Overview

EE450: Introduction to Computer Networks

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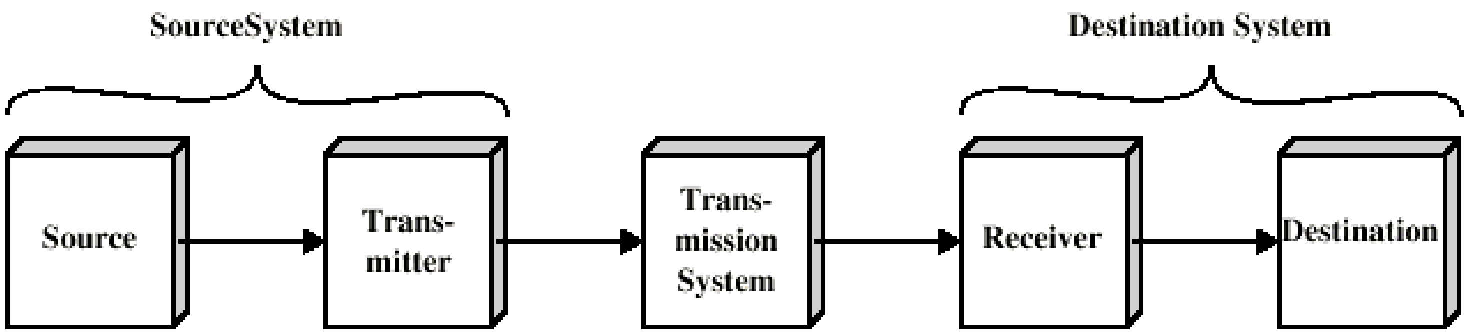
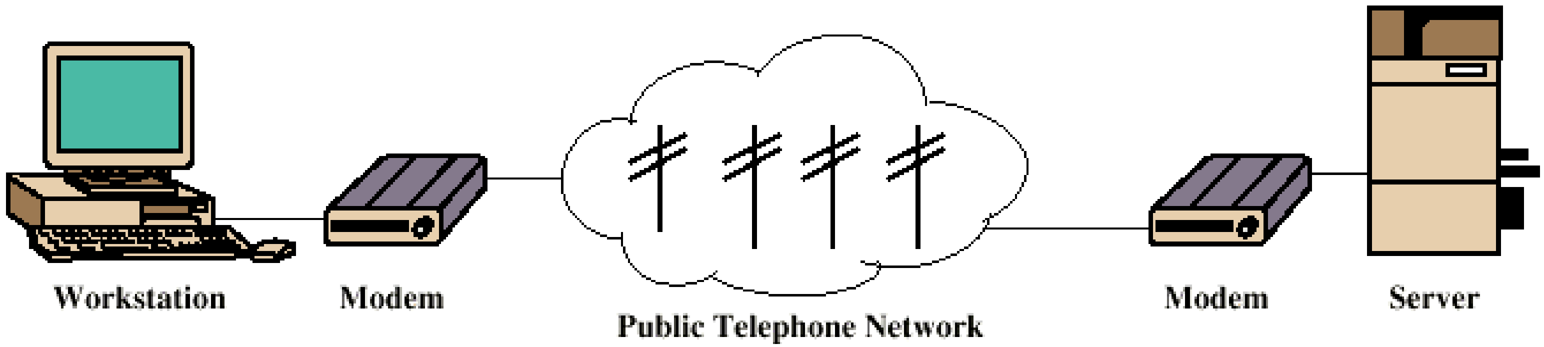
Course Overview

- Part 1: Data Communications & Networking
- Part 2: Computer Networking Protocols (TCP/IP)
- Part 3: Wide Area Networks (WANs)
- Part 4: Local Area Networks (LANs)
- Part 5: Internetworking
- Part 6: Transport Layer Protocols
- Part 7: Network Applications

Simple Data Communications Model



(a) General block diagram



(b) Example

Key Data Communications Tasks

- Interfacing
- Signal Generation
- Synchronization
- Exchange Management
- Error detection and correction
- Addressing and routing
- Recovery
- Message formatting
- Security
- Network Management
- Many more…

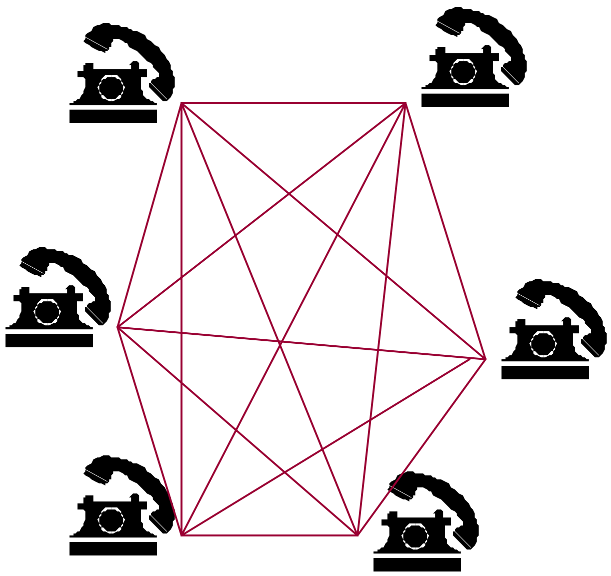
Computer Network

- A Computer Network is a set of nodes such as routers, switches, hosts, etc.. interconnected via transmission facilities such as copper, cable, fiber, satellite, radio, microwave, etc.. for the purpose of providing *services* to end systems/users

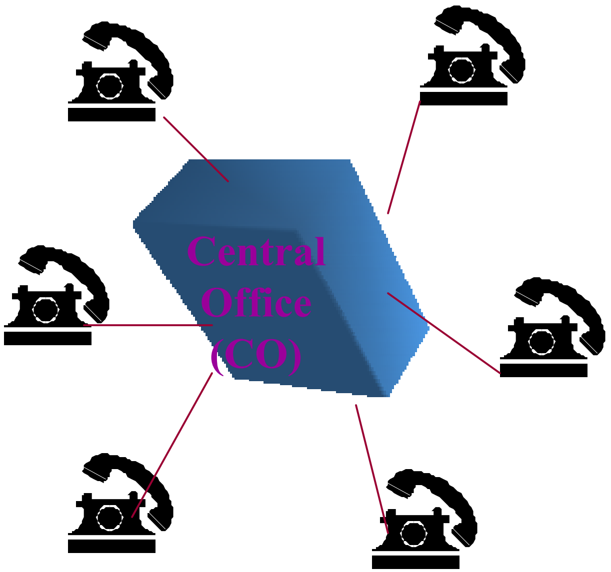
- Do we need networking? Yes we do!

- Point-to-point communication is not practical!
  - Devices are too far apart
  - Large set of devices would need impractical number of connections. See illustration next chart

Example: Telephone Network



Fully-Connected Mesh
# of FDX links = N(N-1)/2
e.g., N=6; 6(5)/2=15 links
Total # ports = N(N-1)
e.g., N=6; 6(5)=30 ports



With Central Office
# of FDX links = N
e.g., N=6; 6 links
Total # of ports = N
e.g. N=6, 6 ports

Multimedia Convergence

Major Industries

Broadcast TV
Film

Video

- pre-recorded / on-demand
  (e.g., MPEG, Real Net)
- live (video phone,
  video teleconference)

Data

- e-mail
- files
  - -- executables
  - -- source code
  - -- data
  - -- html
  - -- image

Computer Software
Financial, e-Commerce, etc.

Recording
Broadcast
Radio

Voice / Audio

- pre-recorded /on-demand
  (streaming or file [mp3])
- live (Real Net, VoIP)

Wireless

Telephone companies (Telco)
Internet Service Providers (ISP)

Computer Hardware/Software
Telco/wireless Hardware

Clients, Servers and Peers

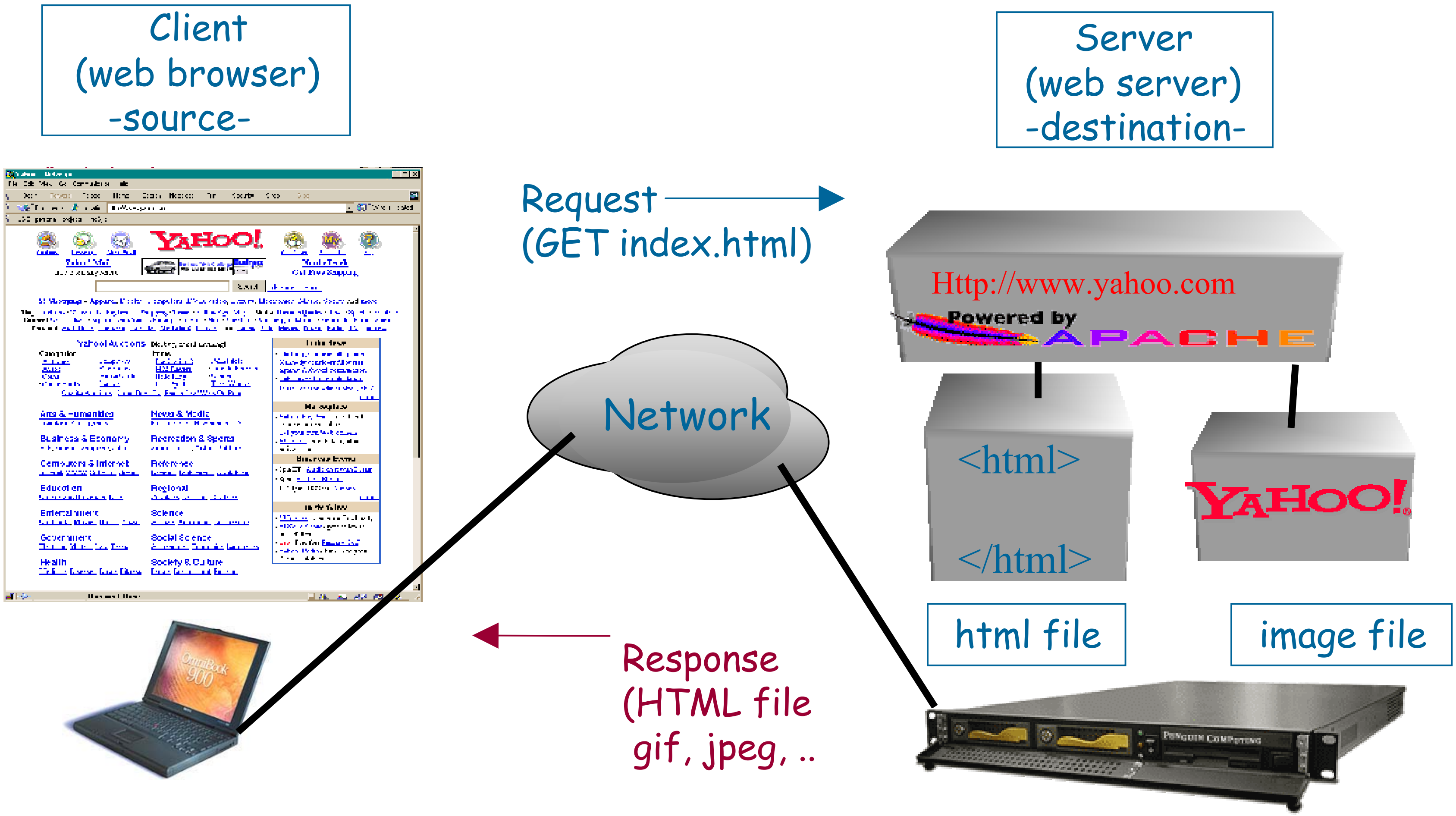
- A network computer can either provide service or request service
- A *server* is a service provider, providing access to network resources
- A *Client* is a service requester
- A *Peer-to-Peer* network does not have a dedicated server. All computers are equal and they both provide and request services.

Server Roles

- Servers can assume several roles and a single server could also have several roles
- Examples of Servers include:
  - File Servers: Manages user access to shared files
  - Print Servers: Manages user access to print resources
  - Application Servers: Similar to FS with some processing
  - Mail Servers: Manages electronic messages between users
  - Communications (Remote Access) Servers: Manages data flow and e-messages from one network to another
  - Web Servers: Runs WWW and FTP servers for access via the Internet/Intranet
  - Directory (DNS) Servers: Locates information about networks such as domains.

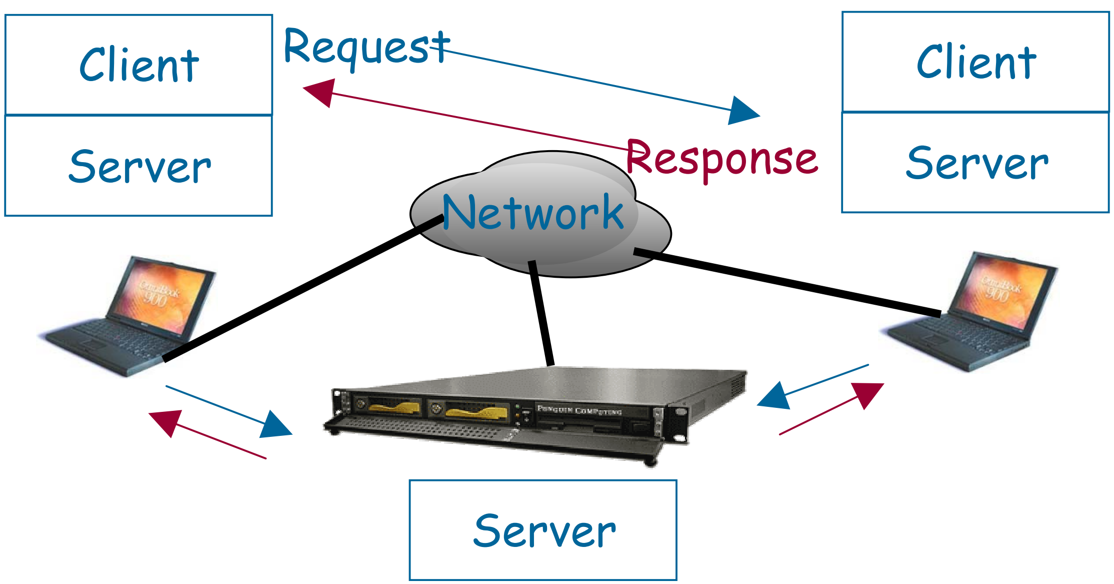
Client/Server Model

Example: World Wide Web



Peer-to-Peer Model

- Peer-to-Peer
  - Each host has both client and server functionalities
  - CPU cycle sharing
  - Example: Gnutella, KaZaA, Skype, etc...



Network Software (I)

- NOS include special functions for connecting hosts into a network
- NOS manages network resources and services
- NOS provide network security for multiple users
- Most common Client/Server NOS include:
  - UNIX
  - Microsoft NT/Windows 2000
  - Novell Netware
  - LINUX
  - OS/2
  - Others

Network Software (II)

- Network hosts communicate through the use of client software called "Shells, Redirectors, Requesters"
- Network Protocols (such as TCP/IP, SPX/IPX, NETBEUI, etc..) enables data transmission across the network
- Client software resides on top of the network protocols.

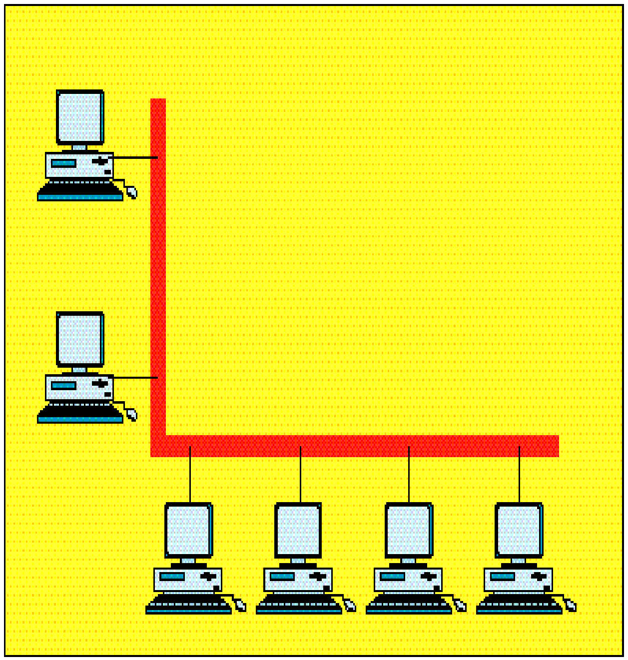
Network Hardware

- Users accessing network resources must have a Pathway to those resources.
- Host connect to networks using expansion cards known as Network Interface Cards (NICs), a.k.a. Adapter Cards.
- Network cards communicate by sending signals through the medium (Twisted pair, Coax, Fiber, Radio, etc..)

