vector<T>::value_type 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 \texttt{typename} is Needed

```c++
int x = 42;

template <class T> void func() {
    // The compiler must be able to check syntactic
    // correctness of this template code without
    // knowing \texttt{T}. Without knowing \texttt{T}, however, the
    // meaning of following line of code is ambiguous.
    // Is it a declaration of a variable \texttt{x} or an
    // expression consisting of a binary operator*
    // with operands \texttt{T::foo} and \texttt{x}?
    T::foo* x; // Does \texttt{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 lines should be valid.
    func<ContainsValue>();
    func<ContainsType>();
}
```

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Example: What is wrong with this code?

// templates_1_0.cpp

#include <iostream>
#include <complex>
#include "templates_1_1.hpp"

int main () {
    std::complex<double> a(0.0, 1.0);
    auto b = square(a);
    std::cout << b << '\n';
}

// templates_1_1.hpp

template <class T>
T square (const T&);

// templates_1_1.cpp

#include "templates_1_1.hpp"

template <class T>
T square (const T& x) {
    return x * x;
}
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

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_;  
    }

private:
    T x_; // real part
    T y_; // imaginary part
};

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

- 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_; 
};
```
```cpp
#include <vector>
#include <list>
#include <deque>
#include <memory>

template <template <class, class> class Container, typename 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;
}
Section 2.5.3

Variable Templates
Variable Templates

- **variable template** is a 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 are quite useful in some situations.
- Syntax has a general form:

  ```
  template <parameter_list> variable_declaration
  ```

- **parameter_list**: parameter list for variable template
- **variable_declaration**: variable declaration or definition
- Example:

  ```
  template <class T>
  T meaning_of_life = T(42);

  int x = meaning_of_life<int>;
  ```
```
#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 template** is 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
language provides ability to specify template that can take variable number of arguments

template that can take variable number of arguments called **variadic template**

alias templates, class templates, function templates, and variable templates may be variadic

variable number of arguments specified by using what is called parameter pack

parameter pack is parameter that accepts (i.e., is placeholder for) zero or more arguments (of same kind)

parameter pack used in parameter list of template to allow to variable number of template parameters

eLLipsis (i.e., “...”) is used in various contexts relating to parameter packs

eLLipsis after designator for kind of template argument in template parameter list designates argument is parameter pack

eLLipsis after parameter pack parameter expands parameter pack in context-sensitive manner
Parameter Packs

- syntax for *non-type* template parameter pack named `Args` and containing elements of type *type* (e.g., `bool`, `int`, `unsigned int`):
  
  ```
  type... Args
  ```

- example:
  
  ```
  template <int... Is> /* ... */
  ```

  `Is` is (non-type) template parameter pack that corresponds to zero or more (compile-time constant) values of type `int`

- syntax for *type* template parameter pack named `Args`:
  
  ```
  typename... Args
  ```

  or equivalently

  ```
  class... Args
  ```

- examples:
  
  ```
  template <typename... Ts> /* ... */
  template <class... Ts> /* ... */
  ```

  `Ts` is (type) template parameter pack that corresponds to zero or more types
syntax for *template* template parameter pack named *Args*:

```cpp
template <parameter_list> typename... Args (C++17)
```
or equivalently

```cpp
template <parameter_list> class... Args
```

element:

```cpp
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*:

```cpp
Args... args
```

element:

```cpp
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*
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 template <class... Us> void g(Us... u) {
3     f(u...);
4     // u... is pack expansion
5     // when g is called by main,
6     // u... expands to 1, 2.0, 3.0f
7 }
8
9 int main() {
10    g(1, 2.0, 3.0f);
11 }
```
#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");
}

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C++ Version: 2017-02-24
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 (C++17)
sizeof... operator yields number of elements in parameter pack

example:

```cpp
template <int... Values>
constexpr int num_parms = sizeof...(Values);

static_assert(num_parms<1, 2, 3> == 3, "");
static_assert(num_parms<> == 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";
}

/* 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>
typename 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>
typename 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);
}
```

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```cpp
#include <iostream>
#include <vector>
#include <string>
#include <set>

template <template <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 << '
';
    return bool(std::cout);
}

int main() {
    std::vector<int> vi{1, 2, 3, 4, 5};
    std::set<int> si{5, 4, 3, 2, 1};
    std::set<std::string> ss{"world", "hello"};
    print_container(vi);
    print_container(si);
    print_container(ss);
}
```
#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 << '
';}
}
```cpp
#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>

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 (C++17)

- 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

<table>
<thead>
<tr>
<th>Fold</th>
<th>Syntax</th>
<th>Expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>unary left</td>
<td>$(\ldots \text{op } E)$</td>
<td>$((E_1 \text{ op } E_2) \text{ op } \ldots) \text{ op } E_N$</td>
</tr>
<tr>
<td>unary right</td>
<td>$(E \text{ op } \ldots)$</td>
<td>$E_1 \text{ op } (\ldots \text{ op } (E_{N-1} \text{ op } E_N))$</td>
</tr>
<tr>
<td>binary left</td>
<td>$(I \text{ op } \ldots \text{ op } E)$</td>
<td>$(((I \text{ op } E_1) \text{ op } E_2) \text{ op } \ldots) \text{ op } E_N$</td>
</tr>
<tr>
<td>binary right</td>
<td>$(E \text{ op } \ldots \text{ op } I)$</td>
<td>$E_1 \text{ op } (\ldots \text{ op } (E_{N-1} \text{ op } (E_N \text{ op } I)))$</td>
</tr>
</tbody>
</table>

unary fold of empty parameter pack:

<table>
<thead>
<tr>
<th>Operator</th>
<th>Value for Empty Parameter Pack</th>
</tr>
</thead>
<tbody>
<tr>
<td>&amp;&amp;</td>
<td>true</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>,</td>
<td>void()</td>
</tr>
</tbody>
</table>
```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";
}

/* Output:
The answer is 42.*/
```
```cpp
#include <iostream>
#include <string>

using namespace std::string_literals;

template <class... Args>
auto sum(Args... args) {
    return (... + 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";
}

/* Output:
The answer is 42.
*/
```
```cpp
#include <iostream>
#include <string>

using namespace std::string_literals;

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);
}

/* 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);
}

/* Output:
The answer is 42.
*/
```
```cpp
#include <cassert>

// Fold Expression Example: All/Any/One/Even

template <class... Args>
bool all(Args... args)
{
    return (... && args);
}

template <class... Args>
bool any(Args... args)
{
    return (... || args);
}

template <class... Args>
bool one(Args... args)
{
    return (0 + ... + args) == 1;
}

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) == true);
    assert(even() == true && one() == false);
    
    return 0;
}
```

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Section 2.5.6

Template Specialization
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:

  \texttt{template <> declaration}

- \textit{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:
  
  ```cpp
template <parameter_list> class_key
class_name <argument_list> declaration
  ```

- syntax for partial specialization of variable template:
  
  ```cpp
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:**

  ```cpp
  // 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

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 verion
    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
```

```cpp
template <class Alloc>
class vector<bool, Alloc>; // partial specialization
```
template <class T>
constexpr bool is_void_v = false;

template <>
constexpr bool is_void_v<void> = true;

template <>
constexpr bool is_void_v<const void> = true;

template <>
constexpr bool is_void_v<volatile void> = true;

template <>
constexpr bool is_void_v<const volatile void> = true;

static_assert(is_void_v<int> == false, "");
static_assert(is_void_v<double*> == false, "");
static_assert(is_void_v<void> == true, "");
static_assert(is_void_v<const void> == true, "");
static_assert(is_void_v<volatile void> == true, "");
static_assert(is_void_v<const volatile void> == true, "");

int main() {}
template <typename T>
const T factorial = T(1) * factorial<T - 1>;

int main() {
    static_assert(factorial(5) == 120,
                  "factorial(5) failed");
    static_assert(factorial(12) == 479001600,
                  "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, known as substitution failure

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)"

if substitution failure were treated as error, this would place heavy burden on programmer to avoid compile errors when using function templates

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
**std::enable_if and std::enable_if_t**

- 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`:
  ```cpp
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`:
  ```cpp
  template <bool B, class T = void>
  struct enable_if {};

  template <class T>
  struct enable_if_t : typename enable_if<B, T>::type;
  ```

- Declaration of alias template `enable_if_t`:
  ```cpp
  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.
# SFINAE Example

```cpp
#include <iostream>
#include <type_traits>
#include <cmath>

// integral version (uses left shift)
template <class T>
std::enable_if_t<std::is_integral<T>::value, T> mult_by_pow_2(T x, unsigned int n) {
    std::cerr << "integral version\n";
    return x << n;
}

// floating-point version (uses pow)
template <class T>
std::enable_if_t<std::is_floating_point<T>::value, T> mult_by_pow_2(T x, unsigned int n) {
    std::cerr << "floating-point version\n";
    return x * std::pow(2.0, n);
}

int main() {
    std::cout << mult_by_pow_2(2, 2) << '\n';  // will call integral version
    std::cout << mult_by_pow_2(0.5, 4) << '\n';  // will call floating-point version
}
```
Section 2.5.8

References


Section 2.6

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 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:

```c
[](double x) -> int { return floor(x); }
[](int x, int y) { return x < y; }
[](std::cout << "Hello, World!\n");
```
- closure object is unnamed (temporary object)
- closure type is unnamed
- `operator()` is always inline
- `operator()` is const member function unless `mutable` keyword used
- 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)
- 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)
#include <iostream>

int main() {
    [{std::cout << "Hello, World!\n"}()};
}

#include <iostream>

struct Hello {
    void operator()() const {
        std::cout << "Hello, World!\n";
    }
};

int main() {
    Hello hello;
    hello();
}
Comparison Functor Example

```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 abs(x) < abs(y); });
    for (auto x : v) std::cout << x << '\n';
}

#include <iostream>
#include <algorithm>
#include <cstdlib>
#include <vector>

struct abs_less {
    bool operator()(int x, int y) const
        { return abs(x) < 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 << '\n';
}
```
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)

to capture class members within member function, capture this

capture of this must be done 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:

```
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;
}
```
```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 << '
';
}

#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 << '
';
}
```
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

- 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;
};

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 << '
';
}``
Product Example: Without Lambda Expression

```cpp
#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
```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;};
- can specify name for captured object in closure type
  
  ```
  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)
  
  ```
  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
```cpp
#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';
}
```cpp
#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; });
}
```
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) << '
';
    }
}

- 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
```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
#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 << '
';
    }
}

- 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
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) << '
';
}
```
in SPLEL software, triangle scan conversion performed by 
scan_triangle template function

declaration:

```cpp
template <class T, class F>
void scan_triangle(T a_x, T a_y, T b_x, T b_y, 
                    T c_x, T c_y, unsigned mask, F scan_line);
```

scan_line is functor to handle single horizontal scan within triangle

scan_line has signature:

```cpp
void scan_line(T y, T x_min, T x_max, 
               unsigned left_mask, unsigned right_mask, 
               unsigned mid_mask);
```
Section 2.6.1

References

Section 2.7

Classes and Inheritance
Section 2.7.1

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 \textit{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 \textit{derived class} and original class called \textit{base class}
- derived class said to \textit{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:
  \begin{verbatim}
  class derived_class : base_class_specifiers
  \end{verbatim}
- \textit{derived_class} is name of derived class; \textit{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
};
```
// 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_;}
};
```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_;}
    // ... (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 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:

- 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.
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></td>
<td>Public Inheritance</td>
</tr>
<tr>
<td>public</td>
<td>public</td>
</tr>
<tr>
<td>protected</td>
<td>protected</td>
</tr>
</tbody>
</table>
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
```cpp
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
}
```
```cpp
// Protected Inheritance Example

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

```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 policy_; // ...
};

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
}
```
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 
};

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
assignment operators to be inherited with `using` statement may still be hidden by assignment operators in derived class
cannot inherit destructor
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)
}
during construction of object, all of its base class objects constructed first

order of construction:

1. base class objects as listed in type definition left to right
2. data members as listed in type definition top to bottom
3. constructor body

order of destruction is exact reverse of order of construction, namely:

1. destructor body
2. data members as listed in type definition bottom to top
3. base class objects as listed in type definition right to left
#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");
}
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)
- in case of public inheritance, can upcast without explicit type-cast operator
- in case of protected or private inheritance, cannot upcast, except with C-style cast (which also can bypass access protection)
- example:

```cpp
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 (`static_cast` for non-polymorphic case, `dynamic_cast` for polymorphic case, C-style cast for either case)
- example:

```cpp
class Base { /* ... (nonpolymorphic) */ };
class Derived : public Base { /* ... */ };
void func() {
    Derived d;
    Base* bp = &d;
    Derived* dp = static_cast<Derived*>(bp);
}
```
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*  
}  
```
```cpp
#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
}
```

would be nice if `processPerson` called version of `print` that corresponds to actual type of object referenced by function parameter `p`
**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)
}
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
}
#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 *nondependent* names

result of nondependent name lookup must be *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 *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 “**this**→” or employ **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 << std::endl;};
    Real x;
};

template <class T>
struct Derived : Base<T> {
    Derived(Real y_ = Real()) : y(y_) {}
    // ERROR: Real (which is nondependent and looked up at
    // template definition time) is assumed to be defined
    // outside class
    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;
    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 2.7.2

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 is 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**.
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 \textit{automatically} be virtual in all derived classes, regardless of whether \texttt{virtual} keyword is used in derived classes. 

therefore, not necessary to repeat \texttt{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_ << '
';}

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_ << '
';
    }

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
    // ...
};
```
s sometimes, may want to prevent any further overriding of virtual function in any subsequent derived classes

adding 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)

example:

```cpp
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
    // ...
};
```
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

```cpp
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
}
```
```cpp
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_;
};

void process(Base* bp) {
    // ...
    delete bp; // invokes destructor polymorphically
}

int main() {
    process(new Base);
    process(new Derived);
}
```
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.
```cpp
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());
}```
Pure Virtual Functions

- 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)
Abstract Class Example

```cpp
#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
};
```
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
Curiously-Recurring Template Pattern (CRTP)

- 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
- example:

