TDTS06: Computer Networks

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Office Hours: TBA

Notes derived from "*Computer Networking: A Top Down Approach*", by Jim Kurose and Keith Ross, Addison-Wesley.

The slides are adapted and modified based on (among other things) slides from the book's companion Website, as well as modified slides by A. Mahanti and C. Williamson.

People

- Examiner and lecturer
  - Niklas Carlsson, Associate Professor
  - Research area: Design, modeling, and performance evaluation of distributed systems and networks
- Lecturer
  - Jose Pena, Associate Professor
  - Research area: Machine learning
- Lab assistants
  - Vengatanathan Krishnamoorthi, PhD student
  - Farrokh Ghani Zadegan, PhD student
- Director of studies
  - Patrick Lambrix

Course Overview

- Written exam
  - Grads: 'fail', 3, 4, 5.
- Four (4) mandatory lab assignments
  - Must pass all four labs
  - Eight lab opportunities
  - Please register on webreg right away!! (deadline on Friday)
- One (1) optional assignment
  - Up to 4 bonus marks for exam
- Eleven (11) lectures + one (1) exam prep.
- See website for more information ...

My expectations

- Read textbook
  - Good textbook, written by highly regarded researchers in the field
  - Lots of content
  - Not time to cover everything during lectures
- Work hard
  - Pay attention during lectures
  - Make sure you understand the material
  - Start assignments early (some will take time)
- Follow deadlines and office hours

What to expect? (What will be covered?)

- Design principles for computer networks
  - Conceptual view of Internet architecture
- Design, resource, and performance tradeoffs
  - General working knowledge of protocols/applications
  - Detailed knowledge of selected protocols/applications
  - Some practical hands on experience
- Glimpse into the future of the Internet
  - Emerging trends and technologies

Roadmap (today's lecture)

- What is a Computer Network?
- Applications of Networking
- Classification of Networks
- Layered Architecture (and Protocols)
- Network Core
- Delay & Loss in Packet-switched Networks
- Structure of the Internet
- Summary

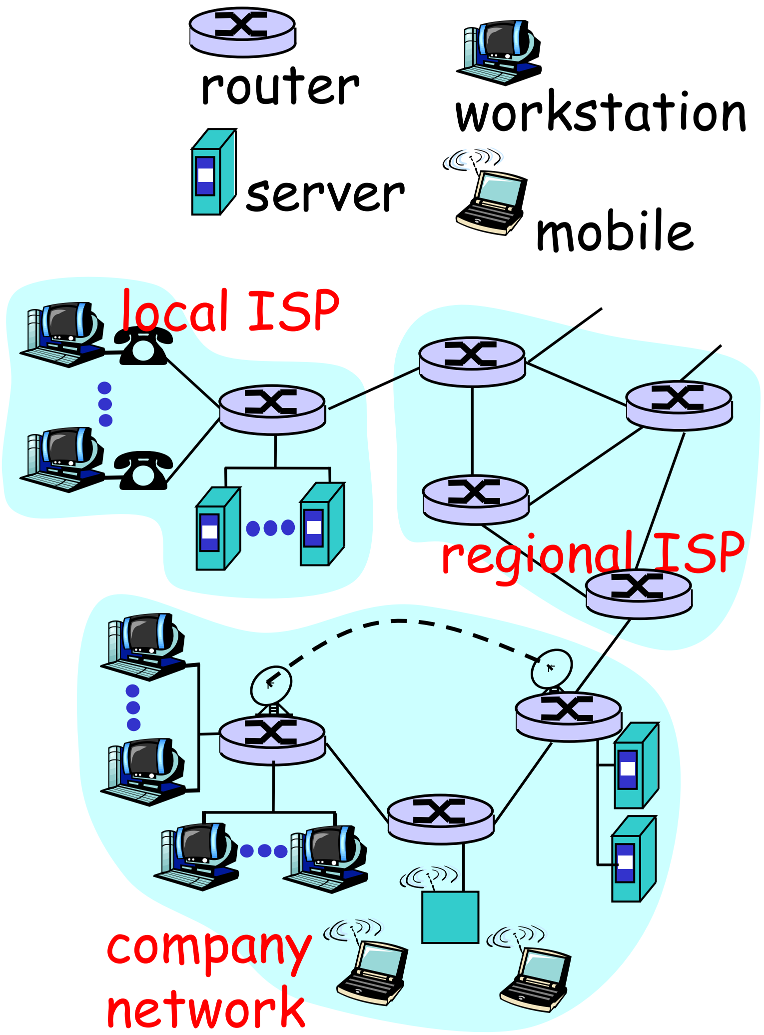
- E.g., https://www.youtube.com/watch?v=w42EsCDAhB4

- So, what are computer networks?

Computer Network?

- "interconnected collection of autonomous computers connected by a communication technology"
- What is the Internet?
  - "network of networks"
  - "collection of networks interconnected by routers"
  - "a communication medium used by millions"
    - Email, chat, Web "surfing", streaming media
- Internet $\neq$ Web

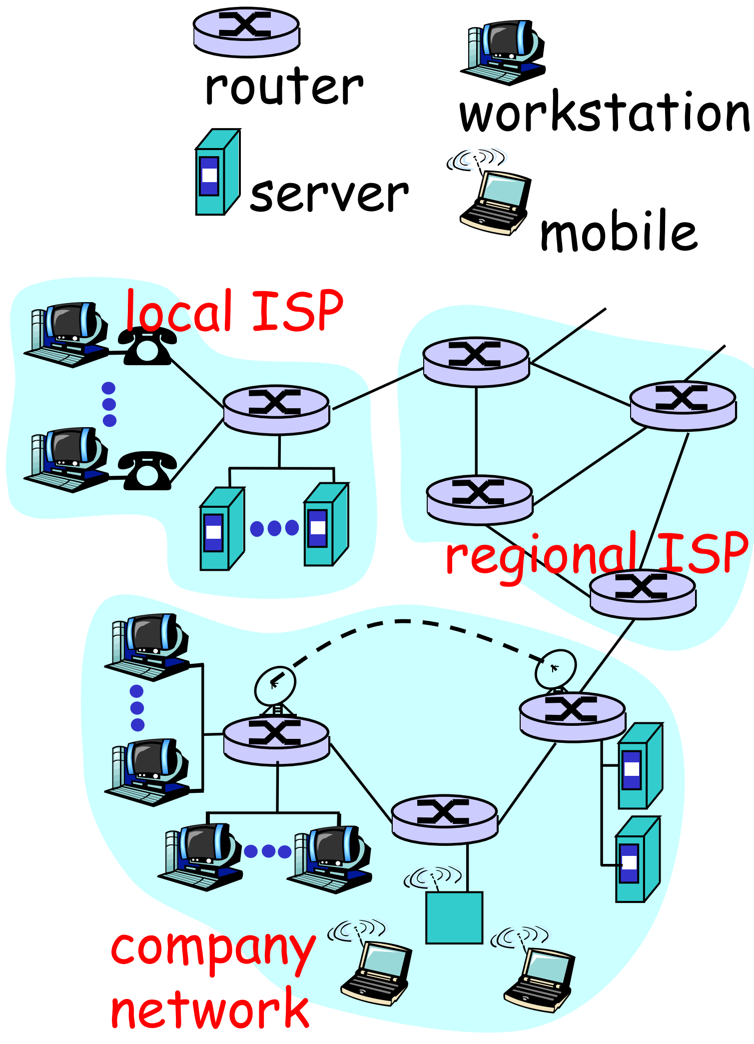
The "nuts and bolts" view of the Internet



The “nuts and bolts” view of the Internet

- millions of connected computing devices called *hosts or end-systems*
  - PCs, workstations, servers
  - PDAs, phones, toasters

  running *network apps*
- *communication links*
  - fiber, copper, radio, satellite
  - links have different capacities (*bandwidth*)
- *routers:* forward packets
- packet: piece of a message (basic unit of transfer)



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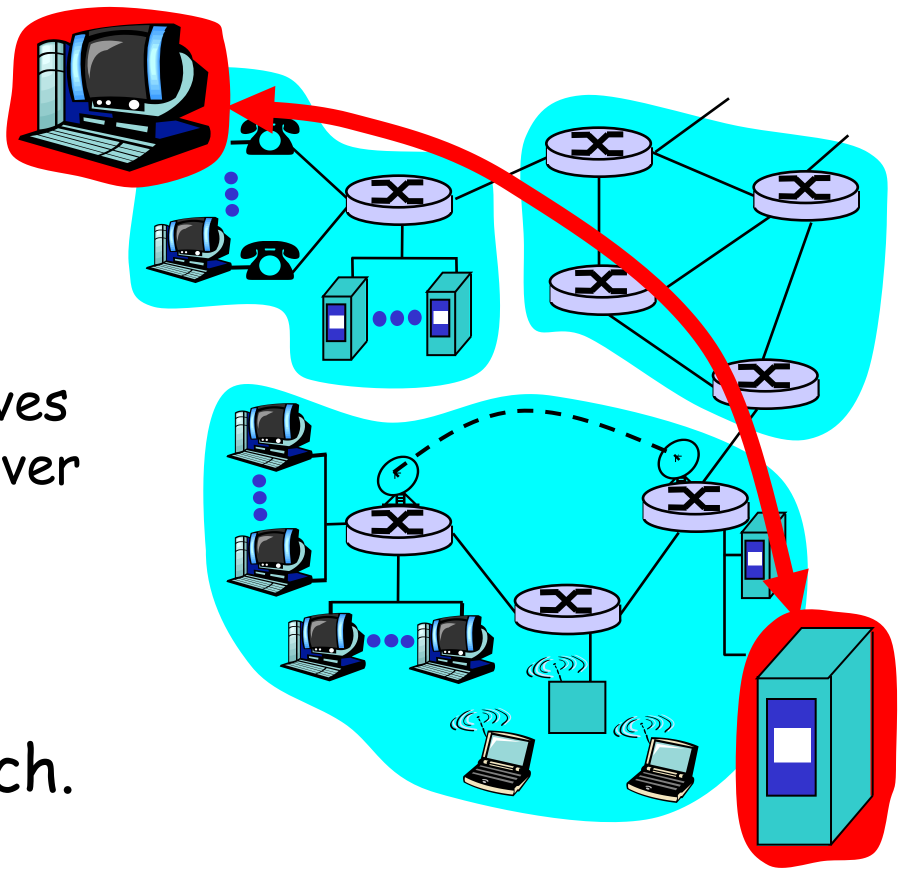
Service/company landscape include

Applications: Example classes

- File transfer
- Remote login (telnet, rlogin, ssh)
- World Wide Web (WWW)
- Instant Messaging (Internet chat, text messaging on cellular phones)
- Peer-to-Peer file sharing
- Internet Phone (Voice-Over-IP)
- Video-on-demand
- Distributed Games
- … and many more to come/discuss …

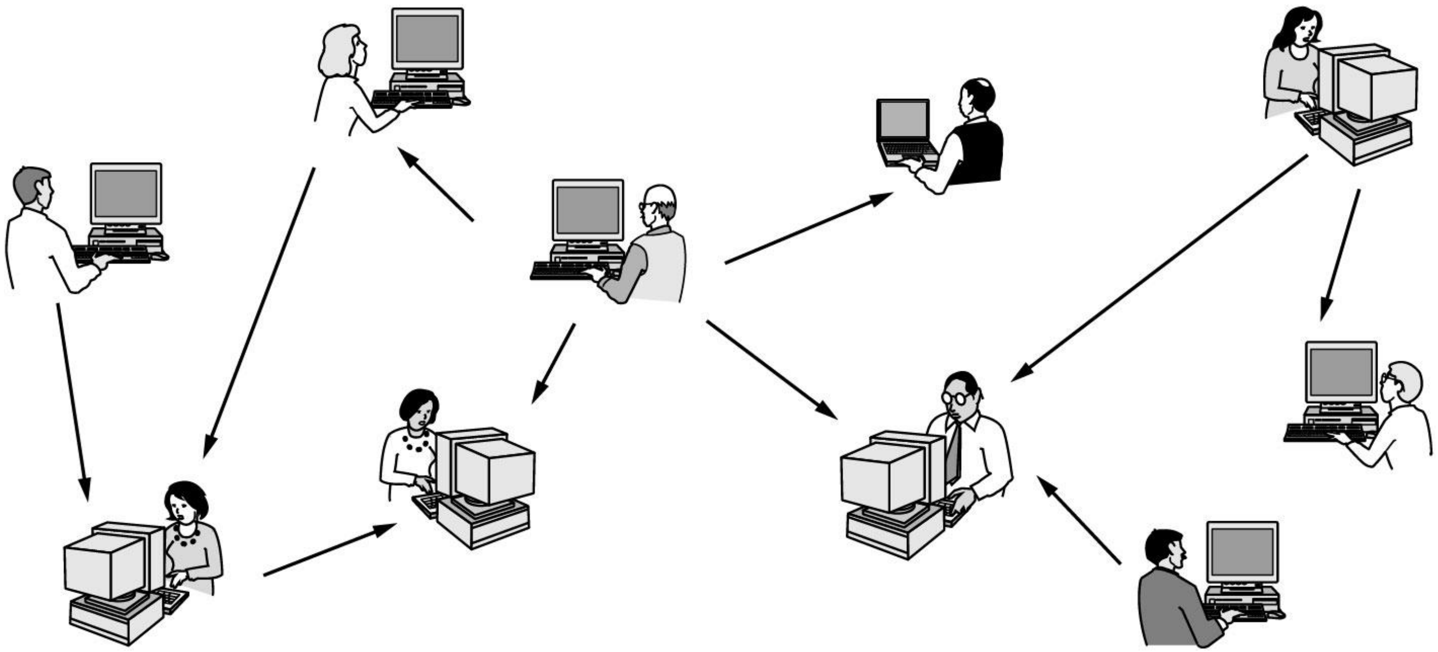
Applications (2)

- end systems (hosts):
  - run application programs
  - e.g. Web, email, ftp
  - at "edge of network"
- client/server model
  - client host requests, receives service from always-on server
  - e.g. Web browser/server; email client/server
- Client/server model has well-defined roles for each.



Applications (3)

- peer-to-peer model:
  - No fixed clients or servers
  - Each host can act as both client and server at any time
- Examples: Napster, Gnutella, KaZaA, BitTorrent



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- Internet is an example of an internetwork.
  - Internetwork: interconnection of networks
  - Subnetwork: a constituent of an internet
  - Intermediate system: a device used to connect two networks allowing hosts of the networks to correspond with each other
    - Bridge
    - Router

A Classification of Networks

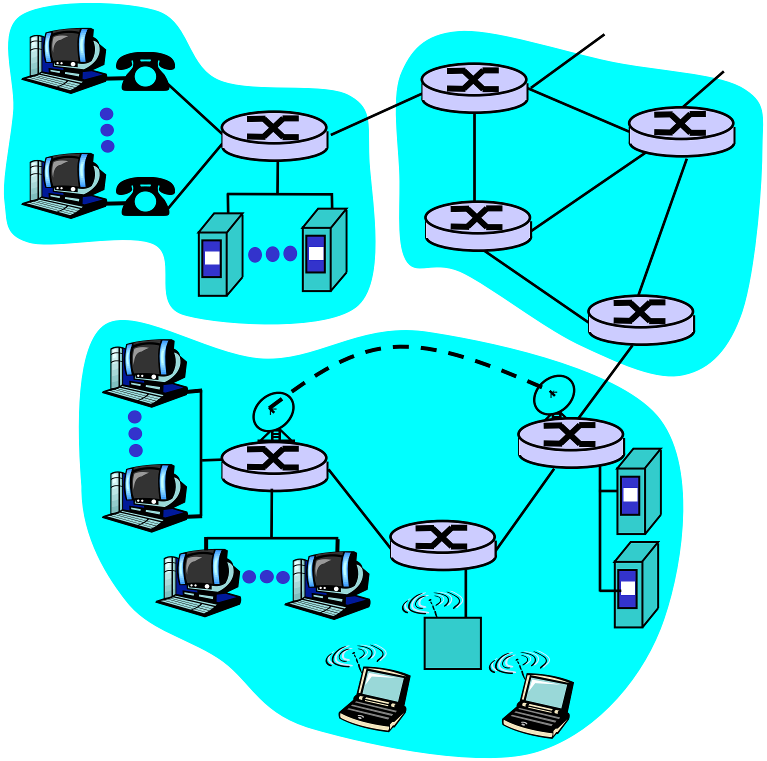
- Wide Area Network (WAN)
- Metropolitan Area Network (MAN)
- Local Area Network (LAN)

- Wireless LAN (WLAN)
- Home Networks
- Personal Area Network (PAN)
- Body Area Network (BAN)

- … and more (incl. sensor and ad-hoc) …

Wide Area Network (WAN)

- Spans a large geographic area, e.g., a country or a continent
- A WAN consists of several transmission lines and routers
- Internet is an example of a WAN

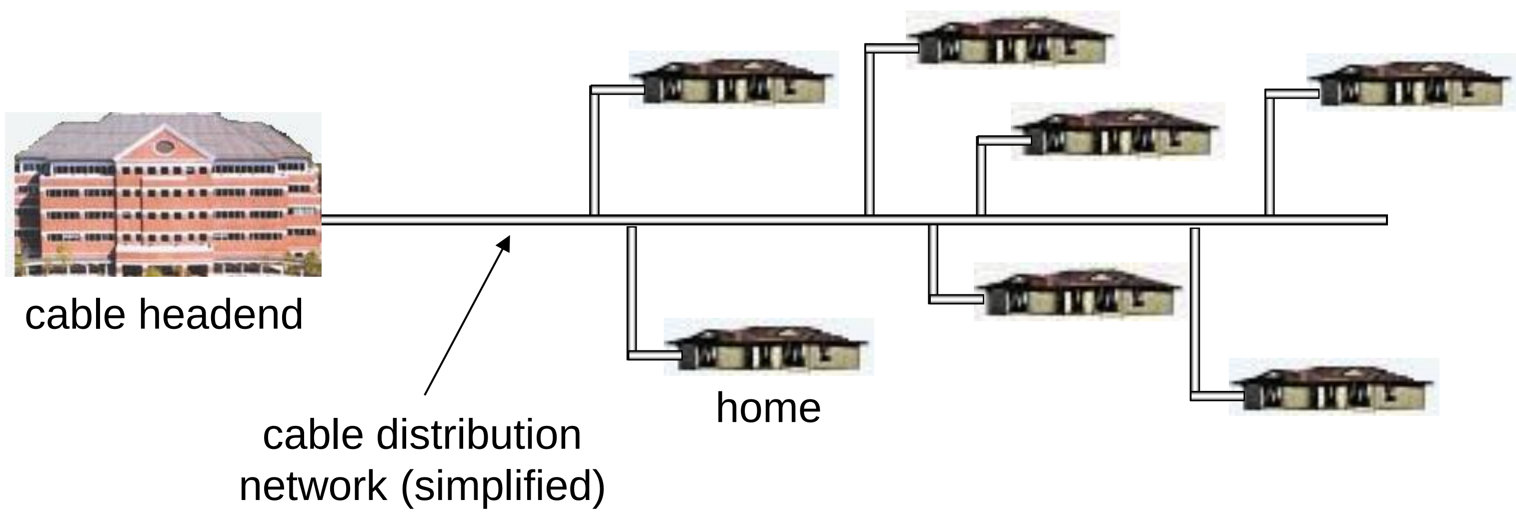


Metropolitan Area Network (MAN)