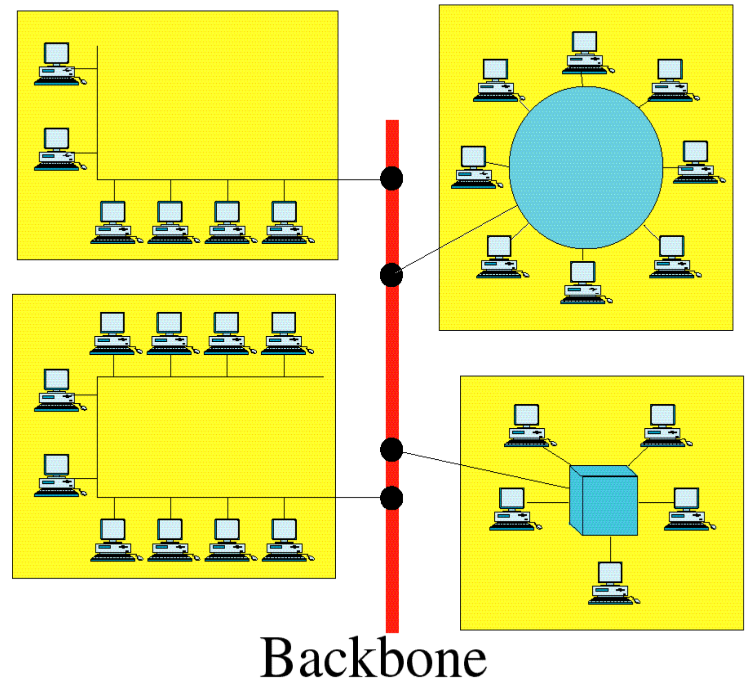
Network Classifications

- Networks can be classified based on Coverage into
  - LANs: Local Area Networks
  - WANs: Wide Area Networks
  - Others including MAN (Metropolitan Area Networks, PAN (Personal Area Networks), Home Networks, etc…
- Networks could also be classified as Switched or Shared (Broadcast) networks

Local Area Networks (I)

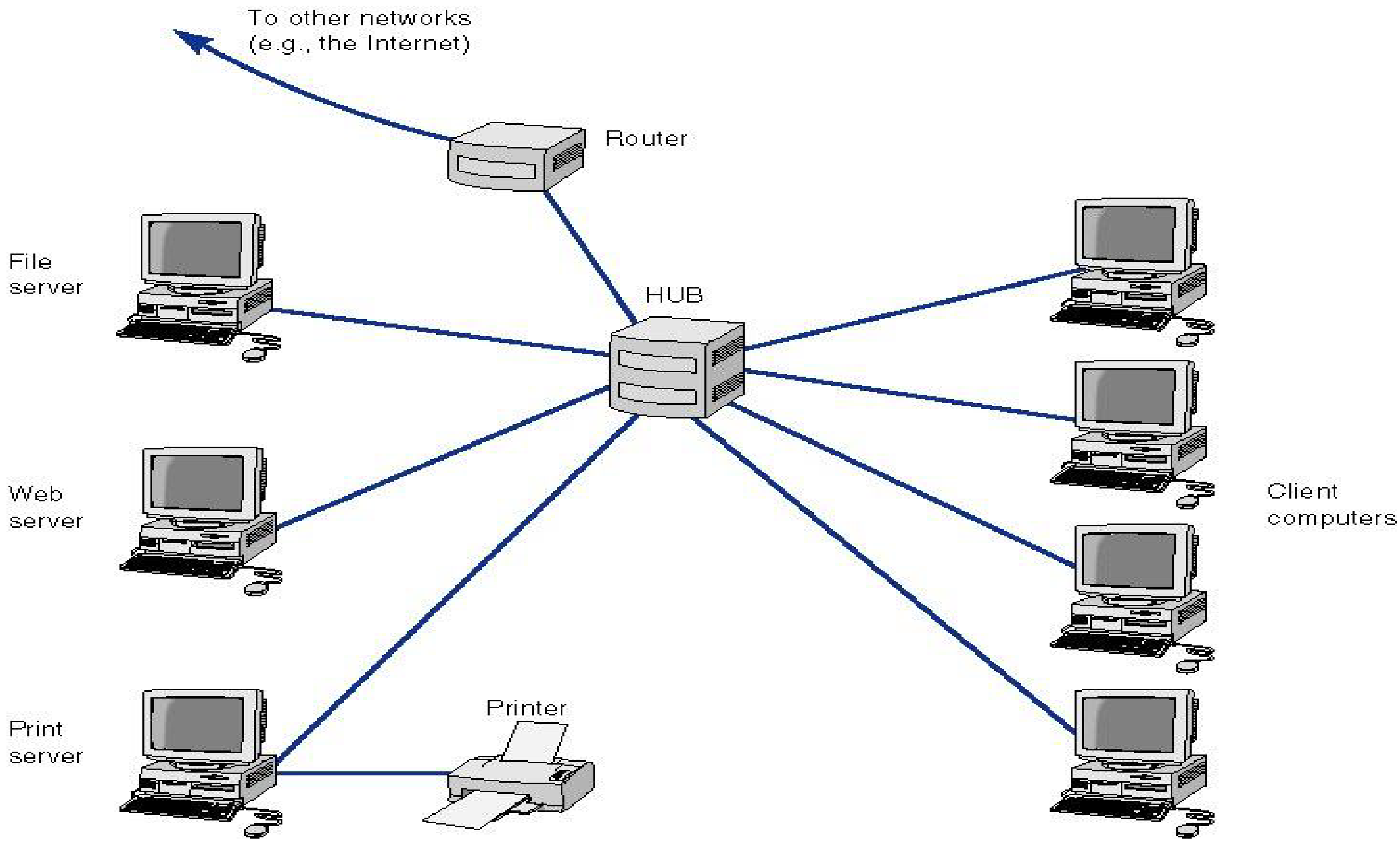


Single building LAN

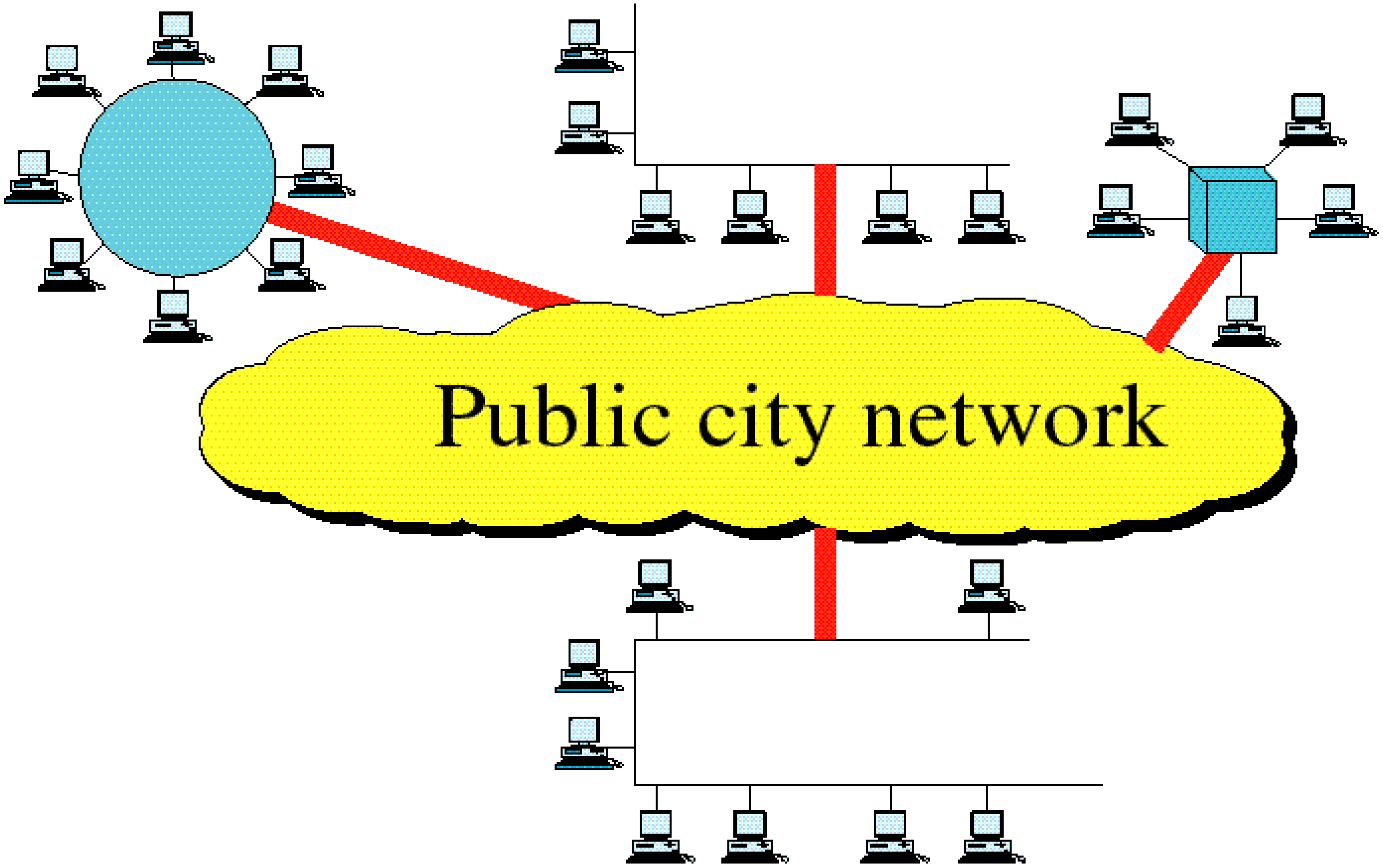


Multiple building LAN

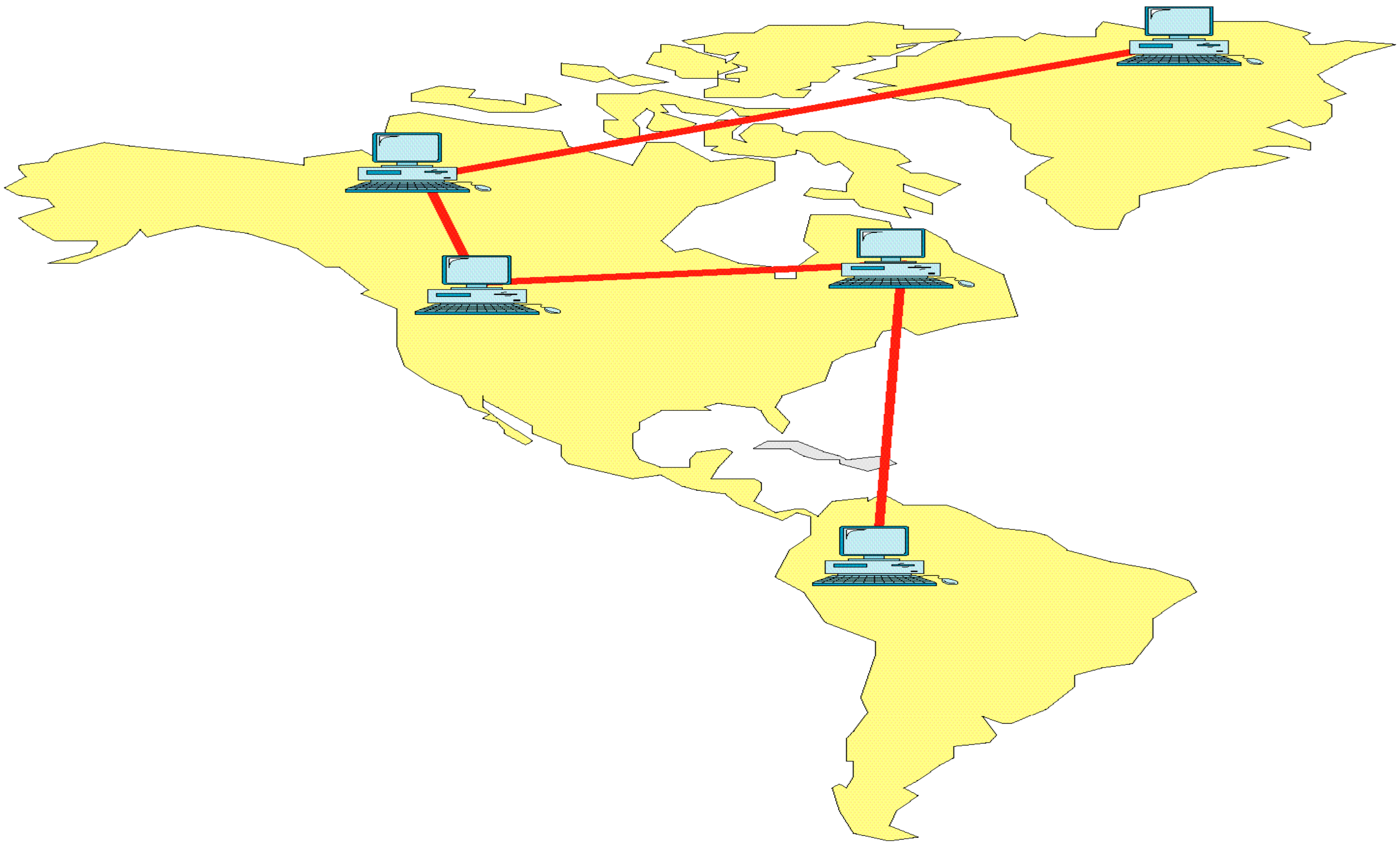
Local Area Networks (II)



