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 Devices (Routers, Switches, etc.)

Part 6: Transport Layer Protocols

Part 7: Network Applications

Part 8: Network Security

Focus throughout the course is on the public Internet

Broad coverage of topics (important topics in depth)

Why EE450?

- Indispensable part of modern society
  - Commercial: e-commerce, banking, inventorying, telecommunications, archiving, health, education
  - Social – critical infrastructure, homeland security, policing
  - Human interaction/communication – email, chat, videoconferencing, social networking, entertainment
- Appears in every facet of engineering
  - Modern trend – Network every (electronic) device (computers, phones, sensors, planes, cars, TVs, appliances, heart monitors, …)
- Prolific field to pursue graduate studies
  - Many problems remain unsolved
  - Research funding is still strong

Growth of CN

- Computer networks are everywhere
- In 1980, the Internet was a research project that involved a few dozen sites. Today, the Internet has grown into a huge Network that reaches all of the world
- The advent and utility of networking has created dramatic economic shifts
  - Network has made telecommuting available to individuals
  - An entire industry emerged that develops networking technologies, products, and services
  - The importance of computer networks has produced a demand in all industries for people with more networking expertise
  - Companies need professionals to plan, acquire, install, operate, and manage the hardware and software systems for networks

Multimedia Convergence

Major Industries

Data

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

Computer Software
Financial, e-Commerce, etc.

Broadcast TV
Film

Video

- pre-recorded / on-demand
  (e.g., MPEG, Real Net)
- Streaming Video (Netflix, Hulu)
- Gaming Industry

Recording
Broadcast
Radio

Voice / Audio

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

Telephone companies (Telco)
Internet Service Providers (ISP)

Wireless

PDA

Cell phone

Pager

Computer Hardware/Software
Telco/wireless Hardware

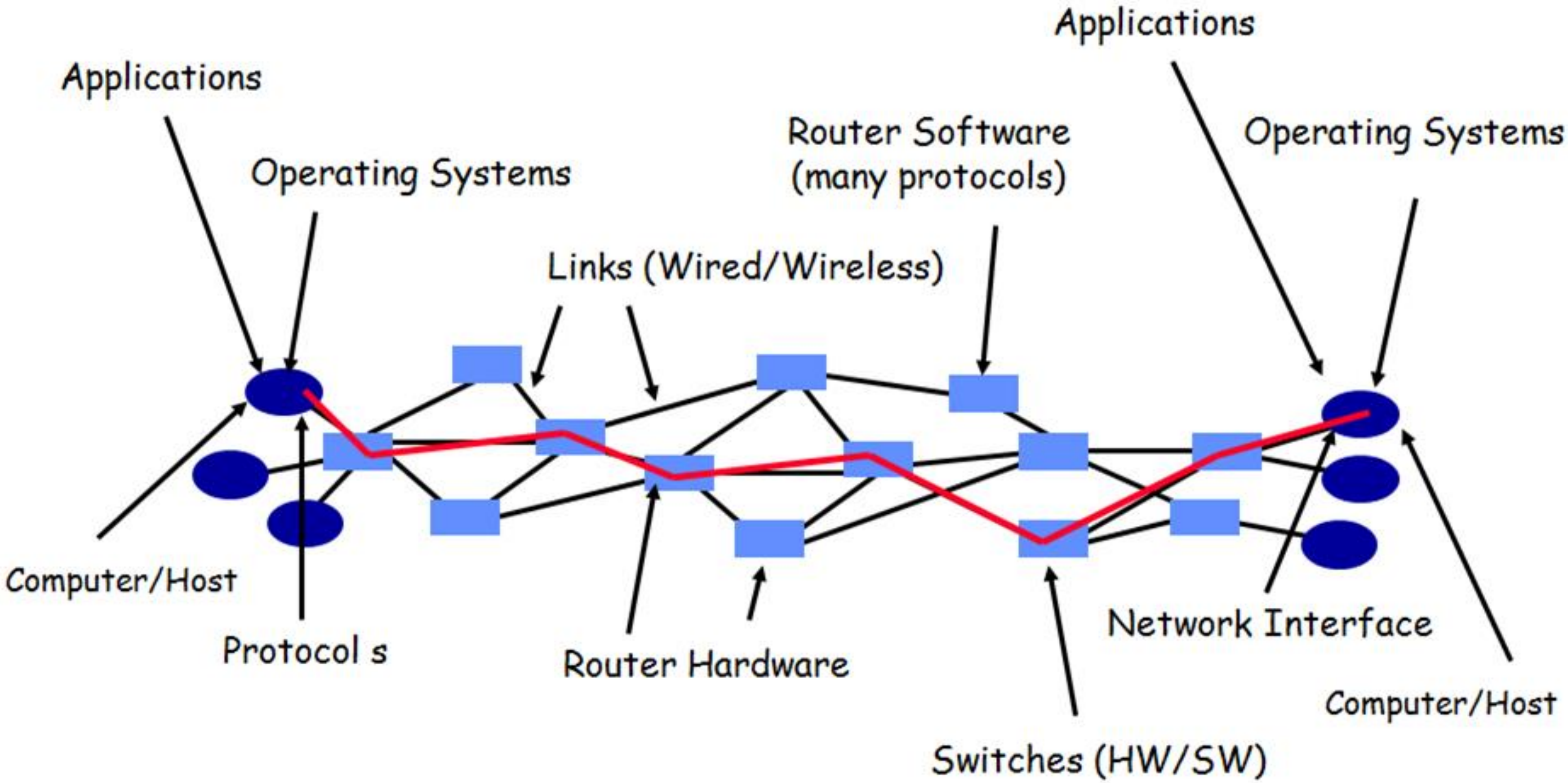
Computer (?) Networks

- 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

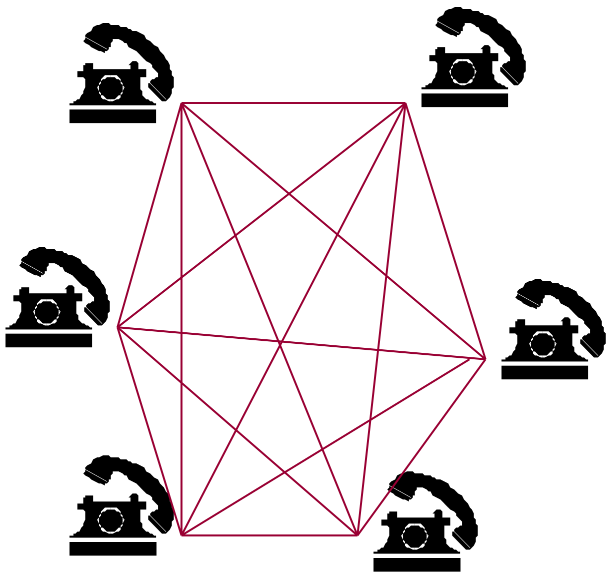
- So why the question mark?? Non-traditional end systems (Laptops, Cell Phones, Tablets, gaming Consoles, Sensor devices, Toasters, Refrigerators, etc...) are being connected to the internet

- 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

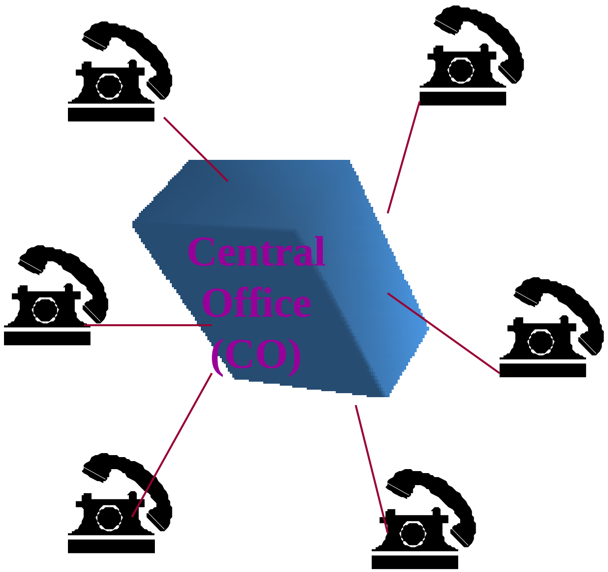
Generic Computer Network



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

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. *A*ll 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.

Network Applications

- E-mail
- WWW
- Instant messaging
- Remote login
- P2P file sharing
- Multi-user network games
- Streaming audio/video
  - You Tube, Hulu, Netflix
- Voice over IP (e.g. Skype)
- Real-time video conferencing
- High definition and 4K video
- On-line Social Network
  - Facebook, Twitter, etc…
- E-Commerce
- Distributed Databases
- Search

Note: different applications may have different
- Requirements (delay, loss, Throughput, jitter bounds, security)
- Number of participants (unicast, multicast, broadcast, etc…)
- Architecture (client-server, p2p, flat, hierarchical, hybrid, etc…)
- All applications can communicate over a single shared network

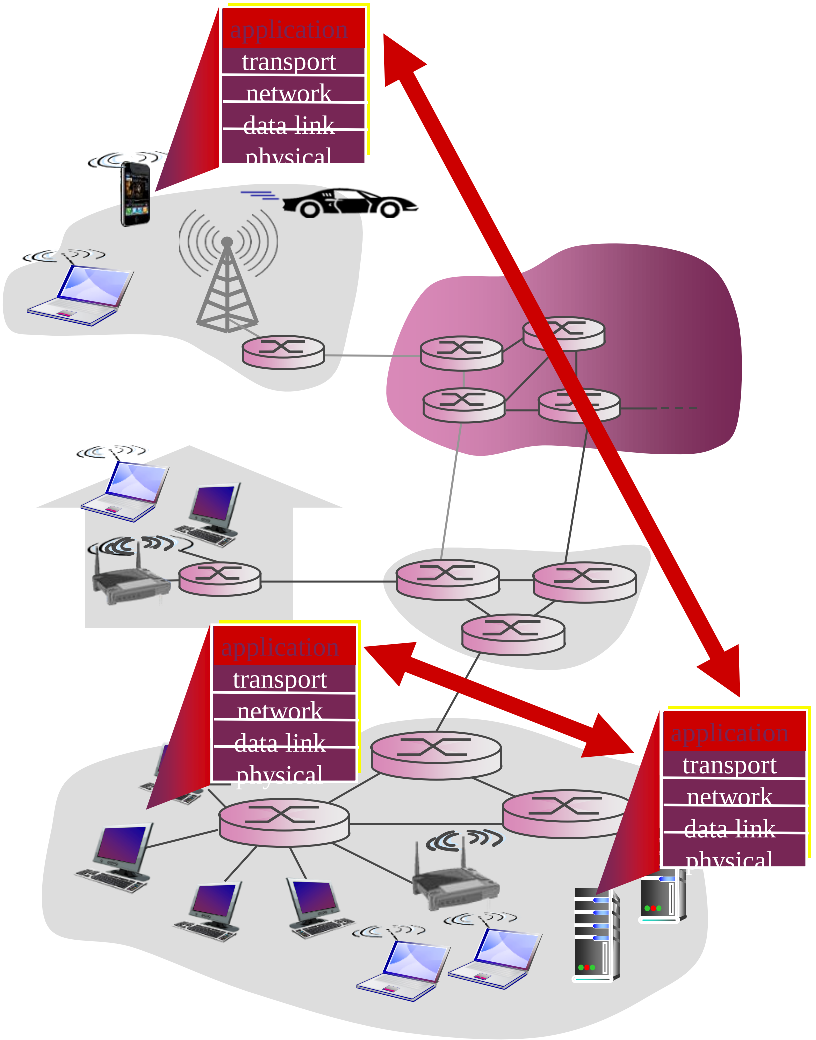
Creating a Networked Application

Write programs that:

- run on (different) end systems
- communicate over network
- e.g., web server software communicates with browser software

No need to write software for network-core devices

- network-core devices do not run user applications
- applications on end systems allows for rapid application development



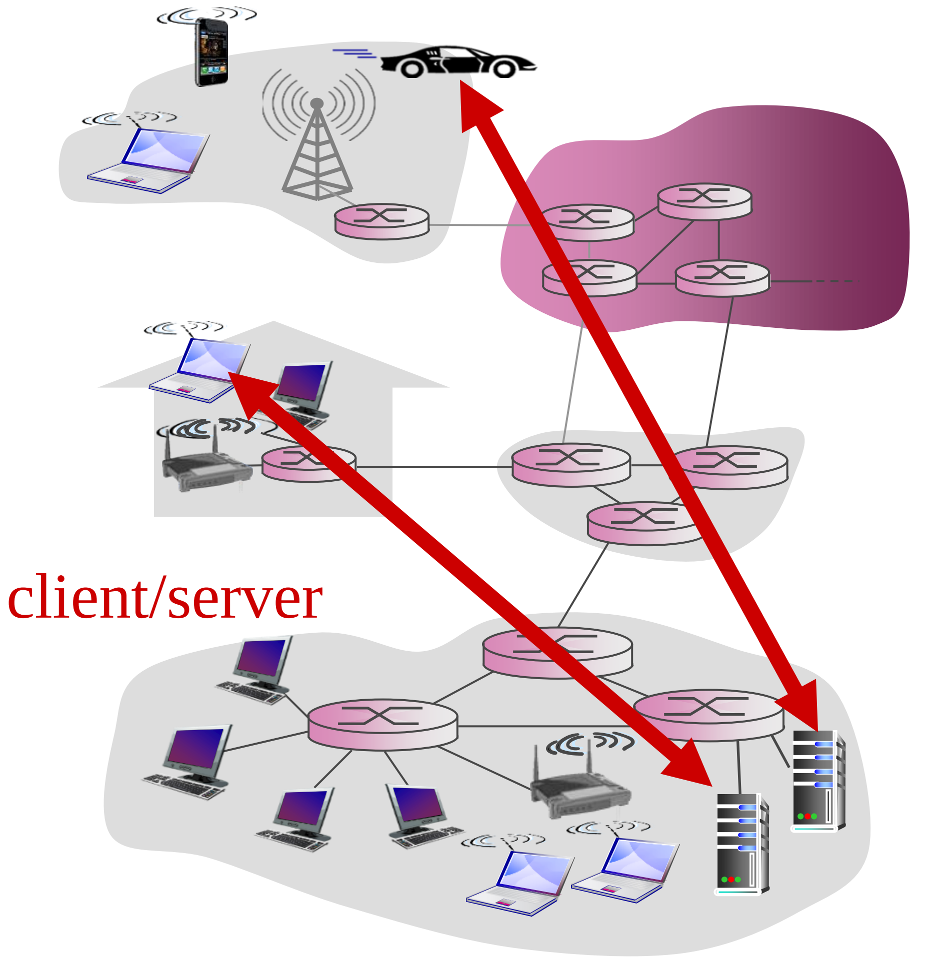
Client Server Architecture

Server:

- Always-on host
- Permanent IP address
- Data centers for scaling

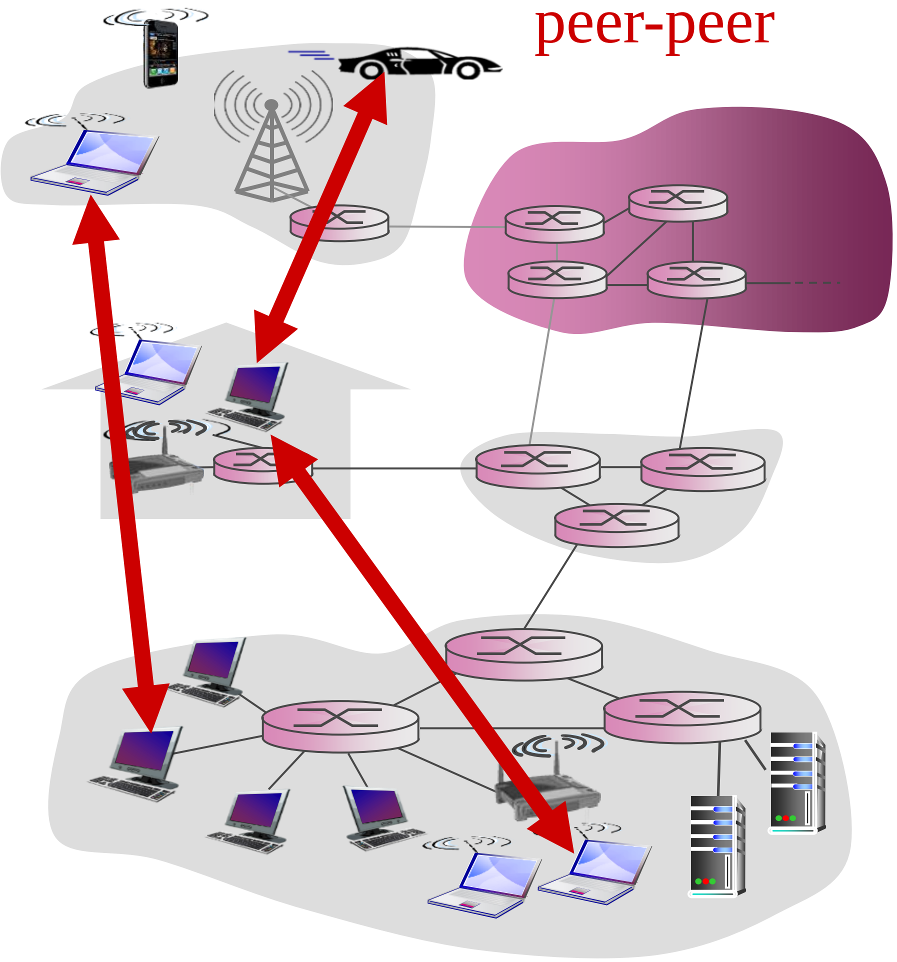
Clients:

- Communicate with server
- May be intermittently connected
- May have dynamic IP addresses
- Do not communicate directly with each other



P2P Architecture

- No always-on server
- arbitrary end systems directly communicate
- Peers request service from other peers, provide service in return to other peers
  - self scalability – new peers bring new service capacity, as well as new service demands
- Peers are intermittently connected and change IP addresses (e.g. Bit Torrent)
  - complex management (No central Control)



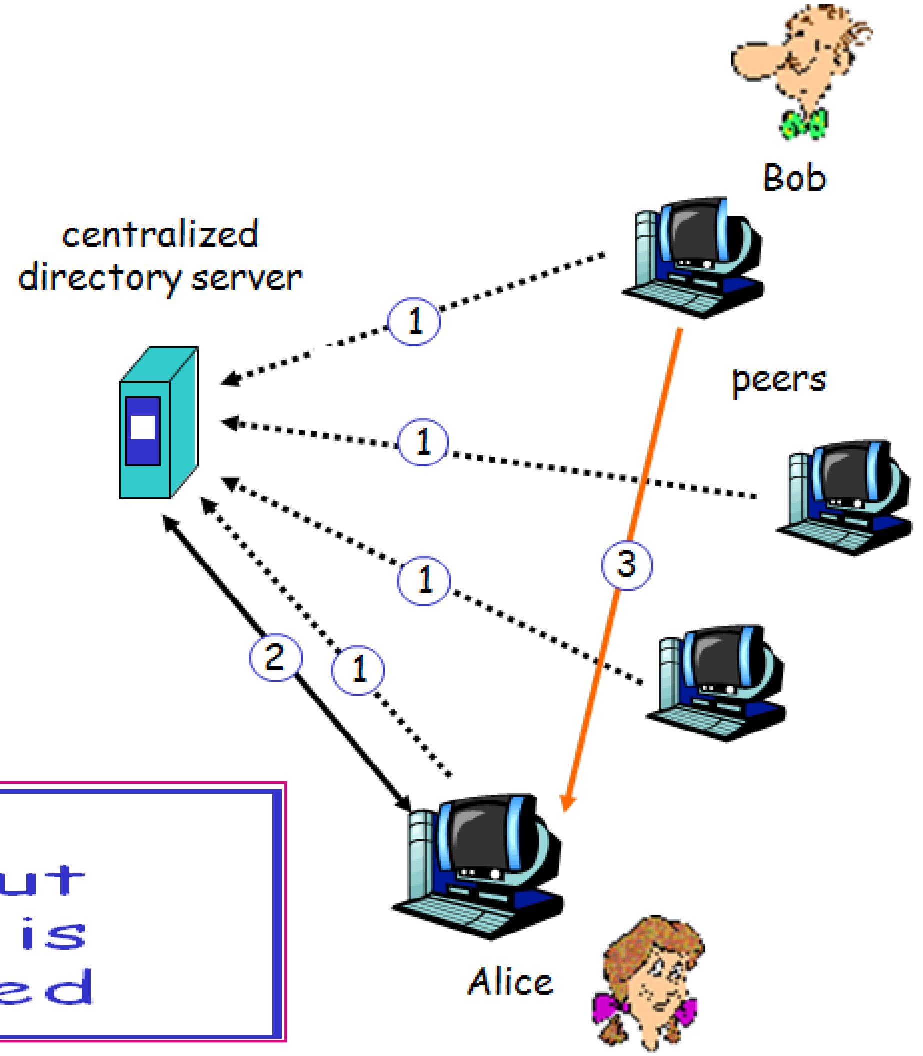
P2P: Centralized Directory

original "Napster" design

1) when peer connects, it informs central server:
   - IP address
   - content

2) Alice queries for "Hey Jude"

3) Alice requests file from Bob



file transfer is decentralized, but locating content is highly centralized

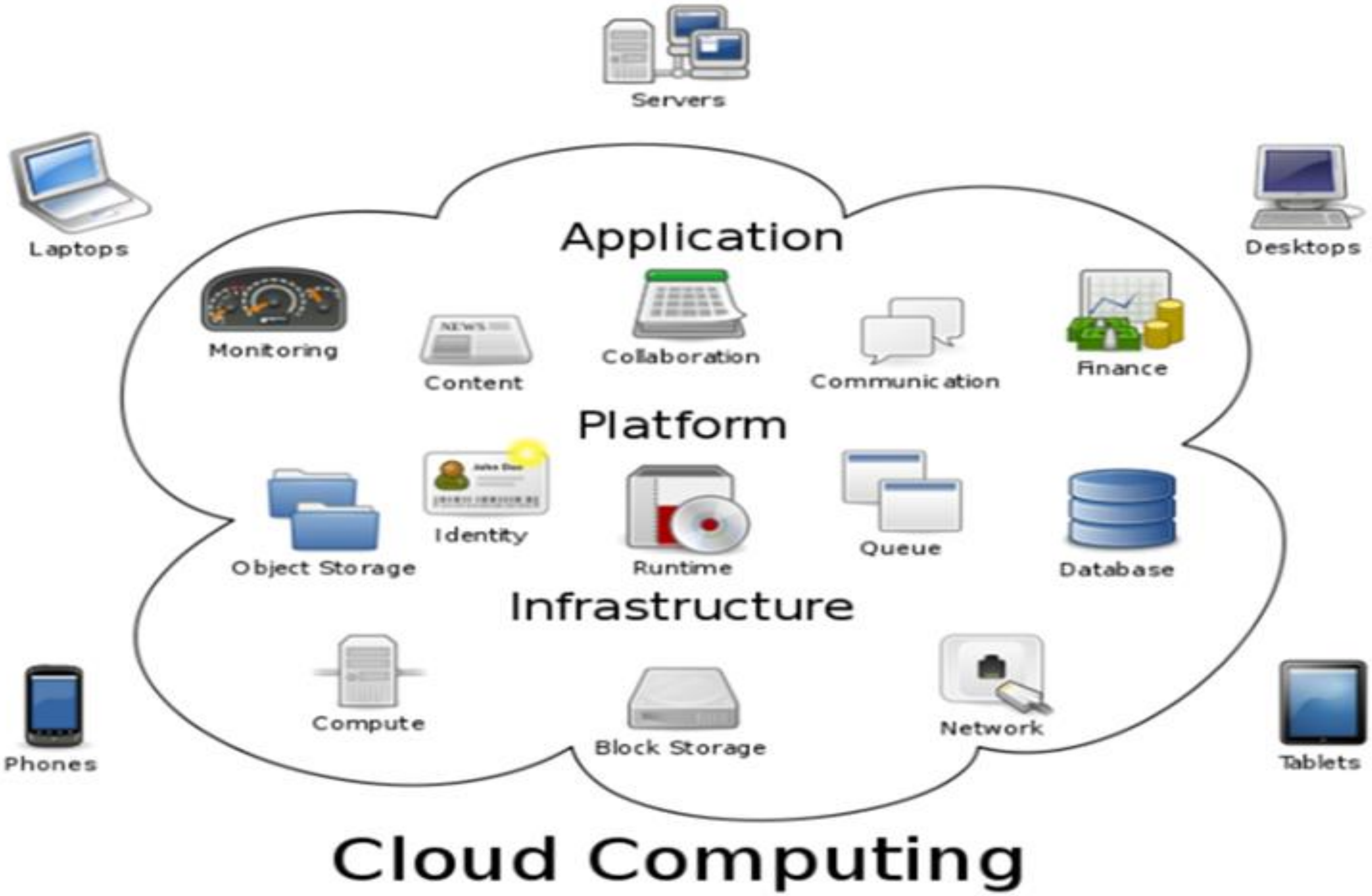
Distributed (Cloud) Computing Model

- **Elastic resources**
  - Expand and contract resources
  - Pay-per-use
  - Infrastructure on demand
- **Multi-tenancy**
  - Multiple independent users
  - Security and resource isolation
  - Amortize the cost of the (shared) infrastructure
- **Flexible service management**

