CHAPTER 12: Networks and Data Communications

The Architecture of Computer Hardware, Systems Software & Networking:

An Information Technology Approach

4th Edition, Irv Englander

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PowerPoint slides authored by Wilson Wong, Bentley University

PowerPoint slides for the 3rd edition were co-authored with Lynne Senne, Bentley College

Note: This set of slides is well-suited for two lectures.

Data Communications

A simple view

- data - messages to be shared between sender and receiver
- communications channel that can capably and reliably transport messages
- Protocols establish accurate and appropriate meaning to the messages that are understood by both senders and receivers
- Physical connection that is independent of the messaging
  - message sharing “connection” between applications at the sender and the receiver
  - physical connection with signaling that represents the messages being transported
- Examples
  - POTS - plain old telephone service
  - Web servers and Web browsers

HTTP Request and Response

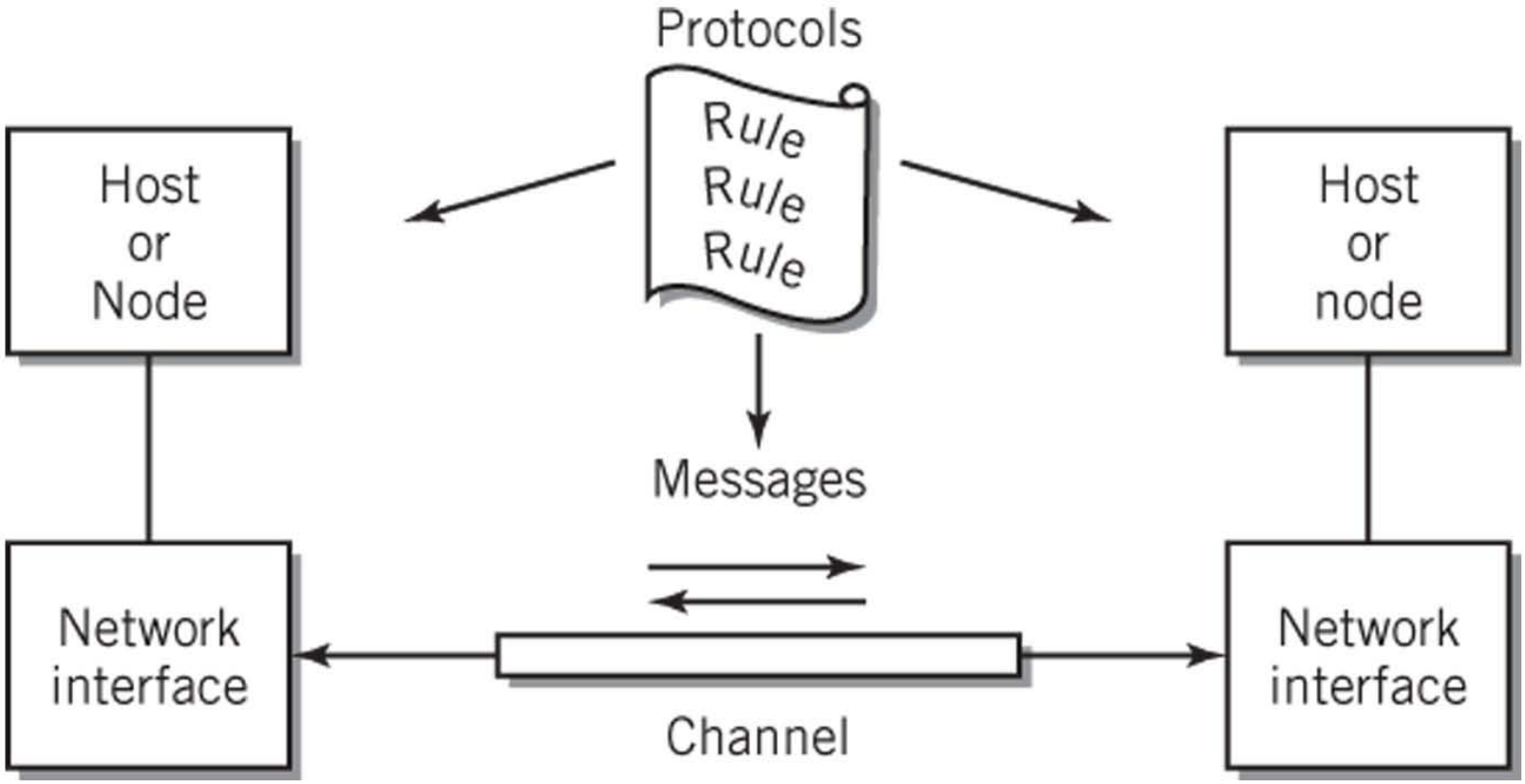
HTTP message sent:

```
GET /webapps/login/ HTTP/1.1
Host: blackboard.bentley.edu
Date: Wed, 23 Jul 2008 22:01:44 GMT
User-Agent: Mozilla/5.0 (Windows; U; Windows NT 5.1;
  en-US; rv:1.8.1.16) Gecko/20080702 Firefox/2.0.0.16
Connection: close
```

HTTP response received:

```
HTTP/1.1·200·OK(CR)(LF)
Date:·Wed,·23·Jul·2008·22:01:46·GMT(CR)(LF)
Server:·Apache/1.3.37·(Unix)·mod_ssl/2.8.28
  OpenSSL/0.9.8d·mod_jk/1.2.21(CR)(LF)
X-Blackboard-product:·Blackboard·Academic·Suite&#8482;
  7.2.383.23(CR)(LF)
Pragma:·no-cache(CR)(LF)
Cache-Control:·no-cache(CR)(LF)
Set-Cookie:·session_id=@@C296D067A2A703542F0C959C25\
  314FFE(CR)(LF)
Set-Cookie:·JSESSIONID=0115BEF92808AF234DD8843E\
  509AD2BD.root;·Path=/webapps/login(CR)(LF)
Connection:·close(CR)(LF)
Transfer-Encoding:·chunked(CR)(LF)
Content-Type:·text/html;charset=UTF-8(CR)(LF)
(CR)(LF)
<HTML content>
```

Model of a Communication Channel



Messages

- Communication between cooperating applications at each end node
- Can take many forms such as data, a program, a file, or multimedia
- Represented digitally
- Data is described as a byte stream because communications are predominantly serial
- Limitation as a communication tool is the varying message length
  - Long messages could tie up a communication channel indefinitely creating problems for other messages that share that channel

Packets

- A group of related packets make up a single message
- Consist of data encapsulated by the packet header which contains information about the packet
- Used to solve problems of channel availability and maximum utilization
- Equivalent to an envelope that contains pages of data

Packet Header

- Also known as the preamble
- Contains
  - Description of the packet
  - Destination address of receiver
  - Source address of sender
  - Information about the data being sent

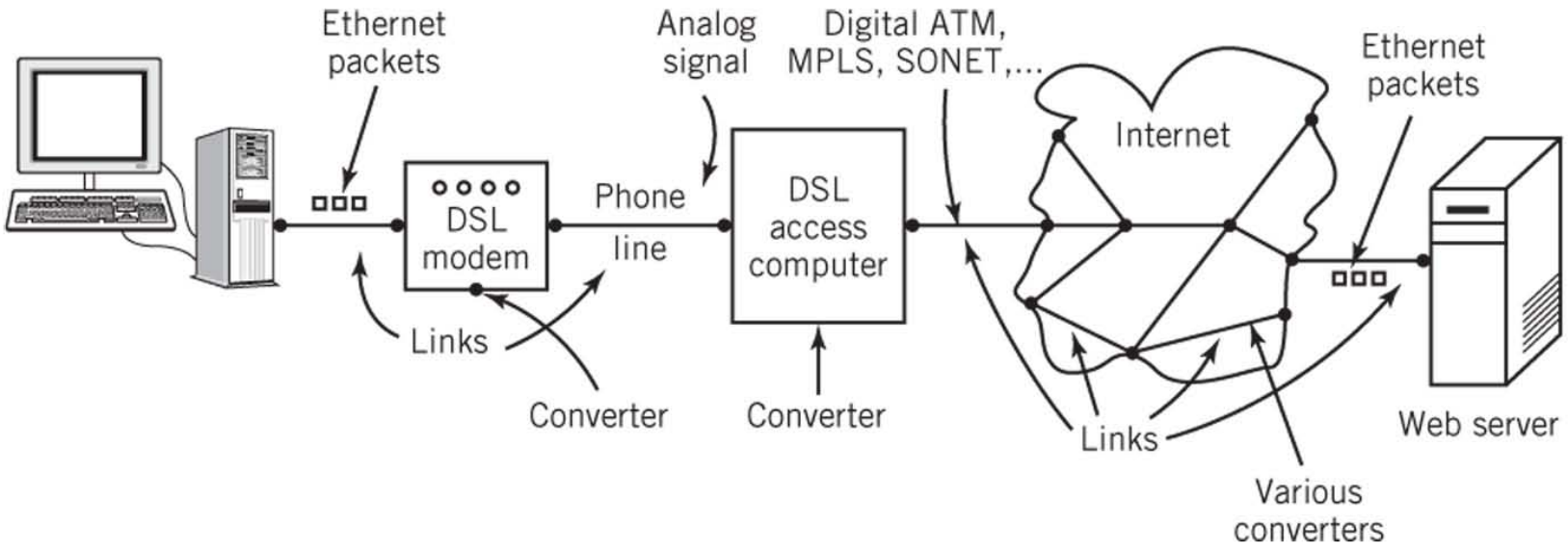
Advantages of Packets

- Simplifies operations and increases communications efficiency
- Reasonable unit for routing of data
- Alternative to dedicating a channel for the entire length of the message
- Packets from several sources can share a single channel
- Each sender/receiver pair appears to have a channel to itself
- Receiving computer can process an entire block of data instead of a character or byte at a time
- Simplifies synchronization of the sending and receiving systems by providing clear start and stop points

Channel Characteristics (1)

- Communication channel
  - The path for the message between two communicating nodes
  - May include intermediate nodes that forward packets to the next node
  - Interfaces at each end of the connection may be different
- Links
  - A segment of a communication channel
- Bandwidth
  - Bit rate of overall channel
- Medium
  - Guided – communications limited to a specific path
  - Unguided – communications not limited to a specific path

A Multi-Link Channel



Channel Characteristics (2)

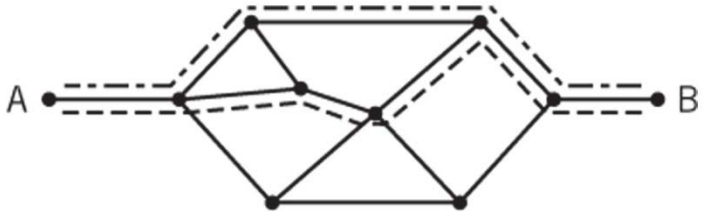
- Data transmission directionality
  - Simplex – messages are carried only in one direction
  - Half-duplex – messages are carried in both directions but only one direction at a time
  - Full duplex – messages are simultaneously carried in both directions
- Number of connections
  - Point-to-point
  - Multipoint
- Digital vs. Analog
- End node interfaces
  - Wired or wireless Ethernet
  - Bluetooth, WiMax, DSL or cable link, modem, etc.