Metropolitan Area Network



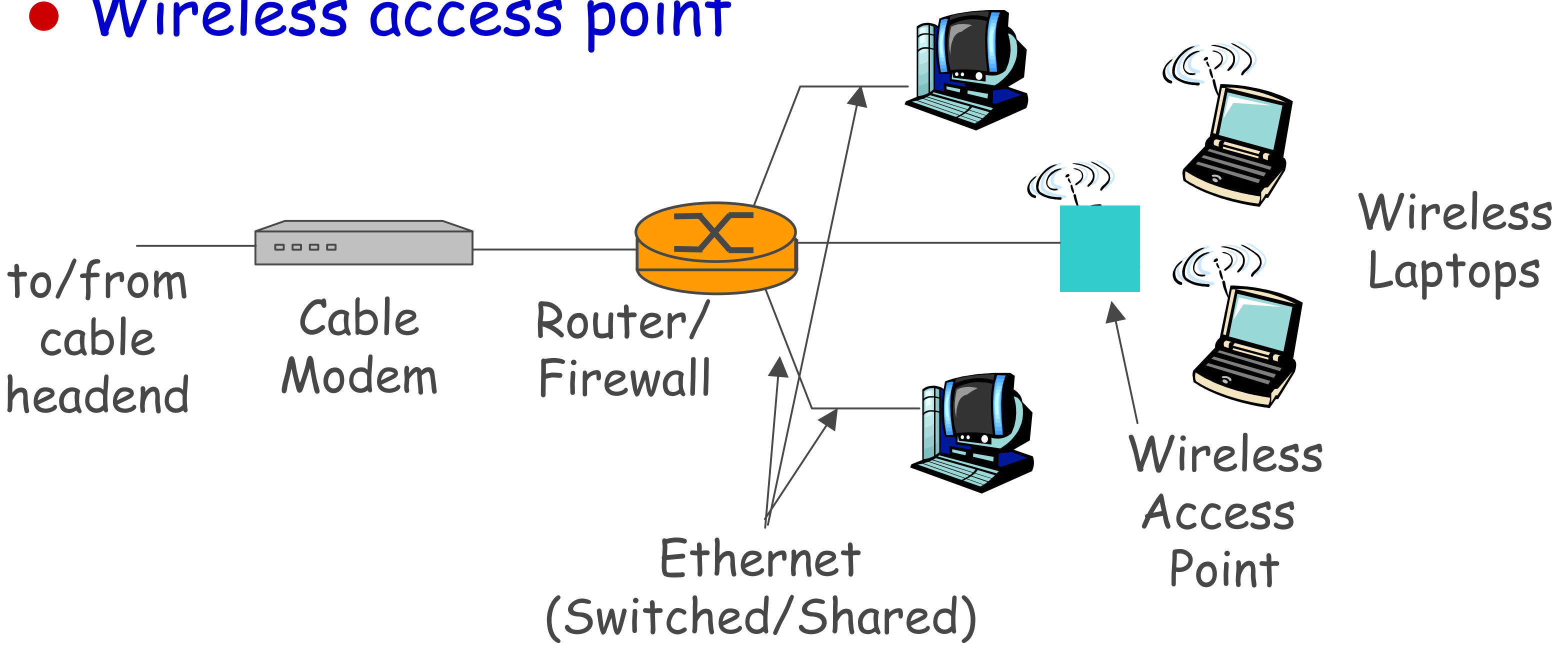
Wide Area Networks



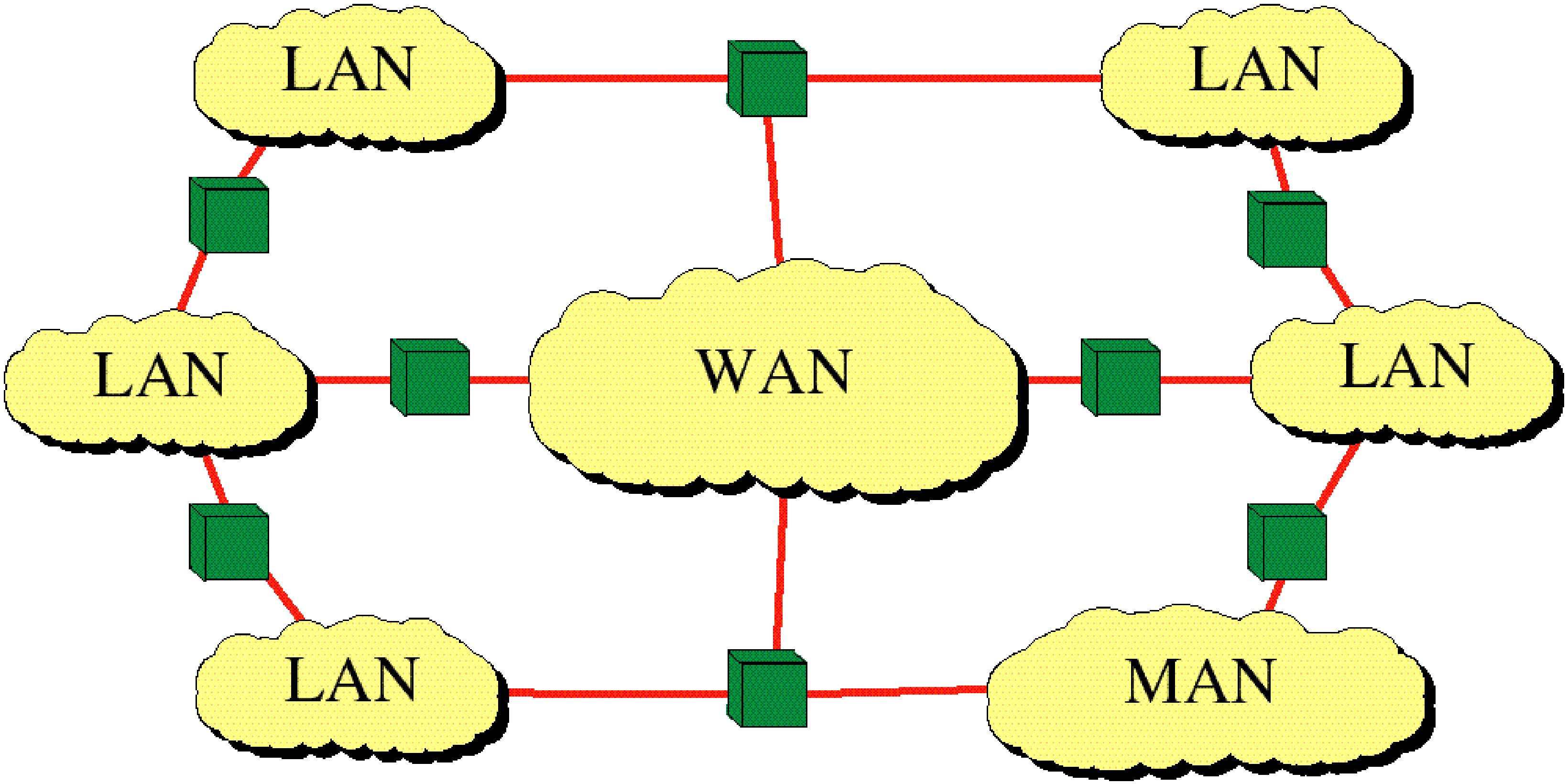
Home Networks

Typical home network components

- ADSL or cable modem
- Router/firewall/NAT
- Ethernet
- Wireless access point



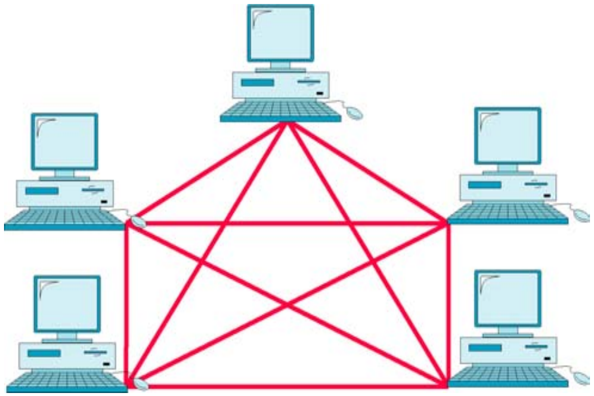
Internetworking

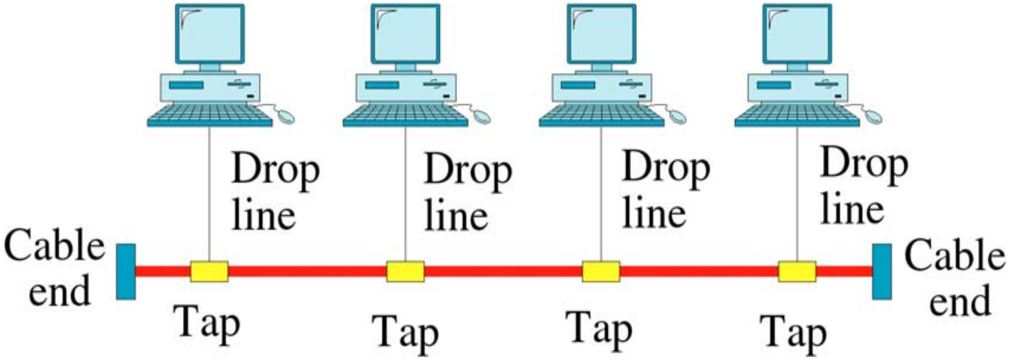


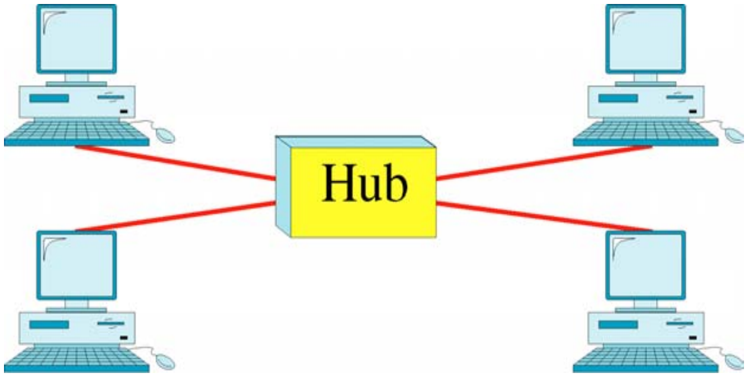
Network Topologies

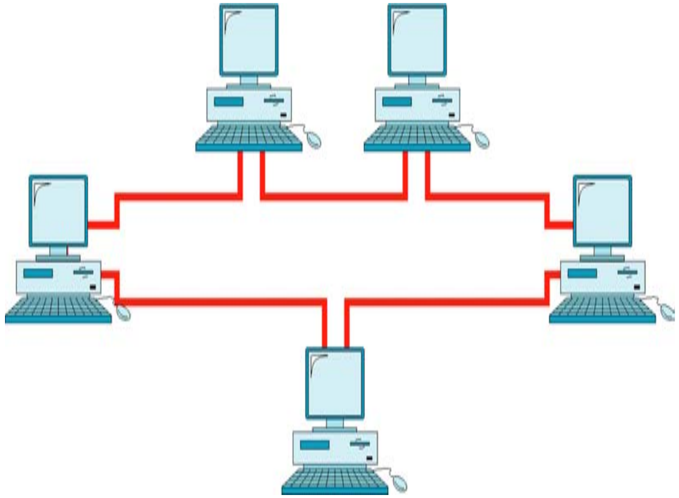
- Network topology is the physical arrangement of the network nodes and the links interconnecting them
  - Mesh topology
  - Star/Hub topology
  - Bus topology
  - Tree Topology
  - Ring topology
- A fully connected network is one in which every node is connected to every other node

Mesh, Hub, Bus and Rings (I)

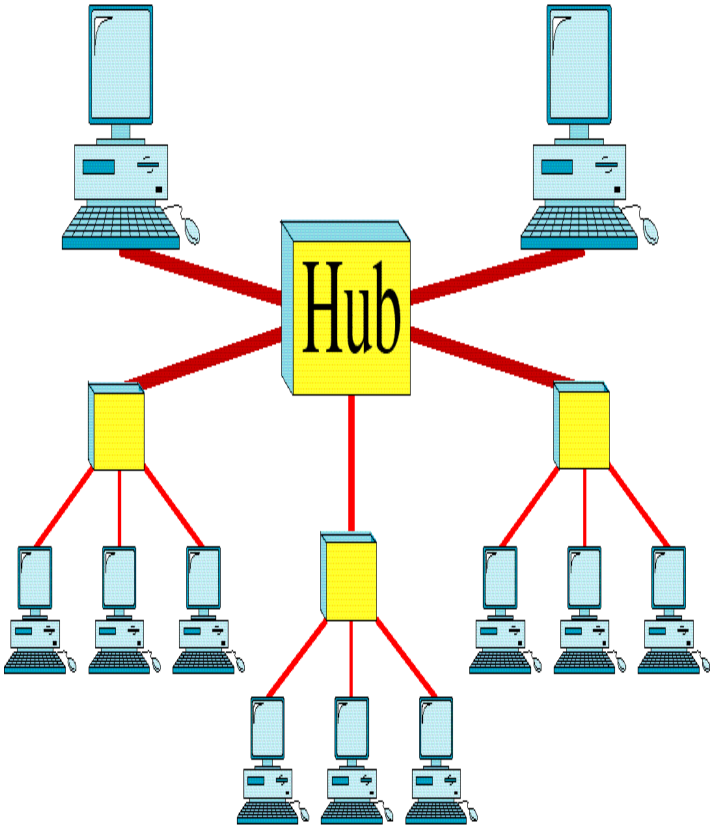


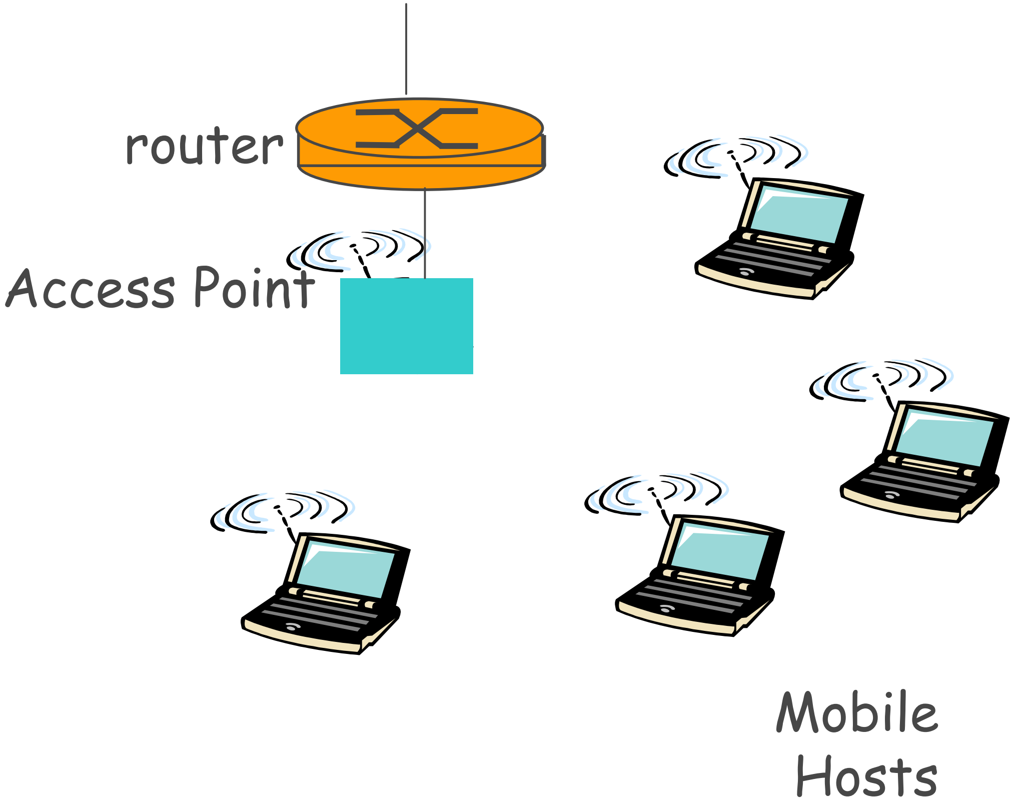






Tree and Wireless (II)





Link Topologies

- Point-to-point
  - Direct link
  - Only 2 devices share link

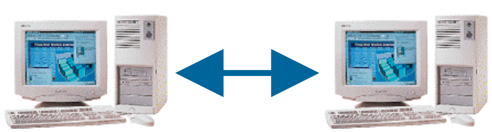
- Multipoint
  - More than two devices share the link

Link Duplicity

- Simplex
  - One direction
  - e.g. Radio/Television broadcasting

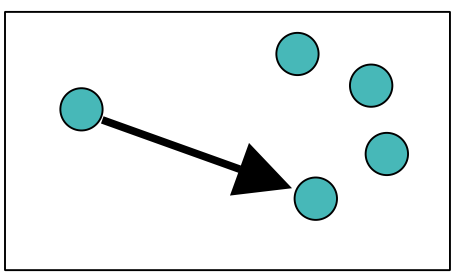
- Half duplex (HDX)
  - Either direction, but only one way at a time
  - e.g. Police radio

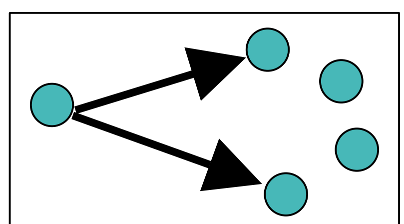
- Full duplex (FDX)
  - Both directions at the same time
  - e.g. Telephony

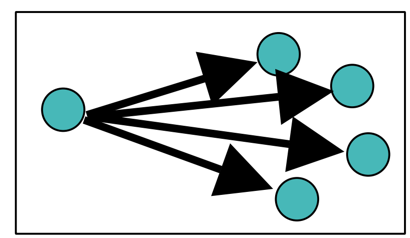


Transmission Modes

Unicast	Multicast	Broadcast
One-to-one	One-to-selected group	One-to-all







Physical Media (I): Copper

- Bit: propagates between transmitter/rcvr pairs
- Physical link: what lies between transmitter & receiver
- Guided media:
  - signals propagate in solid media: copper, fiber, coax
- Unguided media:
  - signals propagate freely, e.g., radio

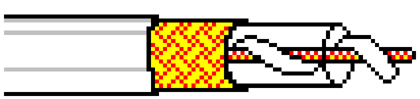
Twisted Pair (TP)

- two insulated copper wires
  - Category 3: traditional phone wires, 10 Mbps Ethernet
  - Category 5: 100Mbps Ethernet

Physical Media (II): Cable

Coaxial Cable:

- Two concentric copper conductors
- Bi-directional
- Baseband:
  - single channel on cable
  - legacy Ethernet
- Broadband:
  - Multiple channels on cable
  - CATV, Cable Access



Fiber Optic Cable:

- Glass fiber carrying light pulses, each pulse a bit
- High-speed operation:
  - high-speed point-to-point transmission (e.g., 10's-100's Gps)
- Low error rate: repeaters spaced far apart ; immune to electromagnetic noise

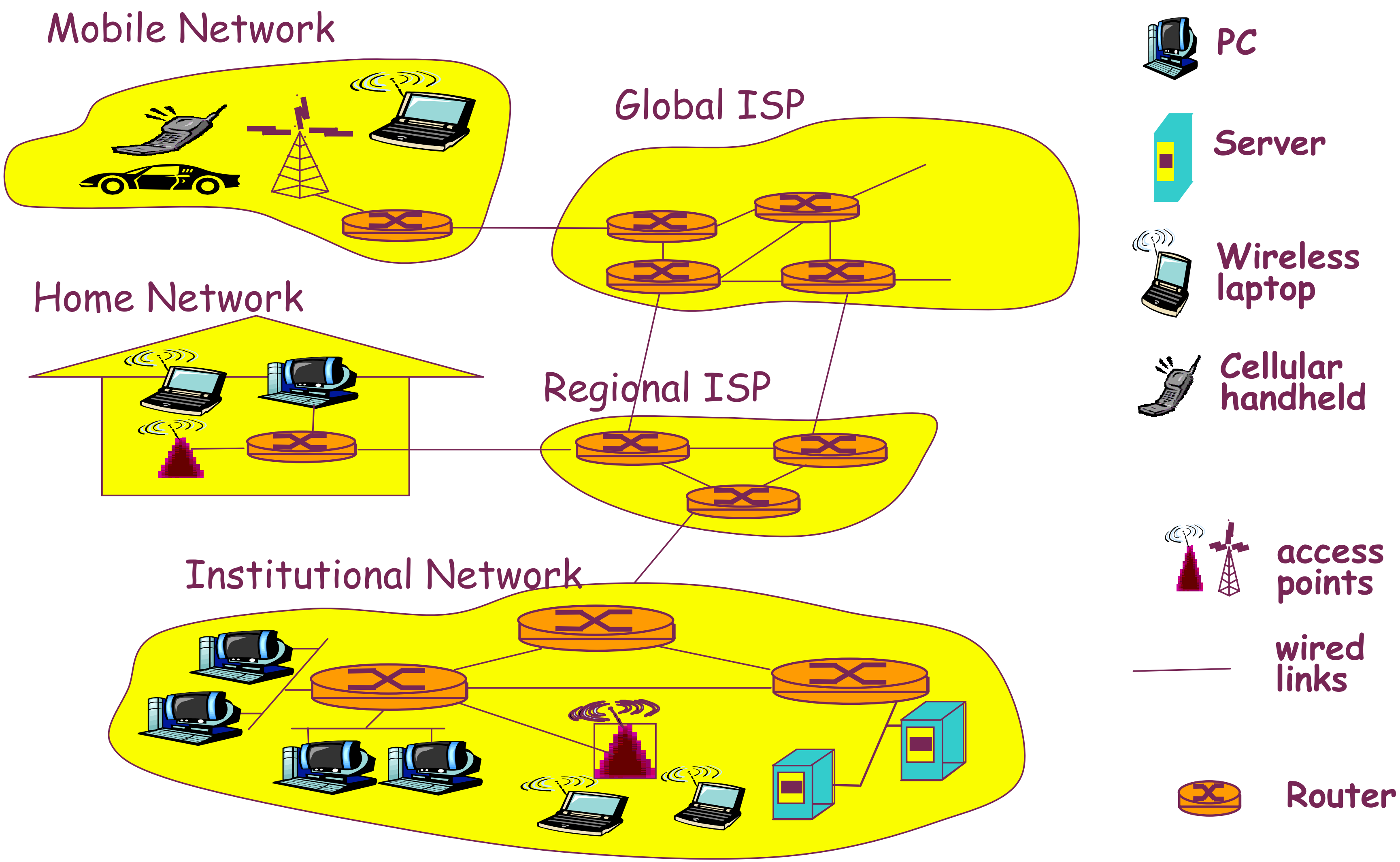
Physical Media (III): Radio

- Signal carried in electromagnetic spectrum
- No physical "wire"
- Bi-directional
- Propagation environment effects:
  - Reflection
  - Obstruction by objects
  - Interference