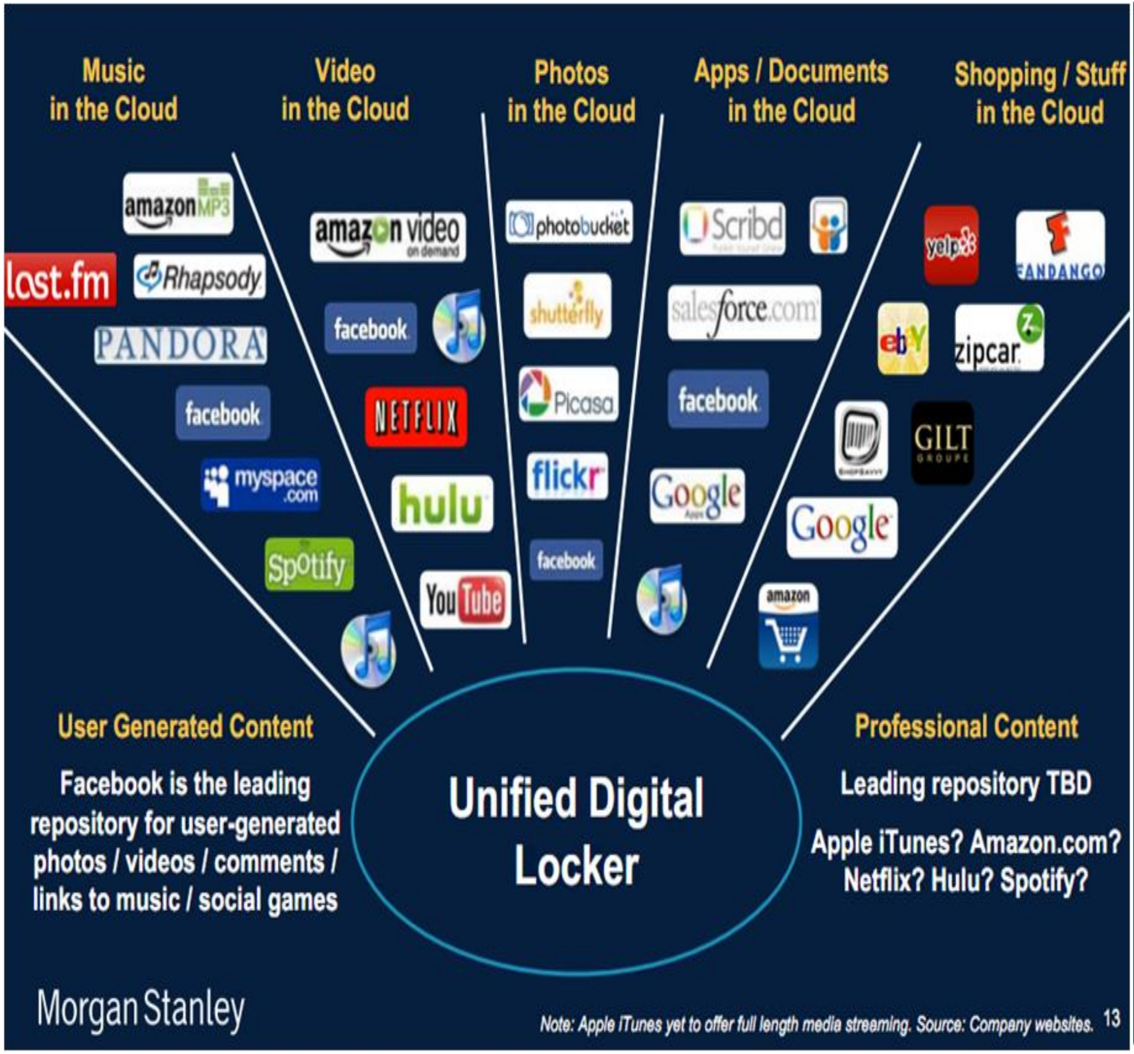
Cloud Computing Service Models

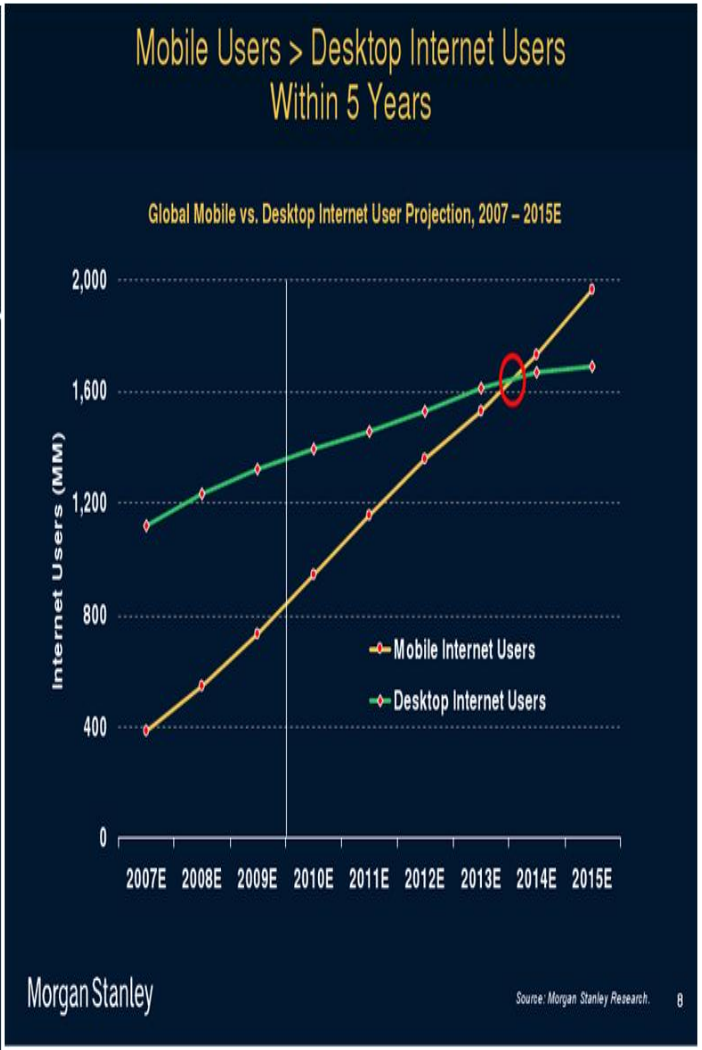
- Software as a Service
  - Provider licenses applications to users as a service
  - E.g., customer relationship management, e-mail, ..
  - Avoid costs of installation, maintenance, patches..
- Platform as a Service
  - Provider offers platform for building applications
  - E.g., Google's App-Engine
  - Avoid worrying about scalability of platform
- Infrastructure as a Service
  - Provider offers raw computing, storage, and network
  - E.g., Amazon's Elastic Computing Cloud (EC2)
  - Avoid buying servers and estimating resource needs

Cloud Computing Services

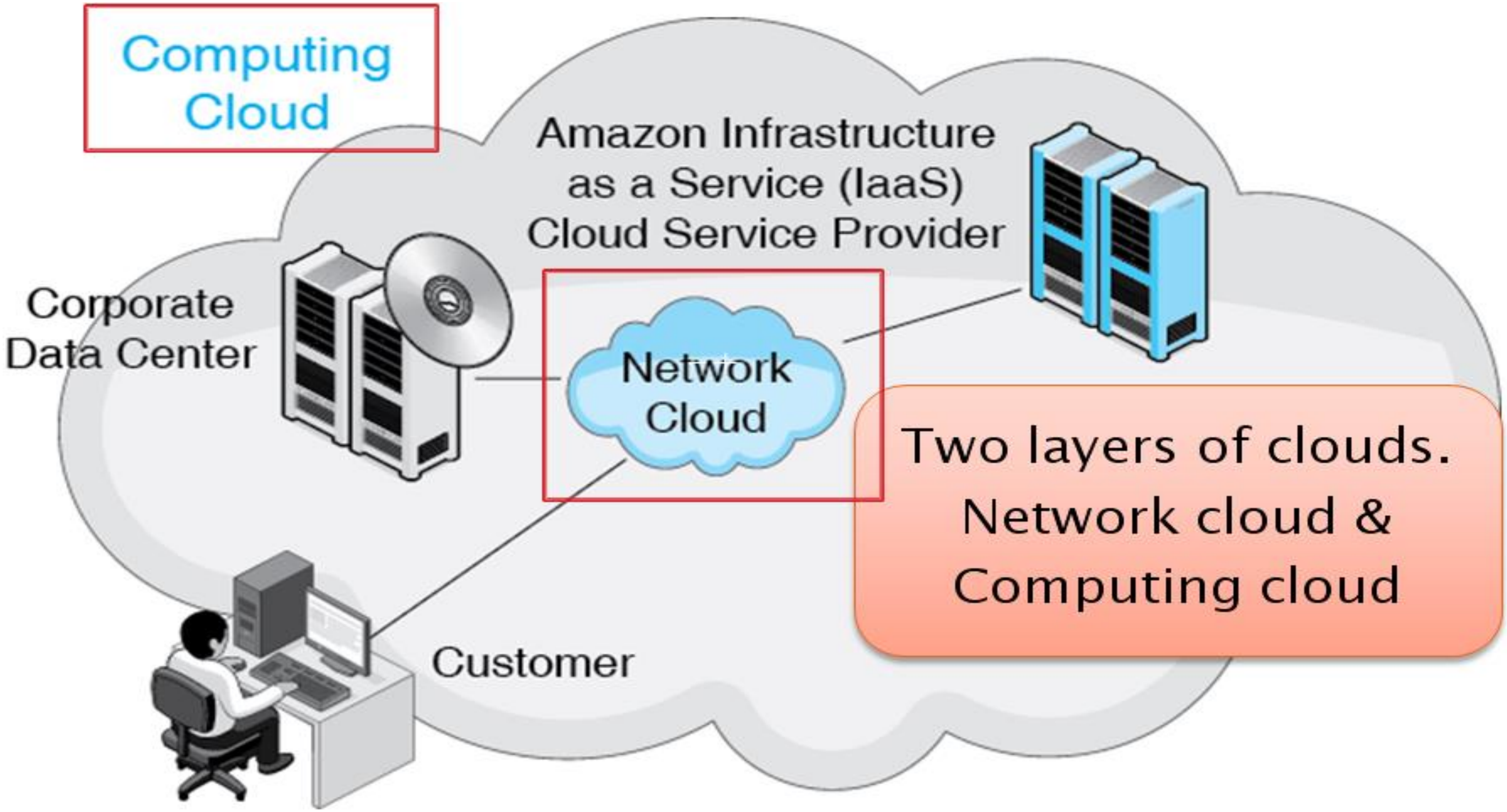


Users Expectations from the Cloud





Cloud Service Providers

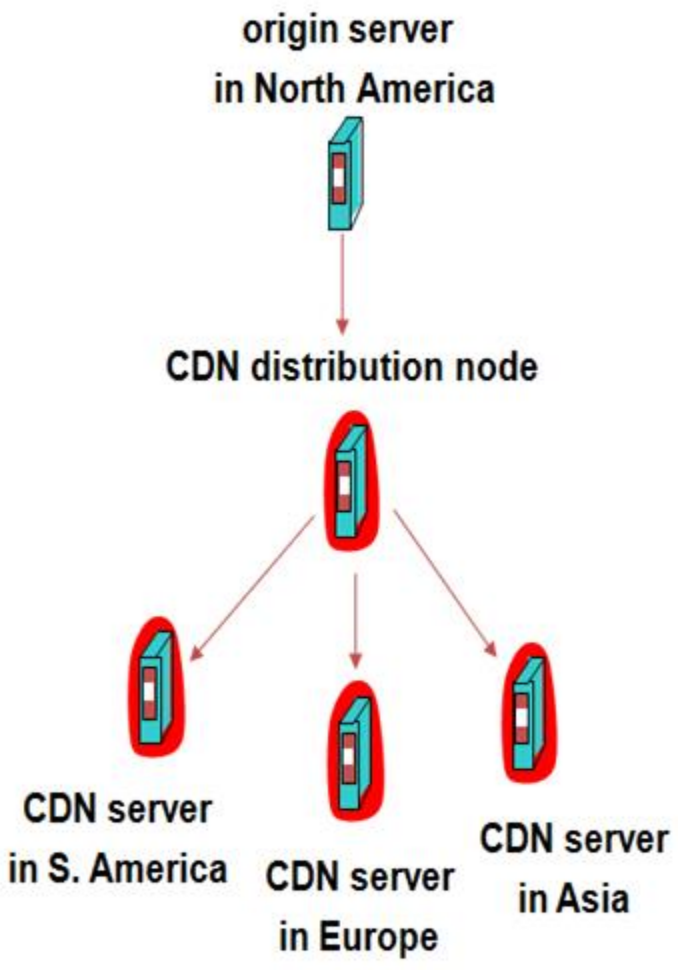


Video Streaming & CDN

- stream video traffic: major consumer of Internet bandwidth
  - Netflix, YouTube, Amazon Prime: 80% of residential ISP traffic (2020)
- challenge: scale - how to reach ~1B users?
  - single mega-video server won't work (why?)
- challenge: heterogeneity
  - different users have different capabilities (e.g., wired versus mobile; bandwidth rich versus bandwidth poor)
- *solution: distributed, application-level infrastructure*

CDN: Content Delivery Networks

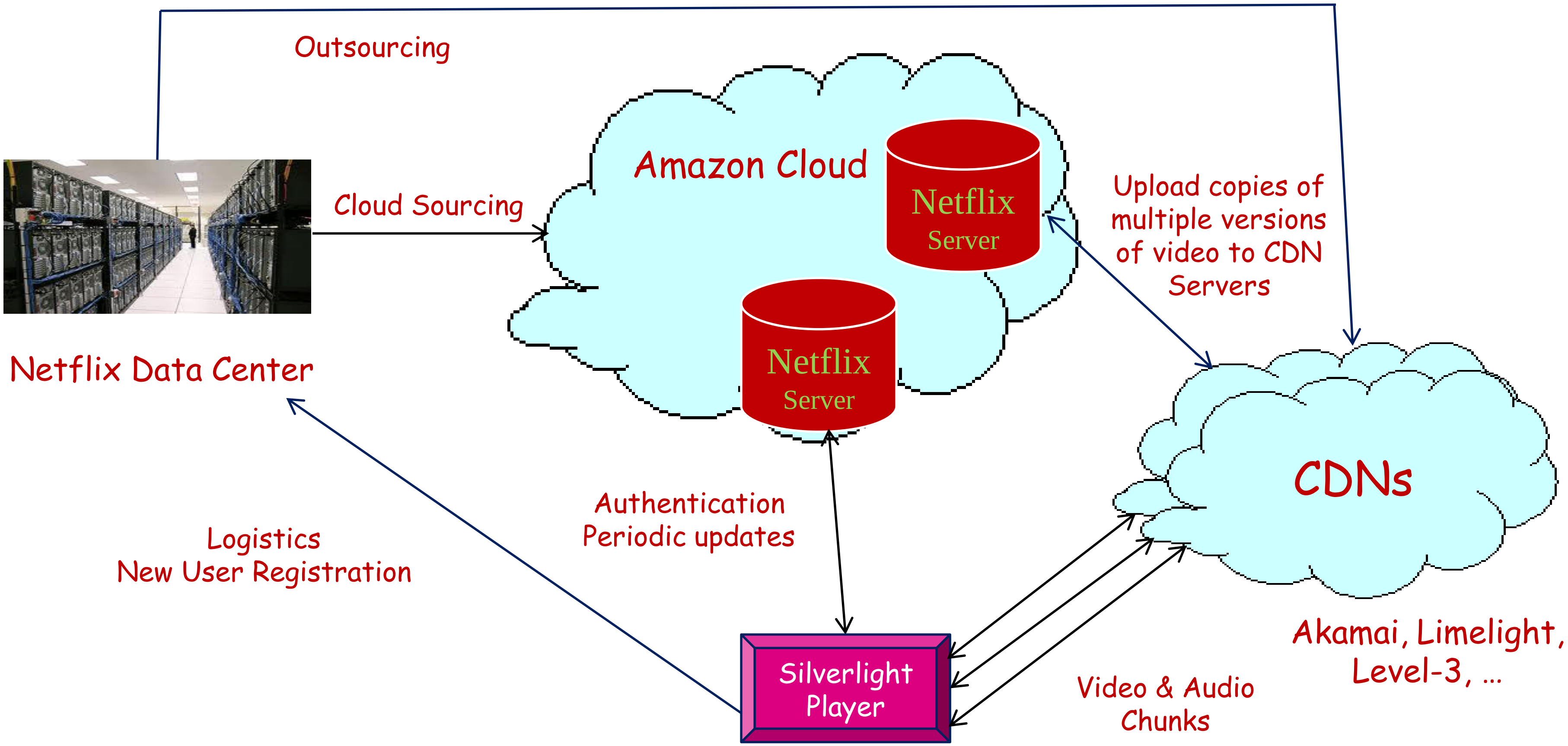
- Proactive content replication
  - Content provider (e.g., CNN) contracts with a CDN
- CDN replicates the content
  - On many servers spread throughout the Internet
- Updating the replicas
  - Updates pushed to replicas when the content changes



Case Study: Netflix

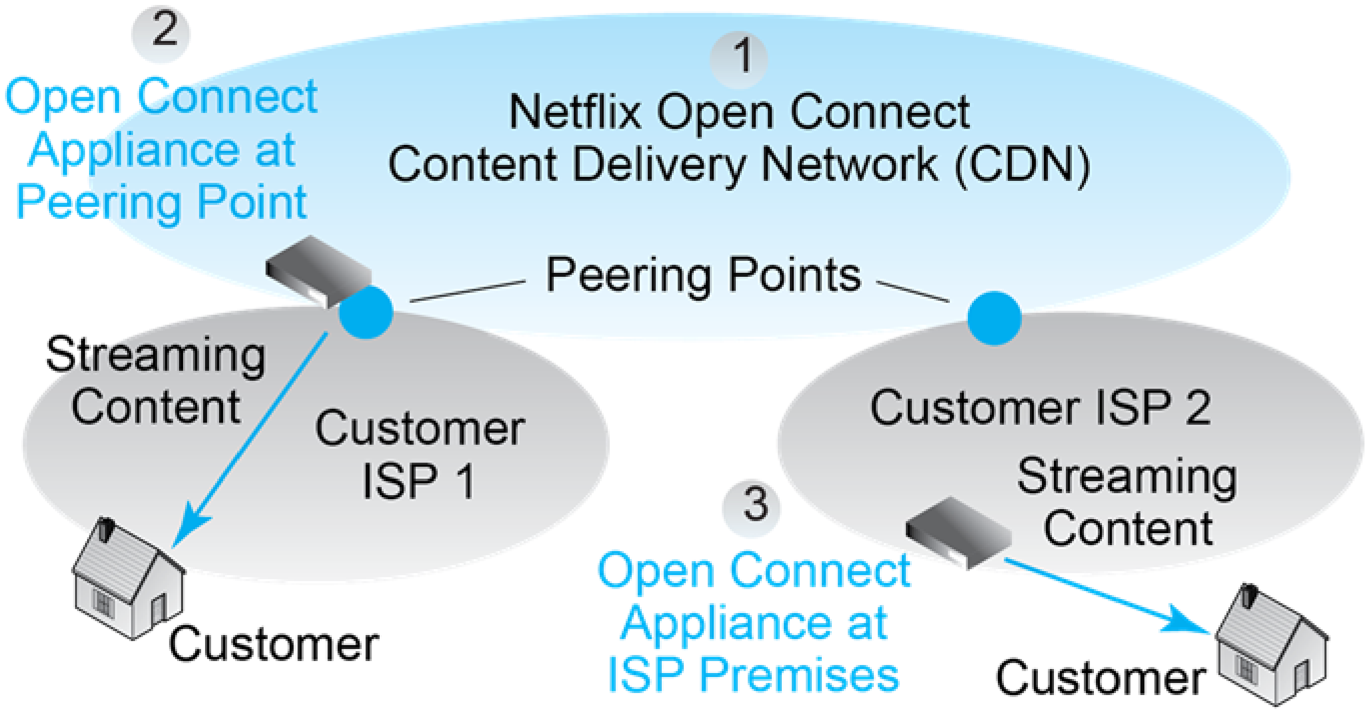
- Netflix uses AWS for many server needs.
- However, it runs its own streaming servers to deliver content to users.
  - This is a core competency kept in-house
- Content Delivery Network (CDN)
  - To deliver content to user with minimum delay
  - Netflix has its own ISP to connect to customer ISPs
  - Caches content in appliances near users
  - Netflix CDN is called Open Connect

Case Study: Netflix Architecture



- Netflix is the single largest source of Internet Traffic
- Consume ~ 35% of Peak Downlink Traffic

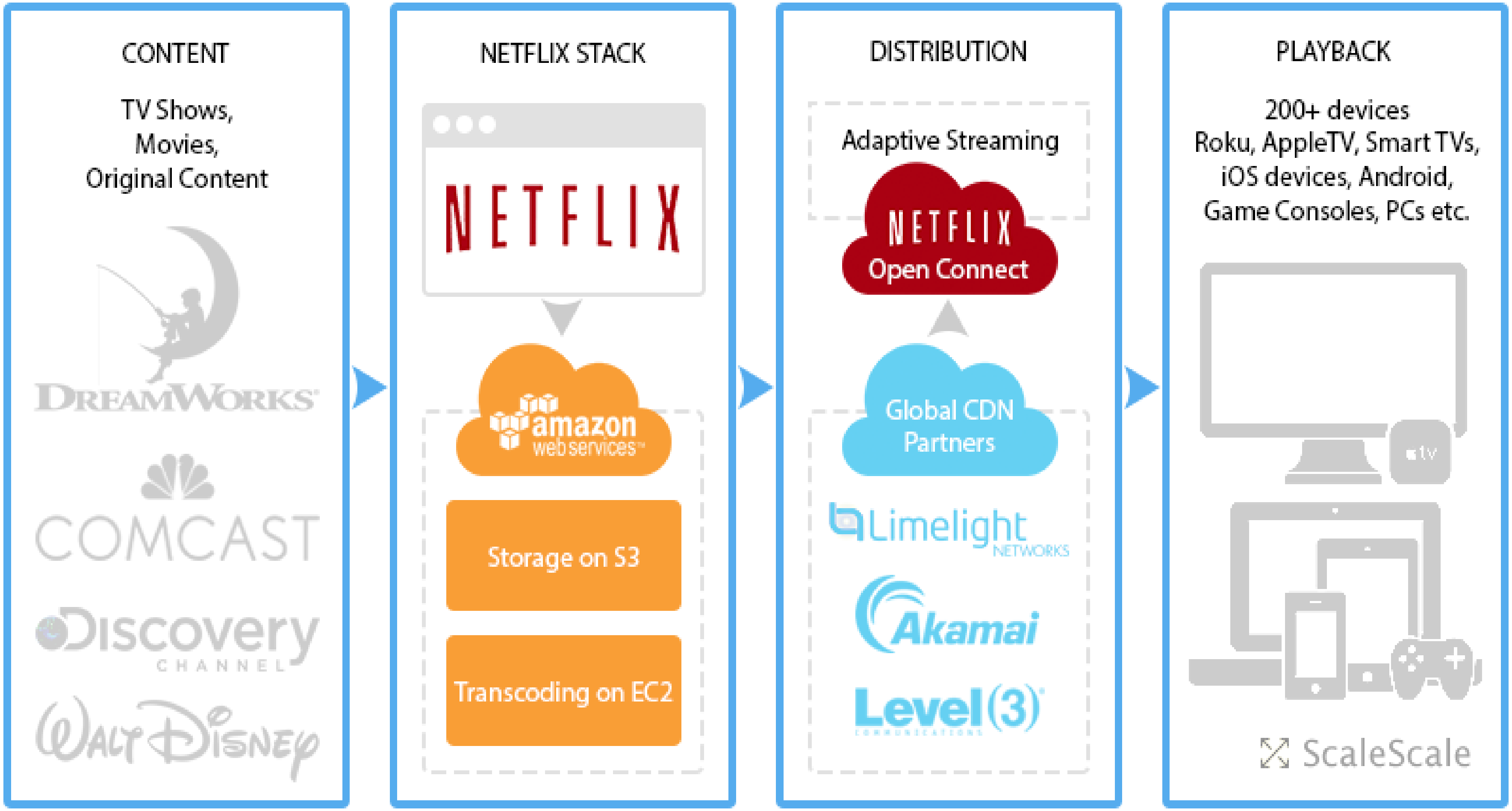
Netflix Open Connect CDN



The Netflix Open Connect CDN is an ISP owned by Netflix

ISPs connect at peering points

Netflix (Summary)



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/LINUX
  - Microsoft Windows
  - Novell Netware
  - 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..)

Links: Medium + Adapter Cards

Communication Medium



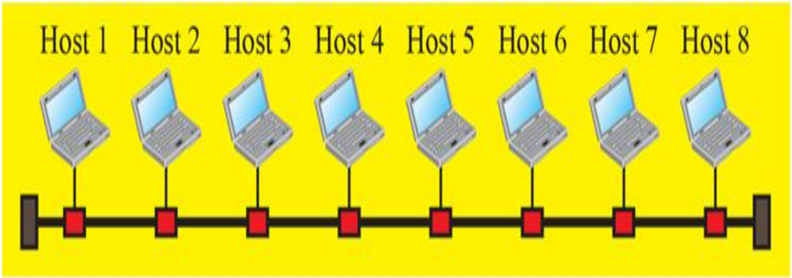

Network Adapter



Network Classifications

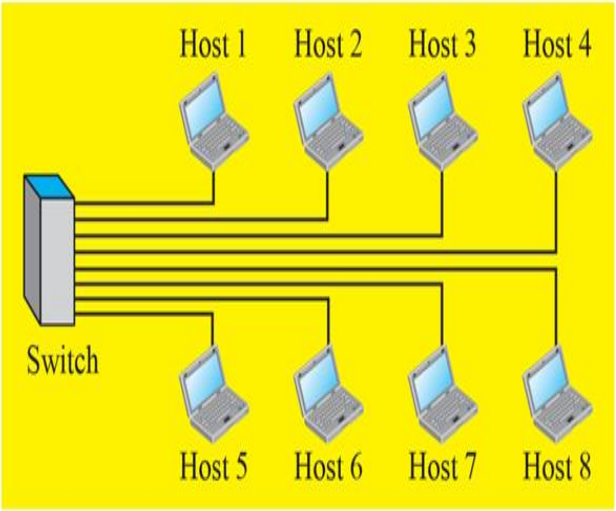
- Networks can be classified based on Coverage into
  - LANs: Local Area Networks
  - WANs: Wide Area Networks
  - Others including MAN (Metropolitan Area Networks, PAN (Personal Area Networks), Home Networks, etc…
- Networks could also be classified as Switched or Shared (Broadcast) networks
- Networks could also be classified based on their functionalities for example Backbone Networks, Content Delivery Networks, Overlay Networks, etc..