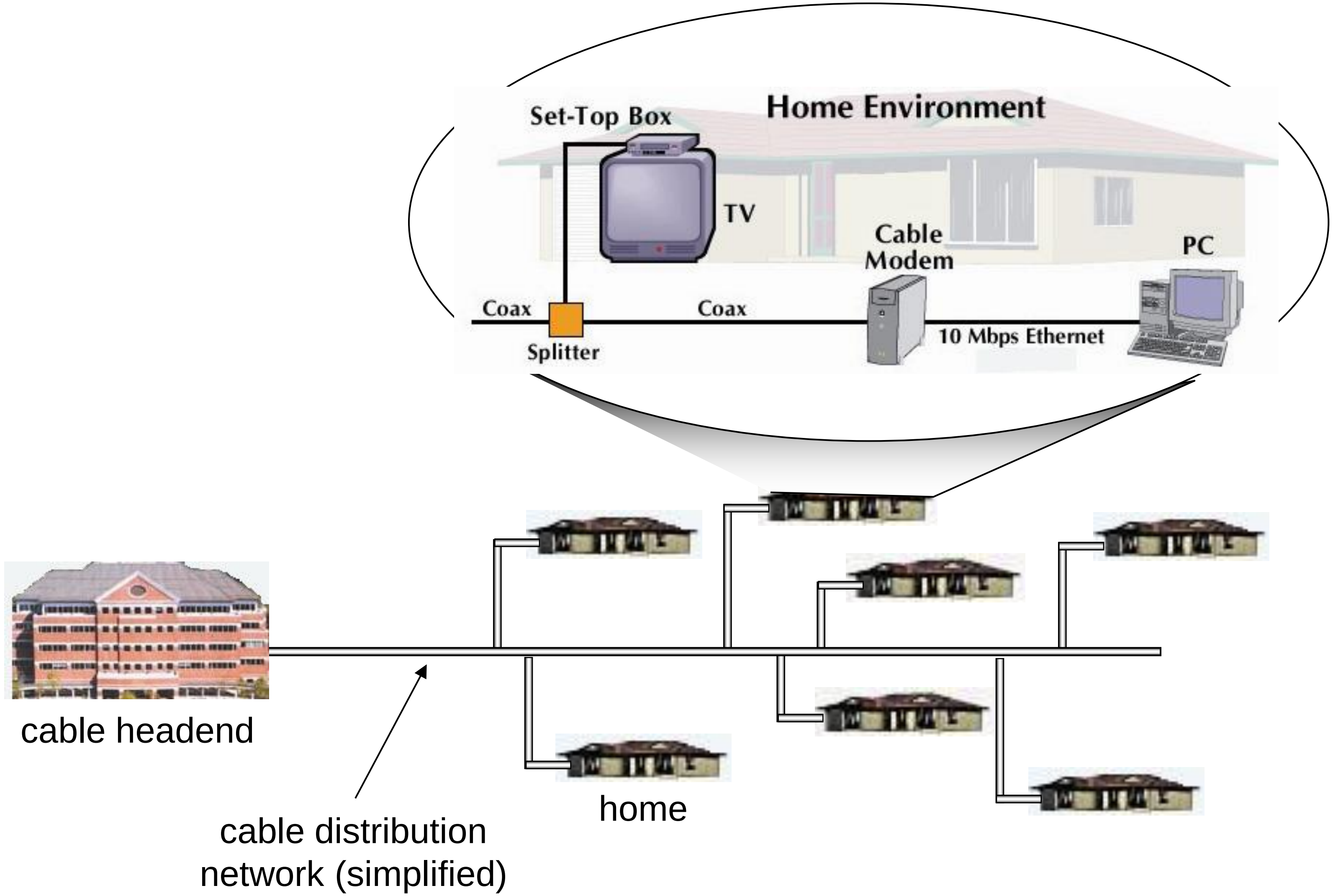
"City sized": tens of kilometers

A Cable TV Network is an example of a MAN

Typically 500 to 5,000 homes



Cable Network Architecture: Overview



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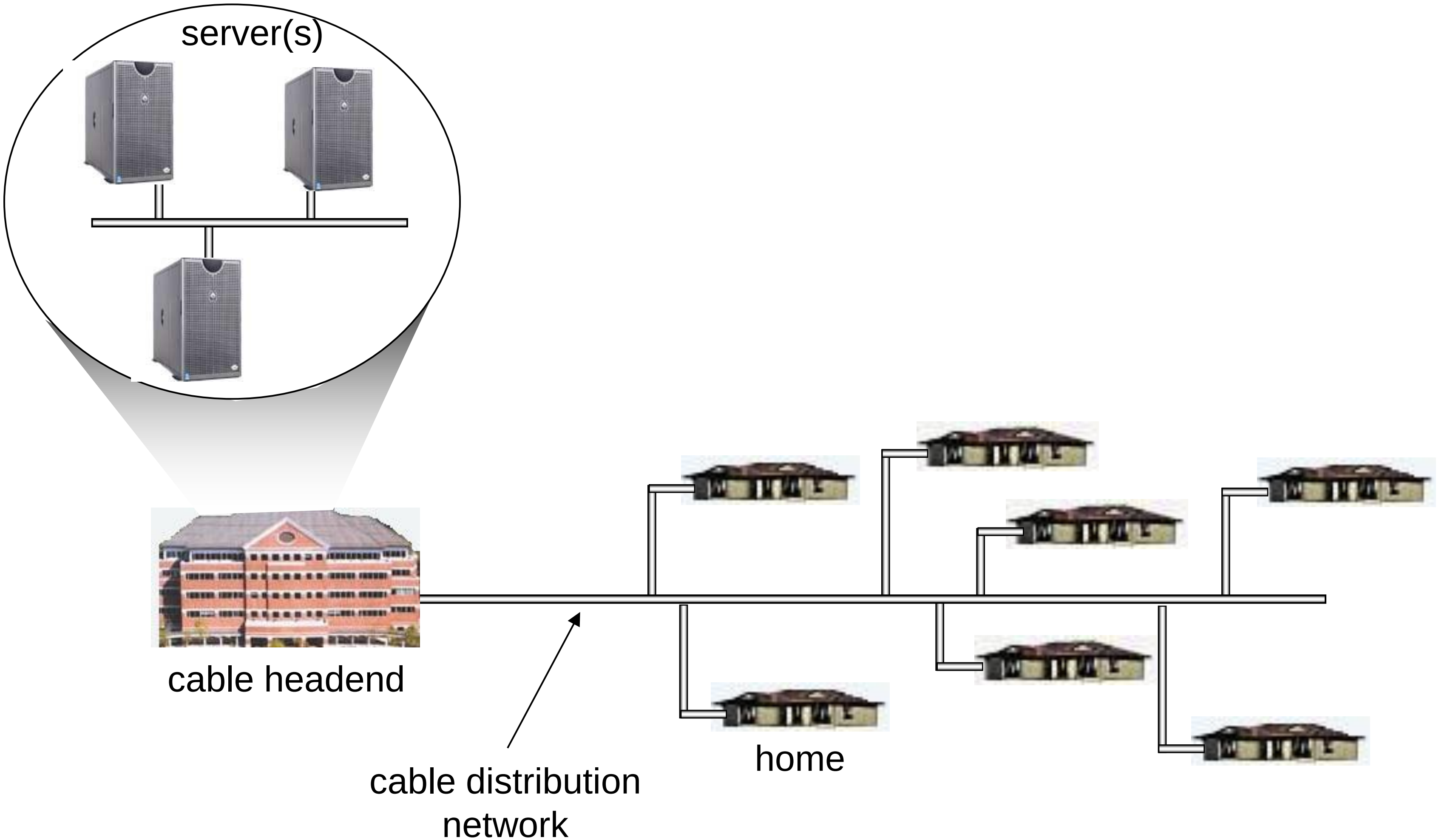
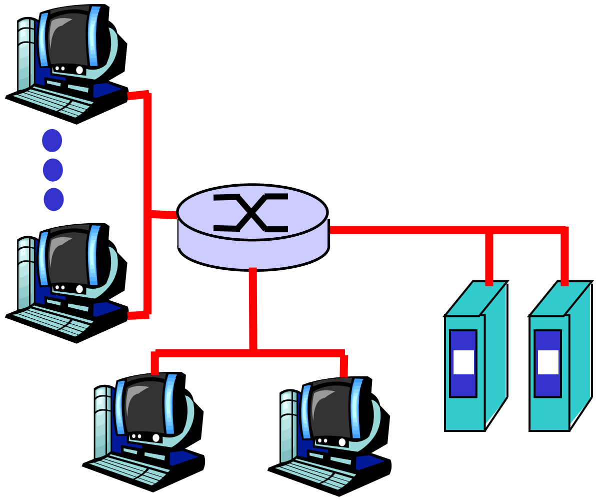


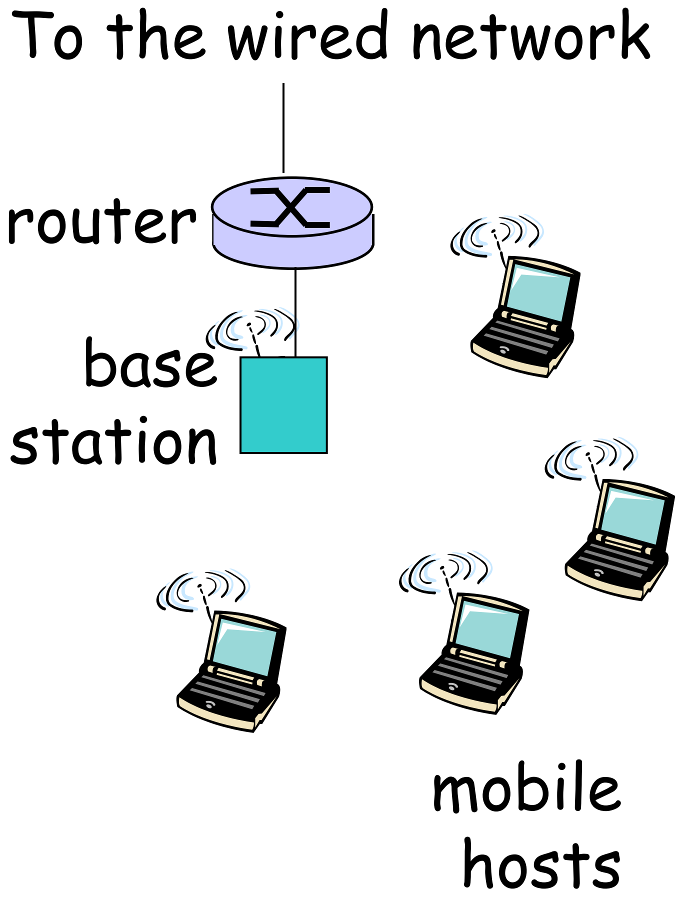
Local Area Network (LAN)

- company/univ local area network (LAN) connects end system to edge router
- Ethernet:
  - shared or dedicated link connects end system and router (a few km)
  - 10 Mbps, 100Mbps, Gigabit Ethernet
- widespread deployment: companies, univ, homeLANs
- LANs: chapter 5



Wireless Networks (WLANs)

- shared *wireless* access network connects end system to router
  - via base station or "access point"
- wireless LANs:
  - 802.11b (WiFi)



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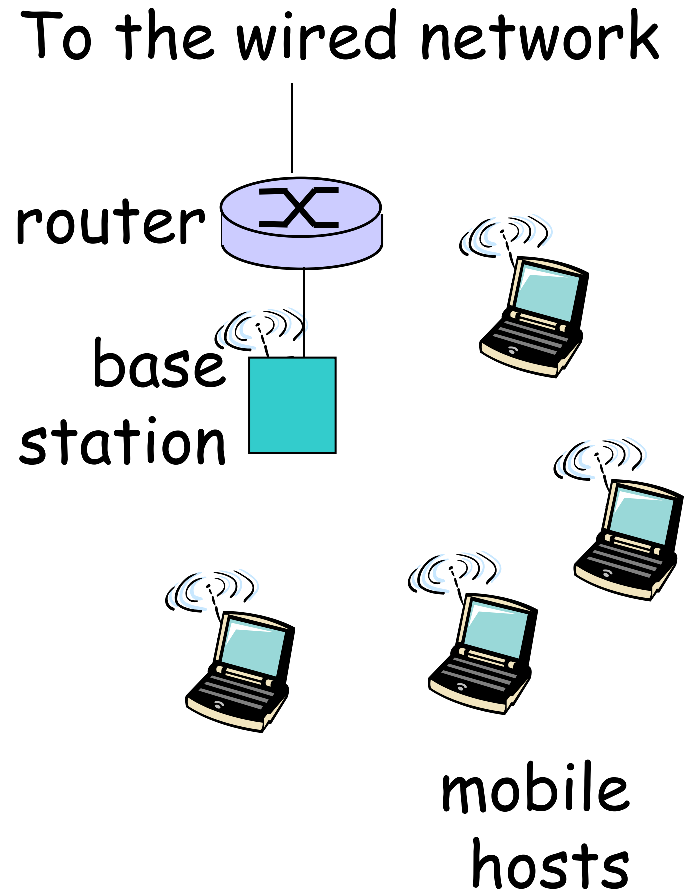
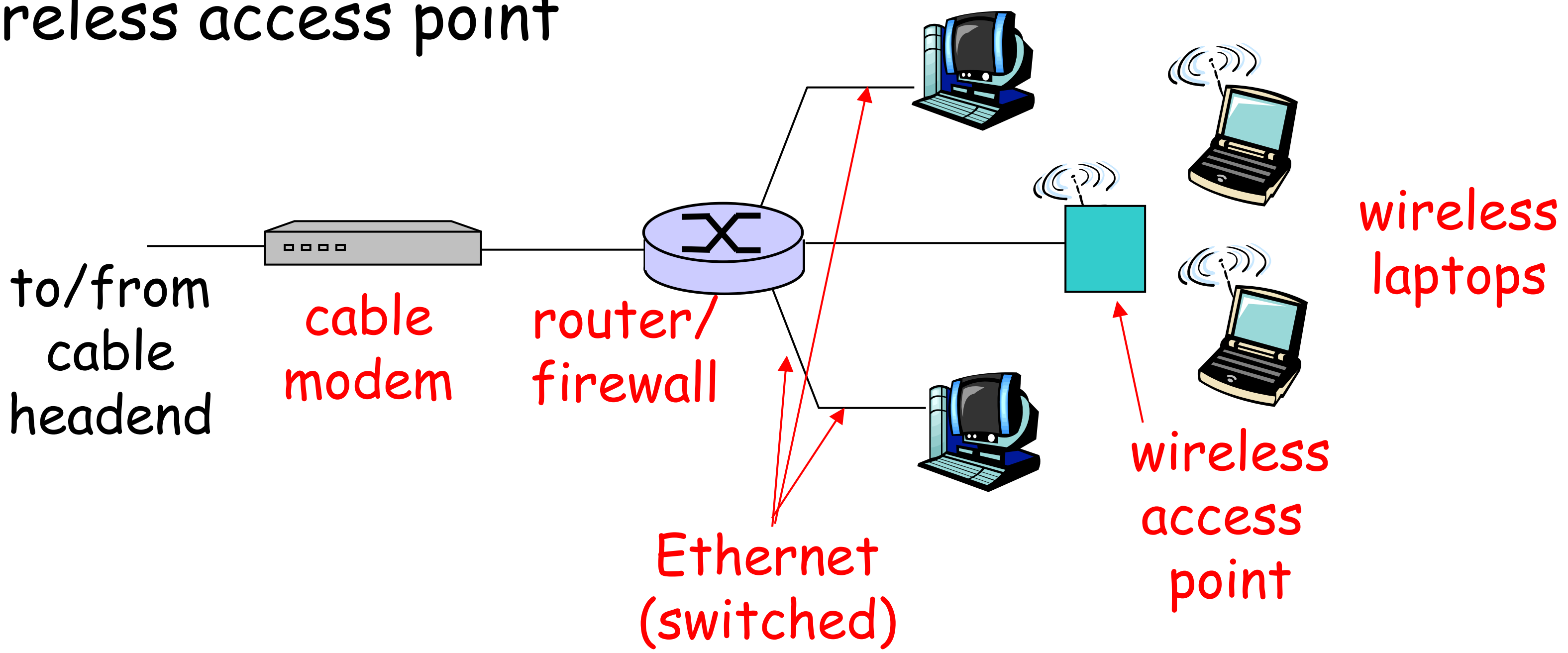
- wider-area wireless access
  - provided by telco operator
  - 3G, 4G
  - WAP/GPRS in Europe
  - WiMax



Home networks

Typical home network components:

- ADSL or cable modem
- router/firewall/NAT
- Ethernet
- wireless access point



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But first ...What's a protocol?

Protocols:

- The rules used for communication
- Proper, accepted, and expected behavior

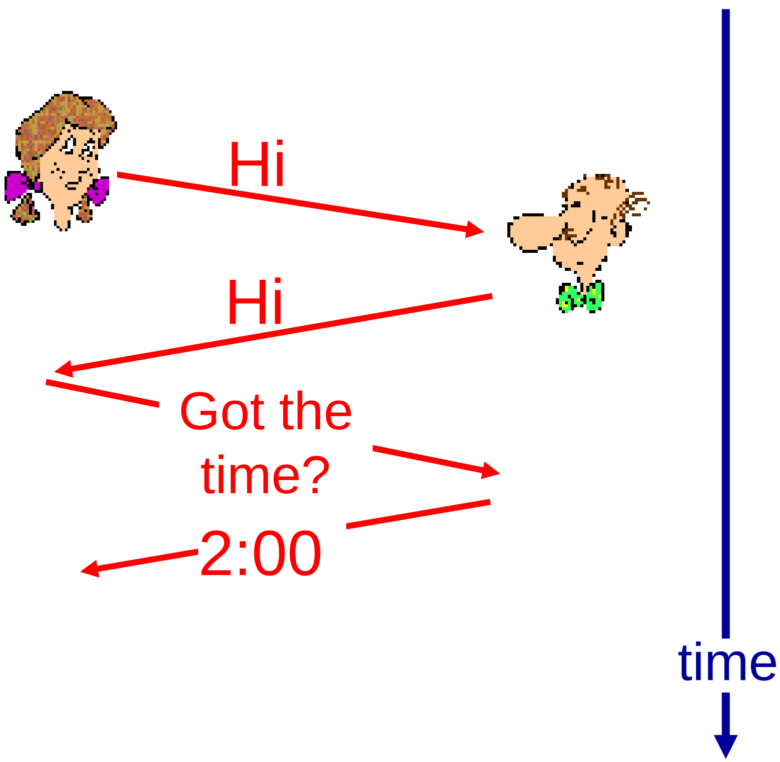
But first … What's a protocol?

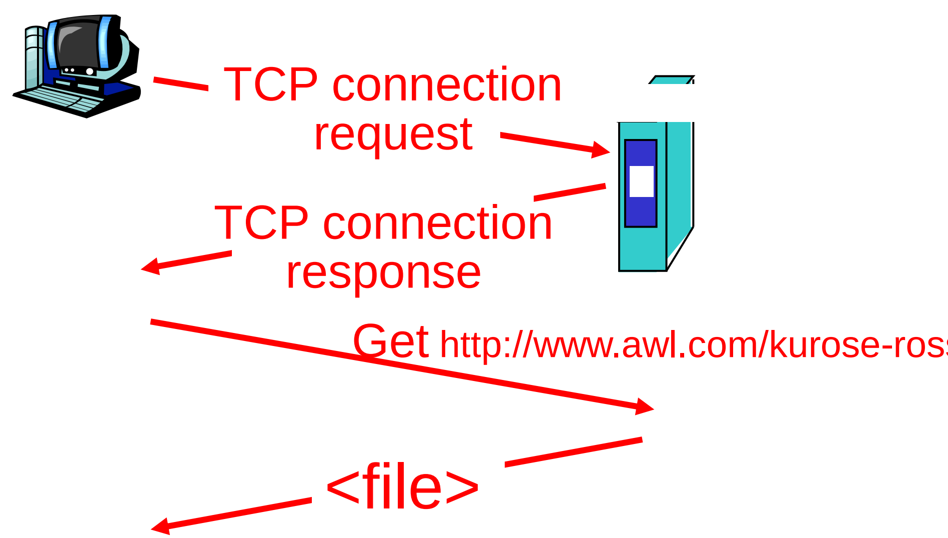
human protocols:

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

network protocols:

- Machines rather than humans
- All communication activity in Internet governed by protocols





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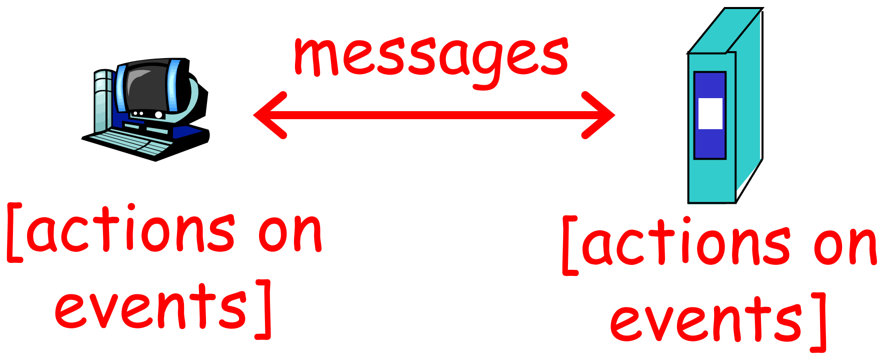
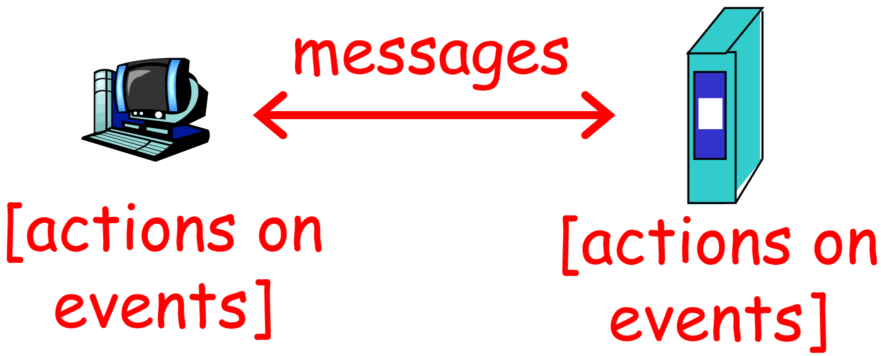


Need:

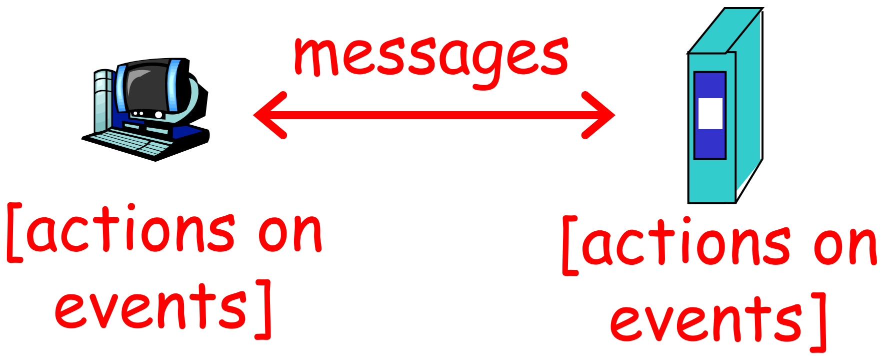
But first ...What's a protocol?