Packet Routing

- Circuit switching
  - Dedicated channel between source and destination for duration of connection
- Virtual circuit
  - A channel path that is used to send packets between two end nodes
  - Intermediate nodes may be shared with other channel paths
- Packet switching (datagram switching)
  - Each packet is routed from node to node independently based on various criteria

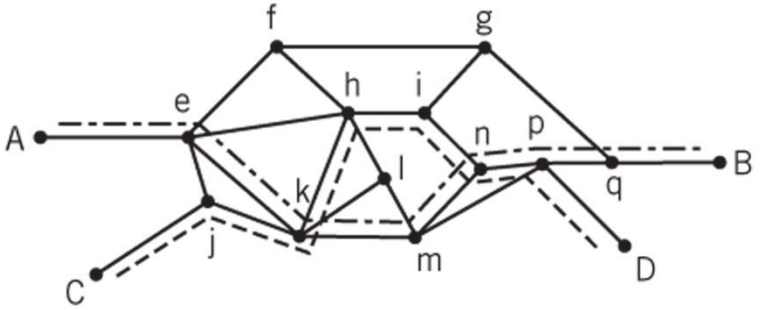
Packet Routing

End-to-end channel with many possible paths through intermediate nodes



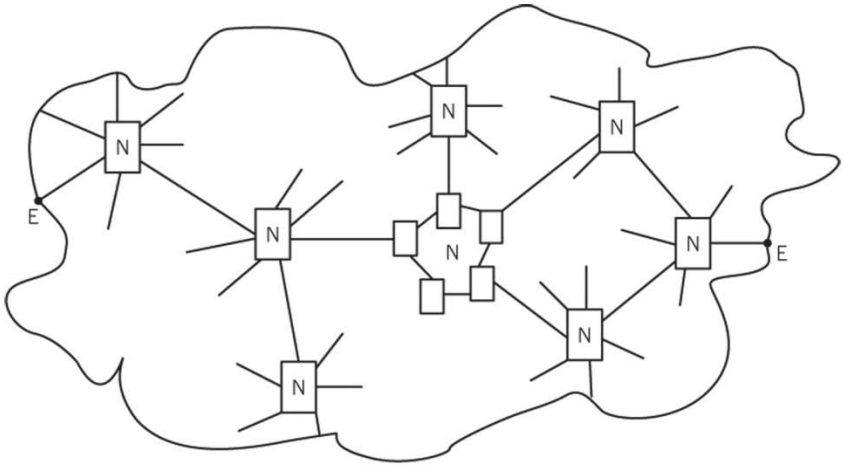
Path 1 ----
Path 2 ----

Virtual Circuits in a Network



A-B Path ----- (AekmnpqB)
C-D Path ---- (CjkhinpD)

Connecting End Points through Links and Networks

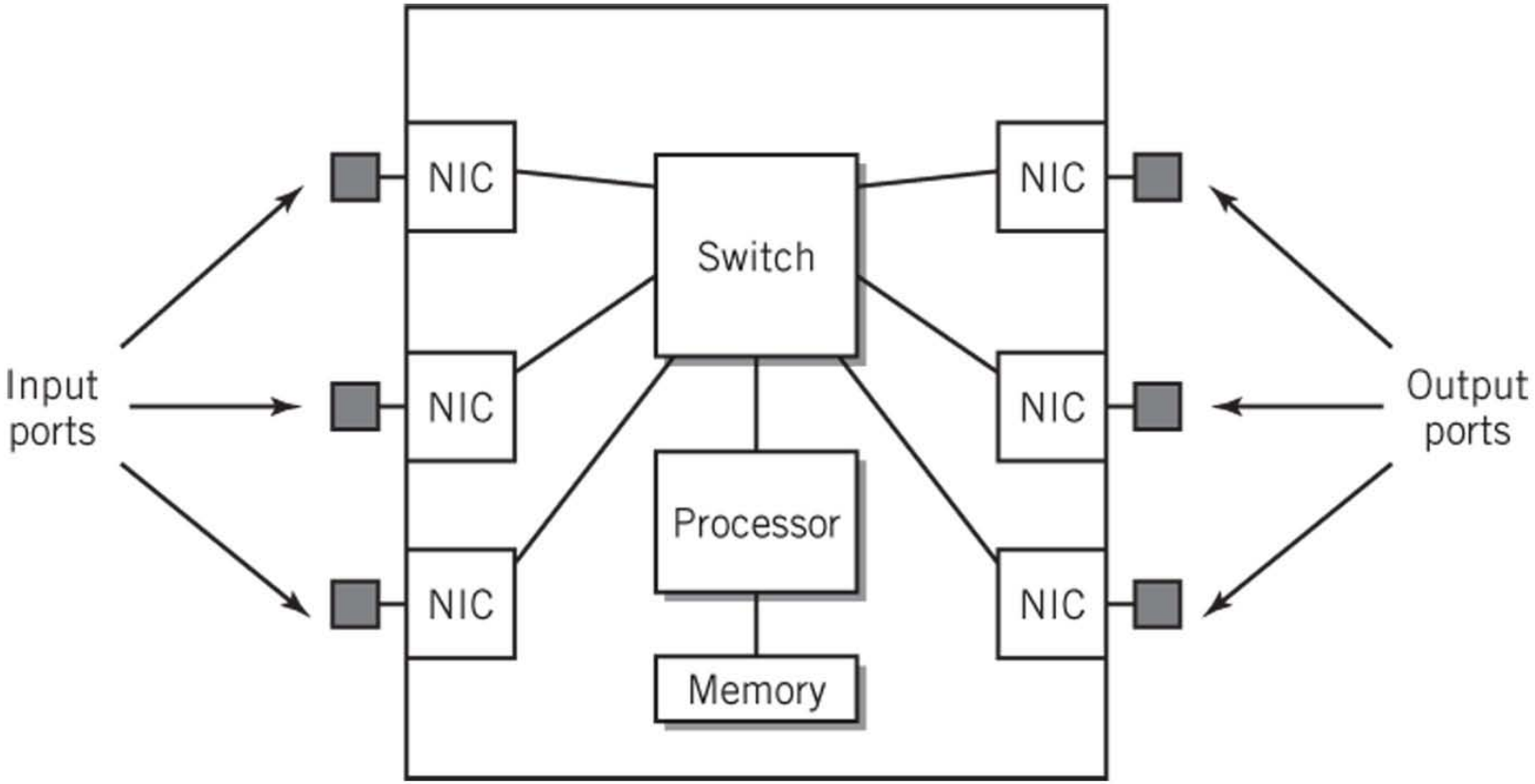


N = Network
E = Endpoint

Packet Routing

- Routers
  - Specialized devices used to interconnect network and pass packets from one network to another
  - Operation (see following slide)
    - When packet arrives at input port
    - Processor decides where packet is to be directed
    - A switch is set to direct the packet to the correct output port
- Gateways
  - Same as routers but connect dissimilar networks together
  - Convert packet headers for the dissimilar networks

Router Block Diagram



Network Overview

- Communication Models
  - TCP/IP
  - OSI
- Addressing
- Network Topology
- Types of Networks
  - Local Area Networks
  - Backbone Networks
  - Metropolitan Area Networks
  - Wide Area Networks
  - Internet Backbones and the Internet
  - Piconets
- Standards

Communication Model

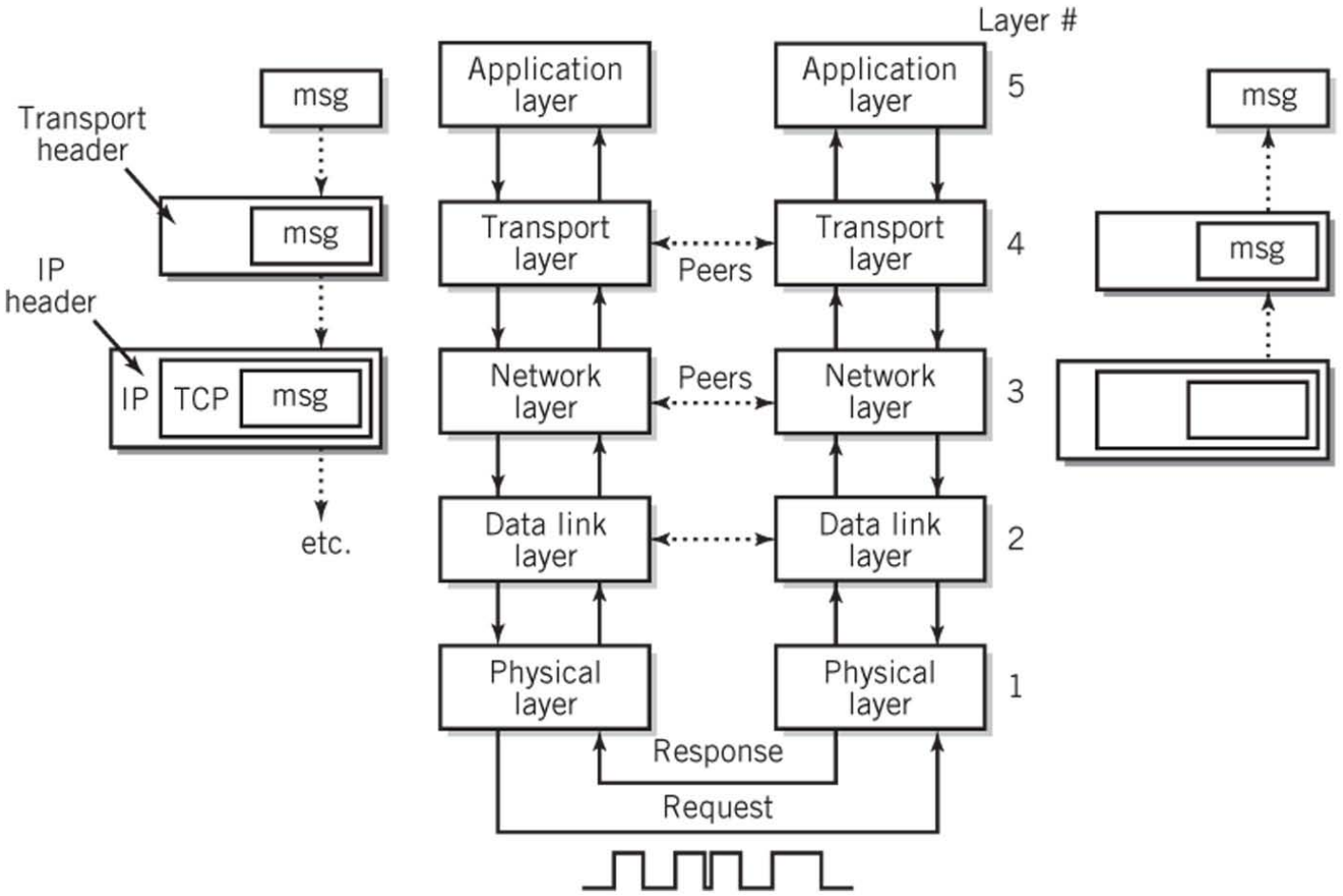
- Implemented as a hierarchical protocol stack
- Each layer of the stack at the sender node contributes information that is used by the corresponding peer layer at the receiver node
- Different protocols for the different aspects of communication
- Separating tasks and including well defined interfaces between the tasks
  - Adds flexibility
  - Simplifies design of protocols
  - Permits modification or substitution of protocols without affecting unrelated tasks
  - Permits a system to select only the protocols needed for a particular application

TCP/IP

- Transmission Control Protocol/Internet Protocol
- Based on five protocol layers, although layers 1 and 2 are not actually specified in the standard. However, the TCP/IP model recognizes the existence of these layers as a necessity.
- The TCP/IP protocol suite encompasses an integrated suite of numerous protocols that work together and guide all aspects of communication.