Radio link types:

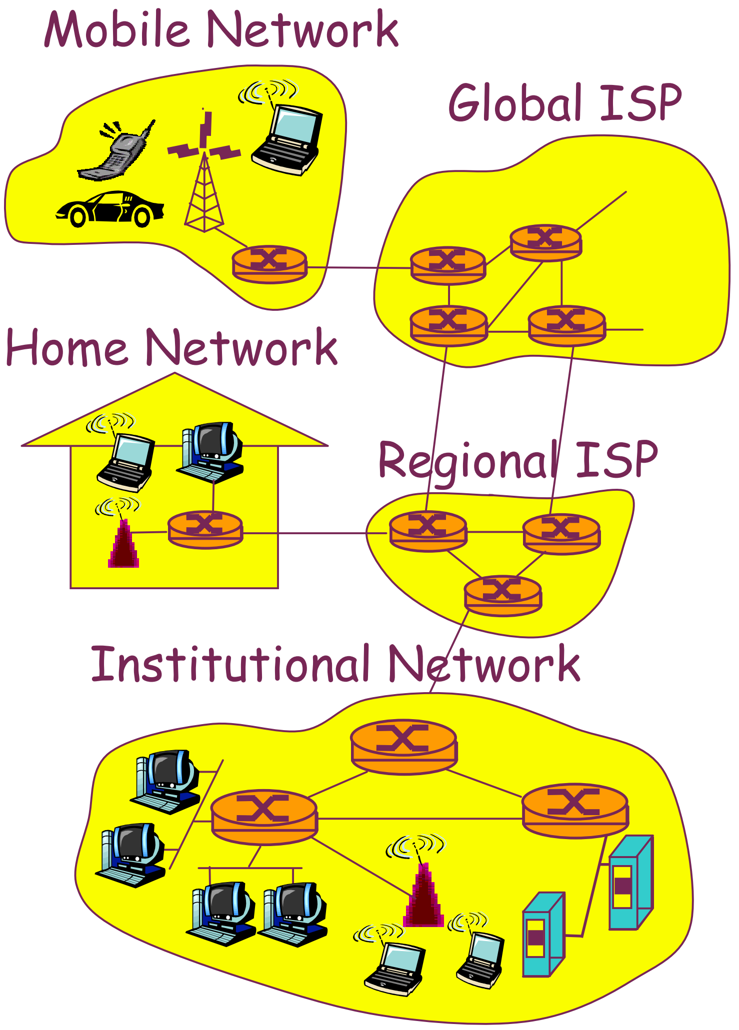
- Terrestrial Microwave
  - e.g. up to 45 Mbps channels
- WLAN (e.g., Wi-Fi)
  - 2Mbps, 11Mbps, 54 Mbps
- Wide-area (e.g., cellular)
  - e.g. 3G: hundreds of kbps
- Satellite
  - Kbps to 45Mbps channel (or multiple smaller channels)
  - 270 msec end-end delay
  - GEO/LEO

What is the Internet? Nuts and Bolts View



What is the Internet? Nuts and Bolts View

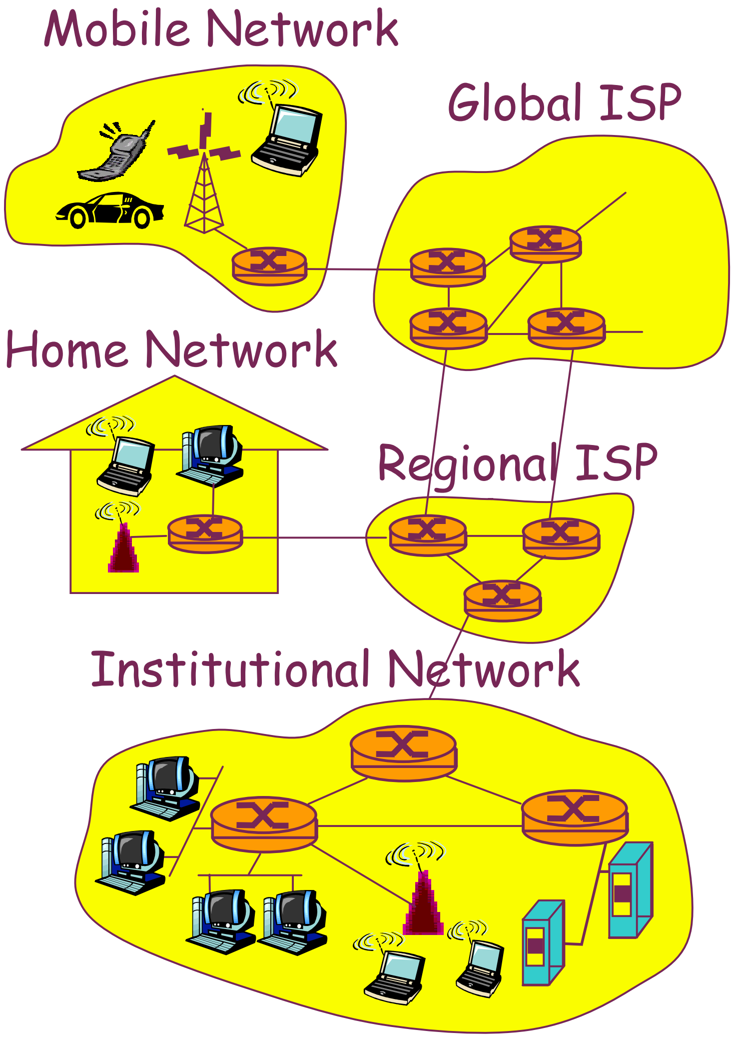
- Millions of connected computing devices
  - Hosts = end systems, run Network Applications
- Communication links
  - Fiber, Copper, Radio, Cable, Satellite, etc...
  - Provides Bandwidth
- Routers:
  - Forward Packets (chunks of data) from source to destination



What is the Internet? Nuts and Bolts View (Continued)

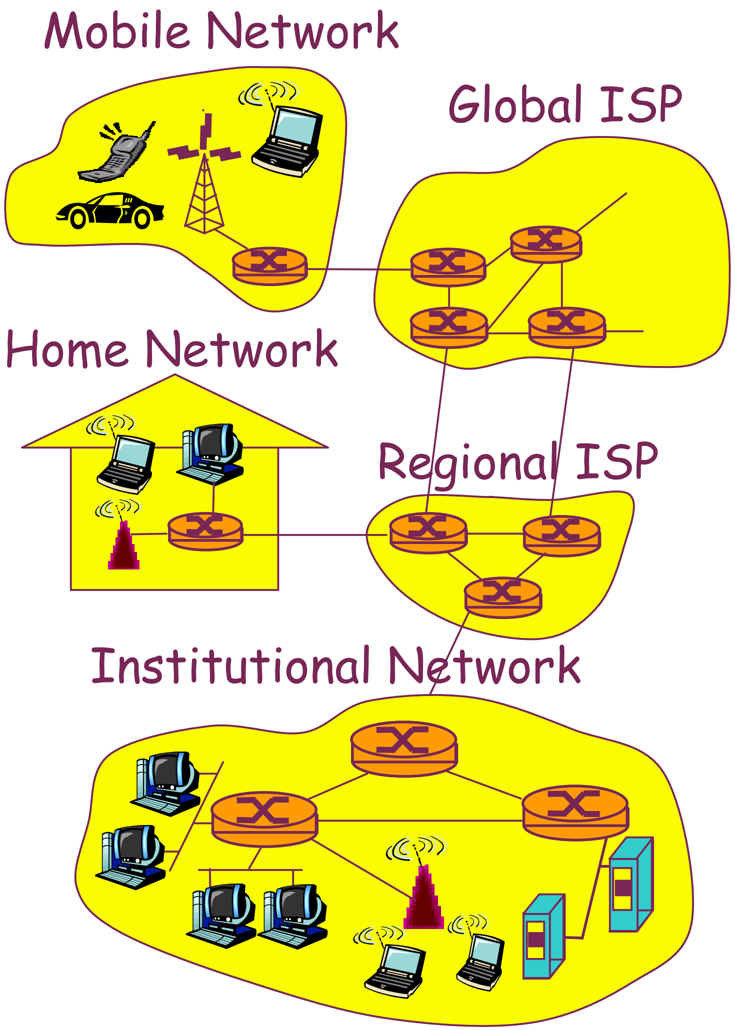
- Protocols control sending, receiving of msgs
  - TCP, IP, HTTP, Ethernet
- Internet:

  "Network of networks"
  - Loosely hierarchical
  - Public Internet v.s. Private Intranet
- Internet standards
  - RFC: Request for comments
  - IETF: Internet Engineering Task Force



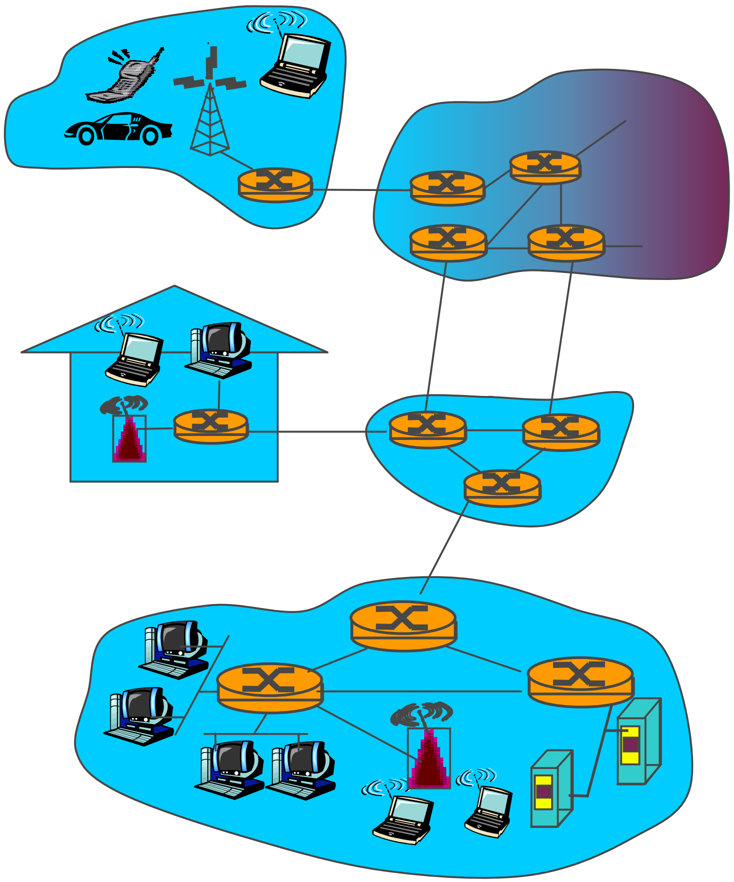
What is the Internet? A Service View

- Communication Infrastructure enables distributed applications:
  - Web, VoIP, email, games, e-commerce, file sharing
- Communication services provided to applications include
  - Reliable data delivery from source to destination
  - "Best effort" (unreliable) data delivery



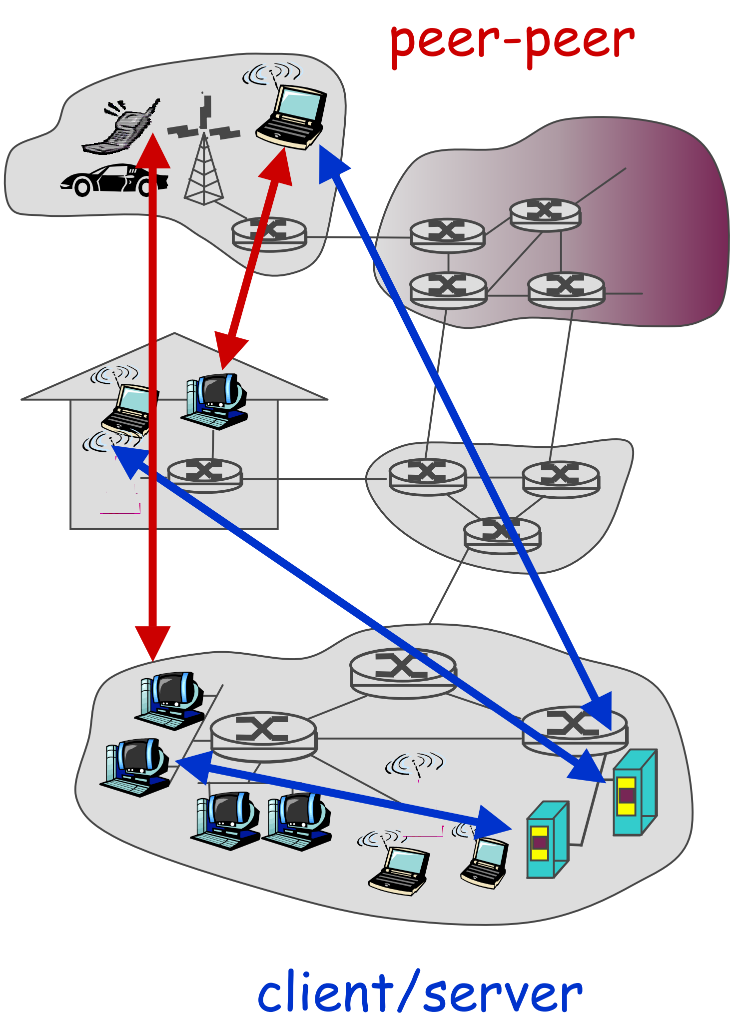
Network Structure

- Network edge: applications and hosts
- Access Networks, physical media: wired, wireless communication links
- Network core:
  - interconnected routers
  - Network of networks



Network Edge

- End systems (hosts):
  - run application programs
  - e.g. Web, email
  - at "edge of network"
- Client-Server model
  - client host requests, receives service from always-on server
  - e.g. Web browser/server; email client/server
- Peer-to-peer model:
  - Minimal (or no) use of dedicated servers
  - e.g. Kazaa, Gnutella, Skype, Napster,..



Network Edge Services (I) "Reliable Service"

Goal: data transfer between end systems

- handshaking: setup (prepare for) data transfer ahead of time
  - Hello, initial establishment
  - set up "state" in two communicating hosts
- TCP - Transmission Control Protocol
  - Internet's reliable data transfer service

TCP service

- reliable, in-order byte-stream data transfer
  - loss: acknowledgements and retransmissions
- flow control:
  - sender won't overwhelm receiver
- congestion control:
  - senders "slow down sending rate" when network congested

Network Edge Services (II)
Best Effort "Unreliable" Service

Goal: data transfer between end systems

- same as before!

