ECE 363
Communication Networks

Introduction

Instructor

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- Course website: https://www.ece.uvic.ca/~agullive/363.html
- Brightspace: https://bright.uvic.ca/d2l/home/429148
- Office hours: Wednesday 11:30-1:30
  – Drop by in the afternoons or make an appointment

Assessment

- 5 Assignments: 25%
  - Posted on website and Brightspace
- 4 Labs: 20%
- Midterm Test: 20% February 26, 2026
- Final Exam: 35%

Labs

- Check UVic timetable for your lab time
- Location: ELW B203 (Note change)
- Lab website: https://www.ece.uvic.ca/~agullive/labs363.html
- Wireshark: https://www.wireshark.org/
- Lab reports due 1 week after the lab
- Every student must submit a report using the template
- Note: Failure to complete all laboratory requirements will result in a grade of N being awarded for the course.

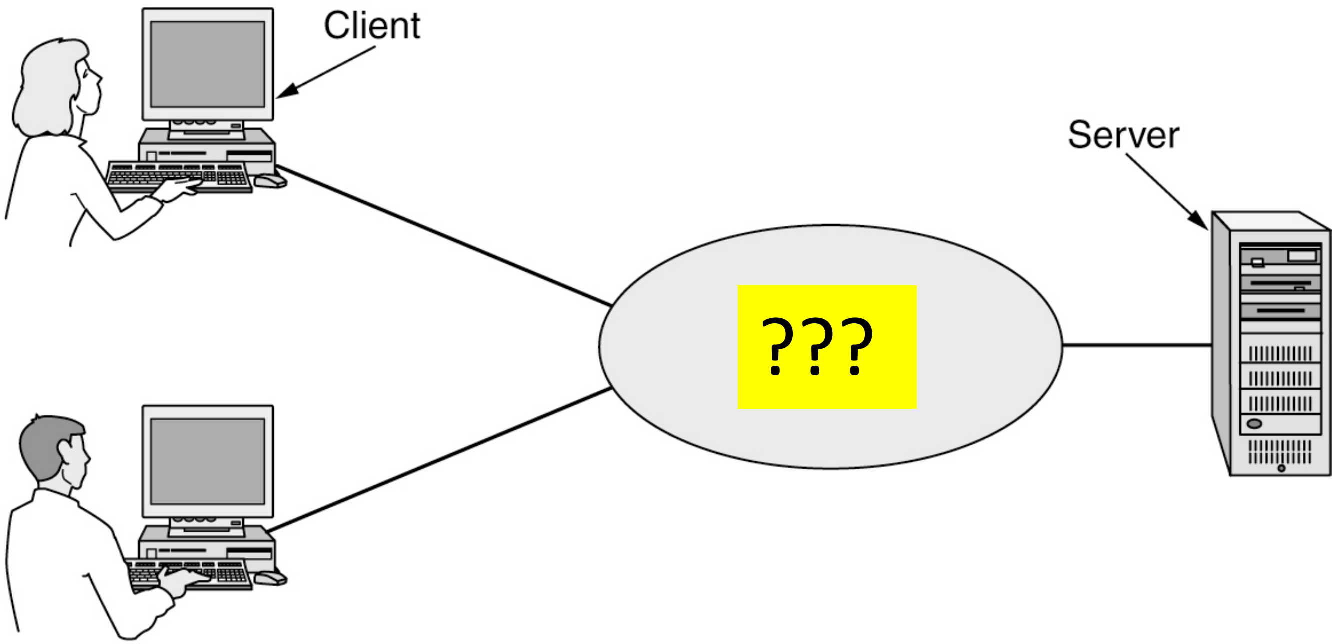
Textbook

- Computer Networks, 6th Ed.
  A.S. Tanenbaum, N. Feamster, and D.J. Wetherall
  Pearson, 2021, ISBN: 978-0-13-752321-4
- Computer Networks, 5th Ed.
  A.S. Tanenbaum and D.J. Wetherall
  Pearson, 2011, ISBN: 978-0-13-212695-3
- Videos by the authors:
  https://www.computernetworksbook.com/video.html
- Lectures by D.J. Wetherall:
  https://media.pearsoncmg.com/ph/streaming/esm/tanenbaum5e_videonotes/tanenbaum_videoNotes.html

Communication Network

- A collection of interconnected, autonomous computing devices
- Interconnected computers can exchange information
- Connections can be via
  - Copper wire
  - Fiber optics
  - Wireless (air, water, space)
- Example: Internet

Focus of the Course



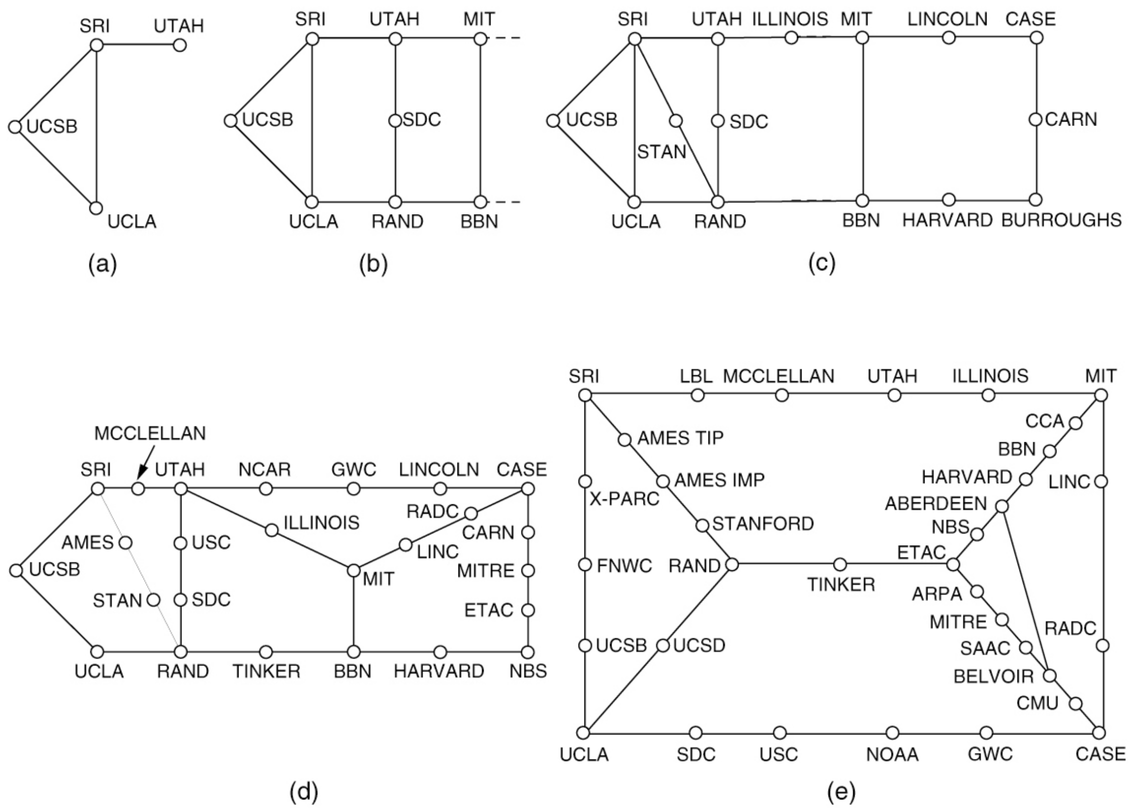
Networking Topics

• Distributed Systems	Applications
• Networking	Packets
• Communications	Signals

Goals

- Learn how the Internet works
  - What really happens when you browse the web?
  - What are TCP/IP, DNS, HTTP, NAT, 802.11?
- Learn the fundamentals of communication networks

ARPANET

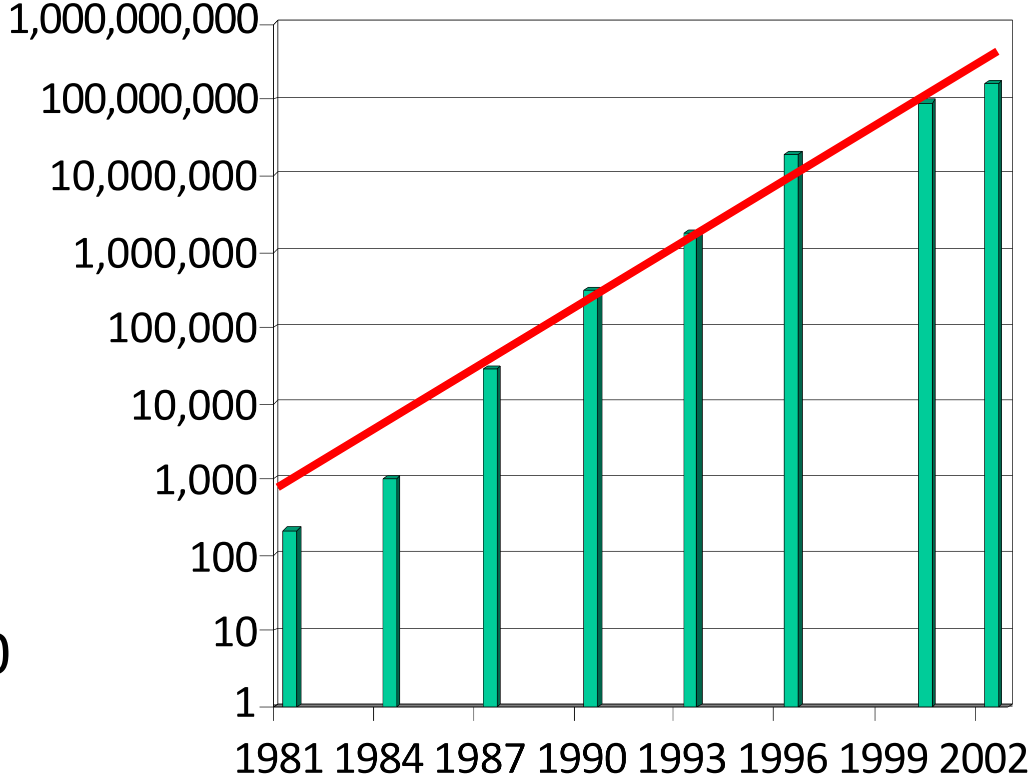


(a) December 1969 (b) July 1970 (c) March 1971 (d) April 1972 (e) September 1972

Internet Growth

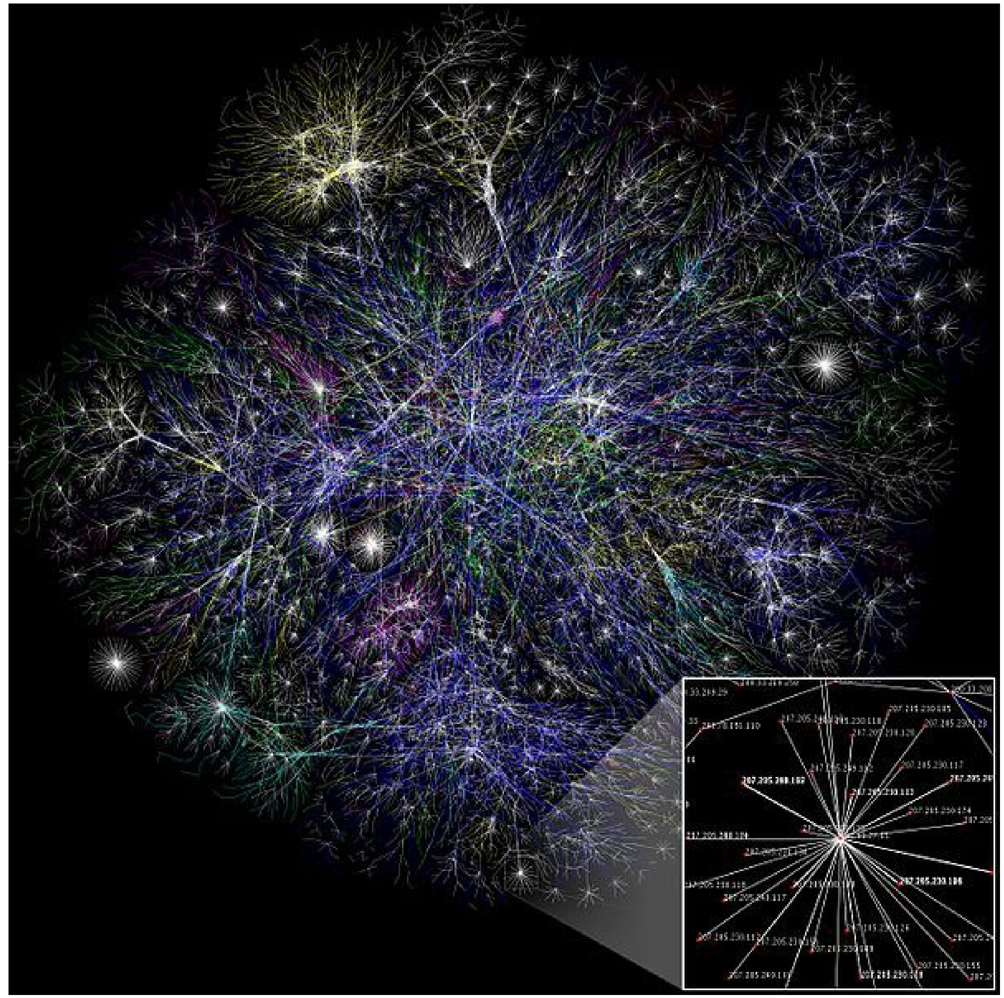
Number of clients

Aug. 1981	213
Oct. 1984	1,024
Dec. 1987	28,174
Oct. 1990	313,000
Jul. 1993	1,776,000
Jul. 1996	19,540,000
Jul. 2000	93,047,000
Jul. 2002	162,128,000