```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
}
```
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;
```cpp
#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);
}
```
#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 << "\n";
}
Section 2.7.3

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 Base1 {
  public:
    void func();
    // ...
}

class Base2 {
  void func();
  // ...
}

class Derived : public Base1, public Base2 {
  public:
    // ...
};

int main() {
  Derived d;
  d.func(); // ERROR: ambiguous function call
  d.Base1::func(); // OK: invokes Base1::func
  d.Base2::func(); // OK: invokes Base2::func
}
Multiple Inheritance Example

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:

![Diamond Inheritance Diagram](image)

- 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
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
}
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
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 2.7.4

References


C++ standard library provides huge amount of functionality (orders of magnitude more than C standard library)

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
functionality can be grouped into following sublibraries:

1. language support library (e.g., exceptions, memory management)
2. diagnostics library (e.g., assertions, exceptions, error codes)
3. general utilities library (e.g., functors, date/time)
4. strings library (e.g., C++ and C-style strings)
5. localization library (e.g., date/time formatting and parsing, character classification)
6. containers library (e.g., sequence containers and associative containers)
7. iterators library (e.g., stream iterators)
8. algorithms library (e.g., searching, sorting, merging, set operations, heap operations, minimum/maximum)
9. numerics library (e.g., complex numbers, math functions)
10. input/output (I/O) library (e.g., streams)
11. regular expressions library (e.g., regular expression matching)
12. atomic operations library (e.g., atomic types, fences)
13. thread support library (e.g., threads, mutexes, condition variables, futures)
## Commonly-Used Header Files

### Language-Support Library

<table>
<thead>
<tr>
<th>Header File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>cstdlib</td>
<td>run-time support, similar to stdlib.h from C (e.g., exit)</td>
</tr>
<tr>
<td>limits</td>
<td>properties of fundamental types (e.g., numeric_limits)</td>
</tr>
<tr>
<td>exception</td>
<td>exception handling support (e.g., set_terminate, current_exception)</td>
</tr>
<tr>
<td>initializer_list</td>
<td>initializer_list class template</td>
</tr>
</tbody>
</table>

### Diagnostics Library

<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>
</tbody>
</table>
## Commonly-Used Header Files (Continued 1)

### General-Utilities Library

<table>
<thead>
<tr>
<th>Header File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>utility</td>
<td>basic function and class templates (e.g., swap, move, pair)</td>
</tr>
<tr>
<td>memory</td>
<td>memory management (e.g., unique_ptr, shared_ptr, addressof)</td>
</tr>
<tr>
<td>functional</td>
<td>functors (e.g., less, greater)</td>
</tr>
<tr>
<td>type_traits</td>
<td>type traits (e.g., is_integral, is_reference)</td>
</tr>
<tr>
<td>chrono</td>
<td>clocks (e.g., system_clock, steady_clock, high_resolution_clock)</td>
</tr>
</tbody>
</table>

### Strings Library

<table>
<thead>
<tr>
<th>Header File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>string</td>
<td>C++ string classes (e.g., string)</td>
</tr>
<tr>
<td>cstring</td>
<td>C-style strings, similar to string.h from C (e.g., strlen)</td>
</tr>
<tr>
<td>cctype</td>
<td>character classification, similar to ctype.h from C (e.g., isdigit, isalpha)</td>
</tr>
</tbody>
</table>
## Commonly-Used Header Files (Continued 2)

### Containers, Iterators, and Algorithms Libraries

<table>
<thead>
<tr>
<th>Header File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>array</td>
<td>array class</td>
</tr>
<tr>
<td>vector</td>
<td>vector class</td>
</tr>
<tr>
<td>deque</td>
<td>deque class</td>
</tr>
<tr>
<td>list</td>
<td>list class</td>
</tr>
<tr>
<td>set</td>
<td>set classes (i.e., set, multiset)</td>
</tr>
<tr>
<td>map</td>
<td>map classes (i.e., map, multimap)</td>
</tr>
<tr>
<td>unordered_set</td>
<td>unordered set classes (i.e., unordered_set, unordered_multiset)</td>
</tr>
<tr>
<td>unordered_map</td>
<td>unordered map classes (i.e., unordered_map, unordered_multimap)</td>
</tr>
<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>
</tbody>
</table>
## Numerics Library

<table>
<thead>
<tr>
<th>Header File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>cmath</code></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><code>complex</code></td>
<td>complex numbers (e.g., <code>complex</code>)</td>
</tr>
<tr>
<td><code>random</code></td>
<td>random number generation (e.g., <code>uniform_int_distribution</code>, <code>uniform_real_distribution</code>, <code>normal_distribution</code>)</td>
</tr>
</tbody>
</table>
### I/O Library

<table>
<thead>
<tr>
<th>Header File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>iostream</td>
<td>iostream objects (e.g., cin, cout, cerr)</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>ios</td>
<td>base classes and other declarations for streams (e.g., ios_base, hex, fixed)</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>iomanip</td>
<td>manipulators (e.g., setw, setprecision)</td>
</tr>
</tbody>
</table>

### Regular-Expressions Library

<table>
<thead>
<tr>
<th>Header File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>regexp</td>
<td>regular expressions (e.g., basic_regex)</td>
</tr>
</tbody>
</table>
# Atomic-Operations and Thread-Support Libraries

<table>
<thead>
<tr>
<th>Header File</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>atomic</td>
<td>atomics (e.g., atomic)</td>
</tr>
<tr>
<td>thread</td>
<td>threads (e.g., thread)</td>
</tr>
<tr>
<td>mutex</td>
<td>mutexes (e.g., mutex, recursive_mutex, timed_mutex)</td>
</tr>
<tr>
<td>condition_variable</td>
<td>condition variables (e.g., condition_variable)</td>
</tr>
<tr>
<td>future</td>
<td>futures (e.g., future, shared_future, promise)</td>
</tr>
</tbody>
</table>
Section 2.8.1

Containers, Iterators, and Algorithms
Standard Template Library (STL)

- 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)
Containers

- **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 and Container Adapters

### 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>
# Associative Containers

## 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 al-</td>
</tr>
<tr>
<td></td>
<td>lowed</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 al-</td>
</tr>
<tr>
<td></td>
<td>lowed</td>
</tr>
</tbody>
</table>
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>operator=</td>
<td>assign all elements of one container to other</td>
</tr>
<tr>
<td>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 << '\n';

    /* 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:

- organization of elements in doubly-linked list container:
consider array/vector container with \texttt{int} elements:

suppose we want to set all elements in container to zero

we could use code like:

\begin{verbatim}
// int* begin; int* end;
for (int* iter = begin; iter != end; ++iter)
  *iter = 0;
\end{verbatim}

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
**iterator**: object that allows iteration over collection of elements, where elements are often (but not necessarily) in container

Iterators support many of the same operations as pointers

In some cases, iterator may actually be a 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)
### Abilities of Iterator Categories

<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><code>istream</code> (istream_iterator)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output</td>
<td>Writes (once only) forward</td>
<td><code>ostream</code> (ostream_iterator), inserter_iterator</td>
</tr>
<tr>
<td></td>
<td></td>
<td></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></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bidirectional</td>
<td>Reads and writes 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>(built-in) array, array, vector, deque, string</td>
</tr>
</tbody>
</table>
### Input 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</td>
<td>dereference as rvalue (i.e., read only); cannot dereference at old position</td>
</tr>
<tr>
<td>a-&gt;m</td>
<td>steps forward (returns new position)</td>
</tr>
<tr>
<td>++a</td>
<td>steps forward</td>
</tr>
<tr>
<td>a ++</td>
<td>steps forward</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>

- 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</td>
<td>dereference as lvalue (i.e., write only); can only be dereferenced once; cannot dereference at old position</td>
</tr>
<tr>
<td>a-&gt;m</td>
<td>not assignable (i.e., no assignment operator)</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., `operator==`, `operator!=`)
### 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

- 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 the 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
#include <iostream>
#include <vector>

int main() {
    std::vector<int> values(10);

    std::cout << "number of elements: " <<
               (values.end() - values.begin()) << '\n';

    // 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 << '\n';
}
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>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>
</tbody>
</table>
### Modifying Sequence Operations

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<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 <code>utility</code> 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>
</tbody>
</table>
## Modifying Sequence Operations (Continued)

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>fill</td>
<td>fill range with value</td>
</tr>
<tr>
<td>fill_n</td>
<td>fill sequence with value</td>
</tr>
<tr>
<td>generate</td>
<td>generate values for range with function</td>
</tr>
<tr>
<td>generate_n</td>
<td>generate values for sequence with function</td>
</tr>
<tr>
<td>remove</td>
<td>remove value from range (by shifting elements)</td>
</tr>
<tr>
<td>remove_if</td>
<td>remove elements from range (by shifting elements)</td>
</tr>
<tr>
<td>remove_copy</td>
<td>copy range removing value</td>
</tr>
<tr>
<td>remove_copy_if</td>
<td>copy range removing values</td>
</tr>
<tr>
<td>unique</td>
<td>remove consecutive duplicates in range</td>
</tr>
<tr>
<td>unique_copy</td>
<td>copy range removing duplicates</td>
</tr>
<tr>
<td>reverse</td>
<td>reverse range</td>
</tr>
<tr>
<td>reverse_copy</td>
<td>copy range reversed</td>
</tr>
<tr>
<td>rotate</td>
<td>rotate elements in range</td>
</tr>
<tr>
<td>rotate_copy</td>
<td>copies and rotates elements in range</td>
</tr>
<tr>
<td>shuffle</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>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>iota</td>
<td>fill range with successive values</td>
</tr>
<tr>
<td>accumulate</td>
<td>accumulate values in range</td>
</tr>
<tr>
<td>adjacent_difference</td>
<td>compute adjacent difference of range</td>
</tr>
<tr>
<td>inner_product</td>
<td>compute inner product of range</td>
</tr>
<tr>
<td>partial_sum</td>
<td>compute partial sums of range</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 << '\t' << i;}
    std::cout << '\n';

    std::sort(values.begin(), values.end());
    std::cout << "sorted order:
    for (auto i : values) {std::cout << '\t' << i;}
    std::cout << '\n';
    }
```
consider `std::transform` function template:

```cpp
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`

`std::transform` might be written as:

```cpp
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<double> v{1.0, 2.0, 3.0};
    std::transform(v.begin(), v.end(), v.begin(), mb);
    for (auto i : v) {std::cout << i << std::endl;} // v contains 2 4 6
}
```
Section 2.8.2

The vector Class Template
The 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:

<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>allocator_type</td>
<td>Allocator (i.e., allocator)</td>
</tr>
<tr>
<td>size_type</td>
<td>type used for measuring size (typically unsigned integral type)</td>
</tr>
<tr>
<td>difference_type</td>
<td>type used to measure distance (typically signed integral type)</td>
</tr>
<tr>
<td>reference</td>
<td>value_type&amp;</td>
</tr>
<tr>
<td>const_reference</td>
<td><code>const</code> value_type&amp;</td>
</tr>
<tr>
<td>pointer</td>
<td>allocator_traits&lt;Allocator&gt;::pointer</td>
</tr>
<tr>
<td>const_pointer</td>
<td>allocator_traits&lt;Allocator&gt;::const_pointer</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>

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C++ Version: 2017-02-24
## 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>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 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><strong>operator[]</strong></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>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>
Invalidation of References, Iterators, and Pointers

- **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:

  ```cpp
  insert, erase, push_back, pop_back, emplace, emplace_back,
  resize, reserve, operator=, assign, clear, shrink_to_fit, swap
  (past-the-end iterator only)
  ```
Iterator Invalidation Example

- **start** denotes pointer to first element in array holding vector elements
- **i** is iterator for **vector** (e.g., `vector<T>::const_iterator`, `vector<T>::iterator`)
- initial vector with three elements and capacity of three:

  \[
  \begin{array}{|c|}
  \hline
  a \\
  b \\
  c \\
  \hline
  \end{array}
  \]

- **push_back**(d) results in new larger array being allocated, contents of old array copied to new one, and then new element added:

  \[
  \begin{array}{|c|}
  \hline
  a \\
  b \\
  c \\
  d \\
  \hline
  \end{array}
  \]

- old array is deallocated, iterator **i** is now **invalid**:

  \[
  \begin{array}{|c|}
  \hline
  a \\
  b \\
  c \\
  d \\
  \hline
  \end{array}
  \]
std::vector<double> v0;
  // empty vector

std::vector<double> v1(10);
  // vector with 10 elements, default constructed
  // (which for double means uninitialized)

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)
```cpp
#include <iostream>
#include <vector>

int main() {
    std::vector<int> 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
```
```cpp
#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 2.8.3

The `basic_string` Class Template
The 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://www.cplusplus.com/reference/string/basic_string](http://www.cplusplus.com/reference/string/basic_string)
  - [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>traits_type</td>
<td>Traits (i.e., character traits)</td>
</tr>
<tr>
<td>value_type</td>
<td>Traits::char_type (i.e., character type)</td>
</tr>
<tr>
<td>allocator_type</td>
<td>Allocator</td>
</tr>
<tr>
<td>size_type</td>
<td>allocator_traits&lt;Allocator&gt;::size_type</td>
</tr>
<tr>
<td>difference_type</td>
<td>allocator_traits&lt;Allocator&gt;::difference_type</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>allocator_traits&lt;Allocator&gt;::pointer</td>
</tr>
<tr>
<td>const_pointer</td>
<td>allocator_traits&lt;Allocator&gt;::const_pointer</td>
</tr>
<tr>
<td>iterator</td>
<td><strong>random-access</strong> iterator type</td>
</tr>
<tr>
<td>const_iterator</td>
<td>const <strong>random-access</strong> iterator type</td>
</tr>
<tr>
<td>reverse_iterator</td>
<td>reverse iterator type</td>
</tr>
<tr>
<td>const_reverse_iterator</td>
<td>(reverse_iterator&lt;iterator&gt;)</td>
</tr>
<tr>
<td>const_reverse_iterator</td>
<td>const reverse iterator type</td>
</tr>
<tr>
<td></td>
<td>(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><code>operator=</code></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>
### 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><code>operator[]</code></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>
<tr>
<td>Member Name</td>
<td>Description</td>
</tr>
<tr>
<td>---------------</td>
<td>--------------------------------------------------</td>
</tr>
<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>operator+=</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>
## Allocators

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>get_allocator</td>
<td>get allocator</td>
</tr>
</tbody>
</table>
## Numeric Conversions

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>stoi</td>
<td>convert string to int</td>
</tr>
<tr>
<td>stol</td>
<td>convert string to long</td>
</tr>
<tr>
<td>stoll</td>
<td>convert string to long long</td>
</tr>
<tr>
<td>stoul</td>
<td>convert string to unsigned long</td>
</tr>
<tr>
<td>stoull</td>
<td>convert string to unsigned long long</td>
</tr>
<tr>
<td>stof</td>
<td>convert string to float</td>
</tr>
<tr>
<td>stod</td>
<td>convert string to double</td>
</tr>
<tr>
<td>stold</td>
<td>convert string to long double</td>
</tr>
<tr>
<td>to_string</td>
<td>convert integral or floating-point value to string</td>
</tr>
<tr>
<td>to_wstring</td>
<td>convert integral or floating-point value to wstring</td>
</tr>
</tbody>
</table>
```cpp
#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 << '
';
}
```
```cpp
#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 2.8.4

Time Measurement
Time Measurement

- time measurement capabilities provided by part of general utilities library (of standard library)
- header file `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:
### 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>
Example: Measuring Elapsed Time

```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 << 'n';
    std::cout << "time (in seconds) " << elapsed_time << 'n';
}
```
// 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:\n" << "period " << granularity<
    std::chrono::system_clock>() << '\n' << "steady " << std::chrono::system_clock::is_steady << '\n';
    std::cout << "high resolution clock:\n" << "period " << granularity<
    std::chrono::high_resolution_clock>() << '\n' << "steady " << std::chrono::high_resolution_clock::is_steady << '\n';
    std::cout << "steady clock:\n" << "period " << granularity<
    std::chrono::steady_clock>() << '\n' << "steady " << std::chrono::steady_clock::is_steady << '\n';
}
Section 2.8.5

Miscellany
```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 2.9

Miscellany
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) 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
```cpp
#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 {};
    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 \texttt{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 \texttt{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 \texttt{swap} function, the name lookup on \texttt{swap} will yield this function through ADL.

Otherwise, the name lookup will find \texttt{std::swap}.

Thus, code like the above will result in a more efficient \texttt{swap} function being used if available, with the \texttt{std::swap} function used as a fallback.
Part 3

More C++
Section 3.1

Smart Pointers
Section 3.1.1

Introduction
Memory Management, Ownership, and Raw Pointers

- 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 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 3.1.2

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)
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 <code>std::unique_ptr</code></td>
</tr>
<tr>
<td>destructor</td>
<td>destroys managed object (if any)</td>
</tr>
<tr>
<td><code>operator=</code></td>
<td>assigns <code>std::unique_ptr</code></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><code>get</code></td>
<td>returns pointer to managed object</td>
</tr>
<tr>
<td><code>get_deleter</code></td>
<td>returns deleter used for destruction of managed object</td>
</tr>
<tr>
<td><code>operator bool</code></td>
<td>check 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);
}
Section 3.1.3

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:
  ```cpp
template <class T> class shared_ptr;
```
- `T` is type of object to be managed (i.e., owned object)
- 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
- thread safety guaranteed for `shared_ptr` object itself but not 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
each `std::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 `std::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
**std::shared_ptr** Reference Counting Example

- **shared_ptr<T>**
  - Pointer to T Object
  - Pointer to Control Block

Control Block

- Pointer to Managed Object
  - Use Count (1)
  - Weak Count (1)
  - Other Data

Managed Object

- T Object
  - Other Data
std::shared_ptr
Reference Counting Example (Continued 1)

shared_ptr<T>

Pointer to T Object

Pointer to Control Block

shared_ptr<T>

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)

shared_ptr<T>
Pointer to T Object
Pointer to Control Block

shared_ptr<T>
Pointer to T Object
Pointer to Control Block

shared_ptr<T>
Pointer to T Object
Pointer to Control Block

Control Block
Pointer to Managed Object
Use Count (3)
Weak Count (1)
Other Data

Managed Object

T Object

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C++ Version: 2017-02-24
### 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>assign <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>replaced 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><code>get</code></td>
<td>returns pointer to managed object</td>
</tr>
<tr>
<td><code>use_count</code></td>
<td>returns number of <code>shared_ptr</code> objects referring to same managed object</td>
</tr>
<tr>
<td><code>unique</code></td>
<td>checks if managed object is managed only by current <code>shared_ptr</code> instance</td>
</tr>
<tr>
<td><code>operator bool</code></td>
<td>checks if there is associated managed object</td>
</tr>
<tr>
<td><code>owner_before</code></td>
<td>provide 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>dereference pointer to managed object</td>
</tr>
<tr>
<td><code>operator-&gt;</code></td>
<td>dereference pointer to managed object</td>
</tr>
<tr>
<td><code>operator[]</code></td>
<td>provide indexed access to managed array</td>
</tr>
</tbody>
</table>
```cpp
#include <memory>
#include <cassert>

int main() {
    auto p1(std::make_shared<int>(0));
    assert(*p1 == 0 && p1.use_count() == 1 && p1.unique());

    std::shared_ptr<int> p2(p1);
    assert(*p2 == 0 && p2.use_count() == 2 && !p2.unique());

