ECEN1012
Computer Programming and Network Fundamentals

Chapter 1: Computer Networks and the Internet

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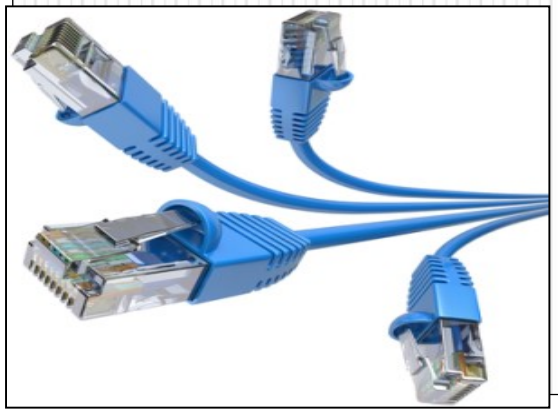
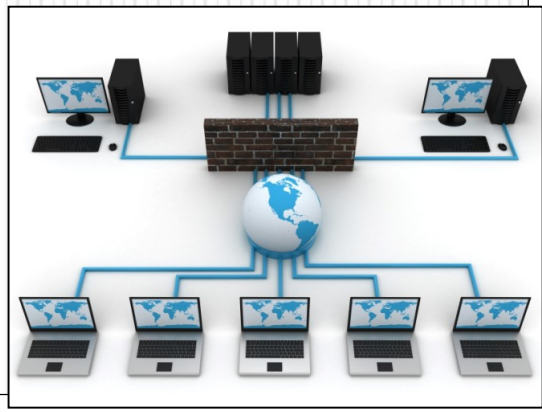
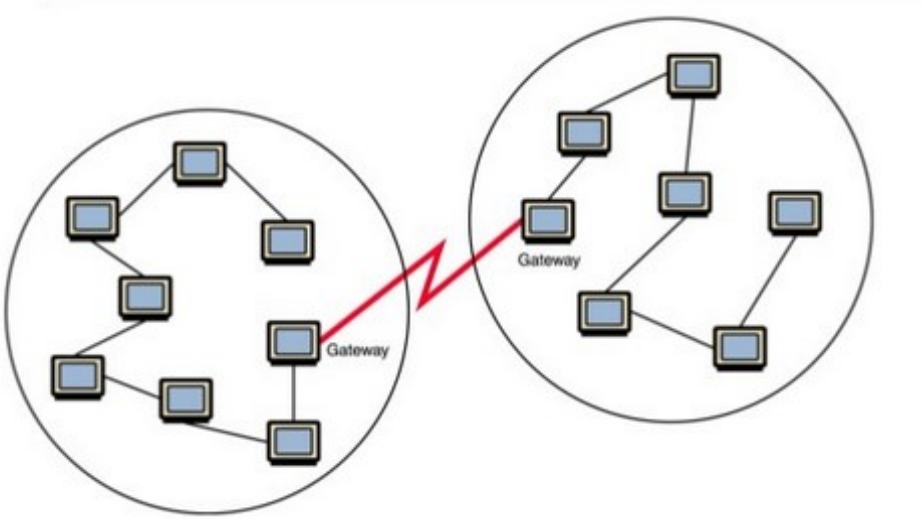
2025



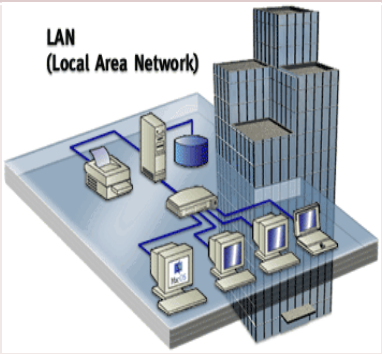
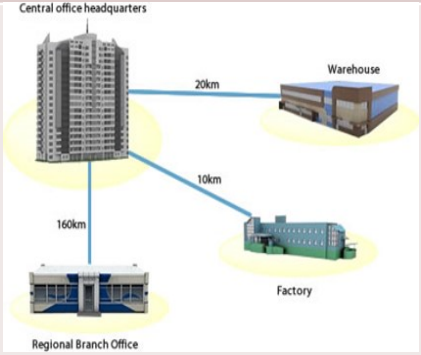
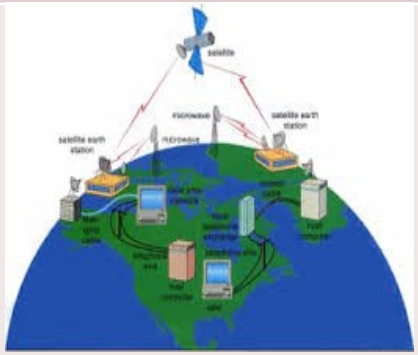


Computer Network

- What is a Computer Network
  - Interconnected Collection of autonomous computers
- Computer Networks are Ubiquitous
  - Cellular communication network
  - Home network
  - Enterprise network
  - Internet



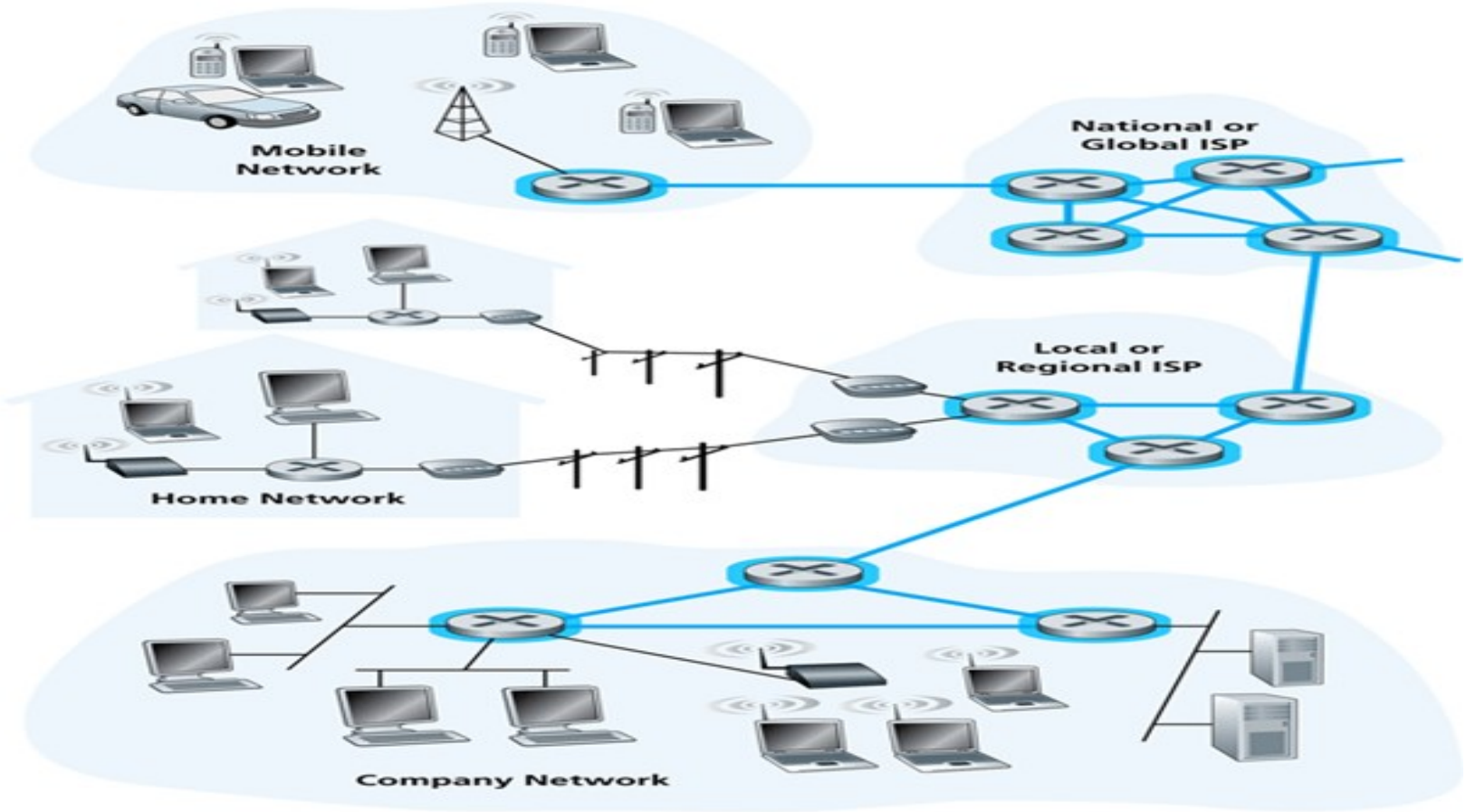
Types of Computer Networks

Personal Area Network 个人区域网	Local Area Network 局域网	Metropolitan Area Network城域网	Wide Area Network 广域网
PAN	LAN	MAN	WAN
			
Computer Network built around for individual use including PCs, Printers, Phones, etc.	Covers small geographical area such as a single building, school, campus, etc.	Covers a city	Covers a wide area such as a whole country or world.

Internet: A Network of Networks

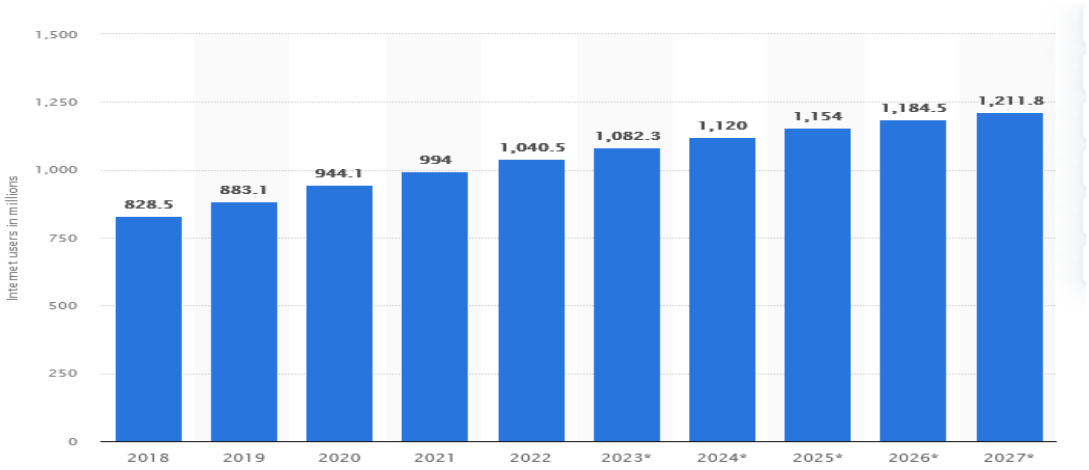
- The word Internet comes from the combination of "interconnection" and "network".
- It is the connection of computer networks which forms and acts as a single huge network for the transmission of data and messages from one computer to any other computer connected to the network.

Internet: A Network of Networks



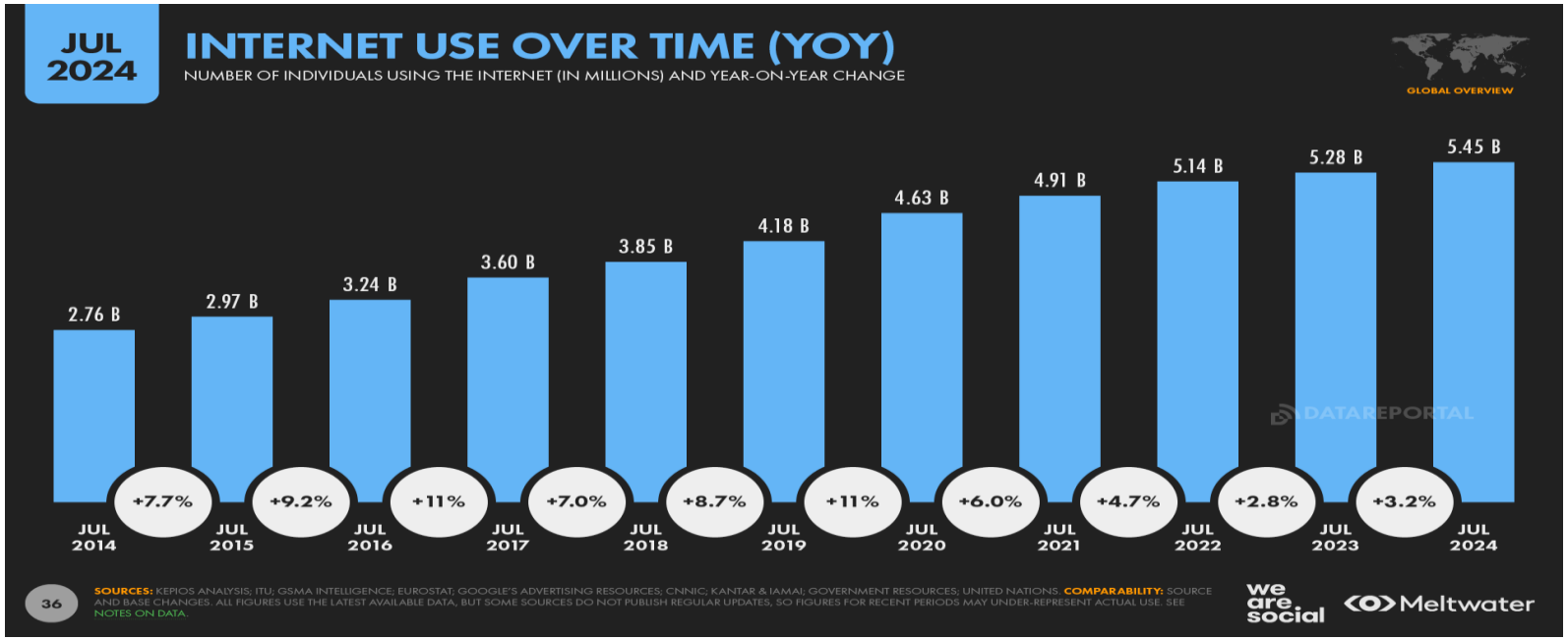
Internet users in China

- CNNIC: China Internet Network Information Center (中国网络信息中心）, established in 1997, with the function of managing the internet address resources in China.
- By the end of year 2005, .CN domain registrations have over 1 million, the increase of 154% in one year.
- The number of internet users in China
  - In 2022, China had around 1.04 billion internet users. And grow up gradually every year.



Internet Users Worldwide

- The number of Internet users worldwide keeps impressive growth in the last few years.
- Global Internet users have almost doubled over the past decade, from 2.76 billion in July 2014 to 5.45 billion in 2024.

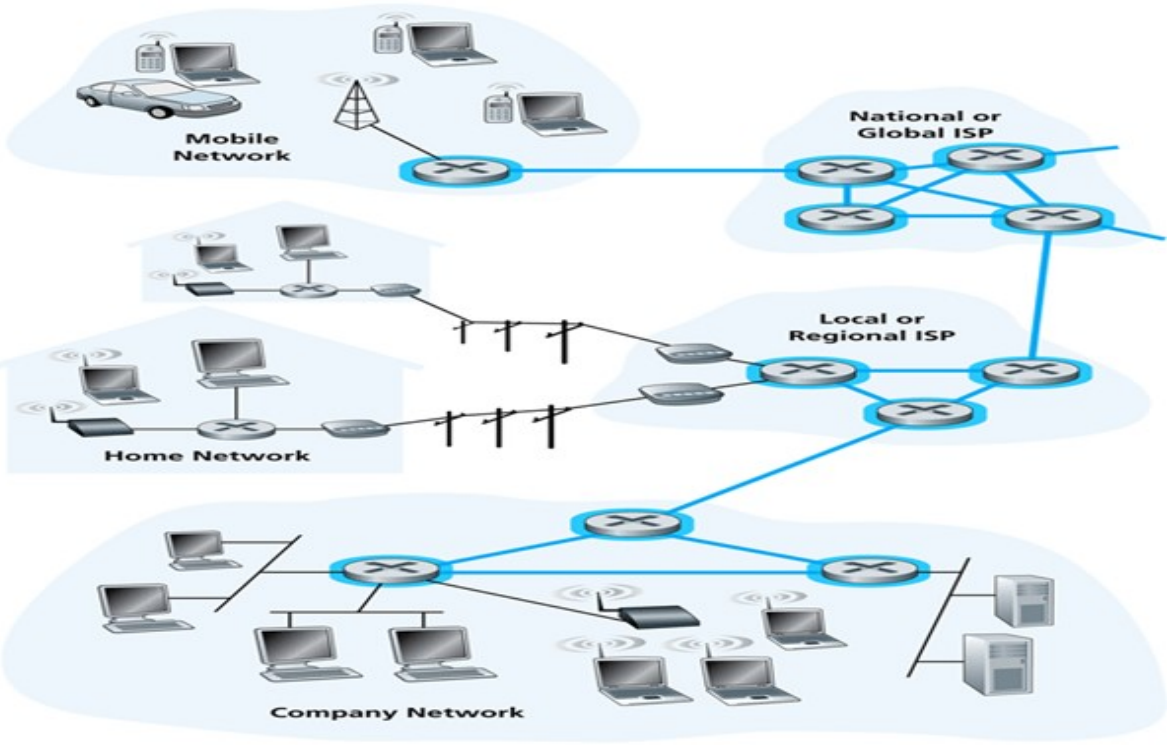


Advantages and Disadvantages of Computer Networks and Internet

- Advantages
  - Ease of communications
  - Sharing files, data and media
  - Save money
- Disadvantages
  - Security issue: some information on the Internet is not secure and may be hacked.
  - Big data: Because of the large amount of materials on the Internet, it can be difficult to find what you want.
  - Internet addiction

Internet Structure

- Modem, Router, Server, Mobile phone, Switch, Hub, etc.
- ISP, Web Browser, etc




router

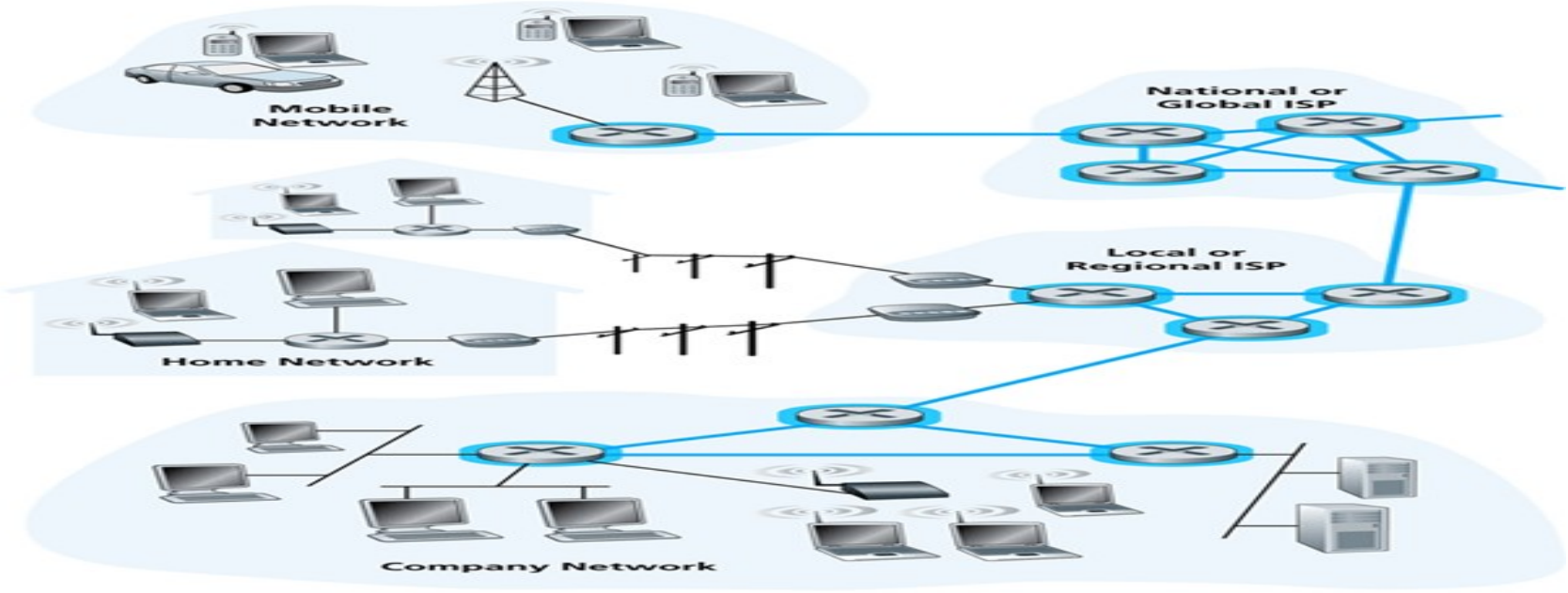

workstation


server


mobile

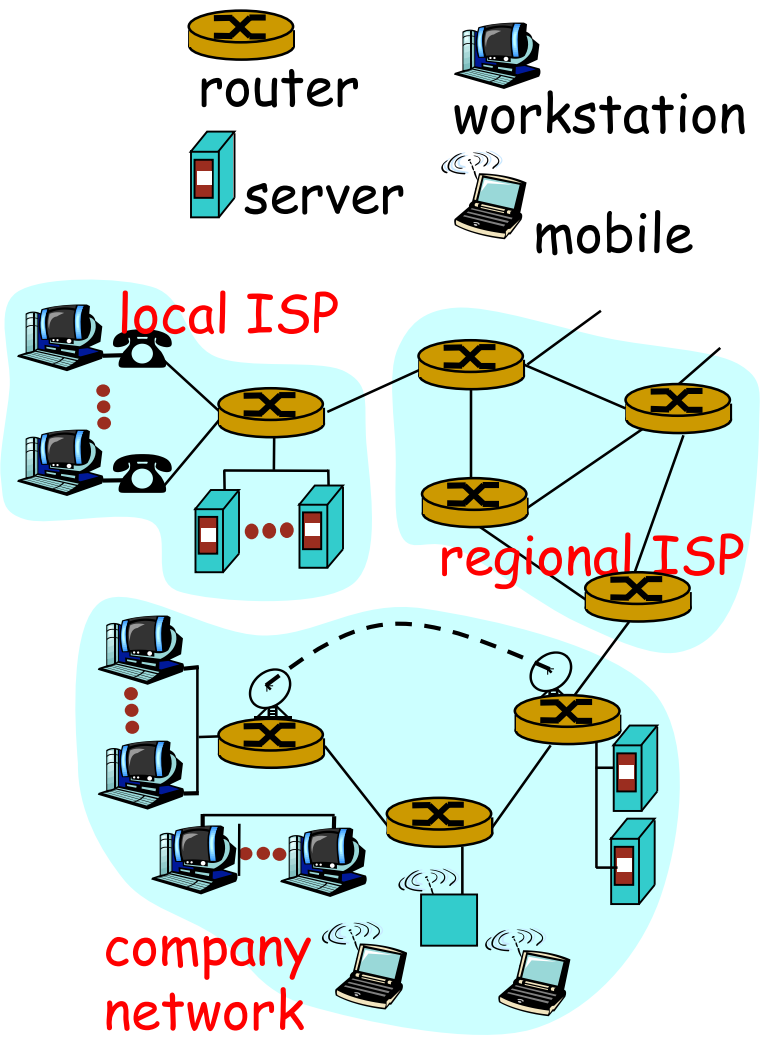
Two Views about the Internet

- "Nuts and bolts" view of the Internet (从细节看Internet)
  - Basic hardware and software components that make up the Internet
- "Service" view of the Internet
  - Describe the Internet in terms of a Networking infrastructure that provides services to distributed applications



What's the Internet: "nuts and bolts" view

- millions of connected computing devices (hosts or end systems):
  - Traditional
  - Nontraditional
- running network apps
- communication links
  - Physical – coaxial同轴线, twisted-pairs双绞线, fiber光纤, copper铜线
  - Wireless - radio, satellite
- Packet switches: forward packets (chunks of data)



Devices： Modem 调制解调器

- Modem is the short for Modulator-Demodulator;
- A modem is a device that enables a computer to transmit data over a telephone or cable line

Devices: Router 路由器

- The primary function of a router is to connect networks together;
- It allows data from one network to another;
- It acts as a firewall to protect your computer from unwanted outside access.