Need:

... specific msgs sent

But first …What's a protocol?

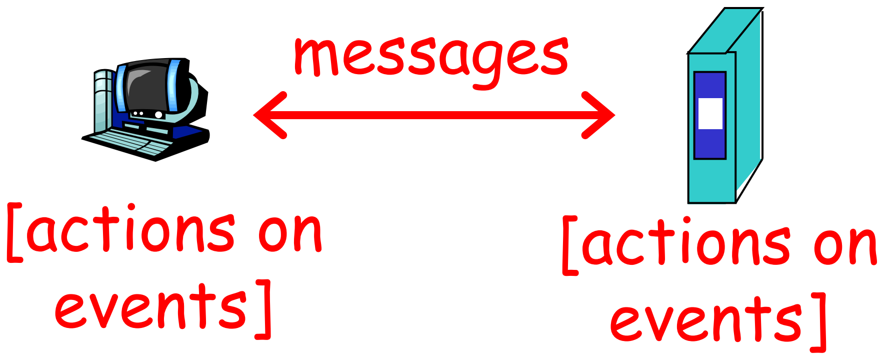


Need:

… specific msgs sent

… specific actions taken when msgs received, or other events

But first …What's a protocol?



Need:

… specific msgs sent

… specific actions taken when msgs received, or other events

Network protocols:

- Define the order and format of messages exchanged
- Defines the actions to take in response to events (e.g., message arrivals, transmissions, losses, and timeouts)

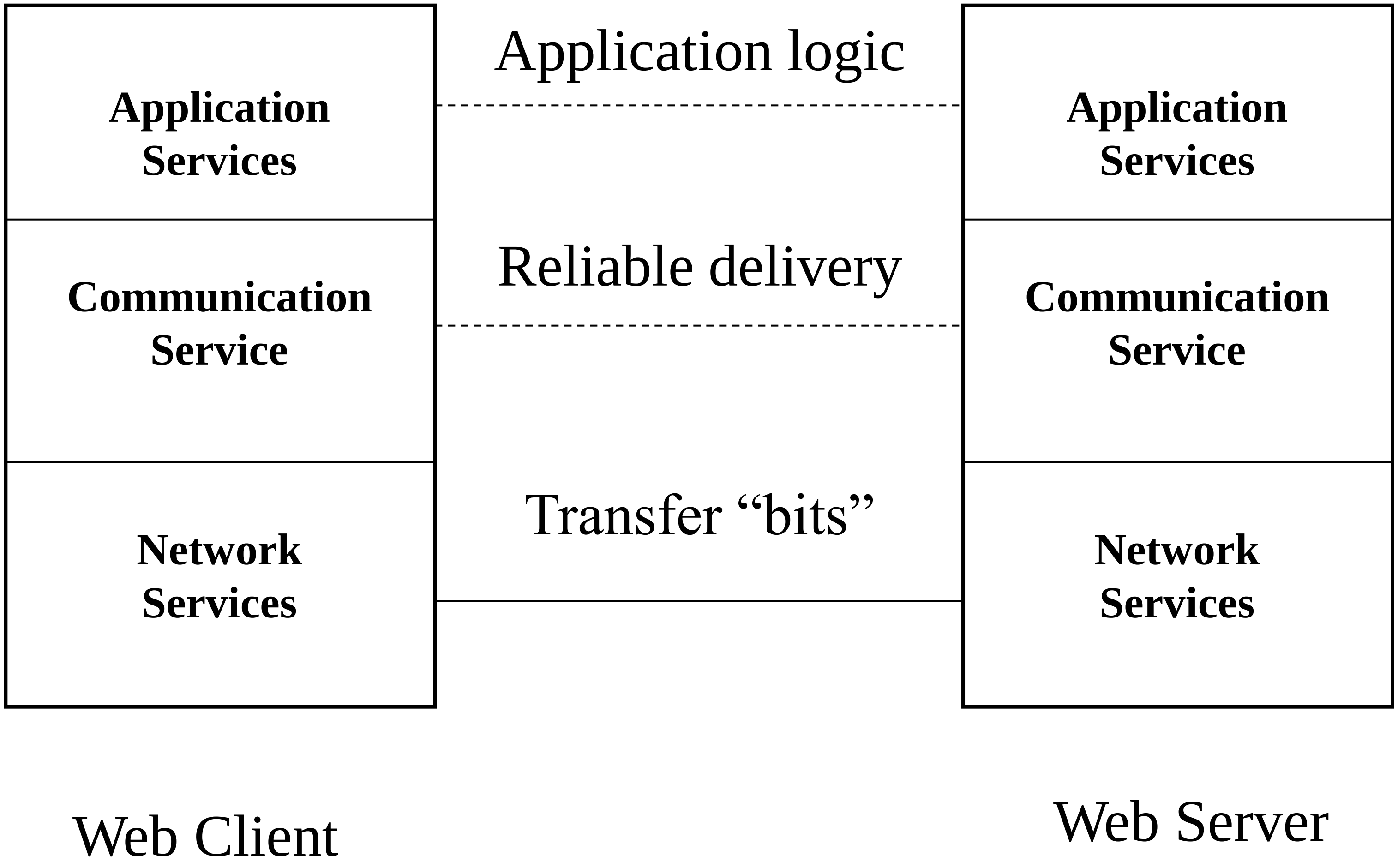
Layered Architecture: Why?

- Networks are complex with many pieces
  - Hosts, routers, links, applications, protocols, hardware, software
- Can we organize it, somehow?

Layered Architecture: Why?

- Networks are complex with many pieces
  - Hosts, routers, links, applications, protocols, hardware, software
- Can we organize it, somehow?
- Let's consider a Web page request …

Motivation Continued …



Motivation Continued …

Dealing with complex systems:

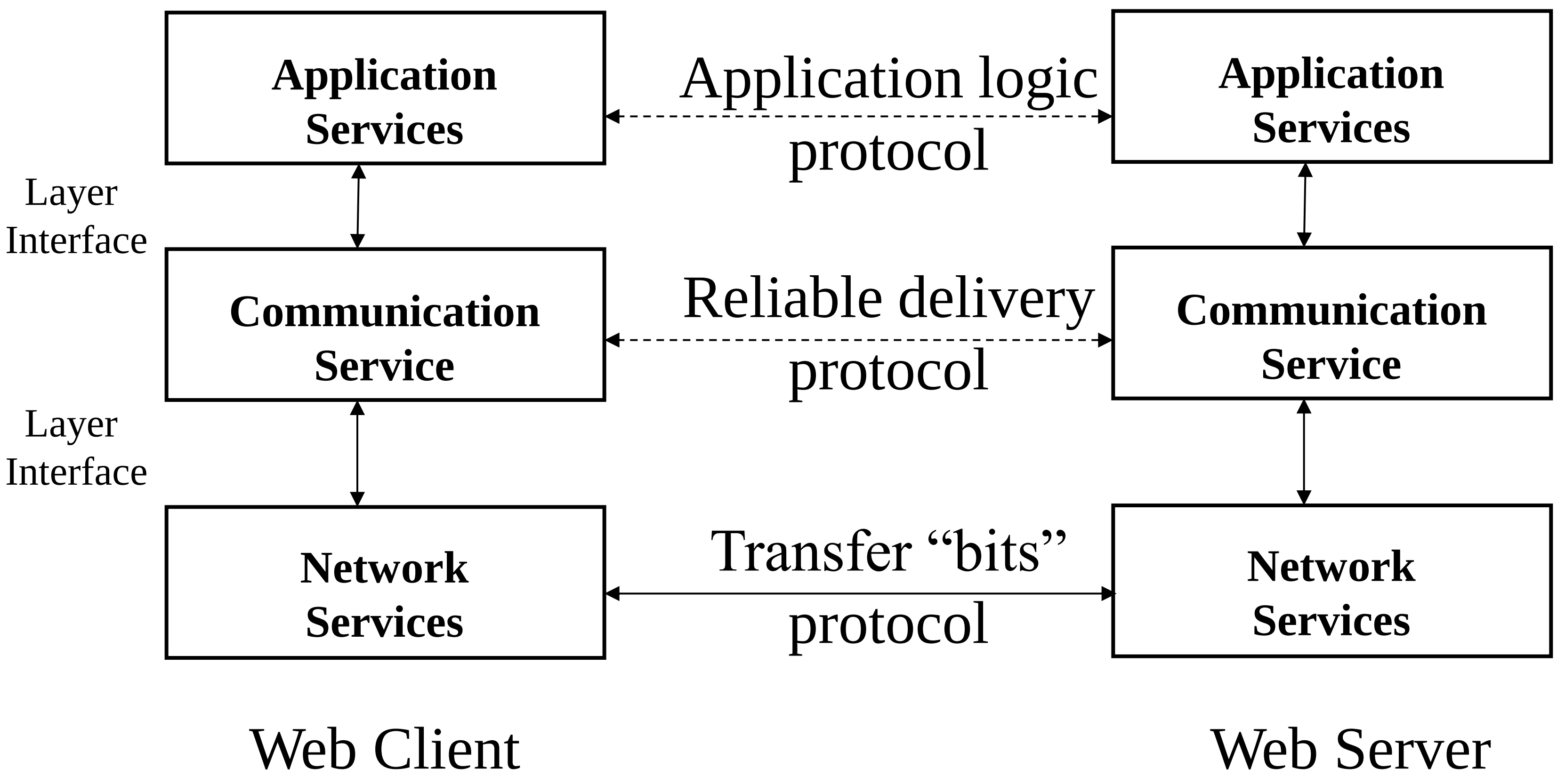
- explicit structure allows identification, relationship of complex system's pieces
  - layered reference model for discussion
- modularization eases maintenance, updating of system
  - change of implementation of layer's service transparent to rest of system
  - e.g., change in network technology doesn't affect rest of system
- layering considered harmful? (design vs implemention)

Layers, Protocols, Interfaces

Layers, Protocols, Interfaces

- Networks organized as a **stack of layers**
  - Offer services to the layer above it using a well-defined **interface**
    - programming language analogy: libraries hide details while providing a service)
  - Reduces design complexity
- **Protocols**: Logical "horizontal" conversations at any layer (between peers)
- **Data Transfer**: each layer passes data & control information over the interfaces (between neighboring layers)

Layers, Protocols, Interfaces



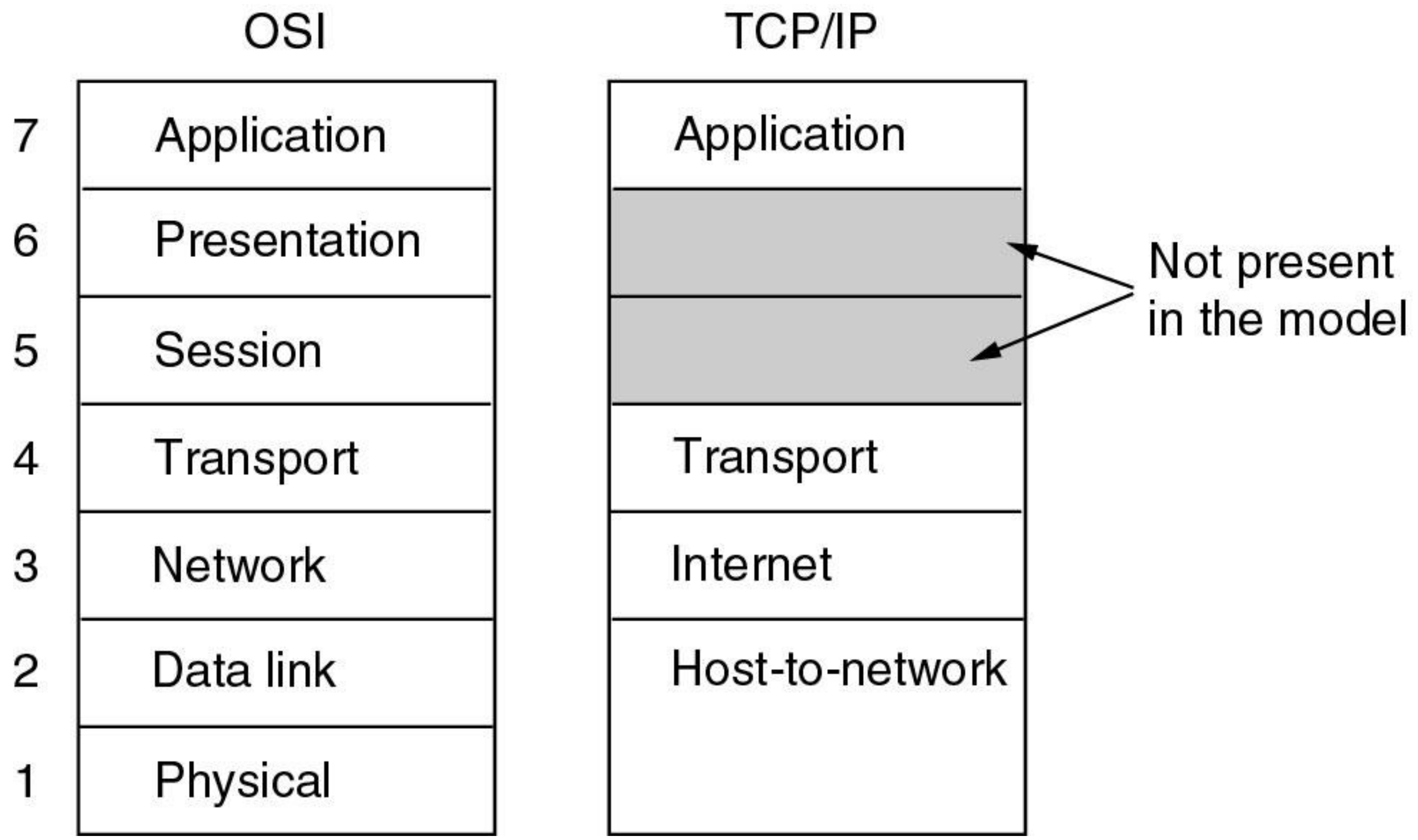
Layered Architecture (cont'd)

- A set of layers & protocols is called a Network Architecture.
- These specifications enable hardware/software developers to build systems compliant with a particular architecture.
  - E.g., TCP/IP, OSI

Layering: Design Issues

- How many layers? What do they each do?
- How to identify senders/receivers?
  - Addressing
- Unreliable physical communication medium?
  - Error detection
  - Error control
  - Message reordering
- Sender can swamp the receiver?
  - Flow control
- Multiplexing/Demultiplexing

Reference Models



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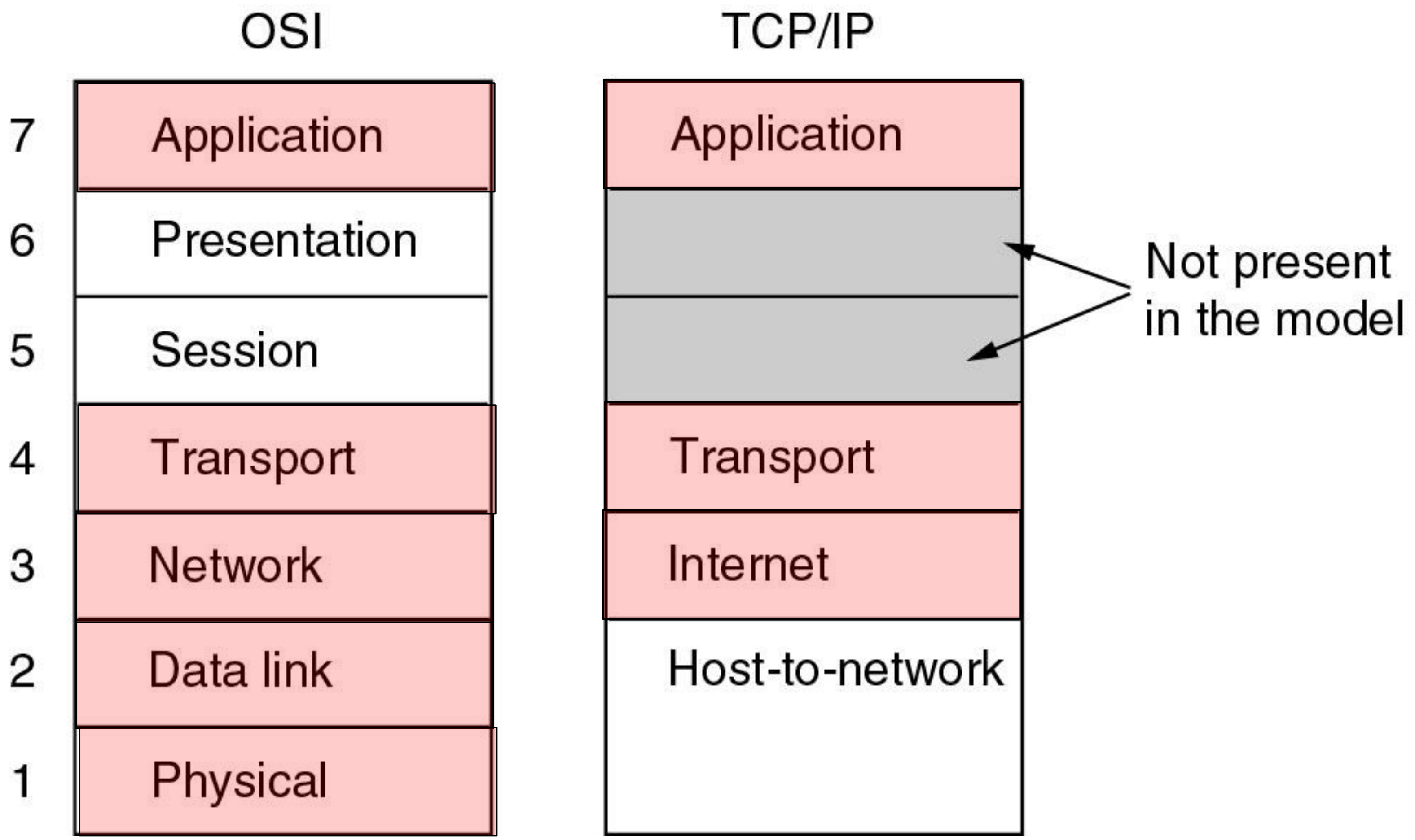
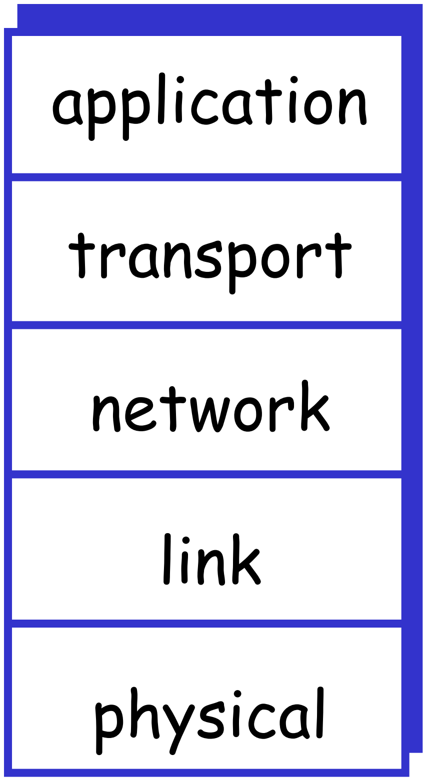


Internet protocol stack

- application: supporting network applications
  - FTP, SMTP, STTP
- transport: host-host data transfer
  - TCP, UDP
- network: routing of datagrams from source to destination
  - IP, routing protocols
- link: data transfer between neighboring network elements
  - PPP, Ethernet
- physical: bits "on the wire"



The Application Layer

- Residence of network applications and their application control logic
- Examples include:
  - HTTP (Hyper-Text Transfer Protocol)
  - FTP (File Transfer Protocol)
  - Telnet
  - SMTP (Simple Mail Transfer Protocol)
  - DNS (Domain Name Service)