Layer 5	Application layer	HTTP SMTP	FTP SSH	DNS POP3	...
Layer 4	Transport layer	TCP	UDP	SCTP	
Layer 3	Network layer	IP	ICMP DHCP	ARP	
Layer 2	Data link layer	Depends on underlying network			
Layer 1	Physical layer	Depends on underlying network			

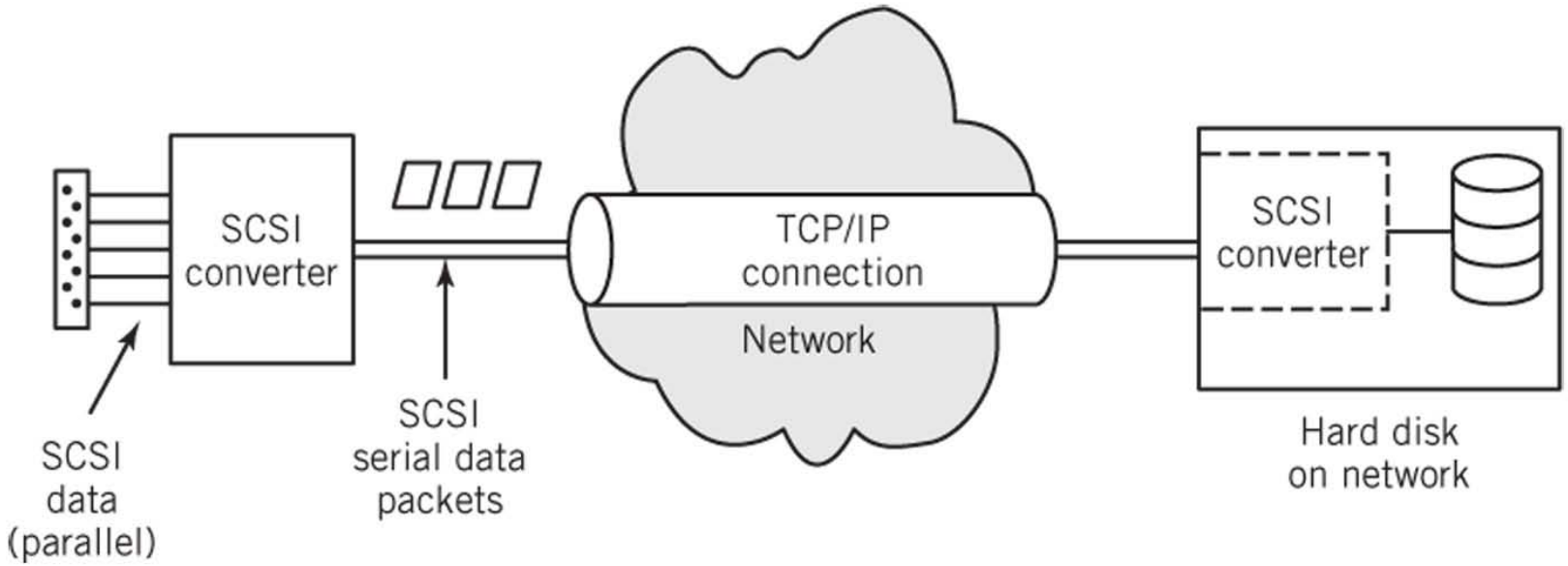
Operation of TCP/IP Model



Application Layer (Layer 5)

- Layer where message is created
- Includes any application that provides software that can communicate with the network layer
- Sockets
  - Originated with BSD UNIX
  - Provide the interface between the application layer and transport layer
  - Used by applications to initiate connections and to send messages through the network
  - A means for adding new protocols and keeping the network facilities current in their offerings
  - Example: SCSI over IP

SCSI over IP



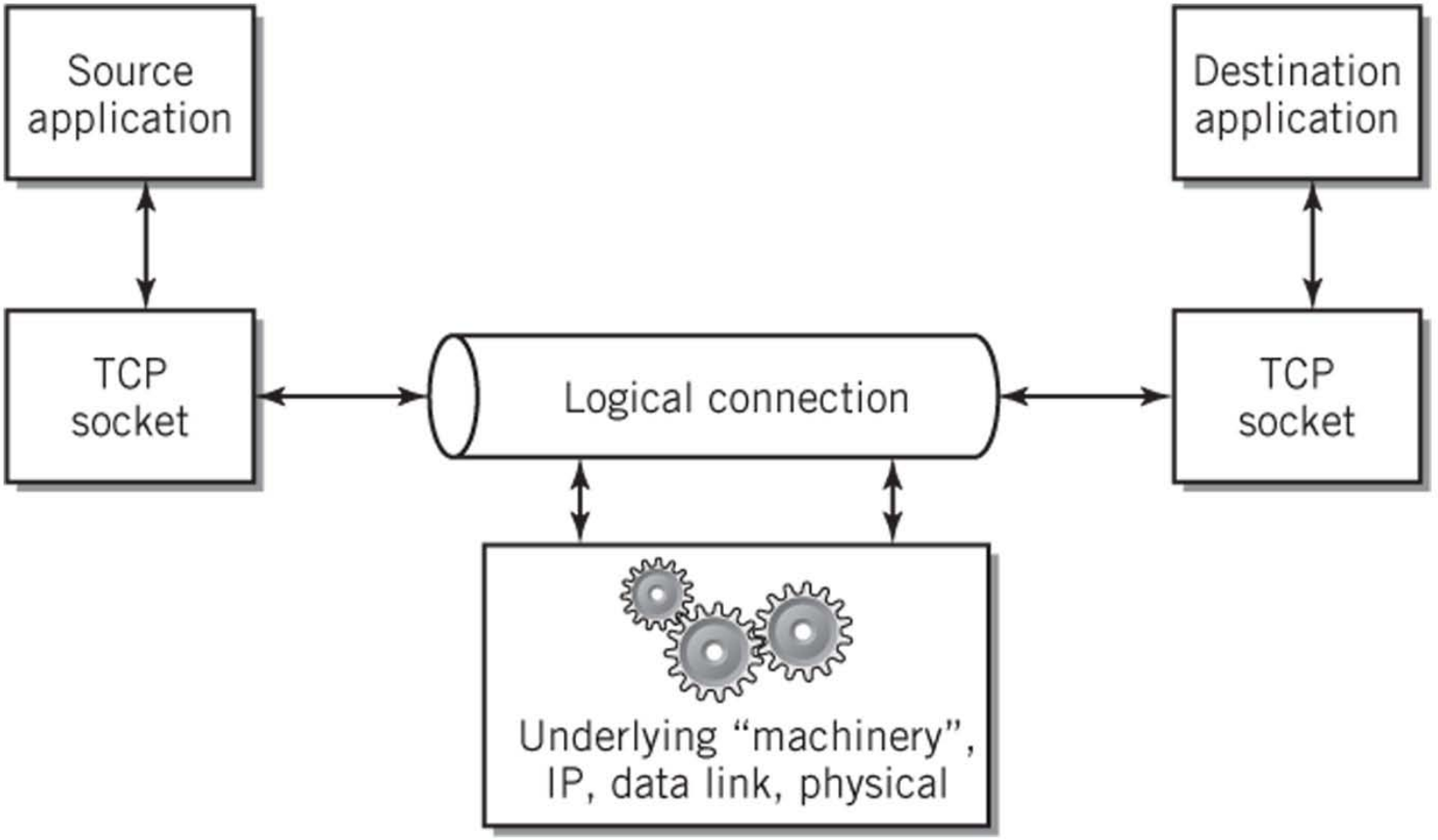
Transport Layer (Layer 4)

- Provides services that support reliable end-to-end communications
- Generates the final address of the destination
- Responsible for all end-to-end communication facilities
- Packetization of the message, breaking up of the message into packets of reasonable size takes place at this level
- Three different protocols
  - TCP
  - UDP
  - SCTP

Transport Layer Protocols

- TCP (Transmission Control Protocol)
  - Reliable delivery service
  - Sending and receiving TCP each create a socket
  - Control packets are used to create a full duplex connection between the sockets
  - A single TCP service can create multiple connections that operate simultaneously by creating additional sockets as needed
  - Routing is the responsibility of the network layer (layer 3)
- UDP (User Datagram Protocol)
  - Unreliable, connectionless service
  - No acknowledgment of receipt by receiving node
  - Example: streaming video
- SCTP (Stream Control Transmission Protocol)
  - Similar to TCP but with improved fault tolerance and ability to transport multiple messages through the same connection

Logical Connection View of TCP



Network Layer (Layer 3)

- The TCP/IP network layer is also called the internetworking layer or the IP layer
- Responsible for the addressing and routing of packets to their proper and final destination
- Unreliable, connectionless, packet switching service
- Does not guarantee delivery nor check for errors
- Routers and gateways are sometimes referred to as level 3 switches to indicate the level at which routing takes place

Network Layer (cont.)