Devices: Server 服务器

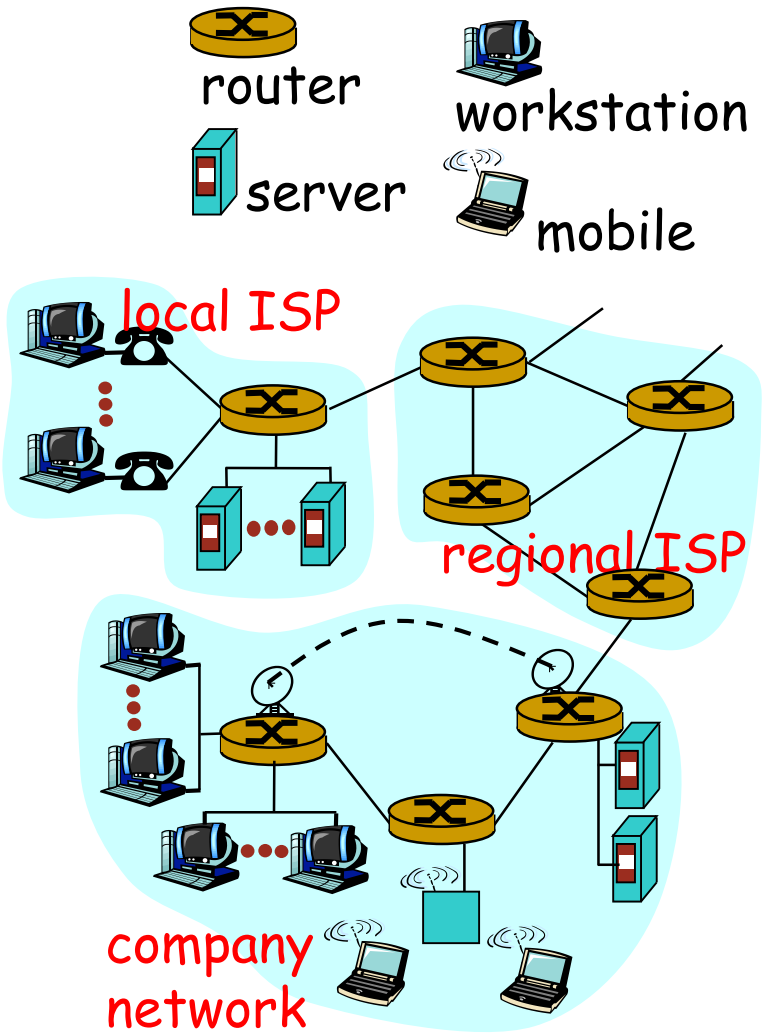
- It is a computer in a central location that runs software or stores data.
- Multiple clients/end users can connect to server for their processing needs.

Devices: Network End Device

- Network end device is an item that uses networks or has internet access. Such as desktop computer, cell phone, laptop, etc.

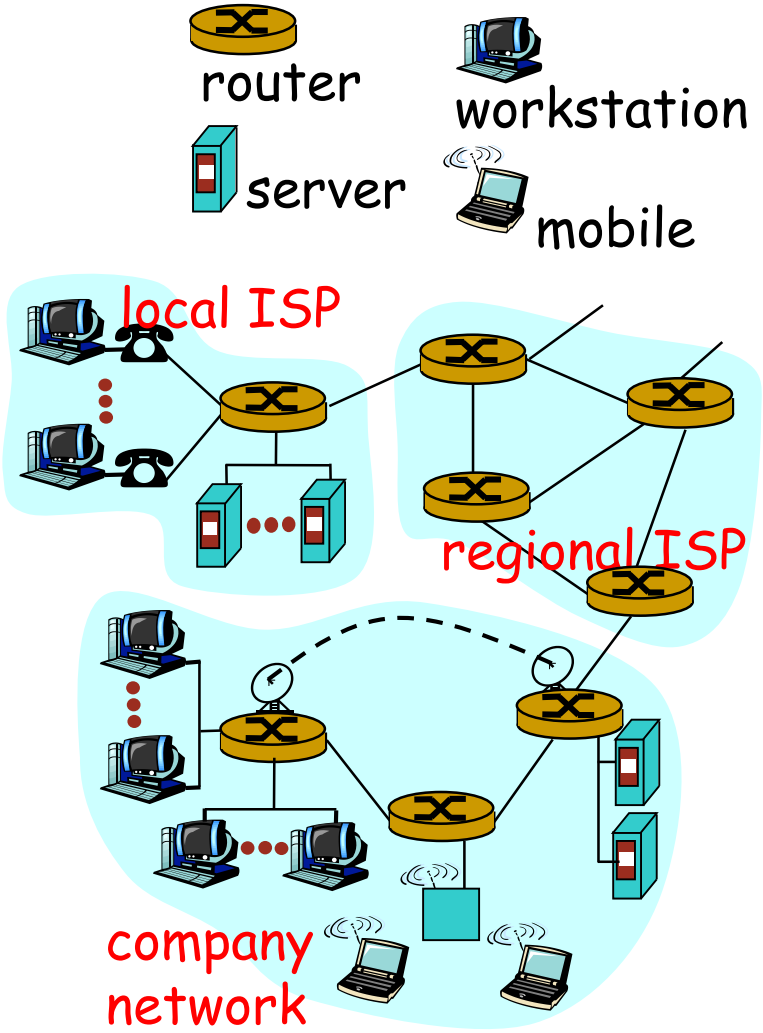
What's the Internet: "nuts and bolts" view (2)

- Packet分组 – the chunk of information
- Types of packet switches
  - Routers路由器: forward packets (chunks of data)
  - Link layer switches
- Route or Path
- Packet switching分组交换
  - End systems share a path or parts of a path, at the same time



What's the Internet: "nuts and bolts" view (3)

- ISP （Internet Service Provider）
  - Internet Service Provider refers to a company that provides Internet services.
  - Each ISP is a network of packet switches and communication links.
  - Residential ISPs – local telephone company, corporate ISPs, university ISPs, other ISPs

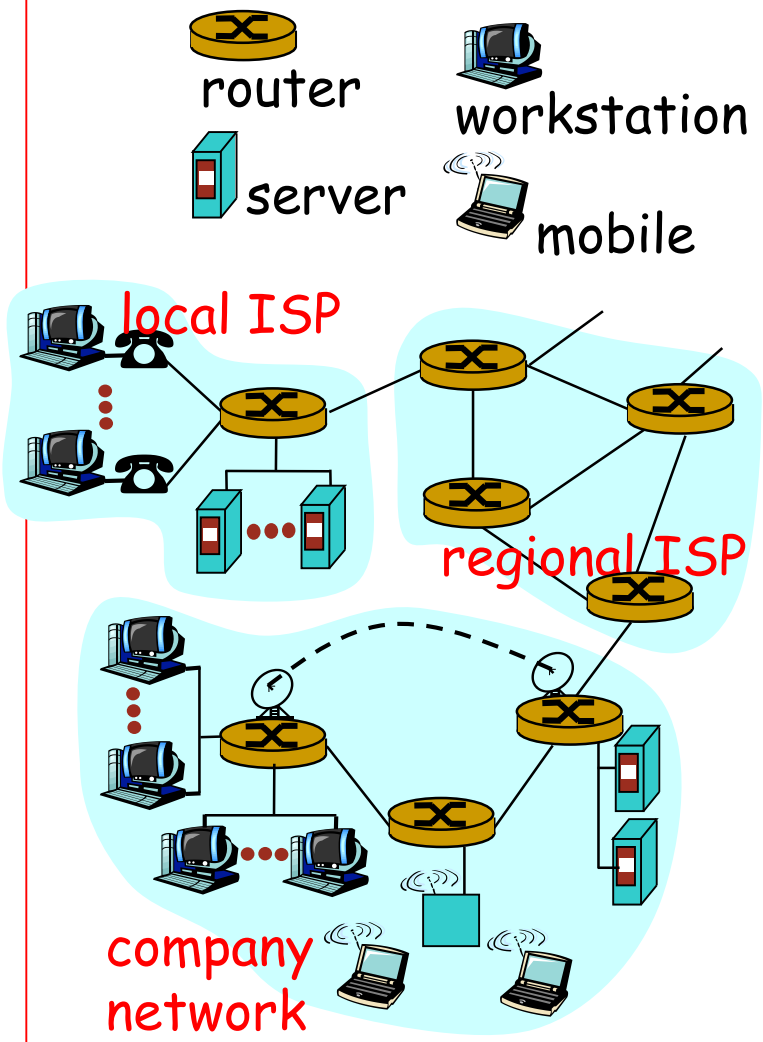


Internet Service Provider (ISP Internet服务提供商)

- Examples： CTM, China Unicom, China Telecom， China Mobile, etc.

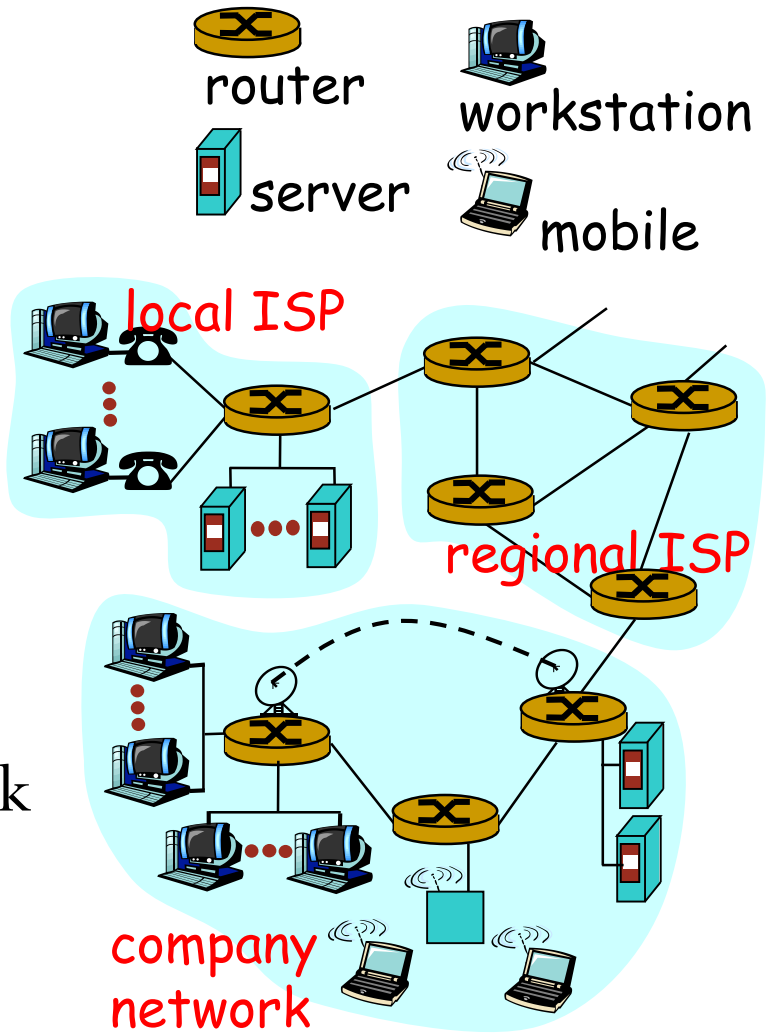
What's the Internet: "nuts and bolts" view (4)

- Services provided by ISP
  - Dialup
  - Broadband(cable/DSL)
  - High speed LAN access
  - Wireless Access
  - Internet access to content providers (Connecting web sites directly to the Internet)
- Tier of ISP
  - Lower tier ISPs
  - National and international upper tier ISPs



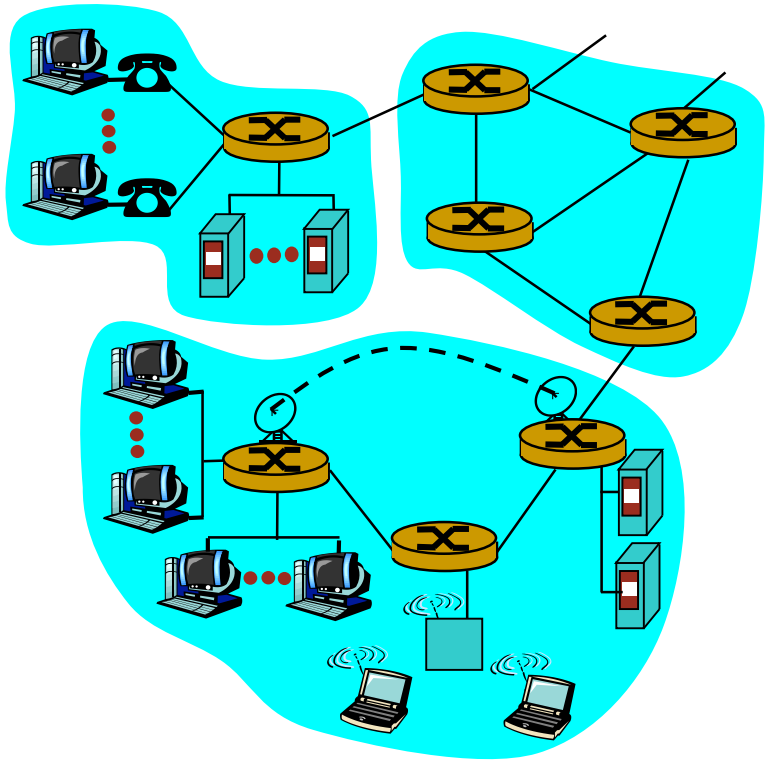
What's the Internet: "nuts and bolts" view (5)

- protocols control sending, receiving of msgs
  - e.g., TCP, IP, HTTP, FTP,
- Internet: "network of networks"
  - loosely hierarchical
  - public Internet versus private intranet (firewall)
- Internet standards
  - IETF: Internet Engineering Task Force
    - RFC: Request for comments
  - IEEE 802 LAN/MAN standards



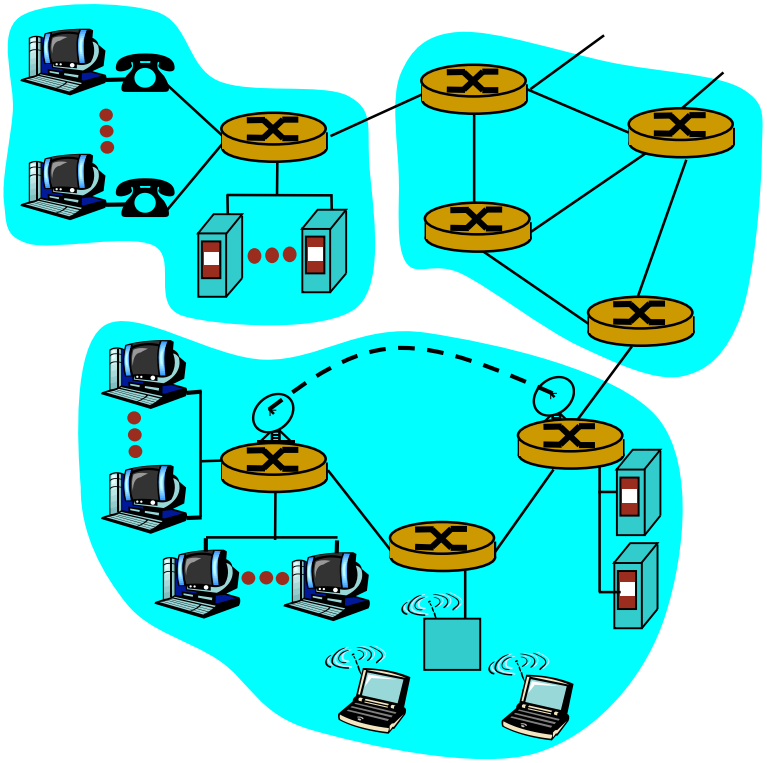
What's the Internet: a service view (1)

- communication infrastructure
  enables distributed applications:
  - Web, email, games, e-commerce, file sharing
- communication services provided to apps:
  - connection-oriented reliable
    - Reliable
  - Connectionless unreliable
    - No guarantees



What's the Internet: a service view (2)

- Currently, the Internet does not provide a service that makes promises about:
  - How long it will take to deliver the data from sender to receiver
  - Increase the access transmission rate
- Advances in the nuts and bolts components of the Internet are being driven by the needs of new applications
  - Internet is an infrastructure in which new applications are being constantly invented and deployed



What's a protocol? (1)

A protocol defines the format and the order of msgs exchanged between two or more communicating entities, as well as the actions taken on the transmission and/or receipt of a message or other event.