    *p2 = 42;
    assert(*p1 == 42);

    p2.reset();
    assert(!p2);
    assert(*p1 == 42 && p1.use_count() == 1 && p1.unique());

    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';
}
```
```cpp
#include <memory>
#include <vector>
#include <cassert>
#include <iostream>

struct Widget {
    Widget (int i_, const std::vector<int>& v_) :
        i(i_), v(v_) {}
    ~Widget () {std::cout << "destructor called\n";}
    int i;
    std::vector<int> v;
};

int main () {
    auto wp(std::make_shared<Widget>(42,
        std::vector<int>{1, 2, 3}));
    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(vp.use_count() == 1 && vp->size() == 3);
    vp = nullptr; // equivalently: vp.reset();
    // managed Widget object destroyed
    // ...
}
Example: std::shared_ptr
1
2
3
4
5

#include
#include
#include
#include

<memory >
<array >
<string >
< iostream >

6
7

using namespace std :: literals ;

8

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]};

9
10
11
12
13
14
15
16

for (auto& x : all ) {
std :: cout << *x << ’ ’ << x. use_count () << ’\n ’;
}

17
18
19
20
21

}

22

/* output:
apple 2
orange 2
banana 1
*/

23
24
25
26

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C++

Version: 2017-02-24

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Section 3.1.4

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
}
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**
### 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>std::weak_ptr</code></td>
</tr>
<tr>
<td>destructor</td>
<td>destroys <code>std::weak_ptr</code></td>
</tr>
<tr>
<td><code>operator=</code></td>
<td>assign <code>std::weak_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>replaced 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>use_count</td>
<td>returns number of <code>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>shared_ptr</code> that manages referenced object</td>
</tr>
<tr>
<td>owner_before</td>
<td>provide owner-based ordering of weak pointers</td>
</tr>
</tbody>
</table>
Typical `std::shared_ptr`/`std::weak_ptr` Implementation

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)
```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);
}
#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
Section 3.1.5

The `boost::intrusive_ptr` Class Template
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 function (provided by user) with signature:
  ```cpp
  void intrusive_ptr_add_ref(T*)
  ```
- reference is eliminated by calling function (provided by user) with signature:
  ```cpp
  void intrusive_ptr_release(T*)
  ```
- `intrusive_ptr_release` responsible for destroying underlying object when reference count reaches zero
intrusive_ptr<T> 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
#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 3.1.6

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
}
```
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:
    // ...
    const std::unique_ptr<Element[]> array_;
    std::size_t size_;
};
```
interface and implementation split across two classes: (i.e., handle class and body class)

known as pointer to implementation (pimpl) idiom

can be used, for example, to reduce compile-time dependencies (to facilitate faster compiles)

class object has pointer that owns implementation object

```cpp
#include <memory>

class Widget {
    // ...

private:
    class Impl; // defined elsewhere
    const std::unique_ptr<Impl> impl_; // incomplete type Impl is allowed
    // ...
};
```
Tree

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)

```
#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, 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_
};
```
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

```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 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::lock_guard<std::mutex> lock(mut);
    auto sp = cache[id].lock();
    if (!sp) {
        sp = std::make_shared<Widget>(id);
        cache[id] = sp;
    }
    return sp;
}
```
Section 3.1.7

References

Section 3.2

Exceptions
Section 3.2.1

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

High-Level Code

Low-Level Code

main
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)
```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;
    }
    // ...
}
```
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
```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::make_pair(false, 0);
    }
    return std::make_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";
        }
    }
}
```
```cpp
#include <iostream>
#include <vector>
#include <utility>

class divide_by_zero {};  

int safe_divide(int x, int y) {
    if (!y) {
        throw 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 divide_by_zero& e) {
            std::cerr << "division by zero\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 3.2.2

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

### Exception Classes Derived from exception Class

<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>bad <code>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>
</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>
</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>
Section 3.2.3

Throwing and Catching 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

```cpp
throw "OMG!";
```

can be caught by handler of `const char*` type, as in:

```cpp
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)
if thrown object is class object, copy/move constructor and destructor must be accessible
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
}
// handle logic_error exception
catch (const std::logic_error& e) {
    // handle logic_error exception
}
// handle runtime_error exception
catch (const std::runtime_error& e) {
    // handle runtime_error exception
}
// handle other exception types
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
Exception During Exception: Catching By Value

```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";
    }
}
#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\n";
    }
    catch (...) {
        std::cout << "not Derived\n";
    }
}
caught exception can be rethrown by throw statement with no operand

example:

```cpp
try {
    // code that may throw exception
}
catch (...) {
    throw; // rethrow caught exception
}
```
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
- if no matching handler found, `std::terminate()` is called
- 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
- process of calling destructors for automatic objects constructed on path from try block to throw expression called **stack unwinding**
- 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
void func1() {
    std::string dave("dave");
    try {
        std::string bye("bye");
        func2();
    } catch (const std::runtime_error& e) { // Handler
        std::cerr << e.what() << '\n';
    }
}

void func2() {
    std::string world("world");
    func3(0);
}

void func3(int x) {
    std::string hello("hello");
    if (x == 0) {
        std::string first("first");
        std::string second("second");
        throw std::runtime_error("yikes"); // Throw site
    }
}

- 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
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() << '
';
    }
```

- 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:
1. base class objects as listed in type definition left to right
2. data members as listed in type definition top to bottom
3. constructor body

order of destruction is exact reverse of order of construction, namely:
1. destructor body
2. data members as listed in type definition bottom to top
3. base class objects as listed in type definition right to left

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)
```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;
```
Section 3.2.4

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`)
- 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
  ```
nontrivial \textbf{bool} expression for \texttt{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<T>::value &&
    std::is_nothrow_move_assignable<T>::value) {
    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

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

if exception due to parameter passing must be avoided, pass by reference or ensure `noexcept` move and/or copy constructor as appropriate

if exception due to return by value must be avoided, ensure `noexcept` move or copy constructor as appropriate
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 <cassert>
#include <utility>

void increment (int&) noexcept;
char* memAlloc (std::size_t);

// does not throw exception, but not declared noexcept
void doesNotThrow () {};

int main () {
    assert (noexcept(1 + 1) == true);
    assert (noexcept(memAlloc(0)) == false);
    // Note: does not evaluate expression
    assert (noexcept(increment(*((int*)0))) == true);
    assert (noexcept(increment(std::declval<int&>())) == true);
    // Note: only uses noexcept specifiers
    assert (noexcept(doesNotThrow()) == false);
}
```
noexcept operator particularly useful for templates

example:

```cpp
#include <iostream>

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<T>::value)
    { 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)) << '
';
    }
```
language offers another mechanism for stating exception specifications known as dynamic exception specifications
dynamic exception specifications are deprecated and should not be used
provide exception specification for function using `throw` specifier
used to specify list of all types of exceptions that can be thrown
in practice, such a list more of hindrance than help
if list of all allowable exceptions specified, must check if thrown exception of expected type, which is unnecessary cost
in terms of compiler optimization, what matters most is whether any exception (regardless of type) can be thrown at all
Section 3.2.5

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 3.2.6

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
void useBuffer(char* buf) { /* ... */ }

void doWork() {
    char* buf = new char[1024];
    useBuffer(buf);
    delete[] buf;
}

- if useBuffer throws exception, code that deletes buf is never reached
Cleanup operations should always be performed in destructors.

The 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 be provided by:
  - destructors
  - 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
implementation 1 (not exception safe; has memory leak):

```cpp
void useBuffer(char* buf) { /* ... */ }

void doWork() {
    char* buf = new char[1024];
    useBuffer(buf);
    delete[] buf;
}
```

implementation 2 (exception safe):

```cpp
template <class T>
class SmartPtr {

public:
    SmartPtr(int size) : ptr_(new T[size]) {}  
    ~SmartPtr() { delete[] ptr_; }  
    operator T*() { return ptr_; }  
    // ...

private:
    T* ptr_;  
};

template <class T>
void useBuffer(char* buf) { /* ... */ }

void doWork() {
    SmartPtr<char> buf(1024);
    useBuffer(buf);
}
```
Section 3.2.7

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
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 3.2.8

Smart Pointers and Other RAII Classes
```cpp
#include <cstddef>
#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());
}
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
std::lock_guard, std::unique_lock, and std::shared_lock can be used to manage 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 3.2.9

Exception Gotchas
shared_ptr Example: Not Exception Safe

```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

- 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
- if step 3 or 4 throws, memory leaked
#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:
   1. construct shared_ptr<T1> via make_shared<T1>
   2. construct shared_ptr<T2> via make_shared<T2>
   3. call func

2. each of T1 and T2 objects managed by shared_ptr at all times so no
   memory leak possible if exception thrown

3. similar issue arises in context of std::unique_ptr and can be resolved
   by using std::make_unique in similar way as above
Stack Example

- 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 3.2.10

Miscellany
```cpp
#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::make_pair(false, 0) : std::make_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";
        }
    }
}
```
#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";
        }
    }
    return 0;
}
Section 3.2.11

References

   A good tutorial on exception safety by an expert on the subject.


   Available online at http://ptgmedia.pearsoncmg.com/images/020163371x/supplements/Exception_Handling_Article.html.

   An early paper that first drew attention to some of the difficulties in writing exception-safe code.


Jon Kalb. Exception-Safe Coding in C++Now, Aspen, CO, USA, May 13–18, 2012. (This talk is in two parts.)
Section 3.3.1

Introduction
Motivation Behind Rvalue References

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**.

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 3.3.2

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:

- **copying**;
- **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).
Consider a class that represents a one-dimensional array.

```cpp
template <class T>
class Vector {
public:
    // ...
private:
    T* data_; // pointer to element data
              // (allocated with new)
    unsigned int size_; // number of elements
};
```

Pictorially, the data structure looks like the following:

```
object
---
data_  d_0
     |    d_1
     |      ...
     |    d_{n-1}
size_  n
```

- How would copying be implemented?
- How would moving be implemented?
Vector 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 (destruction, memory deallocation), one array new (memory allocation, construction), copying of element data (copy assignment, etc.), and updating `data_` and `size_` data members

- copying proceeds as follows:

```plaintext
<table>
<thead>
<tr>
<th>src</th>
<th>dst</th>
</tr>
</thead>
<tbody>
<tr>
<td>data_</td>
<td>data_</td>
</tr>
<tr>
<td>size_</td>
<td>size_</td>
</tr>
<tr>
<td>n</td>
<td>m</td>
</tr>
<tr>
<td>s_0</td>
<td>d_0</td>
</tr>
<tr>
<td>s_1</td>
<td>d_1</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>s_{n-1}</td>
<td>d_{m-1}</td>
</tr>
</tbody>
</table>
```

```plaintext
<table>
<thead>
<tr>
<th>src</th>
<th>dst</th>
</tr>
</thead>
<tbody>
<tr>
<td>data_</td>
<td>data_</td>
</tr>
<tr>
<td>size_</td>
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<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>s_{n-1}</td>
<td>s_{n-1}</td>
</tr>
</tbody>
</table>
```
Vector Example: Moving

- code for moving from source \texttt{src} to destination \texttt{dst}:
  
  ```cpp
  std::swap(src.data_, dst.data_);
  std::swap(src.size_, dst.size_);
  ```

- moving only requires updating \texttt{data\_} and \texttt{size\_} data members

- although not considered here, could also free data array associated with \texttt{src} if desirable to release memory as soon as possible

- moving proceeds as follows:
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 provide the above mechanisms.
Section 3.3.3

References and Expressions
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”).

```c++
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”).

```c++
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 rvalue references differ only in their properties relating to:

- reference binding; and
- overload resolution.
An **expression** is a sequence of operators and operands that specifies a computation.

An expression has a type and, if the type is not void, a value.

**Example:**

```
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</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</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>

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C++ Version: 2017-02-24
Every expression can be classified into exactly one of the three following categories:
1. lvalue
2. prvalue (pure rvalue)
3. xvalue (expiring value)

An expression that is an lvalue or xvalue is called a glvalue (generalized lvalue).

An expression that is a prvalue or an xvalue is called an rvalue.

Every expression is either an lvalue or an rvalue (but not both).

Whether or not it is safe to move (instead of copy) depends on whether an lvalue or rvalue is involved.
Lvalues

- **An lvalue** is an expression that:
  - designates a function or object; and
  - has an identity (i.e., occupies some *identifiable* location in memory and therefore, in principle, can have its address taken).

- **Named objects** and **named functions** are lvalues. Example:

  ```cpp
  int getValue();
  int i = 0;
  const int j = 1;
  i = j + 1; // i and j are lvalues
  getValue(); // getValue is lvalue [Note: not getValue()]
  ```

- **Dereferenced pointer.** If `e` is an expression of pointer type, then `*e` is an lvalue. Example:

  ```cpp
  char buffer[] = "Hello";
  char* s = buffer;
  *s = 'a'; // *s is lvalue
  *(s + 1) = 'b'; // *(s + 1) is lvalue
  ```
The result of calling a function whose \textit{return type is an lvalue reference type} is an lvalue. Example:

```cpp
std::vector<int> v = {{1, 2, 3}};
// int& std::vector<int>::operator[](int);
int i = v[0]; // v[0] is lvalue
```

A \textit{string literal} is an lvalue. Example: "Hello World"

\textit{Named rvalue references} are lvalues. Example:

```cpp
int&& i = 1 + 3;
int j = i; // i is lvalue
```

Rvalue references to functions (both named and unnamed) are lvalues.
Using a move (instead of a copy) is *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
Vector<int> x;
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 below
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 below
```
A **prvalue** (pure rvalue) is an expression that:
- is a temporary object or subobject thereof, or a value that is not associated with an object; and
- does not have an identity.

A prvalue is a kind of rvalue.

**Temporary objects** are prvalues. Example:

```cpp
std::vector<int> v;
v = std::vector<int>(10, 2);  // std::vector<int>(10, 2) is prvalue
std::complex<double> u;
u = std::complex<double>(1, 2);  // std::complex<double>(1, 2) is prvalue
```

A function call whose **return type is not a reference type** is a prvalue. Example:

```cpp
int func();
int i = func();  // func() is prvalue
```
All **literals other than string literals** are prvalues. Examples:

```c
double pi = 3.1415; // 3.1415 is prvalue
int i = 42; // 42 is prvalue
i = 2 * i + 1; // 2 and 1 are prvalues
char c = 'A'; // 'A' is prvalue
```

The result yielded by certain built-in operators (e.g., +, -) is a prvalue. Example:

```c
int i, j;
i = 3 + 5; // 3 + 5 is prvalue
j = i * i; // i * i is prvalue
```

The **this** keyword is a prvalue expression.

Prvalues need not have any storage associated with them.

Not requiring prvalue expressions to have storage gives the compiler more freedom in generating code for such expressions.

```c
int i = 2;
// 2 is prvalue and need not ever be stored in memory
```
Using a move (instead of a copy) is *always safe* when the source is a prvalue (since the prvalue cannot correspond to an object with an identity).

Example (move from temporary object):

```cpp
Vector<int> getVector();
Vector<int> x;
Vector<int> y(getVector());
// can we construct by moving (instead of copying)?
// source getVector() is prvalue
// safe to move since temporary object could not be used below
x = getVector();
// can we assign by moving (instead of copying)?
// source getVector() is prvalue
// safe to move since temporary object could not be used below
```
**Xvalues**

- An **xvalue** (expiring value) is an expression that:
  - refers to an object (usually near the end of its lifetime);
  - has an identity; and
  - is *deemed to be safe* to use as the source for a move.

- An xvalue is a kind of rvalue.

- An xvalue is the result of certain kinds of expressions involving rvalue references.

- The result of calling a function whose *return type is an rvalue reference type* is an xvalue. Example:

  ```cpp
  std::string s("Hello");
  std::string t = std::move(s); // std::move(s) is xvalue
  ```

- In the above example, the template function `std::move` converts its argument to an xvalue (since it returns an rvalue reference type).

- **Unnamed rvalue references to objects** are xvalues.

  ```cpp
  std::string s("Hello");
  std::string t;
  t = static_cast<std::string&&>(s); // static_cast<std::string&&>(s) is xvalue
  ```
Using a move (instead of a copy) is *deemed to be safe* when the source is an xvalue.

Example (forced move):

```cpp
Vector<int> v(100, 5);
Vector<int> u(200, -1);
for (auto i : v) std::cout << i << '
';
for (auto i : u) std::cout << i << '
';
v = std::move(u);
// std::move(u) is xvalue
// safe to force move since later code does
// not to use value of u
for (auto i : v) std::cout << i << '
';
// later code known not to use value of u
```

The function `std::move` only allows for an object to be treated as if it were safe to use as source of a move, but does not perform a move.
With regard to propagating the value from one object to another, we can summarize the preceding results as given below.

- If the source is an \textit{rvalue} (i.e., prvalue or xvalue), using a move instead of a copy is \textit{always safe}.
- If the source is an \textit{lvalue}, using a move instead of a copy is \textit{not guaranteed to be safe}.
- 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.
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*. 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
```
#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 << '
';
    // func1(a)? b = func1(a)?
}
Aside from the exceptions noted below, all of the built-in operators require operands that are rvalues.