- Communications within a local network:
  - No routing is required because nodes are directly addressable
  - Physical addresses for corresponding IP addresses are looked up in a table
  - IP appends a header with the physical address and passes the datagram to the data link layer (layer 2)
- Communications sent outside of the local network
  - At each intermediate node, the network layer removes the current node address and determines the next node address
  - The new address is added to the packet and passed to the data link layer (layer 2)

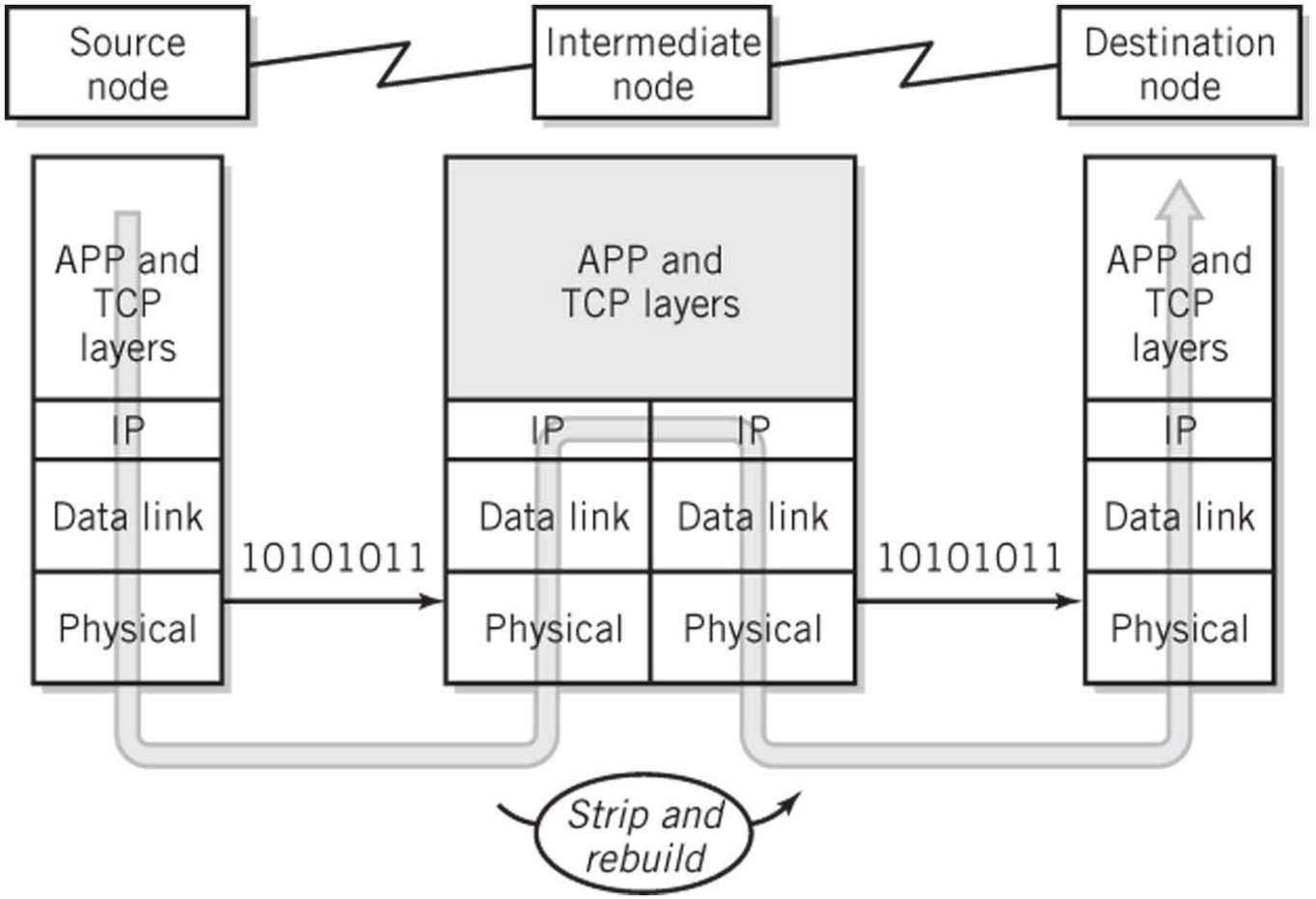
Data Link Layer (Layer 2)

- Responsible for the reliable transmission and delivery of packets between two adjacent nodes
- Packets at this layer are called ***frames***
- Often divided into the following two sublayers:
  - Software logical link control sublayer
    - Error correction, flow control, retransmission, packet reconstruction and IP datagram/frame conversions
    - Numbers frames and reorders received frames to recreate the original message
    - Rarely used
  - Hardware medium-access control sublayer
    - Defines procedures for access the channel and detecting errors
    - Responsible for services such as data encoding, collision handling, synchronization, and multiplexing

Physical Layer (Layer 1)

- Layer at which communication actually takes place consisting of a bare stream of bits
- Primarily implemented in hardware by a network interface controller (NIC)
- Physical access protocol includes
  - Definition of the medium
  - Signaling method, signal parameters, carrier frequencies, lengths of pulses, synchronization and timing issues
  - Method used to physically connect the computer to the medium

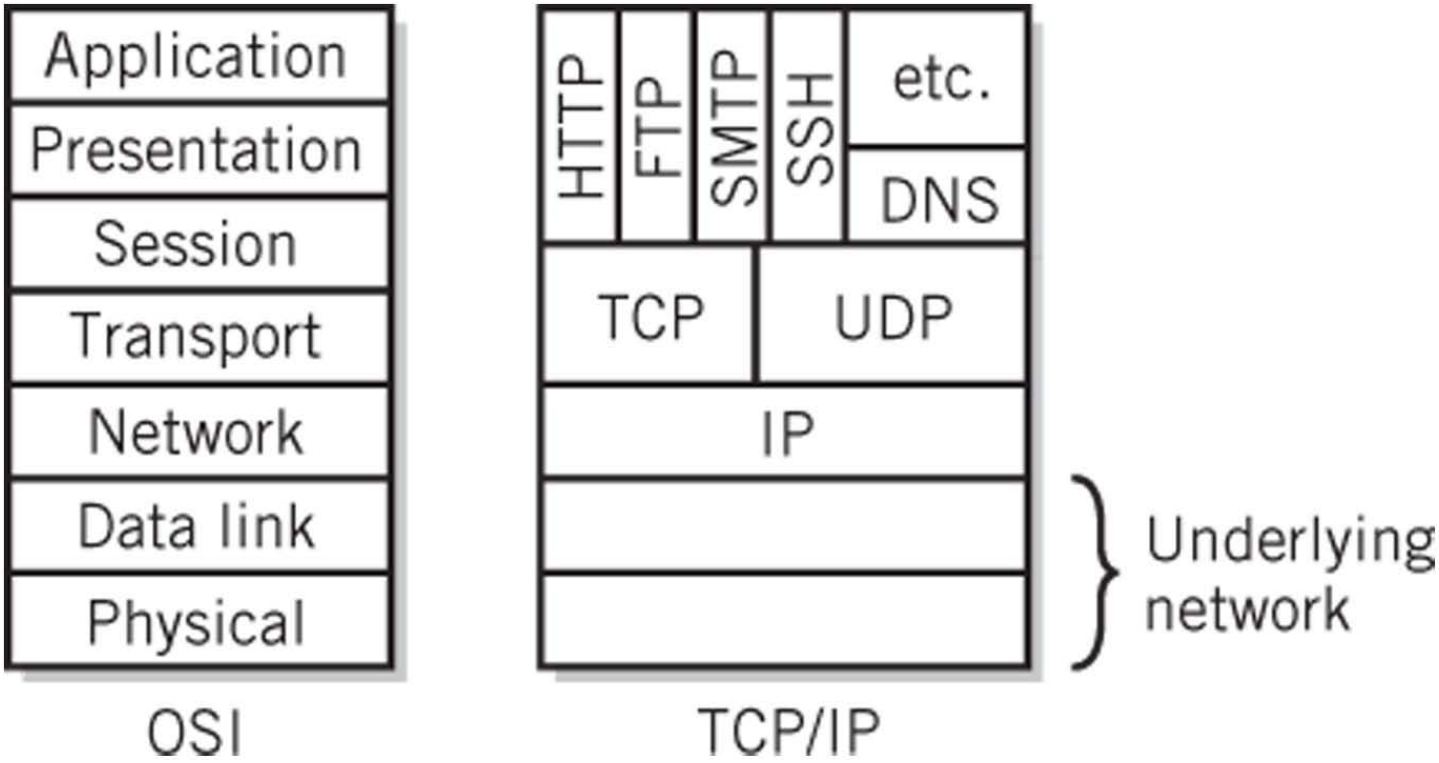
Passing a Message Through an Intermediate Node



OSI Model

- Open Systems Interconnection Reference Model was created by the International Standards Organization (ISO)
- Although a conceptually important model, OSI is not widely accepted or used for actual communication
- Contains seven layers instead of five
- The application layer in the TCP/IP model is essentially represented by three layers in the OSI model
  - Application layer
  - Presentation layer
  - Session layer

Comparison of OSI and TCP/IP



OSI Presentation Layer

- Responsible for presenting data at the destination with the same meaning and appearance as it would have at the source
- Provides common data conversions and transformations that allow systems with different standards to communicate
- Includes services such as data compression and restoration, encryption and decryption, data reformatting, ASCII-Unicode conversion, etc.

OSI Session Layer

- Establishes a dialogue between two cooperating applications or processes at the ends of the communication link
- Responsible for
  - Establishing the session between the applications
  - Controlling the dialogue
  - Terminating the session
- Examples
  - Remote login
  - Print spooling to remote printer

TCP/IP Addressing (1)

- User friendly addresses
  - URL – www.youtube.com
  - Email – somebody@yahoo.com
  - Printer name on the network
- Domain name
  - Standard global domain name system provides global scope for user friendly addresses
  - Hierarchical system for name creation and registration
  - Tools for locating and identifying specific names

TCP/IP Addressing (2)

- Port Addresses (port numbers)
  - Transport layer uses to identify the application that is to receive the message
  - 16 bits in length
  - Example: port 80 is commonly used for Web services
  - First 1024 numbers are called well-known ports because they are standard addresses specified for most common applications
  - User defined port numbers are also available to applications
  - For example, the following Web service uses the user-defined port of 8080
    http://www.somewhere.org:8080/hiddenServer/index.html

Well-Known Port Addresses

ftp	20	file transfer
ssh	22	secure login
smtp	25	simple mail transfer
nicname	43	"who is" request
finger	79	info about system
http	80	Web
kerberos	88	encryption
pop3	110	post office protocol
sqlserv	118	SQL services