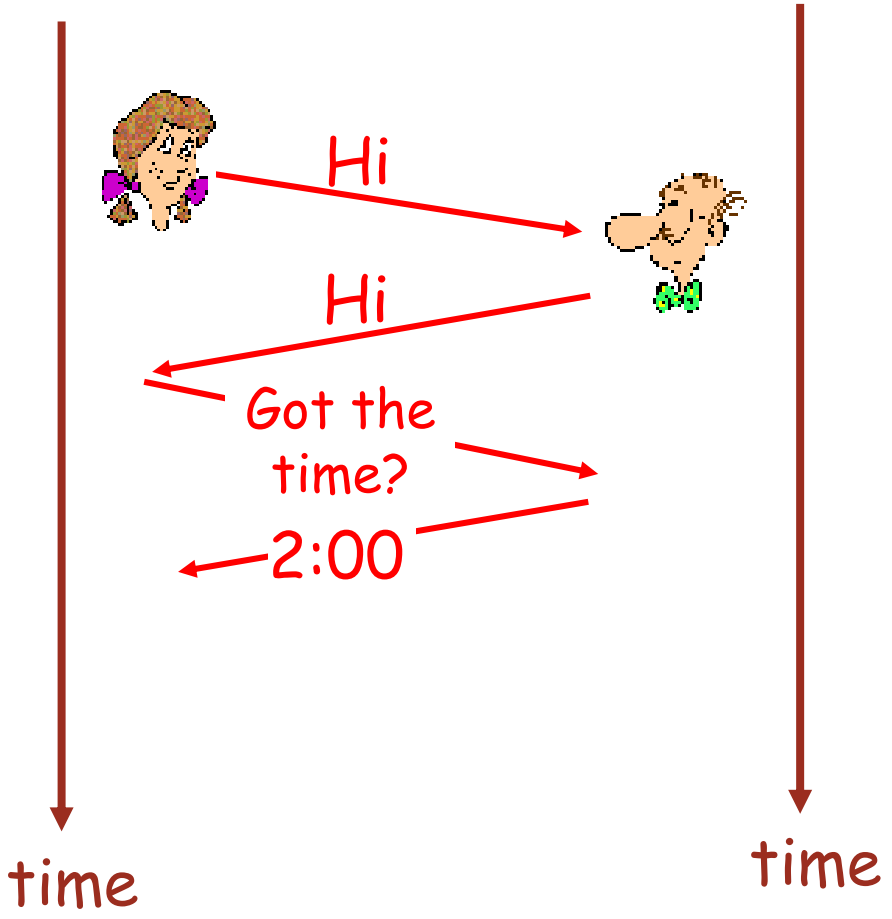
What's a protocol? (2)

human protocols:

- What do we do when we want to ask someone for the time of day?
- "what's the time?"
- "I have a question"
- introductions

… specific msgs sent

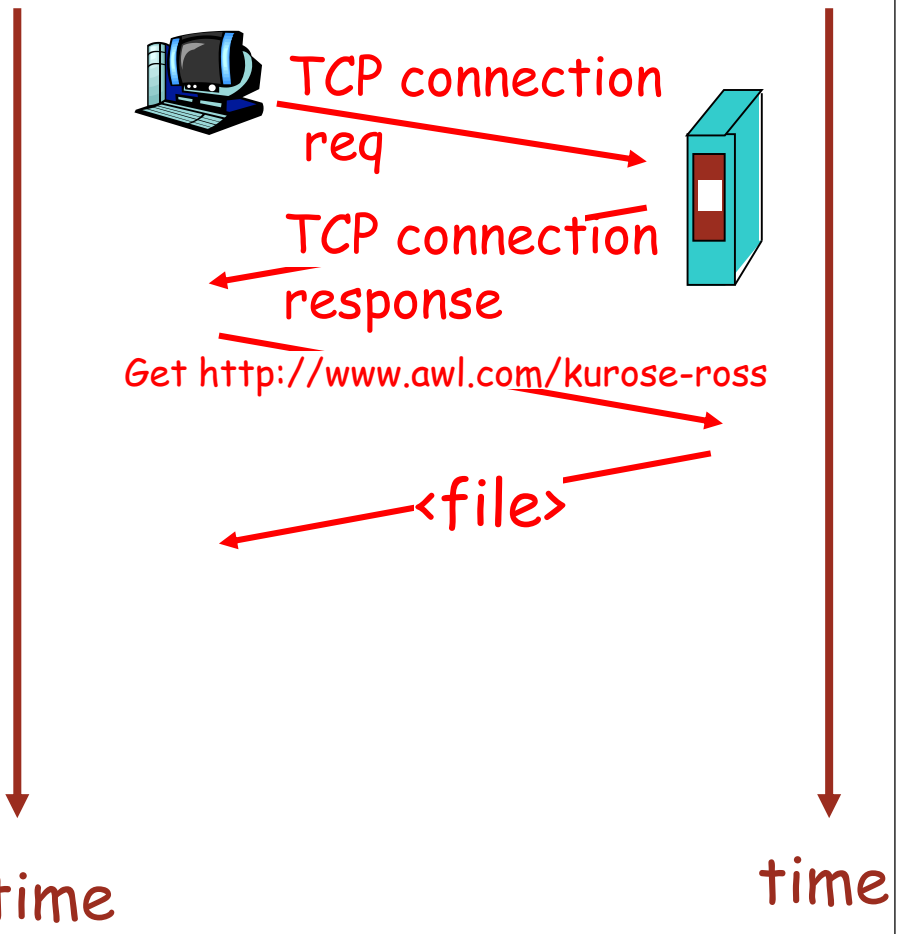
… specific actions taken when msgs received, or other events



What's a protocol? (3)

Network protocols:

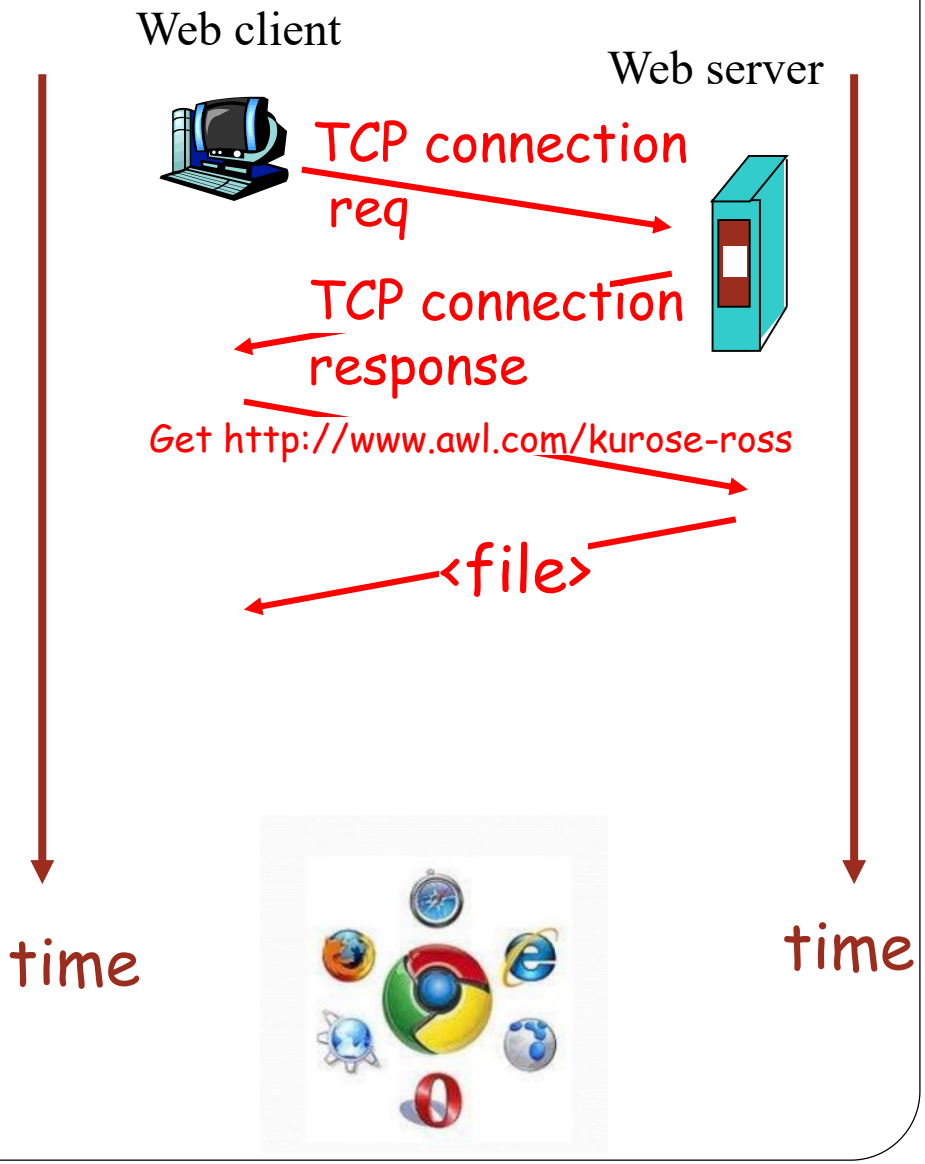
- Implemented on machines rather than humans
- all communication activity in Internet governed by protocols
  - Congestion control protocols in end systems
  - Protocols in routers



What's a protocol? (4)

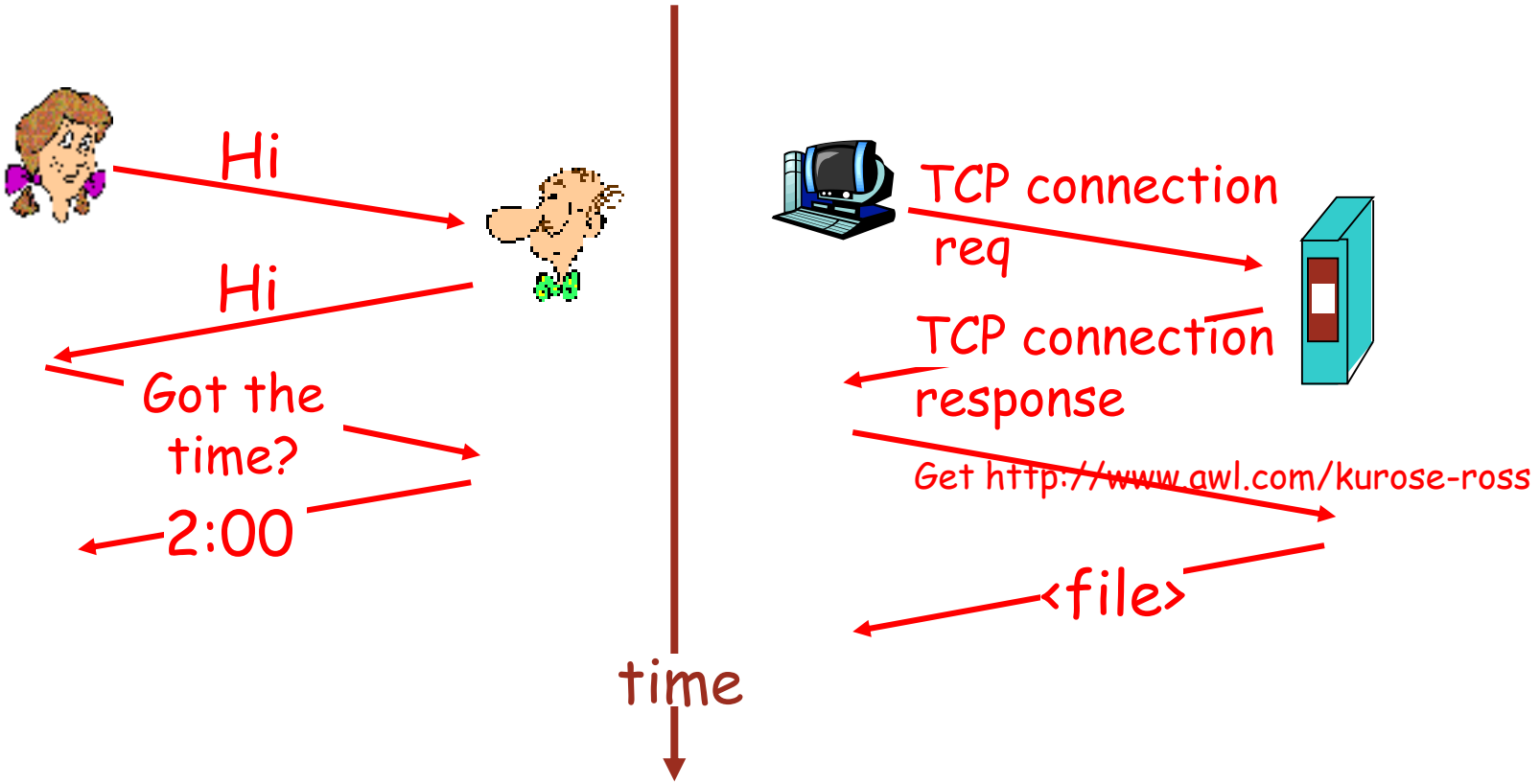
Example of network protocols:

- What happens when you make a request to a web server via a web browser (浏览器)
- Web browser is a software that allows for the browsing of the websites. It is the computer program used for accessing websites or information on Internet. Examples: IE, Firefox, Google Chrome



What's a protocol? (4)

a human protocol and a computer network protocol:



Chapter 1: roadmap

1.1 What is the Internet?

1.2 Network edge

1.3 Network core

1.4 Network access and physical media

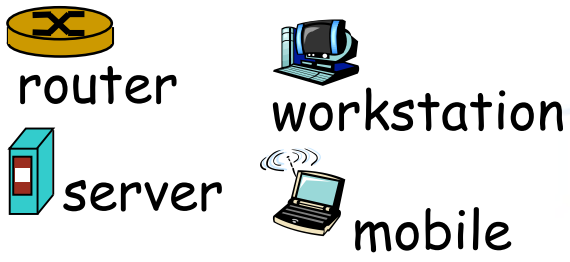
1.5 Internet structure and ISPs

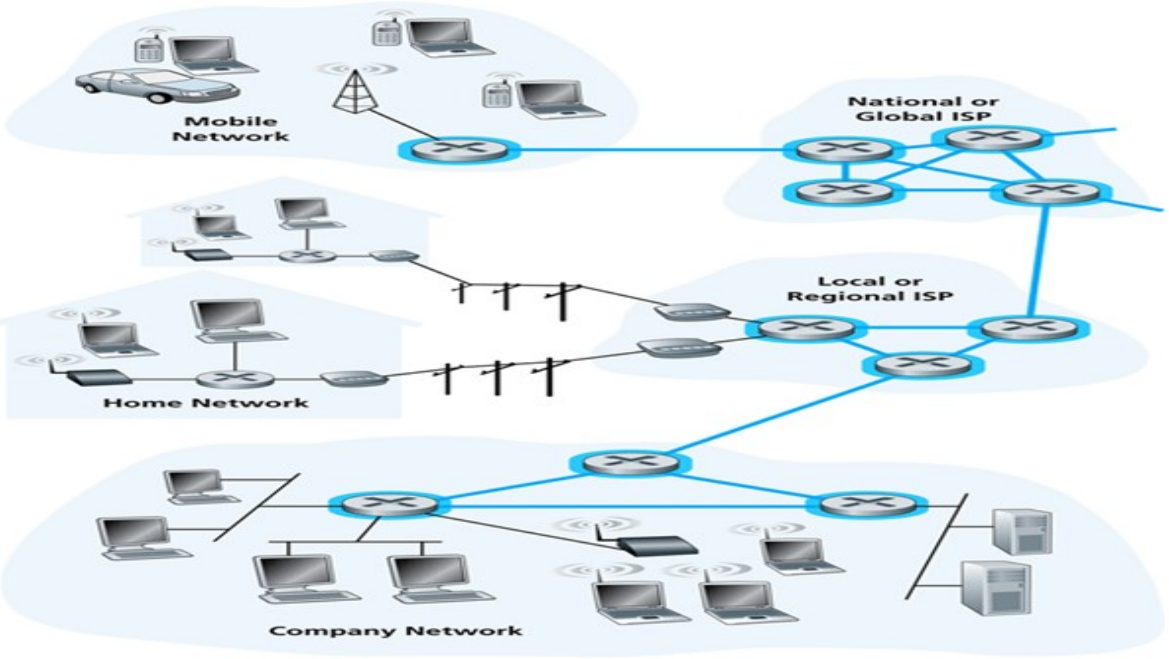
1.6 Delay & loss in packet-switched networks

1.7 Protocol layers, service models

Internet: A Network of Networks

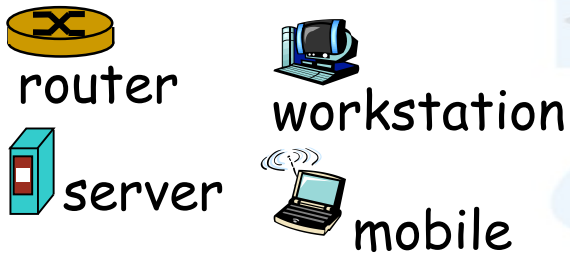
- The Network Edge: at the edge of the Internet. applications and hosts
- The Network Core: at the core/central parts of the Internet. routers, network of networks.

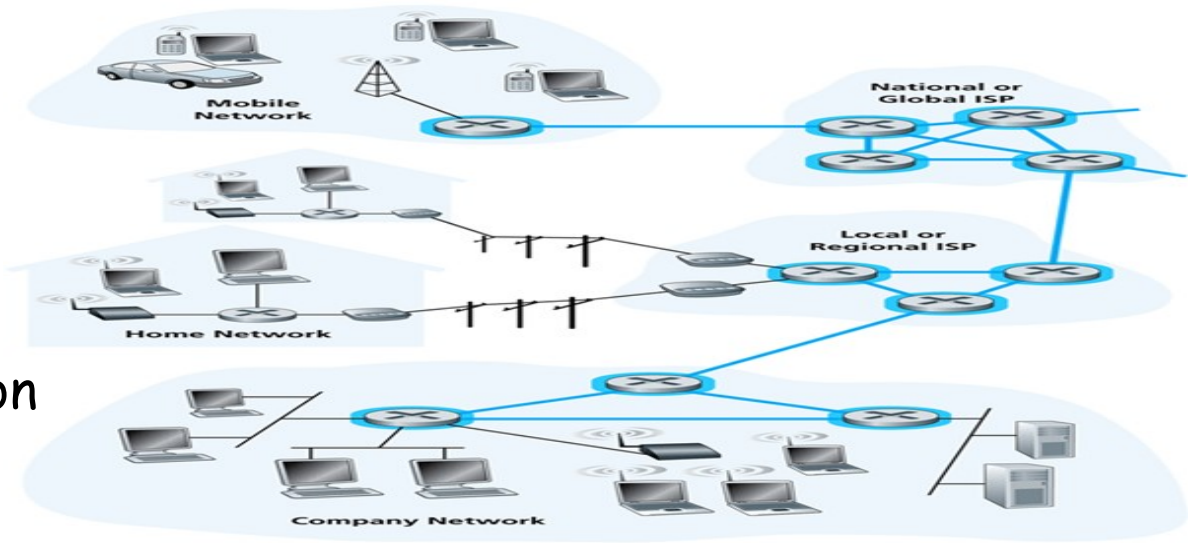




The Network Edge

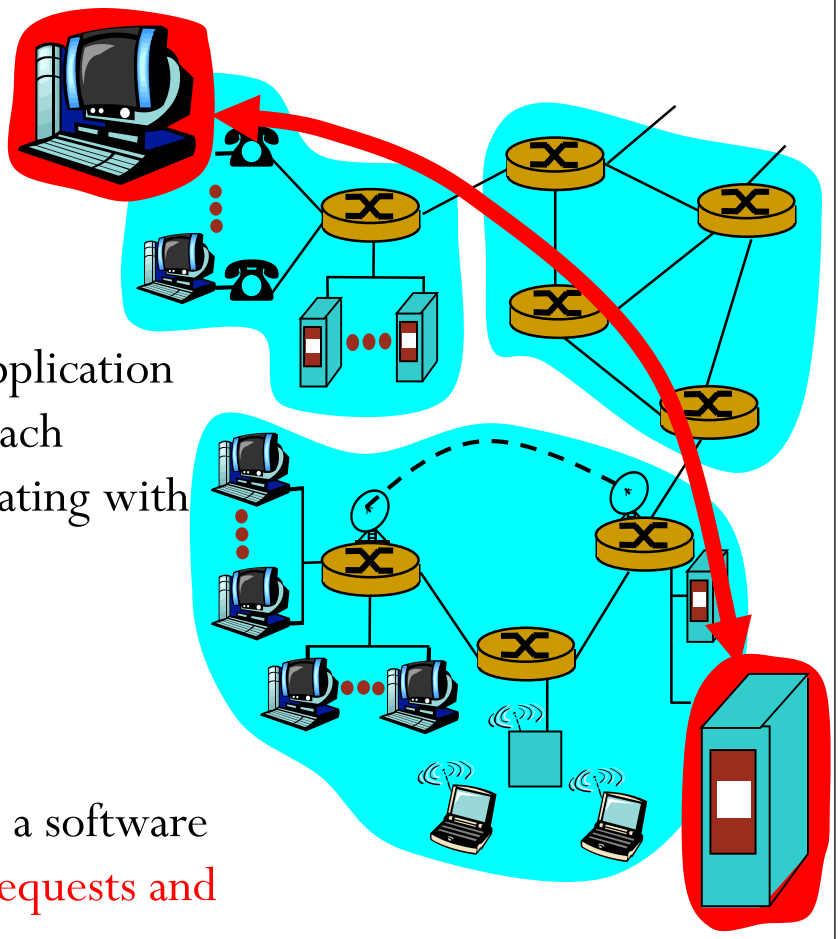
- The Network Edge: at the edge of the Internet.
  - End system 端系统
    - It denotes the devices (such as computer, mobile phone, workstation) at the edge of the Internet. Note that end systems are not network, they are devices.
    - End systems are also referred to as hosts (主机) since they host (i.e., run) application programs such as a Web browser program, an e-mail reader program, etc.
  - Edge router 边缘路由器
    - The first router on a path from one end system to any other distant end system.