The Transport Layer

- Concerned with end-to-end data transfer between end systems (hosts)
- Transmission unit is called <u>segment</u>
- TCP/IP networks such as the Internet provides two types of services to applications
  - "connection-oriented" service – Transmission Control Protocol (TCP)
  - "connectionless" service - User Datagram Protocol (UDP)

The Network Layer

- End systems inject datagrams in the networks
- A transmission path is determined for each packet (routing)
- A “best effort” service
  - Datagrams might be lost
  - Datagrams might arrive out of order
- Analogy: Postal system

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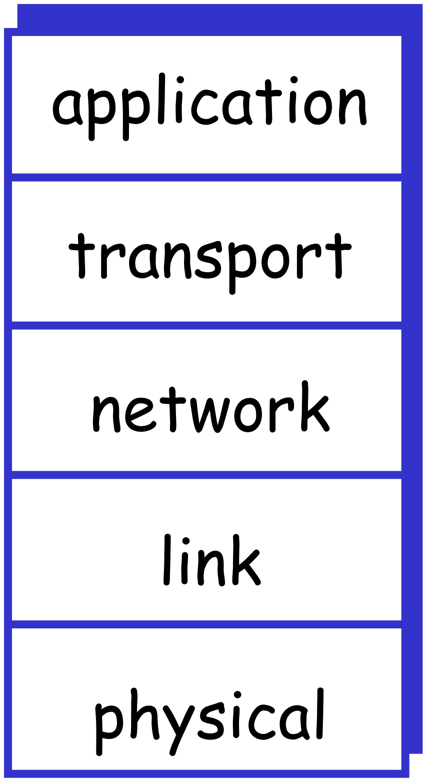
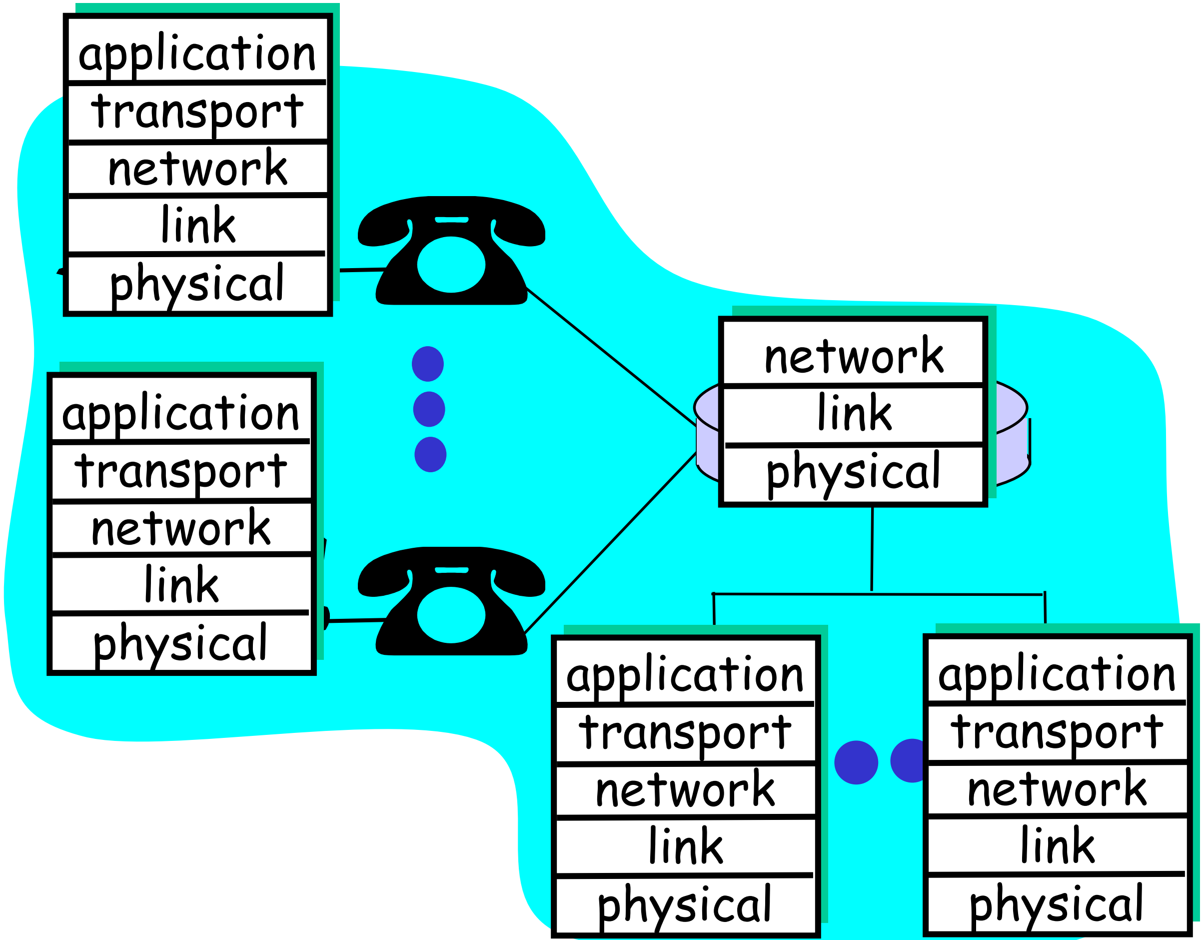
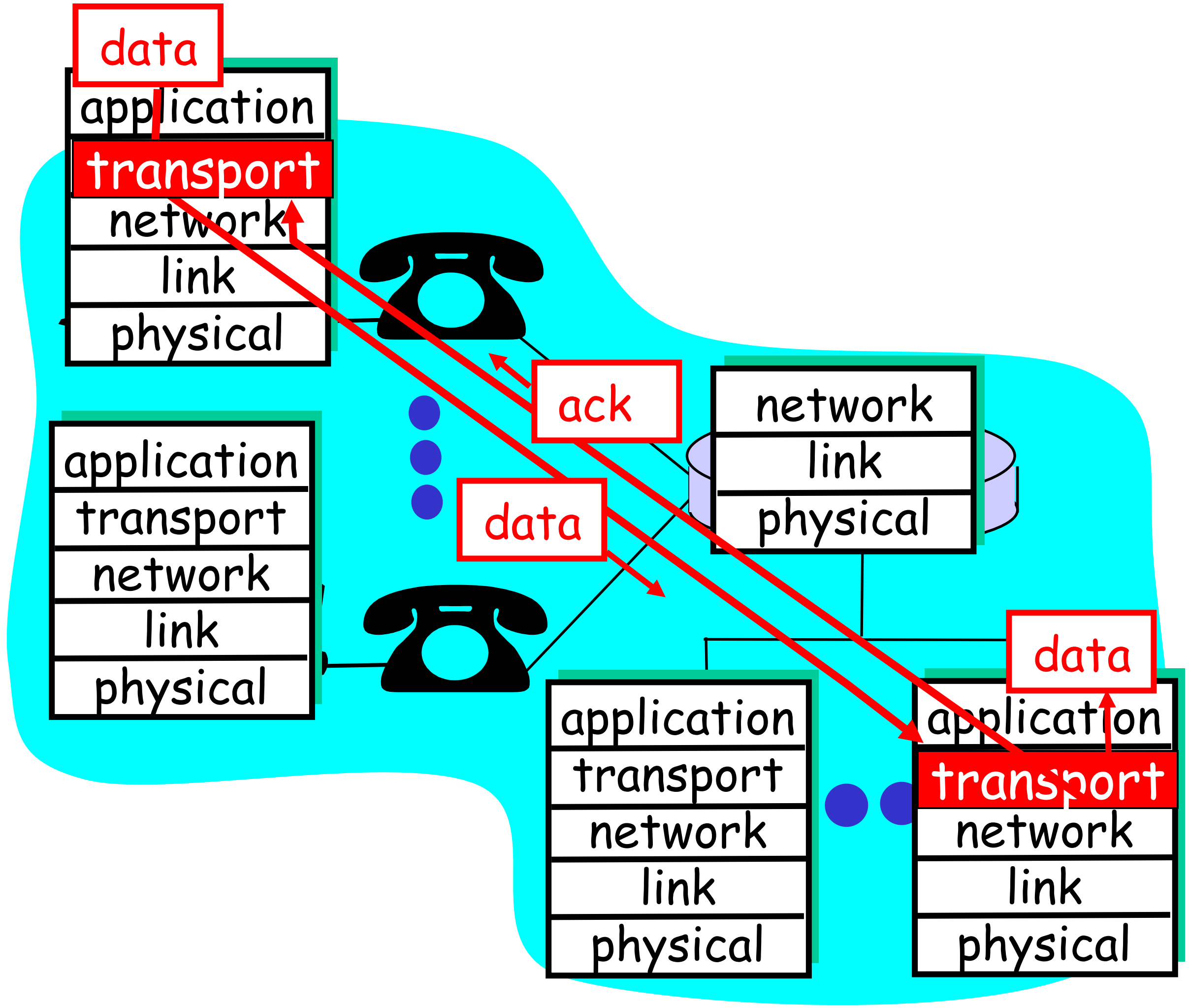


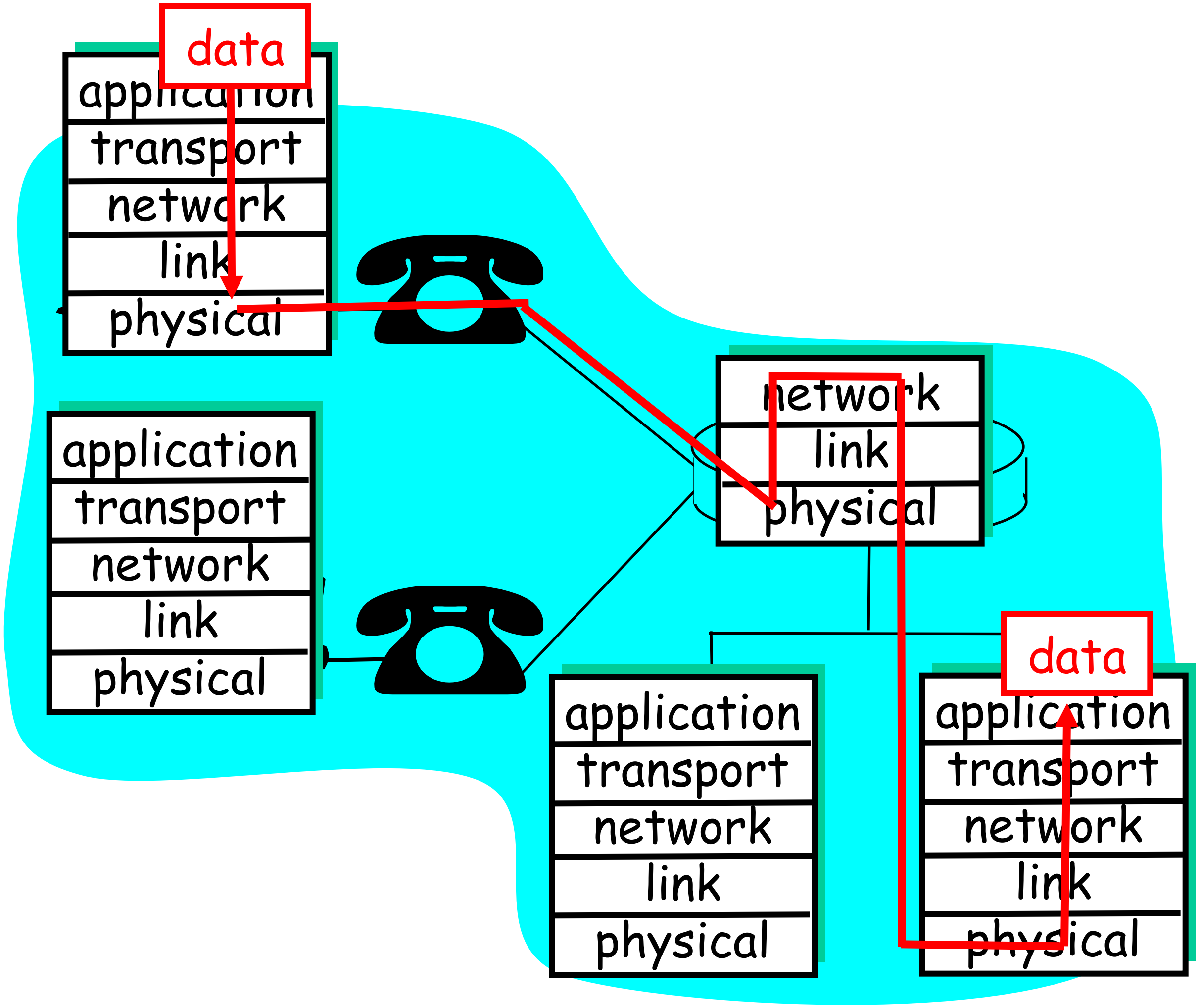
Layering: logical communication



Layering: *logical* communication



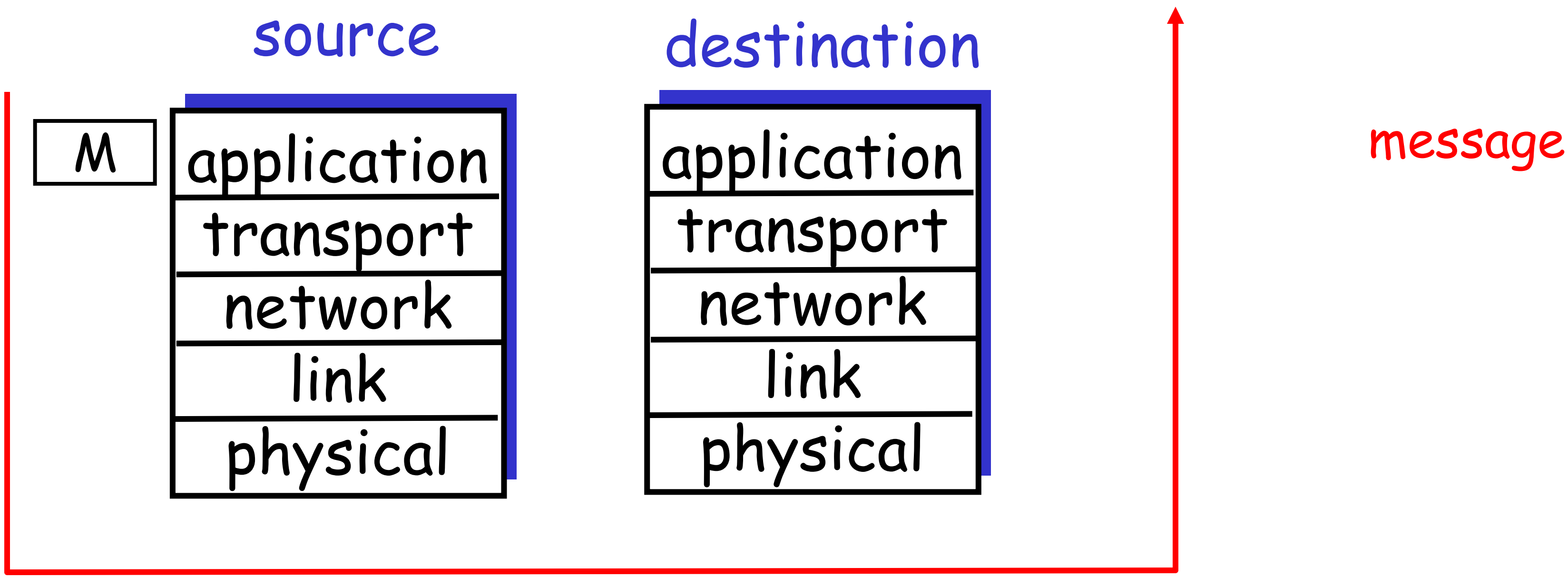
Layering: *physical* communication



Encapsulation: Layering and data

Each layer takes data from above

- adds header information to create new data unit
- passes new data unit to layer below



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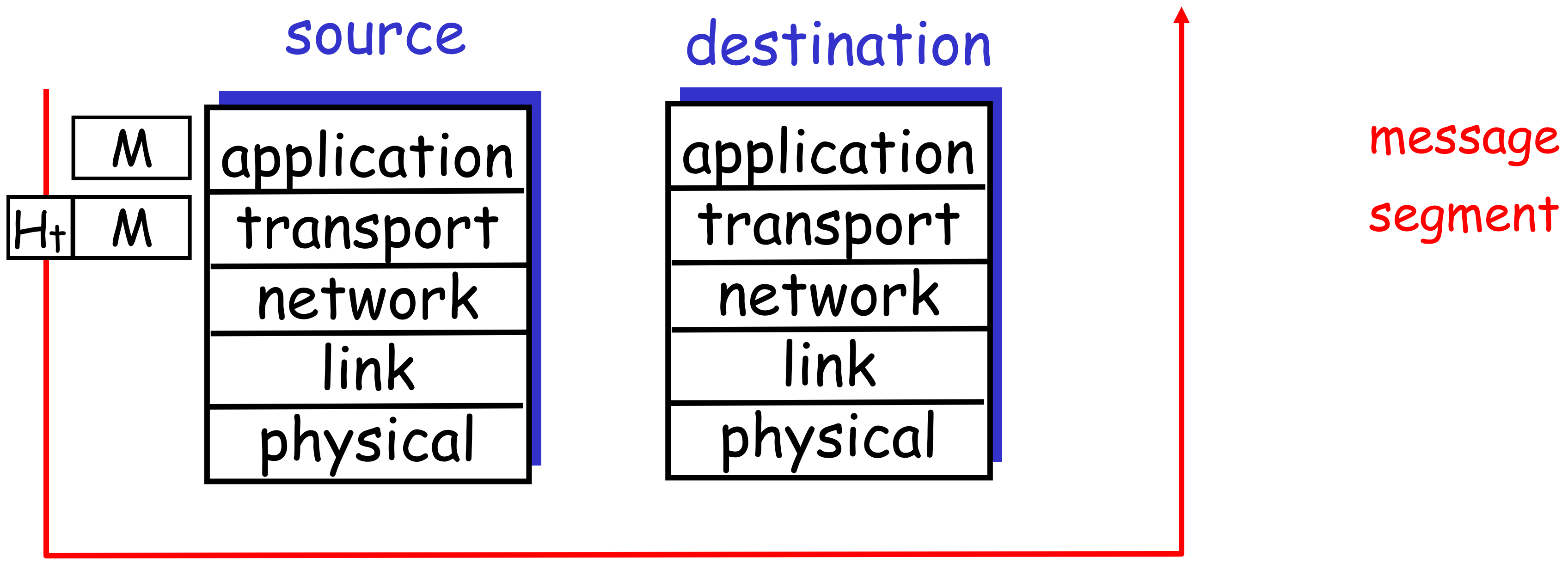

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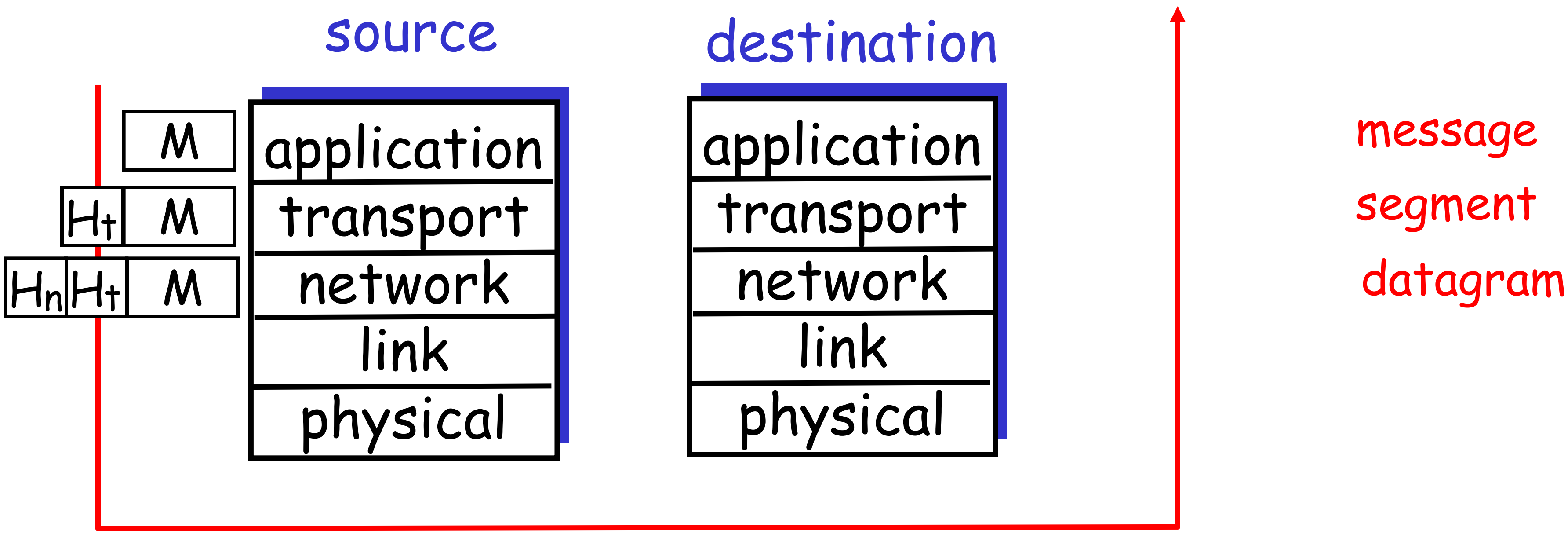