- UDP - User Datagram Protocol:
  - connectionless
  - unreliable data transfer
  - no flow control
  - no congestion control

App's using TCP:

- HTTP (Web), FTP (file transfer), Telnet (remote login), SMTP (email)

App's using UDP:

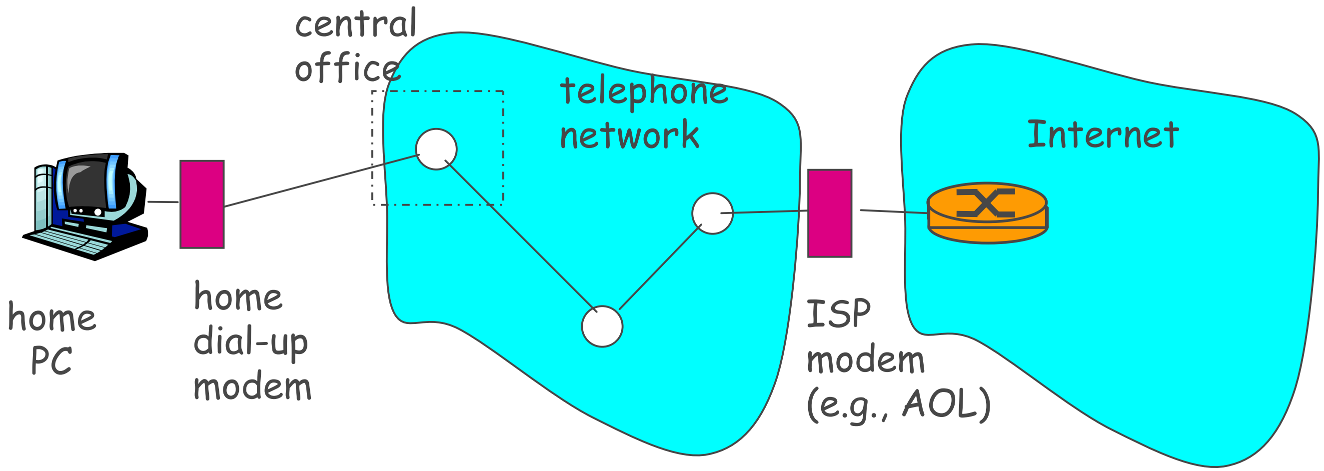
- streaming media, teleconferencing, DNS, Internet telephony

Access Networks

Q: How to connect end systems to edge router?

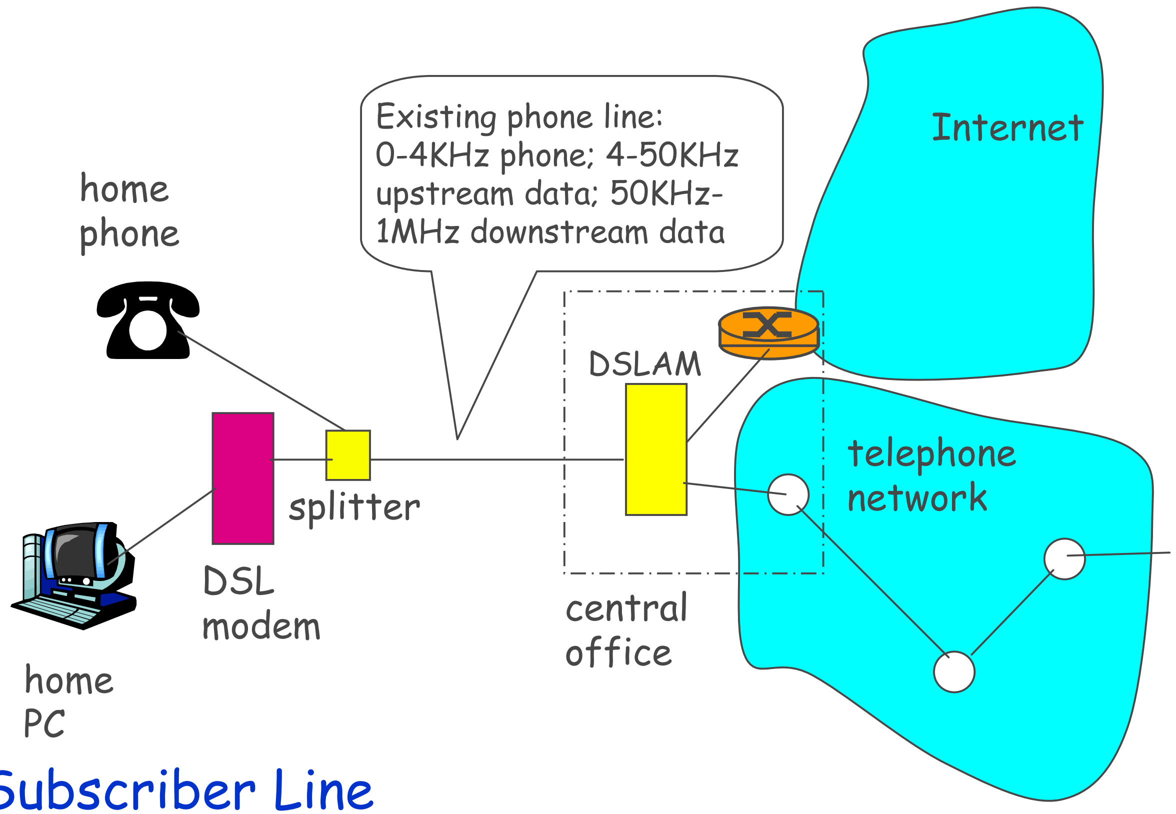
- Residential Access Networks
- Institutional access networks (school, company)
- Mobile access networks
  - Keep in mind:
  - bandwidth (bits per second) of access network?
  - shared or dedicated?

Dial-up Connection



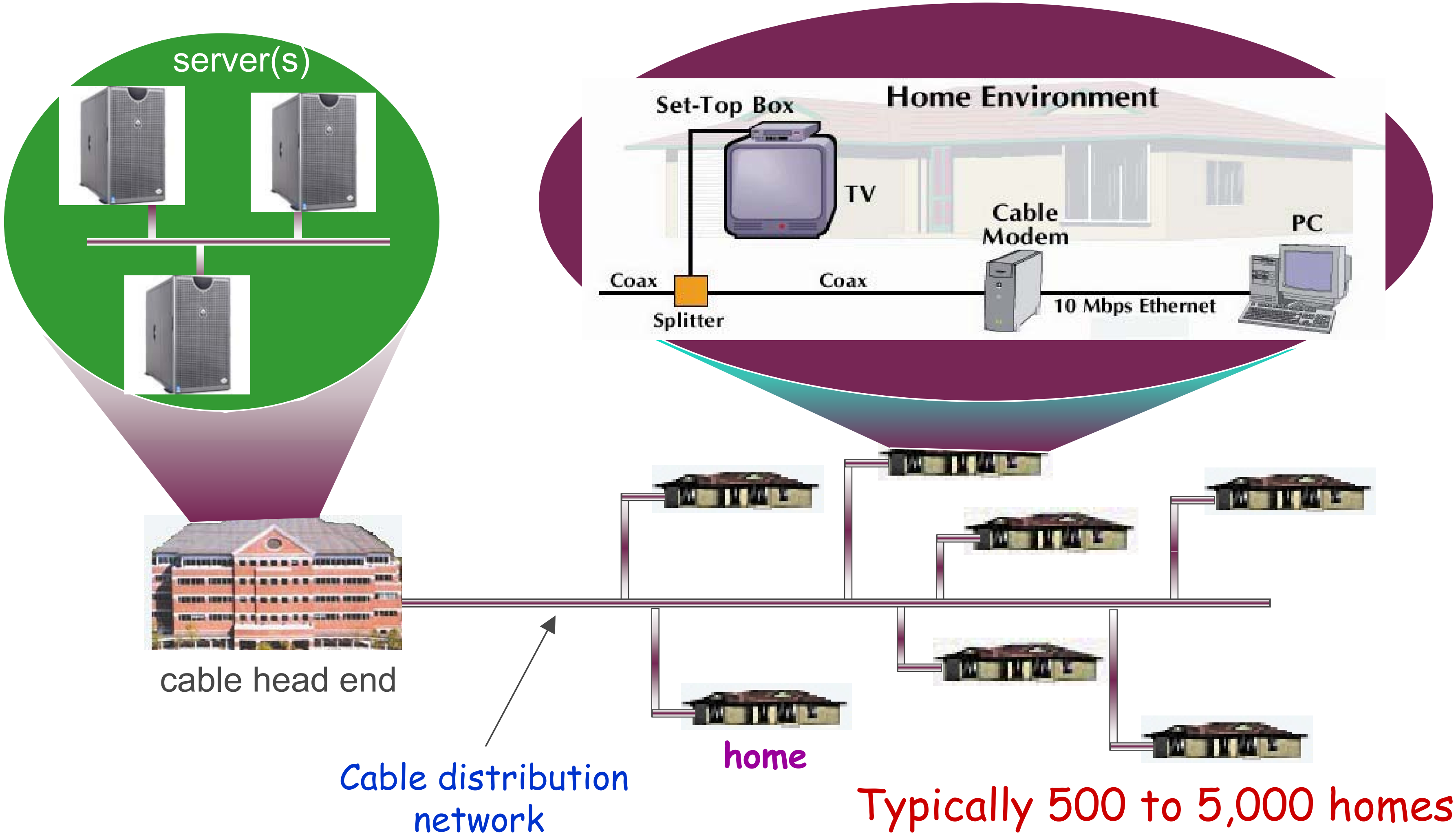
- Uses existing telephony infrastructure
- Home is connected to central office
- up to 56Kbps direct access to router (often less)
- Can't surf and phone at same time: not "always on"

DSL Connection

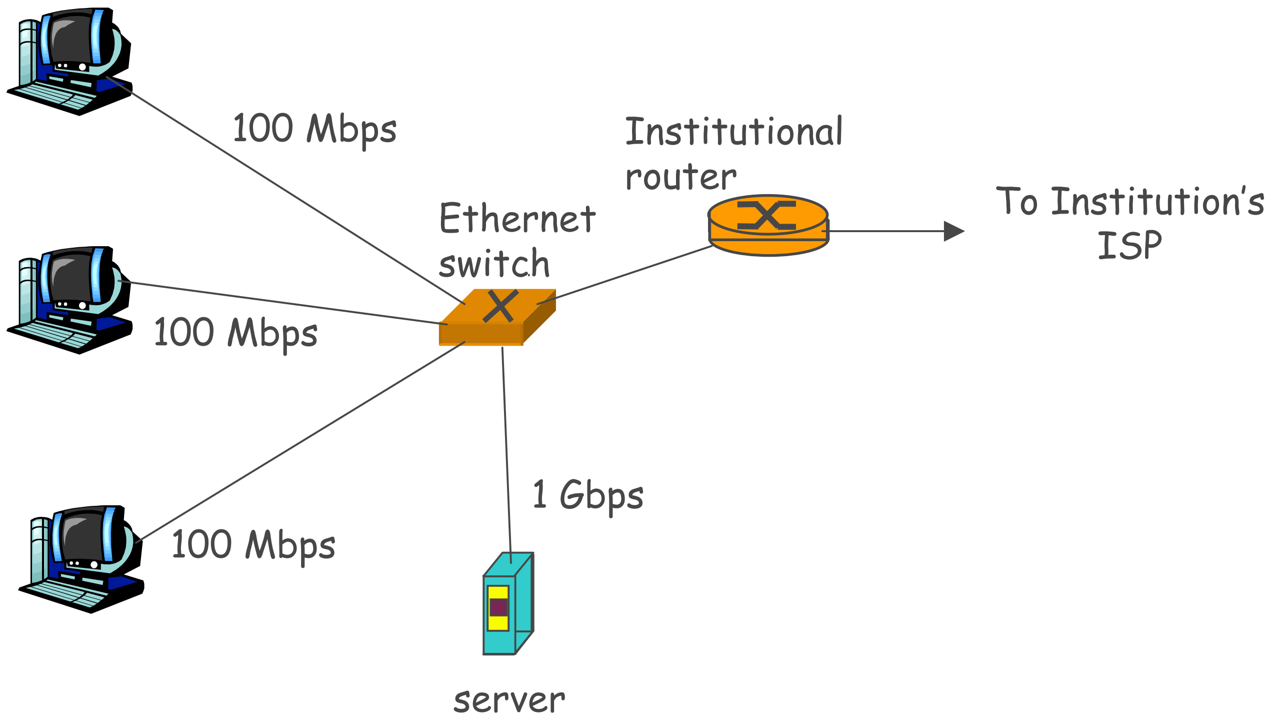


- Digital Subscriber Line
  - deployment: telephone company (typically)
  - up to 1 Mbps upstream (today typically < 256 kbps)
  - up to 8 Mbps downstream (today typically ~ 1 Mbps)
  - Dedicated physical line to telephone central office

Cable Residential Access



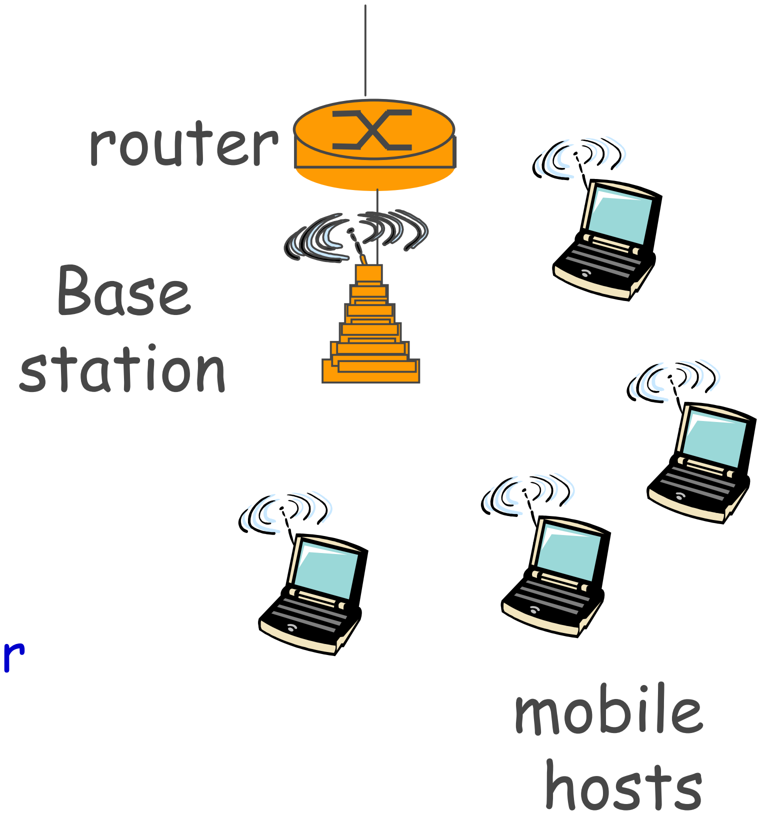
Ethernet Access



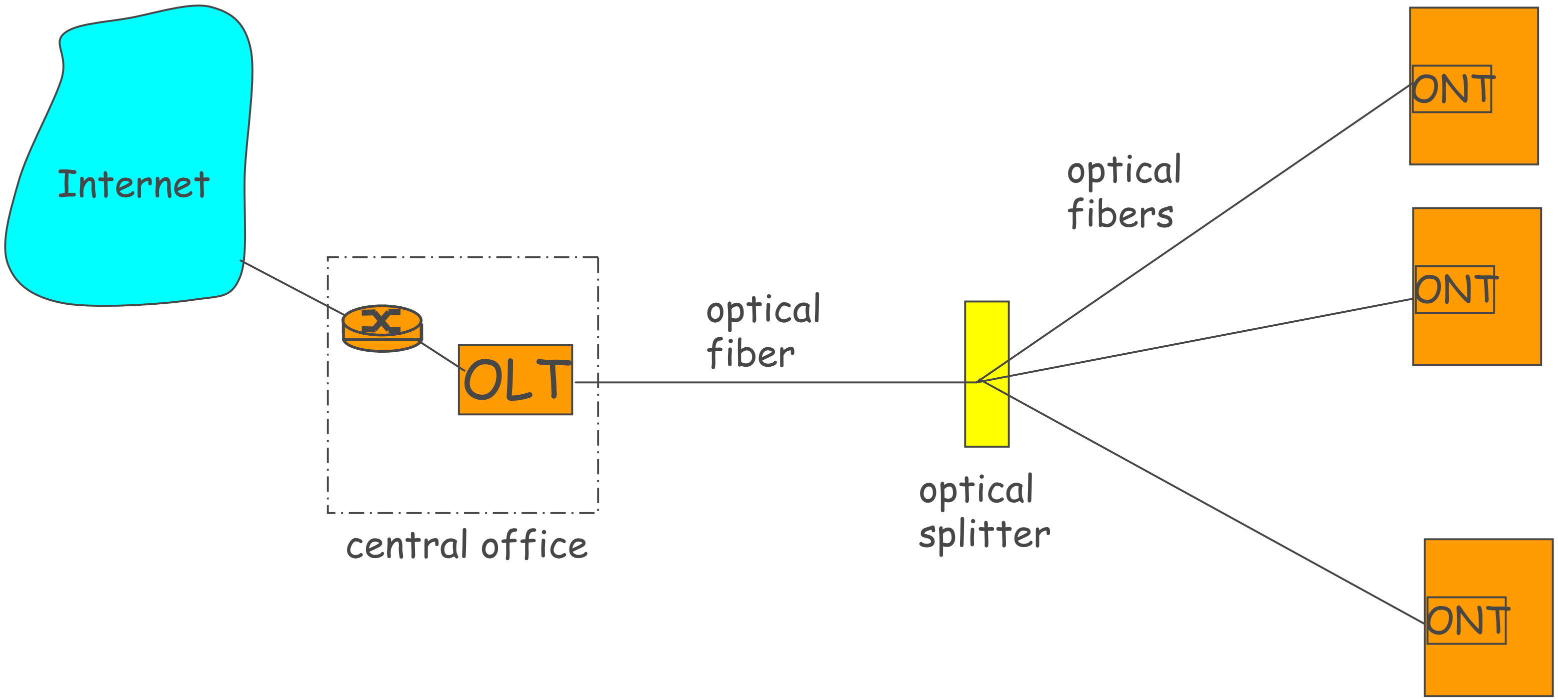
- Typically used in companies, universities, etc
- 10 Mbs, 100Mbps, 1Gbps, 10Gbps Ethernet
- Today, end systems typically connect into Ethernet switch