The Network Edge: Two Types of End Systems

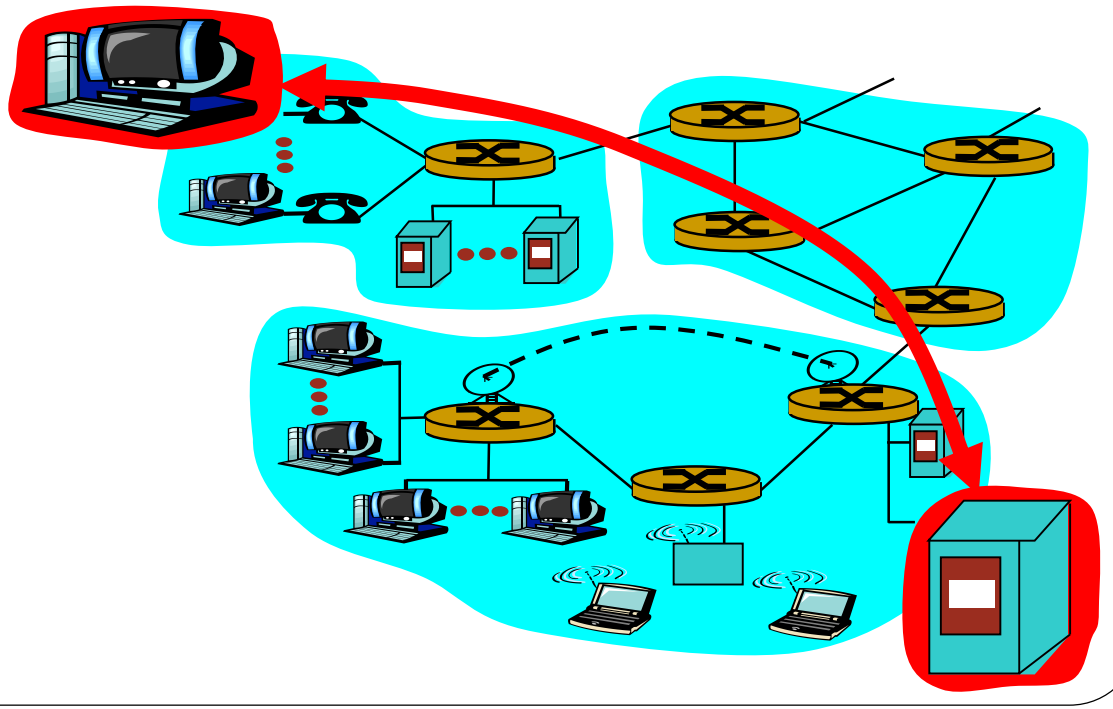
- End systems (hosts):
  - Devices such as computers, workstations, Web servers, mail servers, WebTVs, etc.
  - At the "edge of network"
  - Run application programs (e.g. Web, email). A application function is usually composed of two programs, each running on different end systems and communicating with each other.



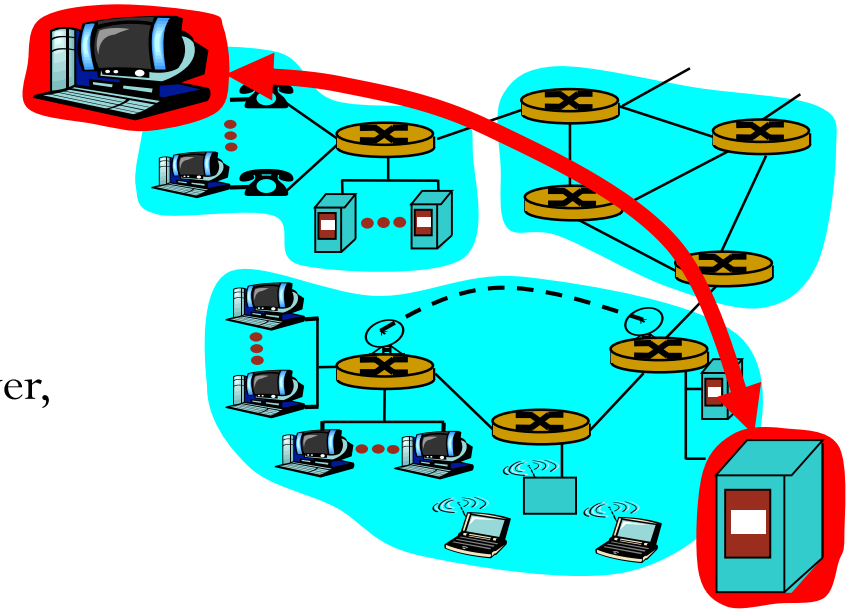
- Two types of end systems
  - Client 客户端:
    - A client is also called as a client program. It is a software or program running on one end system that requests and receives a service from a server or server program running on another end system.
    - Sometime, a computer/device running a client program is called as client computer or client for short, such as desktop, mobile PC, PDAs, etc.

Two Types of End Systems

- Server服务器:
  - A server is also called as a server program. It is a computer program running to serve the requests of other programs, that is, it provides service to serve the requests of some end systems.
  - Based on the service that a server offers, it could be a web server, file server, mail server, etc.

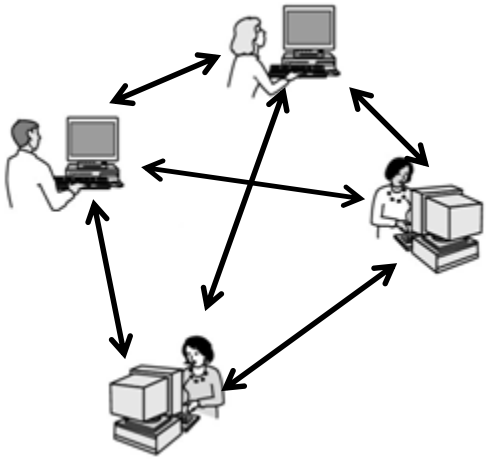


The Network Edge: Two Working Modes



- Client/server mode
  - Client requests and receives service from a always-on server
  - e.g. Web browser/server; email client/server, online banking

- Peer-to-Peer (P2P) mode
  - No fixed clients or servers
  - Each host run programs that performs both client and server function. That is, each host can act as both client and server
  - E.g., eMule, BitTorrent, LimeWire (P2P file sharing application), etc.

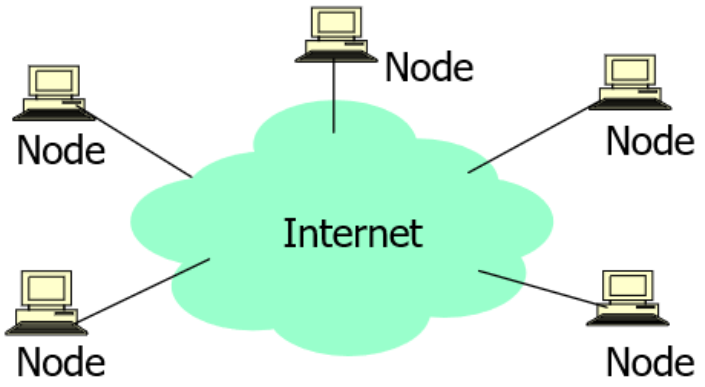


Client/Server Mode

- Advantages:
  - Centralized control: It provides centralized control of the entire network environment. The centralized users accounts, security and access controls simplify network administration.
  - The network operability is dependent on the server. More powerful equipment means more efficient access capability.
  - It can support great number of users.
  - It allows the user of less powerful computers as clients since most of work is done by server
  - It is easier to scale.
  - Provides more security
- Limitations:
  - Expensive: More costly to install and maintain
  - Single point of failure, server shut down, the service shut down
  - Require administration
  - Unused resources at the clients

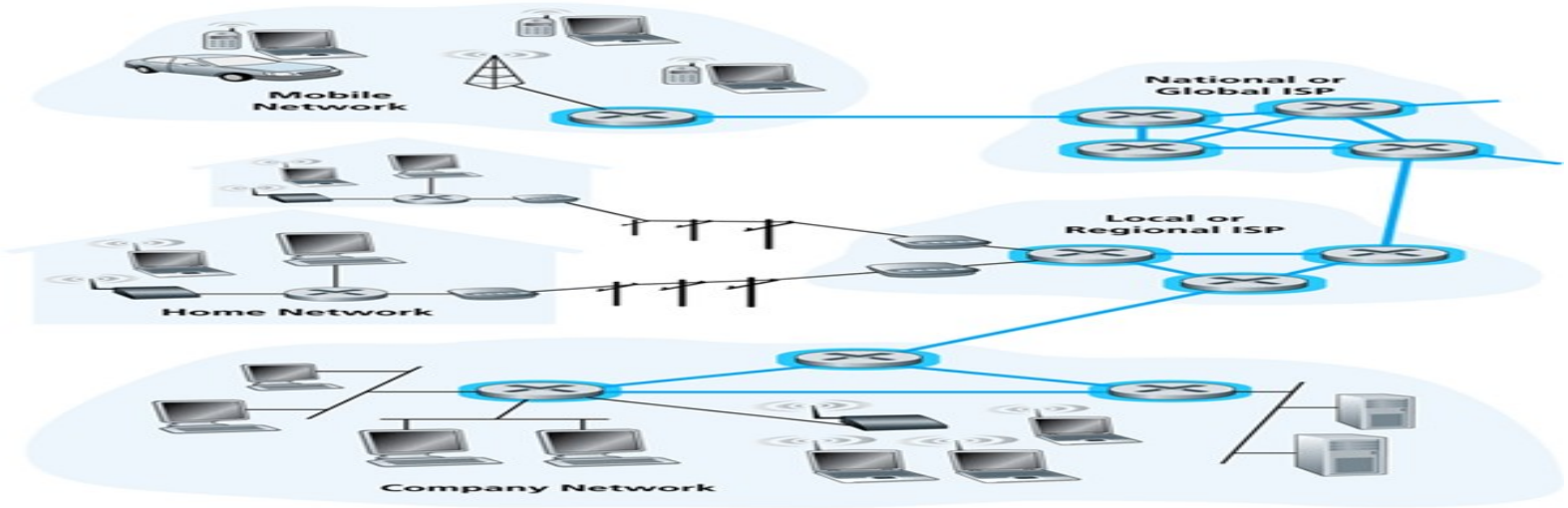
P2P Mode

- Advantages
  - No fixed clients or servers: No need to deploy servers to satisfy demand
  - Efficient use of resources: storage, processing power, bandwidth at the edge of the network.
  - No centralized data source.
  - Reliability: No single point of failure
- Limitation
  - Security is a major concern due to the lack of centralization.



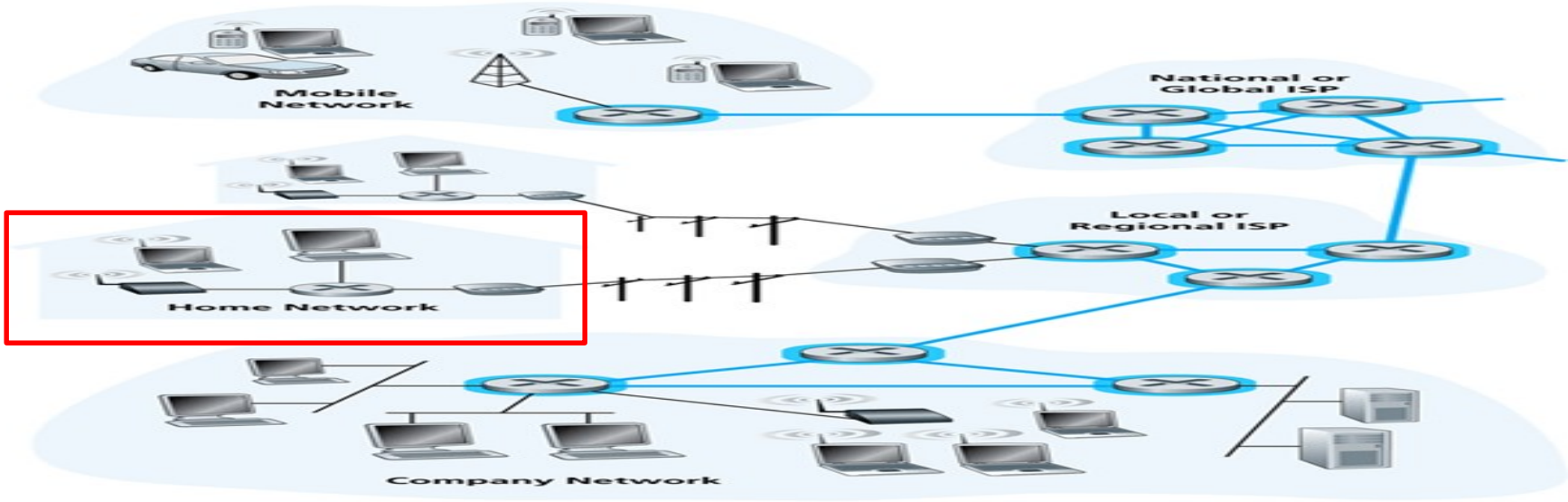
The Network Edge

- The Network Edge: at the edge of the Internet.
  - The access link 接入链路
    - The communication links that connect an end system to the edge router.
    - Fiber optics, twisted-pair copper wire, coaxial cable, radio, satellite.
    - Different links have different capability of transmitting messages.
  - Access network 接入网
    - The part of network that connects end systems to its edge router.
    - It is the network sitting at the edge of the Internet, and the name of access network is contrasted with the core network, which sits at the central of the Internet.



The Network Edge

- **Classification of Access Network**
  - Residential access network/home network
    - Connect home end systems into the Internet.
    - Dial-up modem 拨号上网, DSL(Digital Subscriber Line 数字用户线路) over telephone line, or cable to HFC (Hybrid Fiber-coaxial Cable混合光纤/同轴电缆)
  - Company access network: Ethernet
  - Mobile/wireless access network: cellular mobile access



HFC (Hybrid Fiber/Coax) 混合光纤/同轴电缆 Access networks are extension of the cable system used for broadcasting cable TV

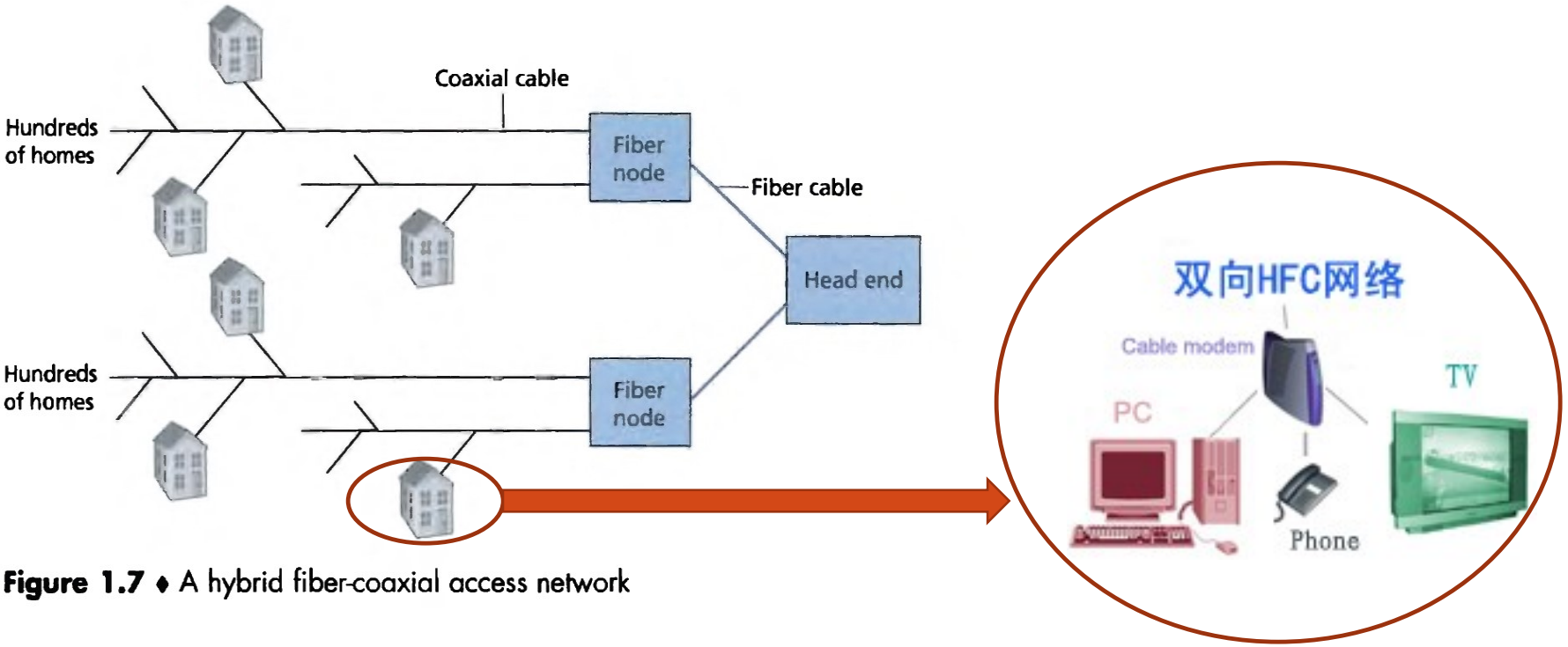
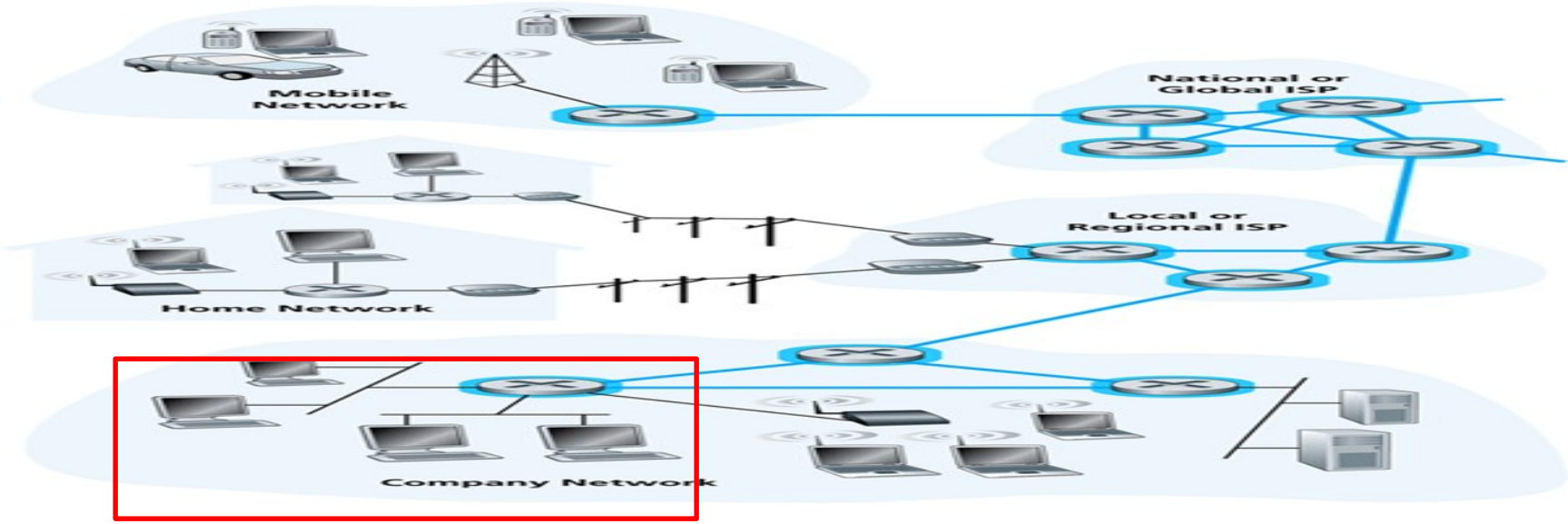


Figure 1.7 ♦ A hybrid fiber-coaxial access network

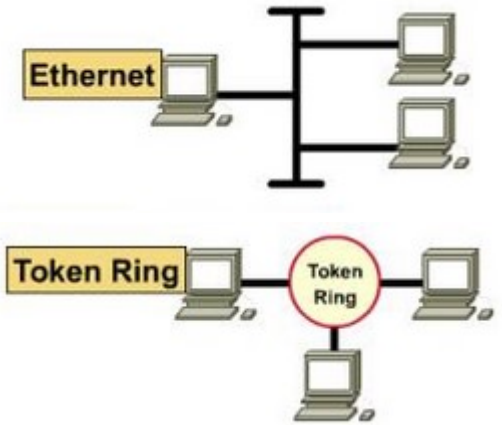
Company Access Network

- On company and university campus, a LAN is typically used to connect an end system to an edge router.
- Many types of LAN technologies: Ethernet 以太网，Token Ring， FDDI （Fiber Distributed Data Interface），etc。