Switched vs. Broadcast Networks

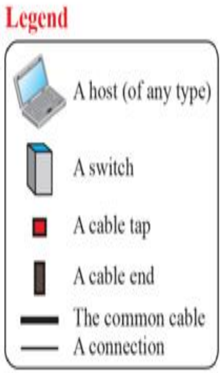


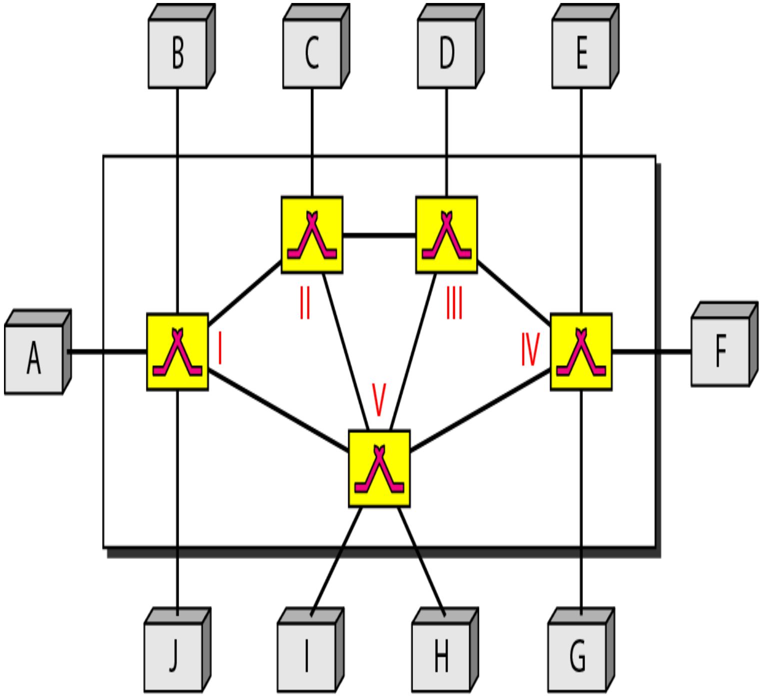
a. LAN with a common cable (past)

Broadcast



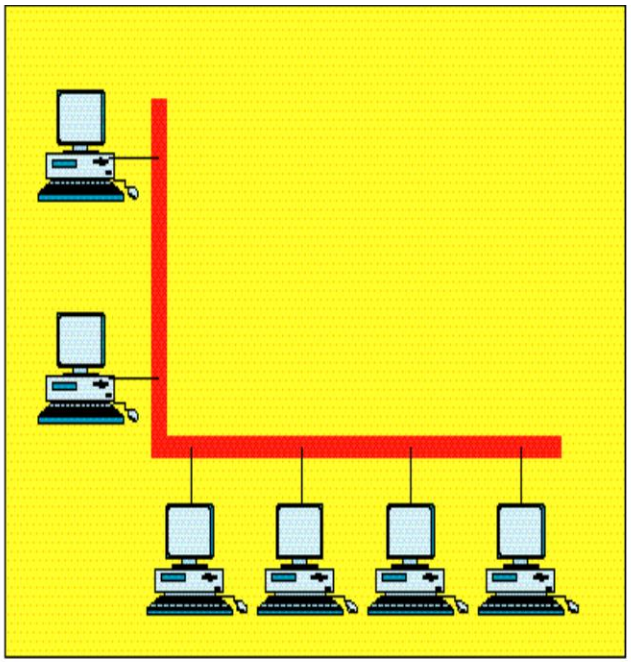
b. LAN with a switch (today)



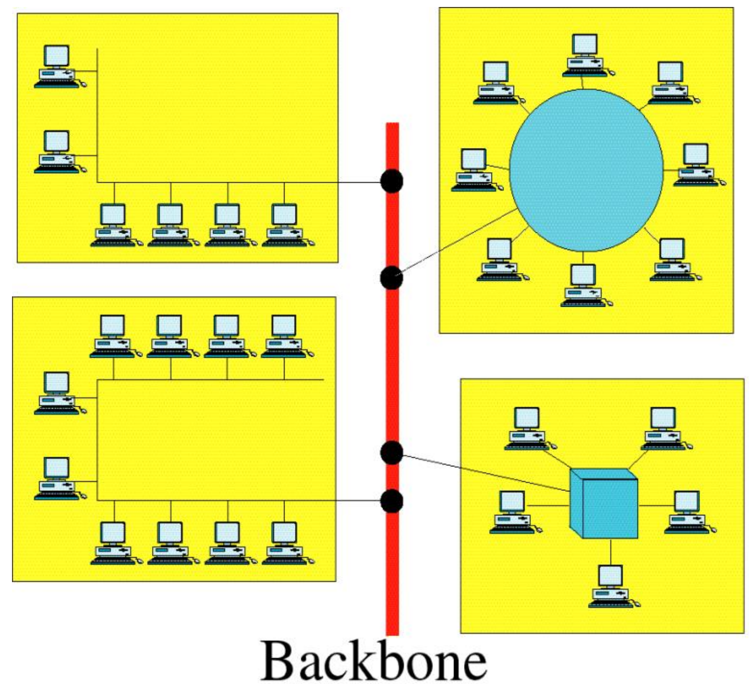


Switched

Local Area Networks (I)

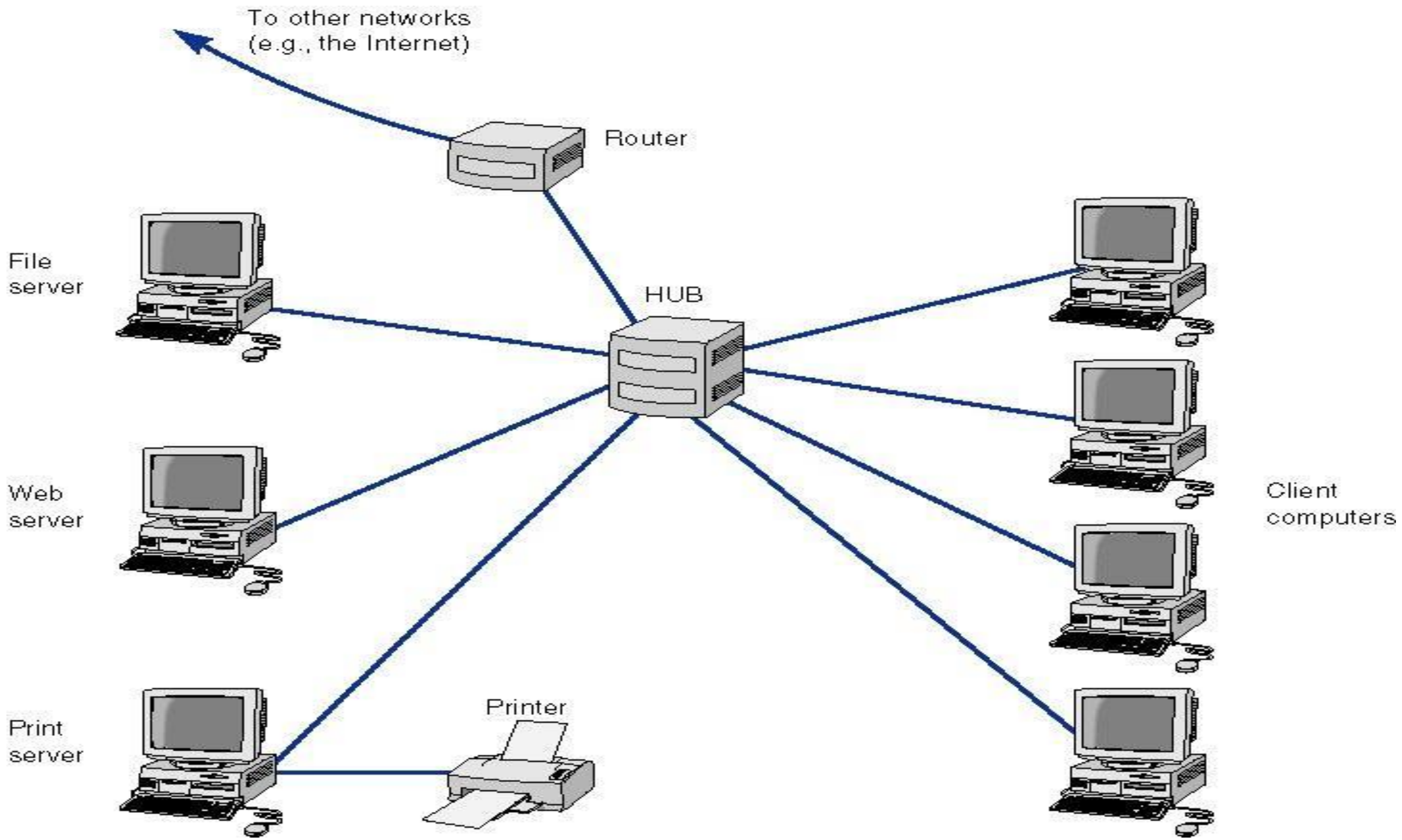


Single building LAN

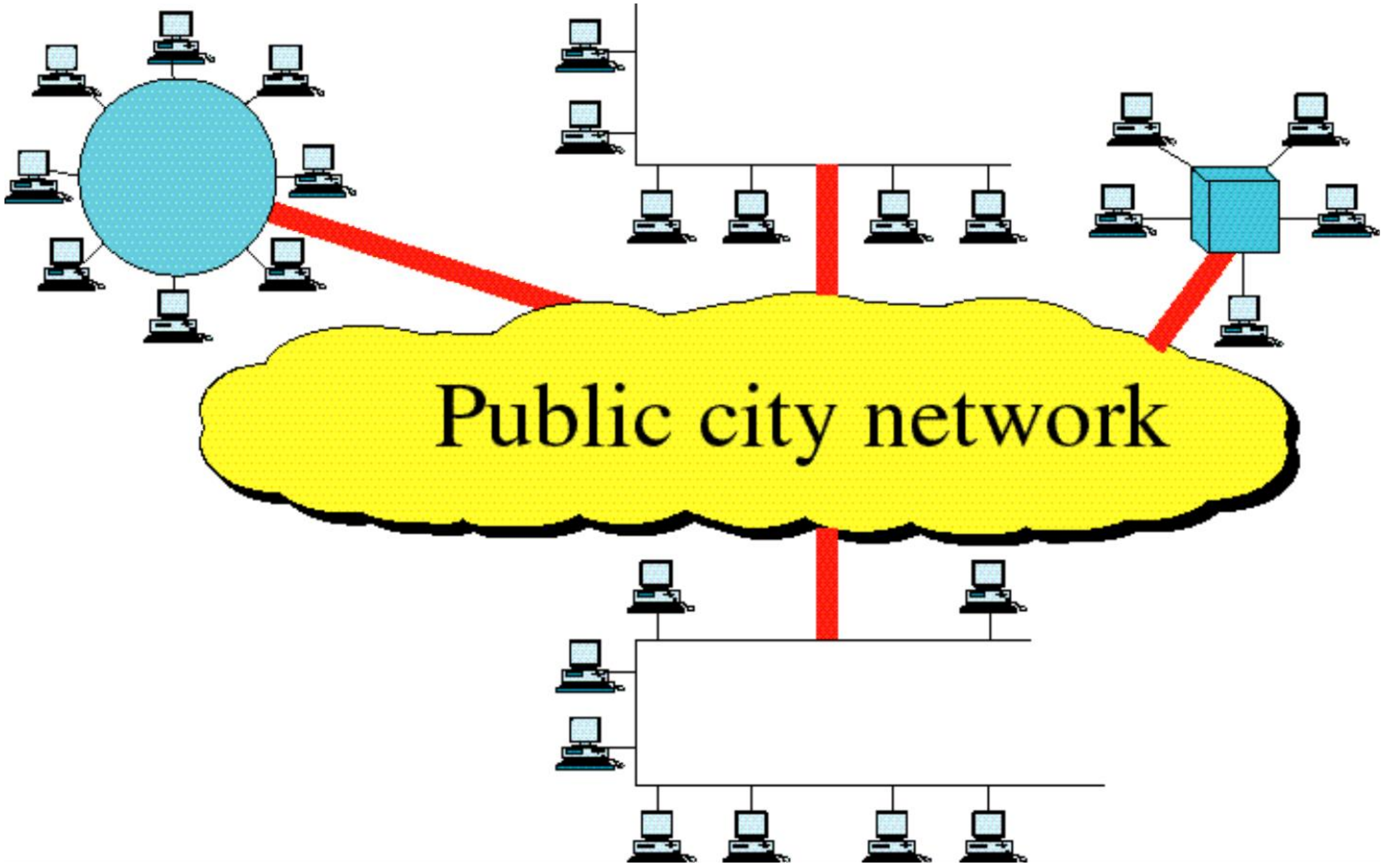


Multiple building LAN

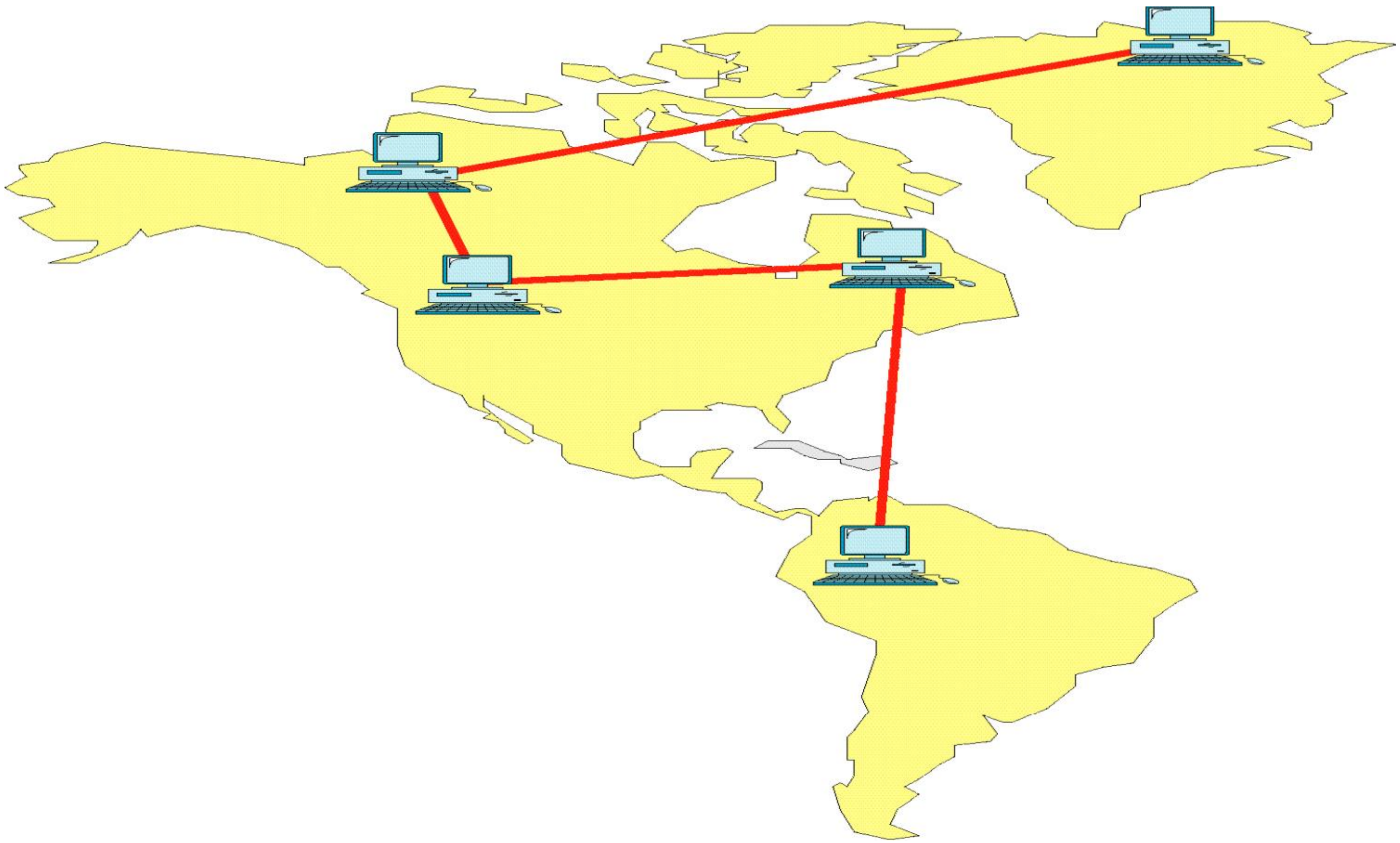
Local Area Networks (II)



Metropolitan Area Network



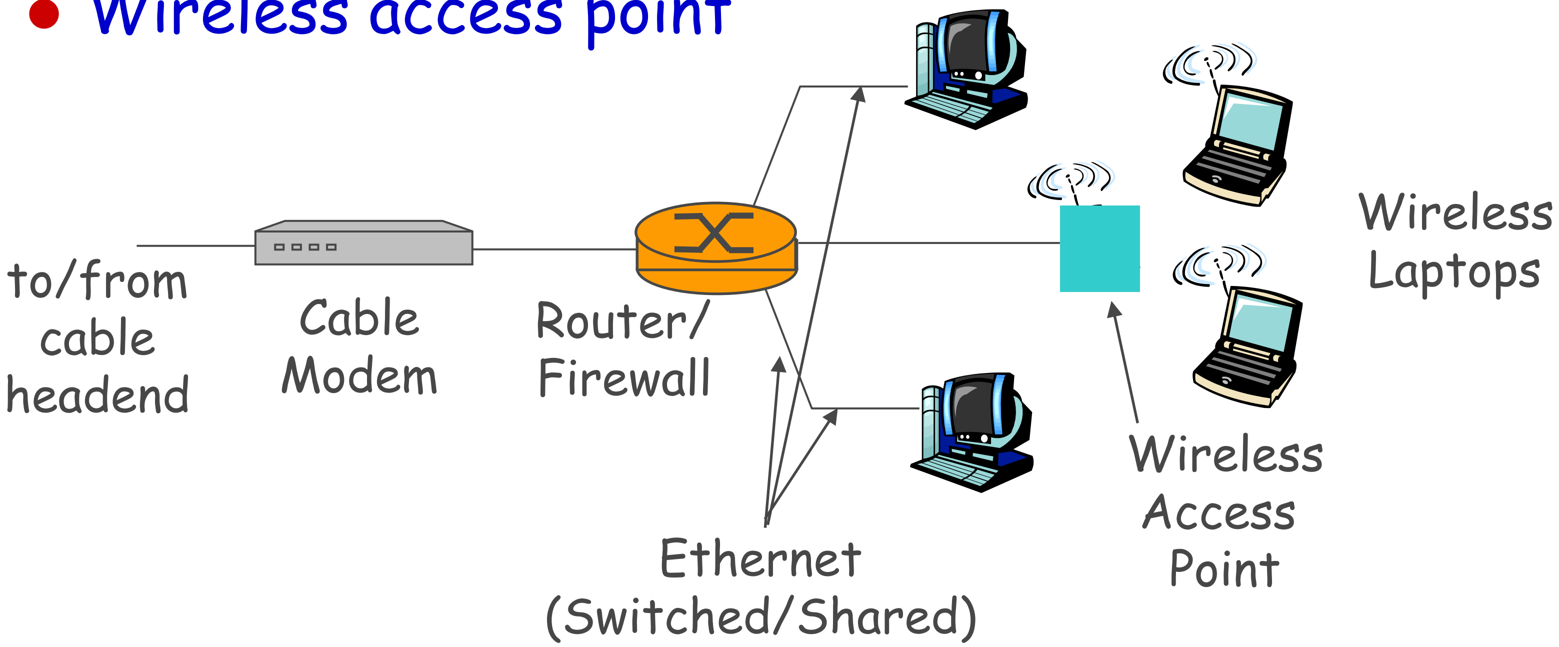
Wide Area Networks



Home Networks

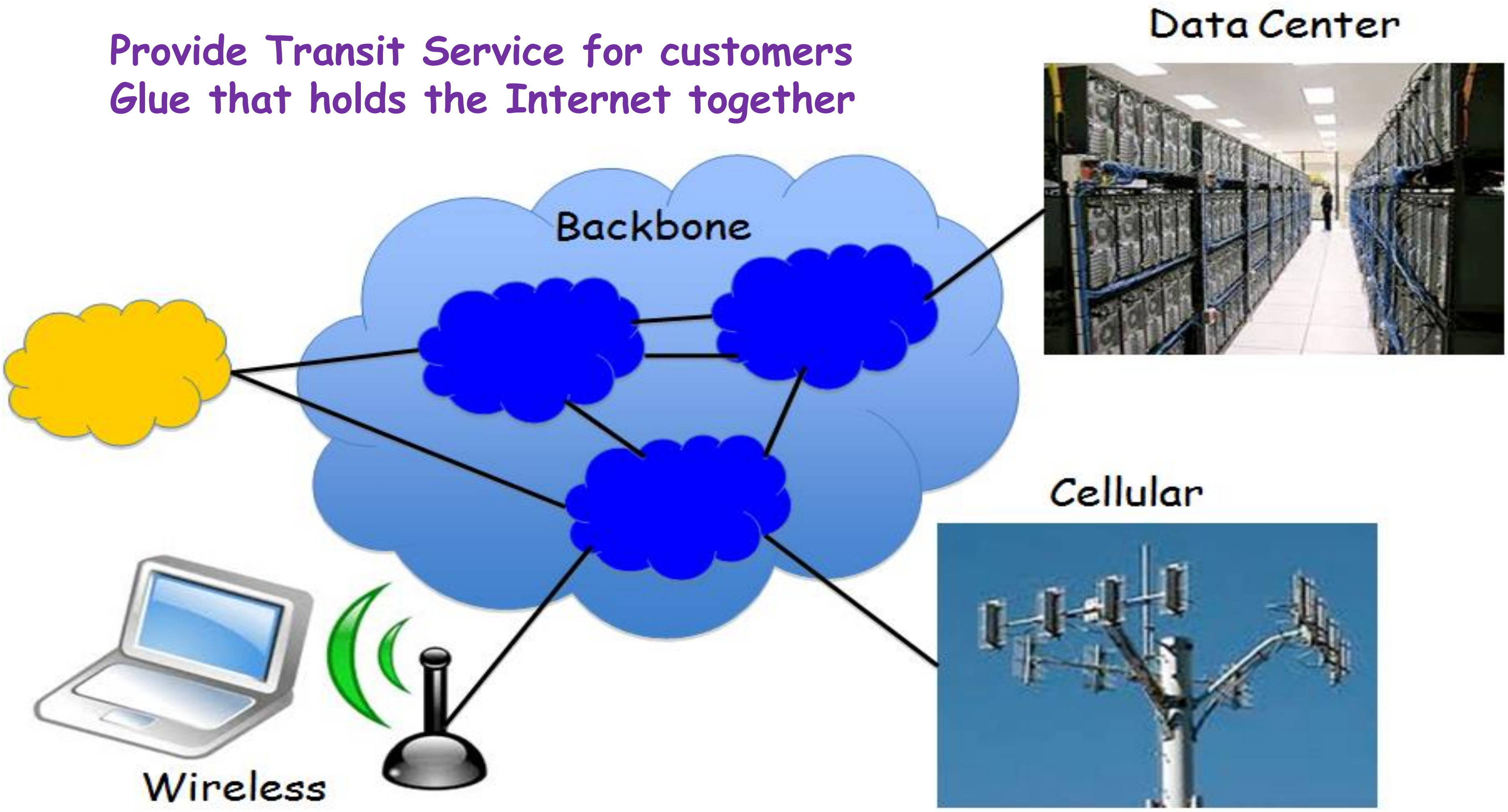
Typical home network components

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

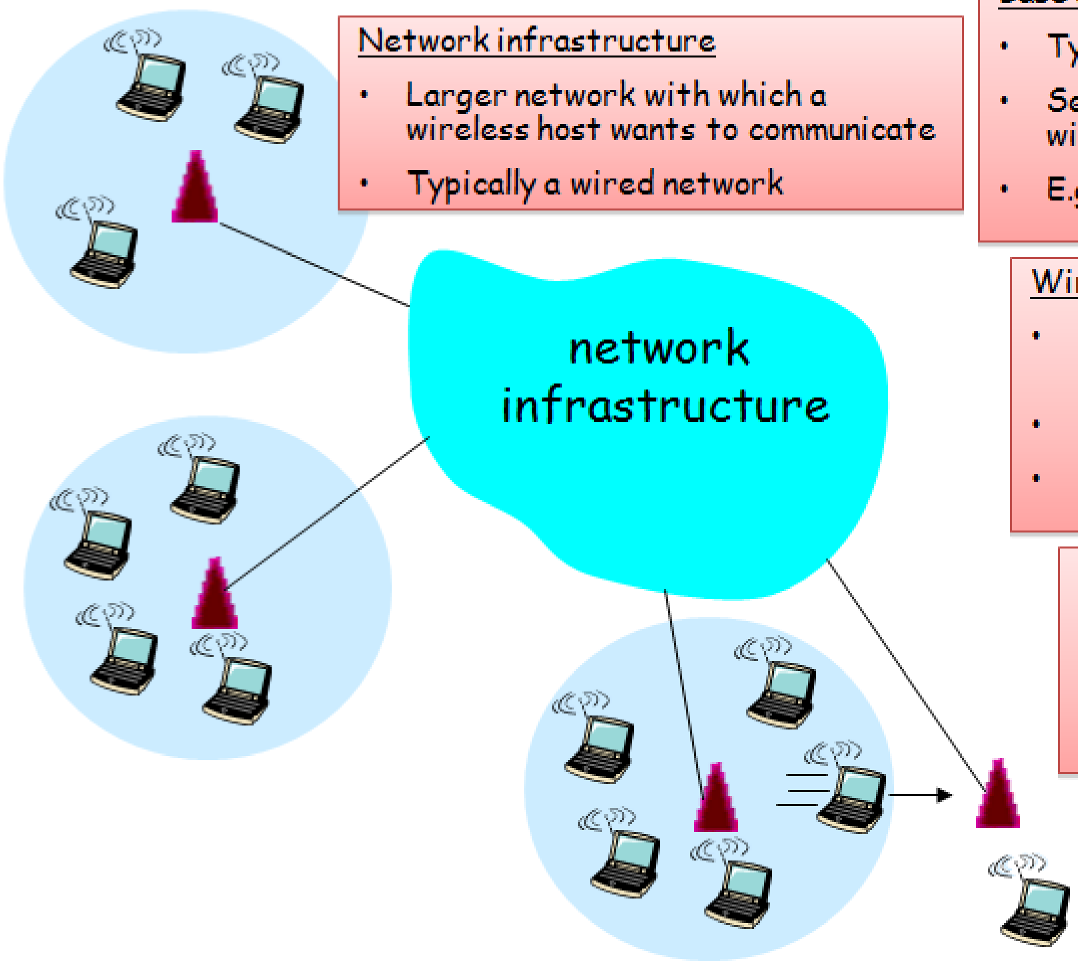


Backbone Networks

Provide Transit Service for customers
Glue that holds the Internet together



Wireless Networks



Network infrastructure

- Larger network with which a wireless host wants to communicate
- Typically a wired network

Base station

- Typically connected to wired network
- Sending packets between wired network and wireless host(s)
- E.g., cell towers, 802.11 access points