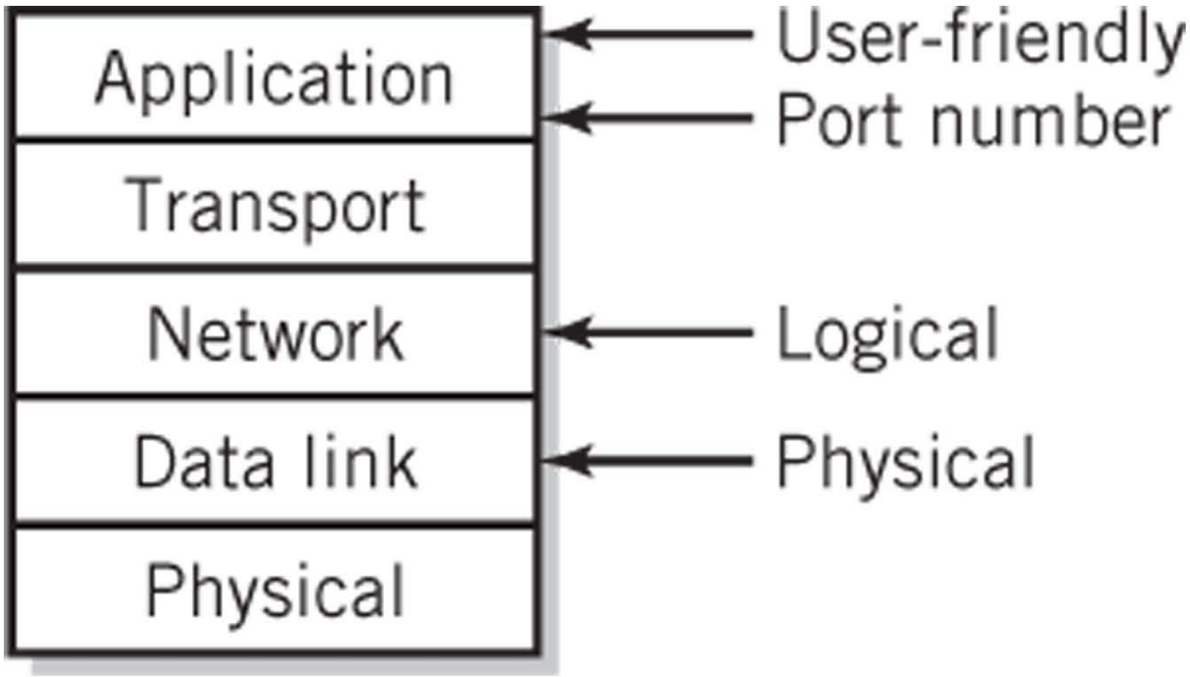
TCP/IP Addressing (3)

- IP addresses
  - Logical addresses
  - IPv4
    - 32-bit addresses arranged as 4 octets, delimited by dots
    - Each octet is written as a decimal number between 0 and 255
    - Example: 208.80.152.2 (Wikipedia's IP address)
  - IPv6
    - Intended to eventually supplant IPv4 to provide additional IP addresses
    - 128-bit addresses arranged as 8 groups of four-digit hexadecimal numbers separated by colons
    - Leading zeros and zero values in one or more consecutive groups may be eliminated
    - Example: 6E:2A20::35C:66C0:0:5500 is the same as 006E:2A20:0000:0000:035C:66C0:0000:550

TCP/IP Addressing (4)

- Domain name translation
  - Translate a user friendly address into an IP address and port address for the transport layer
  - Utilizes a global domain name directory service
- Address resolution protocol (network layer)
  - Translates IP addresses into physical addresses
- MAC (medium-access control) address
  - Most common type of physical address
  - Every manufactured device that may connect to a network anywhere in the world is supplied with a permanent, unique MAC address
  - Format consists of 48 bits arranged as 6 two-digit hexadecimal numbers separated by colons
  - Example: 00:C0:9F:6C:F9:D0

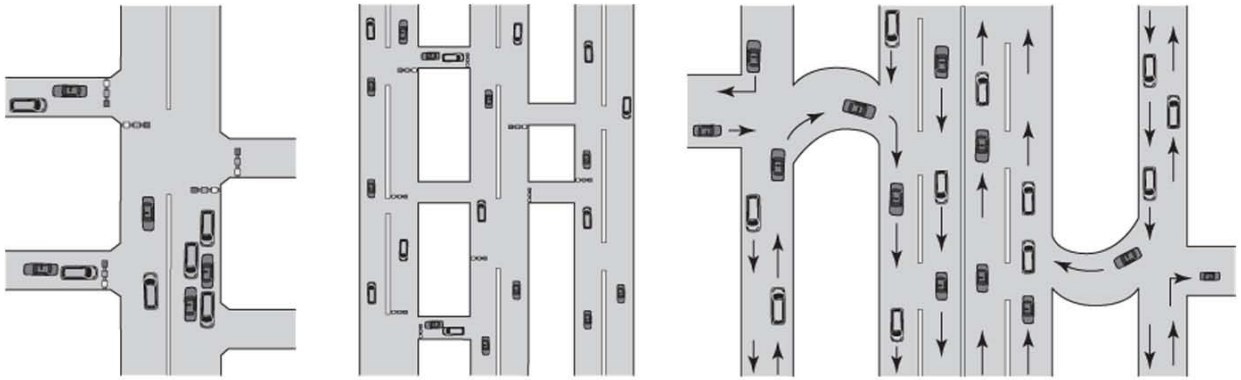
Different Addresses Used in a Network



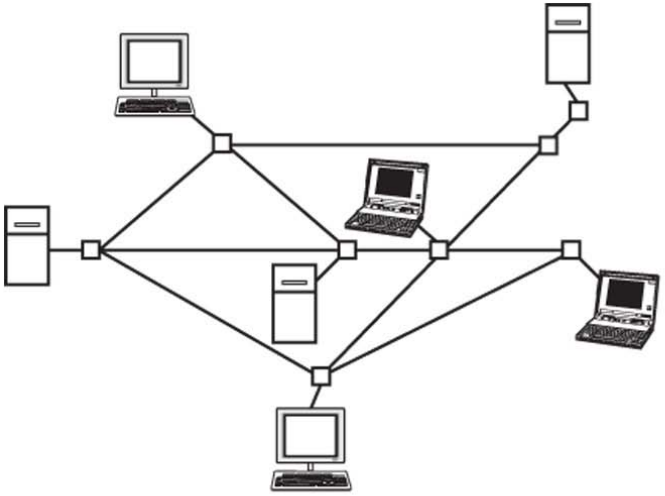
Network Topology

- Fundamental layout of a network
- Describes the path or paths between any two points in the network
- Affects availability, speed and traffic congestion of the network
- Logical topology – operational relationship between the various network components
- Physical topology – actual layout of the network wiring

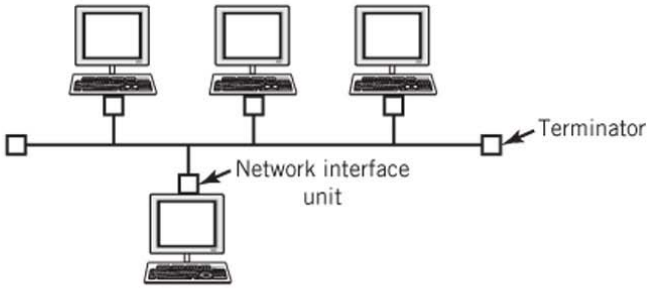
Automobile Traffic Scenarios



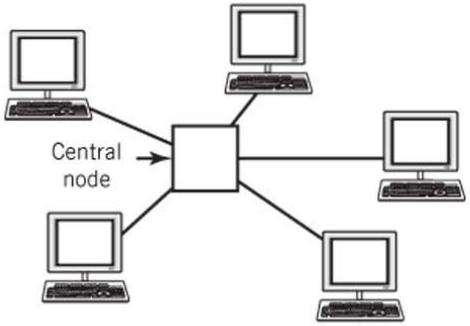
Four Network Topologies



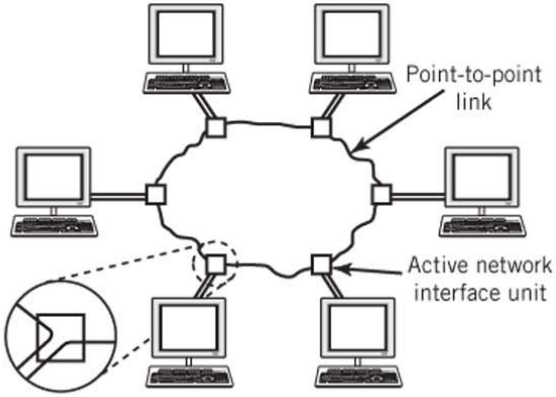
(a) Mesh network



(b) Bus topology



(c) Star topology

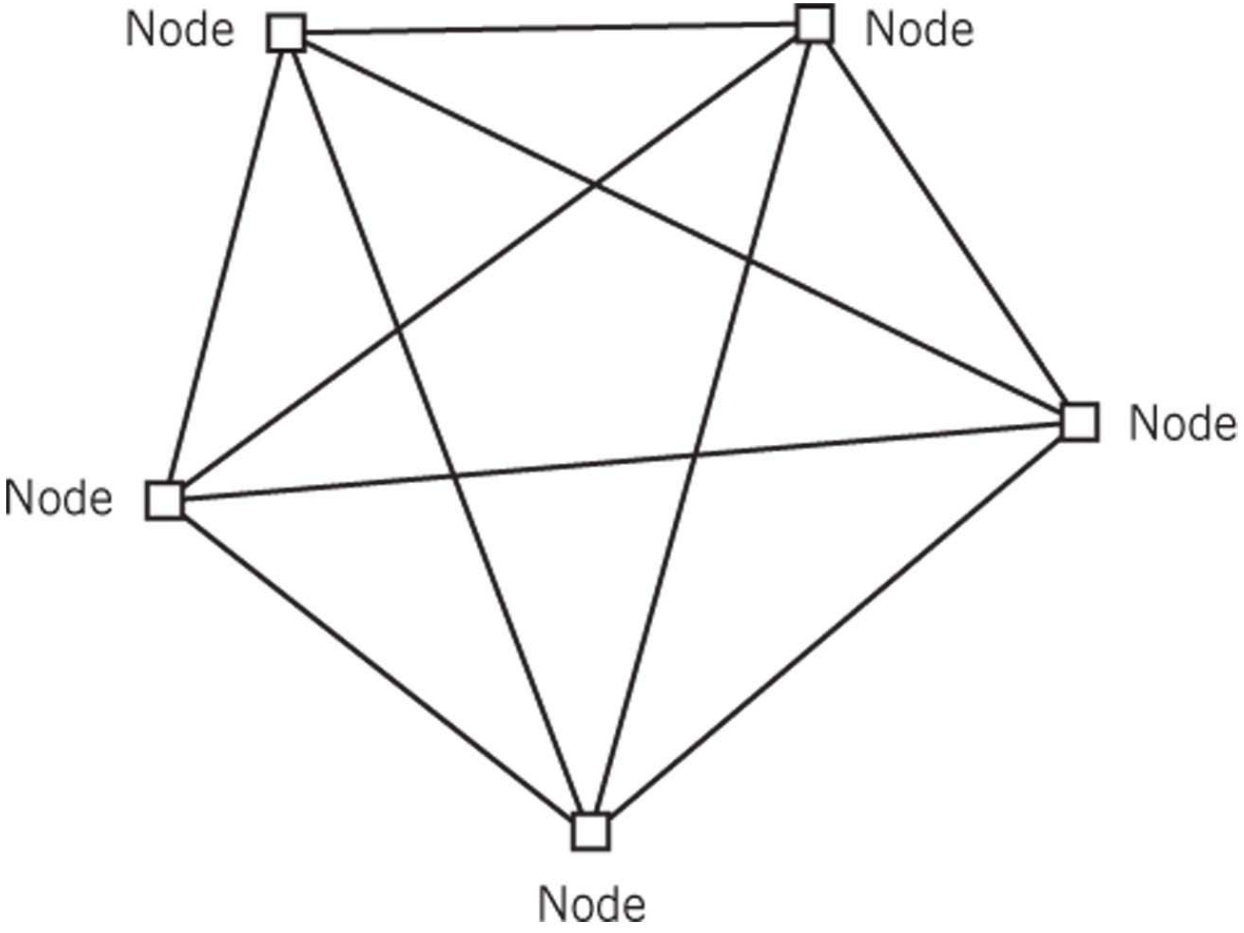


(d) Ring topology

Mesh Topology

- Multiple paths between end nodes
- Failure of an individual intermediate node will slow but not stop the network as long as an alternative path is available
- Large networks that use switches and routers are typically partial mesh networks
- Full mesh network
  - Direct point-to-point channel connecting every pair of nodes
  - Impractical due to the large number of connections needed
  - Number of connections = nodes x (nodes – 1) / 2
  - 500 computer nodes would require 125,000 interconnecting cables!