The operand of each of the following built-in operators must be an lvalue:
- address of (i.e., unary &),
- prefix and postfix increment (i.e., ++),
- prefix and postfix decrement (i.e., --)

The left operand of the following built-in operators must be an lvalue:
- assignment (i.e., =)
- compound assignment (e.g., +=, -=, *=, /=', etc.)

Aside from the exceptions noted below, all of the built-in operators yield a result that is an rvalue.

The following operators yield a result that is an lvalue:
- subscript (i.e., [])
- dereference (i.e., unary *)
- assignment (i.e., =) and compound assignment (e.g., +=, -=, etc.)
- prefix increment (i.e., ++) and prefix decrement (i.e., --)
- function call (i.e., ()) invoking a function that returns a reference type
- cast to reference type
Operators, Lvalues, and Rvalues

- 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.)

- The lvalue/rvalue-ness and type of the result produced by the ternary conditional operator depends on the particular manner in which the operator is employed.
An implicit conversion from lvalues to rvalues is provided, which can be used in most (but not all) circumstances.

Example:

```cpp
int i = 1;
int j = 2;
int k = i + j;
// operands of + must be rvalues
// i and j converted to rvalues
```
Section 3.3.4

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?

\[
\begin{align*}
T& \ r = \ & ; \\
T&& \ r = \ & ; 
\end{align*}
\]

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?

\[
\begin{align*}
T \ operator+(const \ T&, \ const \ T&) ; \\
void \ func(const \ T&) ; \\
void \ func(T&&) ; \\
x; \\
func (x) ; \ // \ calls \ which \ version \ of \ func ? \\
func(x + x) ; \ // \ calls \ which \ version \ of \ func ?
\end{align*}
\]
Implicit lvalue-to-rvalue conversion is disabled when binding to references.

An lvalue reference can bind to an lvalue as long as doing so would not result in the loss of any cv qualifiers.

```cpp
class X { 
public: 
    int i = 0; // ERROR: drops const
    int& r1 = i; // OK
    const int& r2 = i; // OK
    const volatile int& r3 = i; // OK
}
```

The loss of cv qualifiers must be avoided for **const and volatile correctness**.

Similarly, an rvalue reference can bind to an rvalue as long as doing so would not result in the 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 **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
const std::string getConstValue();
std::string& r1 = getConstValue();  // ERROR: drops const
const std::string& r2 = getValue();  // OK
int& ri1 = 42;  // ERROR: not const reference
const int& ri2 = 42;  // 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>
</tr>
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<tbody>
<tr>
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<td></td>
<td>const</td>
<td>volatile</td>
<td>const volatile</td>
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<tr>
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<td>T&amp;&amp;</td>
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<td>volatile</td>
<td>✓</td>
<td>✓</td>
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</tr>
</tbody>
</table>

✓: allowed   C: strips `const`   V: strips `volatile`   X: other
```cpp
#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;
    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;
    const string& r06 = j;
    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>Type</th>
<th>Rvalue</th>
<th>Lvalue</th>
</tr>
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<tbody>
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<td>3</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

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Overloading Example 1

```cpp
#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(std::string&&) called
func(const std::string&) called
*/
```
A rvalue reference cannot 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 3.3.5

Moving
A non-template constructor for class $T$ is a **move constructor** if it can be called with one parameter that is of type $T&&$, $\text{const } T&&$, $\text{volatile } T&&$, or $\text{const volatile } T&&$.

Example (assuming no optimization):

```cpp
struct T {
    T();
    T(const T&); // copy constructor
    T(T&&);     // move constructor
};
T func(int);
T a(func(1)); // calls $T::T(T&&)$
T b = a;     // calls $T::T(\text{const } T&)$
```
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&&`.

Example (assuming no optimization):

```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&)
```

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C++ Version: 2017-02-24
Recall the class from earlier that represents a one-dimensional array.

```cpp
template <class T>
class Vector {
public:
    // ...
private:
    T* data_; // pointer to element data
    // (allocated with new)
    unsigned int size_; // number of elements
};
```

Pictorially, the data structure looks like the following:

```
+------------------------+------------------------+
| object                | data_                  |
|                       |                         |
|                       |     data_               |
|                       |     size_               |
|                       | n                       |
|                       | d_0                    |
|                       | d_1                    |
|                       | :                      |
|                       | d_n-1                  |
```
```cpp
#include <algorithm>
#include <complex>

template <class T>
class Vector {
public:
    Vector(unsigned int size, T value = 0) : data_(new T[size]), size_(size) {
        std::fill_n(data_, size, value);
    }
    Vector(const Vector& a) : data_(new T[a.size_]), size_(a.size_)
        {std::copy_n(a.data_, a.size_, data_);}
    Vector& operator=(const Vector& a) {
        if (this != &a) {
            delete[] data_; size_ = a.size_; data_ = new T[a.size_];
            std::copy_n(a.data_, a.size_, data_);
        }
        return *this;
    }
    ~Vector() {delete[] data_;}
    // ...

private:
    T* data_; // pointer to element data
    unsigned int size_; // number of elements
};

typedef Vector<std::complex<double>> Vec;

Vec getVector() {return Vec(1000, {0.0, 1.0});}

int main() {
    Vec v(0);
    Vec w = getVector(); // construct from temporary object
    v = Vec(2000, {1.0, 2.0}); // assign from temporary object
}
```
```cpp
#include <algorithm>
#include <complex>

template <class T>
template <class T>
class Vector {
public:
    Vector(unsigned int size, T value = 0) : data_(new T[size]), size_(size) {
        std::fill_n(data_, size, value);
    }
    Vector(const Vector& a) : data_(new T[a.size_]), size_(a.size_)
    {
        std::copy_n(a.data_, a.size_, data_);
    }
    Vector & operator=(const Vector& a) {
        if (this != &a) {
            delete[] data_; size_ = a.size_; data_ = new T[a.size_];
            std::copy_n(a.data_, a.size_, data_);
        }
        return *this;
    }
    // Move constructor
    Vector(Vector&& a) : data_(a.data_), size_(a.size_)
    {
        a.size_ = 0; a.data_ = nullptr;
    }
    // Move assignment operator
    Vector & operator=(Vector&& a) {
        std::swap(size_, a.size_); std::swap(data_, a.data_);
        return *this;
    }
    ~Vector() {delete[] data_;}

private:
    T* data_; // pointer to element data
    unsigned int size_; // number of elements
};
typedef Vector<std::complex<double>> Vec;
Vec getVector() {return Vec(1000, {0.0, 1.0});}

int main() {
    Vec v(0);
    Vec w = getVector(); // construct from temporary object
    v = Vec(2000, {1.0, 2.0}); // 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:

```cpp
template <class T>
void swap(T& x, T& y) {
    T tmp(std::move(x)); // move x to tmp
    x = std::move(y); // move y to x
    y = std::move(tmp); // move tmp to y
}
```

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.
By distinguishing between lvalues and rvalues, we can write more efficient code.

Scenario 1:
```cpp
void doSomething(std::complex<double>& z) {
    // can the caller detect a change in z?
}

std::complex<double> z(1.0, 0.0);
doSomething(z);
```

Scenario 2:
```cpp
void doSomething(std::complex<double>&& z) {
    // can the caller detect a change in z?
}
doSomething(std::complex<double>(1.0, 2.0));
```

A function parameter that is bound to a modifiable rvalue can be changed without any observable effect outside the function.

This gives us more freedom in how we deal with the object whose change in value cannot be observed.

For example, this freedom can be used to replace some copies by moves.
• 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
}
```
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 3.3.6

Reference Collapsing and Forwarding References
A reference to a reference is not allowed, since such a construct clearly makes no sense.

```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.
Reference Collapsing Rules

- 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.

<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>\textbf{const} ( TR&amp; )</td>
<td>( T&amp; )</td>
</tr>
<tr>
<td>\textbf{volatile} ( TR&amp; )</td>
<td>( T&amp; )</td>
</tr>
<tr>
<td>\textbf{const volatile} ( TR&amp; )</td>
<td>( T&amp; )</td>
</tr>
<tr>
<td>( TR&amp;&amp; )</td>
<td>( TR )</td>
</tr>
<tr>
<td>\textbf{const} ( TR&amp;&amp; )</td>
<td>( TR )</td>
</tr>
<tr>
<td>\textbf{volatile} ( TR&amp;&amp; )</td>
<td>( TR )</td>
</tr>
<tr>
<td>\textbf{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).
Reference Collapsing Examples

Due to reference collapsing, T&& syntax may not always be an rvalue reference. Example:

```cpp
typedef int& IntRef;
int i = 0;
IntRef&& r = i; // r is int& (i.e., lvalue reference)
```

Example:

```cpp
typedef int& IntRef;
typedef int&& IntRefRef;
typedef const int&& ConstIntRefRef;
typedef const int& ConstIntRef;
typedef const IntRef& T1; // T1 is int&
typedef const IntRefRef& T2; // T2 is int&
typedef IntRefRef&& T3; // T3 is int&&
typedef ConstIntRefRef& T4; // T4 is const int&
typedef ConstIntRefRef&& T5; // 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 \textit{cv-unqualified} rvalue reference that appears in a type-deducing context for template parameters is called a \textit{forwarding reference}.

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:

\begin{verbatim}
  template<class T>
  void f(T&& p);

  f(expr); // invoke f
\end{verbatim}

Let $E$ denote the type of the expression $expr$. The type $T$ is then deduced as follows:

1. If $expr$ is an \textit{lvalue}, $T$ is deduced as $E\&$, in which case the type of $p$ yielded by reference collapsing is $E\&$.
2. If $expr$ is an \textit{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 \textit{inside $f$} based on whether $T\&\&$ is an lvalue reference type or rvalue reference type.
#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 3.3.7

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:

\[
\begin{align*}
\text{wrapper}(expr) &; \\
\text{func}(expr) &;
\end{align*}
\]

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 `wrapper`:

```cpp
template <class T>
void wrapper(T p) {
    func(p);
}
```

If `func` takes its parameter by reference, calls to `wrapper` and `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 *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 *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 \texttt{wrapper}:

\begin{verbatim}
template <class T>
void wrapper(const T& p) {
    func(p);
}
\end{verbatim}

If, for example, the function argument is a non-const object, calls to \texttt{wrapper} and \texttt{func} (with the same argument) will have different behaviors.

Suppose, for example, that we have the following declaration:

\begin{verbatim}
void func(int&);
int i;
\end{verbatim}

Then, the following two function calls are \textit{not equivalent}:

\begin{verbatim}
wrapper(i);
    // ERROR: wrapper cannot call func, as this
    // would discard const qualifier
func(i);
    // OK
\end{verbatim}

Problem: The original and forwarded arguments do not match in terms of \textit{cv-qualifiers}. 
Finally, we propose the following code for the (template) function wrapper:

```cpp
template <class T>
void wrapper(T&& p) {
    func(static_cast<T&&>(p));
}
```

Consider now, for example, the following scenario:

```cpp
int i = 42;
const int ci = i;
int& ri = i;
const int& rci = i;
wrapper(expr);  // invoke wrapper
```

The parameter `p` is an alias for the object yielded by the expression `expr`.

The argument `expr` and argument to `func` match in terms of cv-qualities and lvalue/rvalue-ness.
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 << '
';
    auto result = emphasize(std::forward<A>(arg));
    std::cout << "Return value " << result << '
';
    return result;
}

int main() { 
    std::string s("Bonjour");
    wrapper(s);
    wrapper(std::string("Hello"));
}
```
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:**

```cpp
#include <iostream>
#include <string>
#include <complex>
#include <utility>
#include <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"));
    auto z(factory<std::complex<double>>(1.0i));
    std::cout << *s << ' ' << *z << '
';
}
```
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
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

std::make_pair forwards arguments to std::pair constructor

std::make_tuple forwards arguments to std::tuple constructor
Section 3.3.8

References


This talk discusses rvalue/forwarding references.


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 3.4

Concurrency
Section 3.4.1

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 its 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 *higher clock rates*
- *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 *cube* of frequency
- Greater power consumption translates into *increased heat production*
- Higher clock rates would result in processors *overheating*
- Transistor counts *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 *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 *greater processing power with lower power consumption* and *less heat production*
Section 3.4.2

Multithreaded Programming
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:
- multiple single-threaded processes; or
- a single multithreaded process.

A single multithreaded process is usually preferable, since data can be shared 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 3.4.3

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:
  - $x = 1; y = 1; b = x; a = y$;
  - $y = 1; x = 1; a = y; b = x$;
  - $x = 1; a = y; y = 1; b = x$;
  - $y = 1; b = x; x = 1; a = y$;
Sequential-Consistency (SC) Memory Model

- 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**

\[
\begin{align*}
  x &= 1; \\
  y &= 1; \\
  \text{// ...}
\end{align*}
\]

Suppose that, during optimization, the compiler transforms the preceding code to that shown below, effectively **reordering two stores**.

**Optimized Thread 1 Code**

\[
\begin{align*}
  y &= 1; \\
  x &= 1; \\
  \text{// ...}
\end{align*}
\]

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.

**Original Thread 1 Code**

```c
x = 1;
y = 1;
// ...
```

**Thread 2 Code**

```c
if (y == 1) {
    assert (x == 1);
}
```

Suppose that the compiler makes the same optimization to the code for thread 1 as on the previous slide, yielding the code below.

**Optimized Thread 1 Code**

```c
y = 1;
x = 1;
// ...
```

**(Unchanged) Thread 2 Code**

```c
if (y == 1) {
    assert (x == 1);
}
```

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.

<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 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.
(1) transfer data from register to store buffer
(2) flush store buffer to memory
### 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 $x$ pending</td>
<td>$y = 1;$</td>
</tr>
<tr>
<td>$a = y;$ // $a = 0;$</td>
<td>no change</td>
<td>no change</td>
</tr>
<tr>
<td>$b = x;$ // $b = 0;$</td>
<td>no change</td>
<td>no change</td>
</tr>
<tr>
<td>write 1 to $x$ completed</td>
<td>write 1 to $y$ completed</td>
<td>1</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.
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.

    | Thread 1 Code | Thread 2 Code |
    |----------------|----------------|
    | \( x = 1; \)  | \( y = 1; \)  |
    | \( a = y + z; \) | \( b = x + z; \) |

  - 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.
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:

\[
\begin{array}{c|c}
\text{Byte 0} & \text{Byte 1} \\
00 & 00 \\
\end{array}
\]

Thread 1 writes 12 to the first byte of \( x \), yielding:

\[
\begin{array}{c|c}
\text{Byte 0} & \text{Byte 1} \\
12 & 00 \\
\end{array}
\]

Thread 2 writes 56 and 78 to the first and second bytes of \( x \), respectively, yielding:

\[
\begin{array}{c|c}
\text{Byte 0} & \text{Byte 1} \\
56 & 78 \\
\end{array}
\]

Thread 1 writes 34 to the second byte of \( x \), yielding:

\[
\begin{array}{c|c}
\text{Byte 0} & \text{Byte 1} \\
56 & 34 \\
\end{array}
\]

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 3.4.4

Thread Management
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
- each thread object has ID
- IDs of joinable thread objects are unique
- all unjoinable thread objects have same ID, distinct from ID of every joinable thread object
**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

if thread object joinable when destructor called, exception is thrown

**hardware_concurrency** member function 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)
### 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>
## std::thread Members

<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();
}
```cpp
#include <iostream>
#include <thread>

void doWork(int i, int j)
{
    std::cout << i << ' ' << j << '
';
}

int main()
{
    int i = 42;
    std::thread t1(doWork, i, 1);
    t1.join();
}
```
```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<int> v{1, 2, 3, 4};

    // copy semantics
    std::thread t1(doWork, v);
    t1.join();

    // reference semantics
    std::thread t2(doWork, std::ref(v));
    t2.join();
}
```
```cpp
#include <iostream>
#include <vector>
#include <utility>
#include <thread>

void doWork(std::vector<int>&& v)
{
    for (auto i : v) {
        std::cout << i << '
';
    }
}

int main()
{
    std::vector<int> v{1, 2, 3, 4};
    // move semantics
    std::thread t1(doWork, std::move(v));
    t1.join();
}
```
#include <thread>
#include <iostream>
#include <utility>

// Return a thread that prints a greeting message.
std::thread makeThread() {
  return std::thread([](){
    std::cout << "Hello World!\n";
  });
}