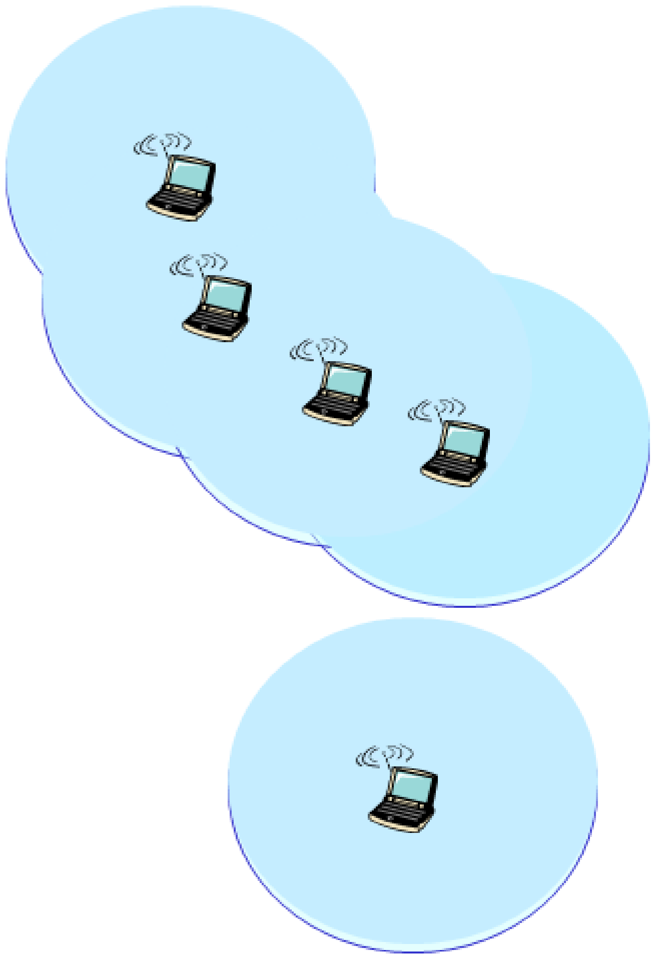
Wireless link

- Typically used to connect mobile(s) to base station
- Also used as backbone link
- Multiple access protocol coordinates link access

Wireless host

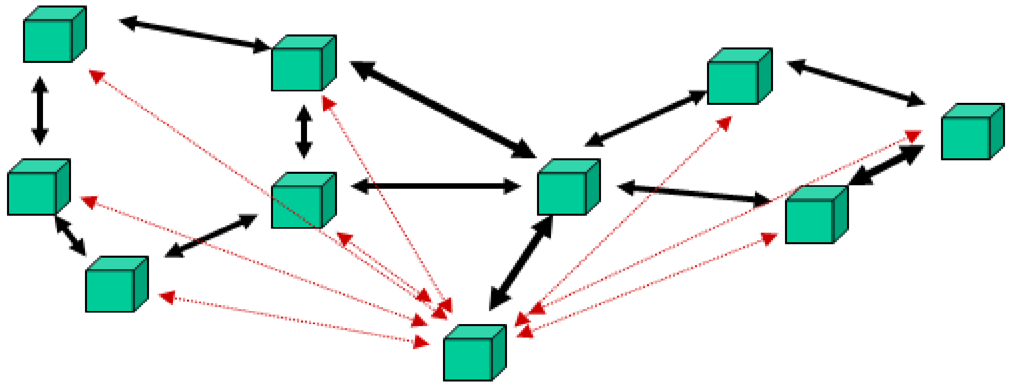
- Laptop, smartphone
- Run applications
- May be stationary or mobile

Ad-Hoc Wireless Mesh

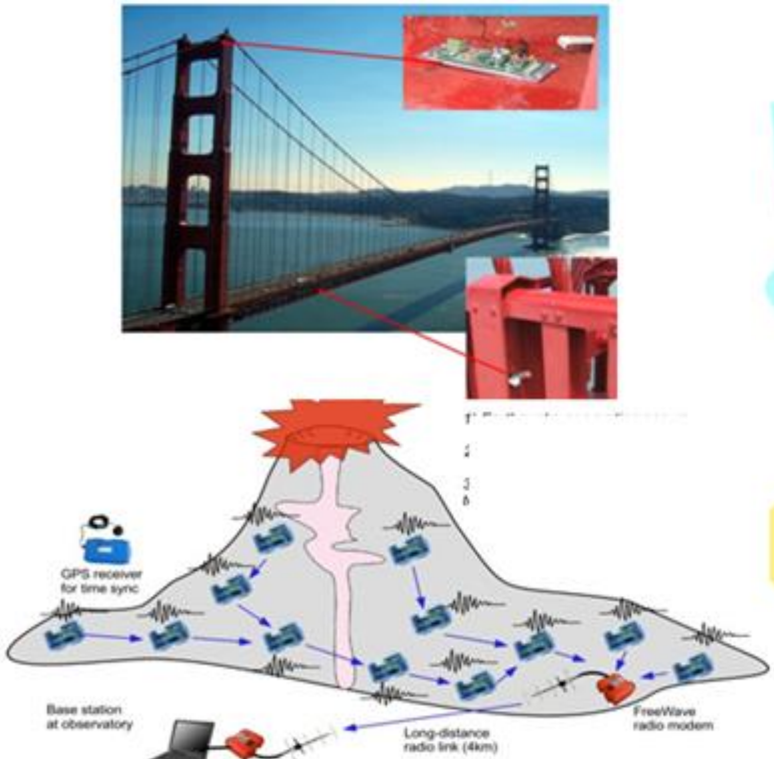


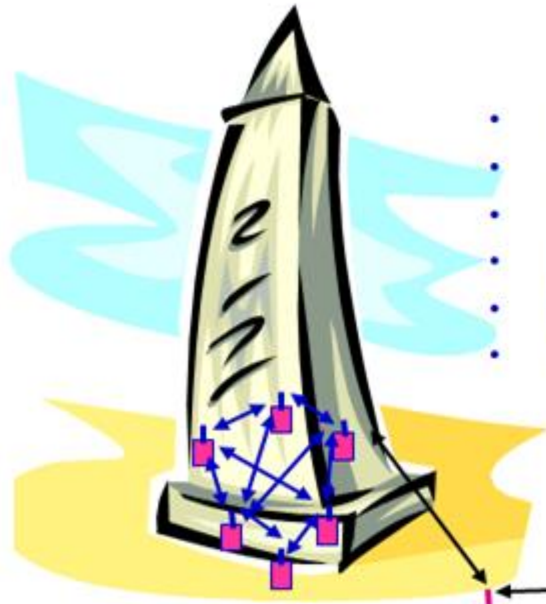
Ad hoc mode

- No base stations
- Nodes can only transmit to other nodes within link coverage
- Nodes self-organize and route among themselves
- Can create multi-hop wireless networks, instead of a wired backend

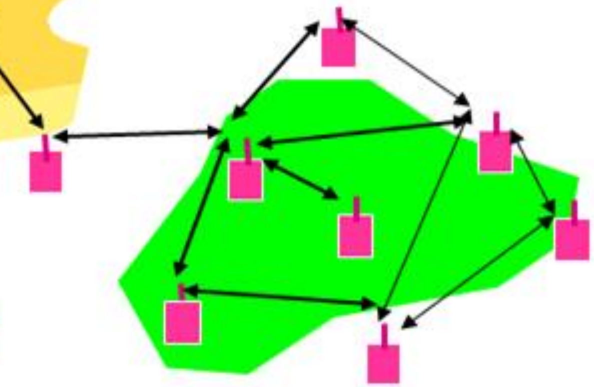


Sensor Networks



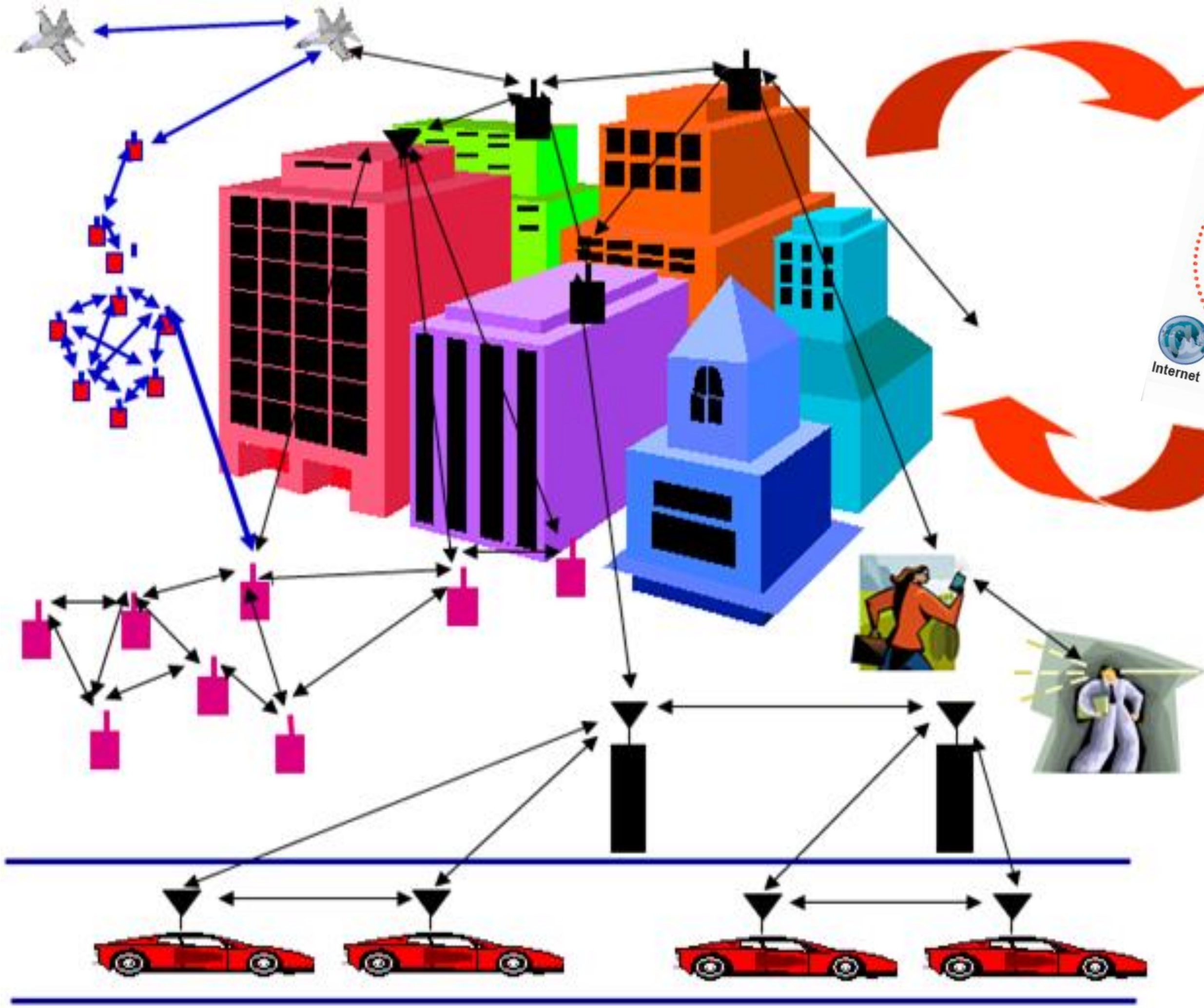


- Smart homes/buildings
- Smart structures
- Search and rescue
- Homeland security
- Event detection
- Battlefield surveillance



- Energy (transmit and processing) is driving constraint
- Data flows to centralized location
- Low per-node rates but tens to thousands of nodes
- Intelligence is in the network rather than in the device

Future Wireless Networks

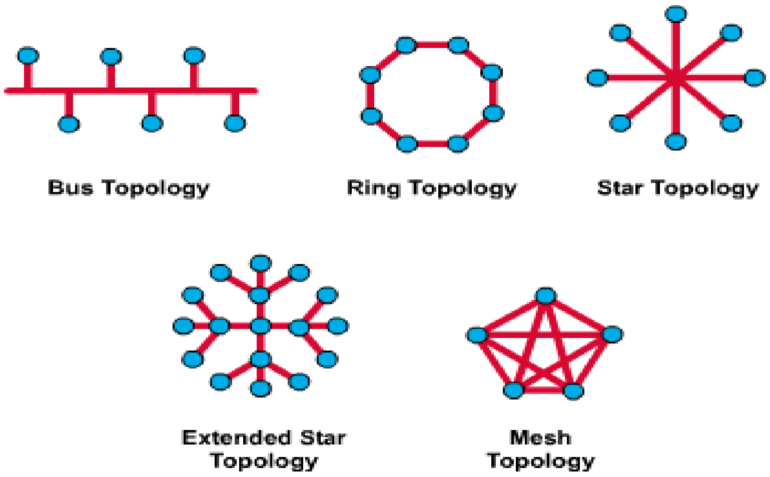


Next-generation Cellular
Wireless Internet Access
Wireless Multimedia
Sensor Networks
Smart Homes/Spaces
Automated Highways
In-Body Networks
All this and more …

Ubiquitous Communication Among People and Devices

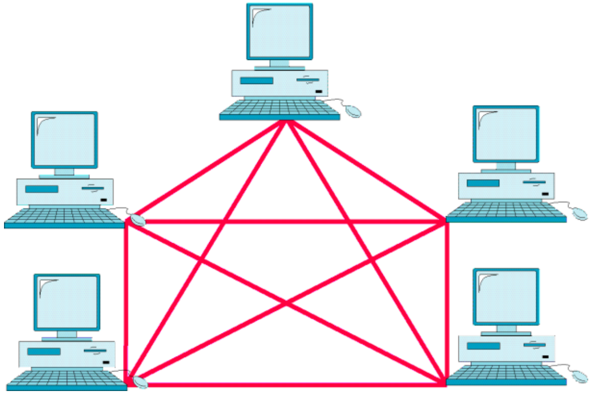
Network Topologies

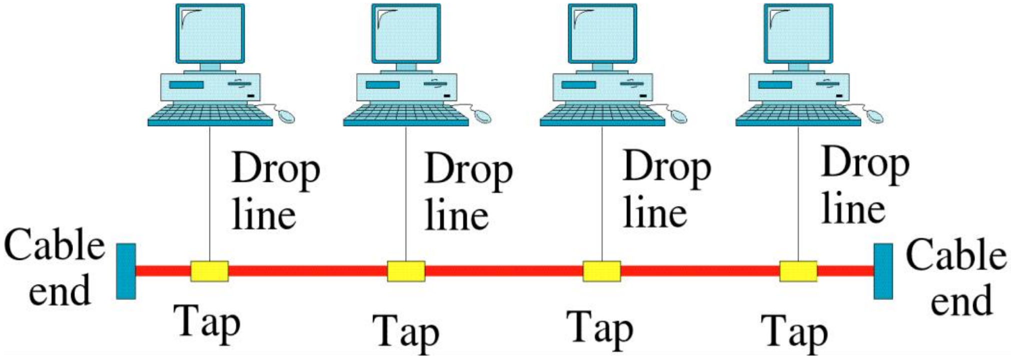
- Network topology is the physical arrangement (Layout) of the network nodes and the links interconnecting them
  - Mesh topology
  - Star/Hub topology
  - Bus topology
  - Tree Topology
  - Ring topology

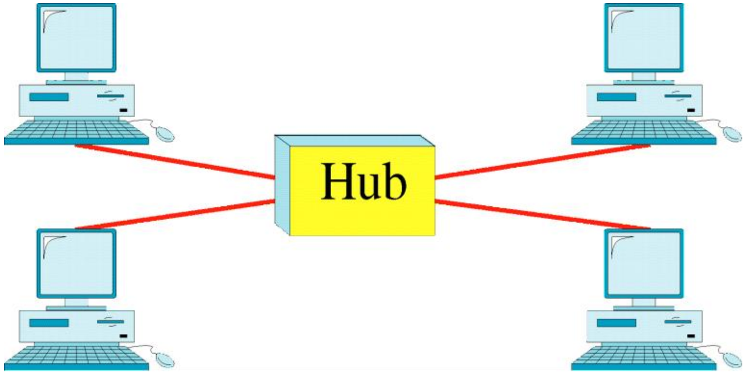


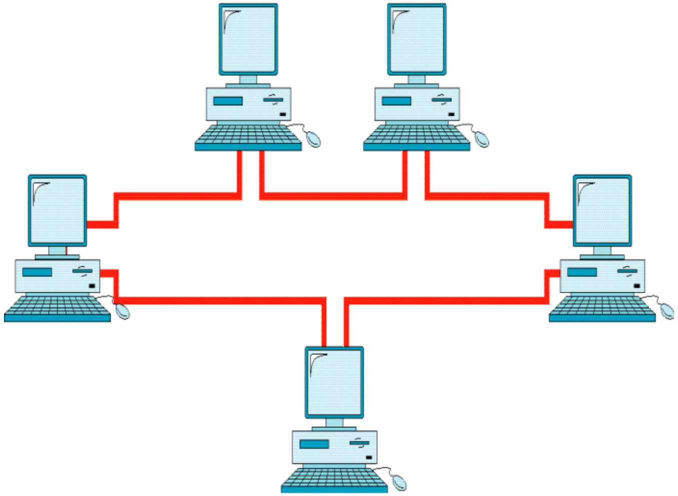
- A fully connected network is one in which every node is connected to every other node

Mesh, Hub, Bus and Rings (I)

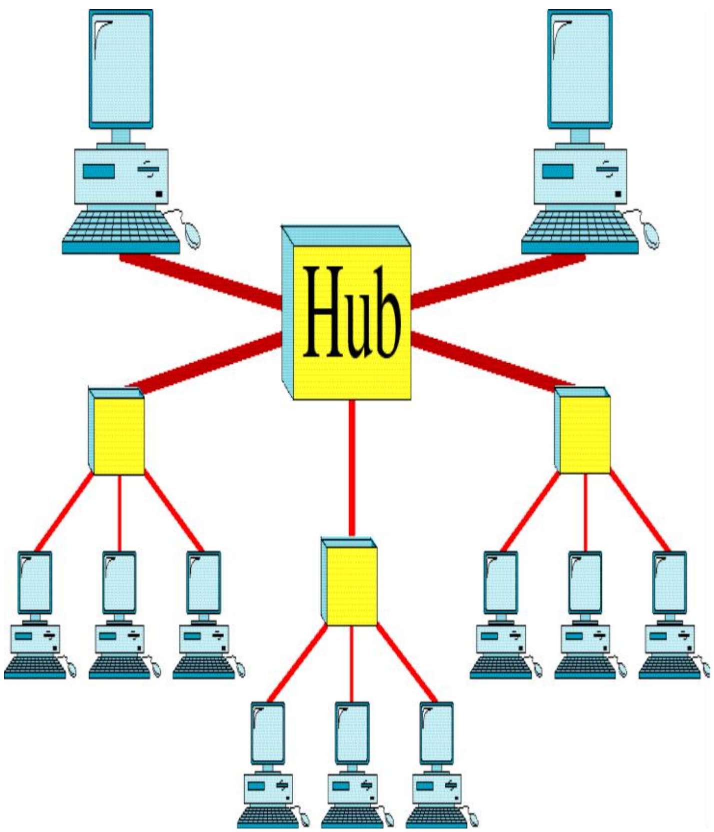


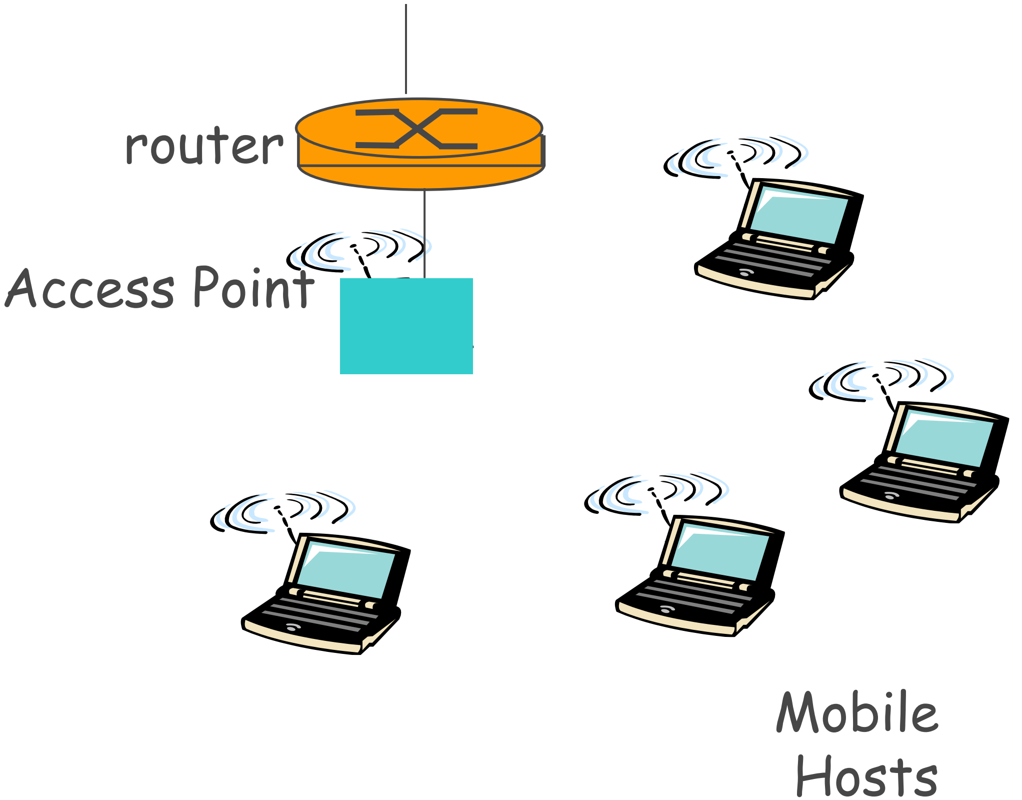




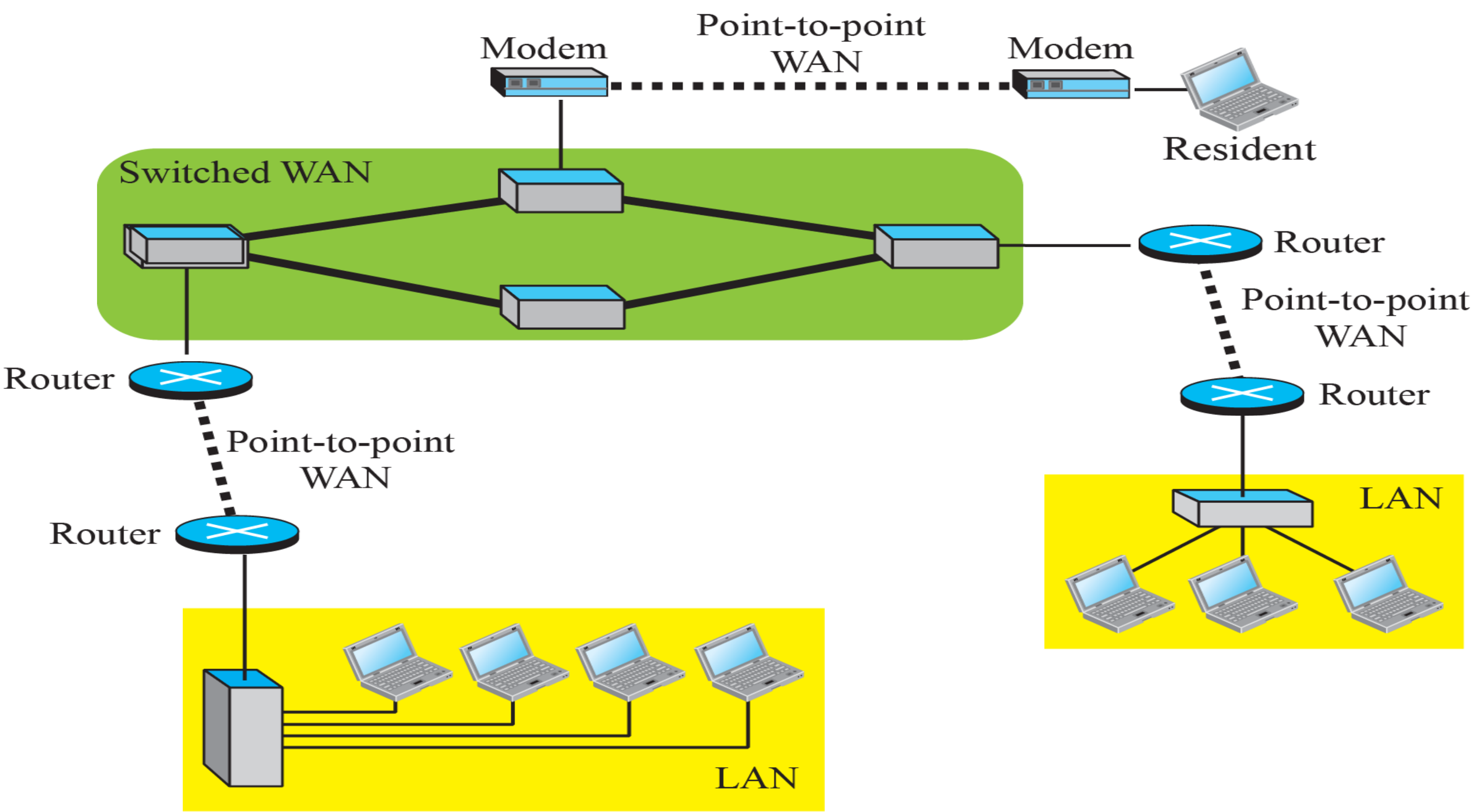


Tree and Wireless (II)





A heterogeneous Internetwork



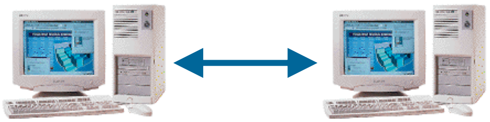
Link Topologies

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

- Multipoint
  - More than two devices share the link

Link Duplicity

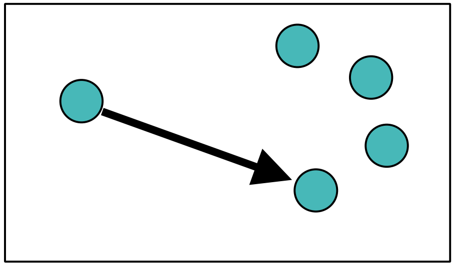
- Simplex
  
  - One direction
  - e.g. Radio/Television broadcasting
- Half duplex (HDX)
  - Either direction, but only one way at a time
  - e.g. Police radio
  

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

Transmission Modes

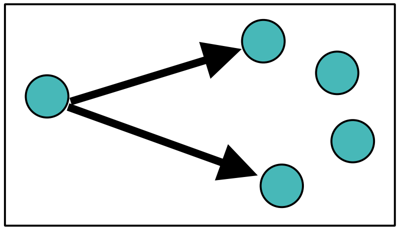
Unicast

One-to-one



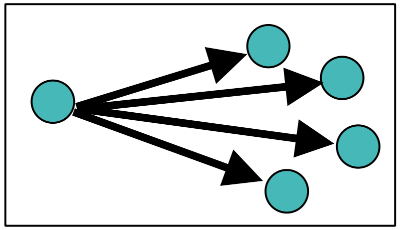
Multicast

One-to-selected group



Broadcast

One-to-all

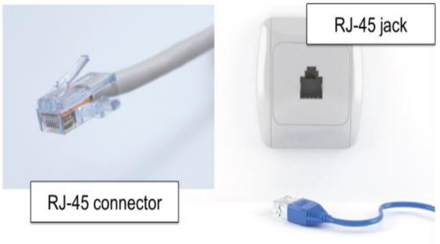


Physical Media (I): Copper

- 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)

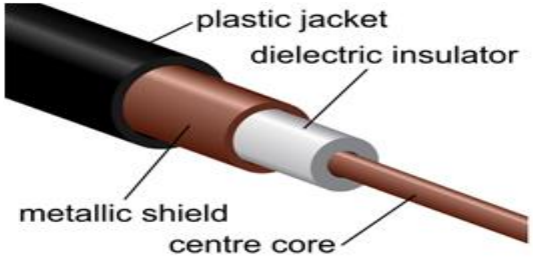
- two insulated copper wires
  - Category 3: traditional phone wires, 10 Mbps Ethernet
  - Category 5/6: 100Mbps ~ 10Gbps Ethernet



Physical Media (II): Cable

Coaxial Cable:

- Two concentric copper conductors
- Bi-directional
- Baseband:
  - single channel on cable
  - legacy Ethernet
- Broadband:
  - Multiple channels on cable. 100's Mbps/Channel
  - 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 Gbps)
- 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

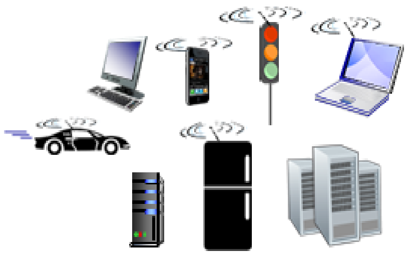
Radio link types:

- Terrestrial Microwave
  - e.g. up to 45 Mbps channels
- WLAN (e.g., Wi-Fi)
  - 2Mbps, 11Mbps, 54 Mbps, 450 Mbps
- Wide-area (e.g., cellular)
  - e.g. 4G: ~10's Mbps
- Satellite
  - ~ 45Mbps channel (or multiple smaller channels)
  - 270 msec end-end delay
  - GEO/LEO

The Internet (Wikipedia)

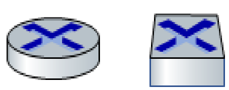
The Internet is the worldwide, publicly accessible network of interconnected computer networks that transmit data by packet switching using the standard Internet Protocol (IP). It is a "network of networks" that consists of millions of smaller domestic, academic, business, and government networks, which together carry various information and services, such as electronic mail, online chat, file transfer, and the interlinked Web pages and other documents of the World Wide Web.