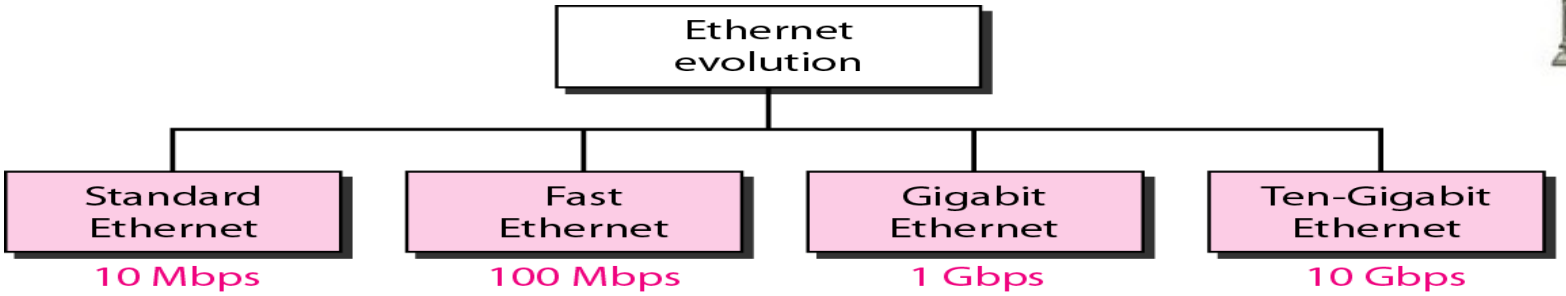


Ethernet (以太网) Overview

- Ethernet: a family of computer networking technologies for wired LAN. It is the most popular physical and data link layer technology for wired LAN.
- Logical bus topology
- Nondeterministic: First-come, first served



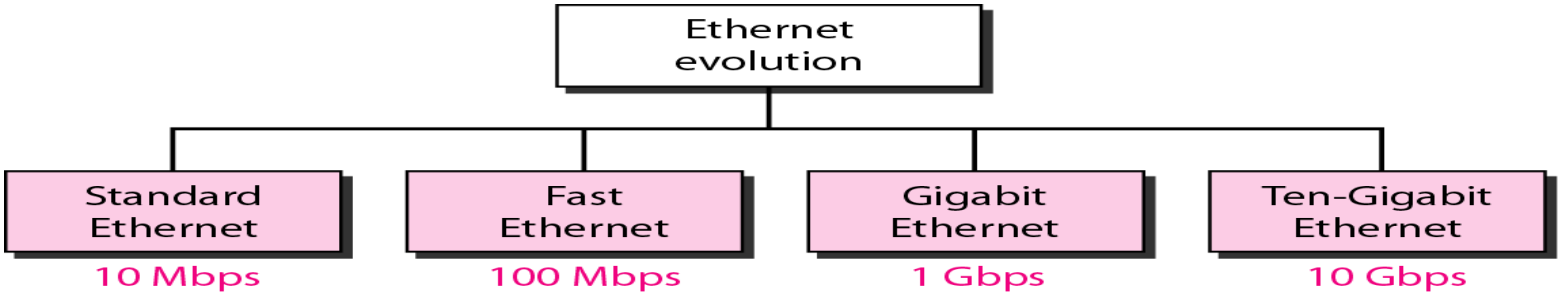
- Data rates



Example: 10Base-T, 10GBase

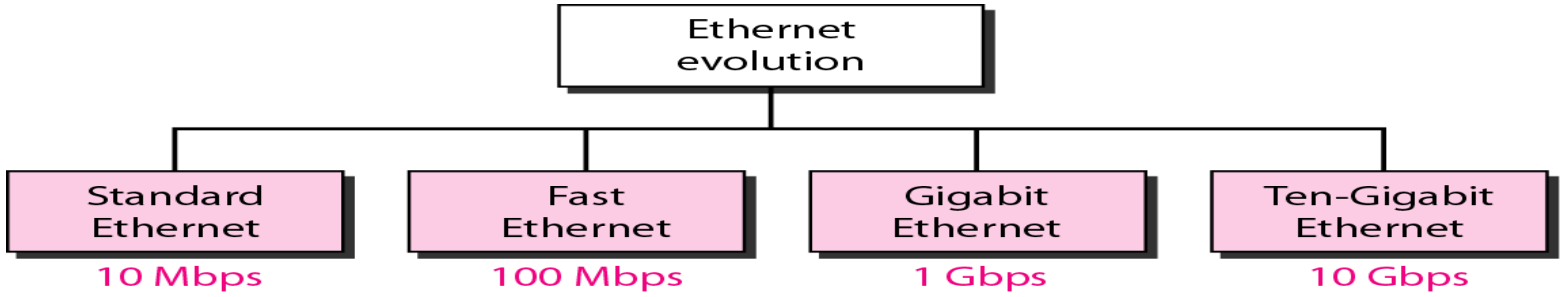
Ethernet Overview

- Signaling method: baseband and broadband.
- Physical medium:
  - Guided media: the waves are guided along a solid medium (fiber-optic cable, twisted-pair copper wire, coaxial cable).
  - Unguided media: the waves propagate in the atmosphere or outer space, such as in a wireless LAN or digital satellite communication



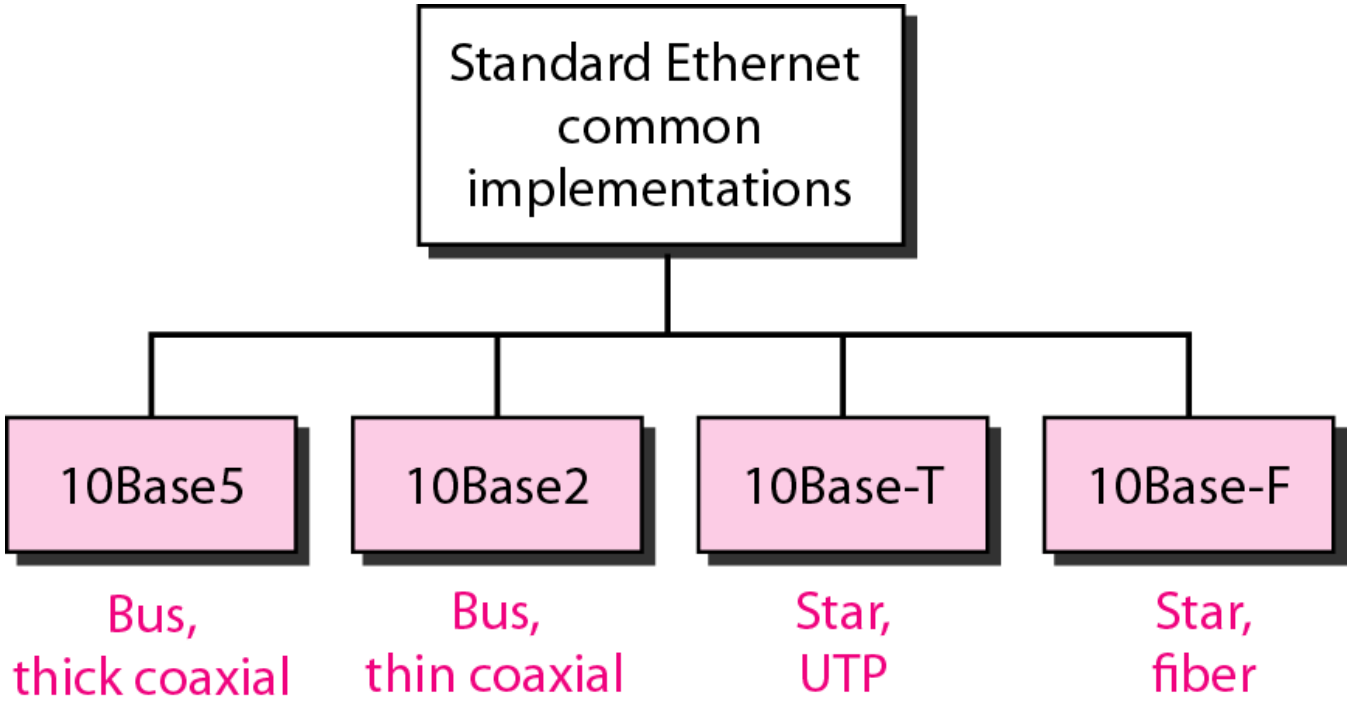
Ethernet Overview

- Topology: Bus and Star topologies are used to connect hosts
  - Hosts attach to network via Ethernet transceiver or hub or switch
  - Hubs/switches are used to facilitate shared connections
- Cabling(T,F)
  - T – Twisted pair
  - F – Optical fiber

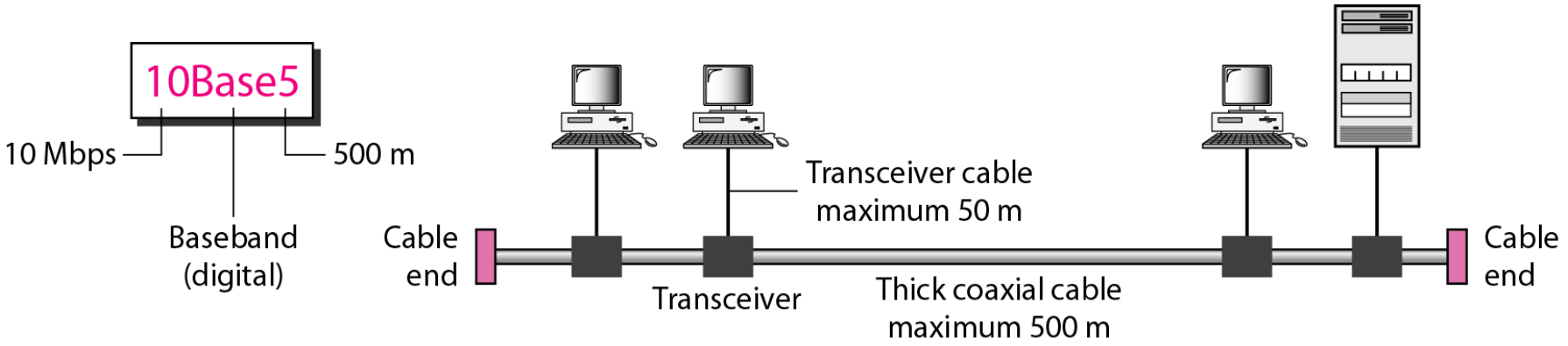


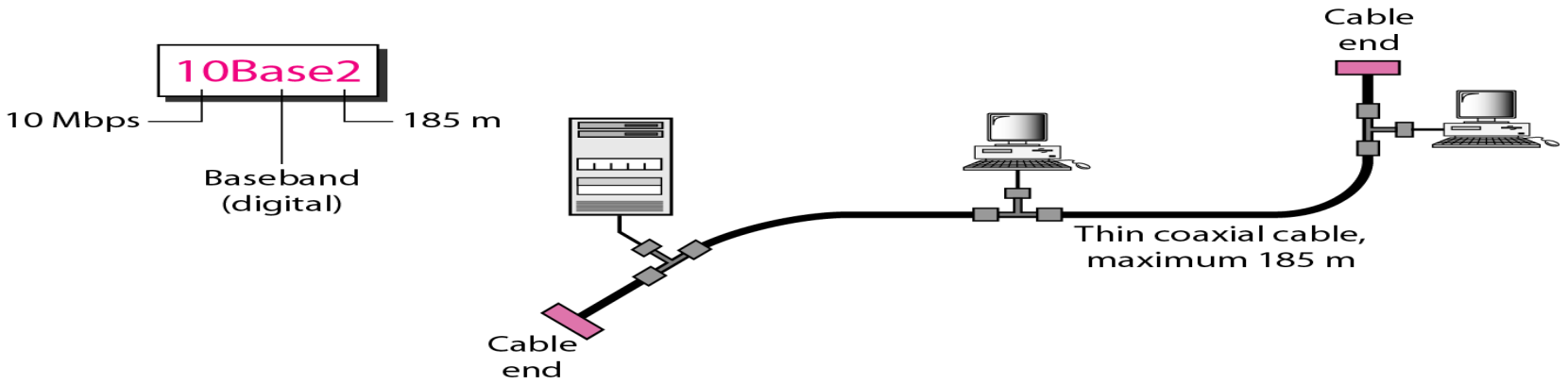
Examples: 10Base-T, 100Base-T

Implementations

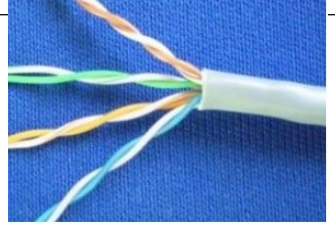


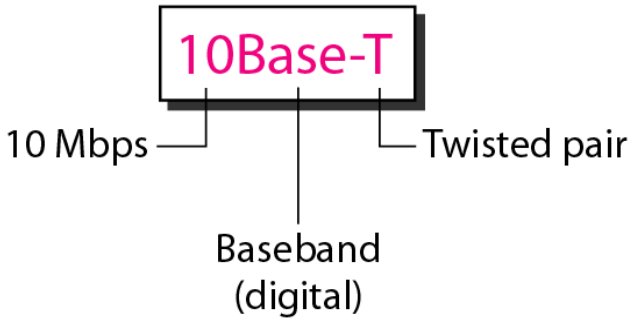
Implementations

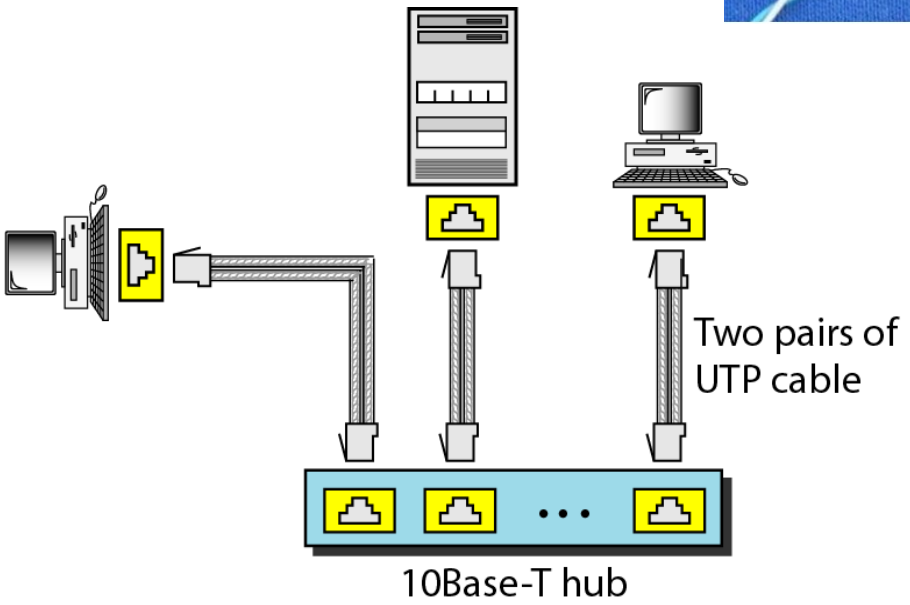


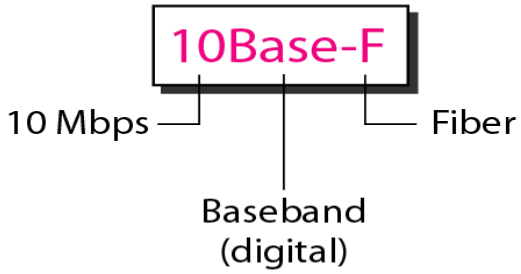


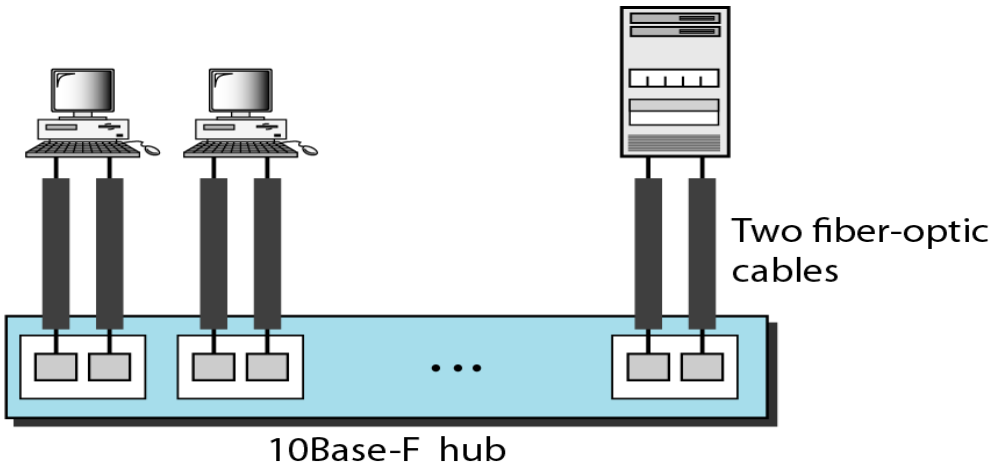
Implementations





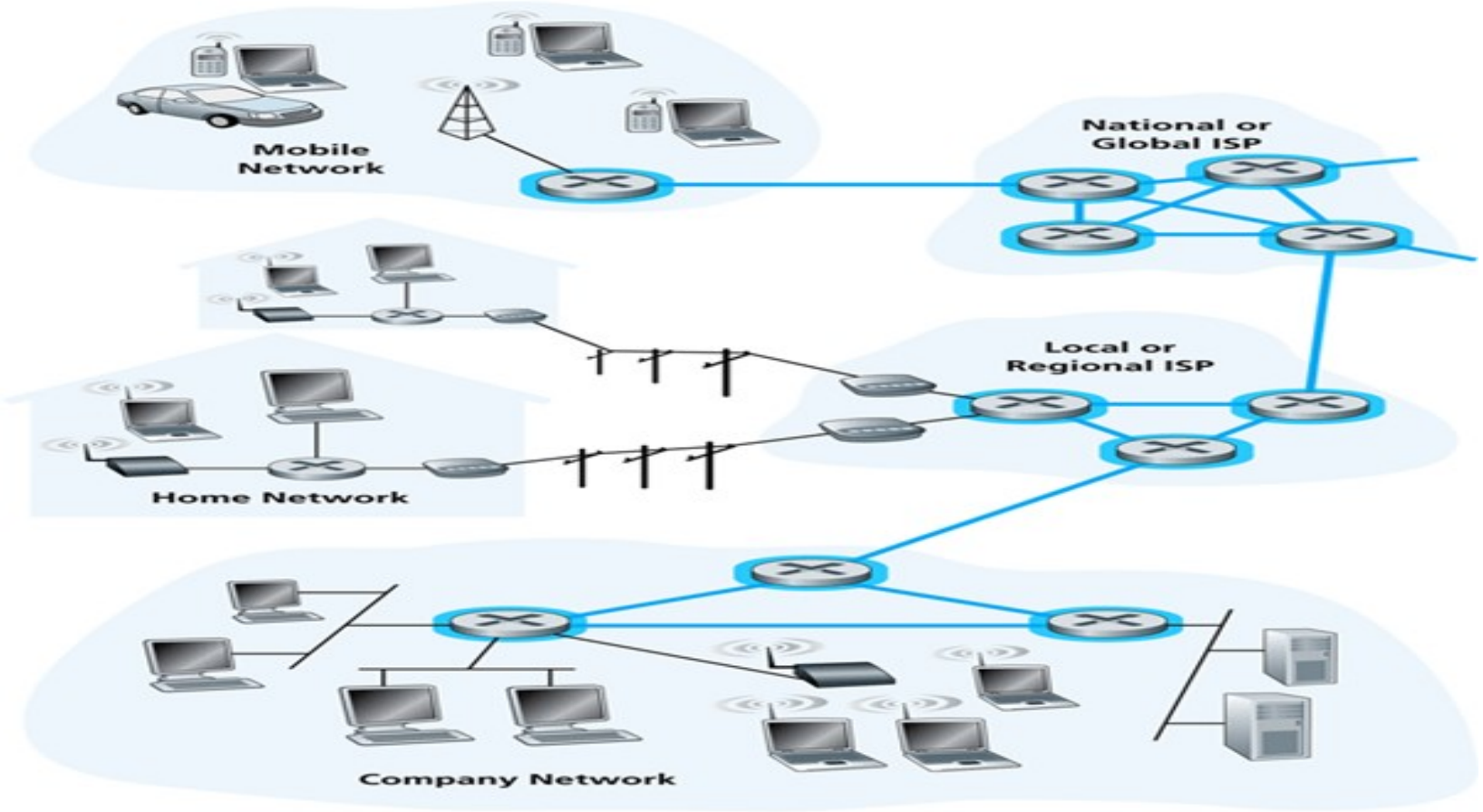






How is Data Transferred Through a Network?

- Network provides services for end systems/hosts by sending and receiving data over the networks. How is data transmitted throughput the core network?