// Return the same thread that was passed as an argument.
std::thread identity(std::thread t) {
  return t;
}

int main() {
  std::thread t1(makeThread());
  std::thread t2(std::move(t1));
  t1 = std::move(t2);
  t1 = identity(std::move(t1));
  t1.join();
}
```cpp
#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) << '\n';
}

void startThread() {
    std::vector<int> v(1000000, 1);
    std::thread 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::thread::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::thread t([]() {
        // call func from secondary thread
        func();
    });
    // call func from main thread
    func();
    t.join();
}
```
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:

```c++
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;
}
```
```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();}
}```
The `std::thread` Class and Exception Safety

- The astute reader will notice that most code examples on these lecture slides (both earlier and later) that directly employ `std::thread` are not exception safe.

- Some of the exception safety problems in these examples could be eliminated by using a RAII class to wrap `std::thread` objects.

- Unfortunately, the standard library does not provide such a RAII class.

- At a very basic level, one could provide a thread wrapper class that has similar functionality to `std::thread`, except that its destructor automatically joins with the underlying thread if the thread is still joinable at destruction time. (See next slide.)

- Although such an approach will work in some situations (such as in the case of many of the simple code examples on these lecture slides), it can potentially lead to deadlocks and other problems in more complex code.

- A more general solution would be to provide a class that allows arbitrary code to be executed just prior to thread destruction, in order to perform the appropriate (application-dependent) “clean-up” action. (For example, see `boost::scoped_thread` in the Boost Threads library.)
```cpp
#include <thread>

// A minimalist inheritance-based replacement for std::thread
// that joins automatically in the destructor.
// (One must be careful not to use this type polymorphically
// since the destructor is not virtual.)
class scoped_thread : public std::thread {
public:
    using std::thread::thread;
    scoped_thread(scoped_thread&&) = default;
    scoped_thread& operator=(scoped_thread&&) = default;
    scoped_thread(const scoped_thread&) = delete;
    scoped_thread& operator=(const scoped_thread&) = delete;
    ~scoped_thread() {
        if (joinable()) {
            join();
        }
    }
};
```
Section 3.4.5

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).
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)
#include <iostream>
#include <thread>

unsigned long long counter = 0;

void func() {
    for (int i = 0; i < 1000000; ++i) {
        ++counter;
    }
}

int main() {
    std::thread t1(func);
    std::thread t2(func);
    t1.join();
    t2.join();
    std::cout << counter << '
';
}

#include <thread>
#include <iostream>
#include <set>

class IntSet {
public:
    bool contains(int i) const
    { return s_.find(i) != s_.end(); }
    void add(int i)
    { s_.insert(i); }
private:
    std::set<int> s_; 
};

IntSet s;

int main() {
    std::thread t1([]() {
        for (int i = 0; i < 1000; ++i) s.add(2 * i);
    });
    std::thread t2([]() {
        for (int i = 0; i < 1000; ++i) s.add(2 * i + 1);
    });
    t1.join(); t2.join();
    std::cout << s.contains(1000) << '
';
}
Section 3.4.6

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.
std::mutex class provides mutex functionality

*not movable* and *not copyable*

lock member function acquires mutex (blocking as necessary)

unlock member function releases mutex

thread that owns mutex should not attempt to lock mutex again

all prior unlock operations on given mutex *synchronize with* lock operation (on *same* mutex) (synchronizes-with relationship to be discussed later)
### 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 (int i = 0; i < 1000000; ++i) {
        m.lock(); // acquire mutex
        ++counter;
        m.unlock(); // release mutex
    }
}

int main() {
    std::thread t1(func);
    std::thread t2(func);
    t1.join();
    t2.join();
    std::cout << counter << '\n';
}
```
The `std::lock_guard` Template Class

- `std::lock_guard` is RAII class for mutexes
- declaration:
  ```cpp
template <class T> class lock_guard;
```
- template parameter `T` specifies type of mutex (e.g., `std::mutex`, `std::recursive_mutex`)
- avoids problem of inadvertently forgetting to release mutex (e.g., due to exception or forgetting `unlock` call)
- constructor takes mutex as argument
- **not movable** and **not copyable**
- acquires mutex in constructor
- releases mutex in destructor
- since language ensures that all objects destroyed at end of lifetime, release of mutex guaranteed (even if some code skipped due to thrown exception)
- advisable to use `lock_guard` instead of calling `lock` and `unlock` explicitly
### std::lock_guard 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 lock guard</td>
</tr>
<tr>
<td>destructor</td>
<td>destroy lock guard</td>
</tr>
</tbody>
</table>
cpp
```cpp
#include <iostream>
#include <thread>
#include <mutex>

std::mutex m;
unsigned long long counter = 0;

void func() {
    for (int i = 0; i < 1000000; ++i) {
        // lock_guard constructor acquires mutex
        std::lock_guard<std::mutex> lock(m);
        ++counter;
        // lock_guard destructor releases mutex
    }
}

int main() {
    std::thread t1(func);
    std::thread t2(func);
    t1.join();
    t2.join();
    std::cout << counter << '
';
}
```
```cpp
#include <thread>
#include <iostream>
#include <set>
#include <mutex>

class IntSet {
public:
    bool contains(int i) const {
        std::lock_guard<std::mutex> lg(m_);
        return s_.find(i) != s_.end();
    }
    void add(int i) {
        std::lock_guard<std::mutex> lg(m_);
        s_.insert(i);
    }
private:
    std::set<int> s_;  
    mutable std::mutex m_; 
};

IntSet s;

int main() {
    std::thread t1([]()
    {
        for (int i = 0; i < 1000; ++i) s.add(2 * i);
    });
    std::thread t2([]()
    {
        for (int i = 0; i < 1000; ++i) s.add(2 * i + 1);
    });
    t1.join(); t2.join();
    std::cout << s.contains(1000) << '
';
}
```
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::lock_guard`, 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`
### 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><code>operator=</code></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>
```cpp
#include <iostream>
#include <thread>
#include <mutex>

std::mutex m;
unsigned long long counter = 0;

void func() {
    for (int i = 0; i < 1000000; ++i) {
        // Create a lock object without locking the mutex.
        std::unique_lock<std::mutex> lock(m, std::defer_lock);
        // ...
        // Lock the mutex.
        lock.lock();
        ++counter;
        // The unique_lock destructor releases the mutex.
    }
}

int main() {
    std::thread t1(func);
    std::thread t2(func);
    t1.join();
    t2.join();
    std::cout << counter << '
';
}
```
**The std::lock Template Function**

- 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
```cpp
#include <thread>
#include <vector>
#include <mutex>

class BigBuf // A Big Buffer
{
public:
    static constexpr int size() { return 16 * 1024 * 1024; }
    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::lock_guard<std::mutex> lock1(m_);
        std::lock_guard<std::mutex> lock2(other.m_);
        std::swap(data_, other.data_);
    }
private:
    std::vector<char> data_; 
    mutable std::mutex m_; 
};
BigBuf a;
BigBuf b;

int main()
{
    std::thread t1([](){
        for (int i = 0; i < 100000; ++i) a.swap(b);
    });
    std::thread t2([](){
        for (int i = 0; i < 100000; ++i) b.swap(a);
    });
    t1.join(); t2.join();
} 
```
```cpp
#include <thread>
#include <vector>
#include <mutex>

class BigBuf // A Big Buffer
{
public:
    static constexpr int size() { return 16 * 1024 * 1024; }
    BigBuf() : data_(size()) {}
    BigBuf& operator=(const BigBuf&) = delete;
    BigBuf& operator=(BigBuf&&) = delete;
    void swap(BigBuf& other) {
        if (this == &other)
            return;
        std::unique_lock<std::mutex> lock1(m_, std::defer_lock);
        std::unique_lock<std::mutex> 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::thread t1([](){
        for (int i = 0; i < 100000; ++i) a.swap(b);
    });
    std::thread t2([](){
        for (int i = 0; i < 100000; ++i) b.swap(a);
    });
    t1.join(); t2.join();
```
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

does **try_lock_for** and **try_lock_until** member functions to try to lock mutex with timeout
```cpp
#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<std::timed_mutex> lock(m,
                                         std::defer_lock);
        int count = 0;
        while (!lock.try_lock_for(
            std::chrono::microseconds(1))) {++count;}
        std::cout << count << '
';
    }
}

int main() {
    std::vector<std::thread> workers;
    for (int i = 0; i < 16; ++i) {
        workers.emplace_back(doWork);
    }
    for (auto& t : workers) {t.join();}
}
```
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_timed_mutex` Class

- `std::shared_timed_mutex` class provides shared mutex
- `shared_timed_mutex` also allows timeout for acquiring mutex
## std::shared_timed_mutex

### Members

#### 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>operator=</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>try_lock_for</td>
<td>try to acquire exclusive ownership of mutex without blocking</td>
</tr>
<tr>
<td>try_lock_until</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><code>lock_shared</code></td>
<td>acquire shared ownership of mutex, blocking if not available</td>
</tr>
<tr>
<td><code>try_lock_shared</code></td>
<td>try to acquire shared ownership of mutex without blocking</td>
</tr>
<tr>
<td><code>try_lock_shared_for</code></td>
<td>try to acquire shared ownership of mutex without blocking</td>
</tr>
<tr>
<td><code>try_lock_shared_until</code></td>
<td>try to acquire shared ownership of mutex without blocking</td>
</tr>
<tr>
<td><code>unlock_shared</code></td>
<td>release shared ownership of mutex</td>
</tr>
</tbody>
</table>
The `std::shared_lock` Template Class

- `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_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::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_timed_mutex counterMutex;

void writer() {
    for (int i = 0; i < 10; ++i) {
        std::lock_guard<std::shared_timed_mutex> 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<std::shared_timed_mutex> lock(counterMutex);
        c = counter;
    }
    std::lock_guard<std::mutex> lock(coutMutex);
    std::cout << std::this_thread::get_id() << ' ' << c << 'n';
    std::this_thread::sleep_for(std::chrono::milliseconds(10));
}

int main() {
    std::vector<std::thread> threads;
    threads.emplace_back(writer);
    for (int i = 0; i < 16; ++i) threads.emplace_back(reader);
    for (auto & t : threads) t.join();
}
std::once_flag and std::call_once

- 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::thread> threads;
    for (int i = 0; i < 16; ++i) {
        threads.emplace_back(worker, i);
    }
    for (auto& t : threads) {
        t.join();
    }
}
```
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);}
    for (auto& t : threads) {t.join();}
}
```
initialization of static local object is thread safe

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 3.4.7

Condition Variables
In concurrent programs, the need often arises for a thread to \textit{wait until a particular event occurs} (e.g., I/O has completed or data is available).

Having a thread \textit{repeatedly check} for the occurrence of an event can be \textit{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 \textit{condition variable} is a synchronization primitive that allows threads to \textit{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 \textit{wait operation} on the condition variable.

A thread that wants to notify one or more waiting threads of an event performs a \textit{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 another thread may have caused condition to change.
The `std::condition_variable` Class

- `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 awakening 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]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>operator=</td>
<td>[deleted]</td>
</tr>
</tbody>
</table>

not movable or copyable
### std::condition_variable Members (Continued)

#### 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>
```cpp
#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<std::mutex> lock(m_);
        c_.wait(lock, [this](){ return !v_.empty(); });
        int x = v_.back();
        v_.pop_back();
        return x;
    }
    void push(int x) {
        std::lock_guard<std::mutex> lock(m_);
        v_.push_back(x);
        c_.notify_one();
    }

private:
    std::vector<int> v_;
    mutable std::mutex m_;        // not empty
    mutable std::condition_variable c_;  
};

constexpr int numIters = 1000;
IntStack s;

int main() {
    std::thread t1([](){
        for (int i = 0; i < numIters; ++i) s.push(2 * i + 1);
    });
    std::thread t2([](){
        for (int i = 0; i < numIters; ++i) std::cout << s.pop() << ' 
';
    });
    t1.join(); t2.join();
}
```
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
Section 3.4.8

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
The `std::promise` Template Class

- `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.
# std::promise Members

## Construction, Destruction, and Assignment

<table>
<thead>
<tr>
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</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>
<tr>
<td>Name</td>
<td>Description</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<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>
std::future provides access to promise-future shared state for reading result

declaration:

    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>
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<tbody>
<tr>
<td>constructor</td>
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</tr>
<tr>
<td>destructor</td>
<td>destroy object</td>
</tr>
<tr>
<td><strong>operator=</strong></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 <code>shared_future</code> object</td>
</tr>
<tr>
<td>get</td>
<td>get result</td>
</tr>
<tr>
<td>valid</td>
<td>check if <code>future</code> 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>
```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::thread 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
```cpp
#include <iostream>
#include <vector>
#include <thread>
#include <future>

void consume(std::shared_future<int> f) {
    std::cout << f.get() << '
';
}

int main() {
    std::promise<int> p;
    std::shared_future<int> f = p.get_future().share();
    std::vector<std::thread> 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<double> 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
";
        }
    }
}
```
**The `std::packaged_task` Template Class**

- `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*. 

---

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### 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><code>valid</code></td>
<td>check if task object currently associated with shared state</td>
</tr>
<tr>
<td><code>swap</code></td>
<td>swap two task objects</td>
</tr>
<tr>
<td><code>get_future</code></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><code>reset</code></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::thread 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::thread t(std::move(task), 2.0, 0.5);
    t.detach();
    std::cout << f.get() << '
';
}
```
Section 3.4.9

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.
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;”
guaranteed to be lock free
intended to be used as building block for higher-level synchronization primitives, such as spinlock mutex
### std::atomic_flag 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>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>
```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 < 100000ULL; ++i)
        {std::lock_guard<SpinLockMutex> lock(m); ++counter;}
}

int main() {
    std::thread t1(doWork), t2(doWork);
    t1.join(); t2.join();
    std::cout << counter << ' \n';
}

// default memory order is suboptimal (and will be revisited later)
```
```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();
}

This is not a particularly good use of atomic_flag.
```
The std::atomic Template Class

- std::atomic class provides types with atomic operations
- declaration:
  ```cpp
template <class T> struct atomic;
  ```
- 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 and bitwise equality comparable
- not required to be lock free
- on most popular platforms atomic is lock free when T is built-in type
- not move constructible and not copy constructible
- assignable but assignment operator returns value not reference
- most operations have memory order argument
- default memory order is SC (std::memory_order_seq_cst)
<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>is_lock_free</td>
<td>check if atomic object is lock free</td>
</tr>
<tr>
<td>store</td>
<td>atomically replaces value of atomic object with given value</td>
</tr>
<tr>
<td>load</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>exchange</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 exchange if equal or <code>load</code> otherwise</td>
</tr>
</tbody>
</table>
## Fetch

<table>
<thead>
<tr>
<th>Member Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<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>

"std::atomic Members (Continued 3)"
```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::thread> v;
    for (int i = 0; i < 10; ++i)
        {v.emplace_back(doWork);}
    for (auto& t : v) {t.join();}
    std::cout << counter.get() << '\n';
}
```
```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<bool> ready(false);
std::atomic<bool> done(false);
std::atomic<int> startCount(0);

void doCounting(int id) {
    ++startCount;
    while (!ready) {}
    for (volatile int i = 0; i < 20000; i++) {} // Simulate heavy computation
    bool expected = false;
    if (done.compare_exchange_strong(expected, true)) // Compare and swap
        {std::cout << "winner: " << id << '\n';}
}

int main() {
    std::vector<std::thread> threads;
    for (int i = 0; i < numThreads; ++i)
        {threads.emplace_back(doCounting, i);} // Emplace the thread
    while (startCount != numThreads) {} // Wait until startCount reaches 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 3.4.10

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).
Happens-Before Relationships

- 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 not equivalent to “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 operation A occurs earlier in time than operation B.

<table>
<thead>
<tr>
<th>Time</th>
<th>Thread 1 (on Core 1)</th>
<th>Thread 2 (on Core 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( x = 1; \ // A )</td>
<td>( y = x; \ // B )</td>
</tr>
</tbody>
</table>

The value read for \( x \) in operation B will not necessarily be 1.
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 $C$.