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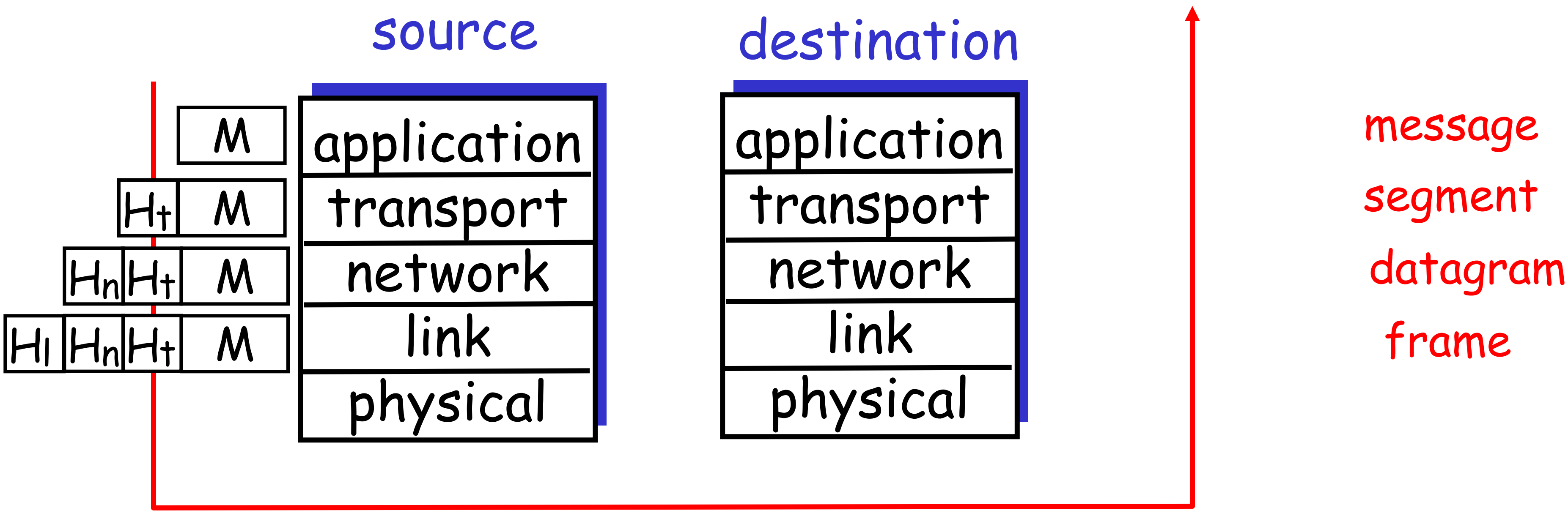

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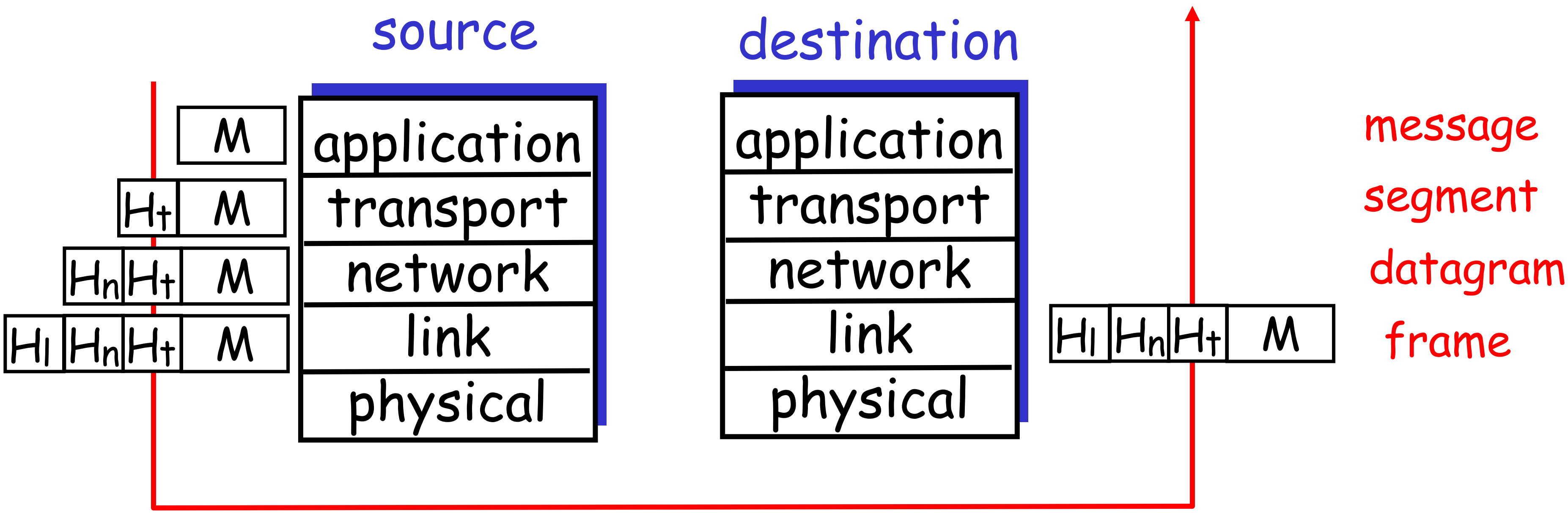

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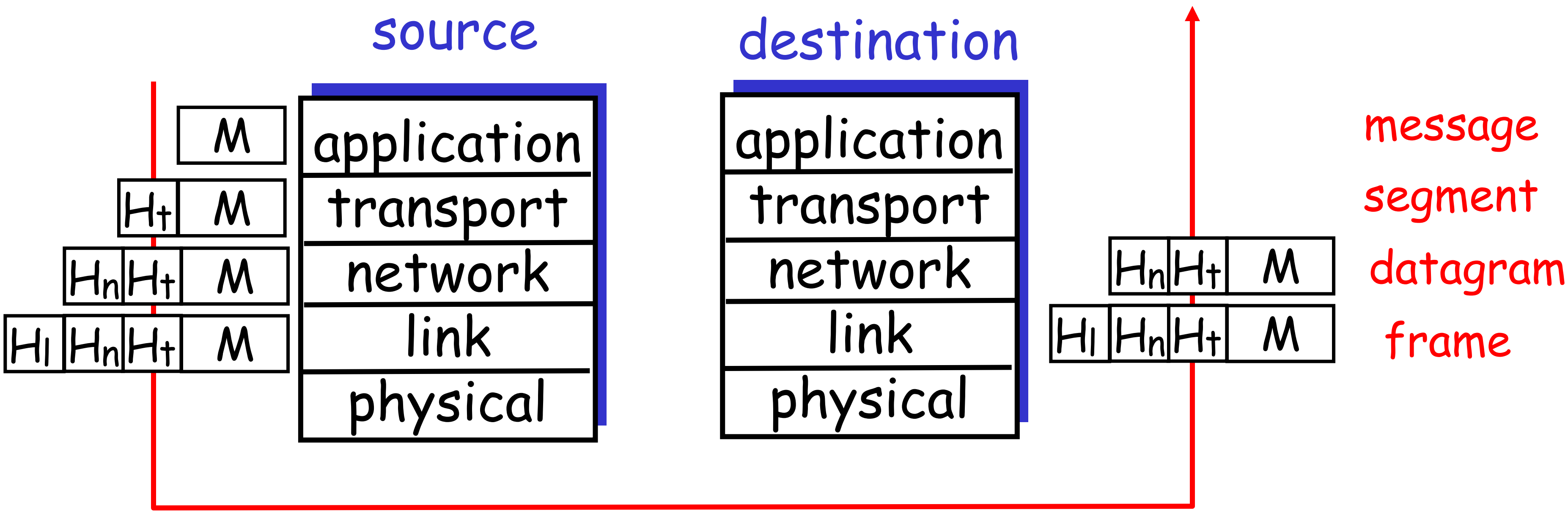

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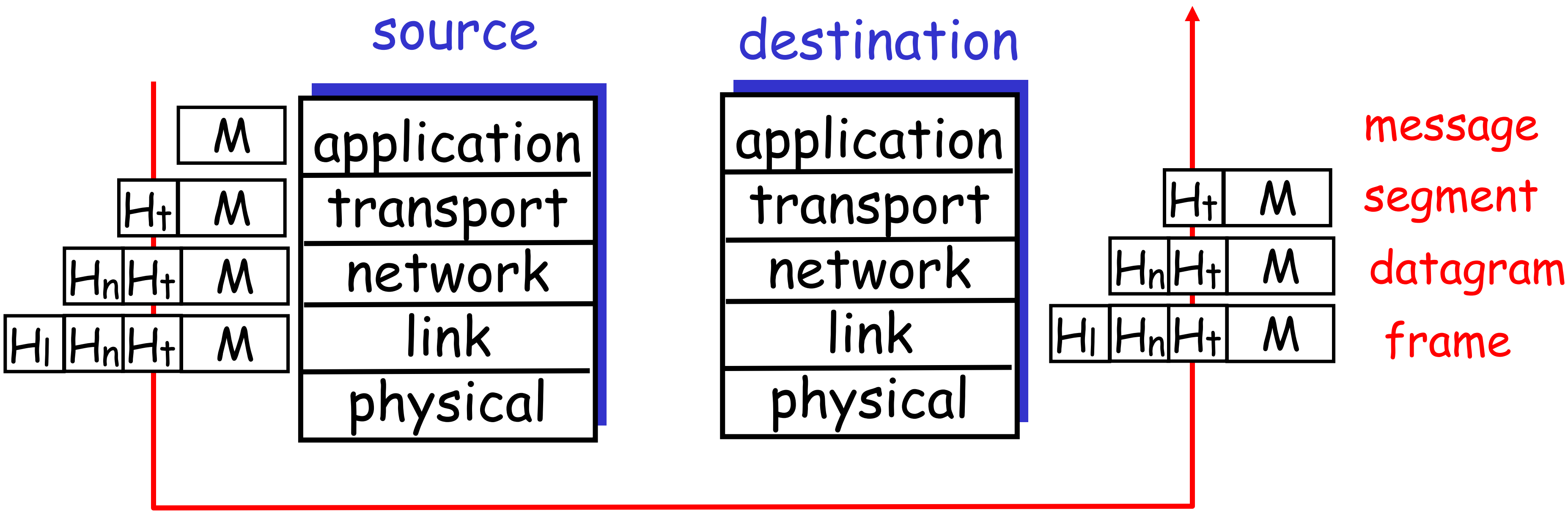

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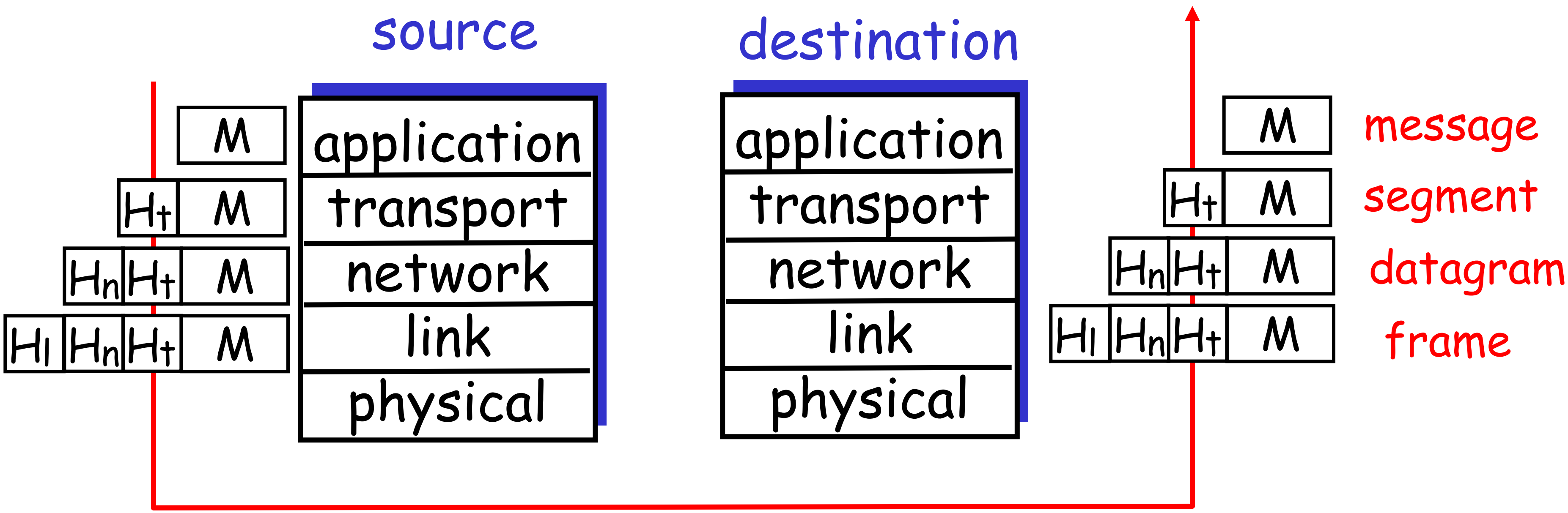

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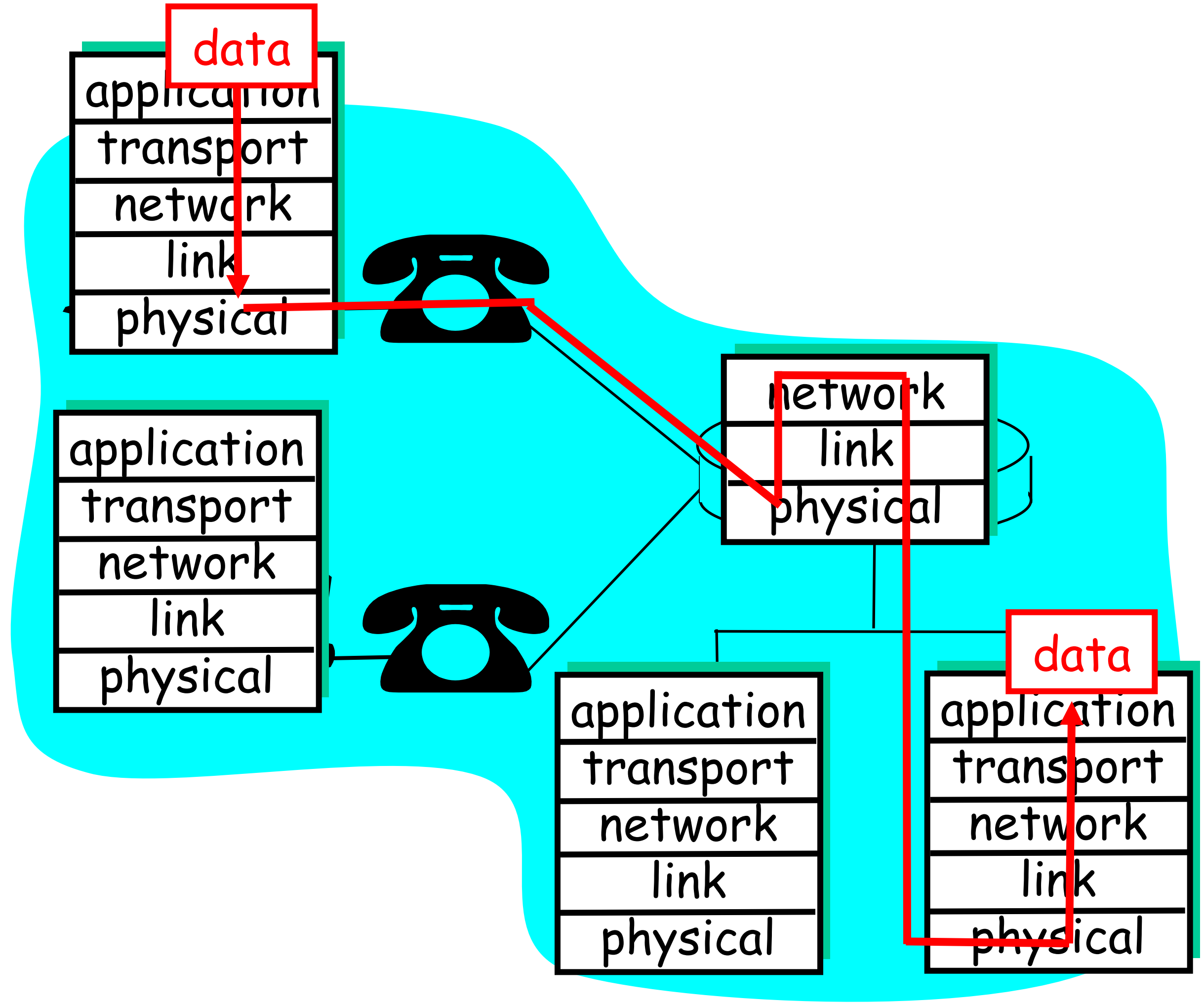

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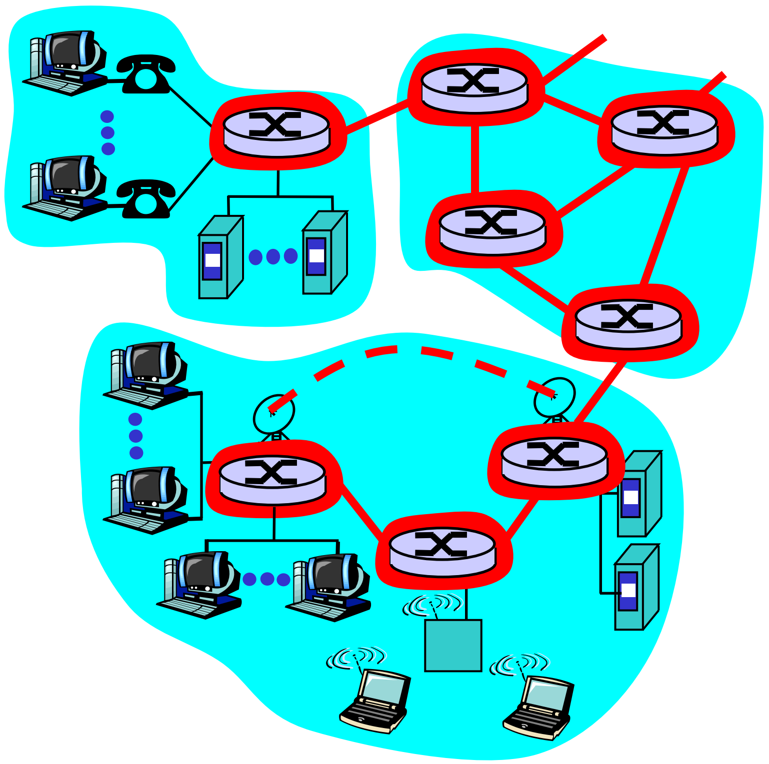
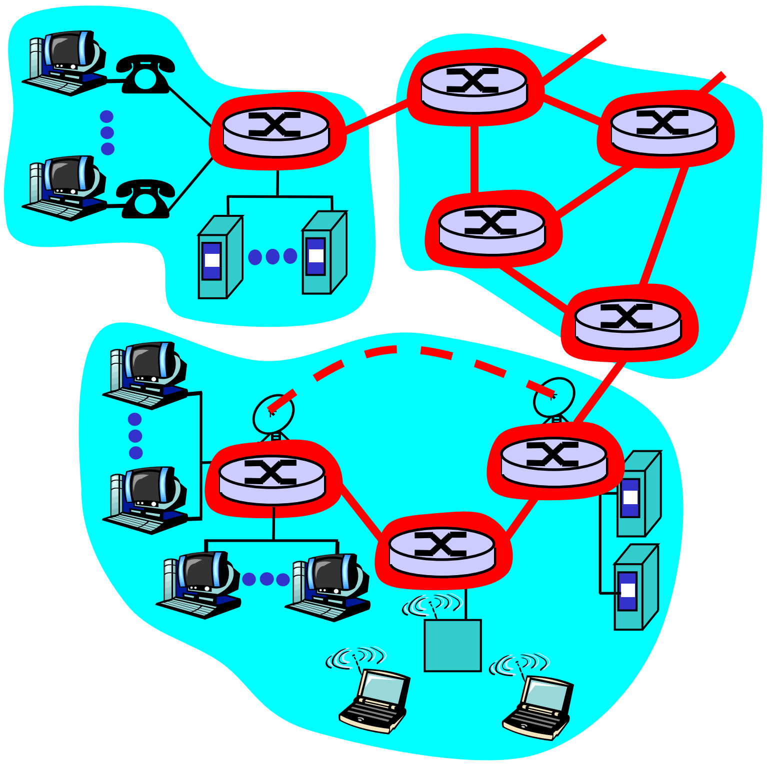
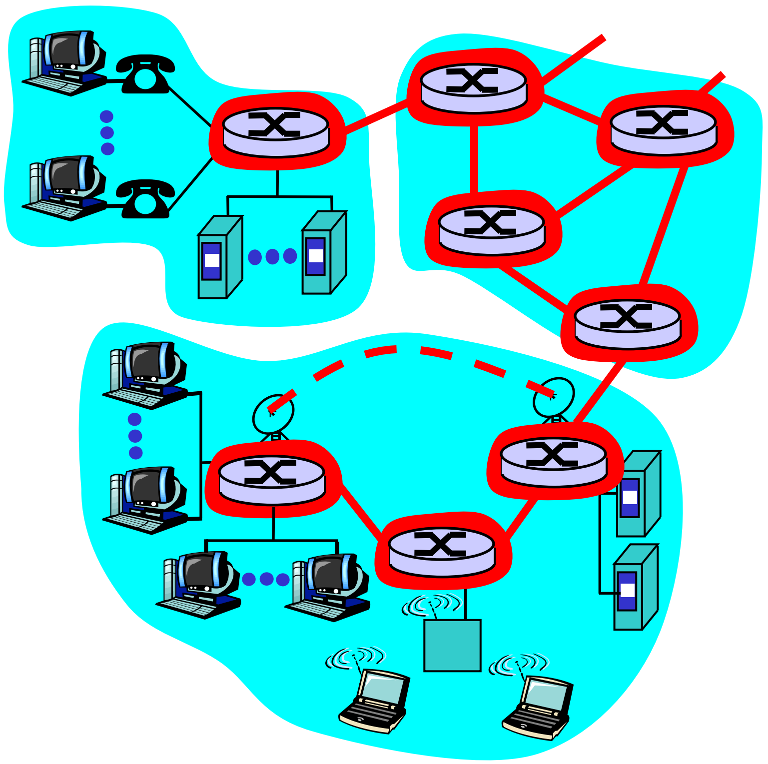
- mesh of interconnected routers