Internet Around 2005

- Every day use at work, home and on-the-go
- Millions of links



Robert M. Metcalfe

- Invented Ethernet in 1973 (along with David Boggs and others) while working for Xerox

Metcalfe's Law

- The value or influence of a communication network is proportional to the square of the number of connected users
- Based on the fact that the number of possible connections between *n* users is

$$n(n-1)/2$$

Societal Impact

- Enabler of social change
  - Easy access to knowledge
  - Electronic commerce
  - Personal relationships
  - Discussion without censorship

Economic Impact

- Engine of economic growth
  - Advertising sponsored search
  - Online stores
  - Online marketplaces
  - crowdsourcing

Motivation

- Pervasiveness of Networked Systems
  - Modern society depends on communication networks for commerce, healthcare, education, transportation, and entertainment
- Rapid Technological Evolution
  - Developing wireless communication, optical networking, and distributed systems requires strong theoretical and practical grounding
- Economic and Industrial Importance
  - Communication networks underpin major industries such as telecommunications, data centers, software platforms, and digital services
- Career and Research Opportunities
  - Expertise in networking leads to roles in telecommunications, equipment design, cloud infrastructure, and cybersecurity
- Societal Impact
  - Communications networks improve access to information and enable global collaboration

Why the Fundamentals Are Important

- Applicable to all communication networks
- Communication networks are constantly evolving
  - Network growth and new technology drive new designs and usage
  - But the fundamentals remain the same

Example

- Key challenge: reliability
  - Any part of the Internet may fail
  - Messages can be corrupted
- How to provide reliability?
- Solution
  - Codes to detect/correct errors
  - Redundancy in the network topology
  - Routing around failures

Network Challenges

- Reliability
- Network growth and evolution
- Allocation of resources such as bandwidth
- Security

Goals

- Architectures and Protocols
  - Understand how data is transmitted, routed, controlled, and delivered across networks
- Scalable Systems
  - Maximize throughput, minimize latency, ensure reliability, and scale effectively with growing numbers of users and devices
- Ensure Reliability
  - Mechanisms that guarantee availability, fault tolerance, congestion control, and service diverse applications
- Optimize Resource Utilization
  - Allocate bandwidth, spectrum, power, and computational resources while balancing performance and cost constraints
- Support Emerging Technologies
  - Build foundations for cloud computing, IoT, 5G/6G, edge computing, and cyber-physical systems

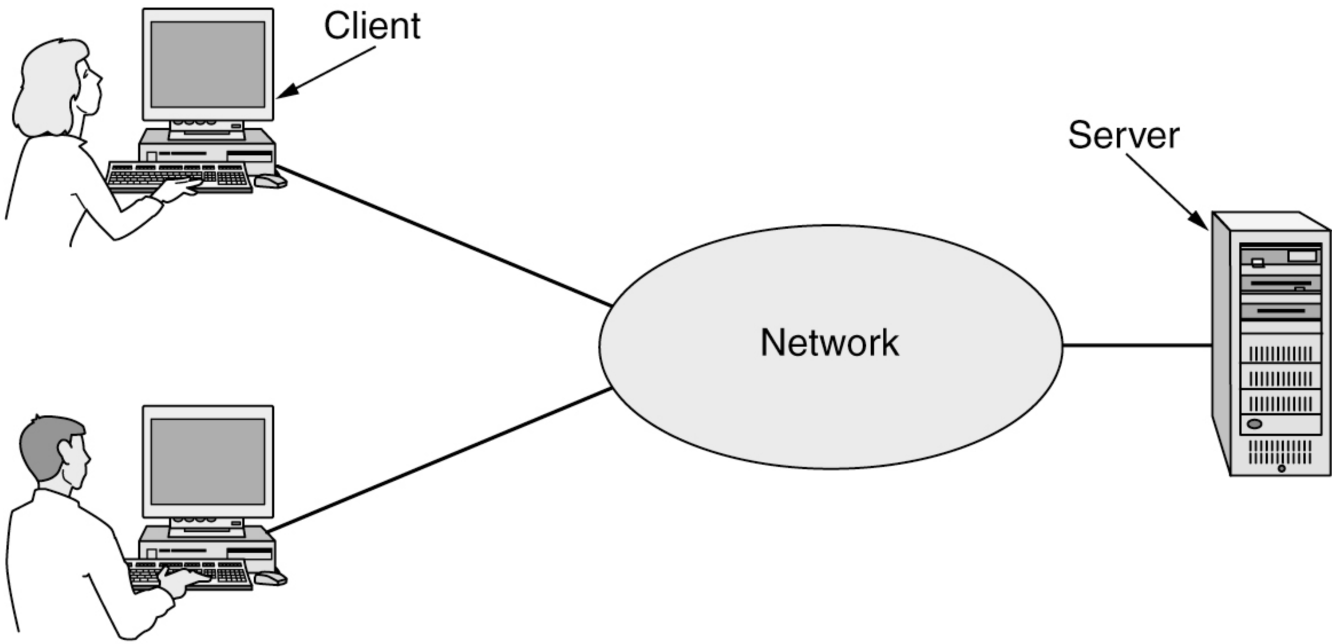
Syllabus

1. Network overview
2. Physical layer technologies
3. Link error control
4. Resource management and medium access control
5. Network routing algorithms and protocols
6. Transport layer flow control
7. Error control and congestion control
8. Internet applications

Communication Network

- A collection of interconnected, autonomous computing devices
- Interconnected computers can exchange information
- Connections can be via
    - Copper wire
    - Fiber optics
    - Wireless (air, water, space)
- Example: Internet
- Network uses
    - Access to information
    - Person-to-person communication
    - Electronic commerce
    - Entertainment
    - Internet of Things

Access to Information

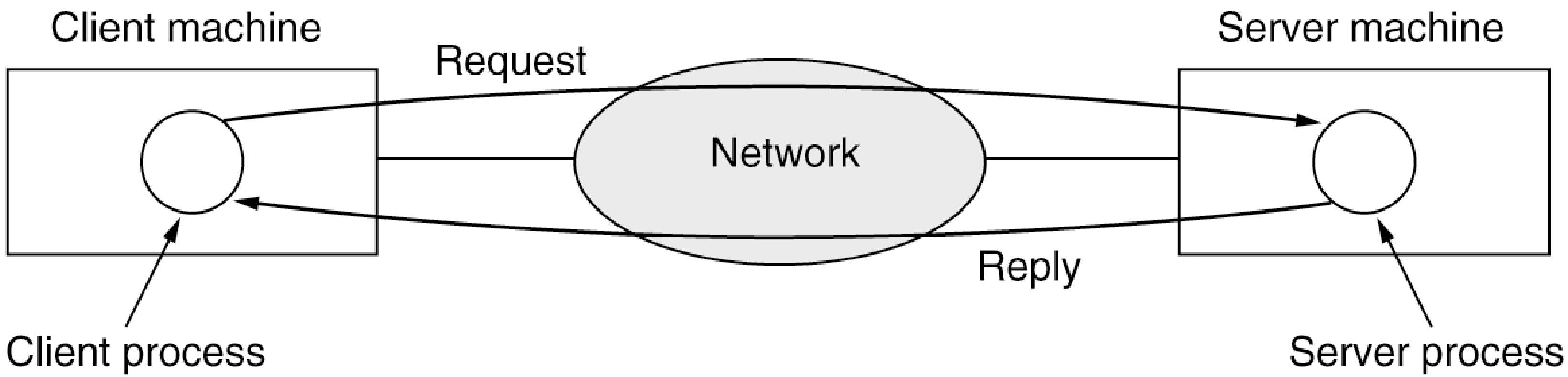


In the client-server model, a client explicitly requests information from a server that hosts the information.

Access to Information

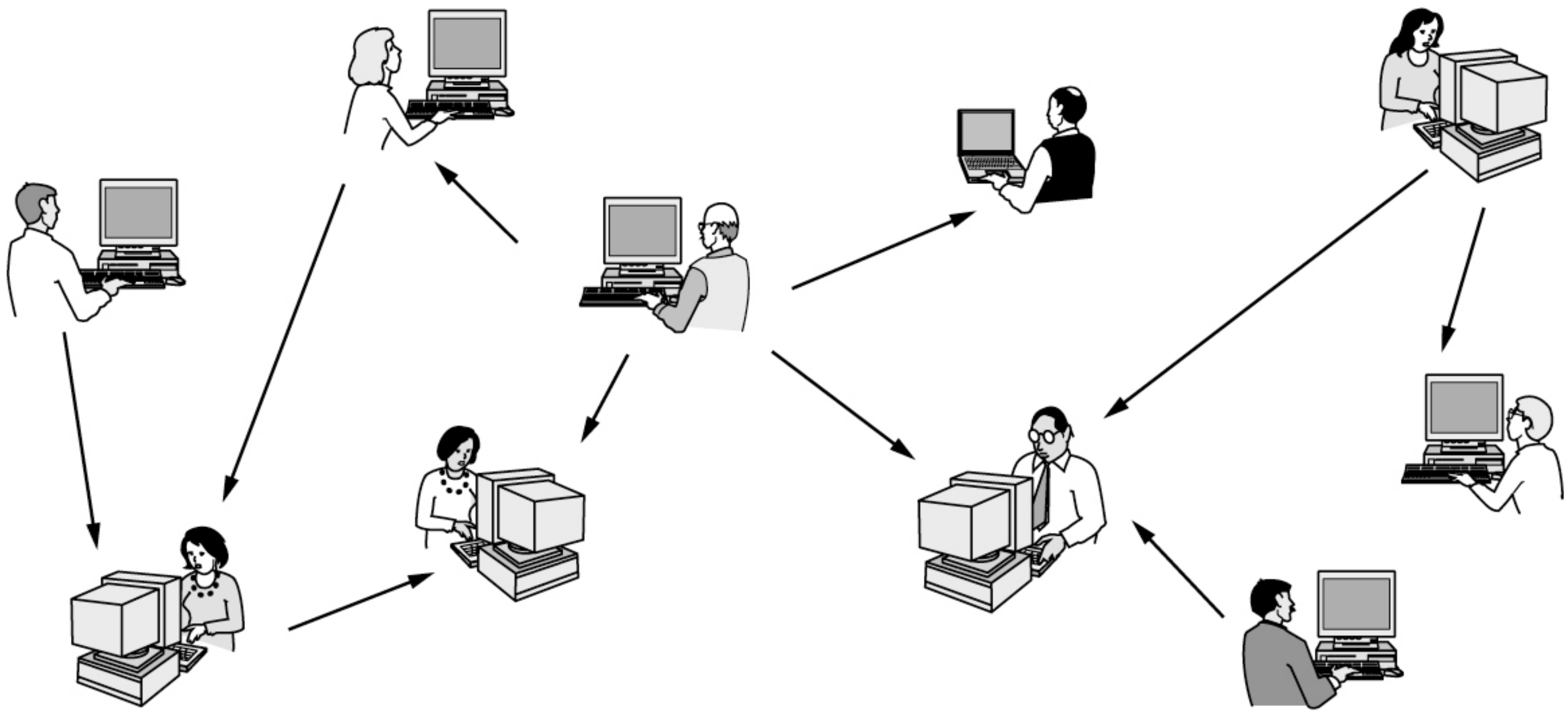
- Web browsers and smart phones retrieve information from websites
- Social media platforms support targeted behavioral advertising
- Online digital libraries and retail sites host digital content
- Client-server model forms the basis of much network usage
- Web applications: Server generates webpages in response to client requests

Access to Information



Communication takes the form of the client process sending a message over the network to the server process. The client process then waits for a reply message.