Wireless Access

- shared wireless access network connects end system to router
  - via base station aka "access point"
- wireless LANs:
  - 802.11ab/g (Wifi): 11/54 Mbps
- wider-area wireless access
  - provided by Telco operator
  - ~1Mbps over cellular system (EVDO, HSDPA)
  - Next up: WiMax (10's Mbps) over wide area



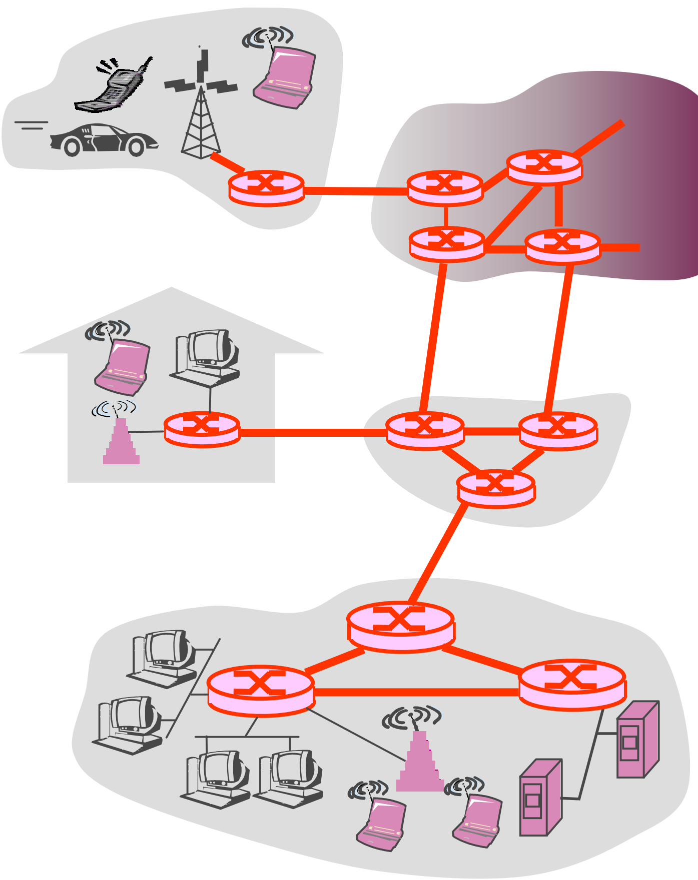
Fiber to the Home (FTTH)



Much higher Internet rates; fiber also carries television and phone services

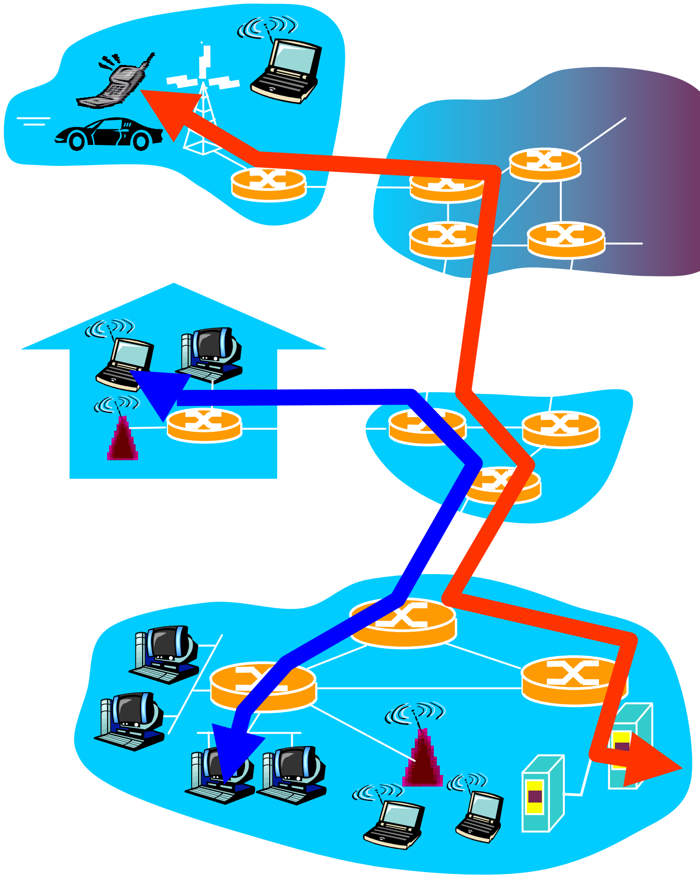
The Core Network

- Mesh of interconnected routers
- <u>The</u> fundamental question: how is data transferred through net?
  - Circuit Switching: dedicated circuit per call: telephone network (PSTN)
  - Packet Switching: data sent thru net in discrete "chunks": Internet



Circuit Switching

- End-end resources reserved for duration of call
- link bandwidth, switch capacity
- dedicated resources: no sharing
- circuit-like (guaranteed) performance
- call setup required
- re-establish call upon failure
- Example: PSTN



Packet Switching

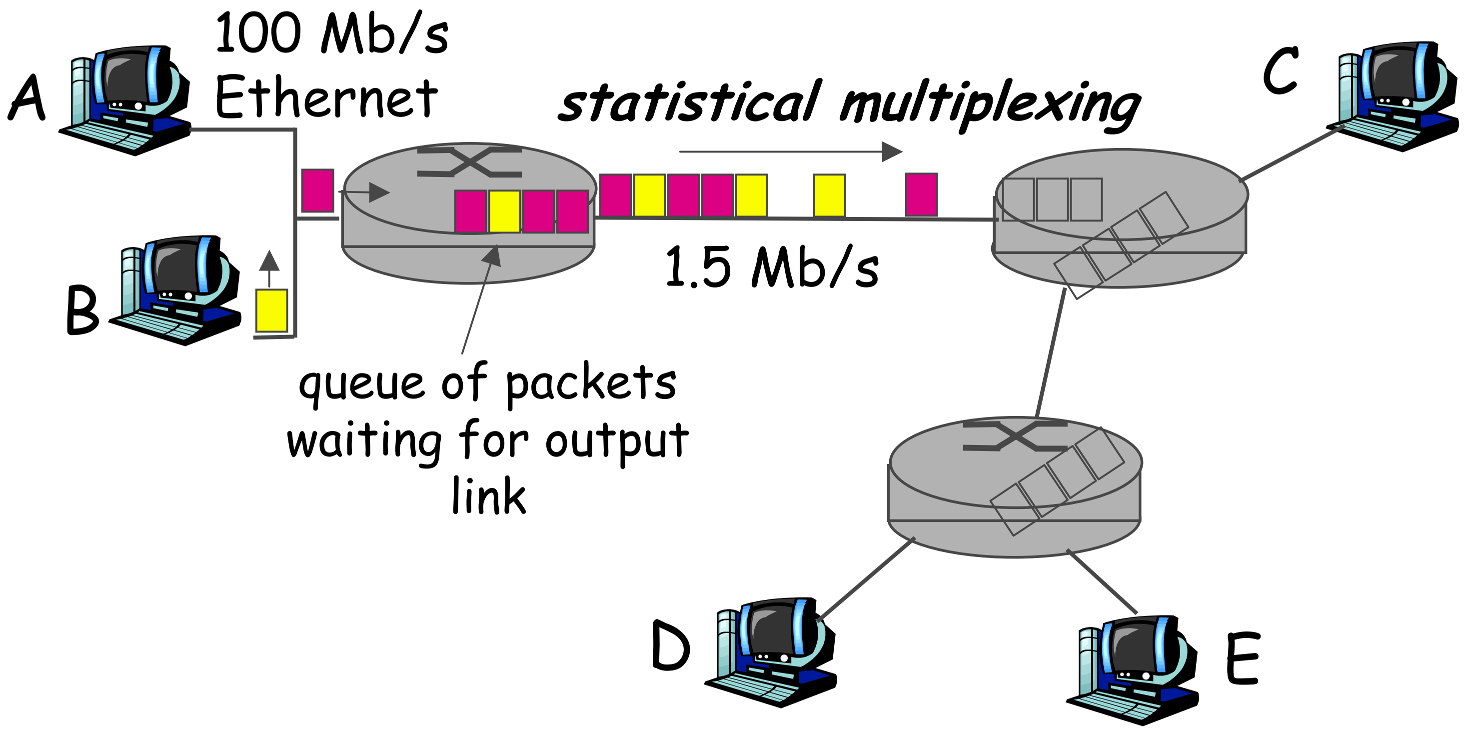
- each end-end data stream divided into packets
- user A, B packets share network resources
- Each packet uses full link bandwidth
- Resources used *as needed*

~~Bandwidth division into "pieces"~~
~~Dedicated allocation~~
~~Resource reservation~~

Resource contention:

- aggregate resource demand can exceed amount available
- congestion: packets queue, wait for link use
- store and forward: packets move one hop at a time Node receives complete packet before forwarding

Packet Switching (Continued)



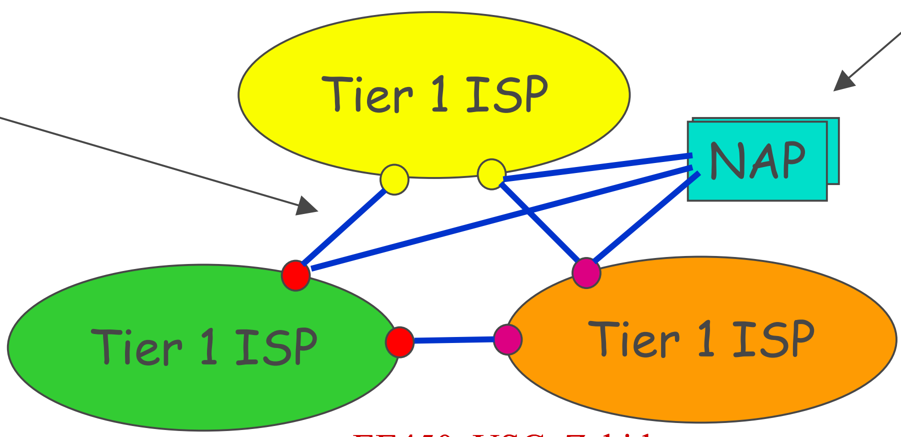
Packet vs. Circuit Switching

- PS great for bursty data
  - resource sharing (scalable!)
  - simpler, no call setup, more robust (re-routing)
- excessive congestion: packet delay and loss
  - Without admission control: protocols needed for reliable data transfer, congestion control
- Q: How to provide circuit-like behavior?
  - Bandwidth guarantees needed for audio/video apps
  - Possible solution: Virtual circuit

Internet Structure (Tier 1)

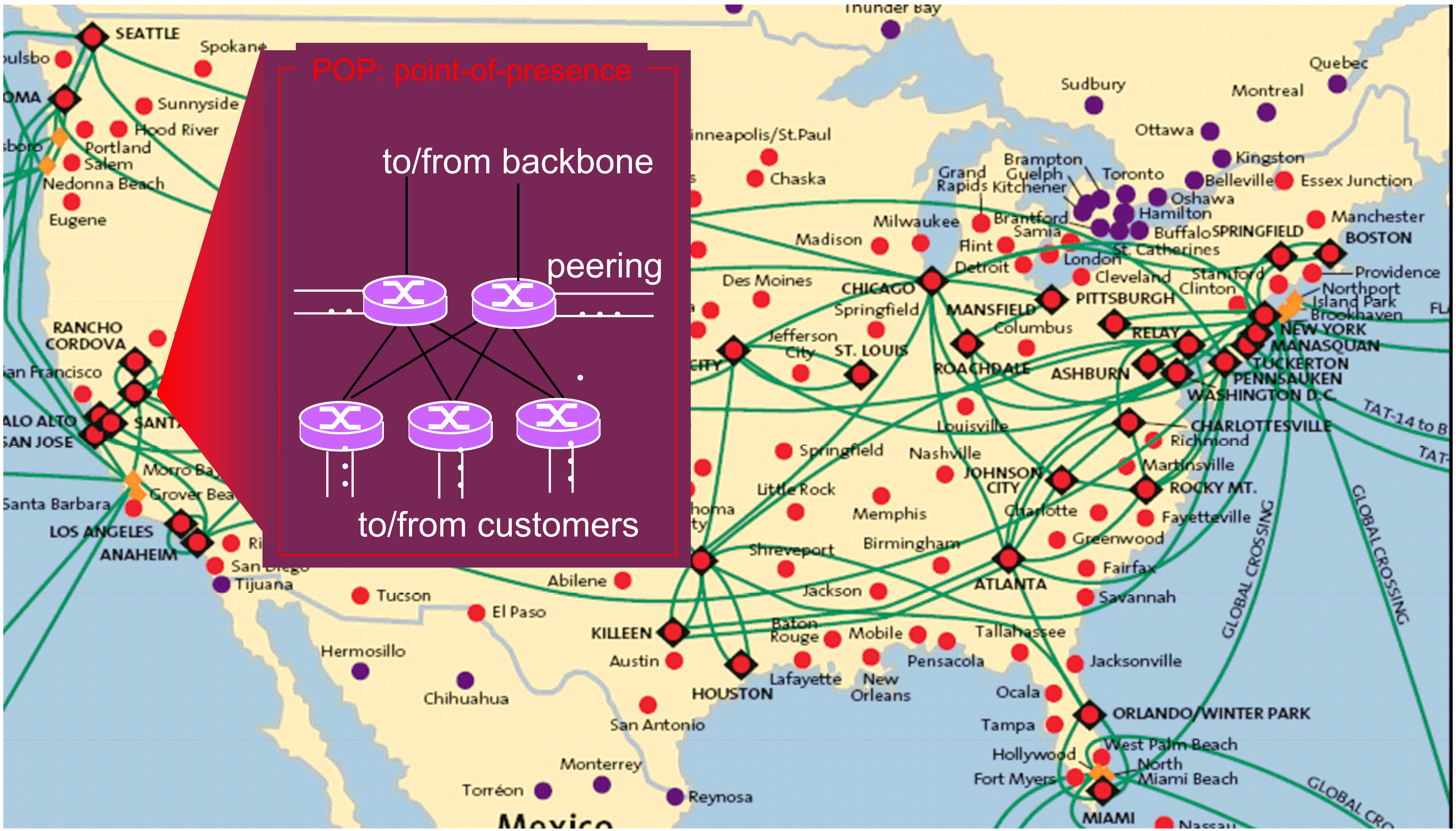
- Roughly hierarchical
- at center: "tier-1" ISPs (e.g., Verizon, Sprint, AT&T, Cable and Wireless), national/international coverage
  - treat each other as equals

Tier-1 providers interconnect (peer) privately



Tier-1 providers also interconnect at public network access points (NAPs)

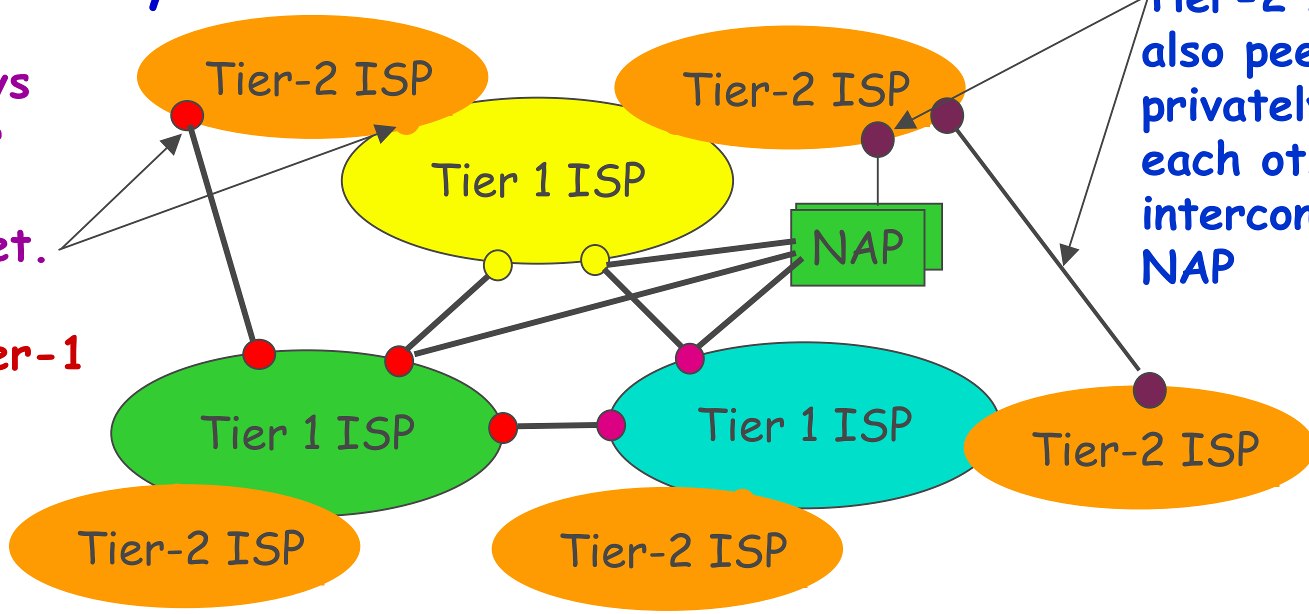
Tier 1 ISP: Sprint



Internet Structure (Tier 2)