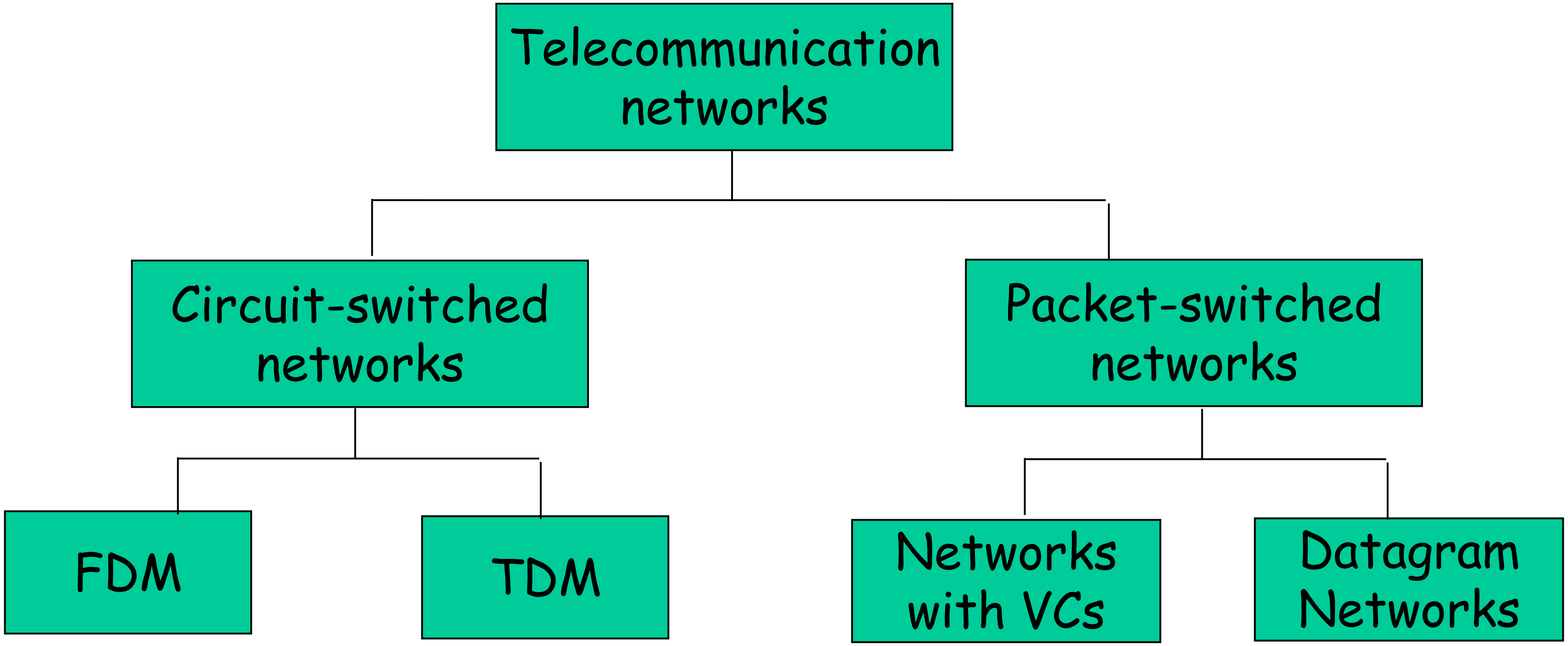
- mesh of interconnected routers
- *the* fundamental question: how is data transferred through net?



- mesh of interconnected routers
- *the* fundamental question: how is data transferred through net?
  - circuit-switching: dedicated circuit per call: telephone net
  - packet-switching: data sent thru net in discrete "chunks"



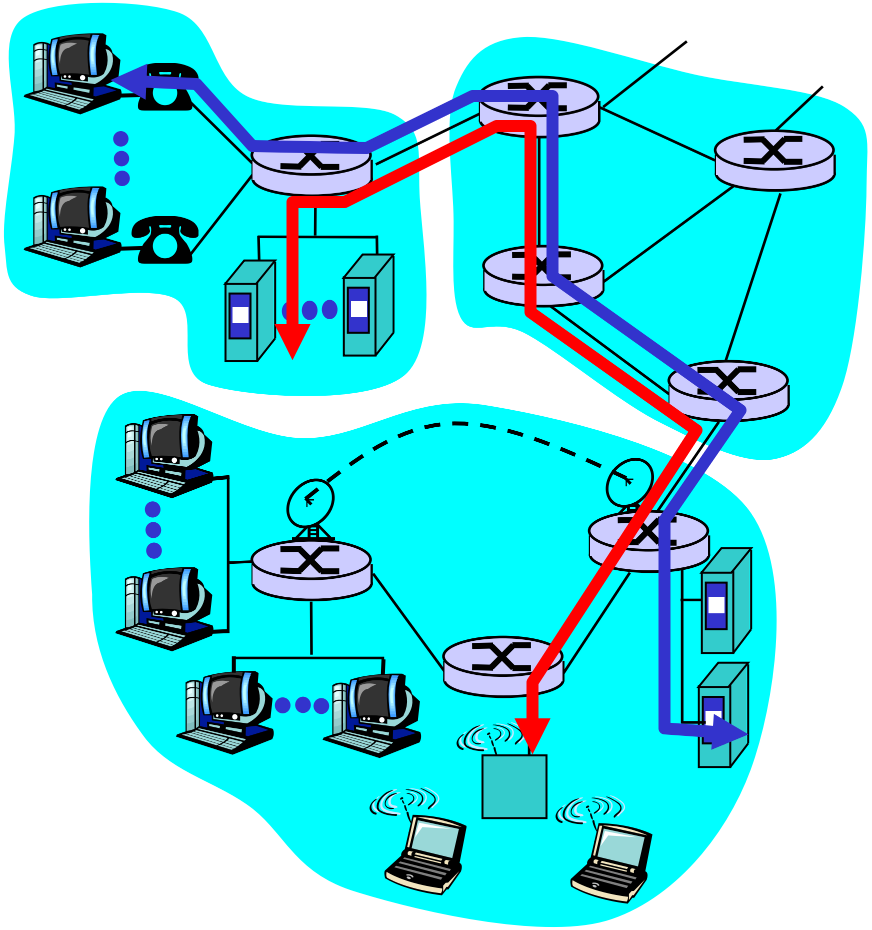
Network Taxonomy



Alt. 1: Circuit-Switching

End-to-end resources reserved for "call"

- Link bandwidth, switch capacity
- Dedicated resources with no sharing
- Guaranteed transmission capacity
- Call setup required
- "Blocking" may occur



Alt. 1: Circuit-Switching

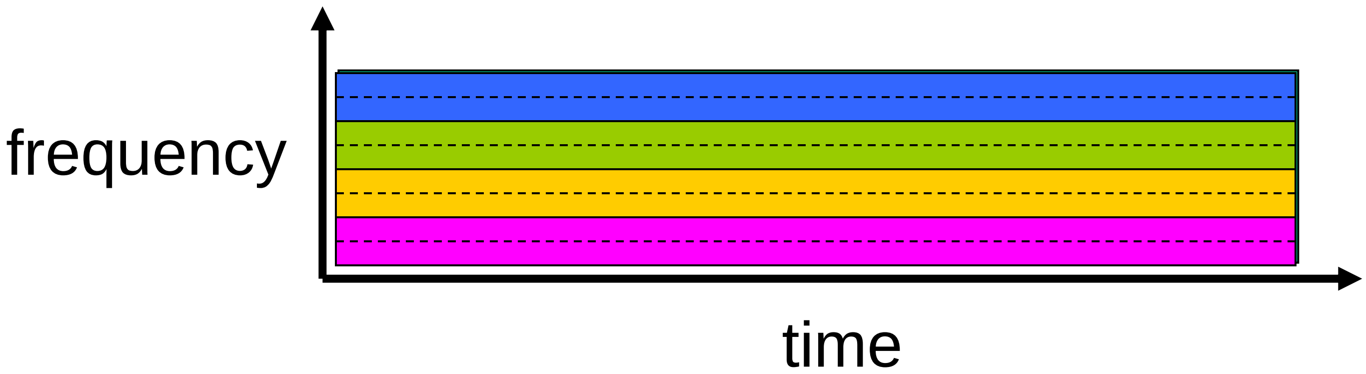
- Capacity of medium exceeds the capacity required for transmission of a single signal
  - How can we improve “efficiency”? Let’s multiplex.
- Divide link bandwidth into “pieces”:
  - frequency division - FDMA
  - time division – TDMA
  - code division - CDMA (cellular networks)
  - wavelength division - WDM (optical)

Circuit-Switching: FDMA and TDMA

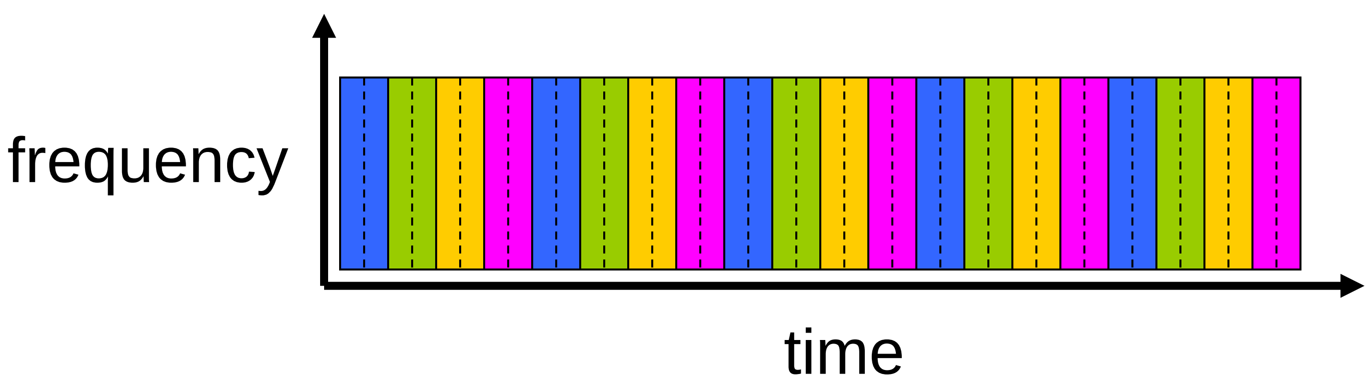
Example:

4 users

FDMA



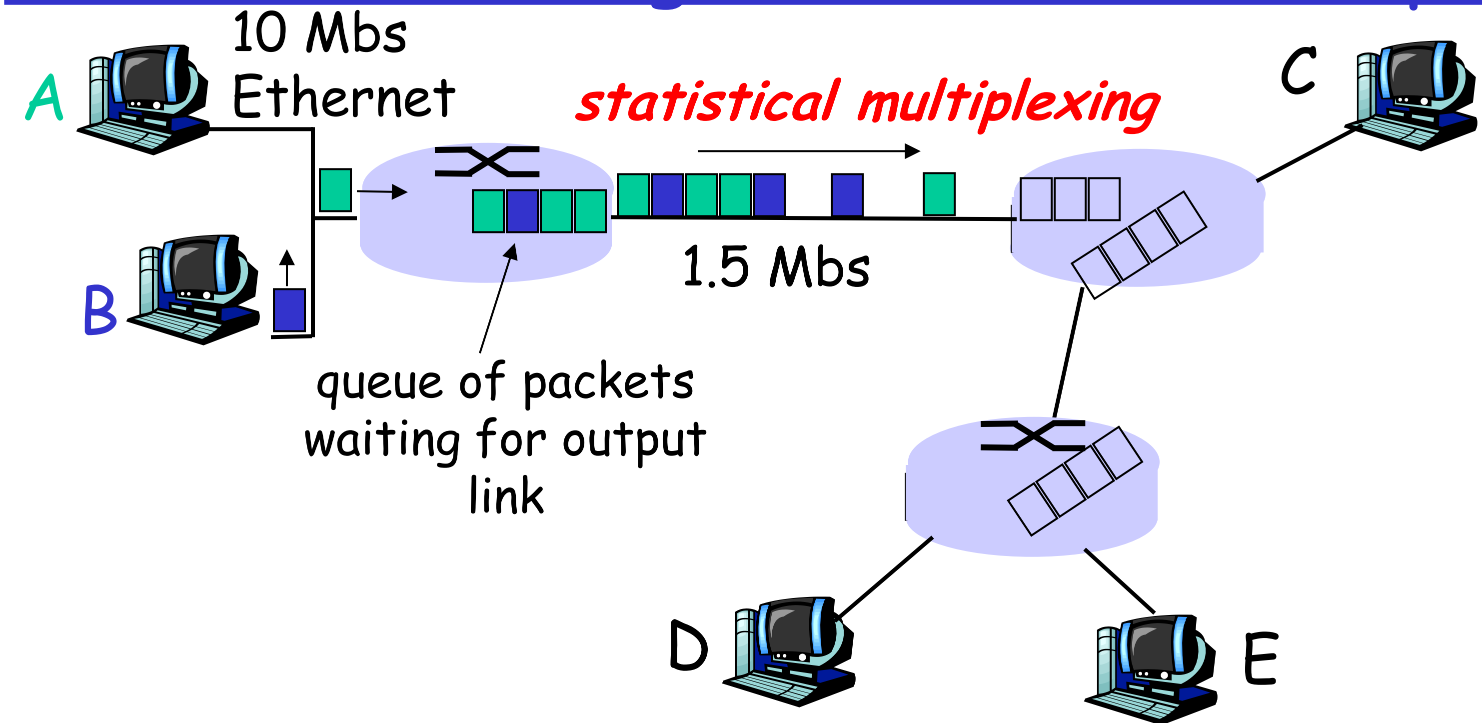
TDMA



Alt. 2: Packet-Switching

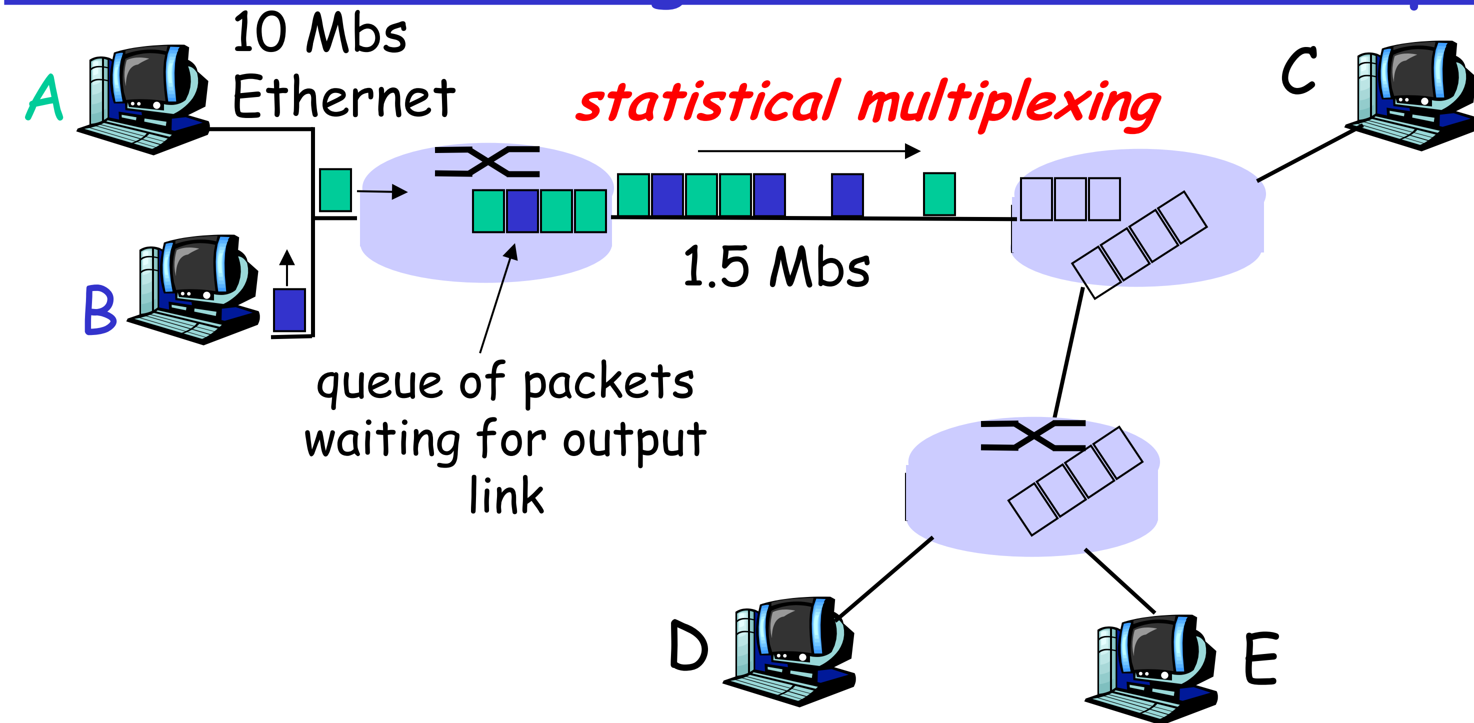
- source breaks long messages into smaller "packets"
- "store-and-forward" transmission
  - packets *share* network resources
  - each packet briefly uses full link bandwidth
- resource contention
  - aggregate resource demand can exceed amount available
  - congestion: packets queue, wait for link use
  - analogy: rush hour traffic in cities

Packet-Switching: Statistical Multiplexing



- Resource sharing great for bursty traffic
  - E.g., Sequence of A & B packets does not have fixed pattern - ***statistical multiplexing***.
  - In contrast: In TDM each host gets same slot in revolving TDM frame.