```cpp
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.

```cpp
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.
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 \( C \).

\[
\begin{align*}
x & = 1; & \text{ // A} \\
y & = 2; & \text{ // B} \\
z & = x + 1; & \text{ // C}
\end{align*}
\]
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 *same or different* threads, $A$ happens before $B$ if:
  1. $A$ and $B$ are in the *same* thread and $A$ is sequenced before (i.e., intra-thread happens before) $B$; or
  2. $A$ and $B$ are in *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 *transitive*.

- Inter-thread happens-before relationships are *transitive*.

- Happens-before relationships are *mostly but not always transitive*.

- A happens-before relationship is important because it tells us if the result of one operation *can be seen* by a thread performing another operation.
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 call of the function `foo` is known to synchronize with the return from the function `bar`, which implies that $A$ synchronizes with $B$.

Since $A$ synchronizes with $B$, $A$ must inter-thread happen before $B$, which 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 $T$.

- **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 $T$.

- **Mutex unlock/lock.** All prior unlock operations on a mutex $M$ synchronize with (the return of) a lock operation on $M$.

- **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();
```

Thread 1 Execution

1. `m.lock();`
2. `x = 1;`
3. `m.unlock();`

Thread 2 Execution

1. `m.lock();`
2. `y = x;`
3. `m.unlock();`
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**.
Modification Order

- 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 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 \textit{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.
shared data:
  \(x\) and \(y\) are of type `std::atomic<int>` and both are initially zero

thread 1 code (writes \(x\)):
  \[x\text{.store}(1, \text{std}::\text{memory}\_\text{order}\_\text{seq}\_\text{cst});\]

thread 2 code (writes \(y\)):
  \[y\text{.store}(1, \text{std}::\text{memory}\_\text{order}\_\text{seq}\_\text{cst});\]

thread 3 code (reads \(x\) then \(y\)):
  \[\text{int } x1 = x\text{.load(}\text{std}::\text{memory}\_\text{order}\_\text{seq}\_\text{cst});\]
  \[\text{int } y1 = y\text{.load(}\text{std}::\text{memory}\_\text{order}\_\text{seq}\_\text{cst});\]

thread 4 code (reads \(y\) then \(x\)):
  \[\text{int } y2 = y\text{.load(}\text{std}::\text{memory}\_\text{order}\_\text{seq}\_\text{cst});\]
  \[\text{int } x2 = x\text{.load(}\text{std}::\text{memory}\_\text{order}\_\text{seq}\_\text{cst});\]

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 \(x\))
```c++
#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::thread 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.
Acquire-Release Model

- 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 $W$).

- 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 \(x\)):
  ```cpp
  x.store(1, std::memory_order_release);
  ```

- thread 2 code (writes \(y\)):
  ```cpp
  y.store(1, std::memory_order_release);
  ```

- thread 3 code (reads \(x\) then \(y\)):
  ```cpp
  int x1 = x.load(std::memory_order_acquire);
  int y1 = y.load(std::memory_order_acquire);
  ```

- thread 4 code (reads \(y\) then \(x\)):
  ```cpp
  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::thread 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
```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 < 100000ULL; ++i)
        {m.lock(); ++counter; m.unlock();}
}

int main() {
    std::thread t1(doWork), t2(doWork);
    t1.join(); t2.join();
    std::cout << counter << ' \n';
}
```

Example: Spinlock Mutex Using std::atomic_flag

- Uses acquire-release model

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C++  Version: 2017-02-24
Example: Spinlock Mutex and `std::lock_guard`

```
#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 < 100000ULL; ++i)
    {std::lock_guard<SpinLockMutex> lg(m); ++counter;}
}

int main() {
    std::thread t1(doWork), t2(doWork);
    t1.join(); t2.join();
    std::cout << counter << '
';
}
```
Carries-A-Dependency Relationships

- For two operations $A$ and $B$ performed in the same thread, $A$ is said to carry a dependency to $B$ if the result of $A$ is used as an operand for $B$ (ignoring some special cases).
- Example: In the code below, statement $A$ carries a dependency to statement $B$ but not statement $C$.

```cpp
x = 42;      // A
y = x + 1;   // B
z = 0;       // C
```

- Note that “carries a dependency to” is a subset of “is sequenced before” (i.e., the former implies the latter).
- The carries-a-dependency-to relationship is 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 $A$ carries a dependency to statement $B$; and $B$ carries a dependency to statement $C$. Therefore, transitively, $A$ carries a dependency to $C$.

```cpp
x = 42;      // A
y = x + 1;   // B
z = 2 * y;   // C
```
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*:

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).
```cpp
#include <thread>
#include <atomic>
#include <cassert>

int x = 0;
std::atomic<int> 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::thread t1(producer);
    std::thread 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
```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(x == 42); would result in data race
    assert(*s == "Hello");
}

int main () {
    std::thread 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
```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::thread 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::thread> workers;
    for (int i = 0; i < 10; ++i) {
        workers.emplace_back(doWork);
    }
    for (auto& t : workers) {
        t.join();
    }
    std::cout << "counter " << counter << '\n';

    /* 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 */
```
#include <vector>
#include <thread>
#include <atomic>
#include <chrono>

std::atomic<bool> done;

void doWork() {
    while (!done.load(std::memory_order_relaxed)) {
        // do something here
    }
}

int main() {
    std::vector<std::thread> 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 `std::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 `std::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.
#include <thread>
#include <atomic>
#include <cassert>

int x = 0;
std::atomic<int> y(0);

int main() {
    std::thread t1([](){
        x = 42;
        y.store(1, std::memory_order_release); // A
        y.store(2, std::memory_order_relaxed); // B
    });
    std::thread t2([](){
        int r;
        while ((r = y.load(std::memory_order_acquire)) // C
            < 2) {} // C
        assert(x == 42);
    });
    t1.join();
    t2.join();
}

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

```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`
**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.

**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.

**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 $A$.
Example: Incorrect Code Without Fence

```cpp
#include <thread>
#include <atomic>
#include <iostream>

std::atomic<bool> 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::thread t1(produce);
    std::thread 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<bool> 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)) {}
  std::atomic_thread_fence(std::memory_order_acquire);
  std::cout << data << '
';
}

int main () {
  std::thread t1(produce);
  std::thread 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)
```
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 3.4.11

References
A. Williams. *C++ Concurrency in Action*. Manning Publications, Shelter Island, NY, USA, 2012. 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++. **Excellent**


M. Batty. *Multicore Programming: C++0x*. University of Cambridge, Cambridge, UK, Nov. 2010. 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.


Part 4

Even More C++
Section 4.1

Undefined Behavior and Other Evil Stuff
**undefined behavior**: behavior for which standard imposes no requirements (i.e., anything could happen)

**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

**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)

**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:
  ```cpp
  char* p = nullptr;
  char c = *p;  // undefined behavior
  ```

- attempting to modify a string literal or any other const object (excluding mutable data members):
  ```cpp
  const int x = 0;
  const_cast<int&>(x) = 42;  // undefined behavior
  ```

- signed integer overflow

- evaluating an expression that is not mathematically defined; for example:
  ```cpp
  double z = 0.0;
  double x = 1.0 / z;  // undefined behavior
  ```

- not returning a value from a value-returning function (other than main)
  ```cpp
  int& increment(int& x) {
    ++x;
    // 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:

  ```
  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:

  ```
  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:

  ```
  int i = 1;
  i << 10000; // undefined behavior
  ```

- using an automatic variable whose value has not been initialized; for example:

  ```
  void func () {
      int i; ++i; // undefined behavior
  }
  ```
Examples of Unspecified 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?
}
```
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
- sizeof 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`)
- meaning of `asm` declaration
- for more examples, see “Index of implementation-defined behavior” section in C++11 standard
```cpp
#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_> << '\n';
  std::cout << (w.*saved_private_v<Widget_f_>()) << '\n';
  
...
Section 4.2

Best Practices, Tips, and Common Pitfalls
**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 \texttt{eof}

\begin{itemize}
  \item example of \textit{incorrect} use of \texttt{eof}:
    \begin{verbatim}
#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';
  }
}
\end{verbatim}
  \item code incorrectly assumes that \texttt{eof} will only return true if preceding input operation has failed
  \item 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:
    \begin{verbatim}
    1 EOF encountered
    \end{verbatim}
\end{itemize}
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";
    }
}
```
Use of `std::endl`

- `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 ‘\n’ 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`
Stream Extraction Failure

- for built-in types, if stream extraction fails, value of target for stream extraction depends on reason for failure
- in following example, what is value of \( x \) if stream extraction fails:
  ```cpp
  int x;
  std::cin >> x;
  if (!std::cin) {
      // what is value of \( x \)?
  }
  ```
- in above example, \( x \) 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
- \textit{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("9999999999999999999999999999999999999999");
    x = -1;
    s2 >> x;
    // Overflow; x set to closest machine-representable value.
    assert(s2.fail() && x == std::numeric_limits<int>::max());
}
```
The abs Function

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 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 abs function is declared as `int abs(int)`, the use of this function will introduce a conversion from double to 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';}
```
Types of Literals

- 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.
Consider `istream` or `ostream` object `s`

- `!s` is equivalent to `s.fail()`
- `bool(s)` is not equivalent to `s.good()`
- `s.good()` is not the same as `!s.fail()`
- Do not use `good` as opposite of `fail` since this is wrong
data members are initialized in order in which declared

**Example:**

```cpp
#include <cassert>

class Widget {

public:
    Widget() : y_(42), x_(y_ + 1) { assert(x_ == 43);}
    int x_; 
    int y_; 
};

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

what will above code do when run?

- in constructor, `x_` initialized before `y_`, which results in use of `y_` before its initialization
- strictly speaking, undefined behavior
- in practice, likely `x_` will simply have garbage value when body of constructor executes and assertion will fail
be careful about initialization order of global objects

Example (program with three source files):

```cpp
int main () {
}

#include <vector>
std::vector<int> v = {1, 2, 3, 4};

#include <vector>
extern std::vector<int> v;
std::vector<int> w = {v[0], v[1]};
```

no guarantee that \( v \) will be constructed before \( w \)
bad things will happen if \( w \) is constructed before \( v \)
no guarantee about order of initialization between translation units (i.e., source files [loosely speaking])
implement postfix increment/decrement in terms of prefix increment/decrement

ensures that prefix and postfix versions 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_; 
};
```
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) << '
';
    std::cout << alignof(int) << ' ' <<
               alignof(Widget) << '
';
}
```

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)
- `struct` Thing {
  char c;
  int i;
};

- suppose `sizeof(int)` is 4 and `alignof(int)` is 4

- implementation adds padding to structure so that `int` data member is suitably aligned (i.e., offset is multiple of 4)
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

Example:

```cpp
#include <cassert>

int main () {
  assert (5 % 3 == 2);
  assert (5 % (-3) == 2);
  assert ((-5) % 3 == -2);
  assert ((-5) % (-3) == -2);
}
```
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();
```
Classes Holding Multiple Resources

What is wrong with this code?

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 \texttt{new} Y throws, x_ will be leaked.

Fix:

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";
}
```
What is wrong with the following code?

```cpp
std::vector<int> getVector() {
    std::vector<int> v;
    // calculate v
    return std::move(v);
}
```

Due to the use of `std::move`, the type of the expression in the return statement does not match the function return type (i.e., `std::vector<int>` versus `std::vector<int>&&`).

RVO/NRVO can only be applied if the type of the expression in the return statement matches the function return type.

So, **RVO/NRVO cannot be applied** in this case.

If the types **would not have matched** anyways (e.g., a two-element `std::tuple` and a `std::pair`), `std::move` would be reasonable to employ.
Avoid Returning an Rvalue Reference to an Rvalue Reference Parameter

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:
    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).
```
Never provide explicit template arguments to `std::make_pair`.

Let \( x \) and \( y \) be objects of type \( X \) and \( Y \), respectively.

What is wrong with the following code?

```cpp
std::make_pair<X, Y>(x, y)
```

`make_pair` declared as:

```cpp
template <class T1, class T2>
    pair<V1, V2> make_pair(T1&& x, T2&& y);
```

where \( V1 \) and \( V2 \) are (except in special case) `std::decay_t<T1>` and `std::decay_t<T2>`, respectively

If, for example, \( X \) and \( Y \) are `int`, then `make_pair` has two rvalue reference parameters which cannot bind to the lvalues \( x \) and \( y \).

Use `make_pair(x, y)` or sometimes `pair<X, Y>(x, y)`. 
When creating `std::shared_ptr` objects, prefer to use `std::make_shared` (as opposed to explicit use of `new` with `shared_ptr`)

- more efficient
- control block and owned object can be allocated together
- one memory allocation instead of two; better cache efficiency
- better exception safety (avoid resource leaks)
#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
Section 4.3

Idioms
proxy class provides modified interface to another class
```cpp
#include <iostream>
#include <utility>

class BoolVector;

class Proxy {
public:
    ~Proxy() = default;
    Proxy& operator=(const Proxy&) = default;
    operator bool() const;
    void operator=(bool b);
private:
    friend class BoolVector;
    Proxy(const Proxy&) = default;
    Proxy(BoolVector* v, int i) : v_(v), i_(i) {}
    BoolVector* v_; 
    int i_; 
};

class BoolVector {
public:
    BoolVector(int n) : n_(n), d_(new unsigned char[(n + 7) / 8]) {
        std::fill_n(d_, (n + 7) / 8, 0);
    }
    ~BoolVector() {delete [] d_;}
    int size() const { return n_;}
    bool operator[](int i) const { return getElem(i);}
    Proxy operator[](int i) { return Proxy(this, i); }
private:
    friend class Proxy;
    bool getElem(int i) const { return (d_[i / 8] >> (i % 8)) & 1; }
    void setElem(int i, bool b) {
        (d_[i / 8] &= ~(1 << (i % 8))) |= (b << (i % 8));
    }
    int n_; 
    unsigned char* d_; 
};

inline void Proxy::operator=(bool b) { v_->setElem(i_, b);}
inline Proxy::operator bool() const { return v_->getElem(i_);}
```
```
#include "proxy_class_example_1.hpp"

int main() {
    BoolVector v(16);
    for (int i = 0; i < v.size(); ++i) {
        v[i] = (i & 1);
    }
    for (int i = 0; i < v.size(); ++i) {
        std::cout << v[i];
    }
    std::cout << '\n';

    const BoolVector& cv = v;
    for (int i = 0; i < cv.size(); ++i) {
        std::cout << cv[i];
    }
    std::cout << '\n';
}
```
Section 4.4

C Compatibility
Although C++ attempted to maintain compatibility with C where possible, there are numerous incompatibilities between the languages. Unfortunately, as C++ and C continue to evolve, the number of incompatibilities between these languages continue 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++. A few examples of incompatibilities between C++ and C are given in what follows.
C++ introduces many new keywords.

Some C programs might use some of these keywords as identifiers (e.g., `new`, `delete`).
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.
C provides an implicit conversion from `void*` to any pointer type, while C++ does not.
C and C++ both allow nested `struct` types, but the scoping rules differ.
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 are later adopted by C++ standard
web site: http://www.boost.org
## Some Boost Libraries

### 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 <code>int</code> to <code>std::string</code> 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>
</tbody>
</table>
Section 5.1.2

Examples
#include <iostream>
#include <boost/math/constants/constants.hpp>

template <class Real>
Real area_of_circle(Real r) {
    namespace bmc = boost::math::constants;
    return bmc::pi<Real>() * r * r;
}

int main() {
    double r;
    while (std::cin >> r) {
        std::cout << area_of_circle(r) << '
';
    }
}
```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
062351700858796178922222789623703897374720000000000000000
000000000000000000000000000000000000000
*/
```
#include <iostream>
#include <cmath>
#include <boost/multiprecision/gmp.hpp>

using boost::multiprecision::mpf_float;

mpf_float pi(const mpf_float & tolerance) {
    static const mpf_float one(1), two(2), four(4);
    mpf_float result(four);
    mpf_float i(1);
    bool minus(true);
    mpf_float term;
    do {
        term = four / (two * i + one);
        if (minus) {
            result -= term;
        } else {
            result += term;
        }
        minus = !minus;
        ++i;
    } while (abs(term) > tolerance);
    return result;
}

int main() {
    std::cout << std::setprecision(16) << pi(1e-7) << '\n';
}
Section 5.1.3

References


Section 5.2

Computational Geometry Algorithms Library (CGAL)
For information on the CGAL library, refer to the textbook and lecture slides available from the following web site:

http://www.ece.uvic.ca/~mdadams/waveletbook
Section 5.3

Open Graphics Library (OpenGL)
For information on the OpenGL library, refer to the textbook and lecture slides available from the following web site:

http://www.ece.uvic.ca/~mdadams/waveletbook
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
const int maxTableSize = 100;
std::vector<TableEntry> table(maxTableSize);
```
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 is more than 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.

Avoid the use of *global objects*. For example, use static data members instead of global objects. In well designed code, global objects are rarely needed.

Ensure that the code is *const correct*.

If an object does not need to change, make it const. This improves the readability of code. This also helps to ensure const correctness of code.

Avoid bringing many unknown identifiers into scope. For example, avoid constructs like:

```cpp
using namespace std;
```

Only bring identifiers into scope if you need them.
Do not rely on *undefined/unspecified/implementation-defined behavior*. Do not rely on any behavior that is not promised by the language. Do not rely on undocumented features of libraries. That is, do not write code in a way that it may only work on certain computing platforms or when the moon is full.