Access to Information

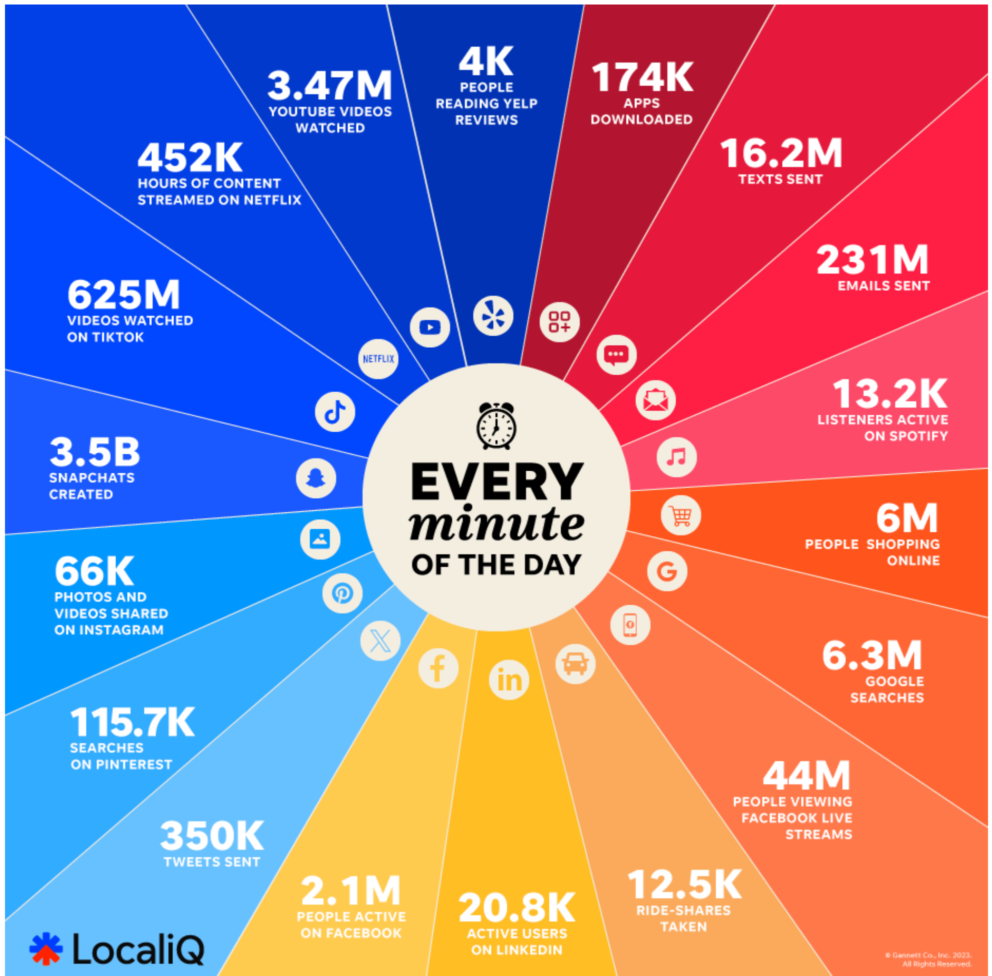


In a peer-to-peer system, there are no fixed clients and servers. Individuals form a group to communicate with each other.

Person-to-Person Communication

- Instant messaging
  - Allows two people to send messages to each other in real time
- Multi-person messaging
  - Allows people to send short messages to their circle of friends or other followers or the whole world
- Social network applications
  - Information flow driven by the relationships that people declare between each other
- Wiki content is a collaborative website the members of a community edit

Internet Minute



Electronic Commerce

- Online shopping and financial institution transactions follow the client-server model
- Online auctions follow the peer-to-peer model
  - Consumers act as buyers and sellers
  - Central server holds the database of products for sale

Entertainment

- IPTV (IP Television) systems
  - TV shows based on IP technology instead of cable TV or radio transmissions
- Media streaming applications
  - Internet radio stations, TV shows, and movies
  - Content usually transmitted wirelessly between devices
- Real-time multi-person gaming
- Virtual worlds provide a persistent setting
  - Thousands of users experience a shared reality with three-dimensional graphics

The Internet of Things

- A network of physical objects embedded with software, sensors, and connectivity to collect and exchange data over the Internet
  - Home security systems wired with door and window sensors
  - Sensors in a smart home monitor
  - Smart refrigerators

Sensor Networks

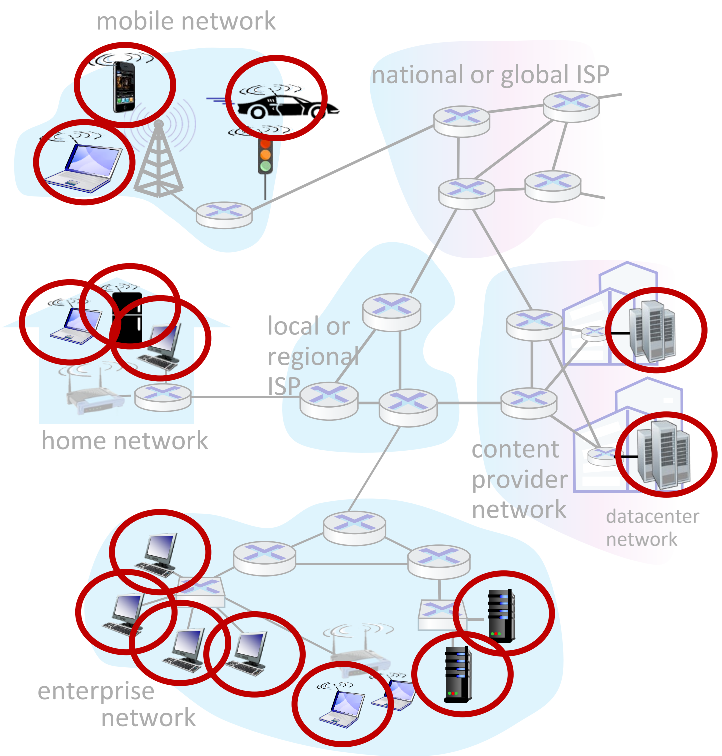
- Sensor networks use nodes to gather and relay information about the physical state of the world
  - Nodes may be embedded in familiar devices (cars or phones)
  - Nodes may be small, separate devices
  - Provide a wealth of data on behavior
  - Example: wireless parking meters

Types of Networks

- Mobile and broadband access networks
  - Networks used to access the Internet
- Data-center networks
  - Networks that house data and applications
- Transit networks
  - Networks that connect different, disconnected networks such as access networks to data centers
- Enterprise networks
  - Networks used on campuses, in businesses, or at other organizations

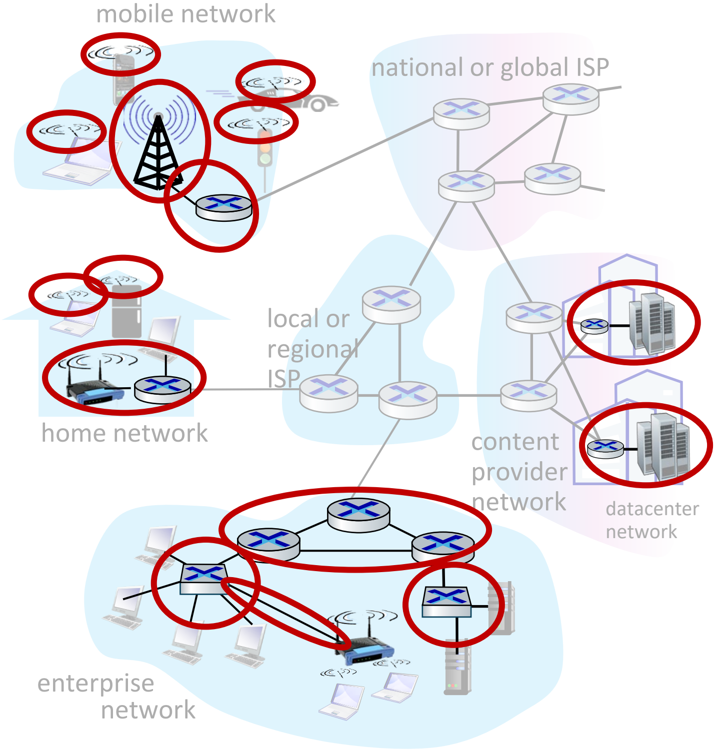
Internet Structure

- Network edge
- hosts: clients and servers
- servers often in data centers



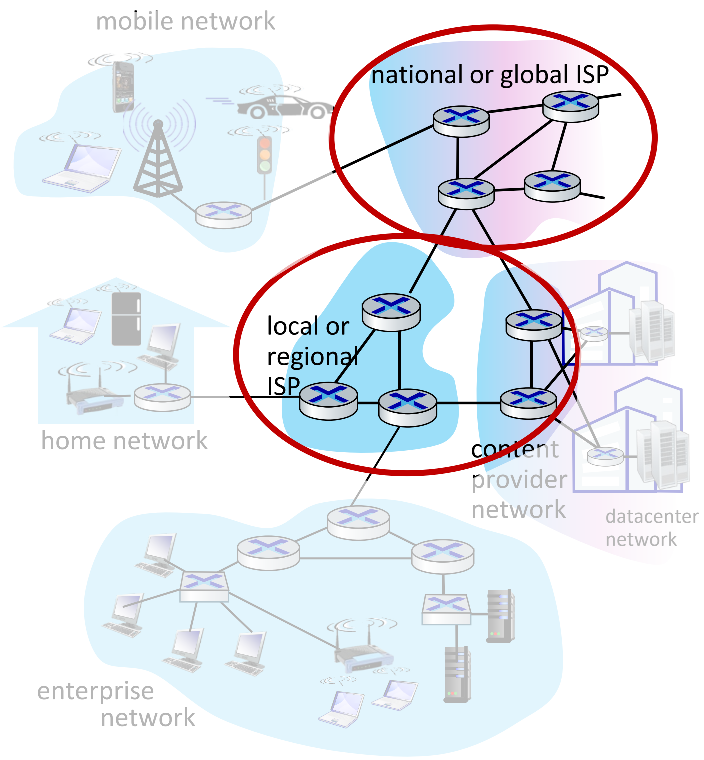
Internet Structure

- Access networks
- wired, wireless communication links



Internet Structure

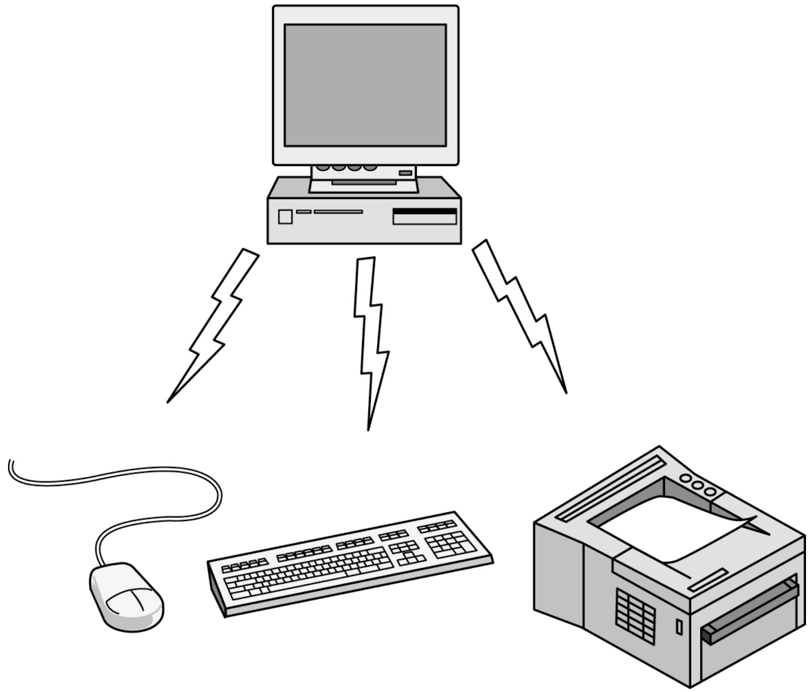
- Network core:
- interconnected routers
- network of networks