Packet-Switching: Statistical Multiplexing



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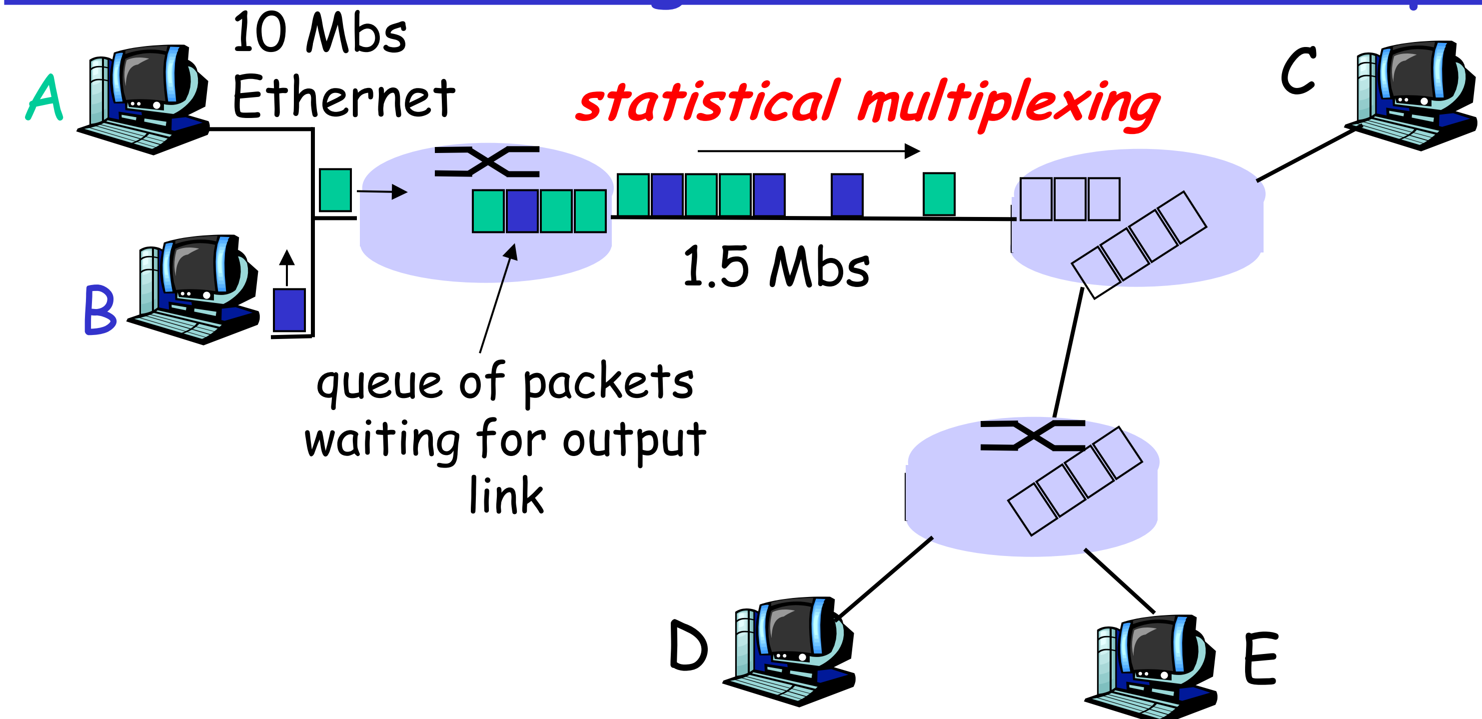

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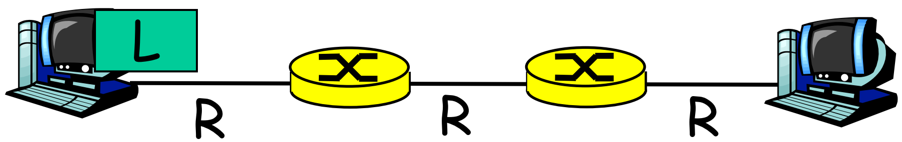
  - E.g., delay/loss and bandwidth guarantees ...

Packet-switching: store-and-forward

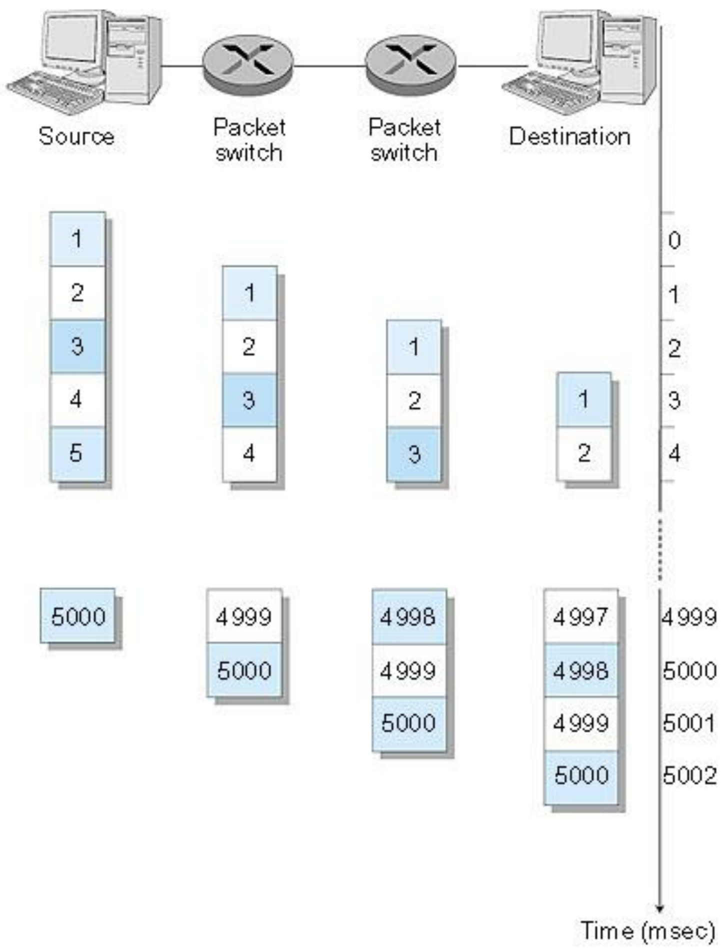


- Takes L/R seconds to transmit (push out) packet of L bits on to link or R bps
- Entire packet must arrive at router before it can be transmitted on next link: *store and forward*
- delay = 3L/R

Example:

- L = 7.5 Mbits
- R = 1.5 Mbps
- delay = 15 sec

Packet-Switching: Message Segmenting



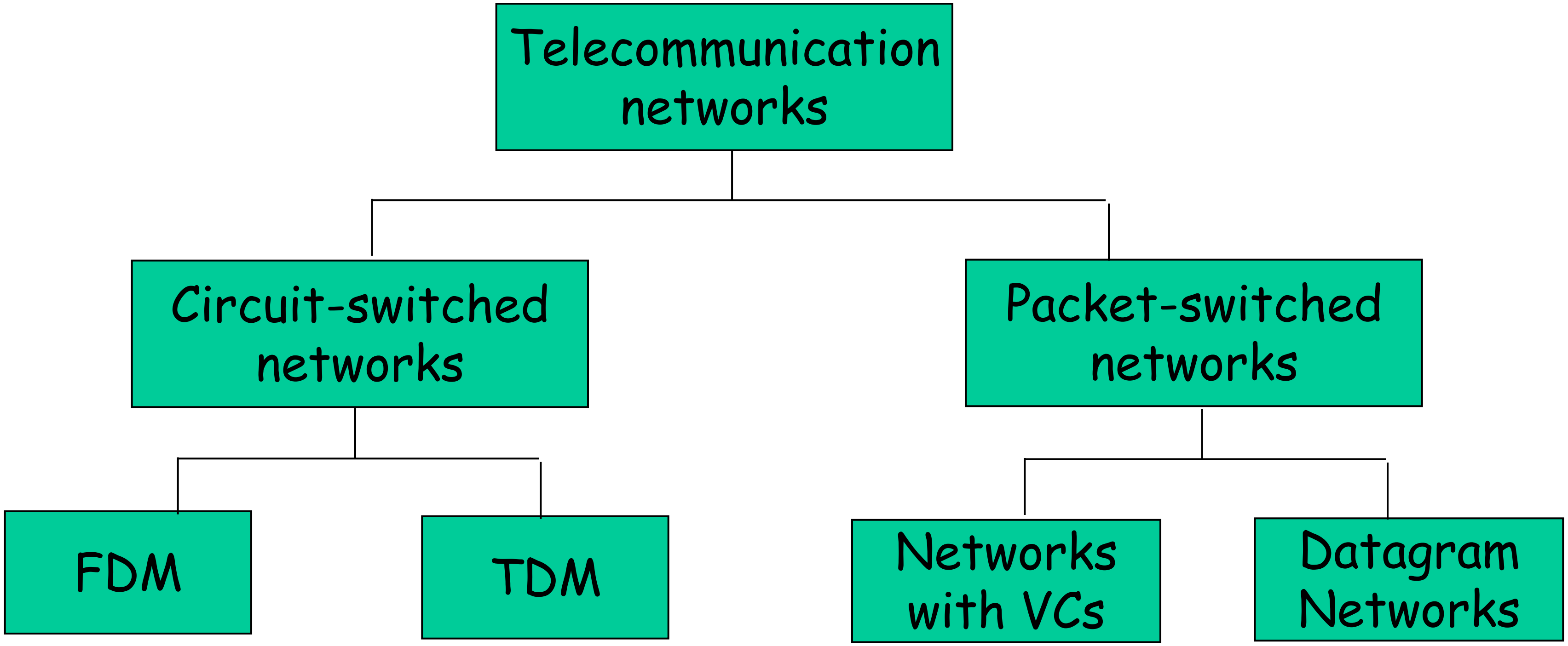
Now break up the message into 5000 packets

- Each packet 1,500 bits
- 1 msec to transmit packet on one link
- *pipelining:* each link works in parallel
- Delay reduced from 15 sec to 5.002 sec

Packet-switched networks: forwarding

- datagram network:
  - *destination address* in packet determines next hop
  - routes may change during session (flexible?)
  - no "per flow" state, hence more scalable
- virtual circuit network:
  - each packet carries tag (virtual circuit ID), tag determines next hop
  - fixed path determined at *call setup time*
  - path is **not** a dedicated path as in circuit switched (i.e., store & forward of packets)
  - *routers maintain per-call state*
- datagram networks need per packet routing.

Network Taxonomy



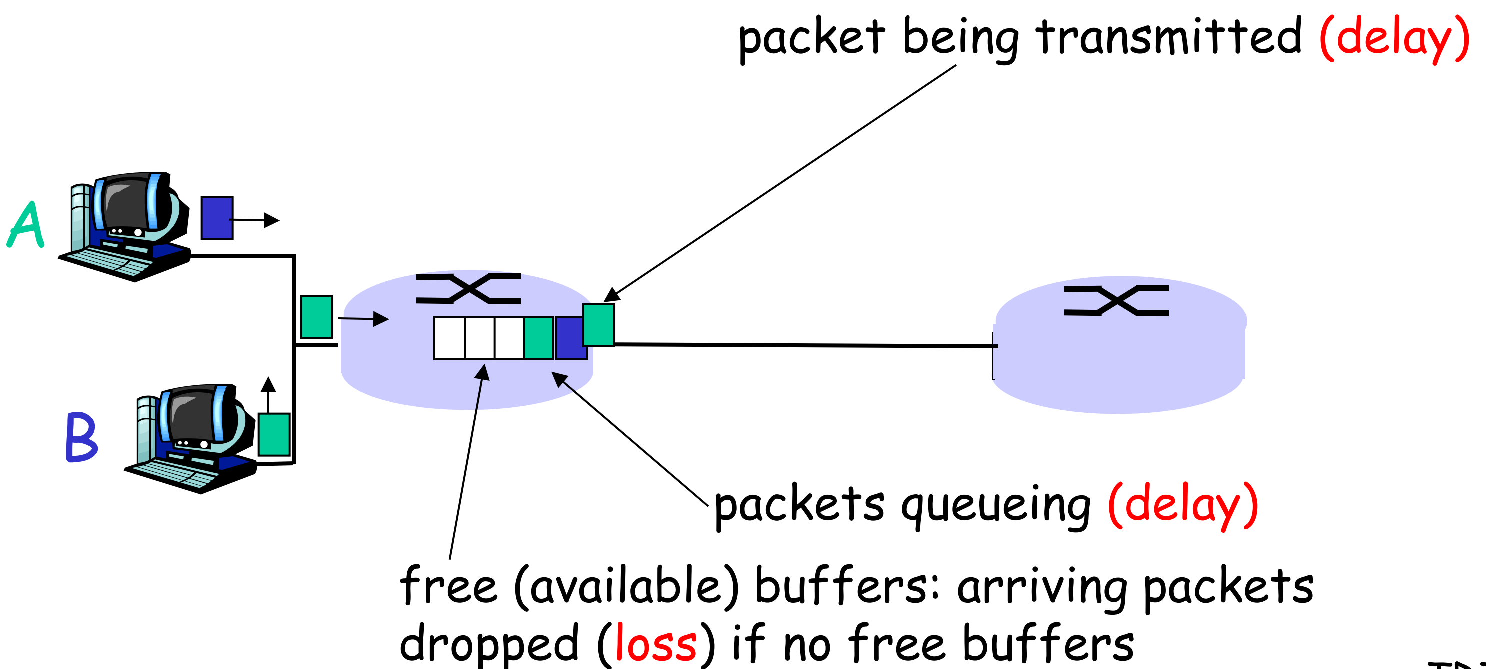
Roadmap

- What is a Computer Network?
- Applications of Networking
- Classification of Networks
- Layered Architecture (and Protocols)
- Network Core
- Delay & Loss in Packet-switched Networks
- Structure of the Internet
- Summary

How do loss and delay occur?

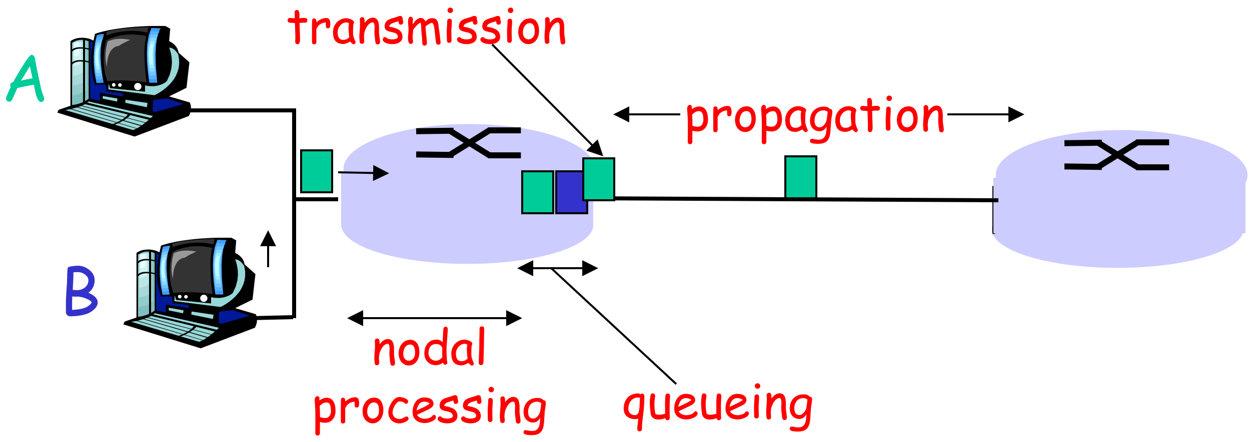
packets *queue* in router buffers

- packet arrival rate to link exceeds output link capacity
- packets queue, wait for turn
- if queue is full, arriving packets dropped (Drop-Tail)



Four sources of packet delay

- 1. Processing delay:
  - check bit errors
  - determine output link
- 2. Queueing delay:
  - time waiting at output link for transmission
  - depends on congestion level of router



Delay in packet-switched networks

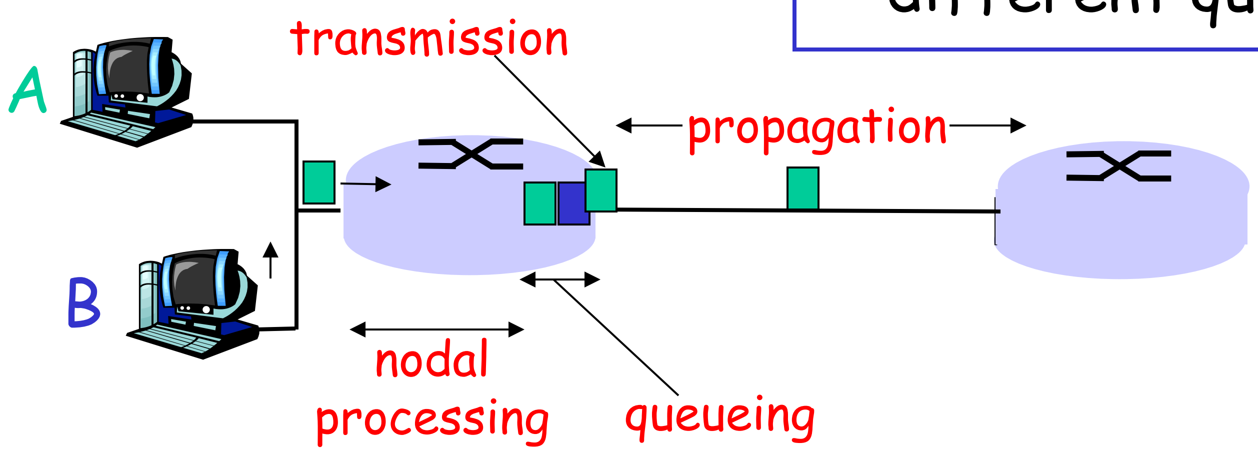
3. Transmission delay:

- R=link bandwidth (bps)
- L=packet length (bits)
- time to send bits into link = L/R

4. Propagation delay:

- d = length of physical link
- s = propagation speed in medium (~2x10^8 m/sec)
- propagation delay = d/s

Note: s and R are *very* different quantities!



Nodal processing delay

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

- d_{proc} = processing delay
  - typically a few microsecs or less
- d_{queue} = queuing delay
  - depends on congestion
- d_{trans} = transmission delay
  - = L/R, significant for low-speed links
- d_{prop} = propagation delay
  - a few microsecs to hundreds of msecs

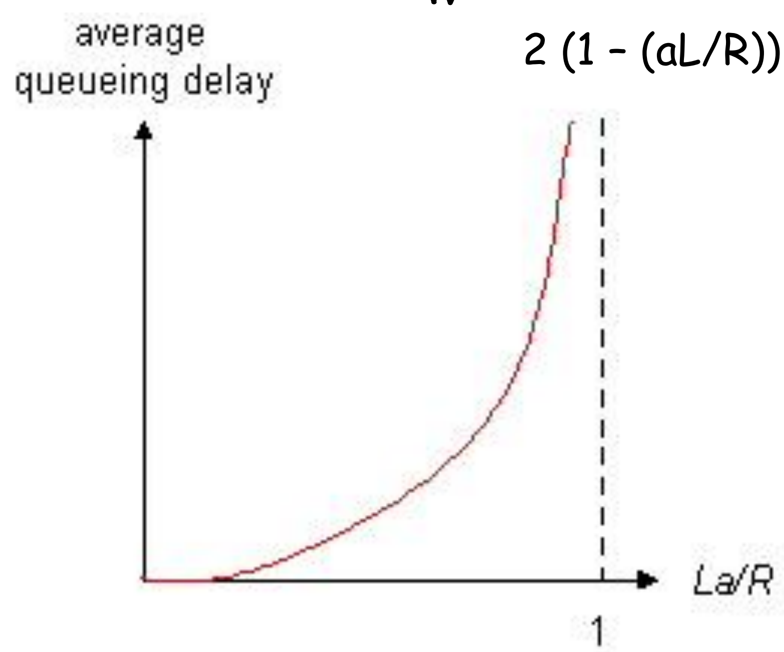
E.g., Assume M/D/1

Queueing delay (revisited)

$$W = \frac{L/R\ (aL/R)}{2\ (1 - (aL/R))}$$

- R=link bandwidth (bps)
- L=packet length (bits)
- a=average packet arrival rate

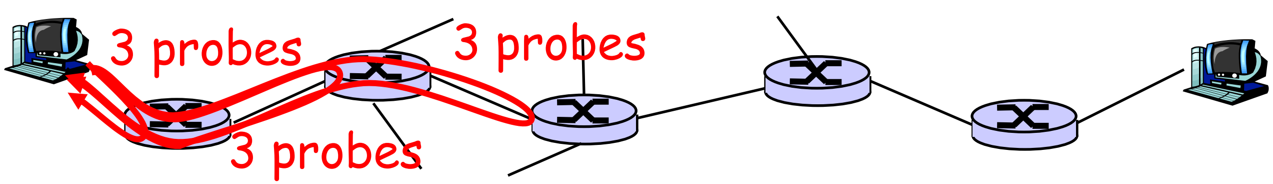
traffic intensity = aL/R



- aL/R ~ 0: average queueing delay small
- aL/R -> 1: delays become large
- aL/R > 1: more "work" arriving than can be serviced, average delay infinite!

"Real" Internet delays and routes

- What do "real" Internet delay & loss look like?
- Traceroute program: provides delay measurement from source to router along end-to-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.