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, terminate program immediately in order to help in localizing bug (e.g., by 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 != 0);
    // 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

Finite-Precision Arithmetic
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";
    }
}
```
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 representation: radix point remains fixed at same position in number

if radix point fixed to right of least significant digit position, integer format results

\[
\text{Integer Format } a_{n-1} a_{n-2} \cdots a_1 a_0
\]

if radix point fixed to left of most significant digit position, purely fractional format results

\[
\text{Fractional Format } a_{n-1} a_{n-2} \cdots a_1 a_0
\]

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 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

\[ (-1)^s 2^E (b_0 \cdot b_1 b_2 \cdots b_{p-1}) \]

where \( s \in \{0, 1\} \), \( E \) is integer satisfying \( E_{\min} \leq E \leq E_{\max} \), 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, $f = .b_1b_2\cdots b_{p-1}$
- 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 the same way as integers, allowing integer comparison to compare floating-point numbers
IEEE 754 Basic Formats (Continued)

- **single format:**

  
  
<table>
<thead>
<tr>
<th>1</th>
<th>8</th>
<th>23</th>
</tr>
</thead>
<tbody>
<tr>
<td>s</td>
<td>e</td>
<td>f</td>
</tr>
</tbody>
</table>

  MSB  | LSB | MSB  | LSB

- **double format:**

  
  
<table>
<thead>
<tr>
<th>1</th>
<th>11</th>
<th>52</th>
</tr>
</thead>
<tbody>
<tr>
<td>s</td>
<td>e</td>
<td>f</td>
</tr>
</tbody>
</table>

  MSB  | LSB | MSB  | LSB

- **summary of encodings:**

<table>
<thead>
<tr>
<th>Case</th>
<th>Exponent</th>
<th>Fraction</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>$E_{\text{min}} \leq E \leq E_{\text{max}}$</td>
<td>$f \neq 0$</td>
<td>$(-1)^s 2^E (1 + f)$</td>
</tr>
<tr>
<td>Denormal</td>
<td>$E = E_{\text{min}} - 1$</td>
<td>$f = 0$</td>
<td>$(-1)^s 2^{E_{\text{min}}} f$</td>
</tr>
<tr>
<td>Zero</td>
<td>$E = E_{\text{min}} - 1$</td>
<td>$f = 0$</td>
<td>$(-1)^s 0$</td>
</tr>
<tr>
<td>Infinity</td>
<td>$E = E_{\text{max}} + 1$</td>
<td>$f \neq 0$</td>
<td>$(-1)^s \infty$</td>
</tr>
<tr>
<td>NaN</td>
<td>$E = E_{\text{max}} + 1$</td>
<td>$f \neq 0$</td>
<td>NaN</td>
</tr>
</tbody>
</table>
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:

$$
\begin{array}{ccc}
  s & e & f \\
  0 & 10000001 & 01010000000000000000000000000000
\end{array}
$$

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, $s = 1$, $e = 3_{10} + 1023_{10} = 1026_{10} = 1000000010_2$, and $f = 001001000 \cdots 0$, resulting in the word:

$$
\begin{array}{ccc}
  s & e & f \\
  1 & 1000000010 & 0010010000000000000000000000000000000000
\end{array}
$$
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.
1. D. Goldberg. *What every computer scientist should know about floating-point arithmetic.*


2. IEEE Std. 754-1985 — IEEE standard for binary floating-point arithmetic, 1985

Section 6.3

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
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: 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:

```bash
sort [-r] [-k $n] [-n]
```

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>-k $n</code></td>
<td>Sort using $n$th field in record; if not specified, $n$ defaults to 1.</td>
</tr>
<tr>
<td><code>-n</code></td>
<td>Treat key as real number (instead of string) for sorting purposes; if not specified, key treated as string.</td>
</tr>
<tr>
<td><code>-r</code></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
Software Design Description (SDD)

- 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
Requirements/Design Document for Degree Project

- 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
References


Part 7

Debugging Tools
Section 7.1

Debugging Tools
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 \textit{arglist} if specified).
print \textit{expr}
    Display the value of the expression \textit{expr}.
bt
    Display a stack backtrace.
list
    Type the source code lines in the vicinity of where the program is currently stopped.
break \textit{function}

Set a breakpoint at the function \textit{function}.

\texttt{watch expr}

Set a watchpoint for the expression \texttt{expr}.

\texttt{c}

Continue running the program (e.g., after stopping at a breakpoint).

\texttt{next}

Execute the next program line, stepping over any function calls in the line.

\texttt{step}

Execute the next program line, stepping into any function calls in the line.
GNU Data Display Debugger (DDD)

- 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
- `ddd` command
Valgrind

- can detect many memory management and threading bugs
- can profile programs in detail
- **home page**: http://www.valgrind.org
- `valgrind` command
- `valkyrie` command (GUI for Memcheck and Helgrind tools in Valgrind)
Section 7.1.1

References


Section 8.1

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 8.2

Make
Make

- **make command**
- controls generation of executables and/or other non-source files from program’s source files
- 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](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:
  ```bash
  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`
• 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 following form:

\[\text{targets} : \text{prerequisites} \\
\quad \text{commands} \\
\quad \ldots\]

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>
# The C++ compiler command.
CXX = g++
# The C++ compiler options.
CXXFLAGS = -g -O
# The linker options (if any).
LDFLAGS =

# 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 *.o

# 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 8.3

CMake
CMake is open-source cross-platform family of tools designed to build, test, and package software. It controls software build process (e.g., compiling and linking) using simple platform- and compiler-independent configuration files. These files are used in conjunction with native build environments. It generates files appropriate for whatever build environment is being used. It supports native build environments such as Unix Make, Apple Xcode, and Microsoft Visual Studio. It automatically generates dependency information for source files and supports parallel builds. CMake was created by Kitware (http://www.kitware.com) and its website is 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 targetting 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 accidently 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.
To generate build files for a native build tool, use a command of the form:

```
cmake [options] [$source_directory]
```

The binary directory is assumed to be the current directory.

The source directory `$source_dir` defaults to the current directory (resulting in an in-source build).

Some options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-D <code>var=val</code></td>
<td>Set the CMake variable <code>var</code> to value <code>val</code>.</td>
</tr>
<tr>
<td>-G <code>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_12_2013</td>
<td>project files for Microsoft Visual Studio 12</td>
</tr>
</tbody>
</table>

The makefile generator produces a top-level makefile with standard targets (e.g., all, clean, and install) as well as targets corresponding to each CMake target in the project.

Some environment variables used by \texttt{cmake} include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>The command for compiling C source.</td>
</tr>
<tr>
<td>CXX</td>
<td>The command for compiling C++ source.</td>
</tr>
</tbody>
</table>

Although undocumented (and \textit{not officially supported}), the source and binary directories can both be specified on the command line by using the options \texttt{"-Hsource\_dir"} and \texttt{"-Bbinary\_dir"}. (There cannot be a space between the option letter and its corresponding argument.)
To invoke the native build tool in a platform-independent manner for the build files in the binary directory `$binary_directory`, use a command of the form:

```
cmake --build $binary_directory [ $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>--</code></td>
<td>Pass the remaining options to the native build tool.</td>
</tr>
</tbody>
</table>
Hello World Example

- **source directory** `$SOURCE_DIR` contains two files:
  - CMakeLists.txt
  - hello.cpp

- **commands to build with binary directory** `$BINARY_DIR`:
  ```
cd $BINARY_DIR
cmake $SOURCE_DIR
cmake --build .
```

$SOURCE_DIR/hello.cpp

```cpp
#include <iostream>

int main() {std::cout << "Hello, World!\n";}
```

$SOURCE_DIR/CMakeLists.txt

```make
# 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)
```
Section 8.3.1

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, the 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>
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")
- 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
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).
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 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.)
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:

- **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`. 

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- **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**
  - [Link](https://cmake.org/cmake/help/v3.7/module/FindBoost.html)
  - `Boost_FOUND`, `Boost_INCLUDE_DIRS`, `Boost_LIBRARY_DIRS`, `Boost_LIBRARIES`

- **CGAL (Computational Geometry Algorithms Library)**
  - `CGAL_INCLUDE_DIRS`, `CGAL_LIBRARY`, `GMP_LIBRARIES`

- **Doxygen**
  - [Link](https://cmake.org/cmake/help/v3.7/module/FindDoxygen.html)
  - `DOXYGEN_FOUND`, `DOXYGEN_EXECUTABLE`

- **GLEW (OpenGL Extension Wrangler Library)**
  - [Link](https://cmake.org/cmake/help/v3.7/module/FindGLEW.html)
  - `GLEW_FOUND`, `GLEW_INCLUDE_DIRS`, `GLEW_LIBRARIES`

- **GLFW (OpenGL Helper Library) [pkg-config module]**
  - `GLFW_FOUND`, `GLFW_INCLUDE_DIRS`, `GLFW_LIBRARIES`
Some Find and Pkg-Config Modules (Continued 1)

- **GLUT (OpenGL Utility Toolkit)**
  - [https://cmake.org/cmake/help/v3.7/module/FindGLUT.html](https://cmake.org/cmake/help/v3.7/module/FindGLUT.html)
  - GLUT_FOUND, GLUT_INCLUDE_DIR, GLUT_LIBRARIES

- **OpenGL (Open Graphics Library)**
  - [https://cmake.org/cmake/help/v3.7/module/FindOpenGL.html](https://cmake.org/cmake/help/v3.7/module/FindOpenGL.html)
  - OPENGL_FOUND, OPENGL_INCLUDE_DIR, OPENGL_LIBRARIES

- **SPL (Signal/Geometry Processing Library)**
  - SPL_FOUND, SPL_INCLUDE_DIRS, SPL_LIBRARY_DIRS, SPL_LIBRARIES

- **Threads**
  - [https://cmake.org/cmake/help/v3.7/module/FindThreads.html](https://cmake.org/cmake/help/v3.7/module/FindThreads.html)
  - CMAKE_THREAD_LIBS_INIT
Section 8.3.2

Examples
Hello World Example Revisited

hello.cpp

```cpp
#include <iostream>

int main() {std::cout << "Hello, World!";}
```

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)
```
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
```
# Specify minimum required version of CMake.
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_SOURCE_DIR}/run_test)
```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";
}
```
Boost Log Example: CMakeLists File

CMakeLists.txt

```cmake
1  cmake_minimum_required (VERSION 3.1 FATAL_ERROR)
2  project(boost_example LANGUAGES CXX C)
3
4  # Find the required libraries (i.e., POSIX threads and
5  # Boost).
6  set(Boost_USE_MULTITHREADED ON)
7  find_package(Threads REQUIRED)
8  find_package(Boost 1.54.0 REQUIRED COMPONENTS log)
9
10  # Set the includes, defines, and libraries.
11  include_directories(${Boost_INCLUDE_DIRS})
12  add_definitions("-DBOOST_LOG_DYN_LINK")
13  link_libraries(${Boost_LIBRARIES} ${CMAKE_THREAD_LIBS_INIT})
14
15  # Define program target.
16  add_executable(my_app main.cpp)
```

Note: Specifies includes, defines, and libraries for all programs.
CMakeLists.txt

```cmake
# Find the required libraries (i.e., POSIX threads and # Boost).
set(Boost_USE_MULTITHREADED ON)
find_package(Threads REQUIRED)
find_package(Boost 1.54.0 REQUIRED COMPONENTS log)

# Define program target.
add_executable(my_app main.cpp)

# Set the includes, defines, and libraries for the # my_app target.
target_include_directories(my_app PUBLIC
  ${Boost_INCLUDE_DIRS})
target_compile_definitions(my_app PUBLIC
  "-DBOOST_LOG_DYN_LINK")
target_link_libraries(my_app ${Boost_LIBRARIES})
target_link_libraries(my_app ${CMAKE_THREAD_LIBS_INIT})
```

Note: Specifies includes, defines, and libraries for specific program.
trivial.cpp

1  #include <cstdlib>
2  #include <GLFW/glfw3.h>

3  void display(GLFWwindow* window) {
4      glfwMakeContextCurrent(window);
5      glClearColor(0.0, 1.0, 1.0, 0.0);
6      glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);
7      glfwSwapBuffers(window);
8  }

9  int main(int argc, char** argv) {
10     if (!glfwInit()) { return EXIT_FAILURE; }
11     glfwSwapInterval(1);
12     GLFWwindow* window = glfwCreateWindow(512, 512, argv[0],
13               nullptr, nullptr);
14     if (!window) {
15         glfwTerminate();
16         return EXIT_FAILURE;
17     }
18     glfwSetWindowRefreshCallback(window, display);
19     while (!glfwWindowShouldClose(window))
20         {glfwWaitEvents();}
21     glfwTerminate();
22     return EXIT_SUCCESS;
23  }
CMakeLists.txt

1. cmake_minimum_required (VERSION 3.1 FATAL_ERROR)
2. project (opengl_example LANGUAGES CXX C)
3. set (CMAKE_CXX_STANDARD 11)
4. set (CMAKE_CXX_STANDARD_REQUIRED TRUE)

# Find the required libraries (i.e., OpenGL, GLEW, and # GLFW).
find_package (OpenGL REQUIRED)
find_package (GLEW REQUIRED)
find_package (PkgConfig REQUIRED)
pkg_search_module (GLFW REQUIRED glfw3)

# Set include directories and libraries.
include_directories (${ GLFW_INCLUDE_DIRS } ${ GLEW_INCLUDE_DIRS } ${ OPENGL_INCLUDE_DIR })
link_libraries (${ GLFW_LIBRARIES } ${ GLEW_LIBRARIES } ${ OPENGL_LIBRARIES })

# Define program target.
add_executable (trivial trivial.cpp)
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 ();
}
```
cmake_minimum_required (VERSION 3.1 FATAL_ERROR)
project (opengl_example LANGUAGES CXX C)

# Find the required libraries (i.e., OpenGL and GLUT).
find_package (OpenGL REQUIRED)
find_package (GLUT REQUIRED)

# Hack needed for some systems.
if (NOT GLUT_Xmu_LIBRARY OR NOT GLUT_Xmi_LIBRARY)
  if (NOT GLUT_Xmu_LIBRARY)
    set (GLUT_Xmu_LIBRARY"
  endif ()
  if (NOT GLUT_Xmi_LIBRARY)
    set (GLUT_Xmi_LIBRARY"
  endif ()
  set (GLUT_LIBRARIES "${GLUT_glut_LIBRARY}"
endif()

# Set include directories and libraries.
include_directories (${GLUT_INCLUDE_DIR}
  ${OPENGL_INCLUDE_DIR})
link_libraries (${GLUT_LIBRARIES} ${OPENGL_LIBRARIES})

# Define program target.
add_executable (trivial trivial .cpp)
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)

# Specify directories for header files.
includedirectories(${ CGAL_INCLUDE_DIRS})

# Specify libraries for linking.
link_libraries(${CGAL_LIBRARY} ${GMP_LIBRARIES})

# Add a program target called orient_test.
add_executable(orient_test orient_test.cpp)
want to be able to build and install HG2G library and application that uses library

project has:

- one library target \texttt{hg2g}
- one executable target \texttt{answer}
- one option \texttt{HG2G\_ZAPHOD} (which takes a boolean value)

files in project:

\begin{verbatim}
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
\end{verbatim}
HG2G Example: Library Source Code

hg2g/include/hg2g/config.hpp.in

```cpp
# ifndef HG2G_CONFIG_H
# define HG2G_CONFIG_H
# define HG2G_VERSION " @HG2G_VERSION@ "
# cmake define HG2G_ZAPHOD
# endif
```

hg2g/include/hg2g/answer.hpp

```cpp
#include <string>
namespace hg2g {
std::string answer_to_ultimate_question();
std::string ultimate_question();
}
```

hg2g/answer.cpp

```cpp
#include "hg2g/answer.hpp"
namespace hg2g {
std::string answer_to_ultimate_question() {return "42";}
}
```

hg2g/question.cpp

```cpp
#include "hg2g/answer.hpp"
namespace hg2g {
std::string ultimate_question() {throw 42;}
}
```
#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";
}

# HG2G Example: CMakeLists Files

## CMakeLists.txt

```cmake
cmake_minimum_required (VERSION 3.1 FATAL_ERROR)
project(hg2g_example LANGUAGES CXX)
option(HG2G_ZAPHOD "Define HG2G_ZAPHOD" FALSE)

# Set the version number and name.
set(HG2G_VERSION_MAJOR 1)
set(HG2G_VERSION_MINOR 42)
set(HG2G_VERSION_PATCH 0)
string(CONCAT HG2G_VERSION "${HG2G_VERSION_MAJOR}" 
"."${HG2G_VERSION_MINOR}" ".${HG2G_VERSION_PATCH}")

# Process the subdirectories hg2g and app.
add_subdirectory(hg2g)
add_subdirectory(app)
```

## app/CMakeLists.txt

```cmake
# Add a program target called answer.
add_executable(answer answer.cpp)

# Link the program against hg2g library.
target_link_libraries(answer hg2g)

# Install the program in bin directory.
install(TARGETS answer DESTINATION bin)
```
hg2g/CMakeLists.txt

1 # Place the names of the header and source files into
2 # variables (for convenience).
3 set(hg2g_headers include/hg2g/answer.hpp
4        "${CMAKE_CURRENT_BINARY_DIR}/include/hg2g/config.hpp")
5 set(hg2g_sources answer.cpp question.cpp)
6
7 # Add a library target called hg2g.
8 add_library(hg2g ${hg2g_sources} ${hg2g_headers})
9
10 # Specify the include directories for library.
11 target_include_directories(hg2g PUBLIC
12     include
13     "${CMAKE_CURRENT_BINARY_DIR}/include")
14
15 # Create a header file containing the config information.
16 configure_file(
17     include/hg2g/config.hpp.in
18     "${CMAKE_CURRENT_BINARY_DIR}/include/hg2g/config.hpp")
19
20 # Install the library in the lib directory.
21 install(TARGETS hg2g DESTINATION lib)
22
23 # Install the header files in the include/hg2g directory.
24 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 NONE)
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()
```
\documentclass{article}
\usepackage{graphicx}
\author{John Doe}
\title{Why I Like C++}
\begin{document}
\maketitle
\section{Why I Like C++}
What can I say?
C++\cite{TCPL 4} is a great language!
\begin{figure}[h]
\centering
\includegraphics[width=1in, height=1in, keepaspectratio]{cpp.png}
\end{figure}
\bibliographystyle{plain}
\bibliography{bib}
\end{document}

@book{
TCPL4,
author = "B. Stroustrup",
title = "The \{C++\} Programming Language",
edition = "4th",
publisher = "Addison Wesley",
year = 2013
}
```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.
Section 8.3.3

References
References

3. CMake FAQ, https://cmake.org/Wiki/CMake_FAQ.
7. UseLATEX GitHub Site https://github.com/kmorel/UseLATEX
Part 9

Version Control Systems
Section 9.1

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
Distributed Version Control

- each user has their own local copy of repository
- examples: Git and Mercurial
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 9.2

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 the 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 and can efficiently handle large numbers of parallel branches. Revision history of file modelled as directed acyclic graph (DAG). Official website: 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)
The revision history can be viewed as a directed acyclic graph (DAG).