What is the Internet? Nuts and Bolts View



Billions of connected computing *devices*:

- *hosts = end systems*
- running *network apps* at Internet's "edge"



Packet switches: forward packets (chunks of data)

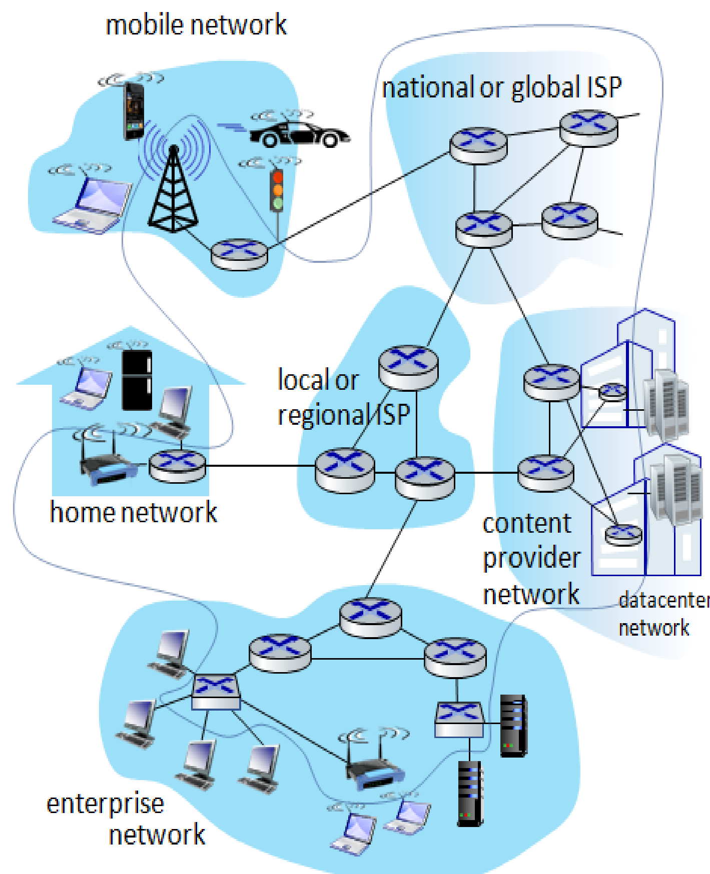
- *routers, switches*

Communication links

- fiber, copper, radio, satellite
- transmission rate: *bandwidth*

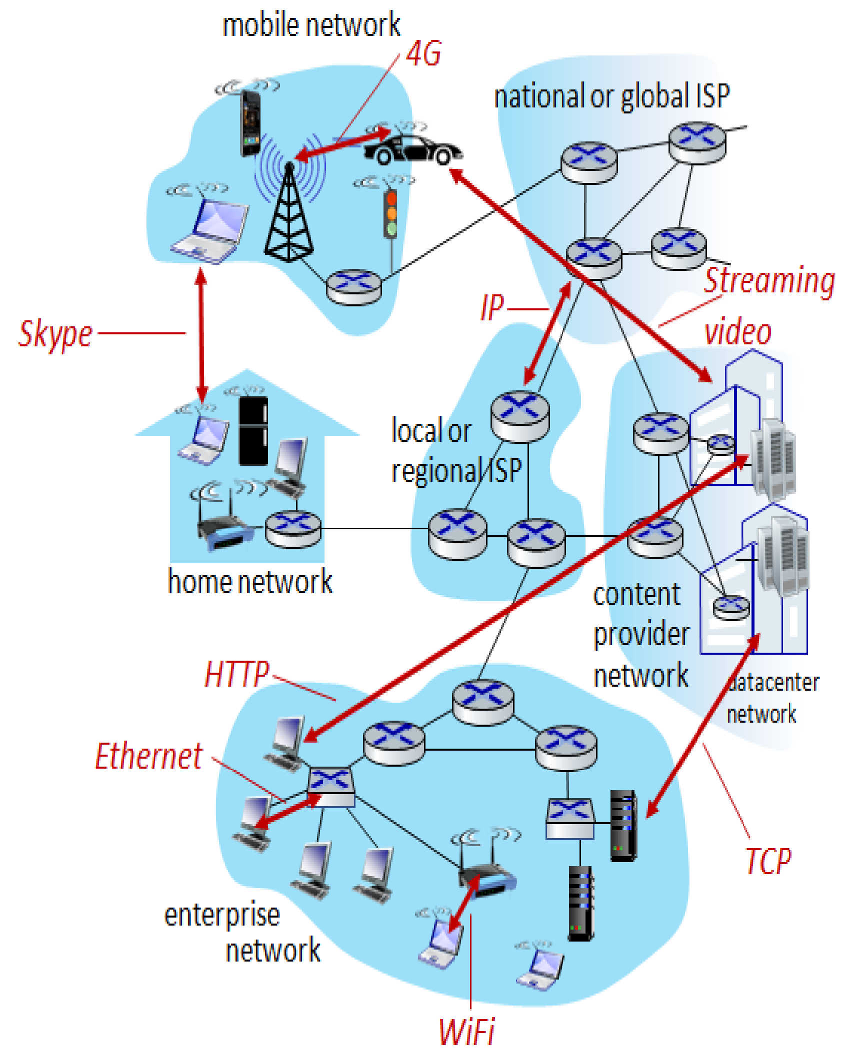
Networks

- collection of devices, routers, links: managed by an organization



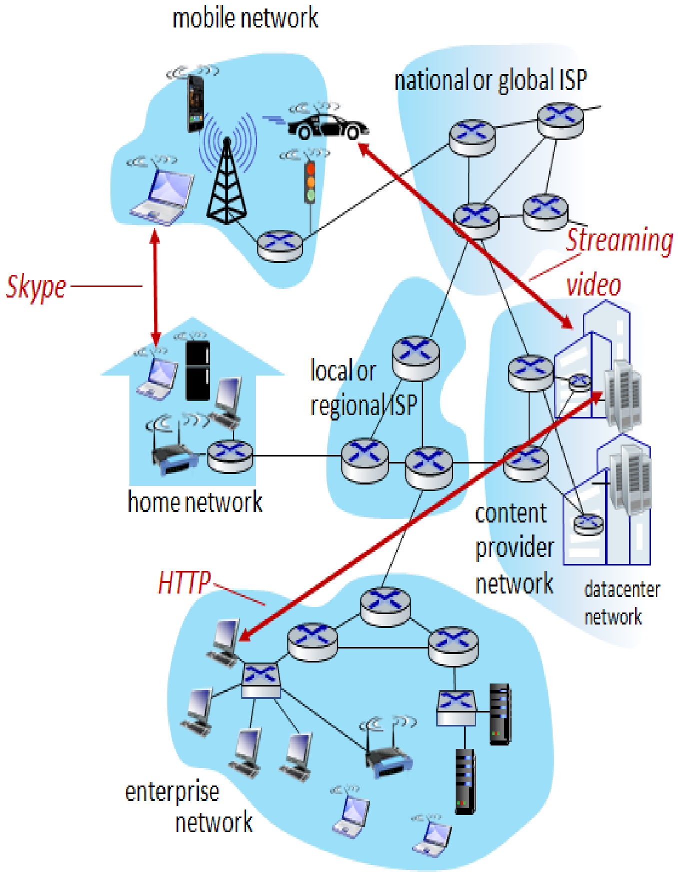
What is the Internet? Nuts and Bolts View (Cont.)

- *Internet: "network of networks"*
  - Interconnected ISPs
- *protocols* are *everywhere*
  - control sending, receiving of messages
  - e.g., HTTP (Web), streaming video, Skype, TCP, IP, WiFi, 4G, Ethernet
- *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 streaming video, multimedia teleconferencing, games, social media, inter-connected appliances, …
- Communication services provided to applications include
  - Reliable data delivery from source to destination
  - "Best effort" (unreliable) data delivery
  - Similar to Postal Services



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:

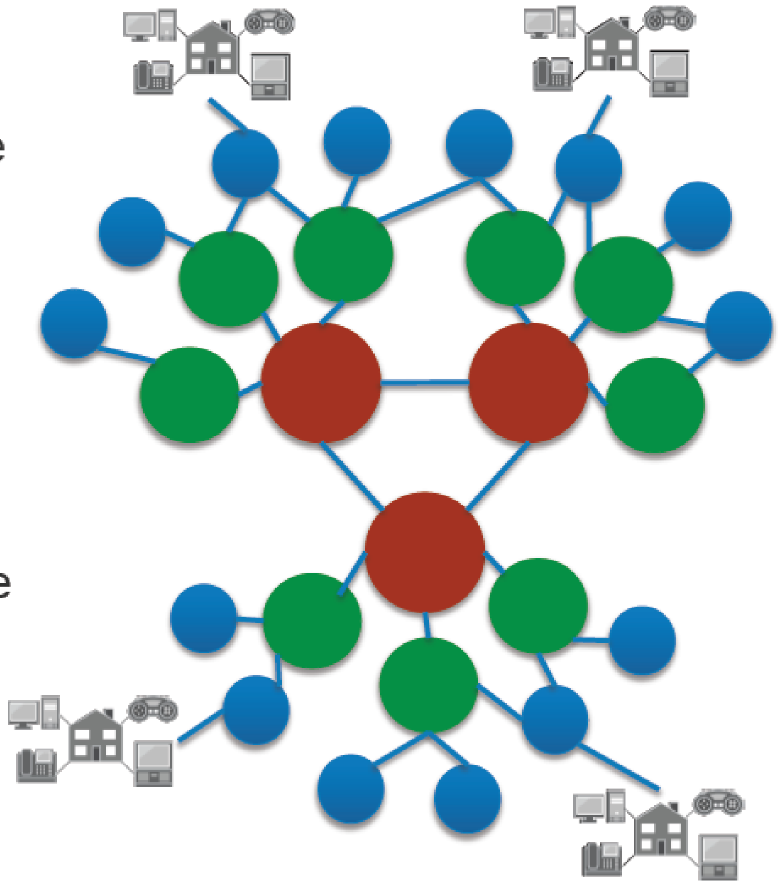
- HTTP (Web), FTP (file transfer), Telnet (remote login), SMTP (email)

App's using UDP:

- streaming media, teleconferencing, DNS, Internet telephony

Networks Structure

- **Edge** – the boundary between the service-provider's premises and the customer's location. The concentration point where large numbers of customer connections will be terminated
- **Aggregation** – A concentration point where data from multiple Edge locations will be funneled
- **Core** - the heart of the network. The major switching locations that form the center of the network, where data from multiple Aggregation sites will be funnelled
  - This is typically where one sees the highest volume of data present in the network

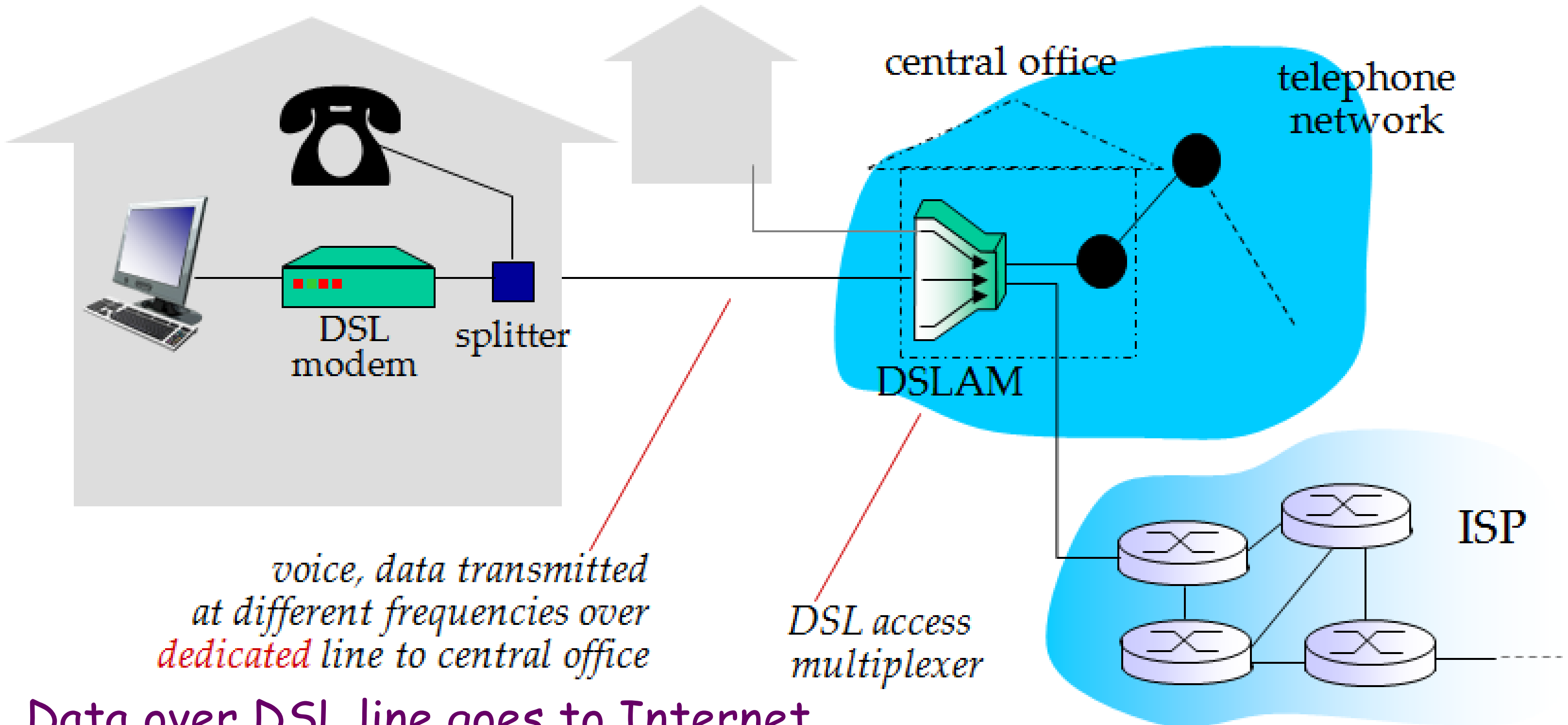


Access Networks

Q: How to connect end systems to edge router?

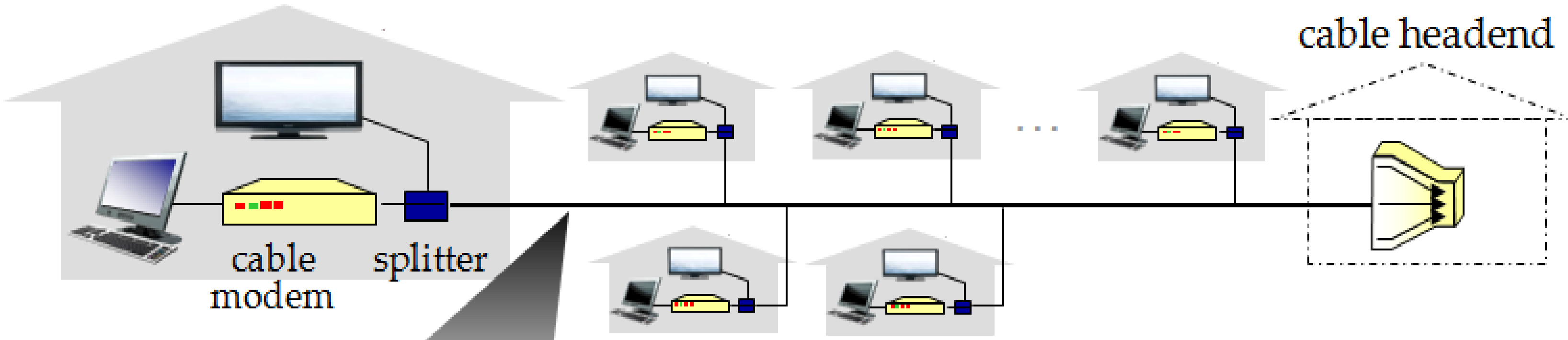
- Residential Access Networks
- Institutional access networks (school, company)
- Mobile access networks (WiFi, 4G/5G, etc..)
- What to look for?
  - Bandwidth (bits per second) of access network?
  - Shared or dedicated access?

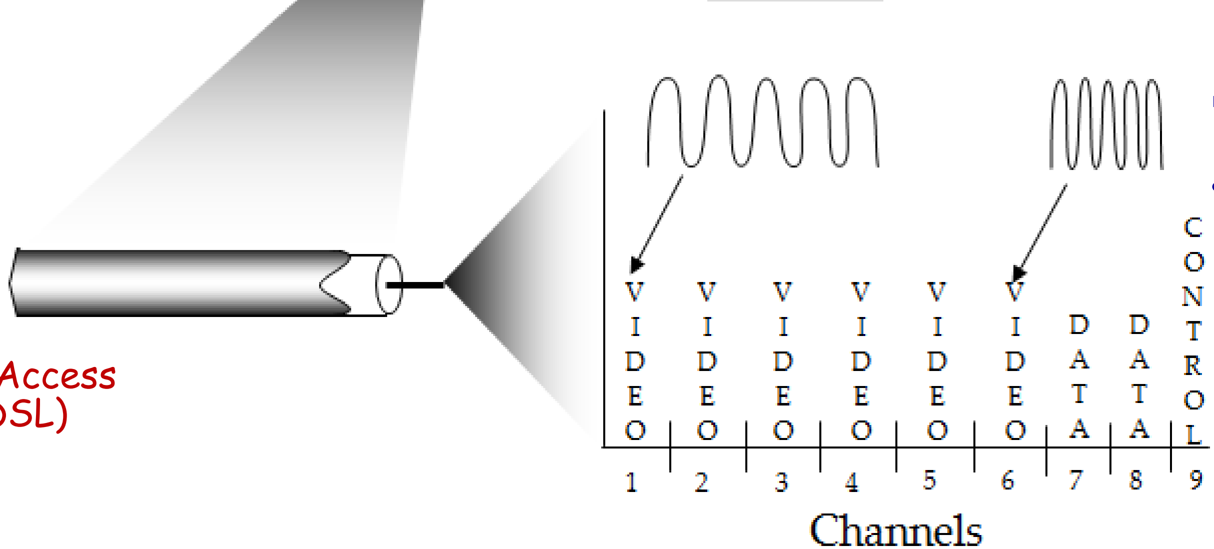
Internet Access: DSL



- Data over DSL line goes to Internet
- Voice over DSL line goes to telephone net
    - up to 15~20 Mbps upstream
    - up to 50 Mbps downstream
    - dedicated physical line to telephone central office

Internet Access: Residential Cable



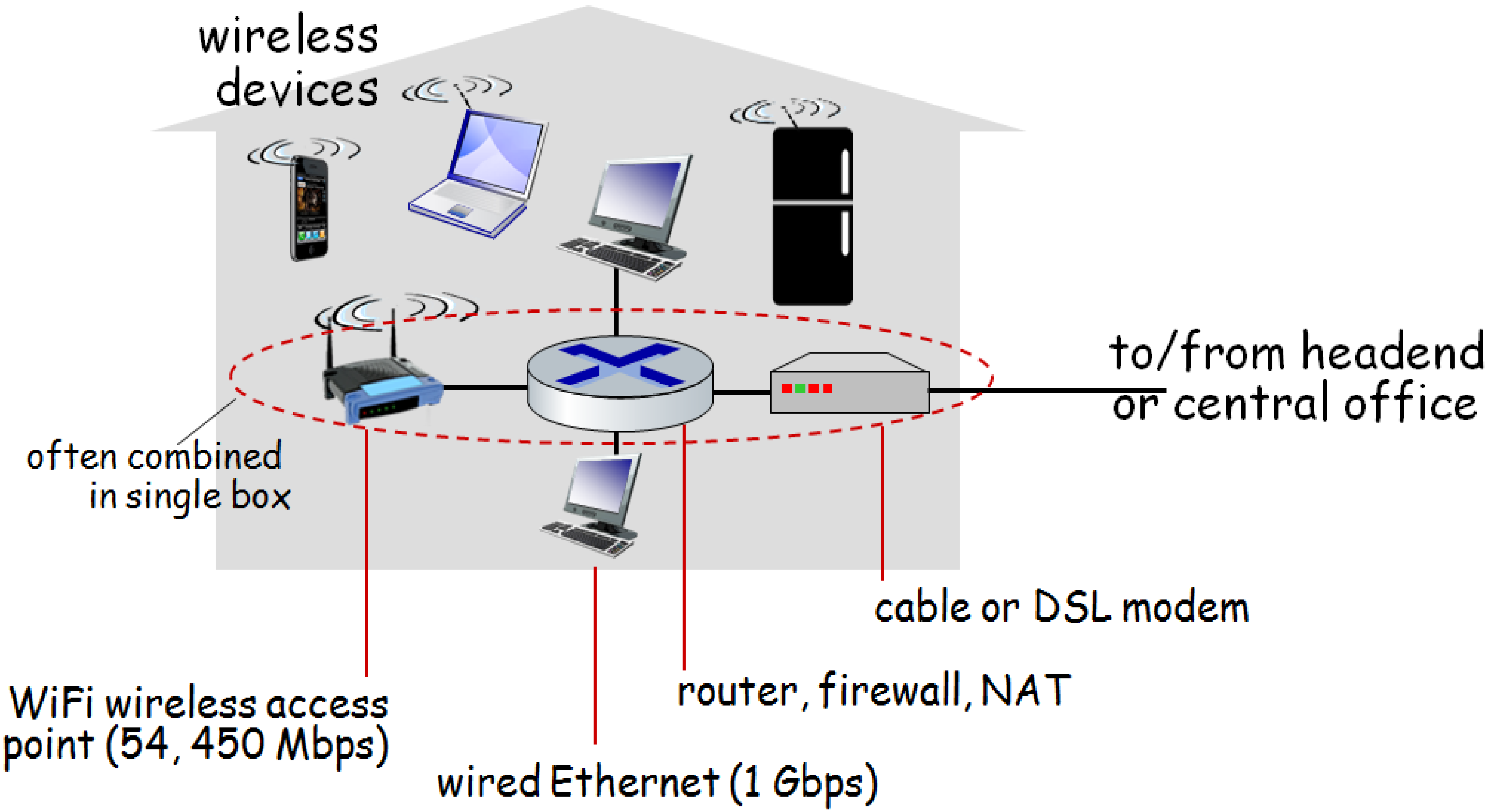


- HFC: hybrid fiber coax
- asymmetric: 40Mbps to 1Gbps downstream transmission rate, 30~100 Mbps upstream transmission rate

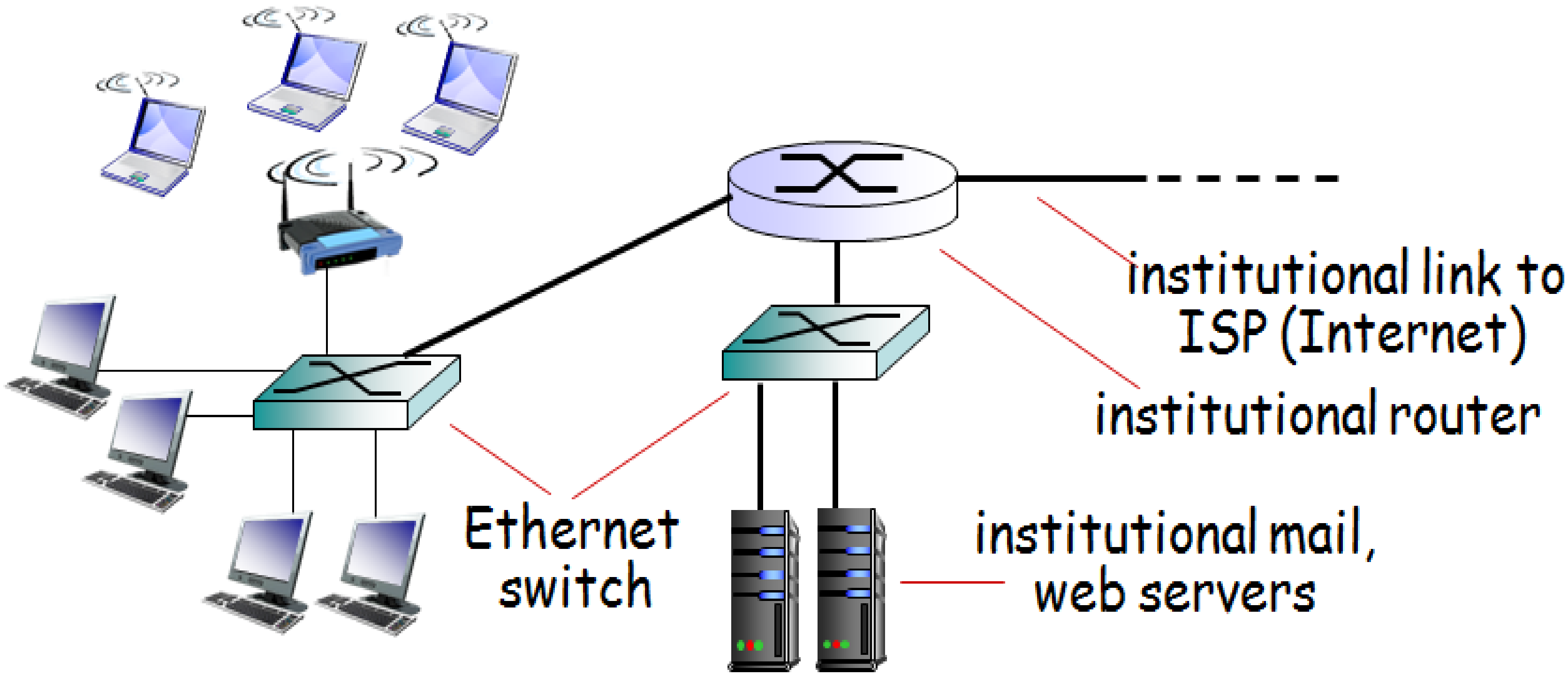
- Shared Access (unlike DSL)