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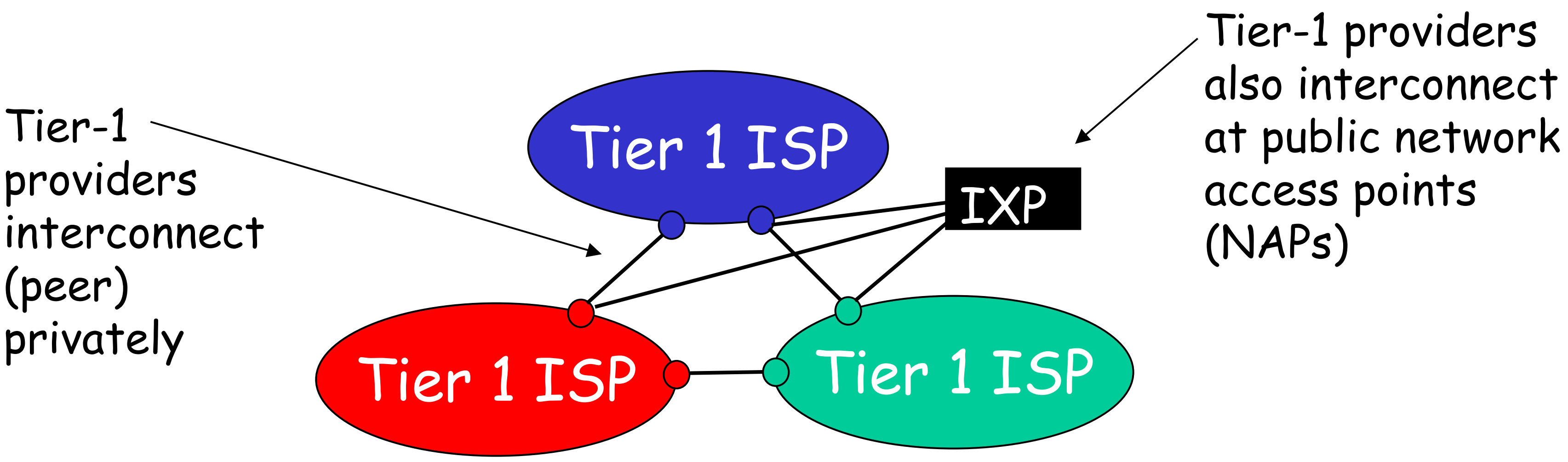
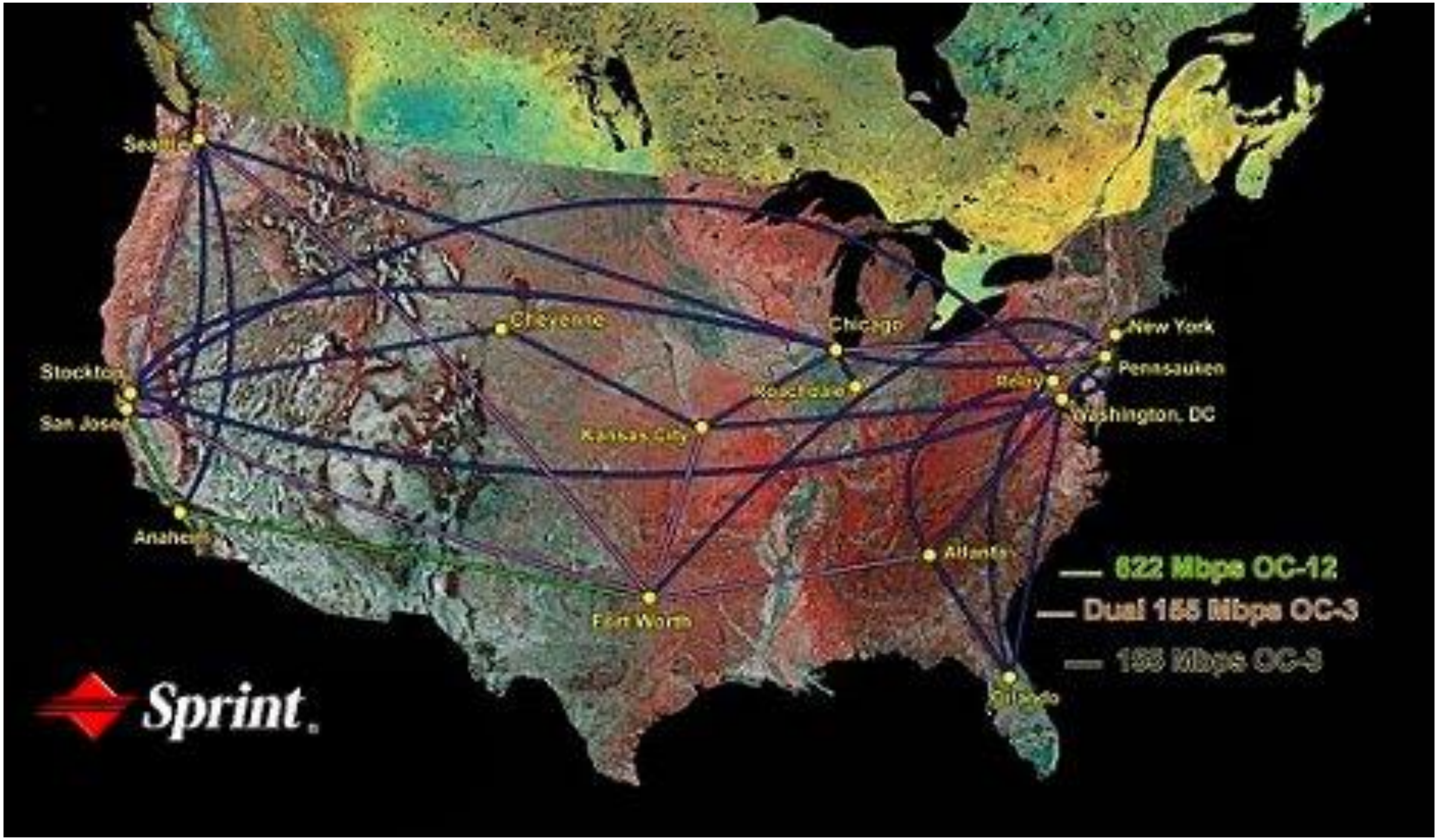
Internet structure: network of networks

- roughly hierarchical
- at center: "tier-1" ISPs (e.g., UUNet, BBN/Genuity, Sprint, AT&T), national/international coverage
  - treat each other as equals



Tier-1 ISP: e.g., Sprint

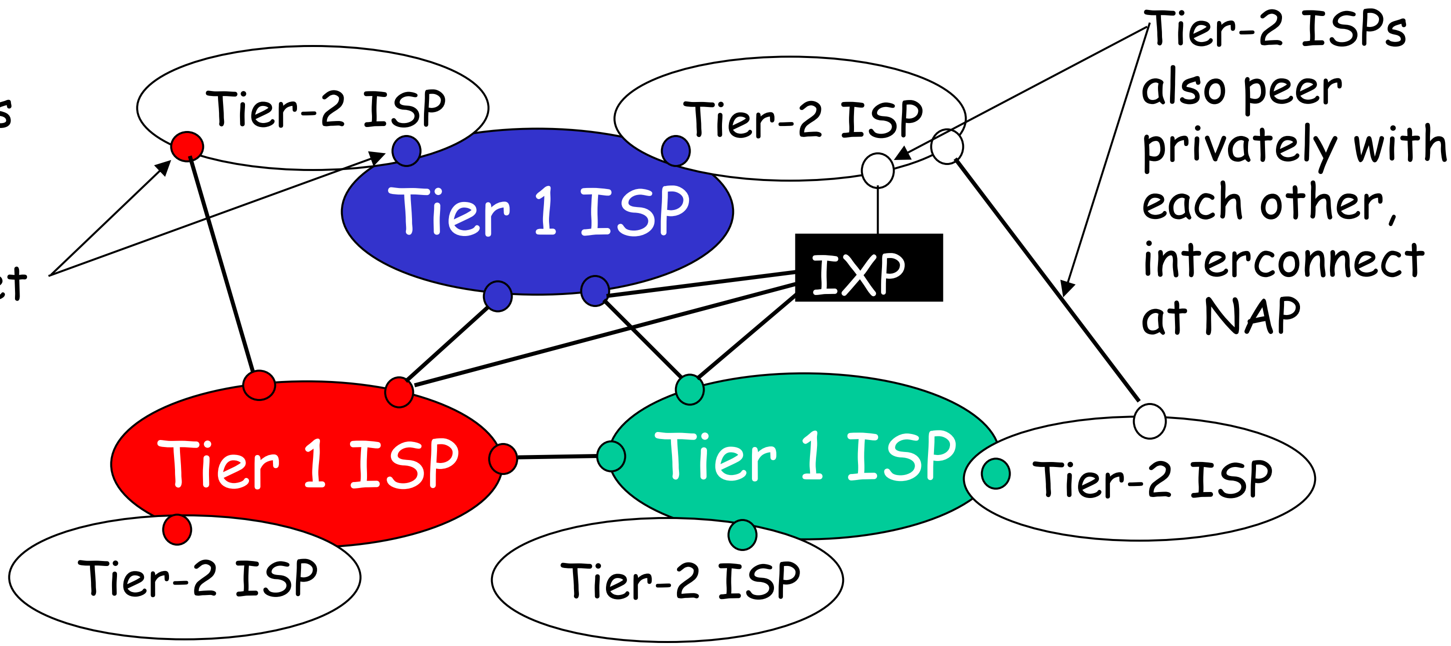
Sprint US backbone network



Internet structure: network of networks

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

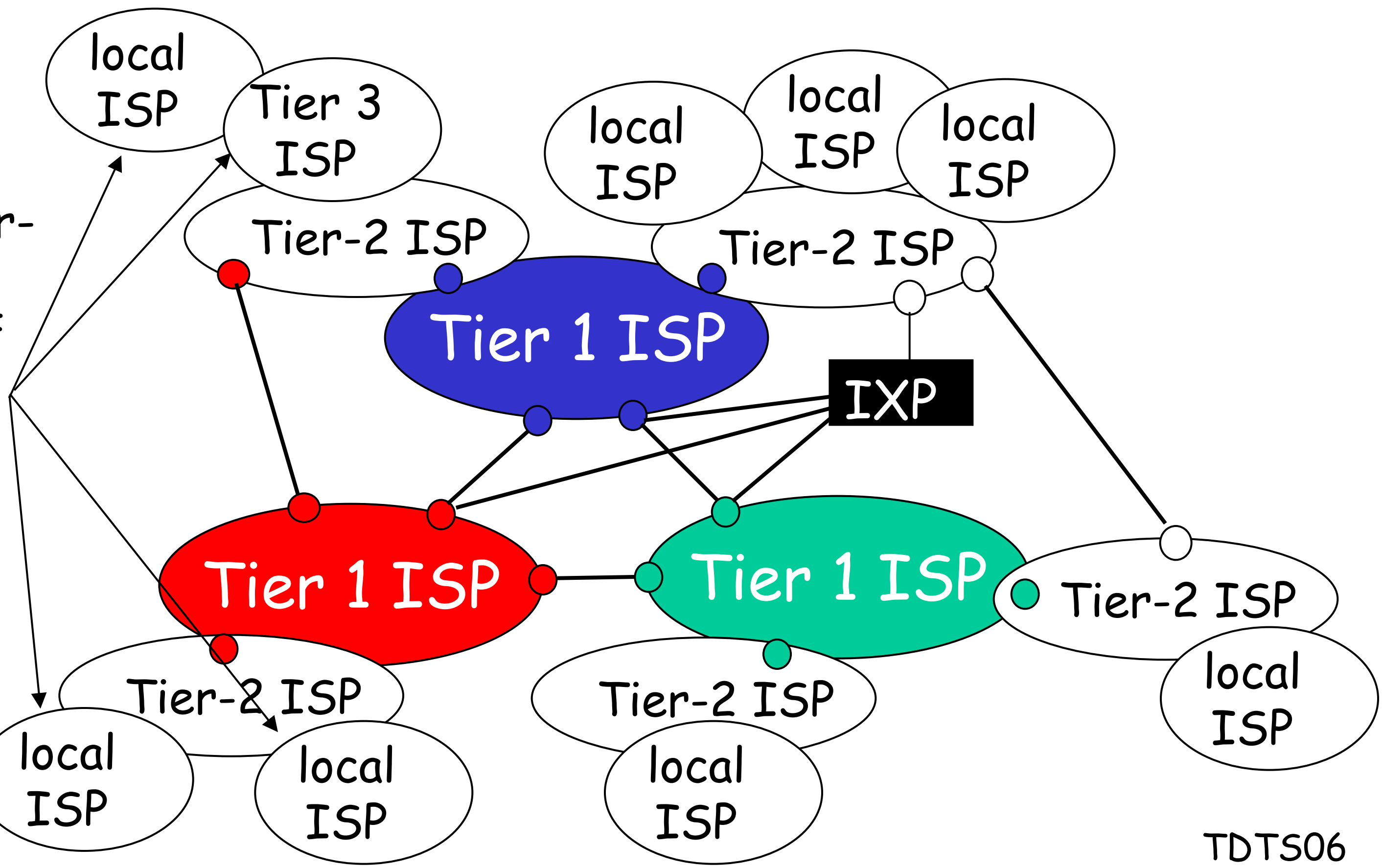
Tier-2 ISP pays tier-1 ISP for connectivity to rest of Internet
- tier-2 ISP is *customer* of tier-1 provider



Internet structure: network of networks

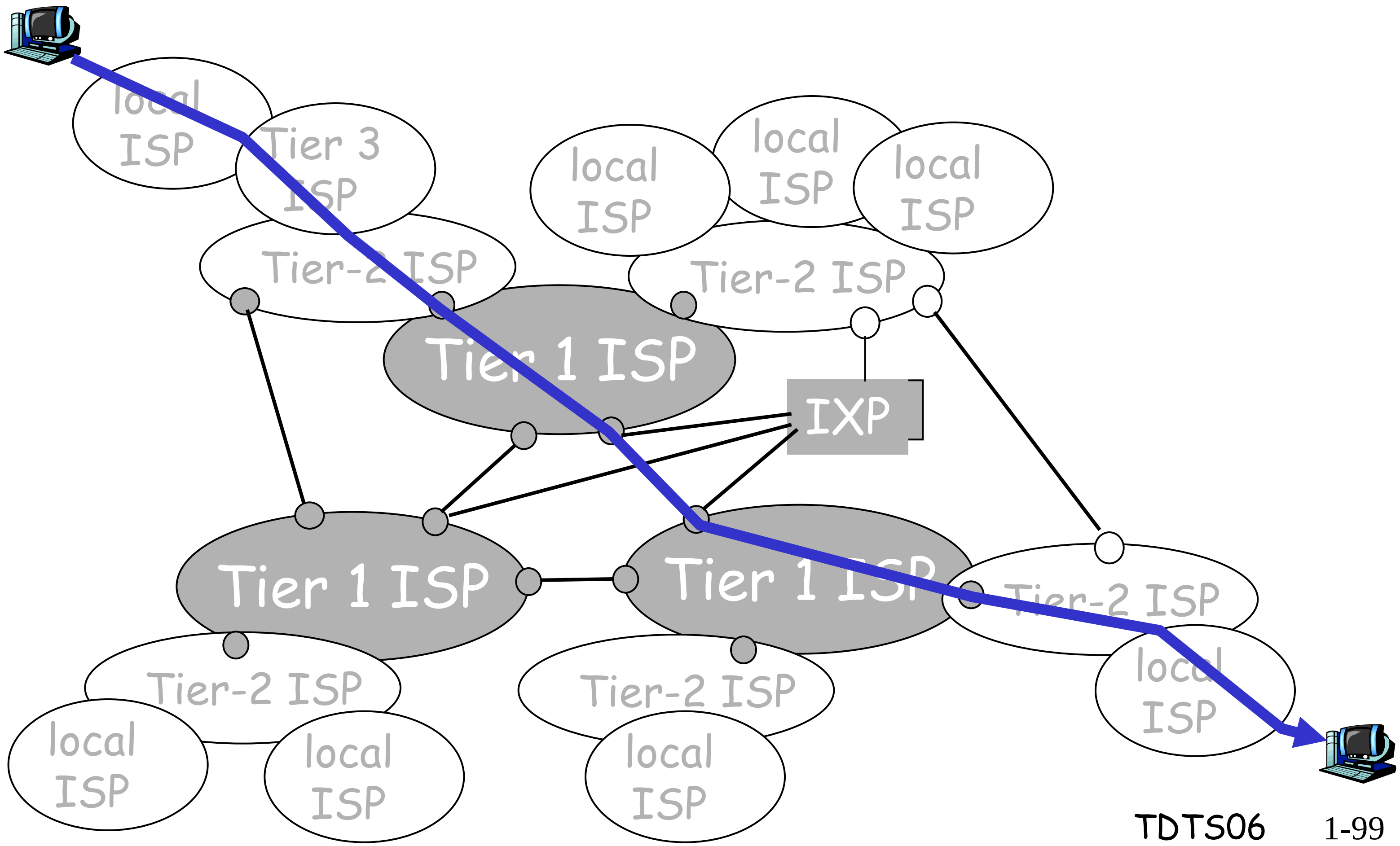
- "Tier-3" ISPs and local ISPs
  - last hop ("access") network (closest to end systems)

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



Internet structure: network of networks

- a packet passes through many networks!



Introduction: Summary

Covered a "ton" of material!

- Internet overview
- what's a protocol?
- network edge, core, access network
  - packet-switching versus circuit-switching
- Internet/ISP structure
- performance: loss, delay
- layering and service models
- Internet history

You now have:

- context, overview, "feel" of networking
- more depth, detail *to follow!*

Ohh, and the history …

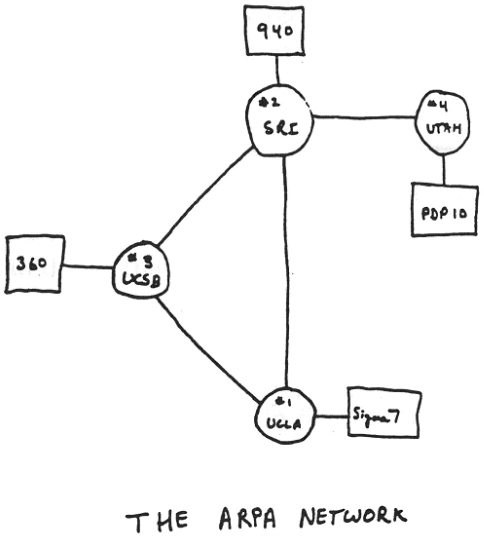
- …

Internet History

1961-1972: Early packet-switching principles

- 1961: Kleinrock - queueing theory shows effectiveness of packet-switching
- 1964: Baran - packet-switching in military nets
- 1967: ARPAnet conceived by Advanced Research Projects Agency
- 1969: first ARPAnet node operational

- 1972:
  - ARPAnet public demonstration
  - NCP (Network Control Protocol) first host-host protocol
  - first e-mail program
  - ARPAnet has 15 nodes



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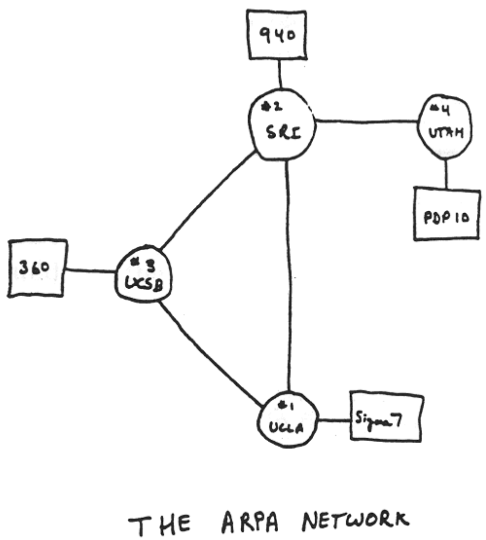

Internet History

1972-1980: Internetworking, new and proprietary nets

- 1970: ALOHAnet satellite network in Hawaii
- 1974: Cerf and Kahn - architecture for interconnecting networks
- 1976: Ethernet at Xerox PARC
- late70's: proprietary architectures: DECnet, SNA, XNA
- late 70's: switching fixed length packets (ATM precursor)
- 1979: ARPAnet has 200 nodes

Cerf and Kahn's internetworking principles:

- minimalism, autonomy - no internal changes required to interconnect networks
- best effort service model
- stateless routers
- decentralized control

define today's Internet architecture

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1980-1990: new protocols, a proliferation of networks

- 1983: deployment of TCP/IP
- 1982: smtp e-mail protocol defined
- 1983: DNS defined for name-to-IP-address translation
- 1985: ftp protocol defined
- 1988: TCP congestion control

- new national networks: Csnet, BITnet, NSFnet, Minitel
- 100,000 hosts connected to confederation of networks

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1990, 2000's: commercialization, the Web, new apps

- early 1990's: ARPAnet decommissioned
- 1991: NSF lifts restrictions on commercial use of NSFnet (decommissioned, 1995)
- early 1990s: Web
  - hypertext [Bush 1945, Nelson 1960's]
  - HTML, HTTP: Berners-Lee
  - 1994: Mosaic, later Netscape
  - late 1990's: commercialization of the Web

late 1990's – 2000's:

- more killer apps: instant messaging, P2P file sharing
- network security to forefront
- est. 50 million host, 100 million+ users
- backbone links running at Gbps

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- voice, video over IP
- P2P applications: BitTorrent (file sharing) Skype (VoIP), PPLive (video)
- more applications: YouTube, gaming, Twitter, facebook, ...
- on-demand streaming
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The future is yours to write