- "Tier-2" ISPs: smaller (often regional) ISPs
  - Connect to one or more tier-1 ISPs, possibly other tier-2 ISPs

Tier-2 ISP pays Tier-1 ISP for connectivity to rest of Internet.
Tier-2 ISP is customer of tier-1 provider

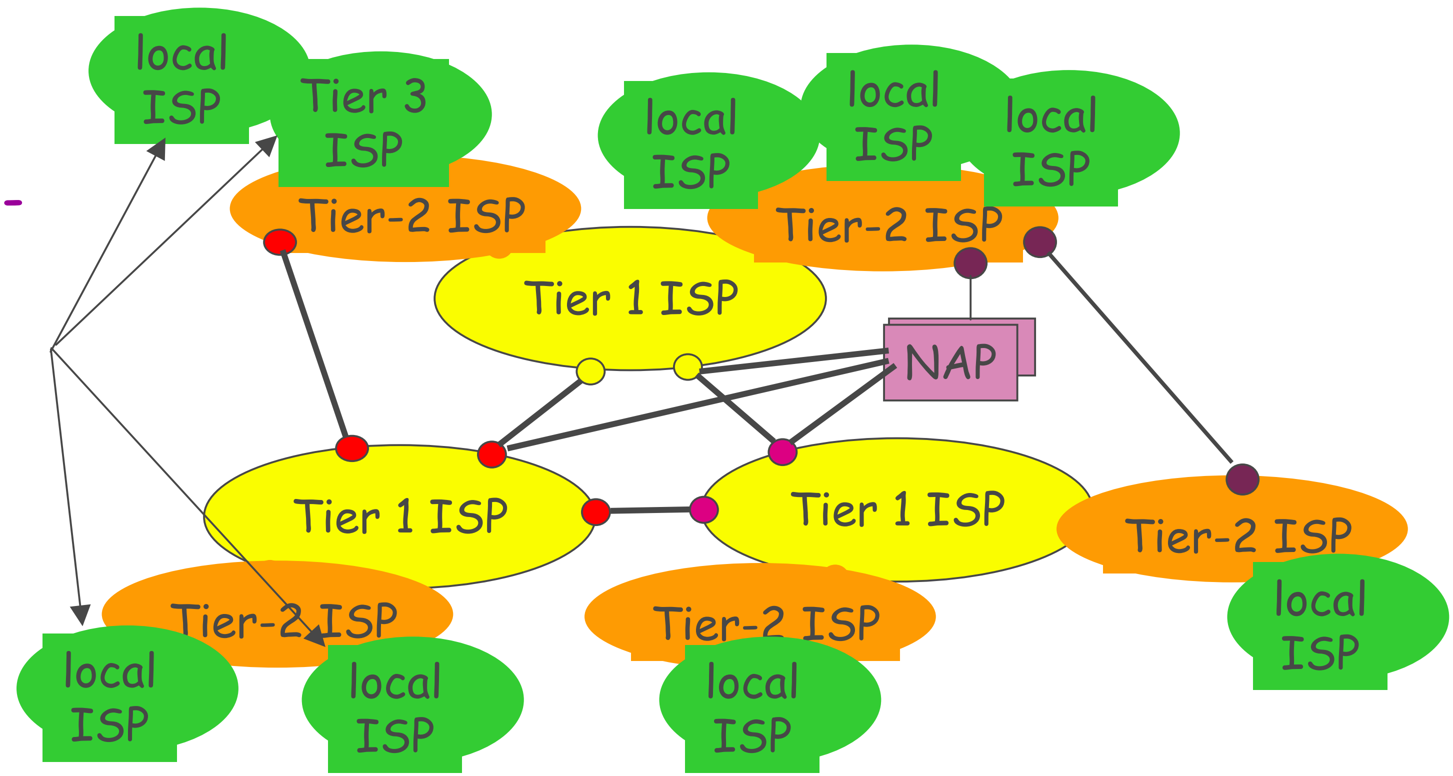


Tier-2 ISPs also peer privately with each other, interconnect at NAP

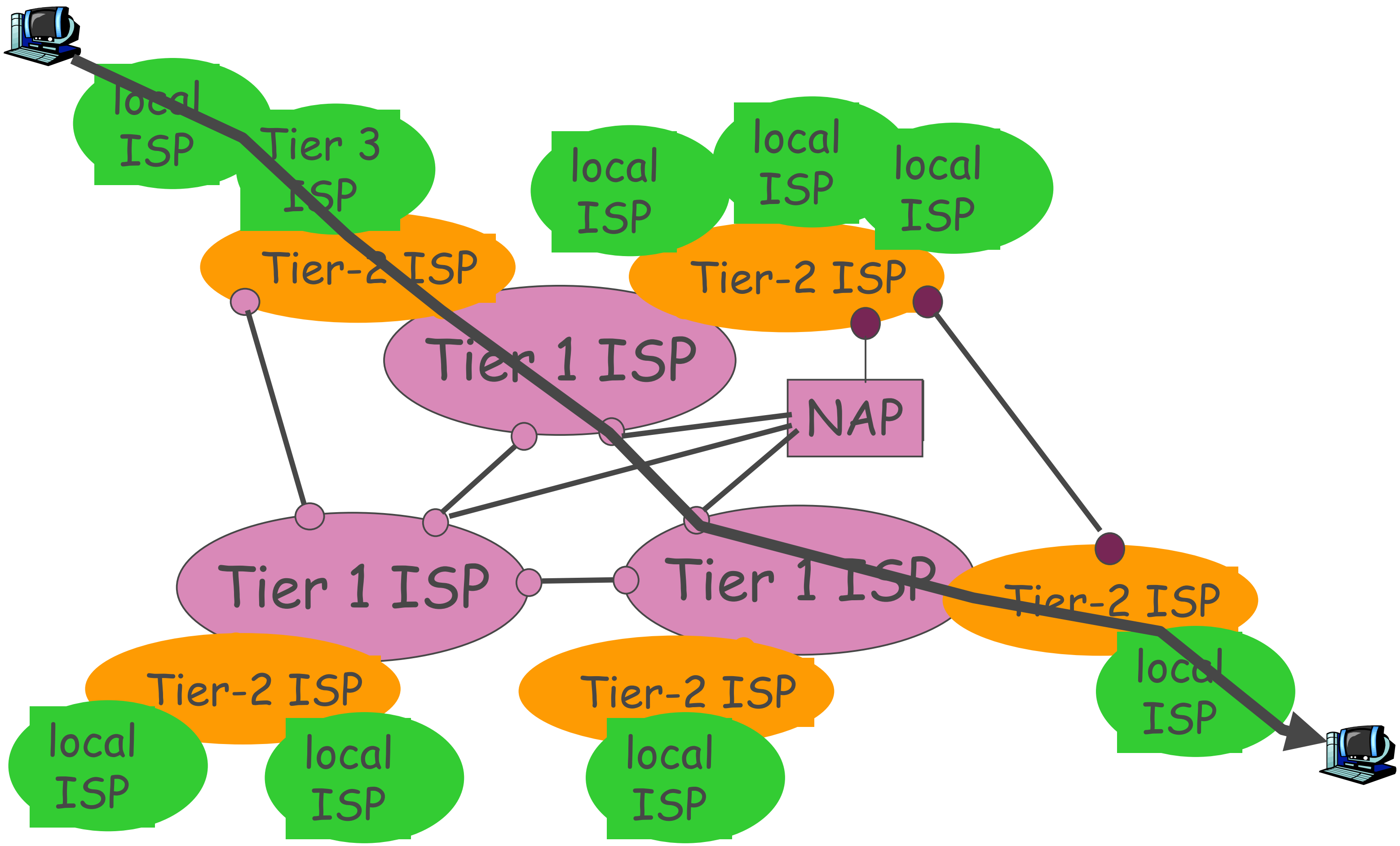
Internet Structure (Tier 3)

- "Tier-3" ISPs and local ISPs
  - last hop, access network, closest to end systems

Local and tier-3 ISPs are customers of higher tier ISPs connecting them to rest of Internet

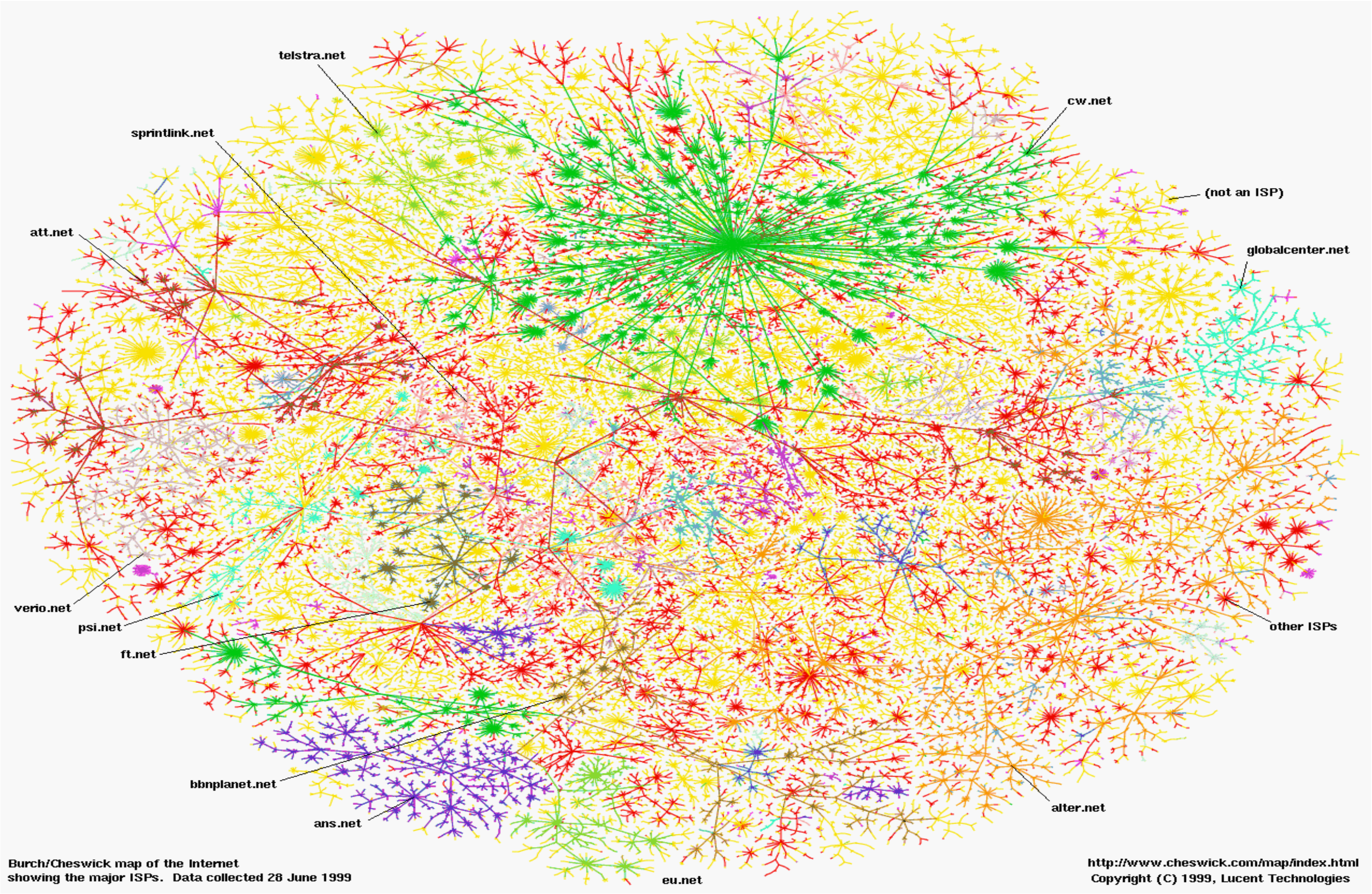


Internet Structure (Summary)

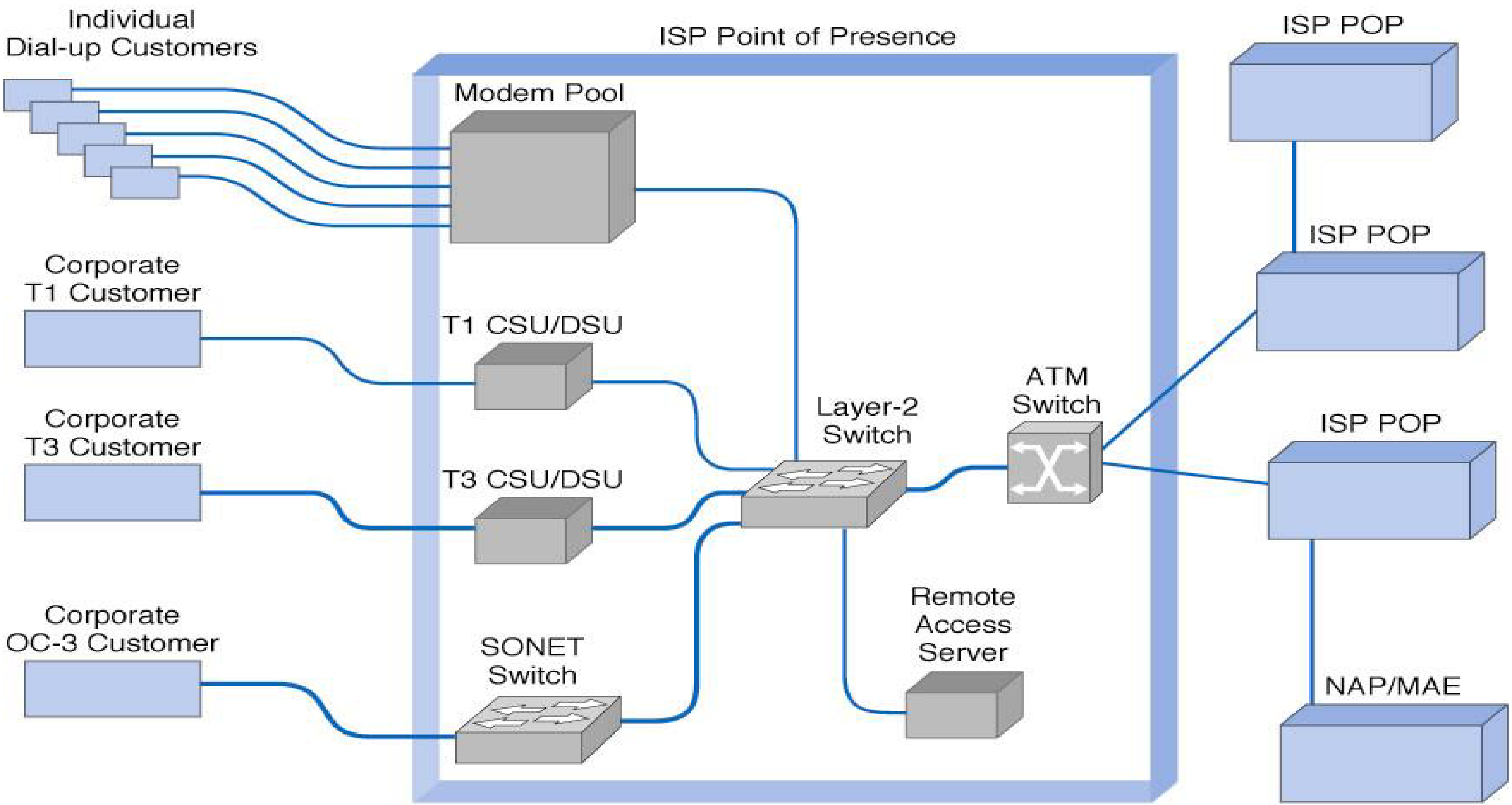


a Packet passes through many networks!

The Internet ?



Anatomy of an ISP



Network Performance Measures

- The two most important network performance measures are Delay/Latency & Throughput
- End-to-end delay consists of several components
  - Transmission time
  - Propagation delay
  - Nodal processing
  - Queuing delay (Random, depends on network loading, link capacities, disciplines, etc..)