Five-Node Full Mesh Network



Bus Topology

- Similar to multipoint buses in chapter 7
- Each node is tapped into the bus along the bus
- To communicate, each node “broadcasts” a message that travels along the bus
- Every node on the bus receives the message but it is ignored by all nodes except the one whose node matches the delivery address in the message
- Transmission from any stations travels entire medium (both directions)
- Termination required at ends of bus to prevent the signal from echoing
- Branches can be added to a bus, expanding it into a tree but messages are still broadcast throughout the entire tree

Bus Network Implementation

- Only requires a single pair of wires from one end of the network space to the other
  - Easiest to wire of the network topologies
  - Low cost
- Traffic congestion is a major issue
- Rarely used in designs of new networks except for wireless networks
- Because of the unguided nature of radio waves, wireless networks require some form of bus topology

Star Topology

- Primarily used for local area networks and sometimes used to connect satellite offices to a central office
- All nodes are connected point-to-point to a central device
- Nodes communicate through the central device
- Switching in the central device connects pairs of nodes together to allow them to communicate directly
- Central device can steer data from one node to another as required
- Most modern switches allow multiple pairs to communicate simultaneously
- Failure of central device causes entire network to go down

Ring Topology

- Point-to-point connection from each node to the next
- Last node is connected back to the first to form a closed ring
- Each node retransmits the signal that it receives from the previous node in the ring
- Packets are placed on the loop at a node, and travel from node to node until the desired node is reached
- Although the ring is inherently unidirectional, it is possible to build a bidirectional ring network
- Popular in the past because they provided a controlled way in which to guarantee network performance
  - Legacy token-ring local area networks
- Used in some FDDI fiber optic backbone and metropolitan area networks

Local Area Networks (LAN)

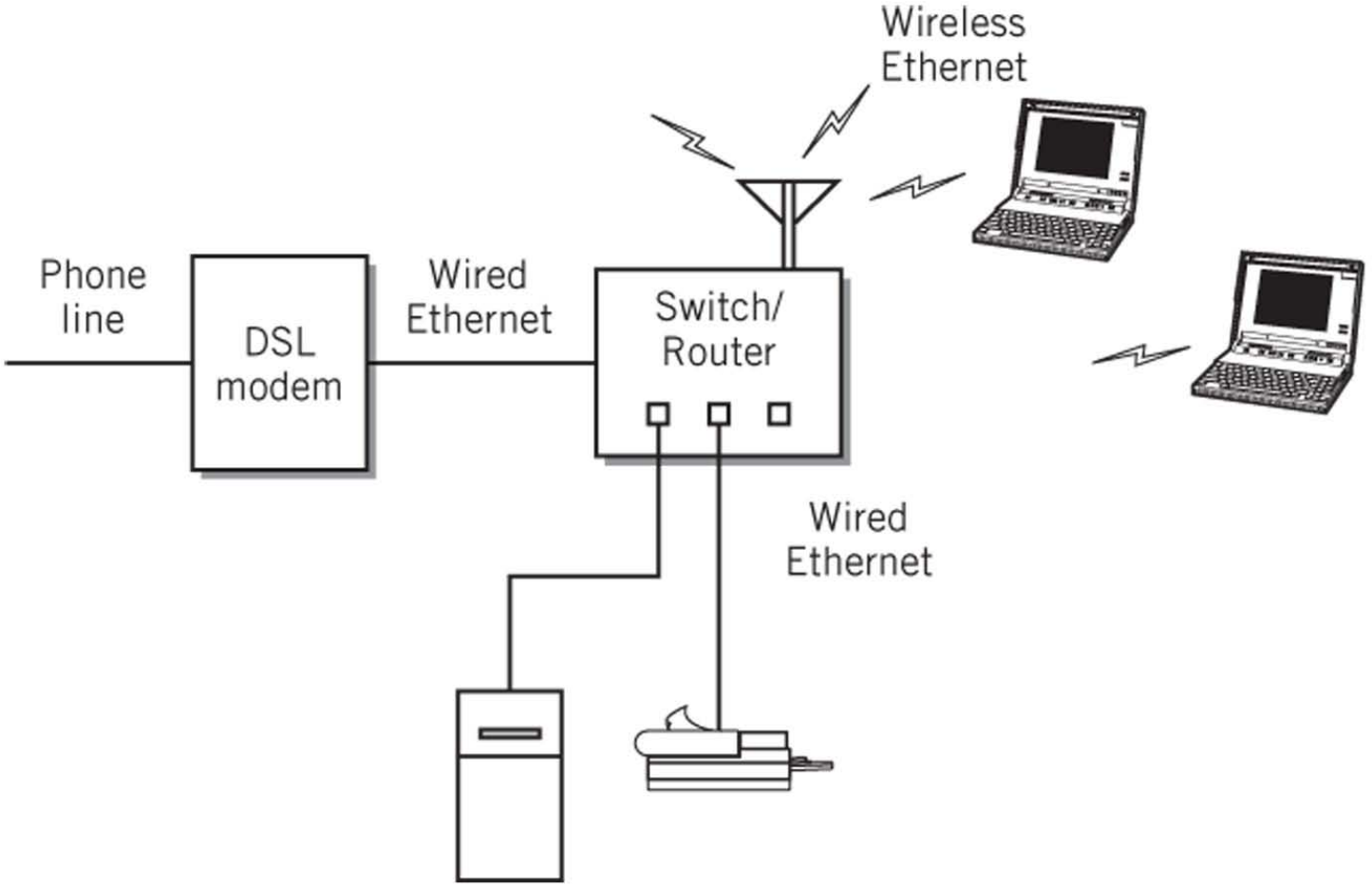
- A network that connections computers and other supporting devices over a relatively small localized area
- Typically ranging in size from a single room to multiple buildings in close range of each other
- Most of the computers are personal computers or workstations
- Routers and perhaps gateways are used to connect the LAN to other networks
- Creating separate LANs for different departments or for different business functions is done to minimize extraneous traffic on the network
- Most modern LANs are based on one of the Ethernet protocol standards

Common Ethernet Standards

Standard	Medium	Speed	Max span	Topology
10 BASE-T	2-UTP	10 Mbps	100 meters	hub or switch
100 BASE-TX "Fast Ethernet"	2-UTP or STP or CAT-5	100 Mbps	100 meters	hub or switch
100 BASE-FX	2-Fiber optics	100 Mbps	100 meters	-
1000 BASE-T "Gigabit Ethernet"	CAT-5 UTP	1 Gbps	100 meters	switch
1000 BASE-SX, LX	2-Fiber optics	1 Gbps	550 meter, 5 km	
10G BASE-X "10-Gigabit Ethernet"	2-Fiber optics	10 Gbps	300 m, 10 km, 40 km	
Under development				
40G BASE-X	2-Fiber optics	40 Gbps	100 m, 10 km	
100G BASE-X	2-Fiber optics	100 Gbps	100 m, 10 km, 40 km	

Key: UTP unshielded twisted pair
STP shielded twisted pair
CAT-5 four UTP in a cable

Typical Home Network



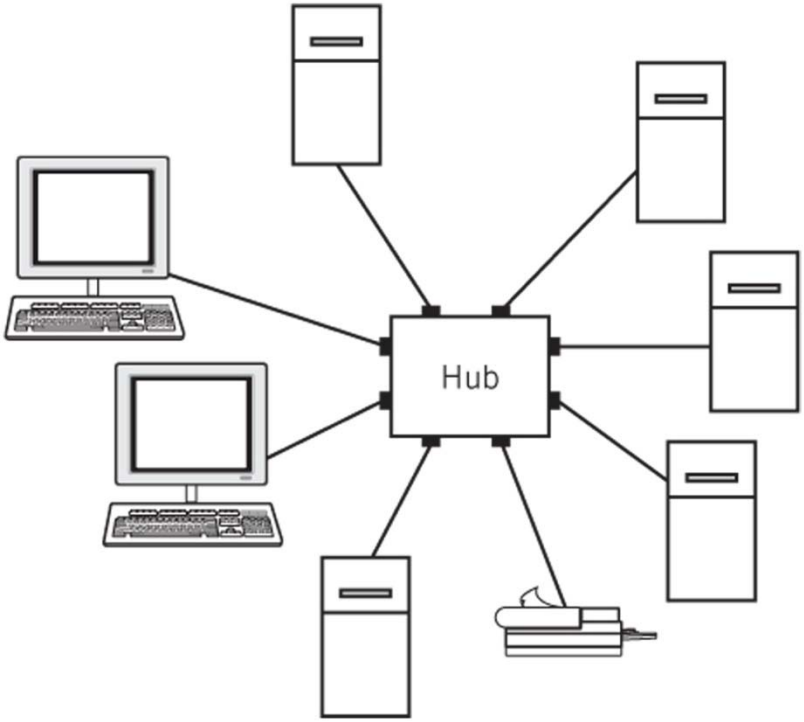
Ethernet Hubs

- Based on bus topology
- A passive central connection device used to simplify wiring and maintenance
- Physical layer device where all of the connections are tied together inside the hub
- Signals are broadcast to every device connected to the hub
- Uses the CSMA/CD medium access control protocol
- Use of hubs is declining because switches often provide better performance