Network Scale

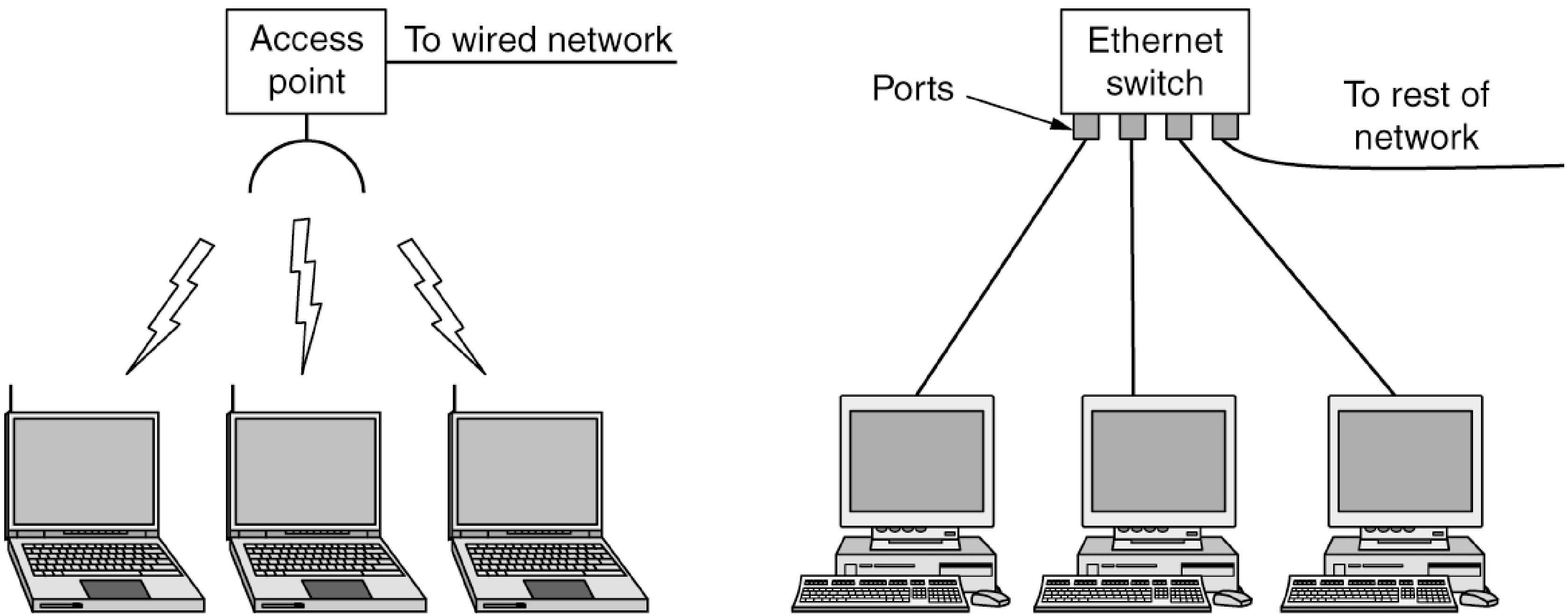
- Personal Area Network (PAN)
  - Up to 1 m
- Local Area Network (LAN)
  - 10 m to 1 km
- Metropolitan Area Network (MAN)
  - 10 km
- Wide Area Network (WAN)
  - 100 km to 1000 km

Personal Area Networks



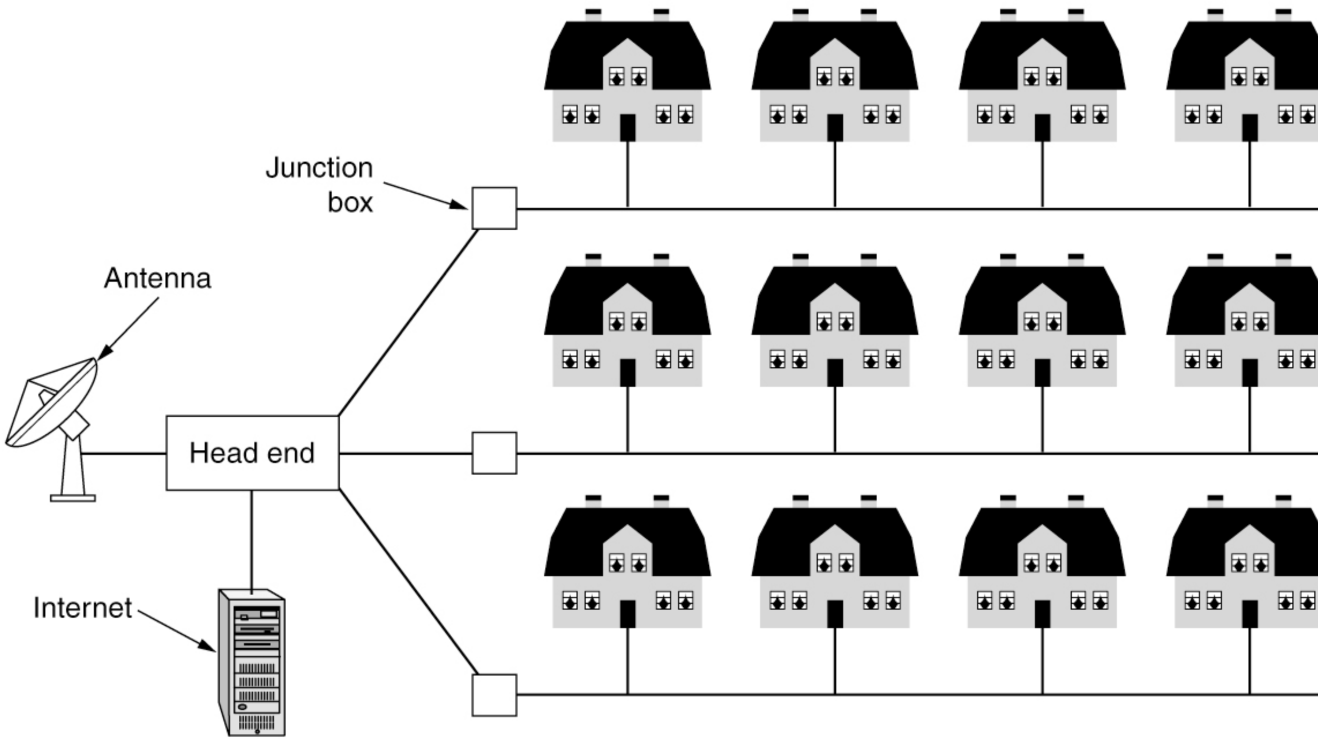
Personal Area Networks (PANs) let devices communicate over the range of a person. Bluetooth is a short-range wireless technology used to connect components without wires.

Local Area Networks



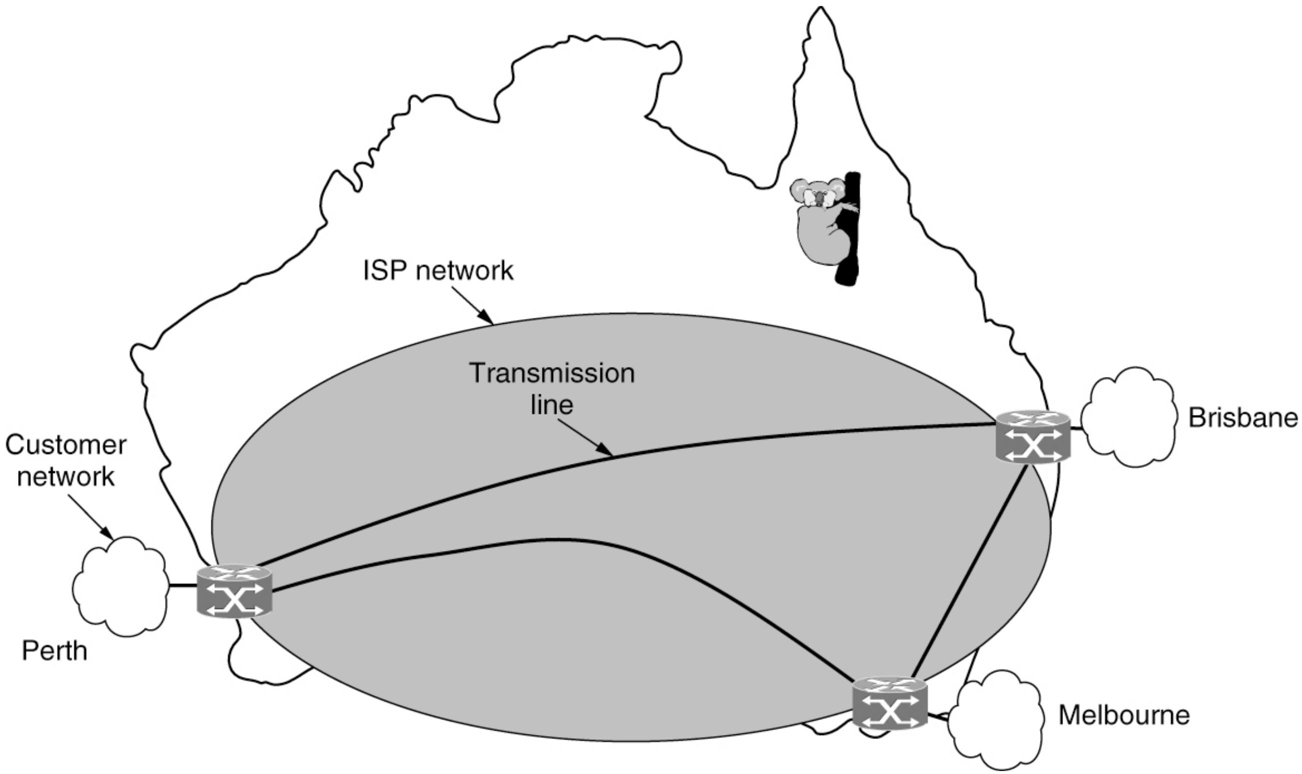
Left represents a wireless 802.11 network.
Right represents a wired switched Ethernet network.

Metropolitan Area Networks



A Metropolitan Area Network (MAN) where both television signals and the Internet are fed into the cable head-end (or cable modem termination system) for subsequent distribution to homes.

Wide Area Networks



A wide area network with hosts in Perth, Brisbane, and Melbourne connected via an ISP.

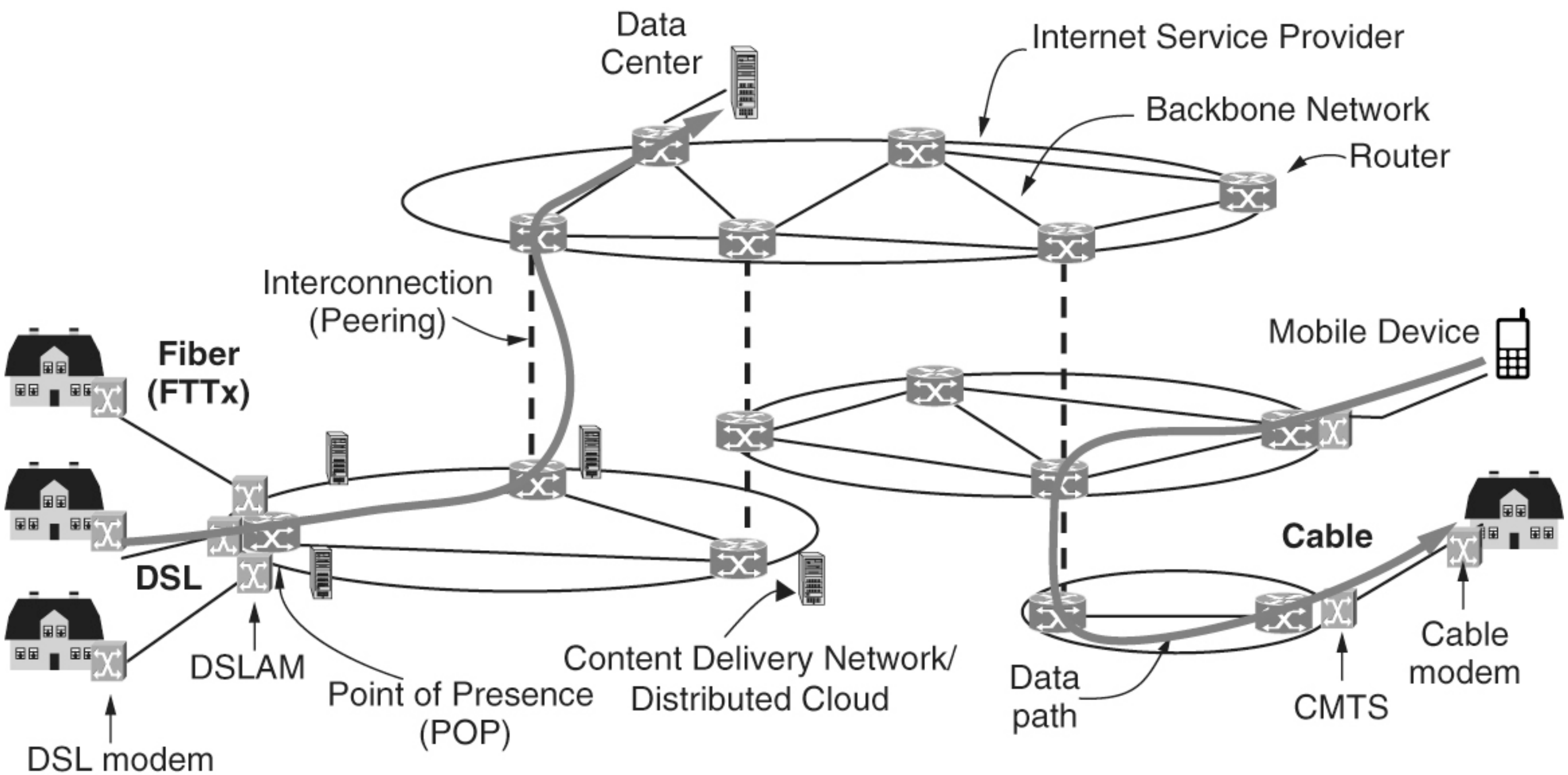
Examples of Networks

- Bluetooth
- WiFi (802.11)
- Ethernet
- Cable/DSL
- Internet
- Mobile networks
  - 3G, 4G, and 5G
- Telephone (PSTN)
- Satellite