Frequency Division Multiplexing: different channels transmitted in different frequency bands

Internet Access: Home Network



Internet Access: Enterprise Network



- typically used in companies, universities, etc
  - 100Mbps, 1Gbps, 10Gbps transmission rates
  - Wireless (54Mbps, 450Mbps)
  - today, end systems typically connect into Ethernet switch

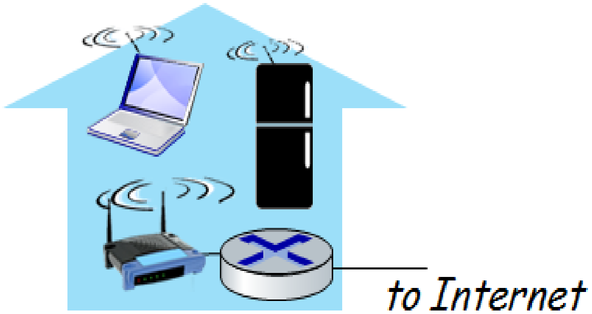
Internet Access: Wireless

Shared *wireless* access network connects end system to router

- via base station aka "access point"

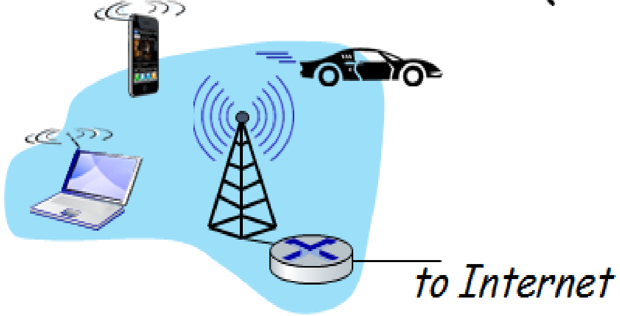
Wireless local area networks (WLANs)

- typically within or around building (~100 ft)
- 802.11b/g/n (WiFi): 11, 54, 450 Mbps transmission rate



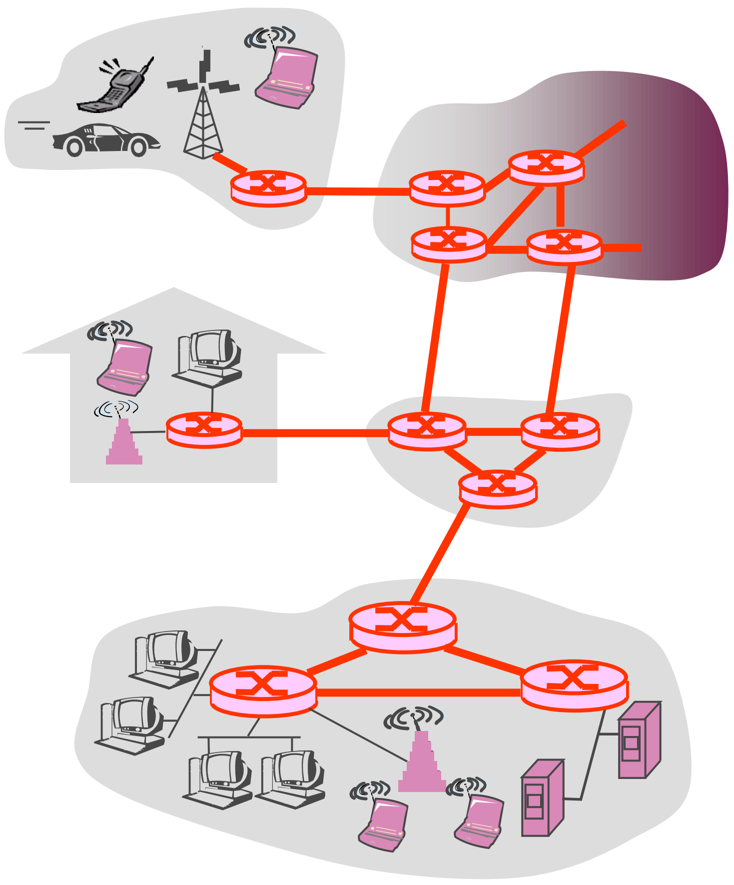
Wide-area cellular access networks

- provided by mobile, cellular network operator (10's km)
- 10's Mbps
- 4G cellular networks (5G coming)



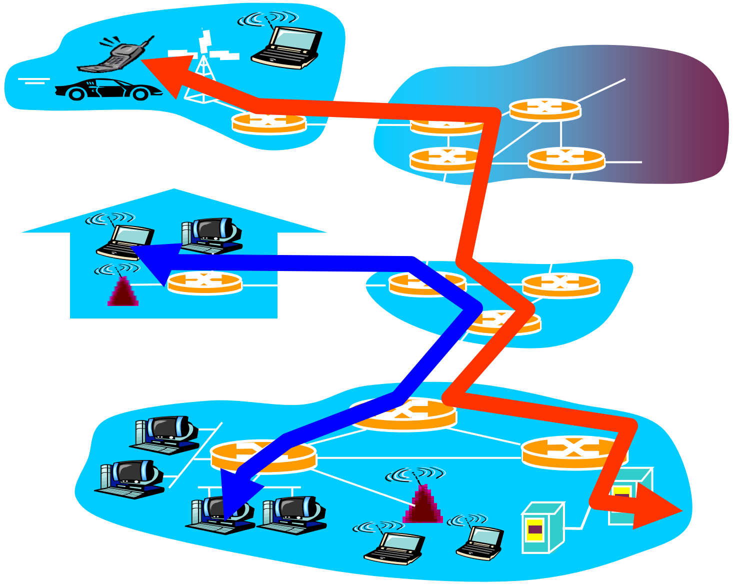
The Core Network

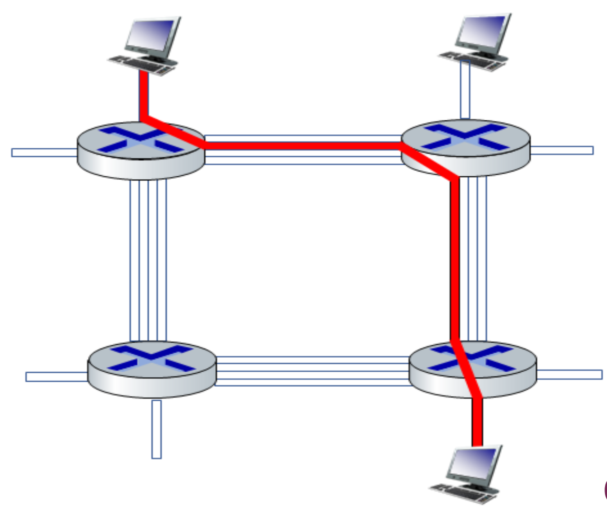
- Mesh of interconnected routers
- The fundamental question: how is data transferred through net?
  - Circuit Switching: dedicated circuit per call: telephone network (PSTN)
  - Packet Switching: data sent thru net in discrete “chunks”. Packets are forwarded from Router to Router (Internet)



Network Core: Circuit Switching

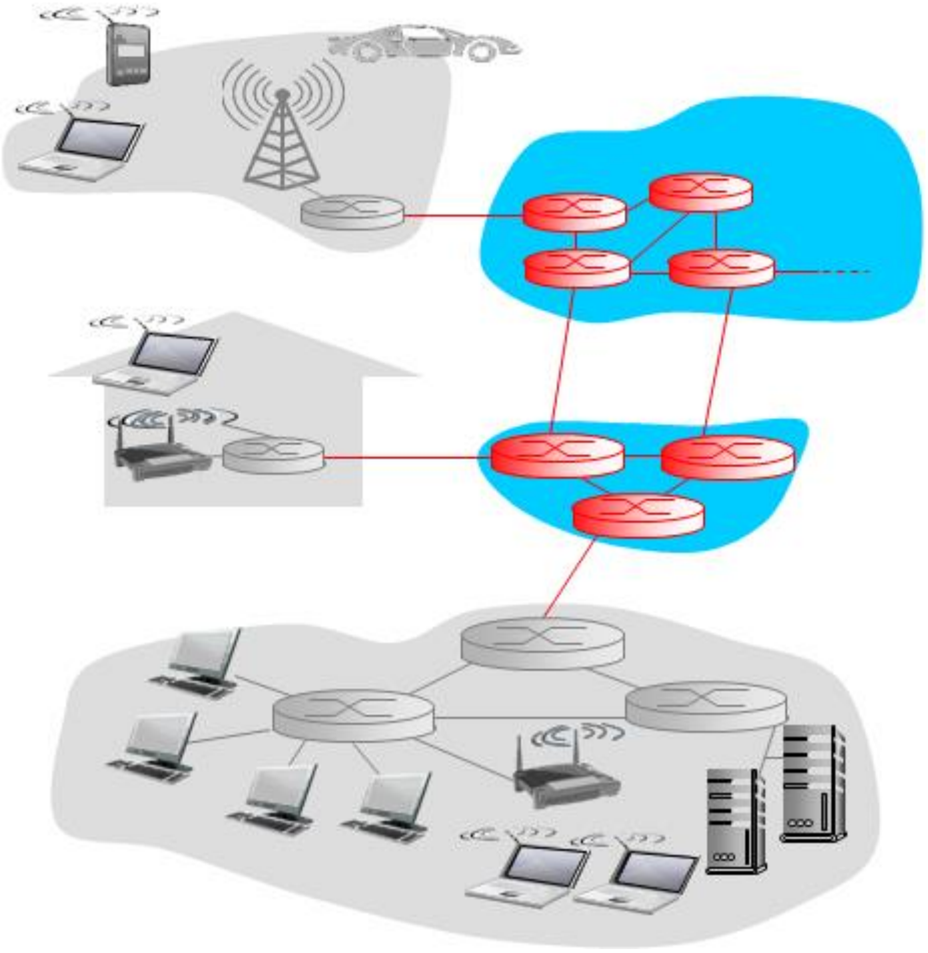
- End-end resources reserved for duration of call (used in PSTN)
- link bandwidth, switch capacity
- dedicated resources: no sharing (predictable)
- circuit-like (guaranteed) performance (High QoS)
- call setup required
- re-establish call upon failure
- in diagram, each link has four circuits. Call gets 2^{nd} circuit in top link and 1^{st} circuit in right link.



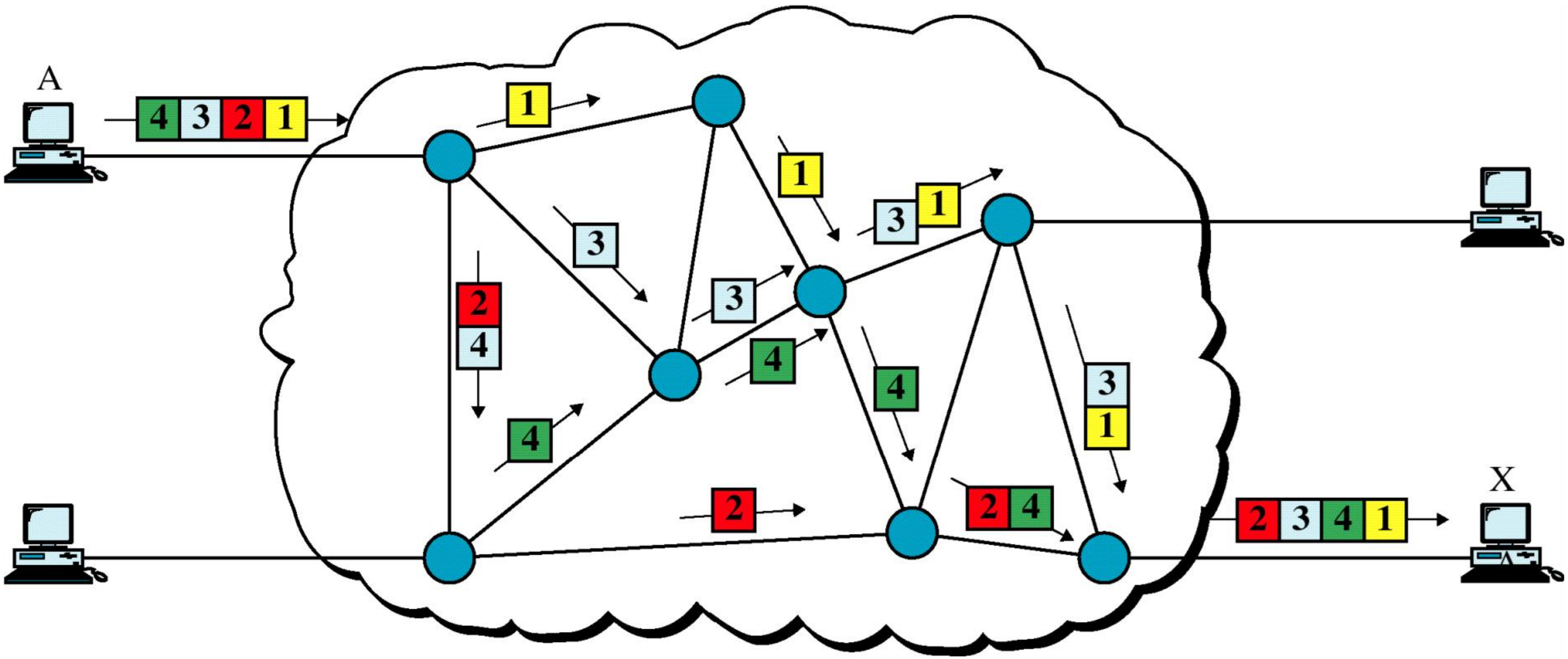


Network Core: Packet Switching

- Mesh of interconnected routers
- Packet-switching: hosts break application-layer messages into Packets
  - forward packets from one router to the next, across links on path from source to destination
  - each packet transmitted at full link capacity



Connection-Less Packet Switching



There is NO guarantee that Packets will be received in order or even received at all)

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"~~

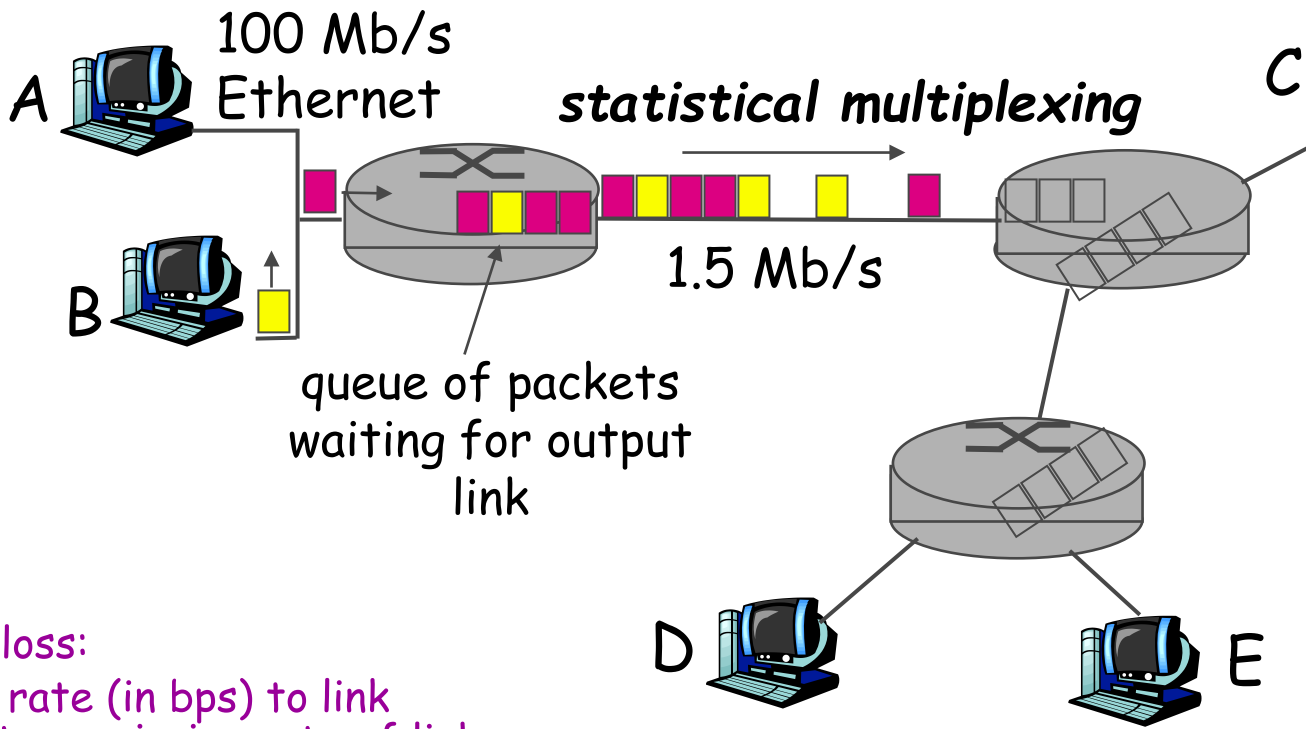
~~Dedicated allocation~~

~~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)

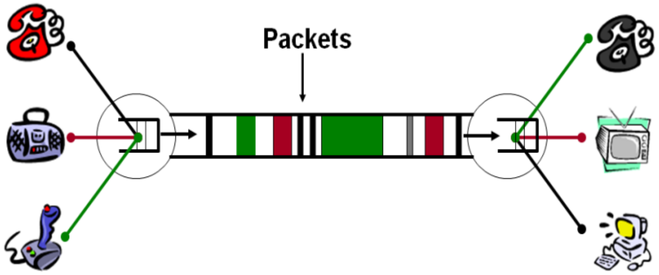


queuing and loss:

- if arrival rate (in bps) to link exceeds transmission rate of link for a period of time:
  - packets will queue, wait to be transmitted on link
  - packets can be dropped (lost) if memory (buffer) fills up

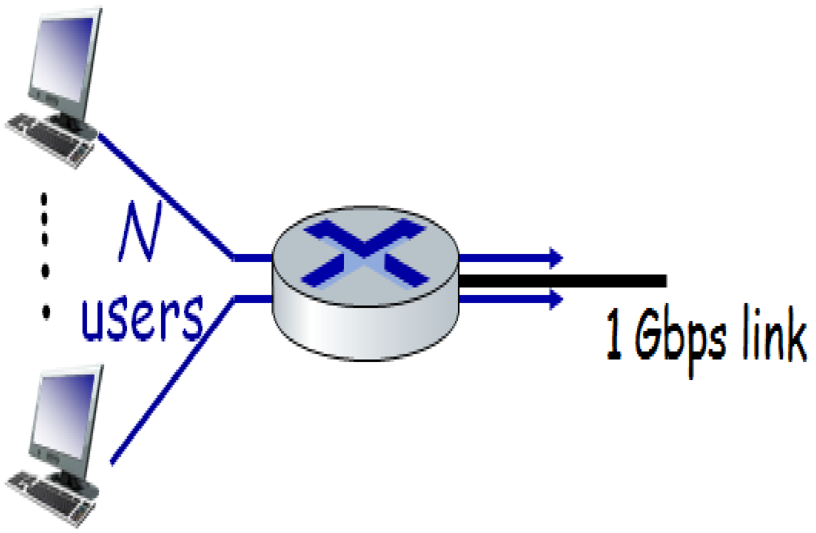
Packet vs. Circuit Switching

- 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
  - Require a per-packet overhead (with source and destination Addresses, etc..)
  - Harder to build applications that require high QoS (No guaranteed Bandwidth!!)



Packet vs. Circuit Switching (Cont.)

- 1 Gbps link
- each user:
  - 100 Mbps when "active"
  - active 10% of time



- *circuit-switching:*
  - 10 users
- *packet switching:*
  - with 35 users, probability > 10 active at same time is less than .0004

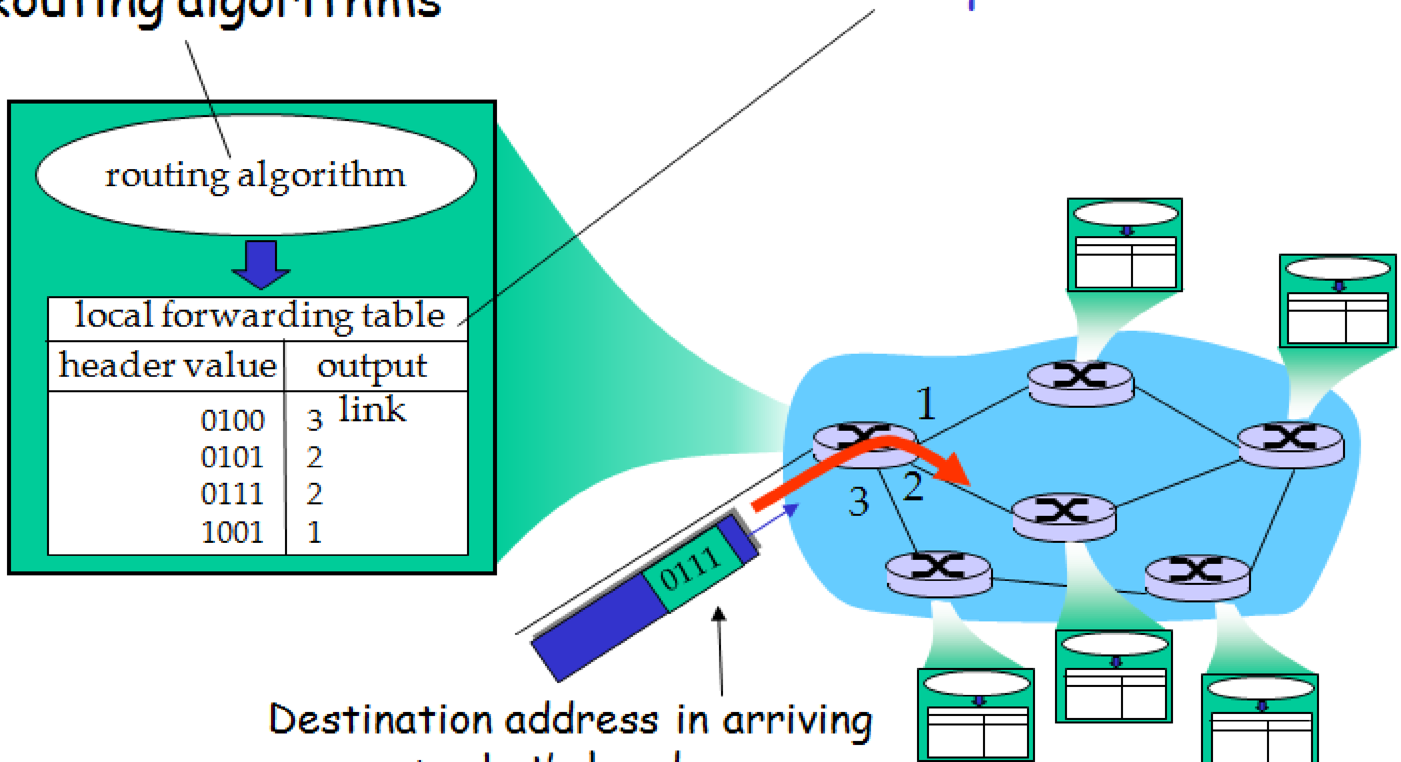
Packet switching allows more users to use network!

Q: how did we get value 0.0004?
Use binomial distribution ...