Transmission Time

- Transmission Time (t_{trans})
  - The time it takes to transmit a group of bits (e.g., a Message/Packet/Frame) of bits into a network

$$t_{tran} = \frac{\text{Number of message bits}}{\text{Data rate [bps]}}$$

Propagation Delay

- Propagation time (t_{prop})
  - The time it takes for a bit to traverse the link

$$t_{prop} = \frac{\text{link length[m]}}{v_{prop}\ [m/s]}$$

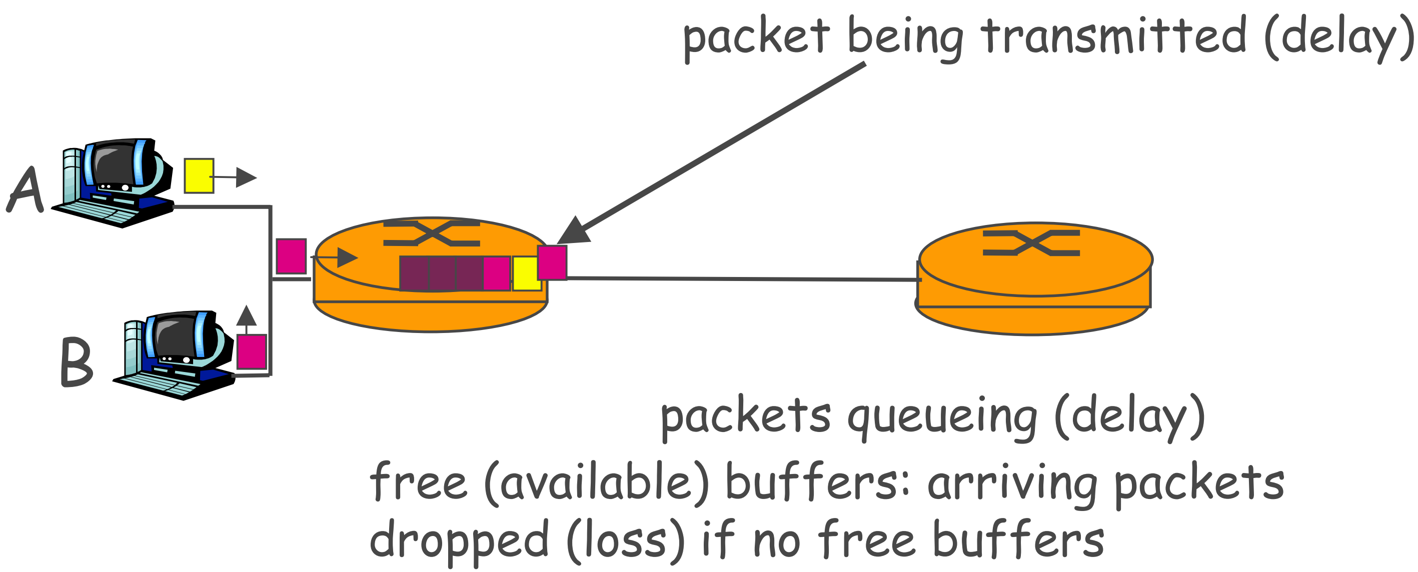
- Example propagation velocities:
  - Air/Free space: $c = 3\times10^8$ meters/sec
  - Cat 5 UTP: $2\sim2.5\times10^8$ meters/sec
  - Optical Fiber: $2\sim2.5\times10^8$ meters/sec

Nodal Processing/Queueing

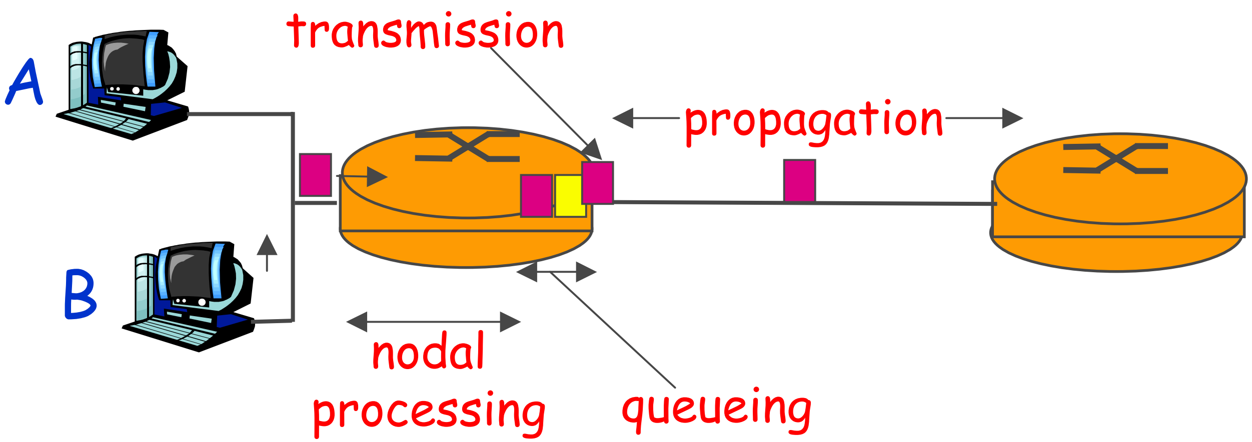
- Nodal processing:
  - Check bit errors
  - Determine output link (Routing decision)
- Queuing
  - Time waiting at output link for transmission
  - Depends on congestion level of router

Loss and Delay: Why?

- packets *queue* in router buffers
- packet arrival rate to link exceeds output link capacity
- packets queue, wait for turn



Summary of Delay Components



Message Transfer Time

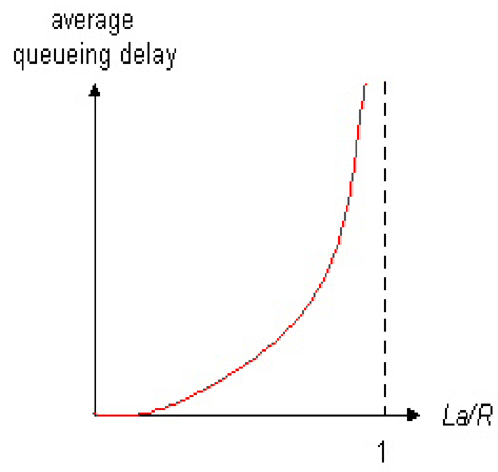
- Message Transfer Time (t_{xfr}) = Message latency
  - Time for sender to transmit message to the receiver and for the receiver to receive the entire message. Also known as the end-to-end delay

$$t_{xfr} = t_{trans} + t_{prop} + t_{queuing/processing}$$

More on Queuing Delay

- R = link bandwidth (bps)
- L = packet length (bits)
- λ = average packet arrival rate (Packets/sec

Traffic intensity = λL/R



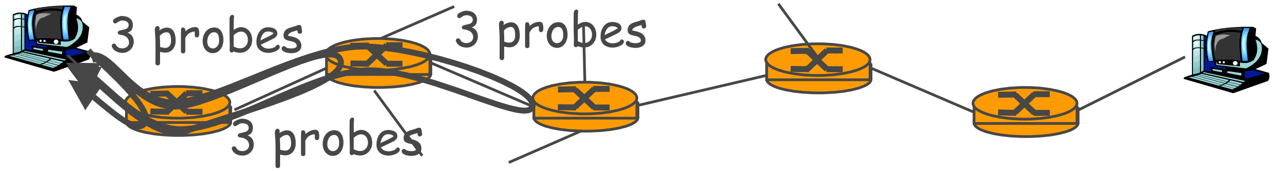
- **λL/R ~ 0: average queueing delay**
- **λL/R -> 1: delays become large**
- **λL/R > 1: more "work" arriving th be serviced, average delay infinite!**

Round Trip Time (RTT)

- Round Trip Time: The time to send a message from a sender to the receiver and receive a response back
- RTT depends on message size, length of link, direction of propagation, propagation velocity, network node processing, network loading, etc…
- For simplicity, RTT is normally assumed to be twice the end-to-end propagation delay although this might not be true if the message and the response traverses different links

Real Internet Delays & Routes

- What do "real" Internet delay & loss look like?
- Traceroute program: provides delay measurement from source to router along end-end Internet path towards destination. For all *i*:
  - sends three packets that will reach router *i* on path towards destination
  - router *i* will return packets to sender
  - sender times interval between transmission and reply.

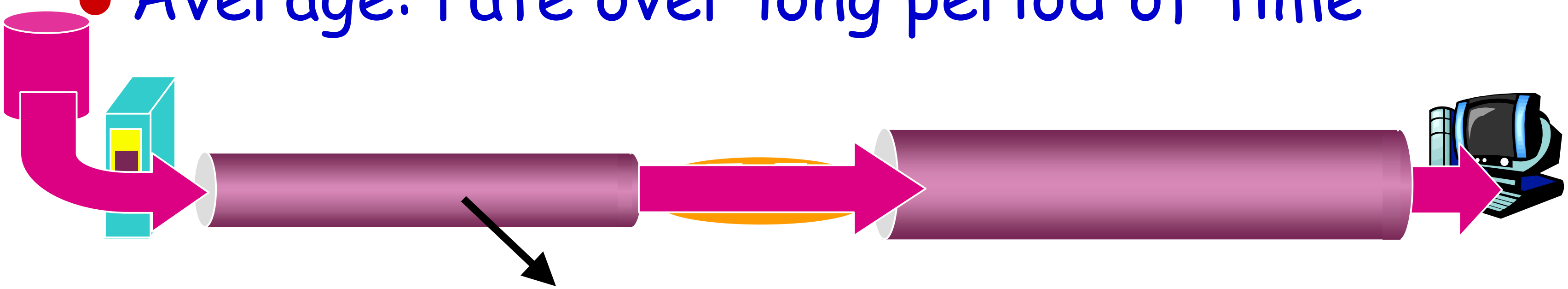


Throughput

- The Throughput is defined as the number of information bits that can be transferred reliably over a certain period of time. It is measured in "bps"
- The throughput is the carried load and it is <u>not</u> equal to the offered load
- Protocols add overhead bits and time delays in addition to the transmission time of the actual information bits. That would result in reduced throughput.
- Link errors are result in reduced throughput

Instantaneous vs. Average Throughput

- Throughput: rate (bits/time unit) at which bits transferred between sender/receiver
  - Instantaneous: rate at given point in time
  - Average: rate over long period of time



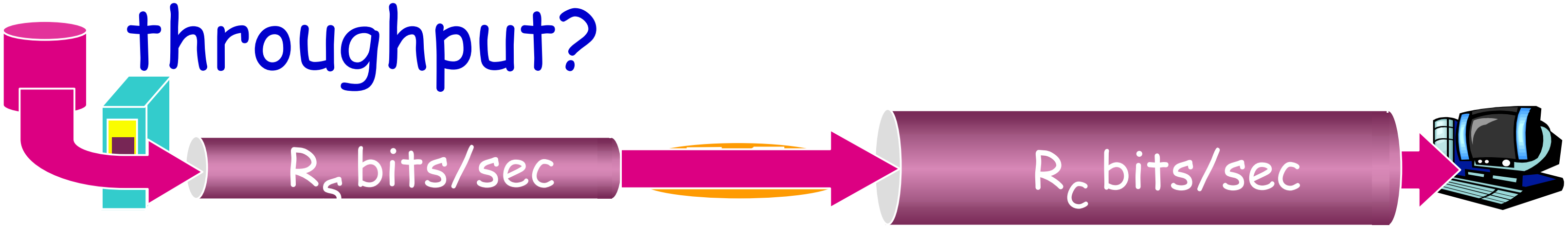
Server sends bits (fluid) into pipe

Pipe that can carry fluid at rate R_s bits/sec)

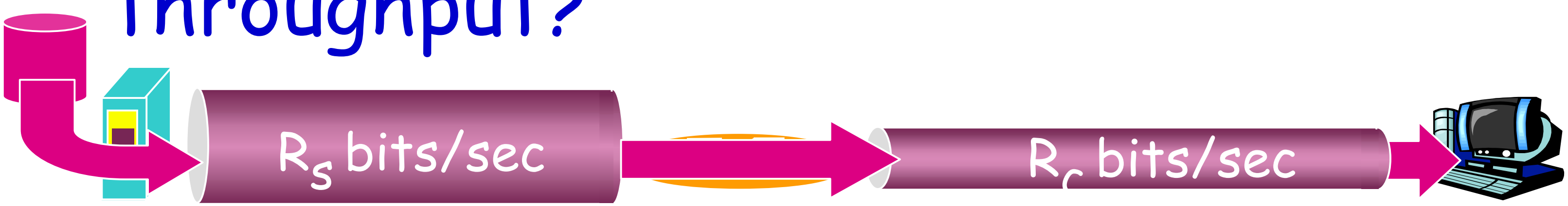
Pipe that can carry fluid at rate R_c bits/sec)

More on Throughput

- $R_s < R_c$ What is average end-end throughput?



- $R_s > R_c$ What is average end-end throughput?

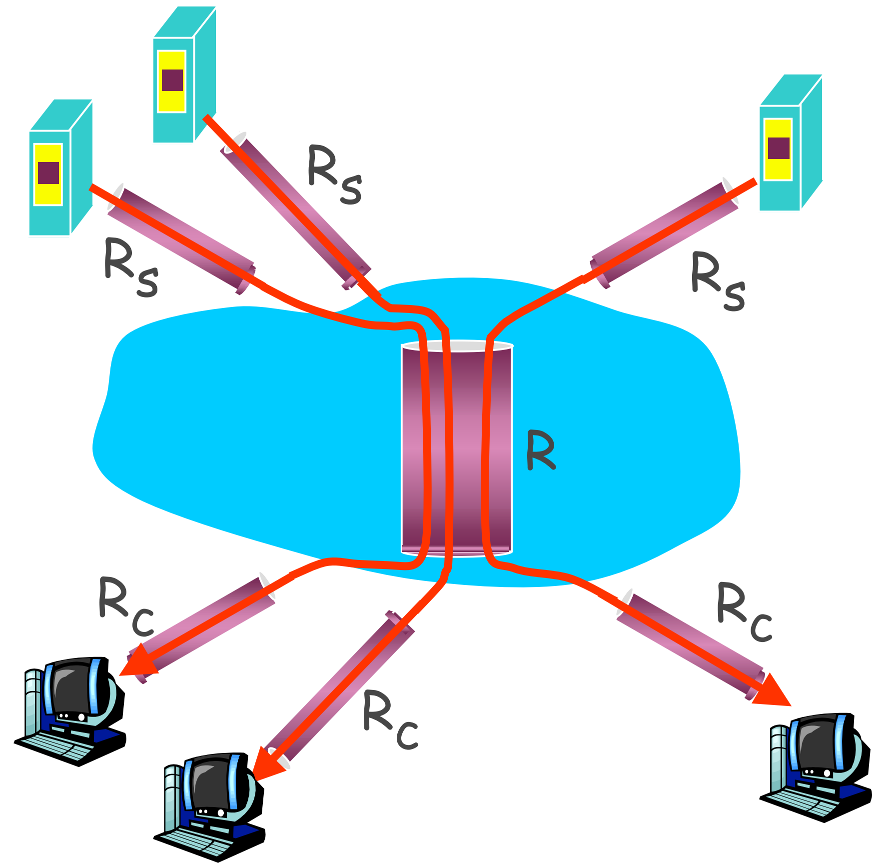


Bottleneck Link

link on end-end path that constrains end-end throughput

Example on Throughput

- per-connection end-end throughput: $\min(R_c, R_s, R/3)$
- In practice: R_c or R_s is often bottleneck
- Trunks have huge BW (i.e. R is v. Large)



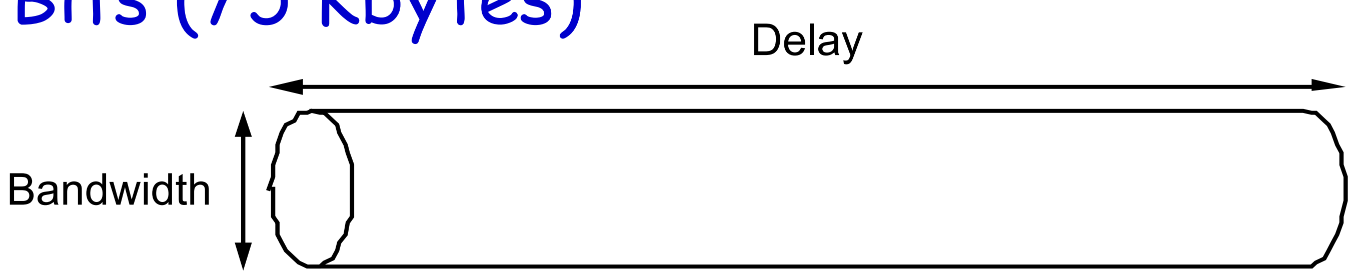
3 connections (fairly) share backbone bottleneck link R bits/sec

Bandwidth/Capacity

- The bandwidth or the data rate is the number of bits that can be transmitted over a certain period of time.
  - For example, 10 Mbps means that 10 million bits are transmitted every seconds.
- Link Capacity is the maximum data rate possible on the link with negligible error rate (Shannon Theorem, to be discussed later)

Bandwidth X Delay Product

- Pipe Size: The maximum amount of data present on the line, usually in an interval of RTT
- Example: If the line bandwidth (data rate) is 10 Mbps and the end-to-end delay is 30 msec, the amount of data found on the line is 600K Bits (75 Kbytes)



Networking Perspective

- Application Programmer / End User
  - Guaranteed timely, reliable and recognizable delivery of message/information
- Network Designer
  - Cost-effective design. Resources (Bandwidth, Memory and CPUs) must be used efficiently and are fairly allocated
- Network Provider
  - Administration & management effort, fault detection/fault isolation, easy to account for usage

The Internet Today

- ~ 500 million hosts
- Voice, Video over IP
- P2P applications: Napster, BitTorrent (file sharing) Skype (VoIP), PPLive (video)
- More applications: YouTube, gaming, social networking
- Wireless, mobility, networked embedded sensors,...