Internetworks

- Internetwork or internet
  - A collection of interconnected networks
- An internet
  - Interconnection of distinct, independently operated networks
  - Connecting a LAN and a WAN or connecting two LANs
  - Gateway devices make connections between two or more networks

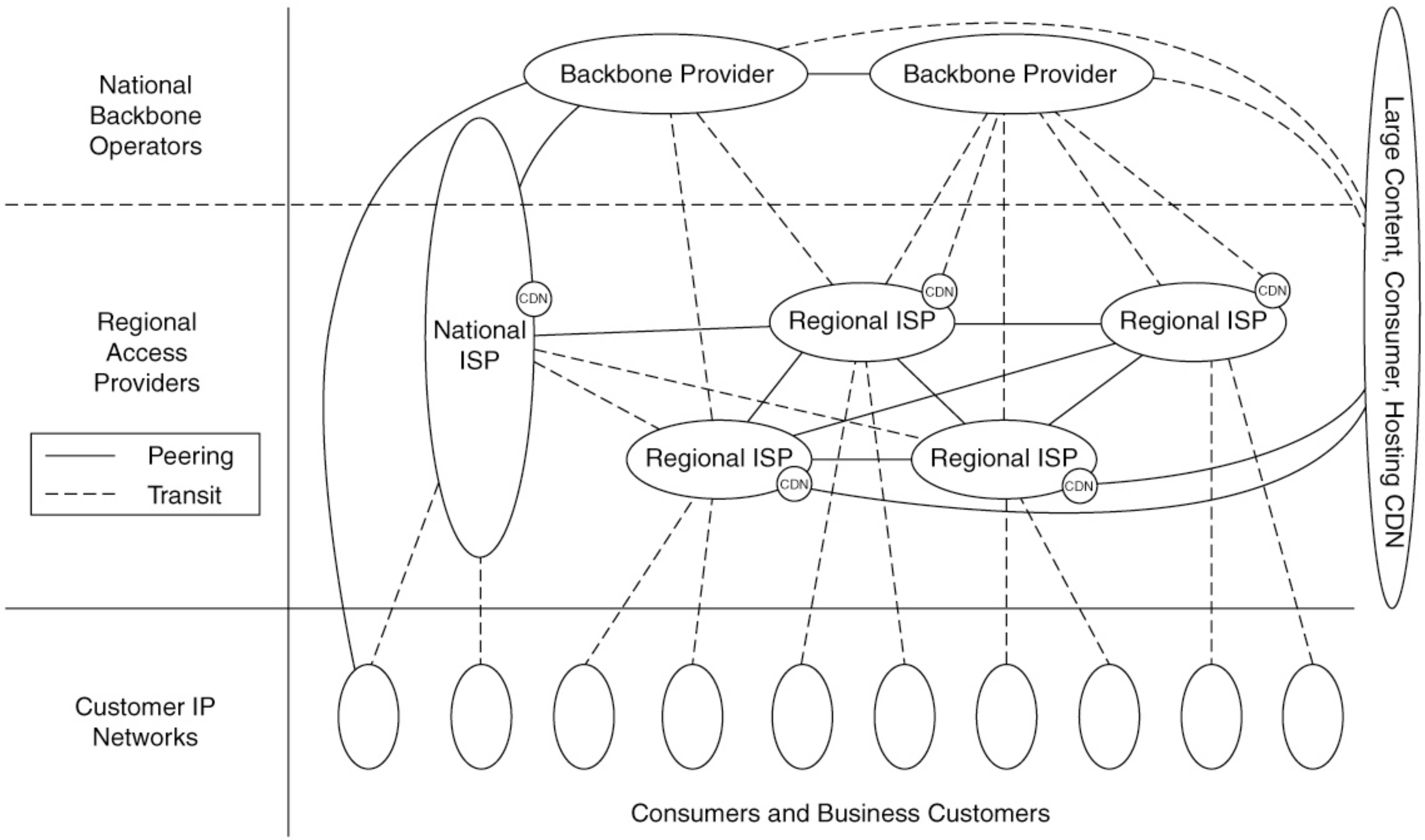
Internet Architecture



Internet Architecture

- Cable television infrastructure connects to the Internet
  - Device at the home end is called a cable modem
  - Device at the cable headend is called the Cable Modem Termination System (CMTS)
  - Modem is short for **mo**dulator **dem**odulator
- Telephone lines and optical fiber also connect to the Internet
  - Digital Subscriber Line (DSL) modem
  - Optical Network Terminal (ONT)

Internet Hierarchy



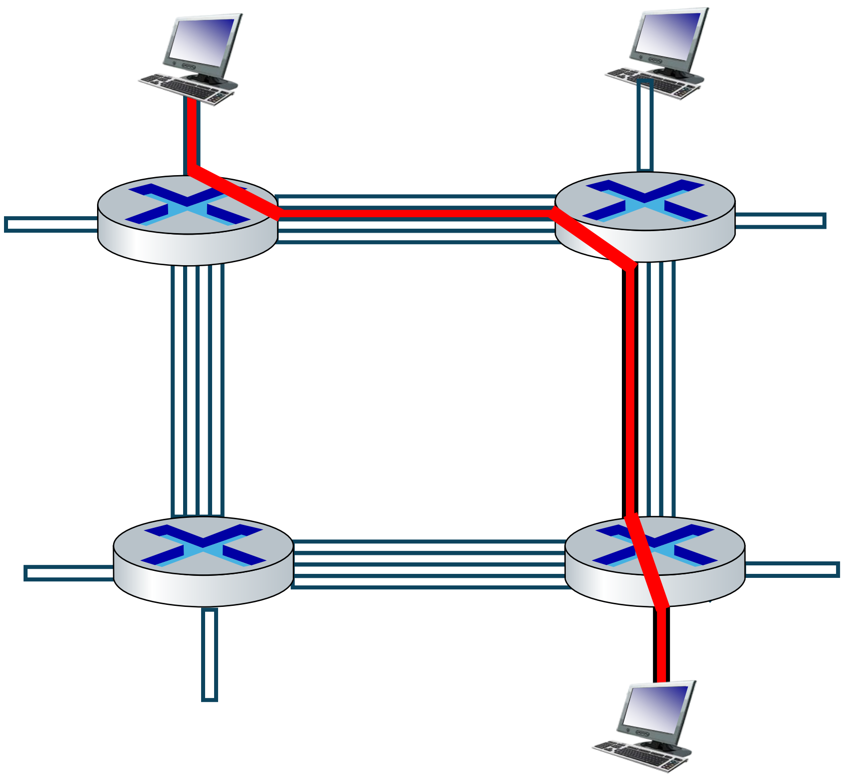
Over the past decade, the conventional hierarchy has evolved and flattened dramatically.

Circuit Switching and Packet Switching

- Circuit switching comes from telephone companies
  - Connection-oriented networks
  - Caller must dial the called party's number and wait for a connection before talking or sending data
  - Route maintained until call is terminated
  - Can support quality of service more easily
- Packet switching comes from the Internet community
  - Connectionless networks
  - Every packet is routed independently
  - If some routers go down during a session, no harm will be done as long as the system can dynamically reconfigure itself

Circuit Switching

- End-end resources reserved for the call
- In the diagram, each link has four circuits.
  - call gets 2nd circuit in top link and 1st circuit in right link.
- Dedicated resources: no sharing
- Guaranteed performance
- Call setup required

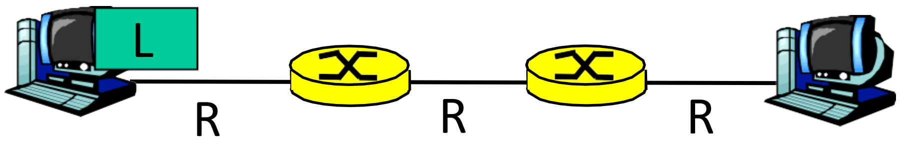


Packet Switching

- Each end-to-end data stream is divided into *packets*
  - Packets from users A and B *share* network resources
  - Each packet uses the full link bandwidth
  - Resources used as needed
- Resource contention
  - aggregate resource demand can exceed amount available
  - congestion: packets queue, wait for link availability
- Store and forward: packets move one hop at a time
  - Node receives complete packet before forwarding

Packet Switching

- Takes L/R s to transmit an L bit packet on a link with rate R bps
- Entire packet must arrive at a router before it can be transmitted on the next link: store and forward
- Total transmission delays of the three-hop path is $3L/R$



Example

L = 7.5 Mbits

R = 1.5 Mbps

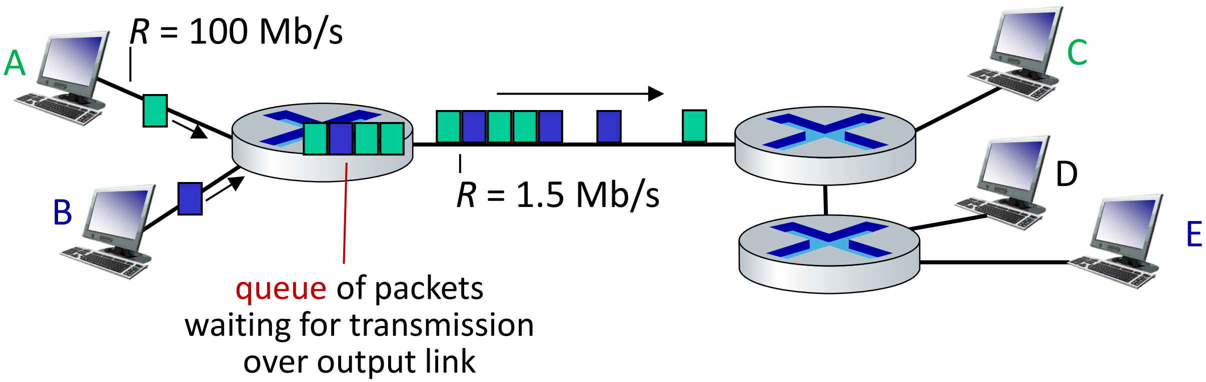
Total transmission delay = 15 s

Packet Switching

- The end-to-end delay consists of four components
  - Transmission delay $t_{trans} = L/R$
  - Propagation delay (link length/propagation speed)

    $t_{prop} = d/v$ $v \approx 2\times10^8$ m/s
  - Processing delay t_{proc}
    - Examine packet header, check for errors, and consult the routing table (typically < msec)
  - Queueing delay t_{queue}
    - The time a packet spends waiting in a buffer (queue) at a router because the network link is busy
    - Depends on the packet arrival rate - often modeled statistically due to its inherent randomness