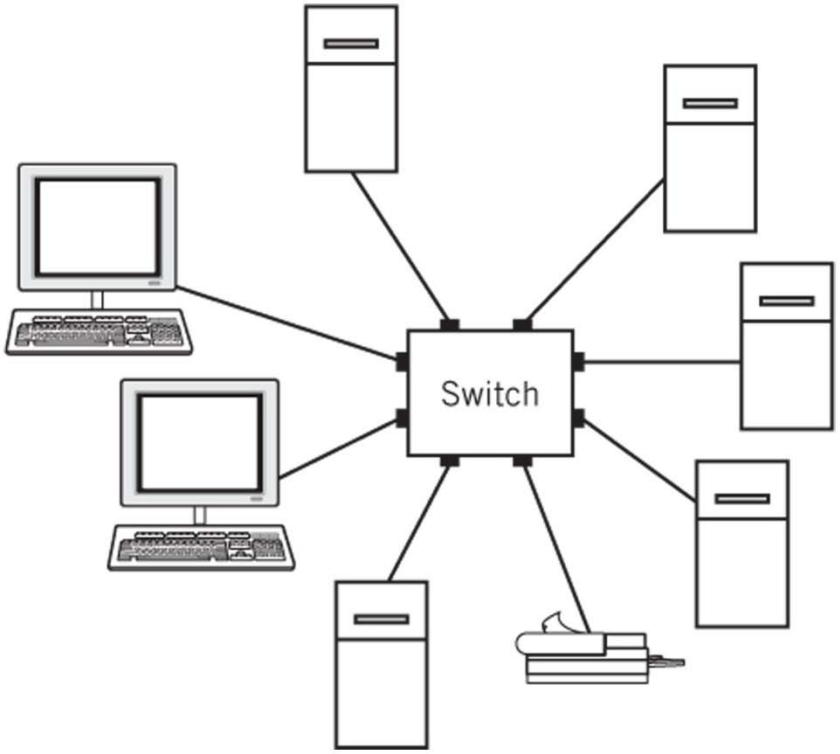
Ethernet Switches

- Logically a star topology, not a bus topology
- Able to set up a direction connection between any two nodes
- Multiple pairs of nodes can communicate at the full bandwidth
- Prevalent method for wired local area networks

Hub vs. Switch Based Ethernet



Logically a bus and can be viewed as a zero-length bus



Logically and physically a star topology

Wireless Ethernet (WiFi)

- Radio-based compatible extension to the Ethernet standard
- Central access point is similar to a hub but is an active node
- Central access point transmits and receives radio waves to communicate with the nodes
- Radio space must be shared between the nodes
- Does not use the CSMA-CD protocol because it is possible for units to be far away that although they can communicate with the access point, they cannot detect one another

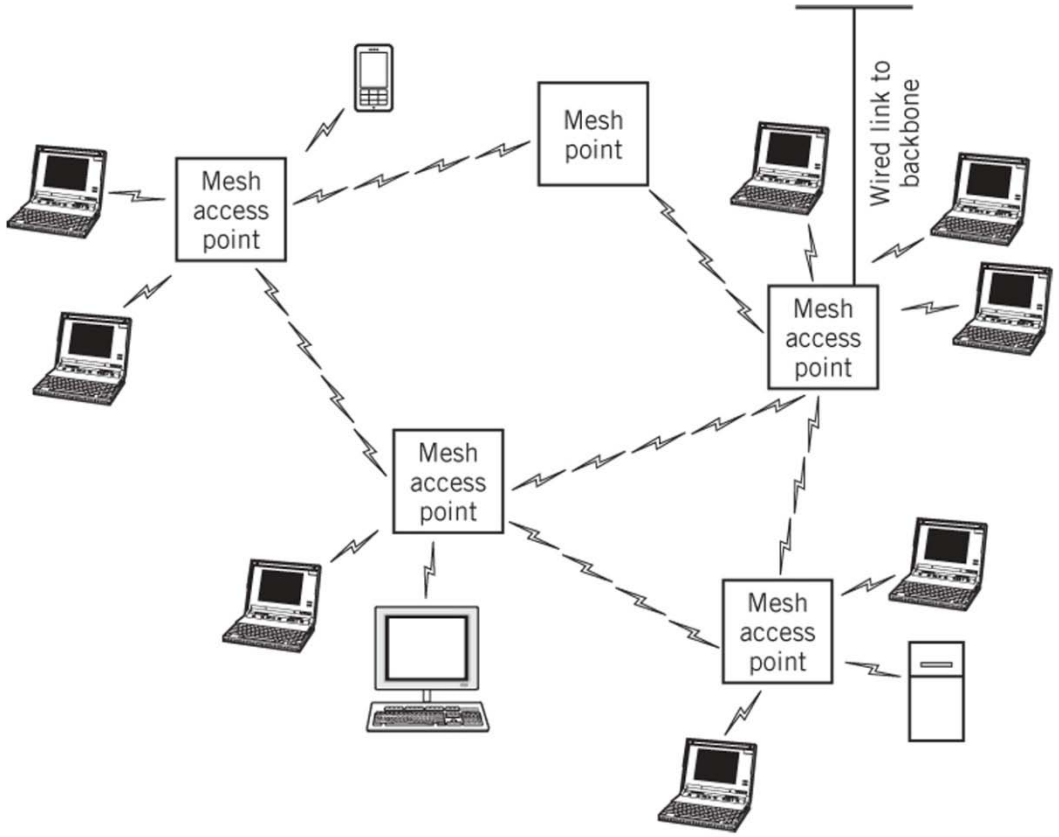
Wireless Ethernet Characteristics

Standard	Carrier band	Max. data rate	Claimed typical max. range
802.11a	5 GHz	54 Mbps	60 feet
802.11b	2.4 GHz	11 Mbps	300 feet
802.11g	2.4 GHz	54 Mbps	300 feet
802.11n*	5, 2.4 GHz	248 Mbps**	600 feet

* Unofficial as of June 2008

** Possible future theoretical maximum data rate of 600 Mbps

Wireless Mesh Network

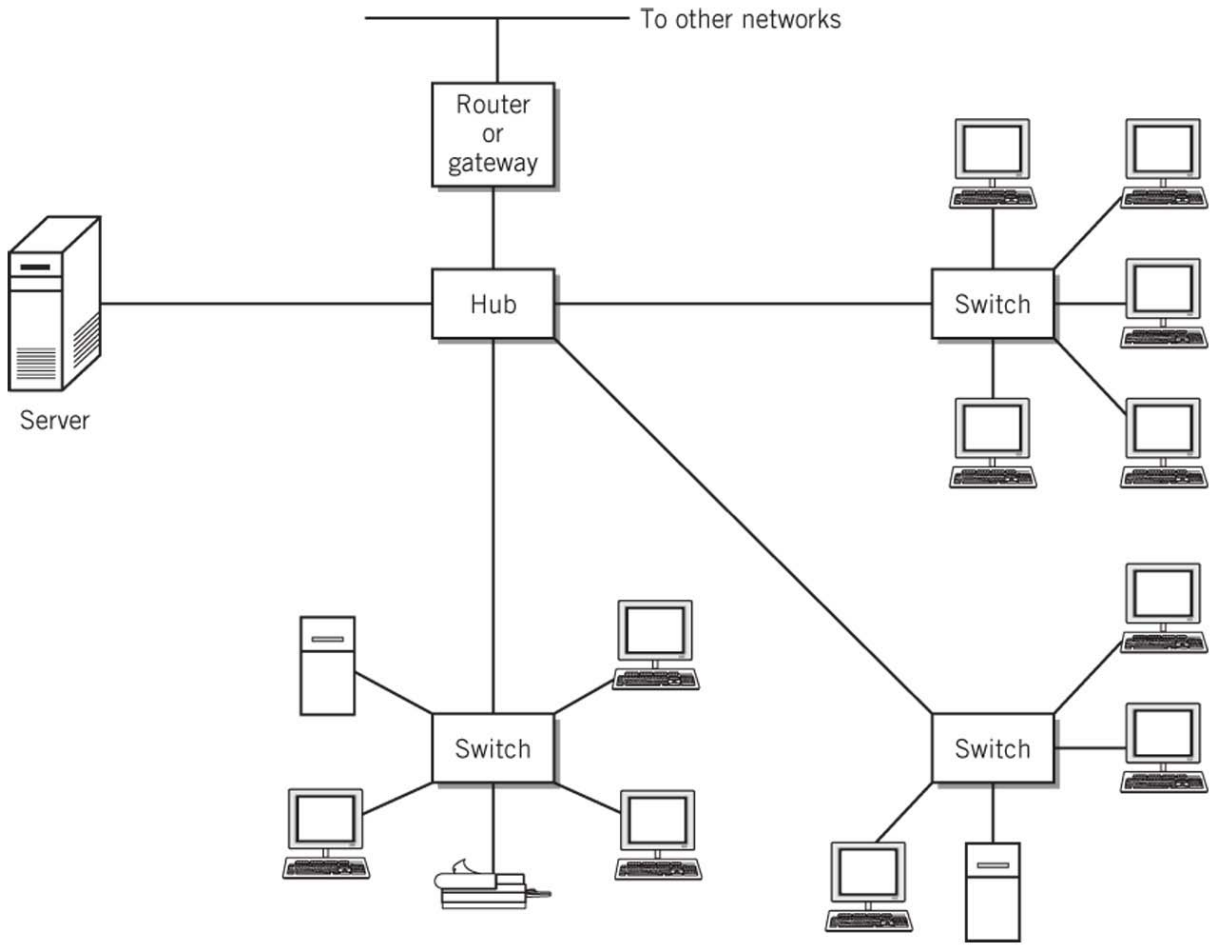


Mesh points operate at the medium-access control layer and do not require wiring

Backbone Networks

- Also called tiered Ethernet
- Ties together LANs and provides access to external networks like the Internet
- Chief motivation is to improve overall performance of a larger network by creating separate networks for groups of users who primarily communicate with one another
- Communicate between the LANs is enabled only when necessary
- Overall range of the network can be extended beyond the limits of a single LAN
- Can be viewed as a large LAN where each node is itself a LAN
- Intranets – an organizational network where user interfaces and applications are primarily based on Web services