Chapter 1: roadmap

1.1 What is the Internet?

1.2 Network edge

1.3 Network core

1.4 Network access and physical media

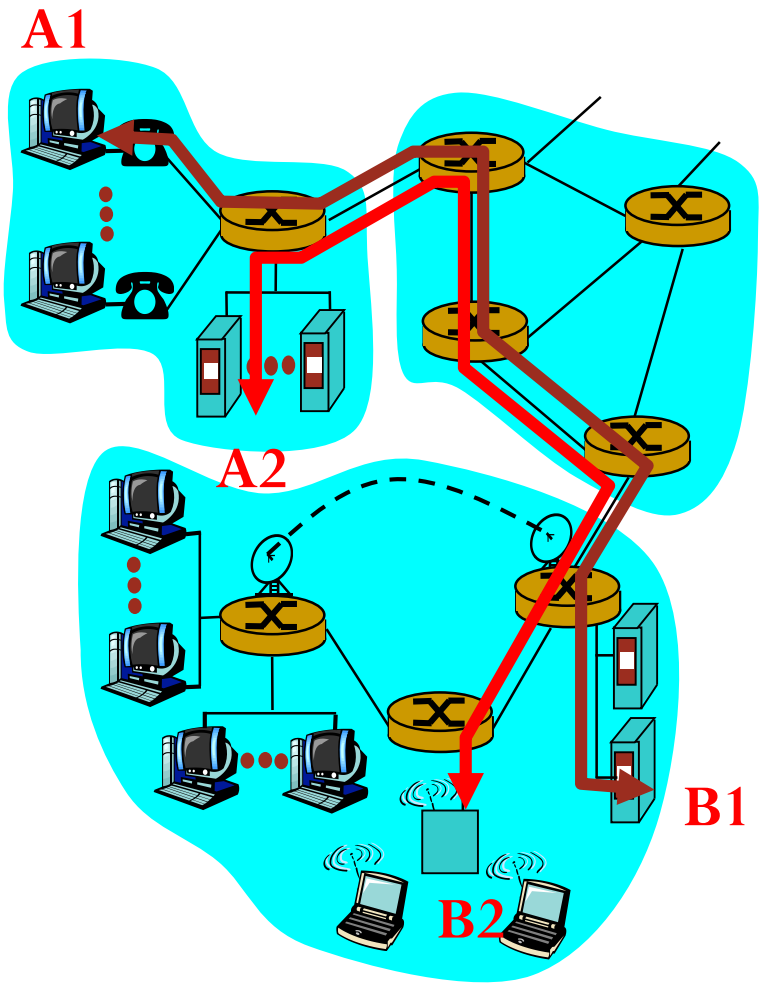
1.5 Internet structure and ISPs

1.6 Delay & loss in packet-switched networks

1.7 Protocol layers, service models

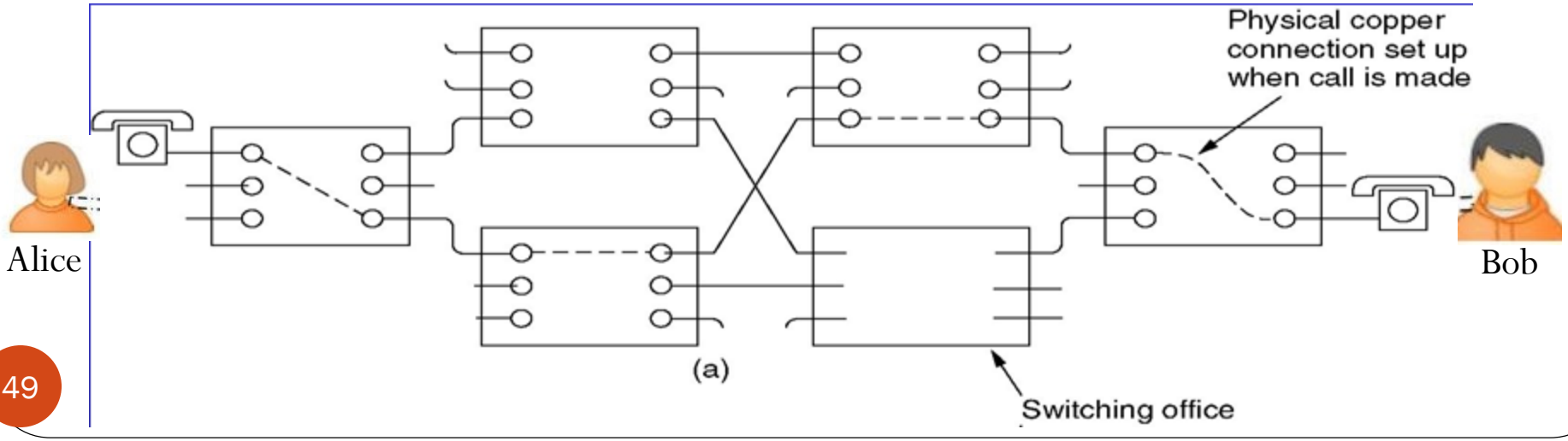
The Network Core

- Core network: the mesh of interconnected routers
- Some natural questions
  - How is data transferred through network core?
  - How is data transmitted through each link, switch, or router in a network?
- Two fundamental approaches:
  - Circuit-switching 电路交换
  - Packet-switching 分组交换
- Analogy:
  - Consider two restaurants: one requires reservations and another no needs.

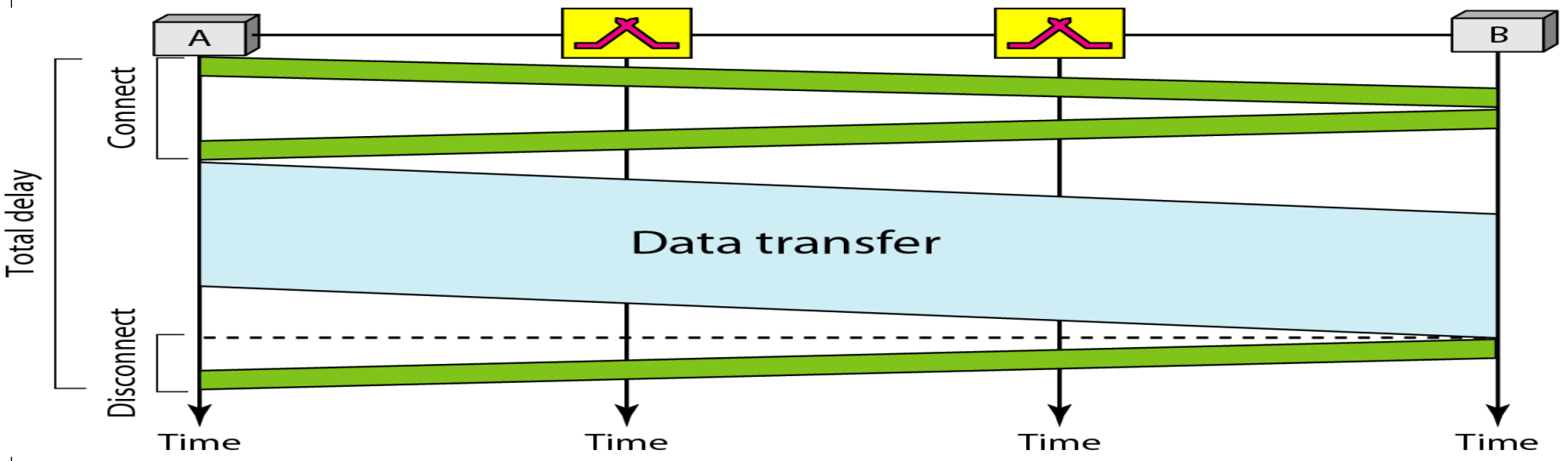


Properties of Circuit Switching: Take Telephone Network as an Example

- Call setup is required
- Dedicated circuit per call. The end-to-end resources are reserved for " per call".
- Dedicated resources with no sharing.
- Guaranteed transmission capacity
- "Blocking" may occur



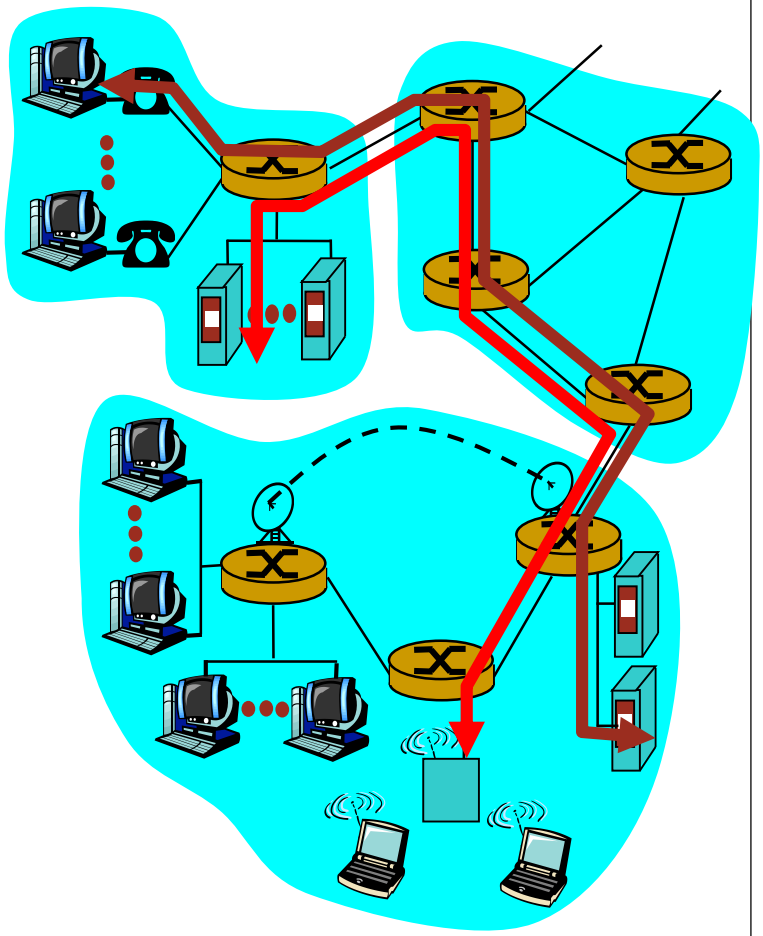
Circuit Switching



- Establish: source creates circuit to destination
  - Node along the path store connection information
  - Nodes reserve resources for the connection
- Transfer: source sends data over the circuit
  - Dedicated resources with no sharing.
  - No destination address is needed since nodes know path.
- Teardown: source tears down circuit when finishing the communications.

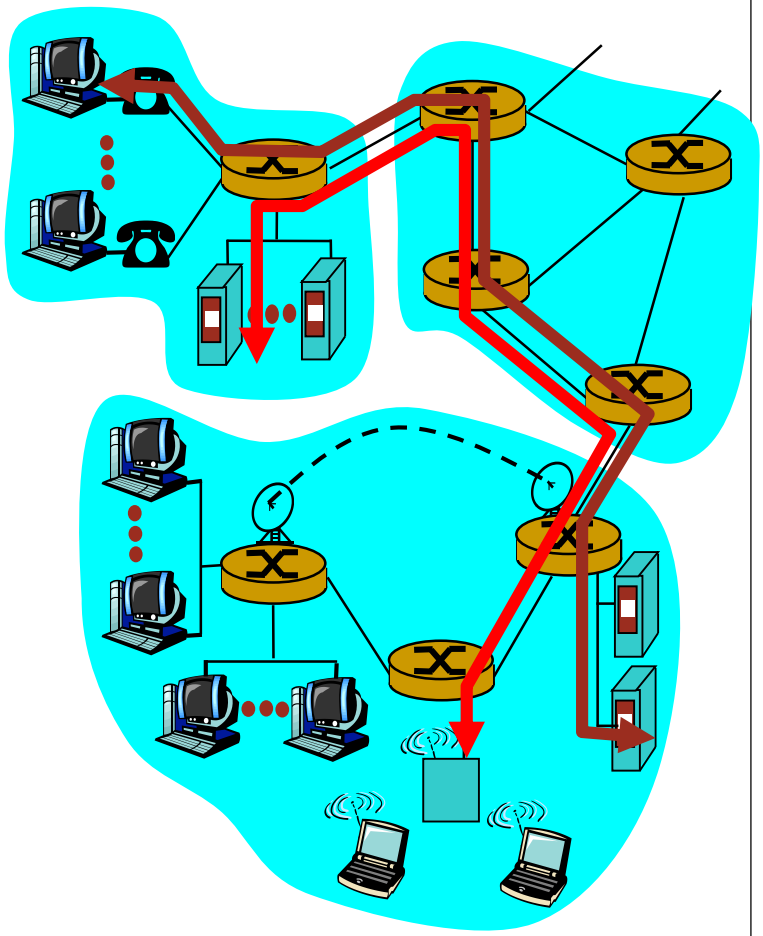
Network Core: Circuit Switching 电路交换

- End-to-end resources reserved for "call/communication"
  - Link bandwidth
  - Dedicated resource: no sharing
  - Circuit-like (guaranteed) performance
  - Call setup required



Network Core: Circuit Switching 电路交换

- **Circuit switching**: it is a methodology of implementing a telecommunications networks in which two hosts establish a dedicated communication path (circuit) through the network before the nodes start to communicate. For the whole length of the communication session between the two communicating nodes, the circuit is dedicated and exclusive, and released only when the session terminates.



Advantages of Circuit-Switching

- Guaranteed bandwidth
  - Predictable communication performance
  - Not "best-effort" delivery
- Simple and reliable
  - Reliable communication channel between hosts
  - No worries about out-of-order packets
  - Simple forwarding based on time slot or frequency
  - No need to inspect a packet header
- Low per-packet overhead
  - Forwarding based on time slot or frequency
  - No IP header on each packet

Disadvantages of Circuit-Switching

- Wasted bandwidth
  - Bursty traffic leads to idle connection during silent period
- Blocked connections
  - Connection refused when resources are not sufficient
- Connection set-up delay
  - No communication until the connection is set up
  - Unable to avoid extra latency for small data transfers
- Network state
  - Network nodes must store per-connection information

Circuit Switching: Resource Division and Multiplexing

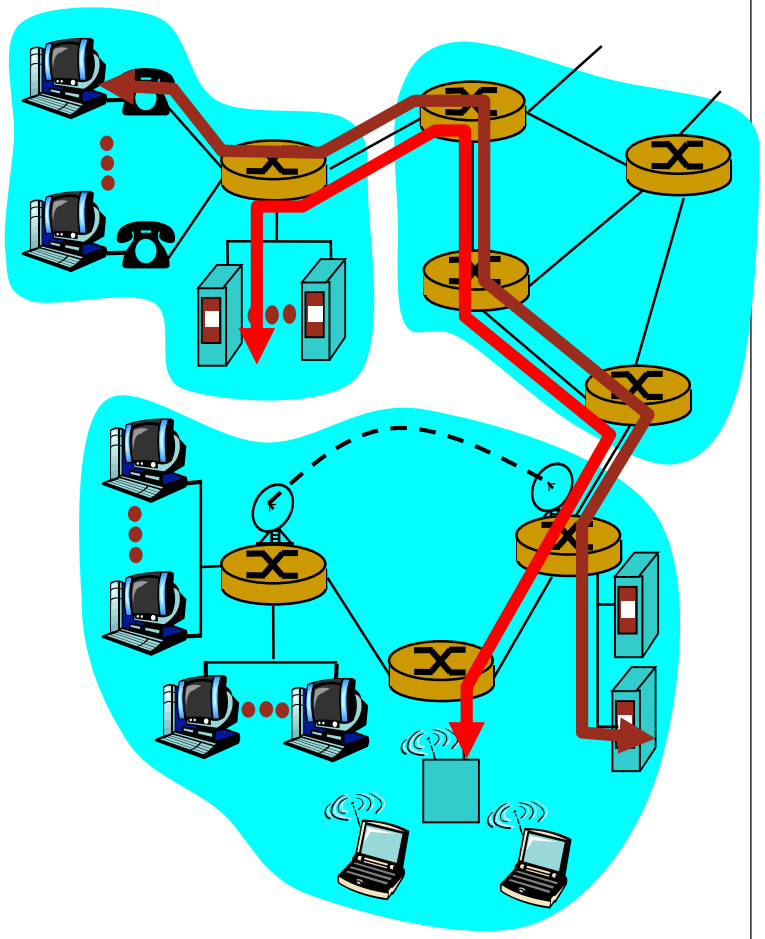
network resources (e.g., bandwidth) divided into "pieces"

- pieces allocated to calls
- resource piece *idle* if not used by owning call *(no sharing)*

- dividing link bandwidth into "pieces"
  - frequency division
    - Ex - telephone networks, FM radio stations
  - time division

Multiplexing 复用

- When the capacity/bandwidth of medium/link exceeds the capacity/bandwidth required for transmission of a single signal, the link can be shared among multiple signals.



Multiplexing

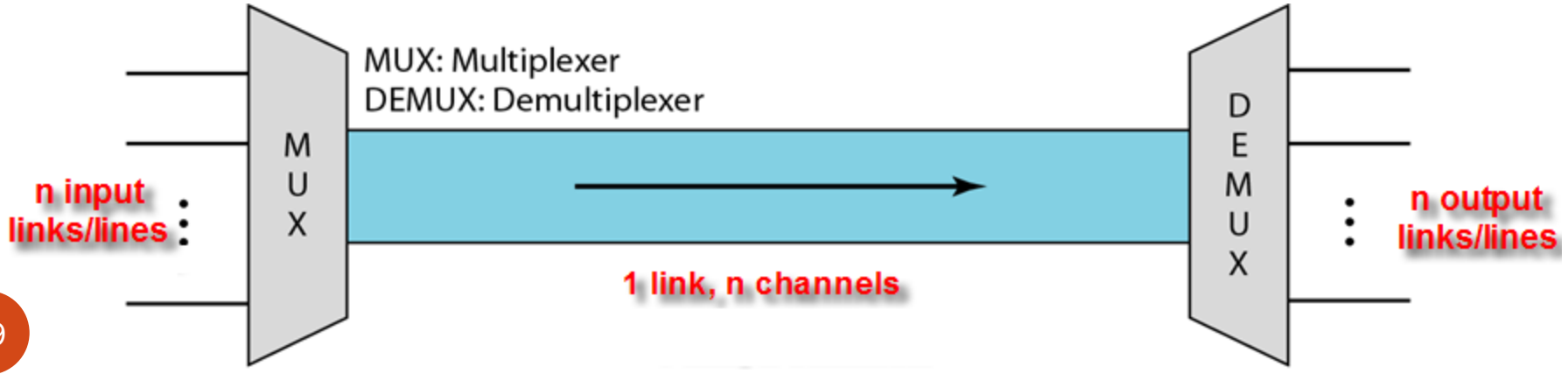
- When the capacity/bandwidth of medium/link exceeds the capacity/bandwidth required for transmission of a single signal, the link can be shared among multiple signals.
- Multiplexing
  - What is multiplexing?
    - It refers to the technique that allows the simultaneous transmission of multiple signals across a single data link. That is the technique that allows several transmission sources to share a large transmission capacity.

Multiplexing

- Why do we use multiplexing?
  - Improve Efficiency: It is a way to improve the efficiency of link utilization.
  - Save resource: Usually, two communicating stations will not utilize the full capacity of a data link. Using multiplexing can support multiple connections over one link.

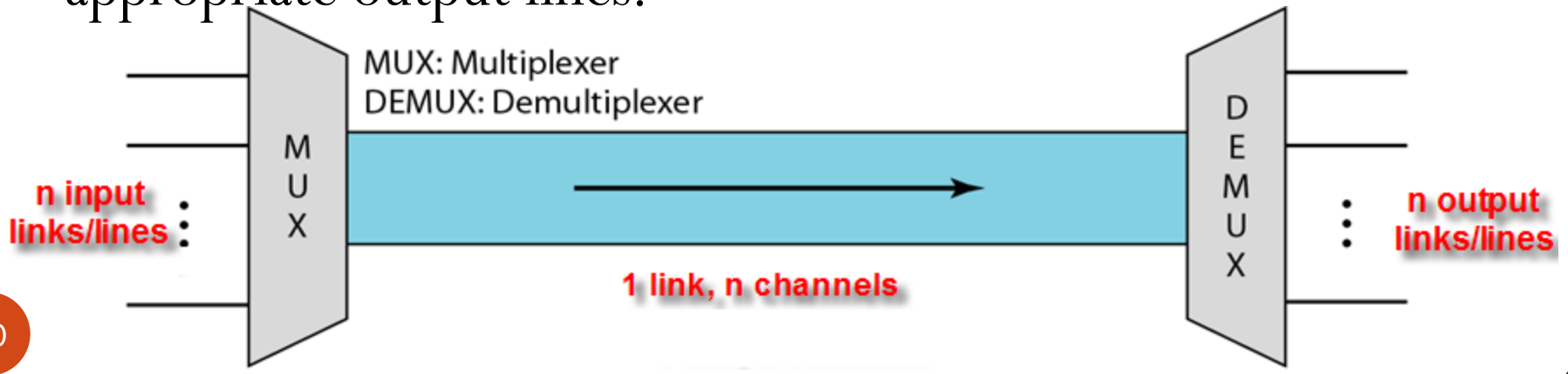
Multiplexing in Circuit Switching

- Multiplexing: it is to divide link capacity/bandwidth into "pieces" and we call these pieces as channels.
- Link: it refers to a physical path, such as a twisted-pair copper wire, coaxial cable, or fiber optics collecting two adjacent nodes.
- Channel
  - The portion of a link that carriers a transmission between a given pair of lines.
  - One link can have many channels (n).