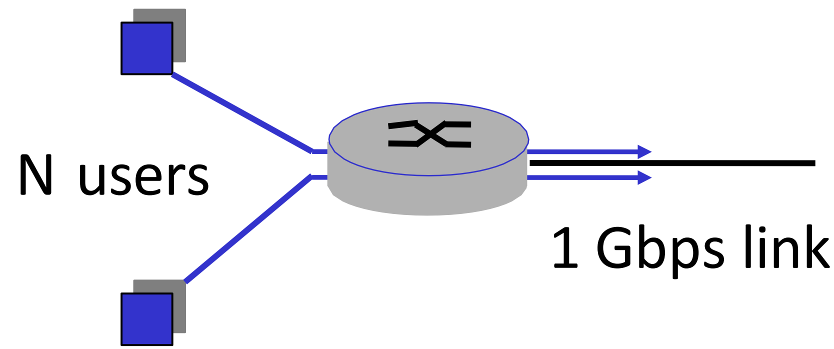
Packet Switching



- If the arrival rate (in bps) exceeds the transmission rate (bps) of the output link for some period of time
  - packets queue waiting to be transmitted on the output link
  - The queue length grows as the arrival rate exceeds the output link capacity
  - packets can be dropped (lost) if the router buffer fills up

Packet Switching versus Circuit Switching

- Packet switching allows more users in the network
  - Statistical multiplexing
- Example: 1 Gbps link
- Each user
  - 100 Mbps when active
  - Active 10% of the time
- Circuit switching
  - 10 users
- Packet switching
  - with 35 users, probability of > 10 active is about .0004



Packet Switching versus Circuit Switching

- Will packet switching always be better?
- Great for bursty data
  - Resource sharing
  - Simpler, no call setup required
- Congestion can occur: packet delay and loss
  - Protocols needed for reliable data transfer
  - Congestion control
- Question: How to provide circuit-like behavior?
  - Bandwidth guarantees needed for audio/video apps
  - Still a challenge

Bandwidth-Delay Product

- Messages take up space on wires
- A volume of bits is stored inside a wire when it is used to send a message
- This quantity is called the bandwidth-delay product

  $$BD = R \times t_{prop}$$

  - Small for networks such as LANs
  - Large for long high bandwidth cross country links
- Example: R = 1 Gbps on a Vancouver to Toronto fiber optic link d = 4500 kms
- $t_{prop} = 4500 \times 10^3 / 2 \times 10^8 = 22.5$ msec
- $BD = 10^9 \times 22.5 \times 10^{-3} = 22.5$ Mbits

What is a Protocol?

Human protocols:

- What's the time?
- I have a question.
- Introductions

… specific messages sent

… specific actions taken when messages are received, or other events

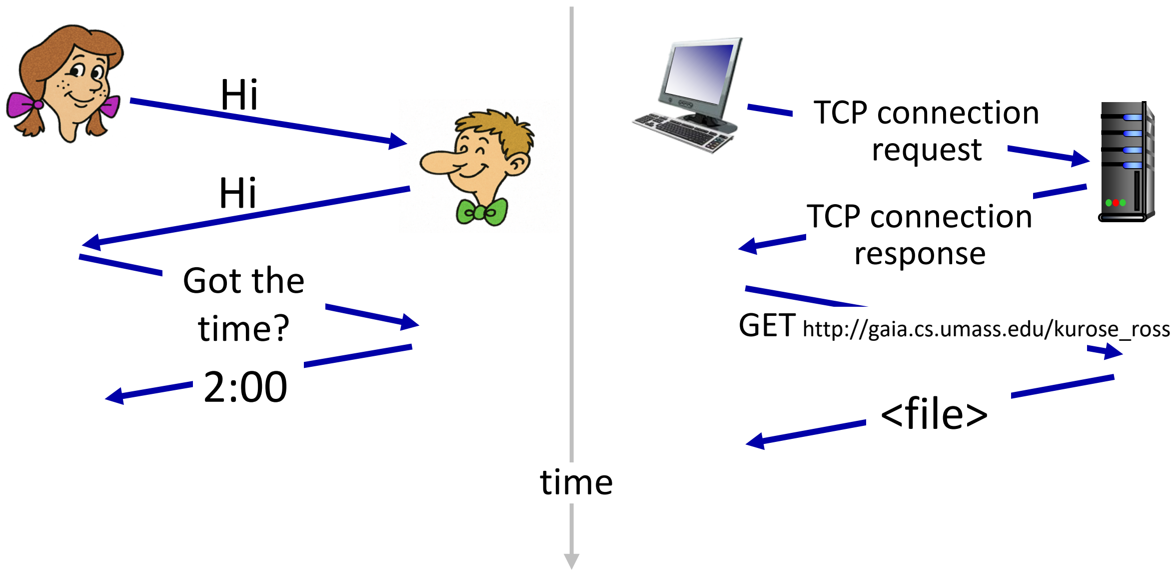
Network protocols:

- Machines rather than humans
- All Internet communications are governed by protocols

Protocols define the format, order of messages sent and received among network entities, and actions taken on message transmission and receipt

What is a Protocol

A human protocol and a computer network protocol.



Protocols

- A protocol is a formal set of rules that governs how data is formatted, transmitted, received, and interpreted between communicating entities in a network.
- The key elements of a protocol are syntax, semantics, and timing.
  - Syntax refers to the structure and format of the data (e.g., header fields, packet layout).
  - Semantics specifies the meaning of each field and the actions taken when events occur (e.g., acknowledgments, error handling).
  - Timing determines when data is sent, how fast it is sent, and how long a sender waits for a response.

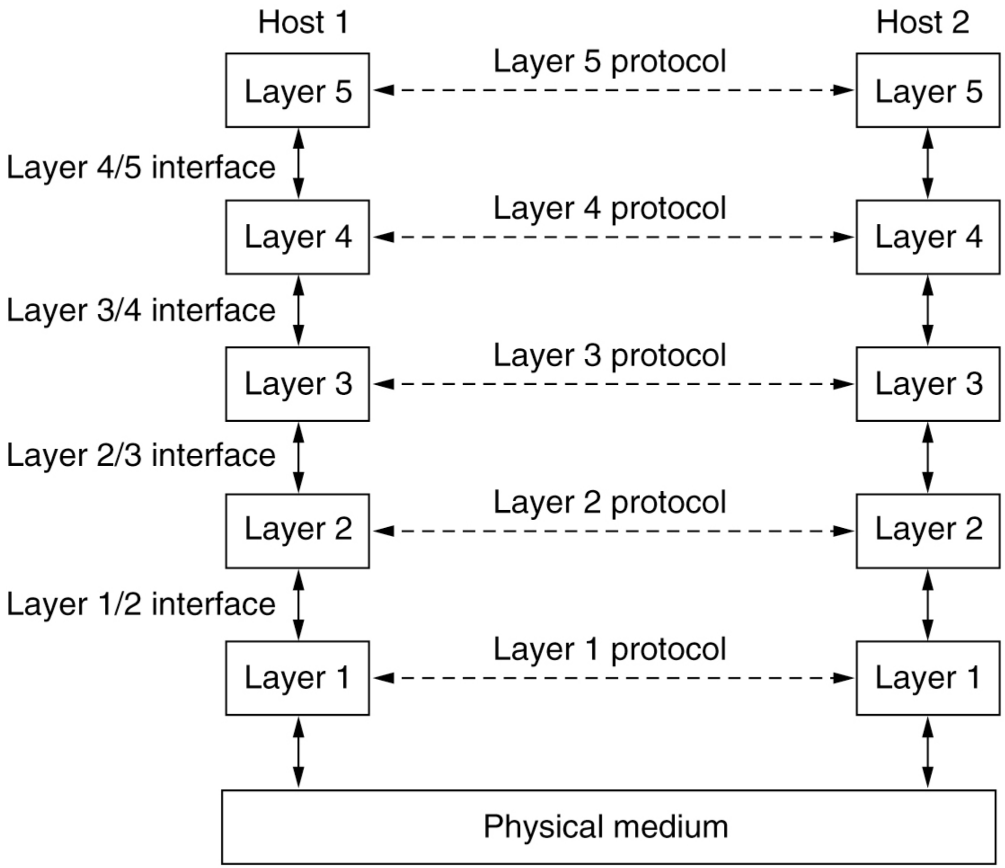
Network Protocol Design Goals

- Reliability
  - ability to recover from errors, faults, or failures
    - Error detection and correction
    - Find a working path through a network using routing
- Resource allocation
  - Sharing access to a common, limited resource
    - Continue to work well when the network gets large
    - Share based on the statistics of demand
    - Flow control and congestion control
- Evolvability
  - Allow for protocol improvements over time based on new technology
  - Use protocol layering to support changes by dividing the problem and hiding implementation details
  - Use addressing or naming mechanisms to identify the senders and receivers involved in a particular message
- Security

Protocol Layering

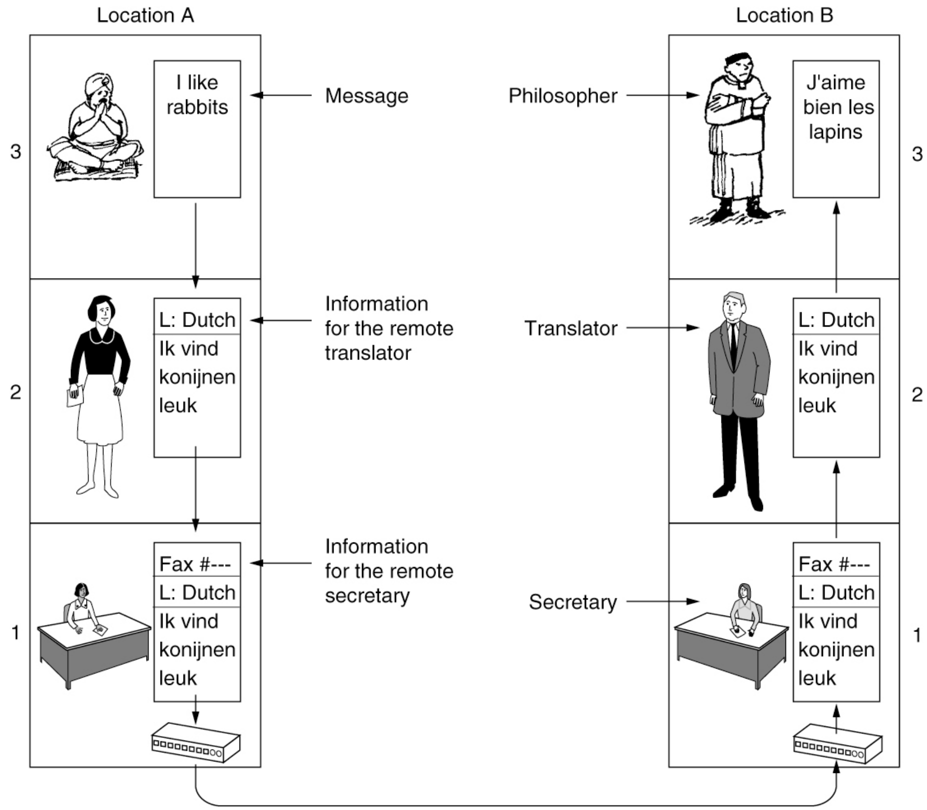
- Networks organized as a stack of layers or levels
  - Each layer built upon the one below it
- Communication between corresponding layers
  - Use a common protocol referred to as a layer *n* protocol
  - Below layer 1 is the physical medium through which actual communication occurs
  - An interface between each pair of adjacent layers
- Network architecture: a set of layers and protocols
- Protocol stack: the protocols used by a system, one protocol per layer