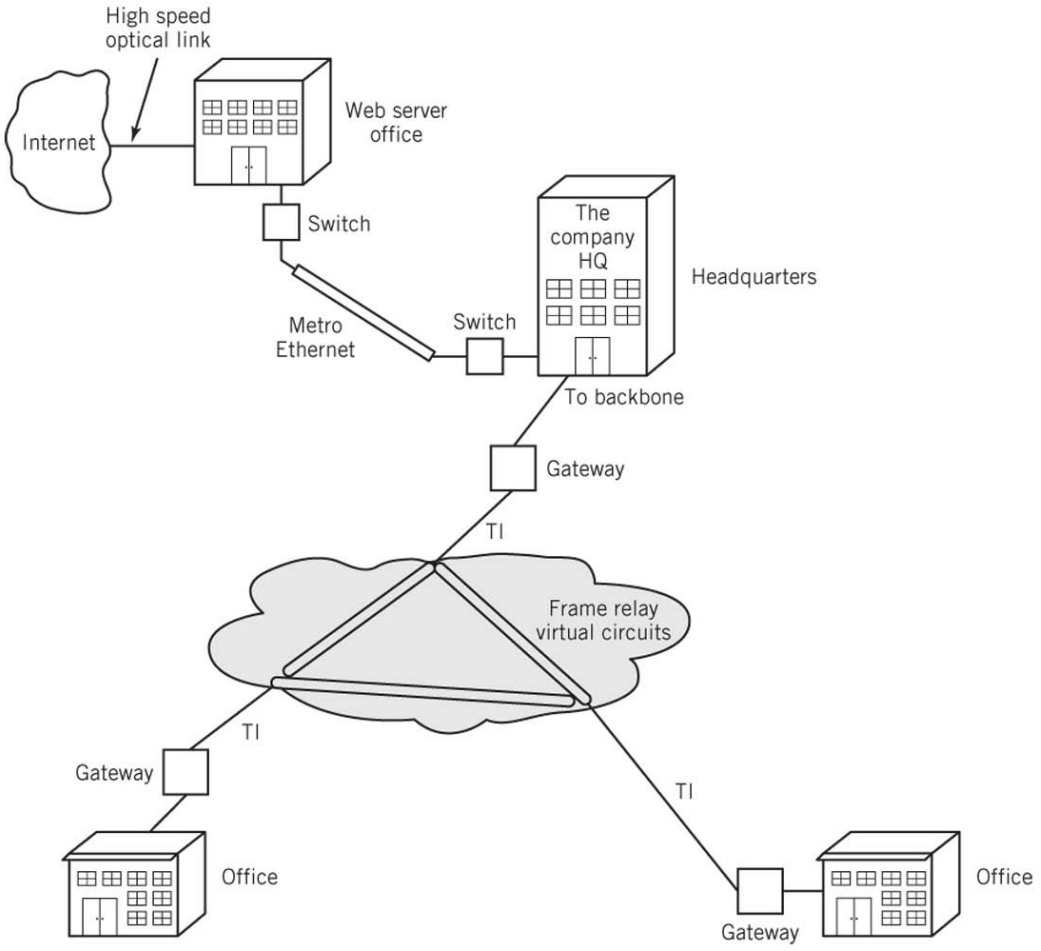
Backbone Network



Metropolitan Area Networks

- A network larger in geographical scope than a LAN but within a range of less than 30 miles or 50 km
- Often there is a desire to create network links to link locations that would require running wires through someone else's property.
  - Requires services from a service provider or public carrier
  - Begins to resemble a WAN
  - Edge connection – a connection at an access point on the customer's premises that connects to a provider
- Campus area network (CAN)
  - Network type between a LAN and a MAN
  - Number of interconnected buildings clustered together

Metropolitan Area Network



Wide Area Networks (WAN)

- Facilitate communications between users and applications over large geographical distances
- Distinguishing feature is the extensive reliance on service providers to provide the required connectivity between nodes
- The carrier network is sometimes represented as a collection of private virtual networks
- Primary reasons for WANs
  - Organization requires data communication links between widely spread facilities and between an organization and its external contacts
  - Organization requires fast access to the Internet, either as a consumer or as a provider of Internet services, or both
- Extranet
  - A connection between a business and its business partners that usually uses the Internet as a medium for its activities

Two Real-World WANs

(a) The SURFnet gigabit Ethernet WAN (Netherlands)

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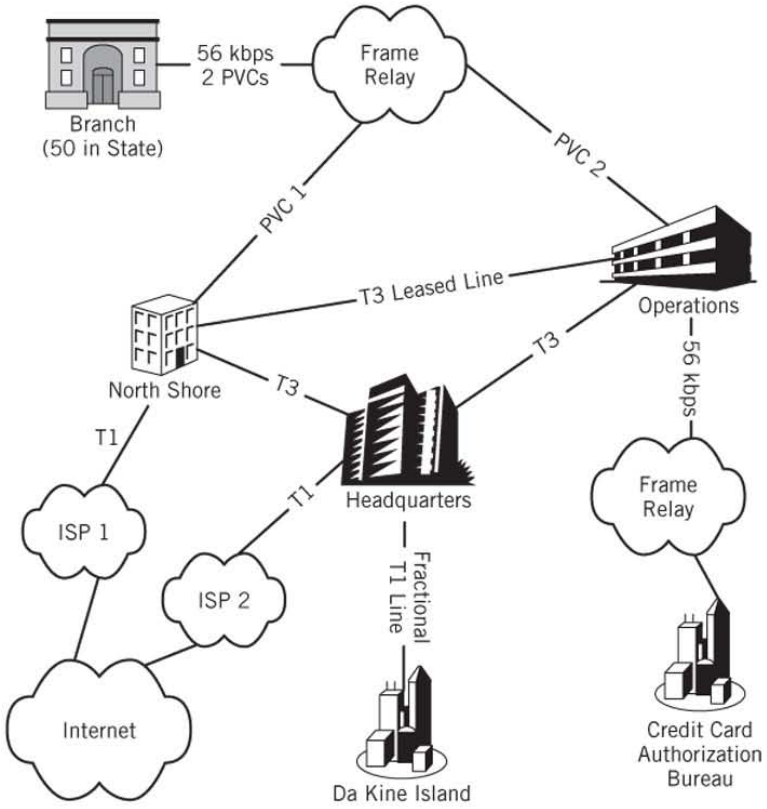


(b) First Bank of Paradise (Hawaii)

Source: From *Business Data Networks and Telecommunications*, 7th ed., R. Panko, Copyright © 2008, by Prentice Hall p. 305. Reprinted with permission.

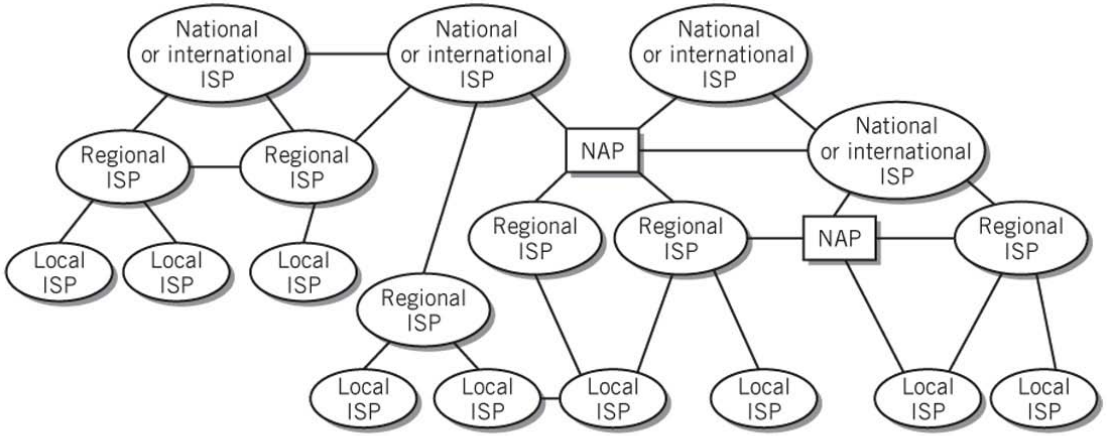
Wide Area Network Carrier Options

Layer	Name	Description	Speed range	Media
1 (Physical)	T-1, T-2, T-3, T-4, E-1, E-3; (fractional T-1)	Traditional telephone co. T-lines, E-lines; known as Digital Service (DS-1, etc.)	1.5 Mbps–275 Mbps (< 1 Mbps)	data-grade UTP or fiber optic
	OCn/STMn	SONET/SDH Optical fiber network	50 Mbps–40 Gbps	fiber optic
2 (Data Link)	DSL (HDSL, HDSL2, SHDSL)	Digital Subscriber Line, business class	384 Mbps–2.3 Mbps	voice-grade UTP
	Frame Relay	Public Switched Data Networks (PSDN)	1.5 Mbps–45 Mbps	depends
	ATM	Asynchronous Transfer Mode	155 Mbps–650 Mbps std., several Gbps unofficial	any
3 (Network)	Internet	Use the Internet, usually with VPN for security	depends on ISP connections	depends on ISP
	IP carrier network	Similar to Internet, but private; used for corporate; carrier may use MPLS, ATM, Ethernet, SONET, ...	depends on carrier	depends on carrier

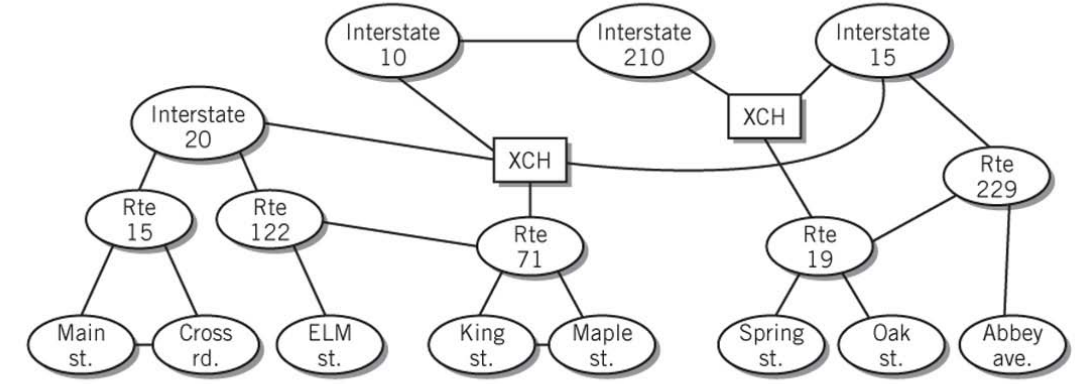
Internet Backbones and the Internet

- Internet Service Providers (ISPs)
- Internet backbone
  - High speed fiber optic networks that carry traffic between major cities throughout the world
  - Speed ranges from 45 to 625 Gbps with faster backbones in the future
  - Created to speed network traffic that would otherwise require many slow hops to the final destination
  - No official central backbone and no official guidance for its development
- Network access points
  - Interchanges between the backbones
- Local ISPs receive their service from regional ISPs who, in turn, receive their service from national ISPs
- Most regional ISPs also interconnect among themselves

Comparison of Internet and Highway Architecture



Internet Architecture



Highway Architecture

Piconets

- Also known as personal area networks (PAN)
- Created for the personal use of an individual
- Generally have ranges of 30 feet or less which is sufficient to permit an individual to interconnect personal computing devices
- Connections between different cooperating users are possible but rare
- Bluetooth is the primary medium for PANs
- Example: interconnection between a cell phone, hands-free speaker and car radio

Standards Organizations

- ISO (International Standards Organization)
  - > 17,000 standards including the OSI Reference model
- IEEE (Institute for Electrical and Electronics Engineers
  - Ethernet standards – Ethernet (802.3), Wi-Fi (802.11), Bluetooth (802.15) and WiMax (802.16)
- IETF (Internet Engineering Task Force)
  - Internet standards based on RFCs (request for comments)
- ICANN
  - Internet Corporation for Assigned Names and Numbers
  - IP address allocation, domain name registration, protocol parameter assignment
  - Management of domain name and root server systems
- IANA (Internet Assigned Numbers Authority
  - Registers application layer port numbers and specific parameter values used in Internet protocol headers

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