Multiplexing in Circuit Switching

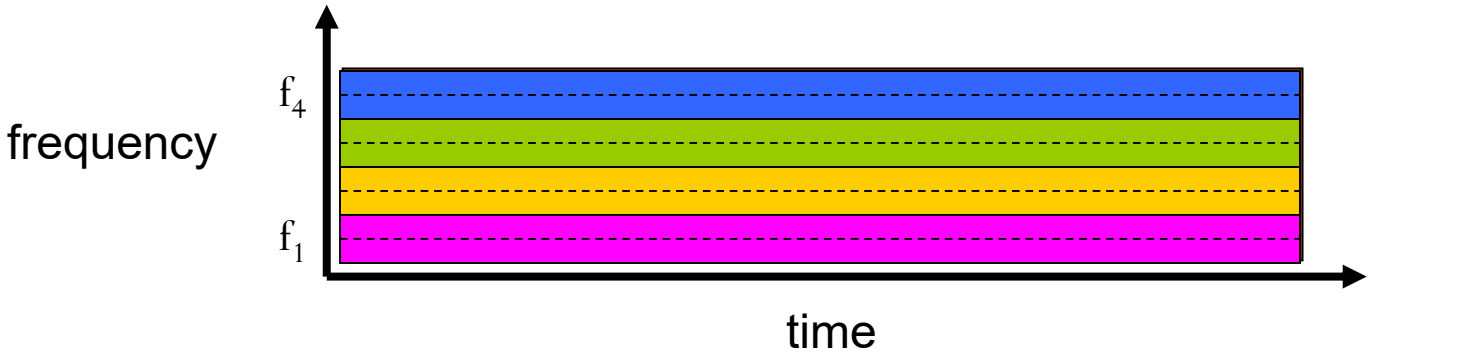
- How does it work?
  - The multiplexer is connected by a single data link to a demultiplexer.
  - The link is divided into n separate channels.
  - The multiplexer combines data from the n input lines and transmits over a higher capacity data link.
  - The demultiplexer accepts the multiplexed data stream, separate the data according to channel, and deliver them to the appropriate output lines.



Two Multiplexing Ways: FDM and TDM

Example: 4 users

FDM: Frequency Division Multiplexing

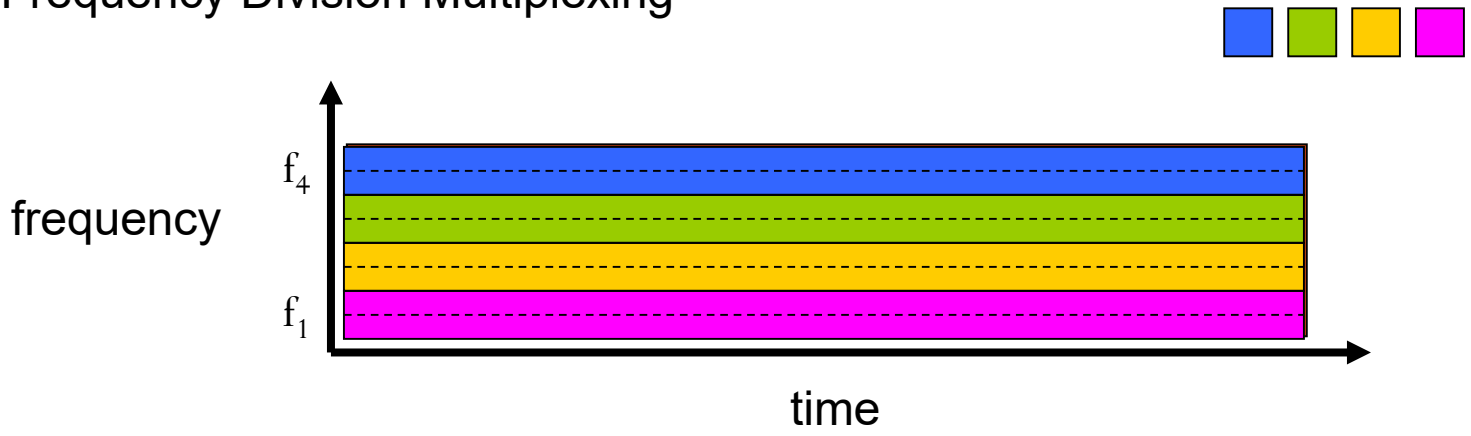


- FDM: it is to divide the frequency band into different ranges, and modulate signals from different users with different carrier frequencies. Example: cable TV.

Two Multiplexing Ways: FDM and TDM

Example: 4 users

FDM: Frequency Division Multiplexing

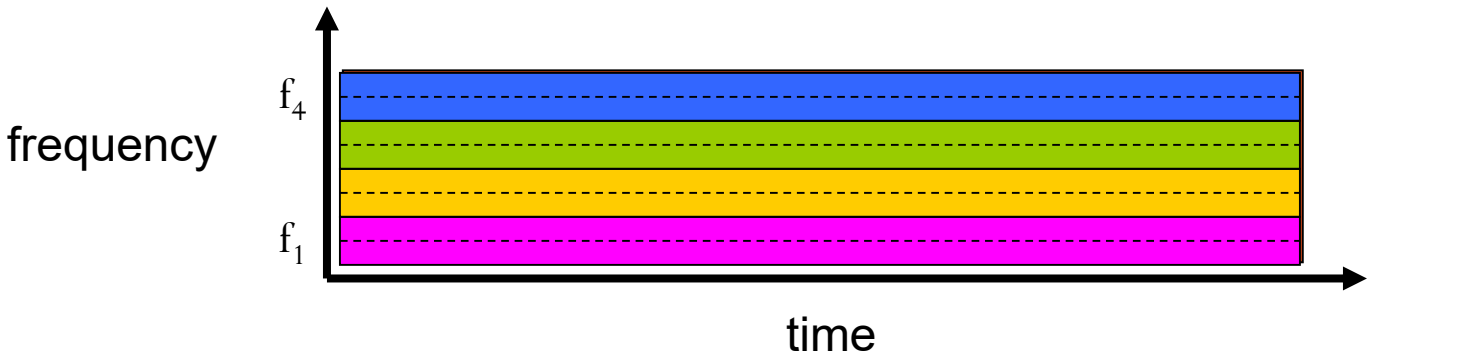


- Main features of FDM
  - Frequency band is divided into N different parts.
  - Each frequency part is assigned to one of the N nodes.
  - Each user transmits with no limitation in time, but use only the assigned frequency.
  - Different users are separated in the frequency domain.

Two Multiplexing Ways: FDM and TDM

Example: 4 users

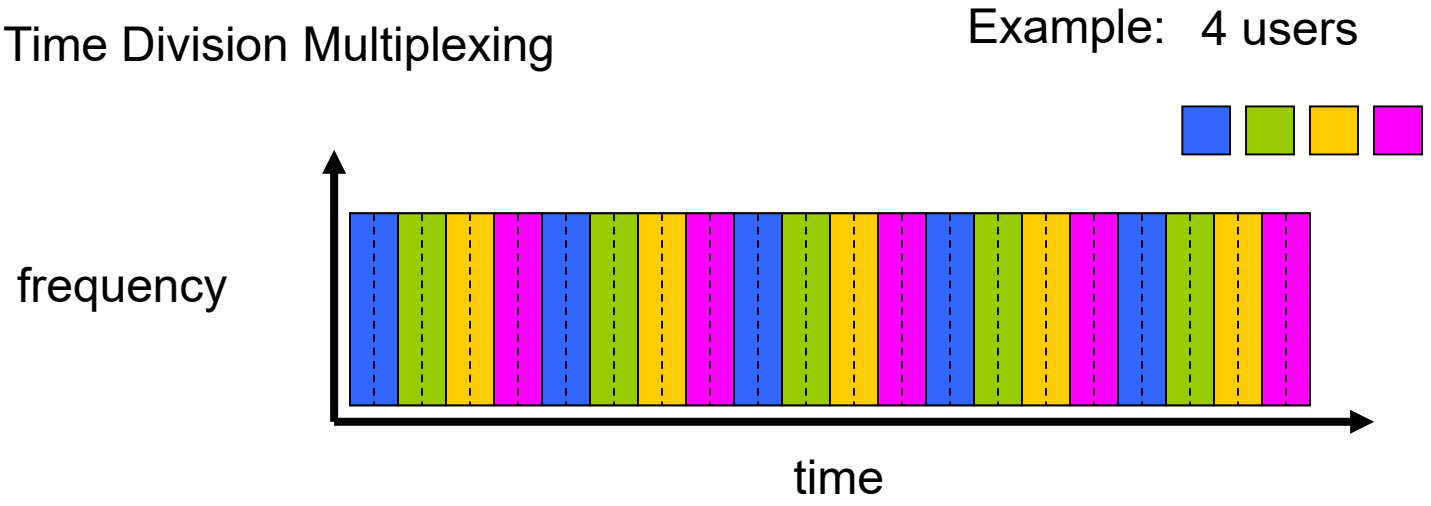
FDM: Frequency Division Multiplexing



- Advantages
  - Simple
  - Eliminate collision
  - Provide fair allocation
- Disadvantage
  - Resource waste due to the inactive nodes

Two Multiplexing Ways: FDM and TDM

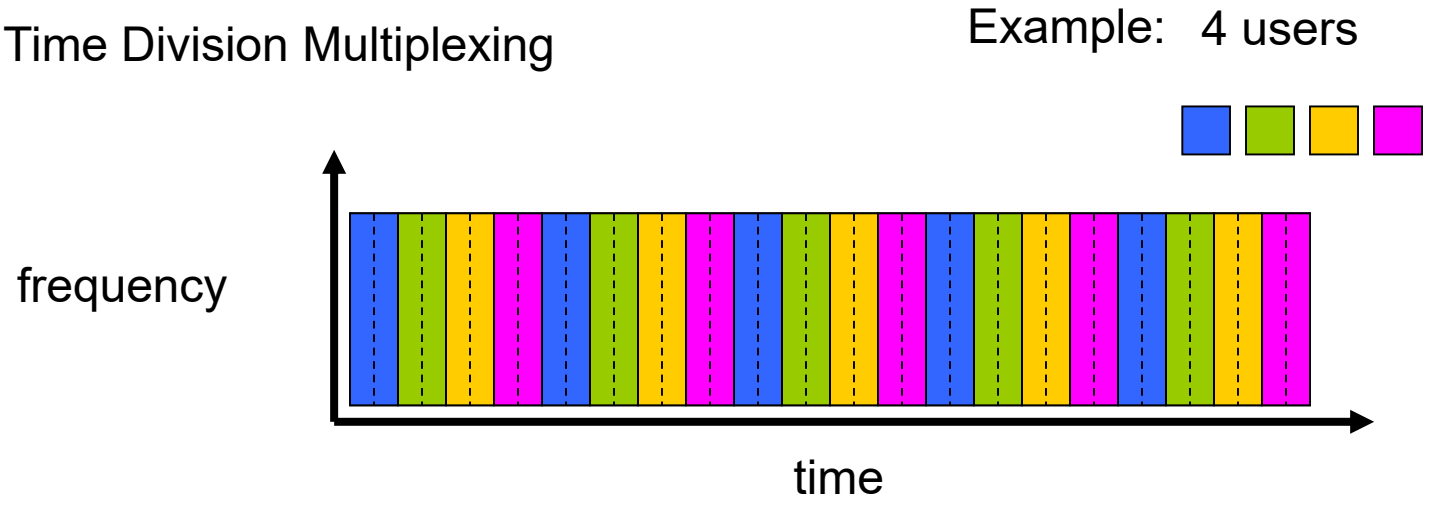
TDM: Time Division Multiplexing



- TDM: it is a type of multiplexing that combines signals of different connections by assigning each connection to a different time slot and repeatedly transmits a fixed sequence of time slots over the whole frequency band of the transmission link.

Two Multiplexing Ways: FDM and TDM

TDM: Time Division Multiplexing



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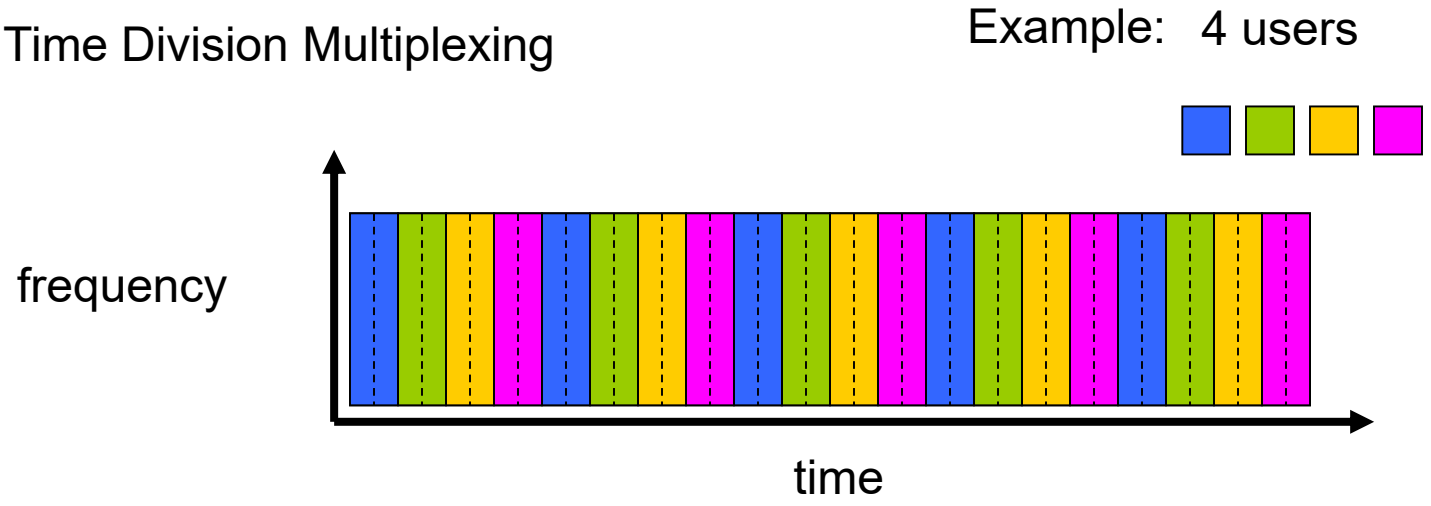
Two Multiplexing Ways: FDM and TDM

TDM: Time Division Multiplexing

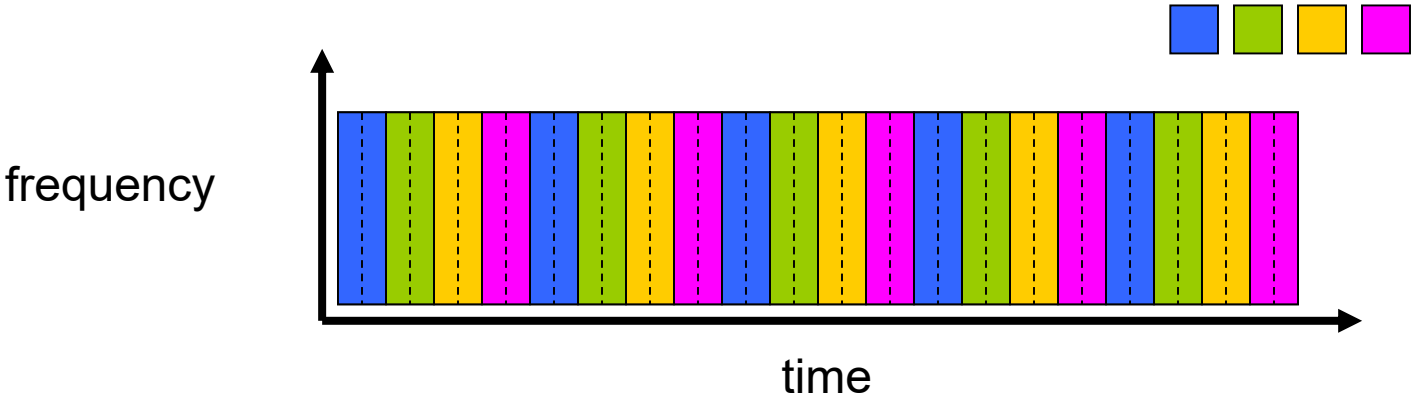


- Main features of TDM
  - Time is divided into frames and each frame is further divided into N time slots.
  - Each time slot is assigned to one of the N nodes.
  - Whenever a node has a packet to send, it transmits the packets during its assigned time slots.
  - Different nodes are separated in the time domain.

Two Multiplexing Ways: FDM and TDM

TDM: Time Division Multiplexing

Example: 4 users

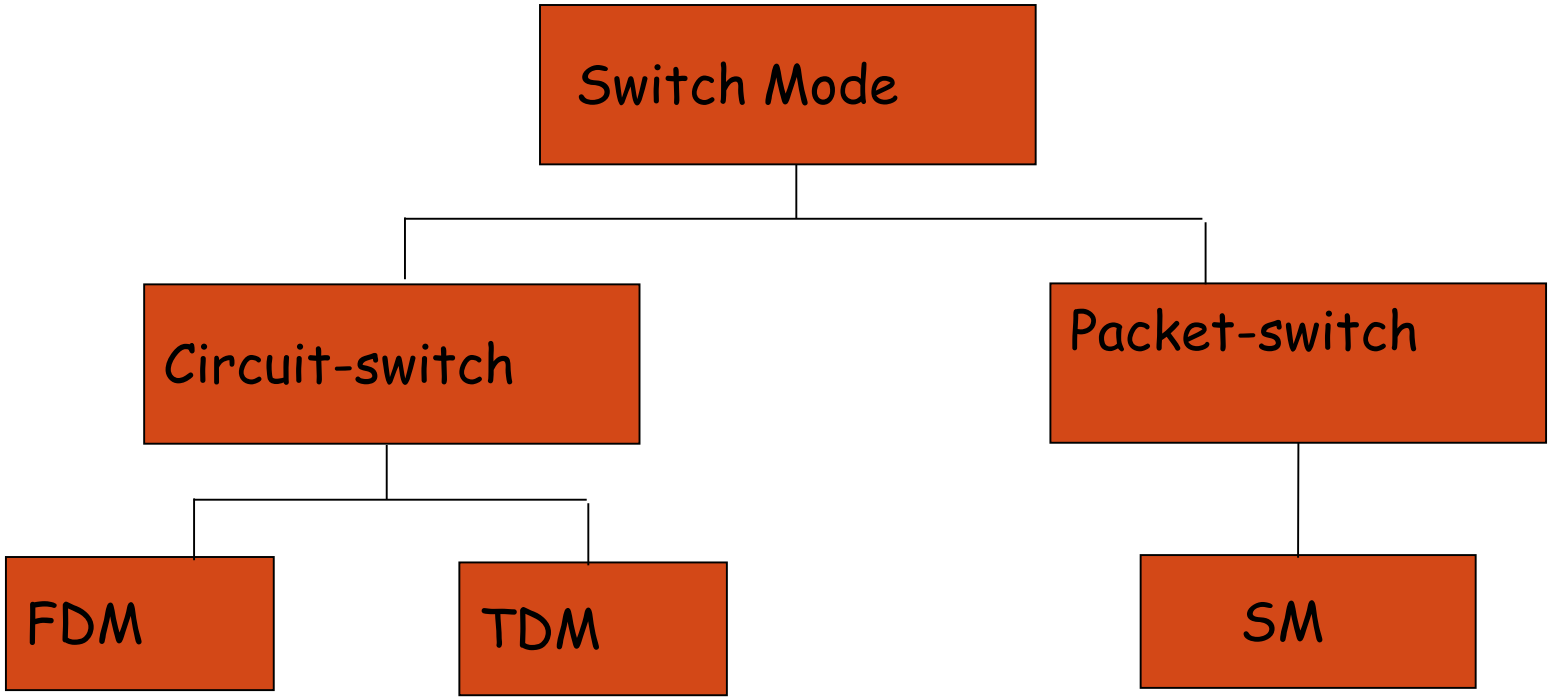


- Advantages
  - Simple
  - Eliminate collision
  - Provide fair allocation
- Disadvantages
  - Resource waste due to the inactive nodes

Numerical example

- How long does it take to send a file of 640,000 bits from host A to host B over a circuit-switched network?
  - All links are 1.536 Mbps
  - Each link uses TDM with 24 slots
  - 500 msec to establish end-to-end circuit

Two Types of Switch Modes



FDM: Frequency Division Multiplexing

TDM: Time Division Multiplexing

SM: Statistical Multiplexing

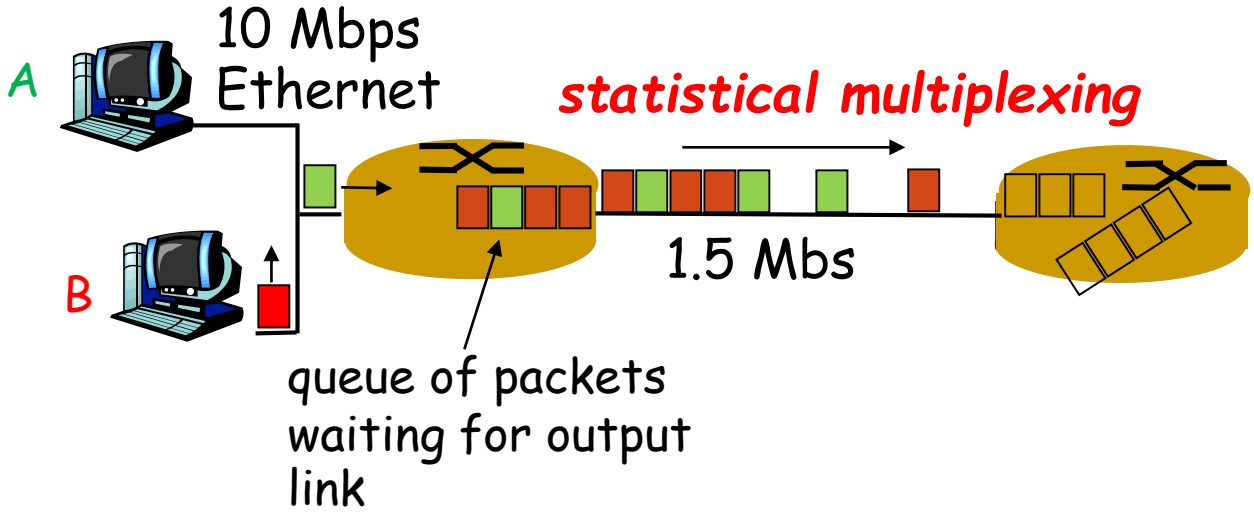
Packet Switching 分组交换

- Packet Switching is an approach to deliver data where messages are divided into packets before they are sent. Each packet is then transmitted individually and may follow different routes to its destination. Once all the packets forming a message arrive at the destination, they are recompiled into the original message.
- Packet is specially formatted unit. Each packet contains data load, IP addresses of source and destination nodes, sequence numbers and some other control information.
- The packets are sent towards the destination irrespective of each other. Each packet has to find its own route to the destination, and there is no predetermined path.