Protocol Hierarchy



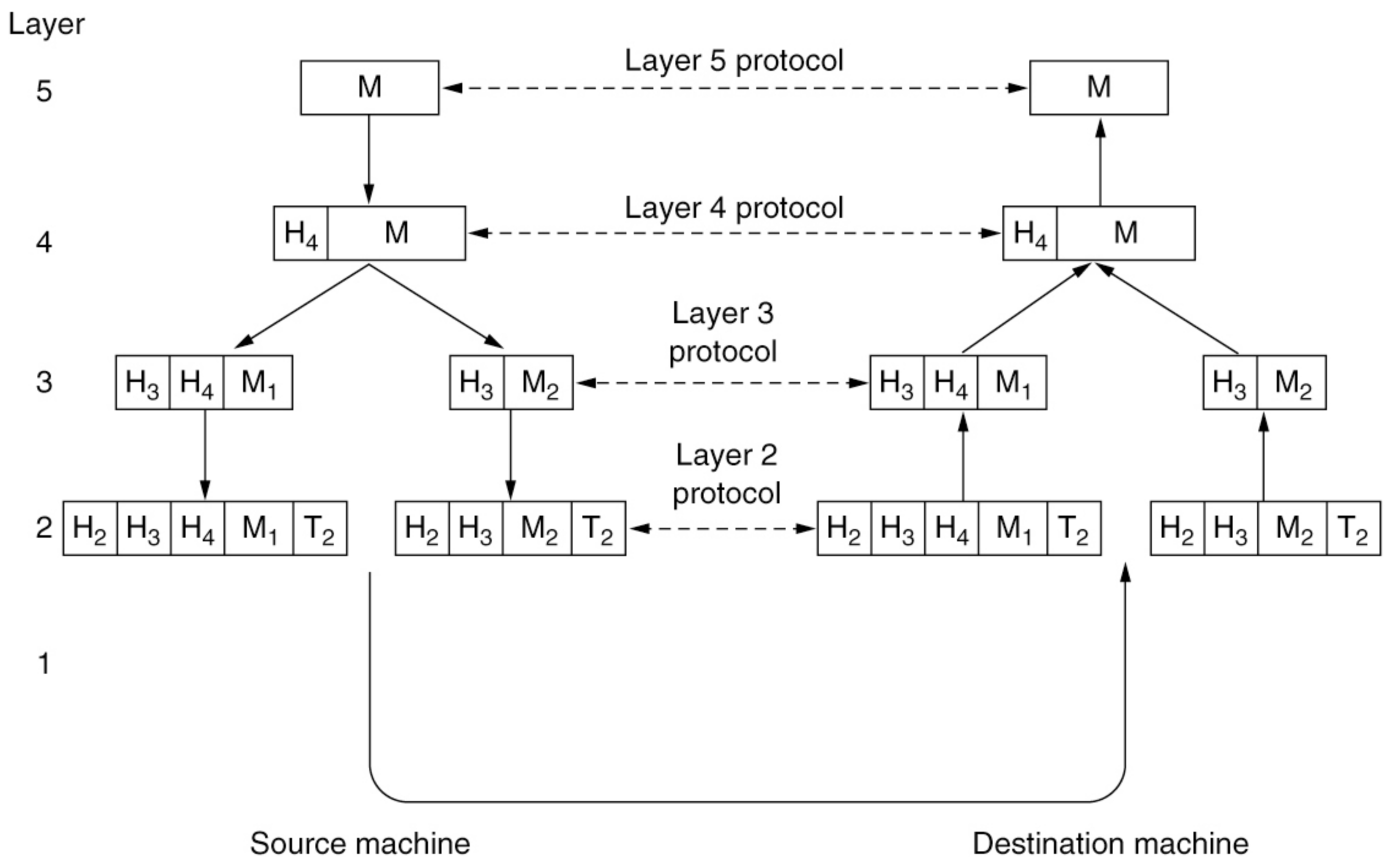
Layers, protocols, and interfaces

Protocol Layering



The philosopher-translator-secretary architecture.
An analogy to explain multilayer communication.

Protocol Layering



Connections and Reliability

- Connection-oriented service
  - Modeled after the telephone system
  - Service user first establishes a connection, uses the connection, and then releases the connection
  - Can negotiate the parameters to be used
- Connectionless service
  - Packet is a message at the network layer
  - Store-and-forward: intermediate nodes receive a message in full before sending it on to the next node
  - Datagram service: Unreliable (not acknowledged)
- Reliability is typically characterized by message acknowledgement

Connections and Reliability

	Service	Example
Connection-oriented	Reliable message stream	Sequence of pages
	Reliable byte stream	Movie download
	Unreliable connection	Voice over IP
Connection-less	Unreliable datagram	Electronic junk mail
	Acknowledged datagram	Text messaging
	Request-reply	Database query

Six common connection-oriented and connectionless services.

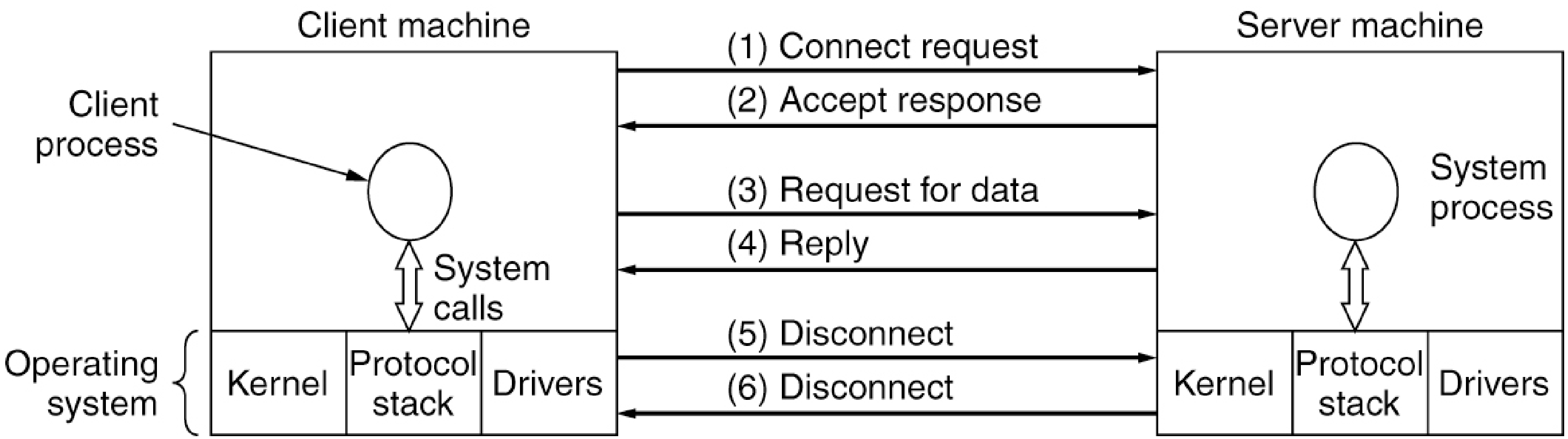
Service Primitives

- Service
  - Formally specified by a set of primitives (operations) available to user processes to access the service
  - Primitives tell the service to perform some action or report on an action taken by a peer entity
- Six core primitives
  - Listen (block waiting for an incoming connection)
  - Connect (establish a connection with a waiting peer)
  - Accept (accept an incoming connection from a peer)
  - Receive (block waiting for an incoming message)
  - Send (send a message to the peer)
  - Disconnect (terminate a connection)

Service Primitives

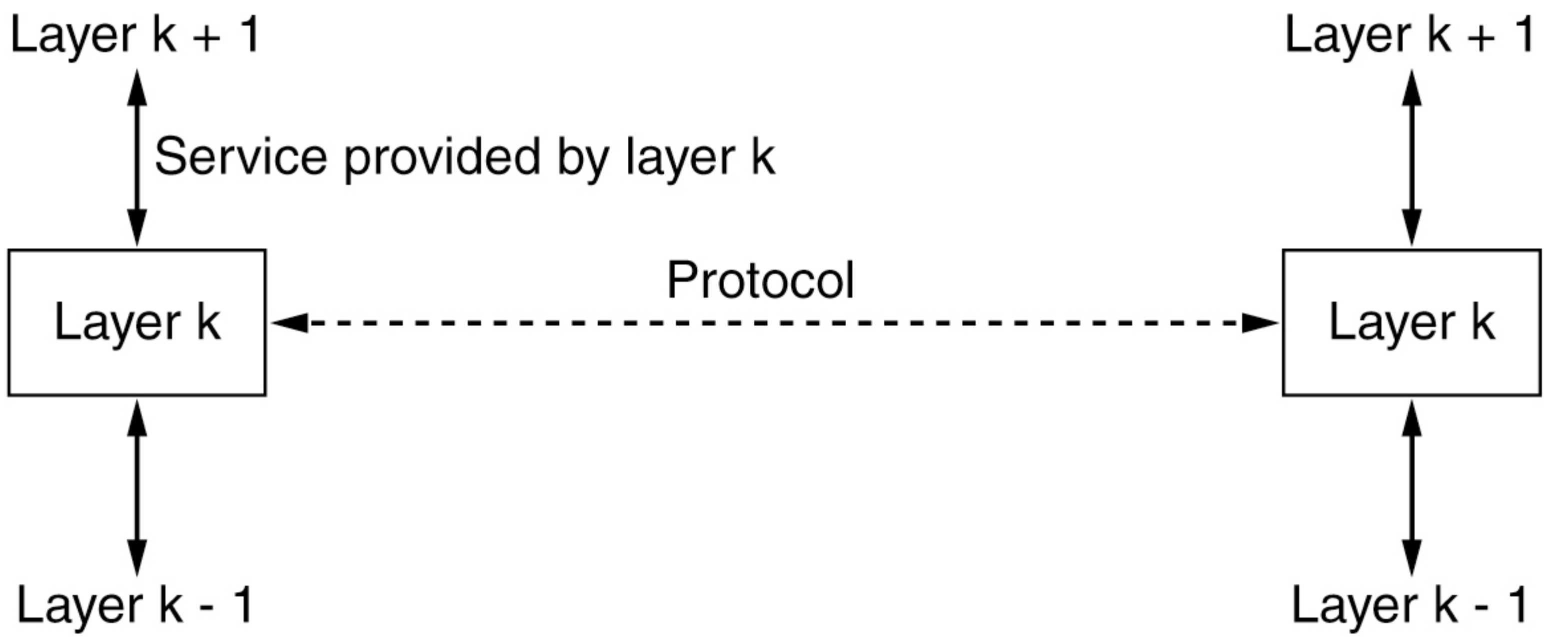
Primitive	Meaning
LISTEN	Block waiting for an incoming connection
CONNECT	Establish a connection with a waiting peer
ACCEPT	Accept an incoming connection from a peer
RECEIVE	Block waiting for an incoming message
SEND	Send a message to the peer
DISCONNECT	Terminate a connection

Service Primitives



Client-server communication with acknowledged datagrams so lost packets can be ignored.

Service Primitives

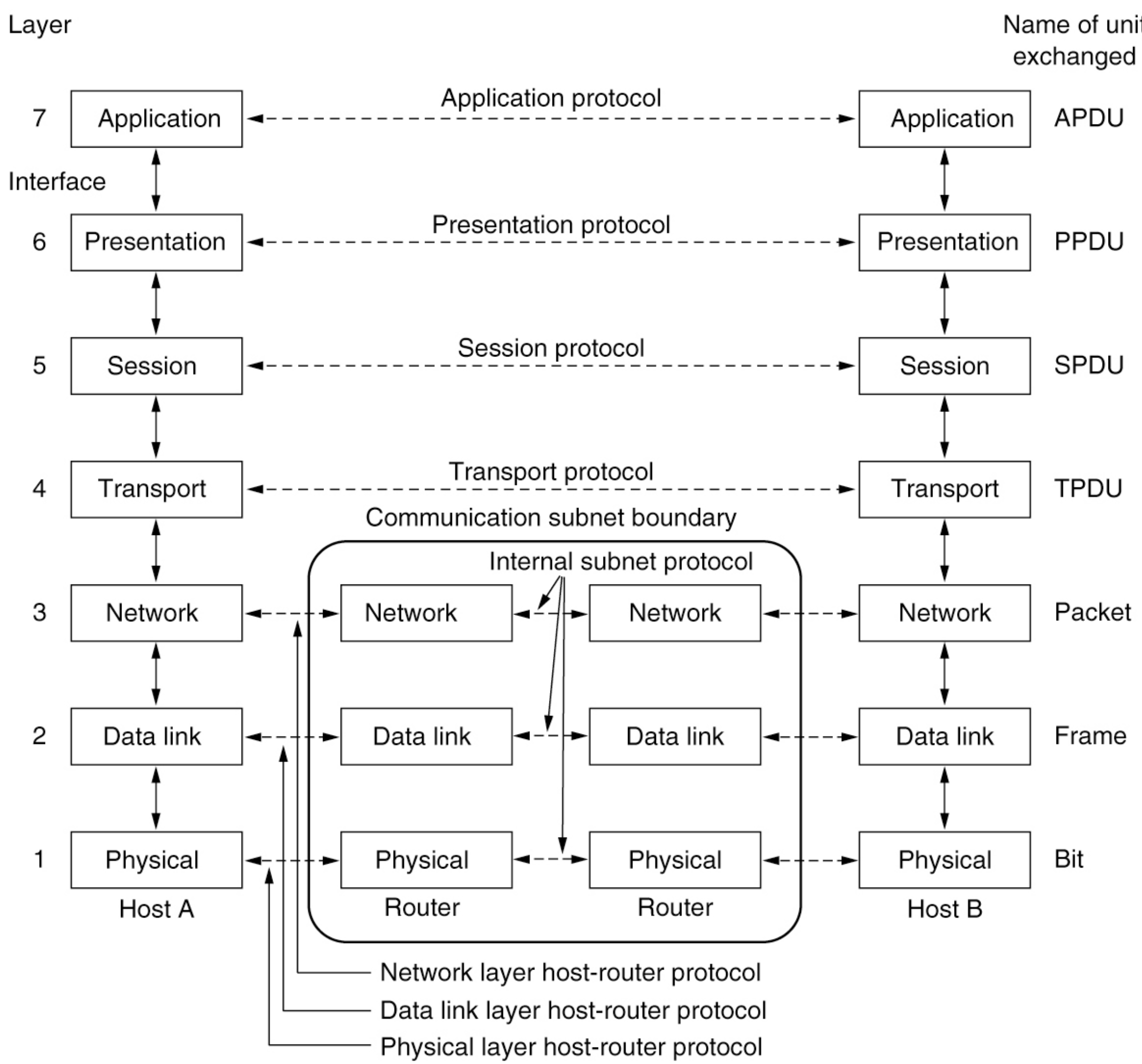


Entities use protocols to implement their services.