Functions of the Core Network

Routing: determines source-destination route taken by packets
- Routing algorithms

Forwarding: Moving packets from router's input to appropriate router output



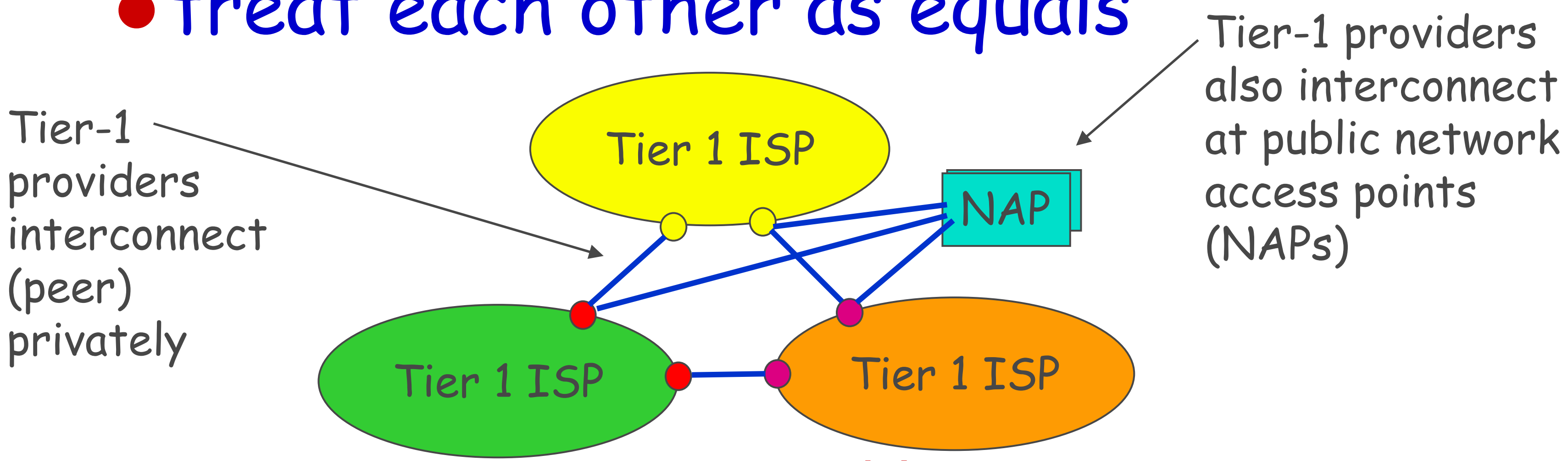
Destination address in arriving packet's header

Internet Structure: a Network of Networks

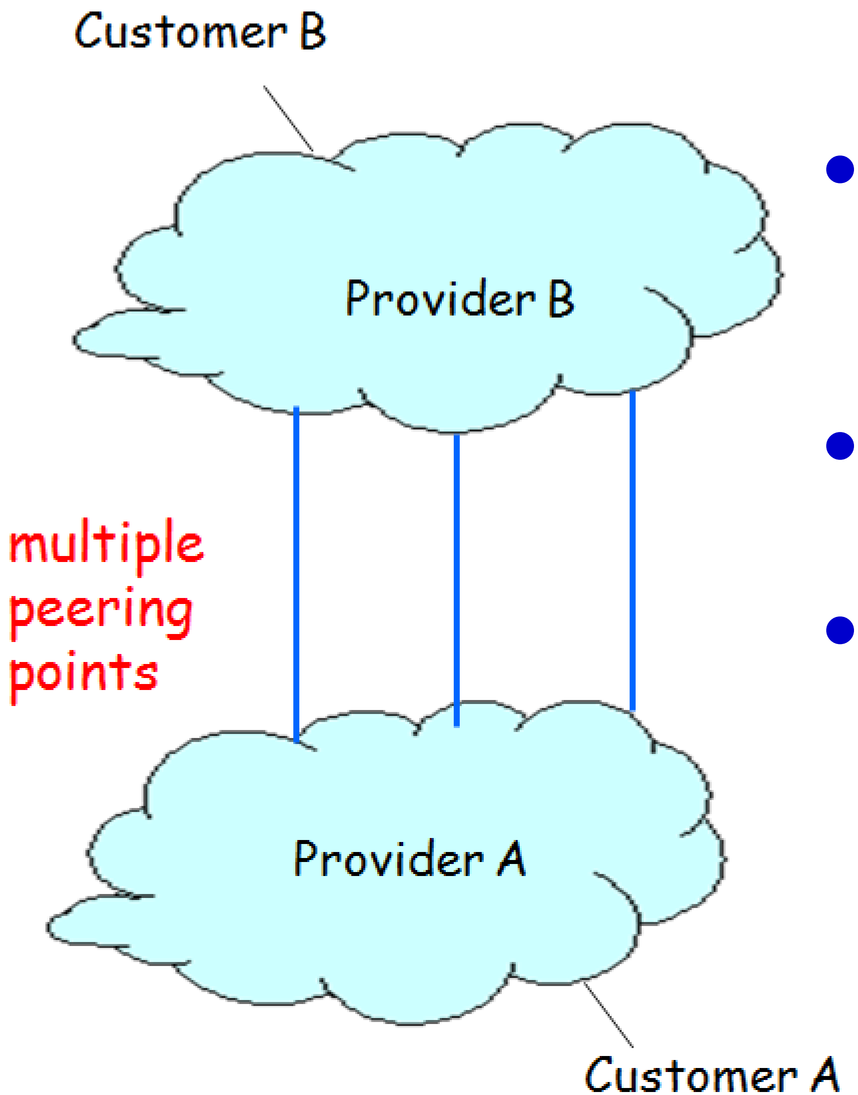
- Hosts connect to Internet via access Internet Service Providers (ISPs)
  - residential, enterprise (company, university, commercial) ISPs
- Access ISPs in turn must be interconnected
  - so that any two hosts can send packets to each other
- Resulting network of networks is very complex
  - evolution was driven by economics and national policies
- Let's take a stepwise approach to describe current Internet structure

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

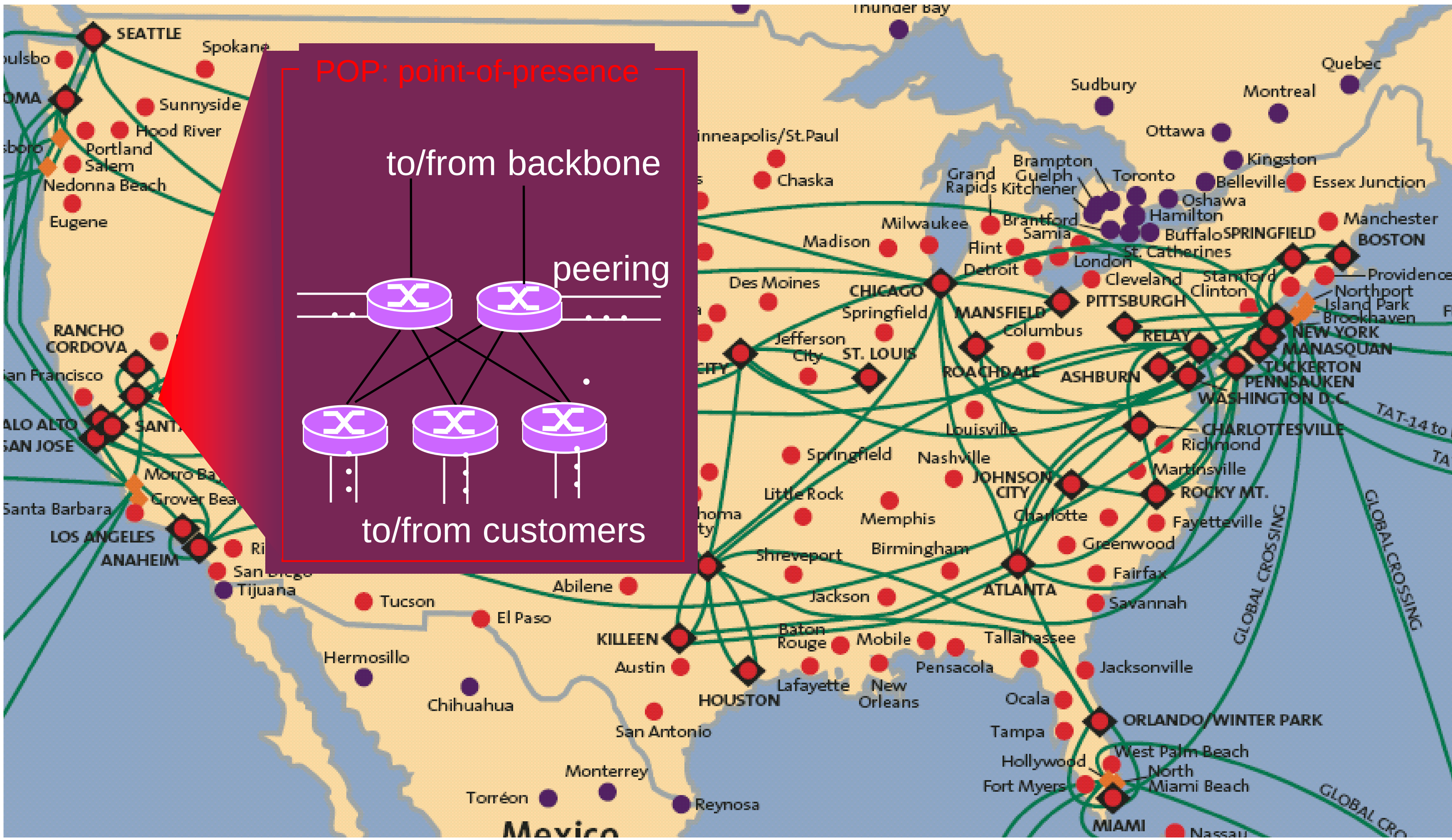


Peering



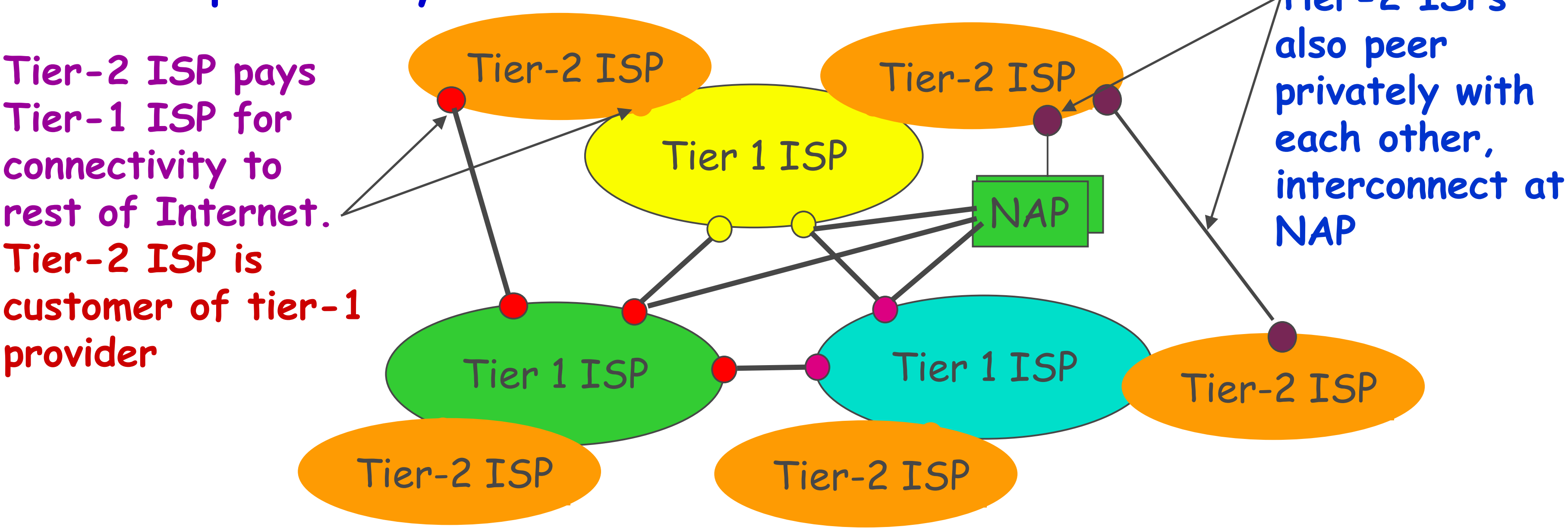
- Exchange traffic between customers
  - Settlement-free
- Diverse peering locations
  - Both coasts, and middle
- Comparable capacity at all peering points
  - Can handle even load

Tier 1 ISP: Sprint



Internet Structure (Tier 2)

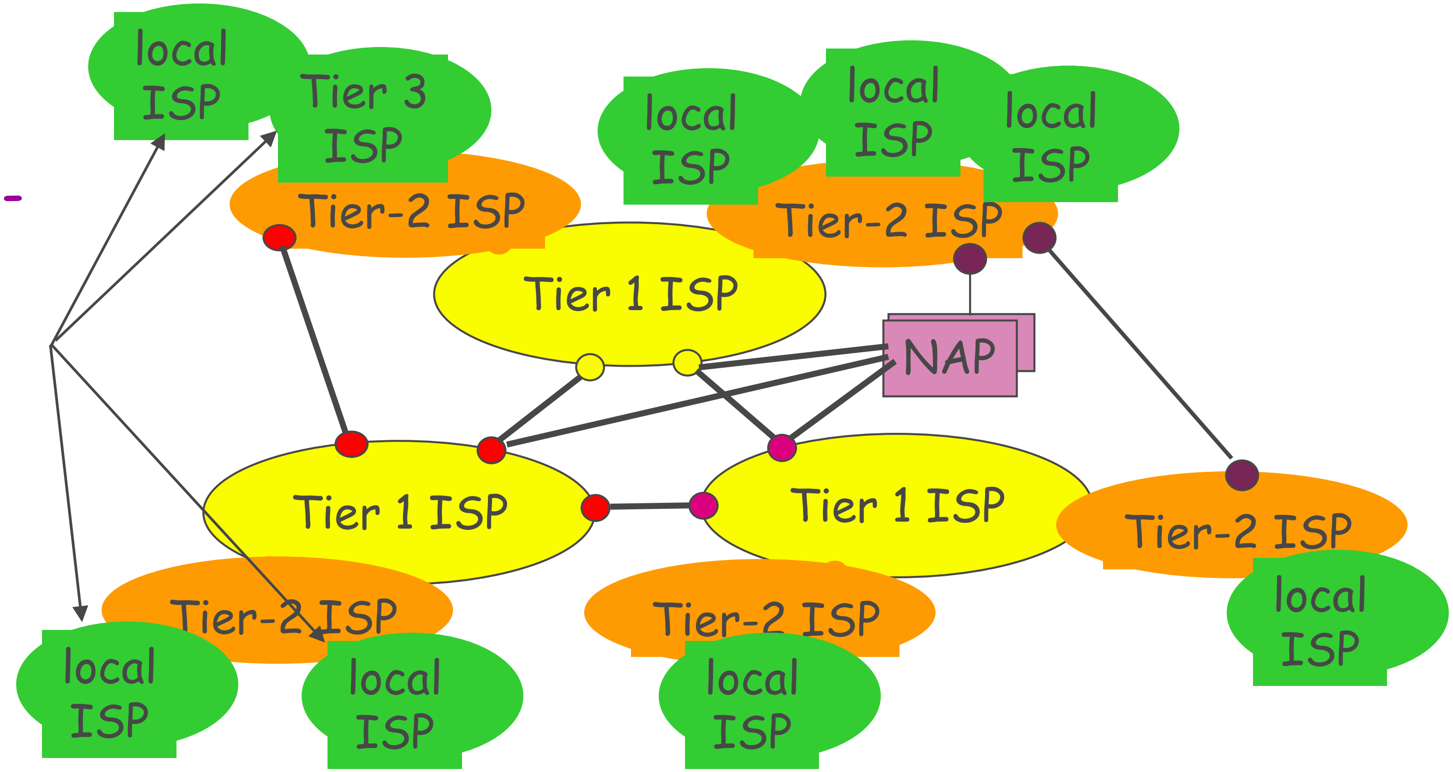
- "Tier-2" ISPs: smaller (often regional) ISPs
  - Connect to one or more tier-1 ISPs, possibly other tier-2 ISPs



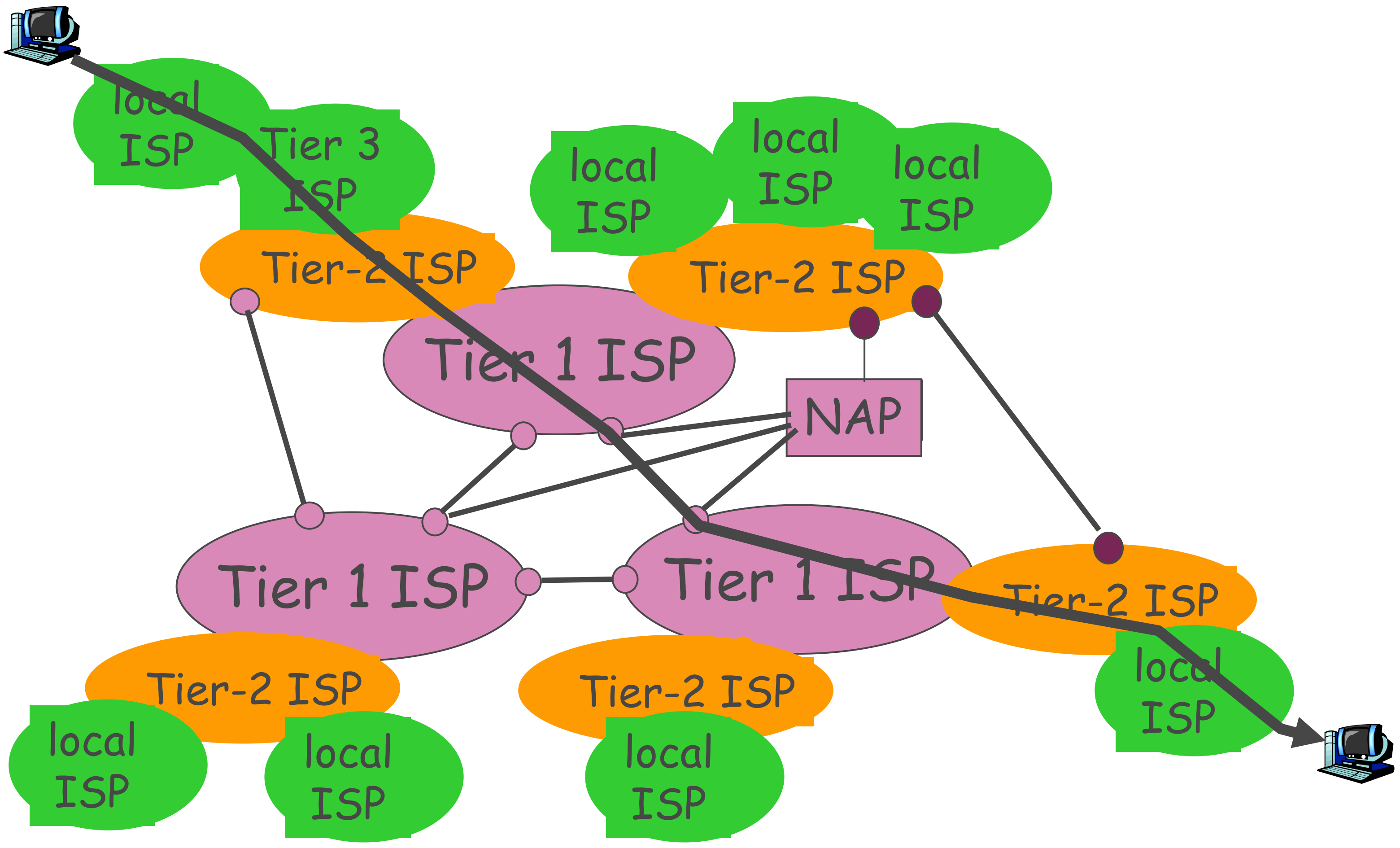
Internet Structure (Tier 3)

- "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



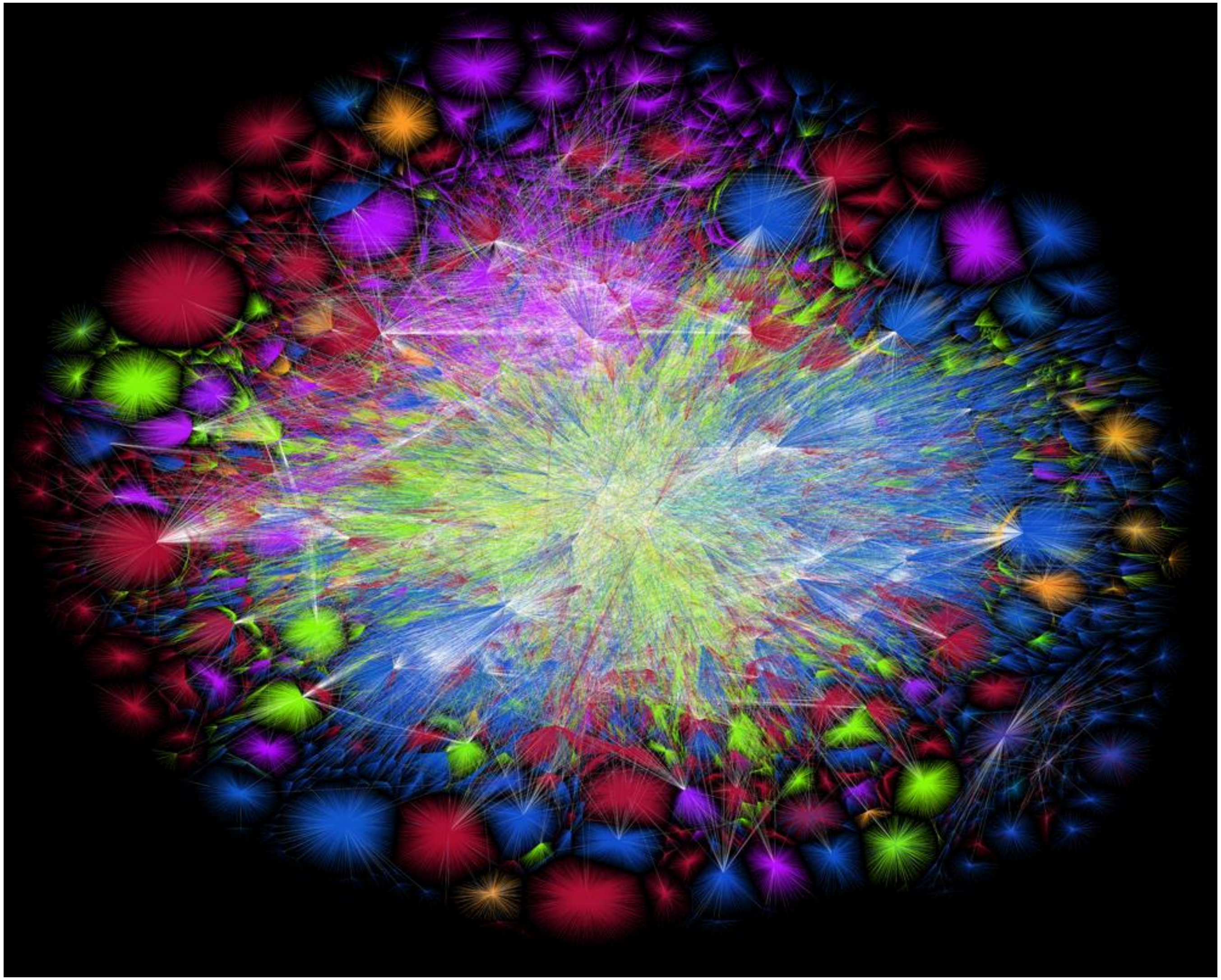
Internet Structure (Summary)



a Packet passes through many networks!

The Internet ?

The Internet Map (More Recent)

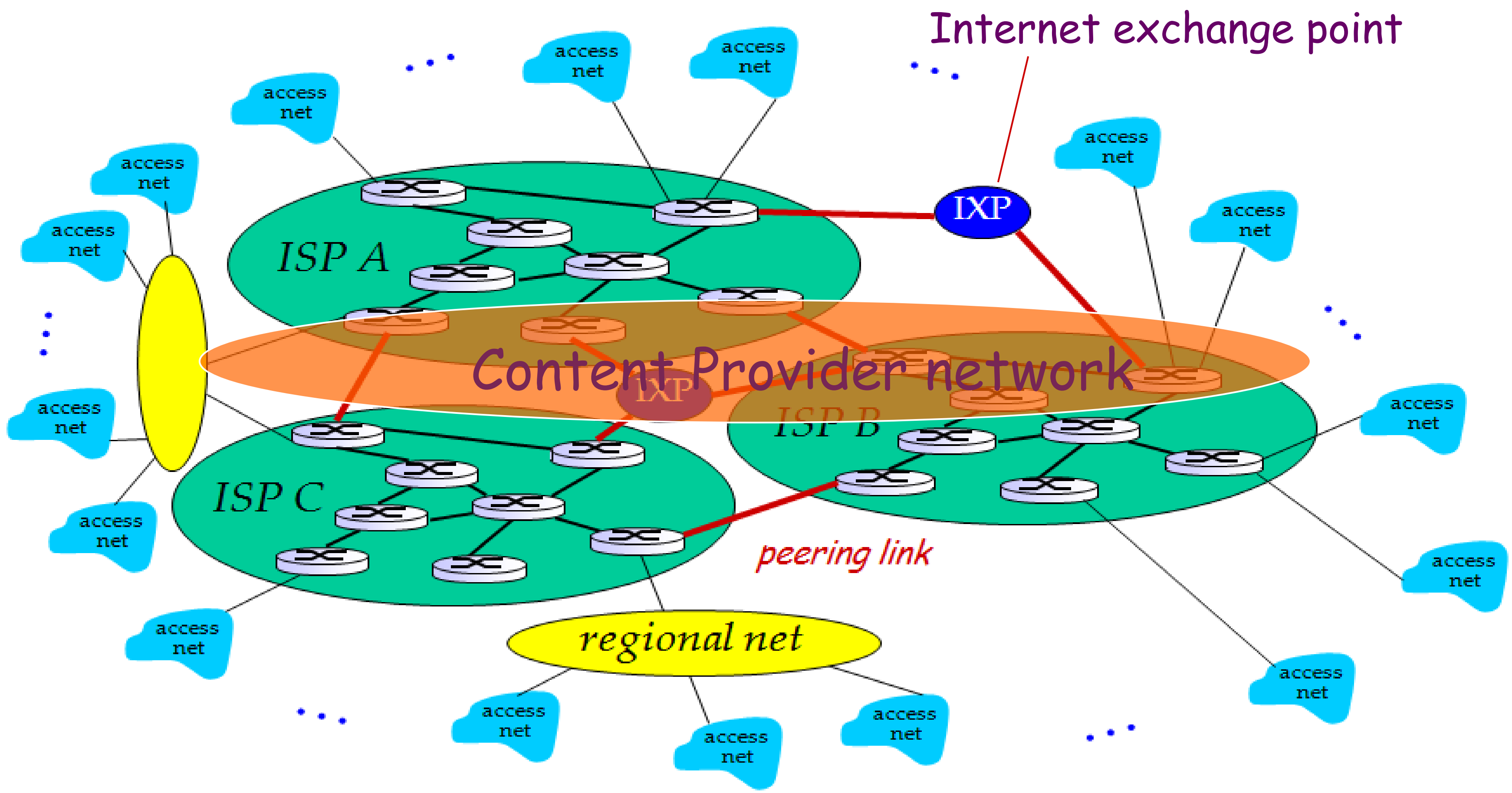


North America (ARIN)
Europe (RIPE)
Latin America (LACNIC)
Asia Pacific (APNIC)
Africa (AFRINIC)

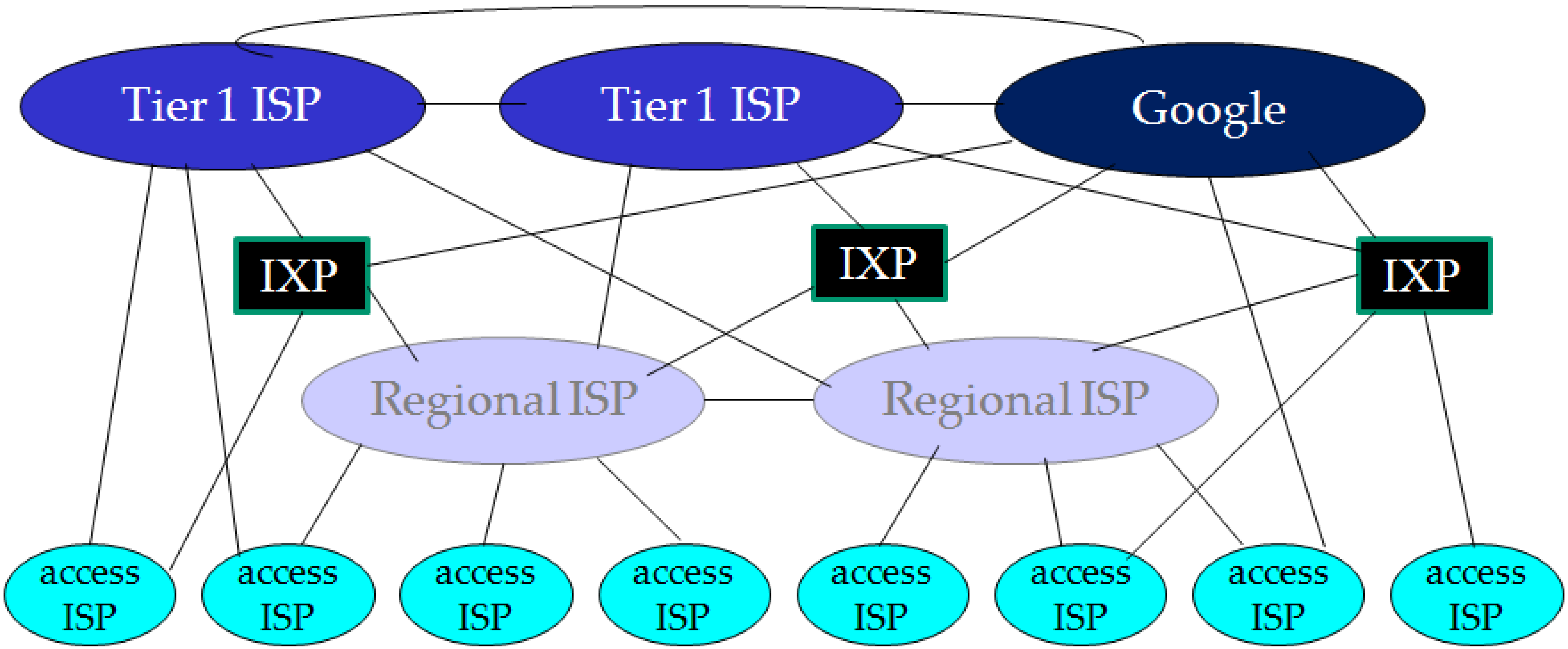
Internet in 2015

Content Provider Networks

Content Provider Networks (e.g., Google, Microsoft, Facebook etc..) run their own Networks, to bring services & content close to end users