Packet Switching

- Source breaks long messages into smaller "packets"
- Packets share network resources by the way of statistical multiplexing （统计复用）
- Each packet uses full link bandwidth

Packet Switching: Statistical Multiplexing



- Packets are served usually based on demand (e.g., first come first service) ➔ on demand resource usage.
- Sequence of A & B packets does not have a fixed pattern ➔ statistical multiplexing.
- "store-and-forward" transmission

Advantages of Packet Switching

- Better utilization of link resources: It does not waste resource if there are data to send from any source.
- High efficiency: supporting multiple simultaneous connections.
- Less costly to implement.

Disadvantages of Packet Switching

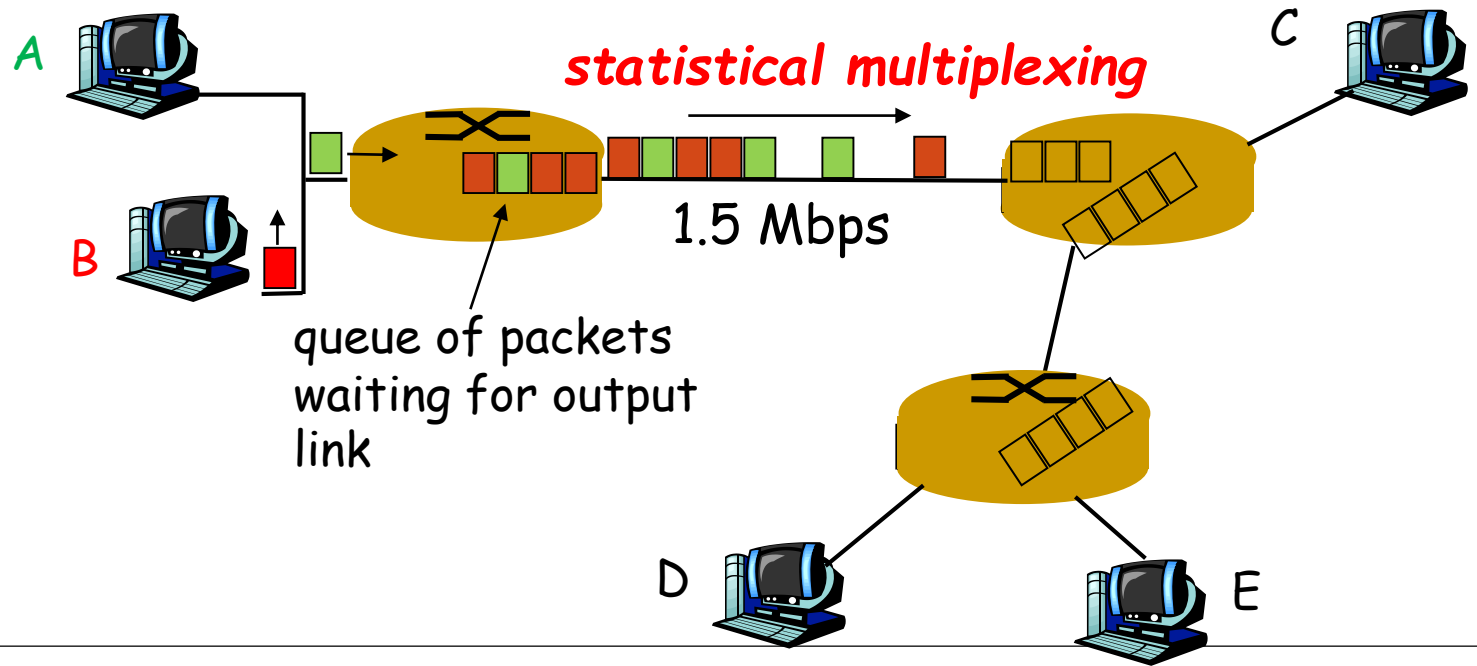
- Not suitable for real-time services because of its variable and unpredictable end-to-end delay
- Out-of-order arriving packets: packets may not arrive at their destination in the order in which they were originally transmitted because packets may take different paths.
- Resource contention and congestion
  - aggregated resource demand may exceed the amount of available resource.
  - congestion: queuing delay, packet loss, etc.

Circuit Switching Versus Packet Switching

- Circuit Switching
  - Resources need to be reserved.
  - Resources remains dedicated for the entire duration of data transmission for each collection/reservation
  - Multiplexing ways: TDM and FDM
  - E.g., traditional telephone network
- Packet Switching
  - No resource reservation. Resources are allocated on demand.
  - Statistical multiplexing
  - E.g., the Internet

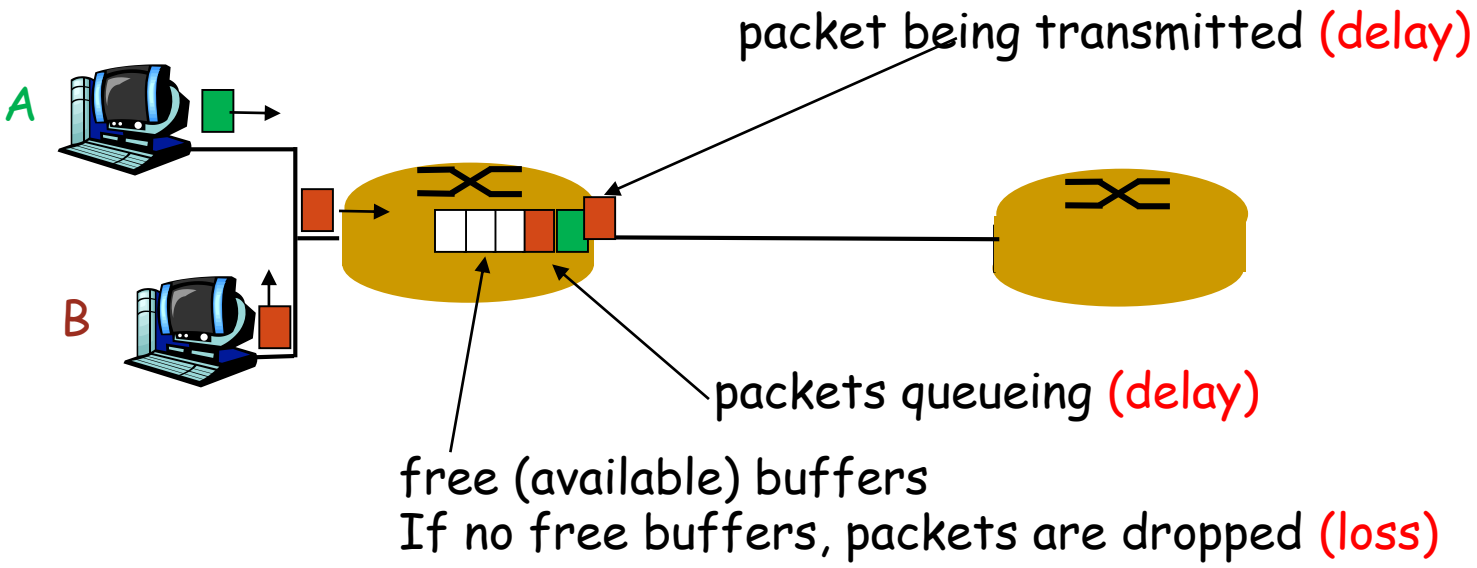
Packet-switched Network (PSN)

- A packet-switched network consists of a set of switches connected by physical links, in which each packet passes through each link by using SM.
- In packet-switched network, the resources are allocated on demand. There is no resource reservation.



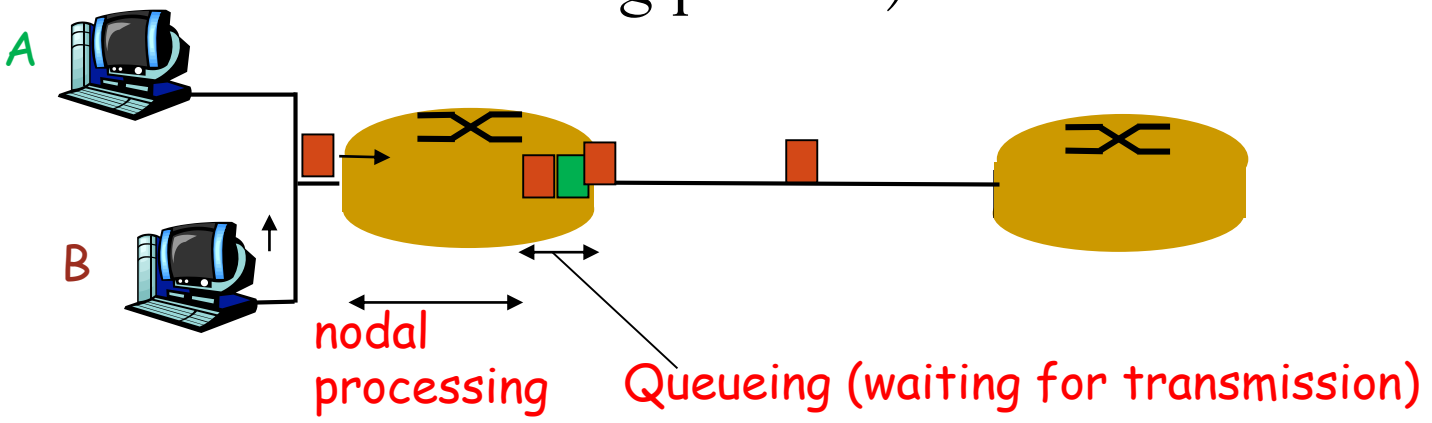
Packet Delay and Loss in PSN

- Each router has multiple links attached to it.
- When the sum of packet arrival rates from these input links exceeds the output link capacity, arriving packets find that the link is busy with the transmission of another packet, then they need to queue at the output buffer, waiting for their turns ➔ packet delay
- If buffer is full, some packets need to be dropped ➔ packet loss



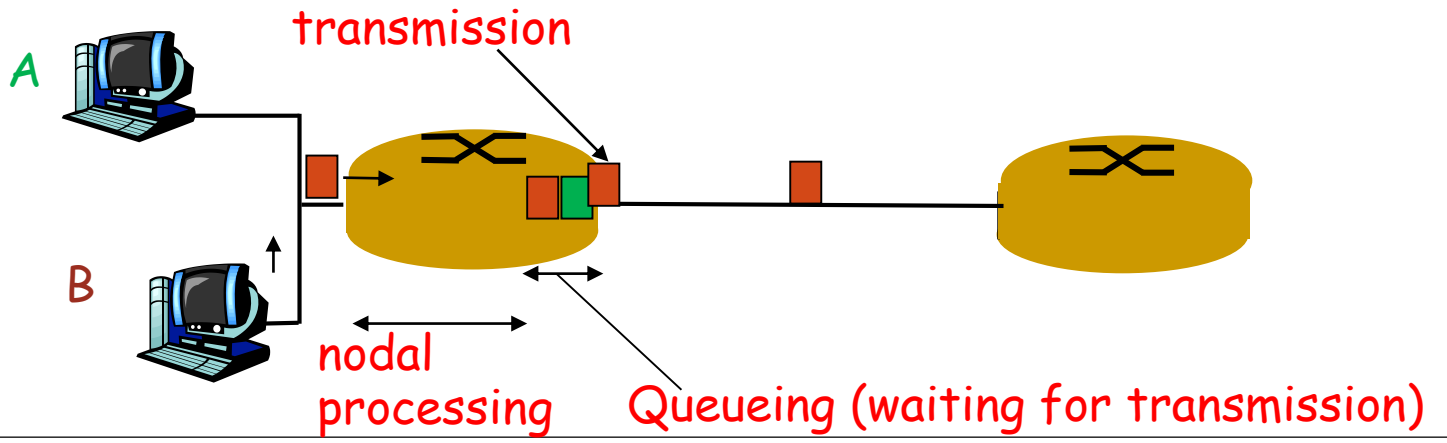
Four Types of Packet Delay

- Processing delay （处理时延）: the time to do the nodal processing such as bit error detection, determine where to direct the packet, check the packet's header, etc.
- Queuing delay （排队时延）
  - The time waiting at output buffer for transmission.
  - It depends on congestion level of router (i.e., the number of earlier-arriving packets).



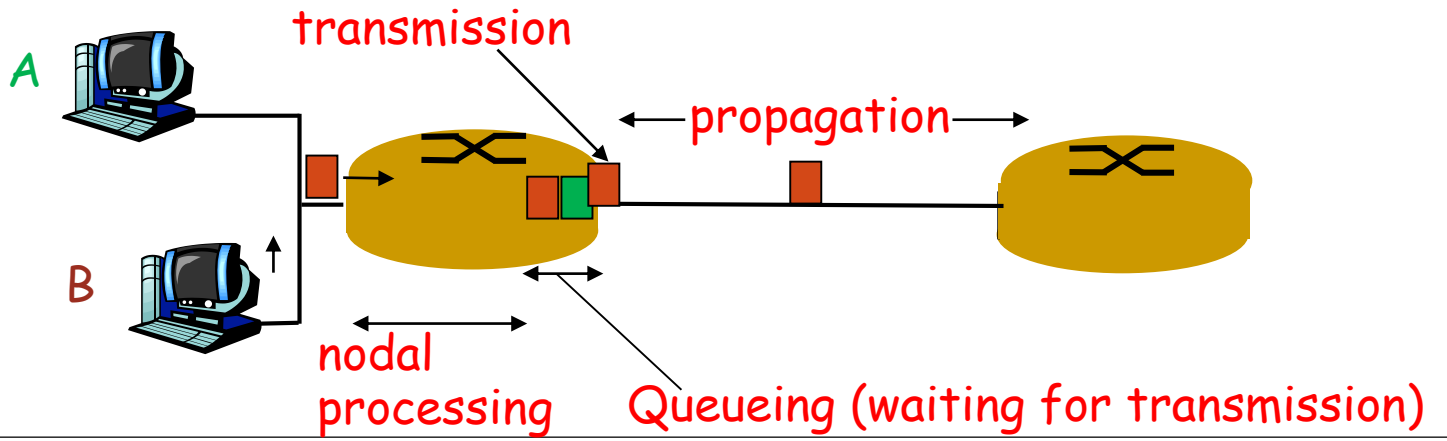
Four Types of Packet Delay

- Transmission delay （传输时延）
  - It is the time to send all of packet's bit into the output link. The time depends on packet length (e.g., L bits) and link transmission rate (i.e., R bps).
  - The transmission delay is L/R seconds.



Four Types of Packet Delay

- Propagation delay (传播时延)
  - The time required for each bit to transmit from the beginning of the link to the next router.
  - It depends on
    - The distance between two routers (i.e., the length of the physical link, denoted as d).
    - Propagation speed of the link (denoted as s).
    - Propagation delay=d/s



Examples

- The distance between two routers is 12,000km and propagation speed is 2.4×10^8m/s in cable. The propagation delay is

- The example shows that one bit can go over the Atlantic Ocean in only 50 ms if there is a direct cable.

Examples

- The distance between two routers is 12,000km and propagation speed is 2.4×10^8m/s in cable. The propagation delay is

$$\text{Propagation time} = \frac{12{,}000 \times 1000}{2.4 \times 10^8} = 50 \text{ ms}$$

- The example shows that one bit can go over the Atlantic Ocean in only 50 ms if there is a direct cable.

Examples

- The transmission rate of a link is 1Gbps. The transmission time for a 2.5-kbyte message (an e-mail) is

- Comparing the propagation time (50ms) and transmission time (0.02ms), we note that because the message is short and the transmission rate is high, the dominant factor is the propagation time, not the transmission time. The transmission time can be ignored.

Examples

- The transmission rate of a link is 1Gbps. The transmission time for a 2.5-kbyte message (an e-mail) is

$$\text{Transmission time} = \frac{2500 \times 8}{10^9} = 0.020 \text{ ms}$$

- Comparing the propagation time (50ms) and transmission time (0.02ms), we note that because the message is short and the transmission rate is high, the dominant factor is the propagation time, not the transmission time. The transmission time can be ignored.

Examples

- The transmission rate of a link is 1Mbps. The size of message is 5Mbyte (an image). The distance of this link is 12,000km, and the propagation speed is 2.4×10^8m/s . We have

- In this case, because the message is very large and the bandwidth is not very high, the dominant factor is the transmission time, not the propagation time. The propagation time can be ignored.

Examples

- The transmission rate of a link is 1Mbps. The size of message is 5Mbyte (an image). The distance of this link is 12,000km, and the propagation speed is 2.4×10^8m/s . We have

$$\text{Propagation time} = \frac{12{,}000 \times 1000}{2.4 \times 10^8} = 50 \text{ ms}$$

$$\text{Transmission time} = \frac{5{,}000{,}000 \times 8}{10^6} = 40 \text{ s}$$

- In this case, because the message is very large and the bandwidth is not very high, the dominant factor is the transmission time, not the propagation time. The propagation time can be ignored.

Total Nodal Delay

$$d_{\text{nodal}} = d_{\text{proc}} + d_{\text{queue}} + d_{\text{trans}} + d_{\text{prop}}$$

- d_{proc} : Processing Delay (Fixed)
  - Typically a few microsec or less
- d_{queue} : Queuing Delay (Variable)
  - Depends on congestion status
- d_{trans} : Transmission Delay (L/R) (Fixed)
  - Depends on transmission rate and packet length.
  - Negligible for transmission rates of 10Mpbs and higher (e.g., LANs), but significant for low-speed links (e.g., dial-up modem links)
- d_{prop} : Propagation Delay (d/s) (Fixed)
  - Depends on distance of two routers and medium speed.
  - A couple of microseconds to hundreds of milliseconds.

Queuing Delay and Traffic Intensity

- Among four types of delays, the queuing delay can vary for different packets.
- We usually use statistical measures, such as average queuing delay, to characterize the performance of queuing delay.
- Traffic intensity
  - It is introduced to estimate the extent of average queuing delay.
  - Traffic intensity = La/R, where L is packet length (in bits), a is the average packet arrival rate, and R is the transmission rate of the link (bps).

Queuing Delay and Traffic Intensity

- Traffic intensity La/R→0: average queuing delay is small
- Traffic intensity La/R→1: delays become large.
- Traffic intensity La/R>1: arrival rate exceeds link capacity, average delay infinite.

Design your system so that the traffic intensity is no greater than 1

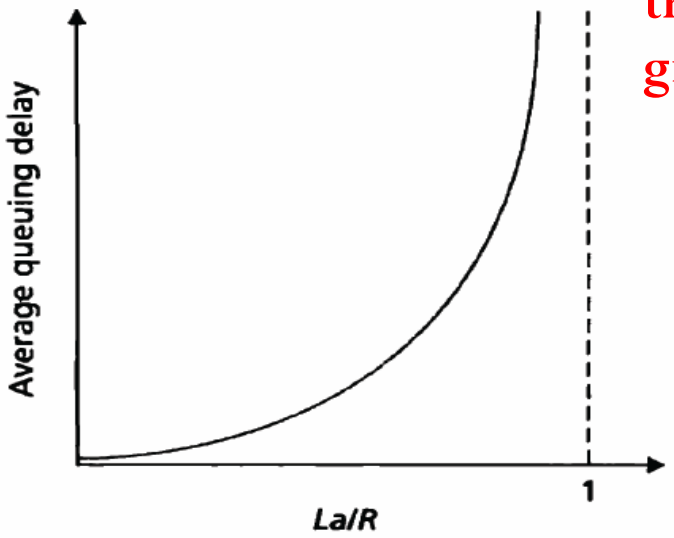


Figure 1.14. Dependence of average queuing delay on traffic intensity

Summary

- The network edge
  - Access network: residential access, company access, wireless access, …
- The network core
  - Circuit switching and multiplexing: TDM, FDM
  - Packet switching and multiplexing: SM
- Packet loss, delay, and traffic intensity
  - Processing delay, queueing delay, transmission delay, and propagation delay.