OSI Reference Model

- Principles for the seven layers
  - Layers created for different abstractions
  - Each layer performs well-defined function
  - Function of layer chosen with definition of international standard protocols in mind
  - Minimize information flow across interfaces between boundaries
  - Number of layers should be optimum
- Three concepts central to the OSI model
  - Services
  - Interfaces
  - Protocols

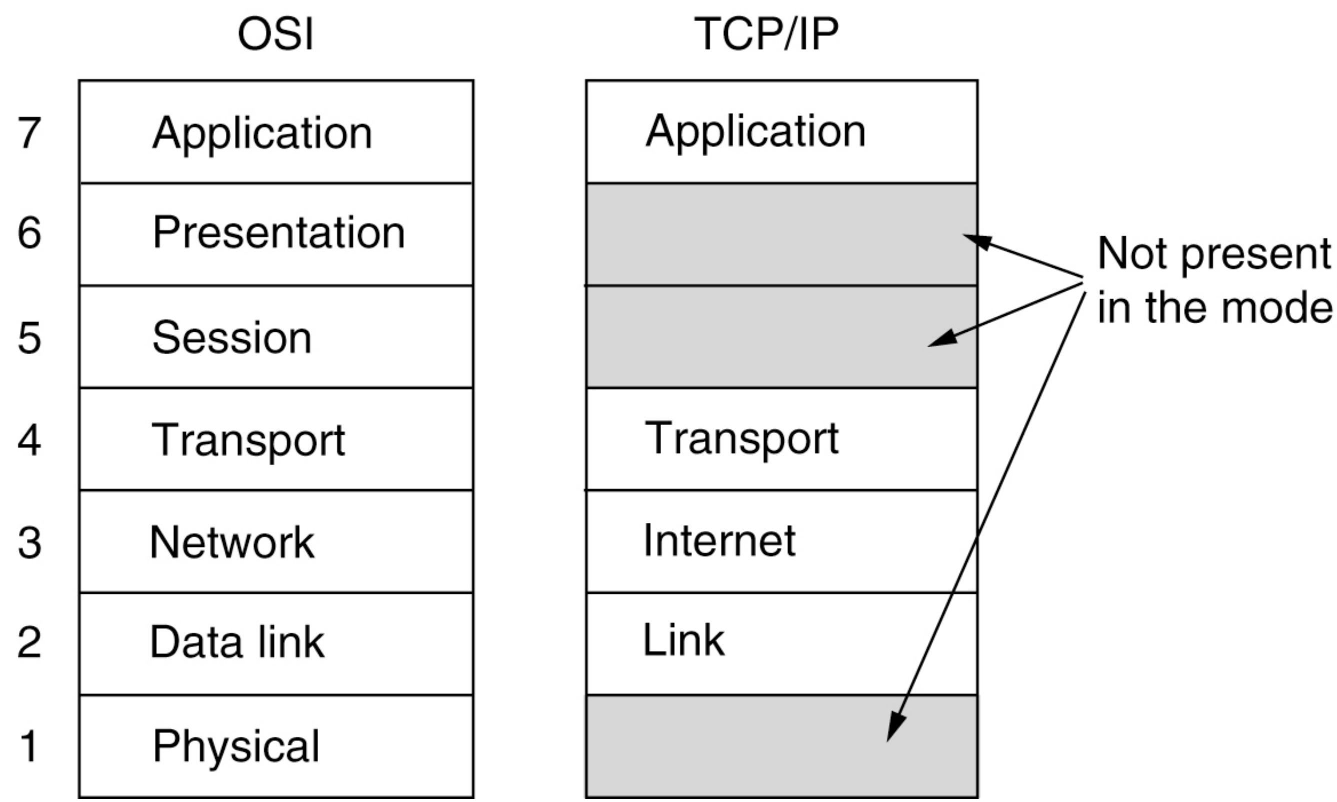
OSI Reference Model



TCP/IP Reference Model

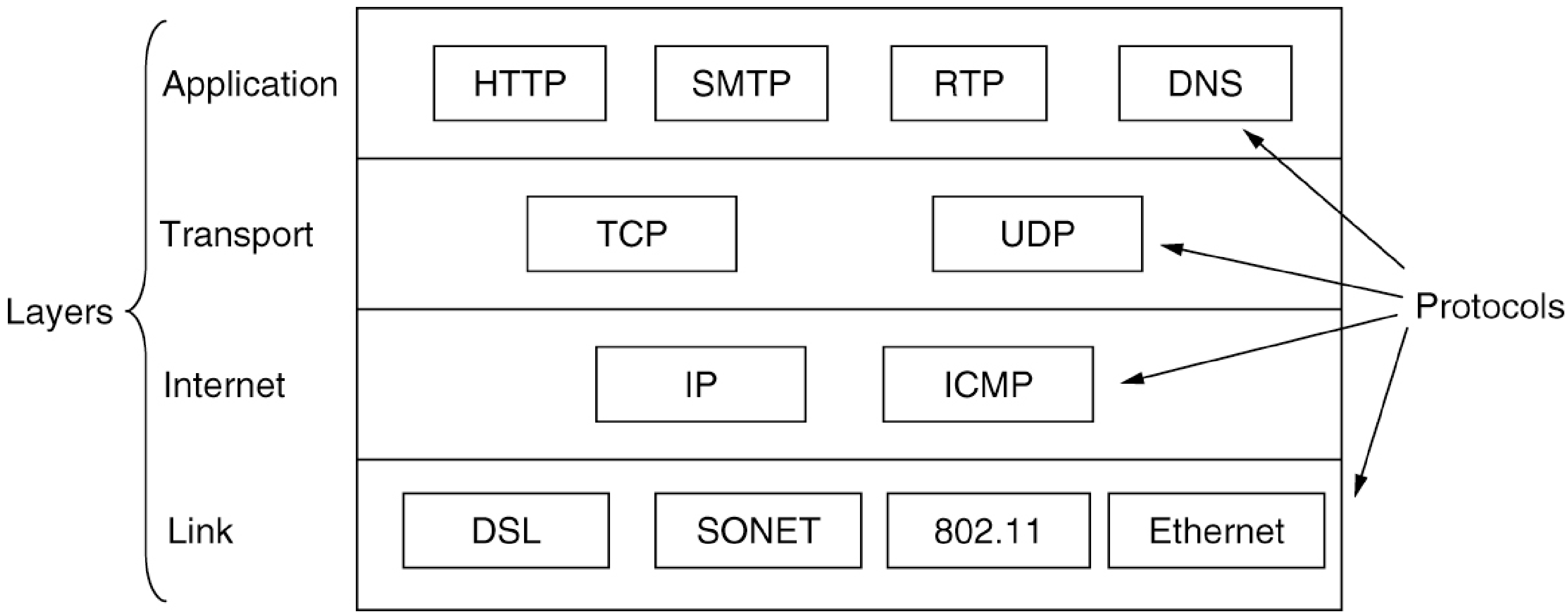
- Link Layer
  - Describes what links must do to meet the needs of the connectionless internet layer
- Internet Layer
  - Permits hosts to input packets to any network and have them travel independently to the destination
  - Packet format and protocol (Internet Protocol)
- Transport Layer
  - Uses two end-to-end transport protocols
    - TCP (Transmission Control Protocol)
    - UDP (User Datagram Protocol)
- Application Layer
  - Higher-level protocols

TCP/IP Reference Model



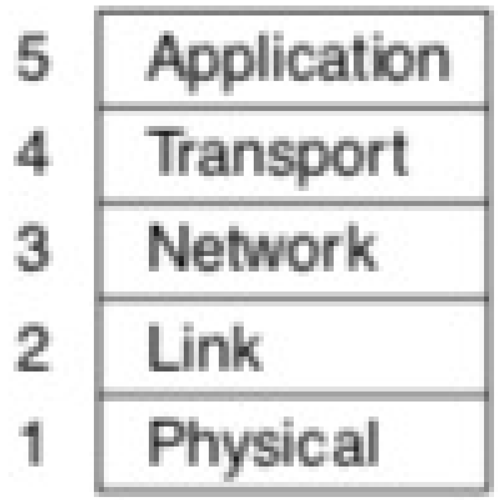
The TCP/IP layers loosely align with the OSI model.

TCP/IP Reference Model



Example protocols in the TCP/IP model.

The Model Used in This Course



Sequence follows the OSI model but without the session and presentation layers.

Standardization

- Standards define what is needed for interoperability
- Two categories of standards
  - De facto standards just happened, without any formal plan
    - HTTP, Bluetooth, Ethernet
  - De jure standards are adopted through the rules of some formal standardization body
    - Open Systems Interconnection (OSI) model

Standardization Organizations

- ITU (International Telecommunication Union)
  - United Nations agency
- ISO (International Standards Organization)
  - Publishes and produces international standards
- NIST (National Institute of Standards and Technology)
  - Develops standards for the U.S.
- IEEE (Institute of Electrical and Electronics Engineers)
  - Largest professional organization in the world
  - IEEE 802 committee develops standards for LANs
- IETF (Internet Engineering Task Force)
  - Develops Internet standards through RFCs
- World Wide Web Consortium (W3C)
  - Develops protocols and guidelines for the Web

IEEE 802 Standards

Number	Topic
802.1	Overview and architecture of LANs
802.2	Logical link control
802.3 *	Ethernet
802.4 †	Token bus (was briefly used in manufacturing plants)
802.5 †	Token ring (IBM's entry into the LAN world)
802.6 †	Dual queue dual bus (early metropolitan area network)
802.7 †	Technical advisory group on broadband technologies
802.8 †	Technical advisory group on fiber-optic technologies
802.9 †	Isochronous LANs (for real-time applications)
802.10 †	Virtual LANs and security
802.11 *	Wireless LANs (WiFi)
802.12 †	Demand priority (Hewlett-Packard's AnyLAN)
802.13	Unlucky number; nobody wanted it
802.14 †	Cable modems (defunct: an industry consortium got there first)
802.15 *	Personal area networks (Bluetooth, Zigbee)
802.16 †	Broadband wireless (WiMAX)
802.17 †	Resilient packet ring
802.18	Technical advisory group on radio regulatory issues
802.19	Technical advisory group on coexistence of all these standards
802.20	Mobile broadband wireless (similar to 802.16e)
802.21	Media independent handoff (for roaming over technologies)
802.22	Wireless regional area network

The important ones are marked with *.
The ones marked with † have been abandoned.

Metric Units

Exp.	Explicit	Prefix	Exp.	Explicit	Prefix
10^{-3}	0.001	milli	10^{3}	1,000	Kilo
10^{-6}	0.000001	micro	10^{6}	1,000,000	Mega
10^{-9}	0.000000001	nano	10^{9}	1,000,000,000	Giga
10^{-12}	0.000000000001	pico	10^{12}	1,000,000,000,000	Tera
10^{-15}	0.000000000000001	femto	10^{15}	1,000,000,000,000,000	Peta
10^{-18}	0.000000000000000001	atto	10^{18}	1,000,000,000,000,000,000	Exa
10^{-21}	0.000000000000000000001	zepto	10^{21}	1,000,000,000,000,000,000,000	Zetta
10^{-24}	0.000000000000000000000001	yocto	10^{24}	1,000,000,000,000,000,000,000,000	Yotta

The principal metric prefixes.

Access Networks

- Access networks connect subscribers to their immediate service provider.
  - Residential access networks connect a home end system to the network.
  - Enterprise access networks connect an end system in a business or educational institution to the network.
  - Mobile access networks connect a mobile end system to the network.