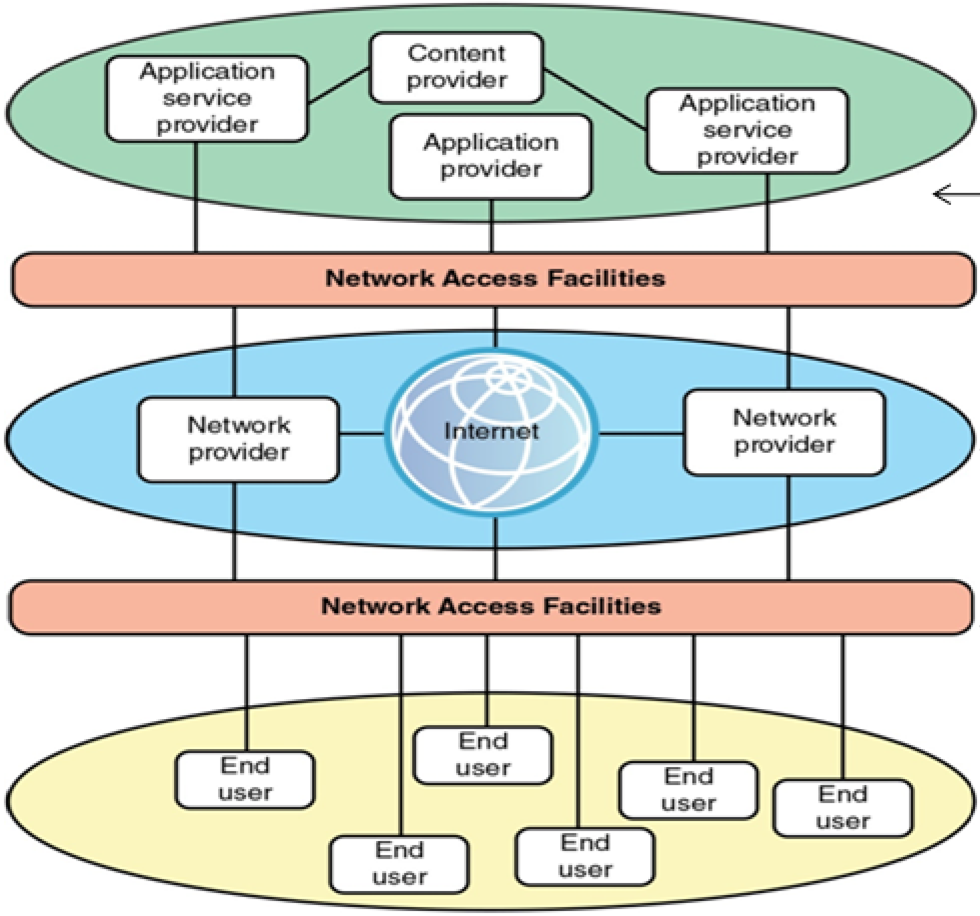


Internet Structure: Summary



- at center: small # of well-connected large networks
  - "Tier-1" commercial ISPs (e.g., Level 3, Sprint, AT&T, NTT), national & international coverage
  - content provider network (e.g., Google, Facebook): Private network that connects it data centers to Internet, often bypassing tier-1, regional ISPs

Summary of Network Ecosystem



Content Providers generate content (entertainment, education, etc.). Ex: Disney, Netflix, etc..

ASPs host the applications within their own facilities. Example: e-mail, web hosting, Cloud services, etc..

Application Providers generate applications to be run on user platform

They deliver communications services Over large areas. Private/Shared Example: ISPs, Cellular, Enterprise, etc..

Include ADSL, Cable, Wi-Fi, WiMax, Cellular, Fiber (FTTH, PON, etc…)

Consumer of applications, data and services on a computing platform. Residential, Corporate, SOHO,

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

$$t_{tran} = \frac{\text{Number of Message (Packet) bits}}{\text{Data rate [bps]}}$$

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: $c = 3 \times 10^8$ meters/sec
  - Cat 5 UTP: $2 \sim 2.5 \times 10^8$ meters/sec
  - Optical Fiber: $2 \sim 2.5 \times 10^8$ meters/sec

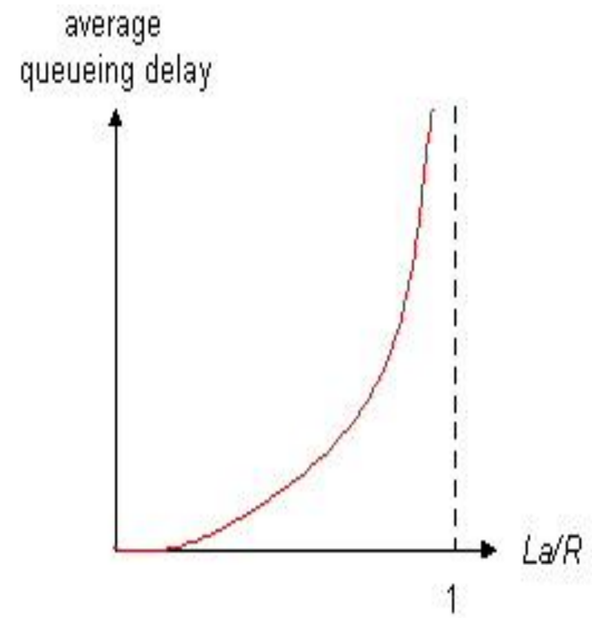
Nodal Processing/Queueing

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

More on Queueing Delay

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

❖ $\lambda L/R \sim 0$: avg. queueing delay small
❖ $\lambda L/R \leq 1$: avg. queueing delay large
❖ $\lambda L/R > 1$: more "work" arriving than can be serviced, average delay ir



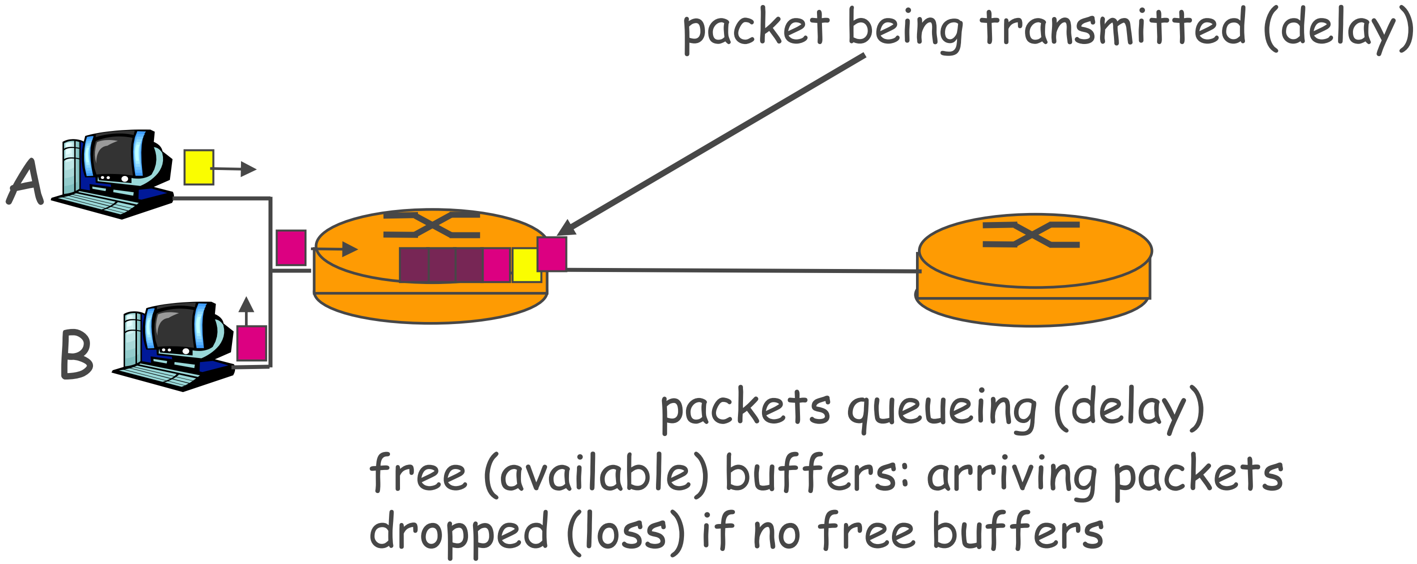
traffic intensity
= $\lambda L/R$

$\lambda L/R \sim 0$

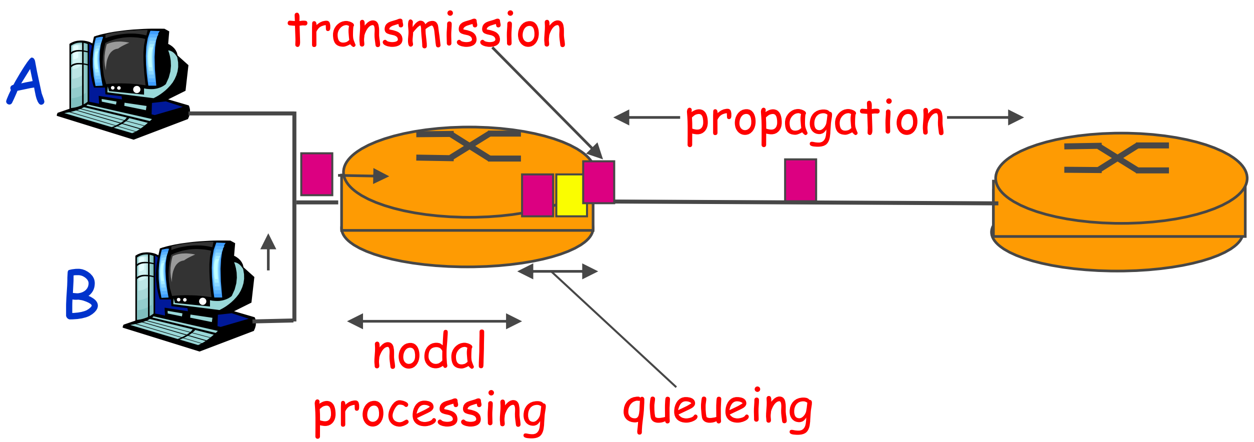
$\lambda L/R \rightarrow 1$

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



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

d_{proc}: nodal processing

- check bit errors
- determine output link
- typically < msec

d_{queue}: queueing delay

- time waiting at output link for transmission
- depends on congestion level of router

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

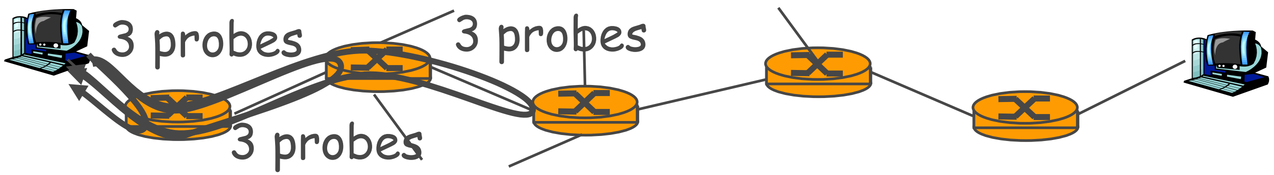
$$\boxed{t_{xfr} = t_{trans} + t_{prop} + t_{queuing/processing}}$$

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.

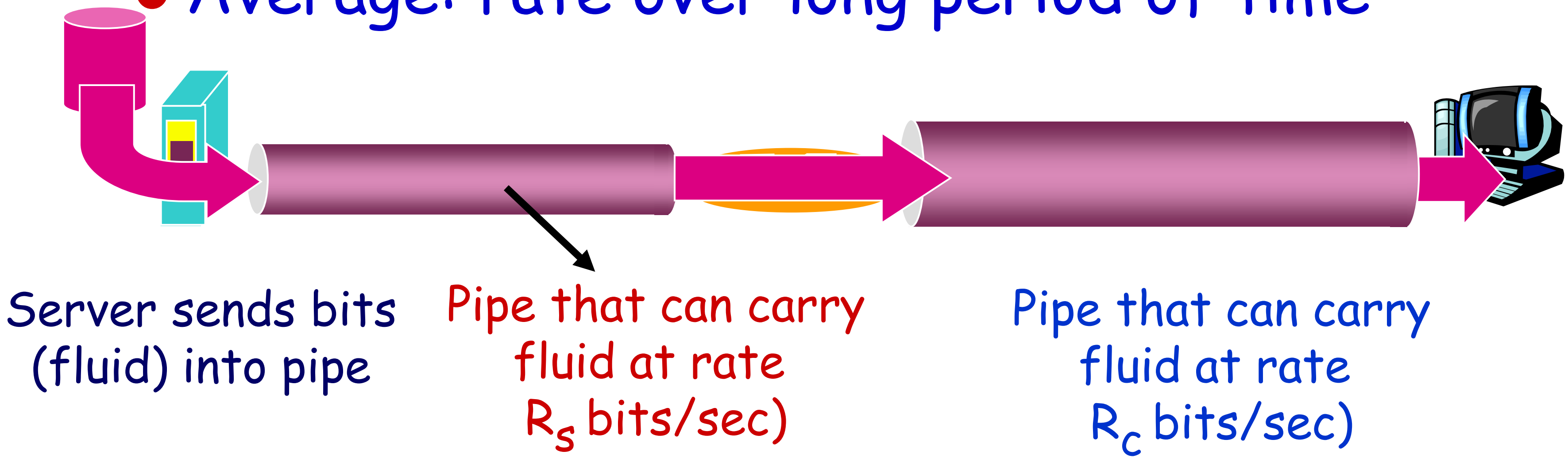


Throughput

- 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

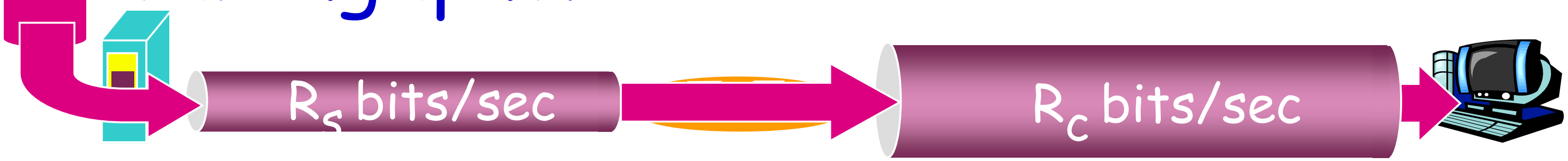
Instantaneous vs. Average Throughput

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

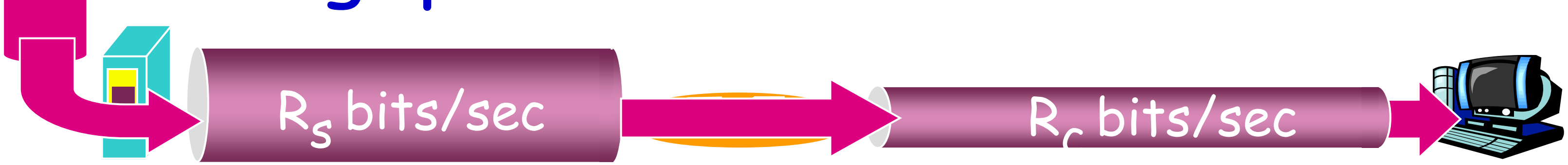


More on Throughput

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



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

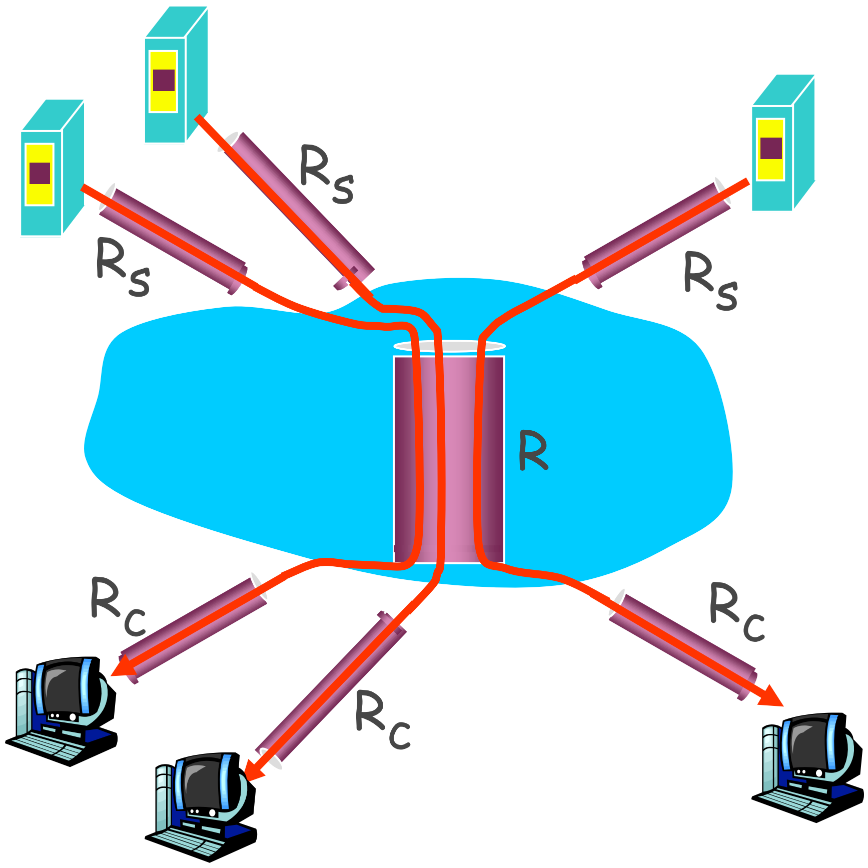


Bottleneck Link

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)



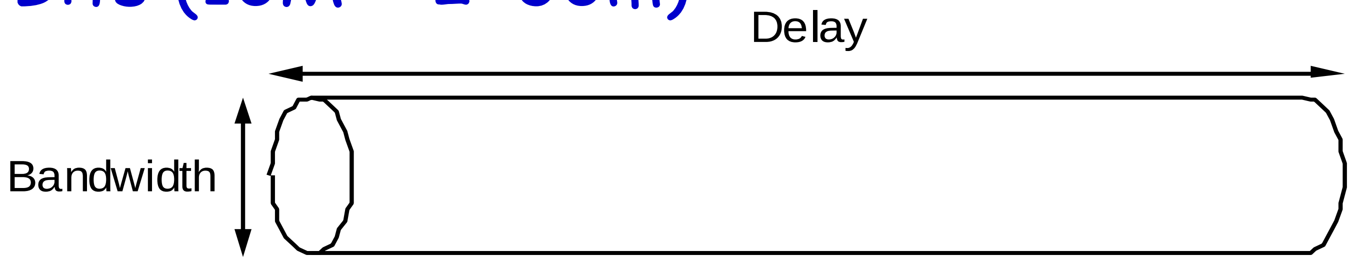
3 connections (fairly) share backbone bottleneck link R bits/sec

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 second.
- 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 (10M * 2*30m)



Networking Perspective

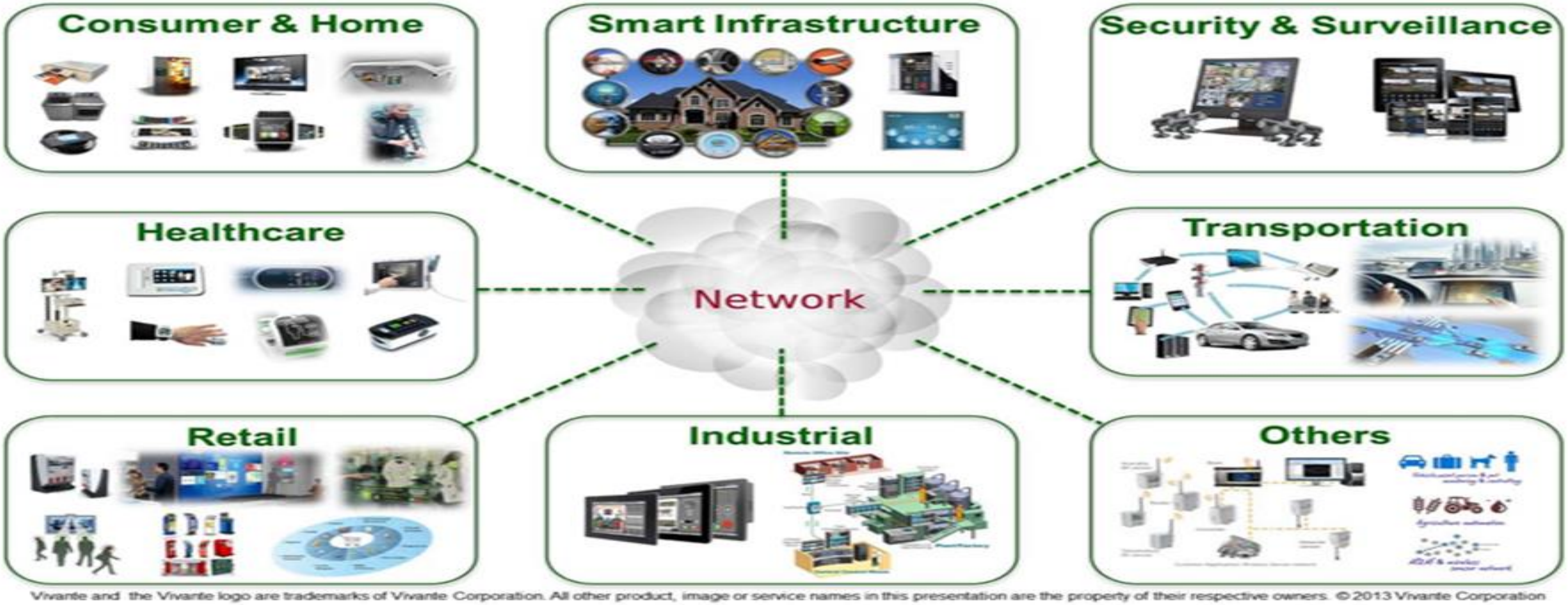
- Application Programmer / End User
  - Guaranteed timely, reliable and recognizable delivery of message/information
- Network Designer
  - Cost-effective design. Resources (Bandwidth, Memory and CPUs) must be used efficiently and are fairly allocated
- Network Provider
  - Administration & management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

The Internet Today

- ~ 20B Internet users/devices, 50B expected by 2025
  - Number of Internet-ready devices exceeding number of users. Smart Phones, Tablets, etc…
- Aggressive deployment of broadband access
- Increasing ubiquity of high-speed wireless access (WiFi, 4G/5G
- Emergence of online social networks:
  - Facebook ~ 2.5 billion users
- Service providers (Google, Microsoft) create their own networks bypassing the Internet and providing "instantaneous" access to search, email, etc.
- E-commerce, universities, enterprises running their services in "cloud" (e.g., Amazon AWS)

On the Horizon: the Internet of Things

- Extending the traditional "IP-over-everything, everything-over-IP" paradigm to smart objects, sensors, actuators, control systems, etc..
- IoT is enabled by the latest developments in RFID, Smart Sensors, embedded devices, communications Technologies, Internet Protocols and applications
- Emerging new applications: Smart Homes, Smart Buildings, e-Health, Smart Grid, Smart Cities, Industrial Automation, Transportation, etc…



Internet-Connected Devices

Amazon Echo

Internet refrigerator

IP picture frame

Pacemaker & Monitor

Tweet-a-watt:
monitor energy use

Web-enabled toaster +
weather forecaster

Security Camera

Slingbox: remote
control cable TV

AR devices

Internet phones

sensorized,
bed
mattress

Fitbit

Others?

Smart Home


Bathroom
Doctors will be able to give you virtual medical checks
Toilets will analyse waste for medical problems such as colon cancer.
Bedroom
Smart books interact with the house's 3D and virtual reality system, bringing to life what you read.
Roof
Power collected through solar panels and stored in backup resources to power house and car.
Bedroom
Clothes made with smart fabrics regulate your temperature and monitor your health
E-commerce will become F-commerce - online consumers will be able to enjoy a tailored shopping experience based on Facebook 'Likes'.
Kitchen
Smart surfaces identify what's on them and have the ability to react accordingly - keeping coffee cups warm and iced-tea cold.
Refrigerators will advise on recipes based on whats in stock and creates personal diets.
PLUSNET ROAD
Living Room
All appliances connected through invisible networking system
Entertainment system creates life like sounds, images and experiences to completely envelop you in near 4D experience.
Garage
Camera at entrance has facial recognition software which is linked to criminal database
Car which is able to drive itself.
Office
See-through electronics, screens, touch panels and tactile displays deliver 3D holographic experiences
Contact lenses allow you to access infinite information resources instantly before your eyes.

Smart City


Environment-friendly design buildings
Regional EMS (Control center)
Smart Buildings linked through Regional EMS
Wind farm
Battery storage systems
Next-generation vehicle center(operation center)
MegaSolar
Intelligent Transportation System (ITS)
Smart House
Biomass fuels
Multi-energy station
EV car sharing
EV car sharing
Smart House
Electric bus
Smart House
Small / Medium-scale Smart Buildings
Solar panel
Offshore wind farm
Multi-energy station

Trend: Everything is Smart

Smart Watch

Smart TV

Smart Car

Smart Health

Smart Home

Smart Kegs

Smart Space

Smart Industries

Smart Cities

The Internet in a minute (2023)