Each node in the graph corresponds to a snapshot of the directory tree under version control.

Each edge points to the immediately preceding snapshot.

Example of DAG:

- $C_1$ based on changing content from $C_0$;
- $C_2$ based on changing content from $C_1$;
- $C_6$ based on *merging* content from $C_4$ and $C_5$;
- ...
Branching Workflows

- single (master) branch:

  - master branch: used for releases (highly stable, well tested)

- master, development, and topic branches:

  - development branch: used for development work (possibly unstable)
  - topic branch: used for highly experimental work
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

c 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 branch currently in use in the repository.

Normally (i.e., except in the case of a detached **HEAD**), **HEAD** refers to the current 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:
Remote-Tracking Branches

Consider a remote repository whose commit history is as shown below, with a single branch `master`.

![Diagram of remote repository with commit history C1, C2, C3 and 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`.

![Diagram of local repository with commit history C1, C2, C3, branch master, and 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:

   ![Diagram](image1)

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:

   ![Diagram](image2)
Committing change $A_1$ to the master branch of the local repository transforms the local repository as follows:

Committing change $A_2$ to the master branch of the local repository transforms the local repository as follows:
Another user committing changes $B_1$ and $B_2$ to the remote repository transforms the remote repository as follows:

Fetching (to the local repository) from the remote repository transforms the local repository as follows:
Merging the `origin/master` branch into the `master` branch (in the local repository) transforms the local repository as follows:

Pushing (from the local repository) to the remote repository transforms the remote and local repositories, respectively, as follows:
TOP_DIR = 'pwd'
cd $TOP_DIR
mkdir remote
cd remote
git init
printf "apple\n" >> fruits.txt
git add fruits.txt
git commit -m "Added file fruits.txt" # Commit C1
printf "banana\n" >> fruits.txt
git add fruits.txt
git commit -m "Added banana to fruits.txt" # Commit C2
git init --bare .git
mv .git $TOP_DIR/remote.git
cd $TOP_DIR
rm -rf remote
cd $TOP_DIR

# Commit A1
1. git clone remote.git local-1
2. cd $TOP_DIR/local-1
3. printf "grape\n" >> fruits.txt
4. git add fruits.txt
5. git commit -m "Added grape to fruits.txt" # Commit A1

# Commit A2
6. printf "orange\n" >> fruits.txt
7. git add fruits.txt
8. git commit -m "Added orange to fruits.txt" # Commit A2

# Commit B1
9. cd $TOP_DIR
10. git clone remote.git local-2
11. cd local-2
12. printf "red\n" >> colors.txt
13. git add colors.txt
14. git commit -m "Added file colors.txt" # Commit B1

# Commit B2
15. printf "green\n" >> colors.txt
16. git add colors.txt
17. git commit -m "Added green to colors.txt" # Commit B2
18. git push

# Commit A3
19. cd $TOP_DIR/local-1
20. git push # ERROR: local repository not up to date
21. git fetch
22. git merge -m "Merged changes." # Commit A3
23. 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.
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 9.2.1

Basic Commands
To query the version of the Git software, type:

```
git --version
```

As of 2016-08-12, the most recent version of Git is 2.9.3.
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><code>-a</code></td>
<td>list all commands for which help available</td>
</tr>
<tr>
<td><code>-g</code></td>
<td>list all available help guides</td>
</tr>
<tr>
<td><code>-w</code></td>
<td>display in HTML format using a web browser</td>
</tr>
<tr>
<td><code>-m</code></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
  ```
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>--system</td>
<td>consider only the system-wide settings</td>
</tr>
<tr>
<td>--global</td>
<td>consider only the global (i.e., per-user) settings</td>
</tr>
<tr>
<td>--local</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><code>core.askPass</code></td>
<td>program for entering user name and password credentials</td>
</tr>
<tr>
<td><code>core.editor</code></td>
<td>program for editing</td>
</tr>
<tr>
<td><code>core.pager</code></td>
<td>program for paging output</td>
</tr>
<tr>
<td><code>credential.helper</code></td>
<td>external program to be called when a user name or password credential is needed</td>
</tr>
<tr>
<td><code>user.name</code></td>
<td>user’s full name</td>
</tr>
<tr>
<td><code>user.email</code></td>
<td>user’s email address</td>
</tr>
<tr>
<td><code>web.browser</code></td>
<td>program for browsing web</td>
</tr>
</tbody>
</table>
To globally set the user name to “John Doe”, type:
```bash
git config --global user.name "John Doe"
```

To globally set the email address to “jdoe@gmail.com”, type:
```bash
git config --global user.email jdoe@gmail.com
```

To list all system, global, and local variables, type:
```bash
git config -l
```

To list only the global variables, type:
```bash
git config --global -l
```

To list only the local (i.e., per-repository) variables for the current repository, type:
```bash
git config --local -l
```
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
```
Creating an Empty Repository

To create an empty repository, use a command of the form:

```bash
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:

```bash
git init hello
```
To clone a repository \$repository, use a command of the form:
\[\text{git clone [options] } \$repository \ [\$directory]\]

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 \url{https://github.com/uvic-aurora/hello-world.git} to the directory hello-world, type:
\[
\text{git clone } \backslash \\
\url{https://github.com/uvic-aurora/hello-world.git} \backslash \\
\text{hello-world}
\]
To add the files/directories $\text{path} \ldots$ to the index (i.e., mark for committing later), use a command of the form::

\[
git \ add \ \text{path}\ldots
\]

The contents of $\text{path} \ldots$ \textit{at the time that the git add 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 \texttt{README} and \texttt{LICENSE} to the index, type:

\[
git \ add \ \text{README} \ \text{LICENSE}
\]

To add the directory \texttt{src} (and everything contained under it) to the index, type:

\[
git \ add \ \text{src}
\]
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
```
Renaming Files

- To move the file/directory $source to $destination, use a command of the form:
  
  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:
  
  git mv [options] $s_1 $s_2 ... $s_n \ $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:
  
  git mv README README.old

- To move the files hello.cpp and goodbye.cpp to the directory src, type:
  
  git mv hello.cpp goodbye.cpp src
To remove the files/directories $\textit{path}$... from the working tree and the index, use a command of the form:

\[
\text{git rm [options] } \textit{path}...
\]

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 $\textit{src}$ and all files and directories beneath it from the working tree and index, type:

\[
\text{git rm -r src}
\]

To remove the files $\textit{README}$ and $\textit{LICENSE}$ from the working tree and index, type:

\[
\text{git rm \textit{README LICENSE}}
\]
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:

```bash
git [options] status
```

Some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>--long</code></td>
<td>give the output in long format (default)</td>
</tr>
<tr>
<td><code>--short</code></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:

```bash
git status
```
To show the commit history of the files/directories $path...$, use a command of the form:

```
git log [options] [$path...]```

If $path...$ is not specified, it defaults to all files and directories.

Some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>--since $date</code></td>
<td>select commits more recent than date $date</td>
</tr>
<tr>
<td><code>--until $date</code></td>
<td>select commits older than date $date</td>
</tr>
<tr>
<td><code>-n $n</code></td>
<td>select last $n$ commits</td>
</tr>
<tr>
<td><code>-S $pattern</code></td>
<td>select commits adding/removing string matching pattern $pattern</td>
</tr>
<tr>
<td><code>--graph</code></td>
<td>draw text-based graph of commit history</td>
</tr>
<tr>
<td><code>--all</code></td>
<td>consider all branches/remotes/tags</td>
</tr>
<tr>
<td><code>--grep $pattern</code></td>
<td>select only commits with message matching $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
```
Showing Changes

- 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
```
To find all lines of text in the files $\text{path\ldots}$ (which defaults to all files) in the working tree that satisfy the condition specified by the $\text{p\_options}$, use a command of the form:

```
git grep [options] [p\_options] -- [$\text{path\ldots}$]
```

Some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-l</td>
<td>print only names of files with matches</td>
</tr>
<tr>
<td>-i</td>
<td>ignore case</td>
</tr>
<tr>
<td>--max-depth $\text{depth}$</td>
<td>descend at most $\text{depth}$ levels of directories</td>
</tr>
<tr>
<td>-v</td>
<td>select non-matching lines</td>
</tr>
<tr>
<td>-F</td>
<td>patterns are fixed strings</td>
</tr>
<tr>
<td>-E</td>
<td>patterns are extended POSIX regular expressions</td>
</tr>
<tr>
<td>-e $\text{pattern}$</td>
<td>specify pattern $\text{pattern}$</td>
</tr>
<tr>
<td>--and</td>
<td>logical and</td>
</tr>
<tr>
<td>--or</td>
<td>logical or</td>
</tr>
<tr>
<td>--not</td>
<td>logical not</td>
</tr>
<tr>
<td>(</td>
<td>for grouping logical operations</td>
</tr>
<tr>
<td>)</td>
<td>for grouping logical operations</td>
</tr>
<tr>
<td>--cache</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:

```
git grep -i -e hello
```

To print only the names of the files that match the pattern specified in the preceding example, type:

```
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:

```
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:

```
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:

```
    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 .gitignore files)</td>
</tr>
</tbody>
</table>

To remove all untracked files and directories in the working tree excluding those ignored by Git, type:

```
    git clean -d -f
```

To remove all untracked files and directories in the working tree including those ignored by Git, type:

```
    git clean -d -f -x
```
.gitignore Files

- 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:

```bash
# 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:

```
# 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 9.2.2

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 $remote
```
To fetch changes from the remote `$remote` (which normally defaults to `origin`), use a command of the form:

```bash
git fetch [$remote]
```

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.
To push changes to the branch \texttt{$branch$} (which normally defaults to the current branch) of the remote \texttt{$remote$} (which normally defaults to \texttt{origin}), use a command of the form:

\begin{verbatim}
git push [options] [$remote$ [$branch$]]
\end{verbatim}

When pushing a new local branch to a remote, the \texttt{-u} option should be specified.

To delete the branch \texttt{$branch$} on the remote \texttt{$remote$} only, use a command of the form:

\begin{verbatim}
git push origin --delete $branch
\end{verbatim}

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 \texttt{$tag$} on the remote \texttt{$remote$} only, use a command of the form:

\begin{verbatim}
git push origin --delete $tag
\end{verbatim}

To push to the default remote and branch, type:

\begin{verbatim}
git push
\end{verbatim}
To pull changes from the branch `$branch` of the remote `$remote`, use a command of the form:

```
    git pull [ $remote [ $branch ] ]
```

To pull from the default remote and branch, type:

```
    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:

```
git merge [$branch]
```

To merge from the default branch, type:

```
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 9.2.3

Branch-Related Commands
To list all of the branches, use a command of the form:
```bash
git branch [options]
```

To create a branch `$branch`, use a command of the form:
```bash
git branch [options] $branch
```

To delete the (local) branch `$branch`, use a command of the form:
```bash
git branch [options] -d $branch
```

Some commonly-used options include:

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>-a</code></td>
<td>list both remote and local branches</td>
</tr>
<tr>
<td><code>-r</code></td>
<td>list or delete remote branches</td>
</tr>
<tr>
<td><code>-v</code></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 $branch, use a command of the form:

```
  git checkout $branch
```

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 9.2.4

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 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 to the remote $remote, use a command of the form:

```
git push $remote $tag
```

To push the tag v1.0 to the remote origin, type:

```
git push origin v1.0
```
Section 9.2.5

Miscellany
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 in particular commit does not delete that file from repository, since file will still exist in other commits.


Section 9.2.6

References
This web site has many excellent resources related to Git, including:

   This web page has the Git software for various platforms, including Linux, Mac OS X, and Windows.

   This online book can also be downloaded in several formats (including PDF).

   This web page has several short videos on various aspects of Git.

This web page has a list of many excellent resources for learning both Git and GitHub.

This online Git tutorial allows the user to try Git in their web browser.
Linus Torvalds, Google Tech Talk: Linus Torvalds on git — Git: Source code control the way it was meant to be!, May 2007. Available online at https://youtu.be/4XpnKHJAok8. Linus Torvalds shares his thoughts on Git, the source control management system he created.


Scott Chacon, Introduction to Git with Scott Chacon of GitHub, June 2011. Available online at https://youtu.be/ZDR433b0HJY. This is another popular introduction to using Git.

Matthew McCullough, Advanced Git: Graphs, Hashes, and Compression, Oh My!, Sept. 2012. Available online at https://youtu.be/ig5E8CcdM9g. This is a very good more advanced talk on Git.
Part 10

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.

Any information on C++ (e.g., books, tutorials, videos, seminars) from the following individuals (who are held in very high regard by the C++ community) is highly recommended:

- Bjarne Stroustrup (the creator of C++)
- Scott Meyers
- Herb Sutter (Convener of ISO C++ standards committee for over 10 years)
- Andrei Alexandrescu
- Stephan Lavavej
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 document provides a very detailed set of guidelines for writing good C++ code.

S. Meyers. *Effective Modern C++: 42 Specific Ways to Improve Your Use of C++11 and C++14.*

This book covers a list of 42 topics on how to better utilize the C++ language.

S. Meyers. *Effective C++: 50 Specific Ways to Improve Your Programs and Designs.*

This book covers a list of 50 topics on how to better utilize the C++ language.
S. Meyers. *More Effective C++: 35 New Ways to Improve Your Programs and Designs.*
Addison Wesley, Menlo Park, California, 1996.
This book covers a list of 35 topics on how to better utilize the C++ language. It builds on Meyers’ earlier “Effective C++” book.

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.

V. A. Punathambekar. *How to interpret complex C/C++ declarations.*
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.


A. Alexandrescu. *Modern C++ Design.*


The web site for the Boost C++ libraries.

B. Karlsson. *Beyond the C++ Standard Library: An Introduction to Boost.*
An introduction to (some parts of) the Boost library.

M. Kilpelainen. *Overload resolution — selecting the function.*
1. Herb Sutter’s Web Site: http://herbsutter.com
Cplusplus Reddit (C++ questions, answers, and discussion): https://www.reddit.com/r/cppplusplus

ACCU Overload Journal: http://accu.org/index.php/journals/c78/

The C++ Source: http://www.artima.com/cppsource

1. Google Code Jam
   https://code.google.com/codejam/

2. Topcoder
   https://www.topcoder.com/

3. IEEEXtreme 24-Hour Programming Competition
   http://www.ieee.org/xtreme

4. ACM International Collegiate Programming Contest (ICPC)
   http://icpcnews.com/

5. 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 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).