Computer Networks

Instructor: Niklas Carlsson

Email: niklas.carlsson@liu.se

Office: B:476

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.

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

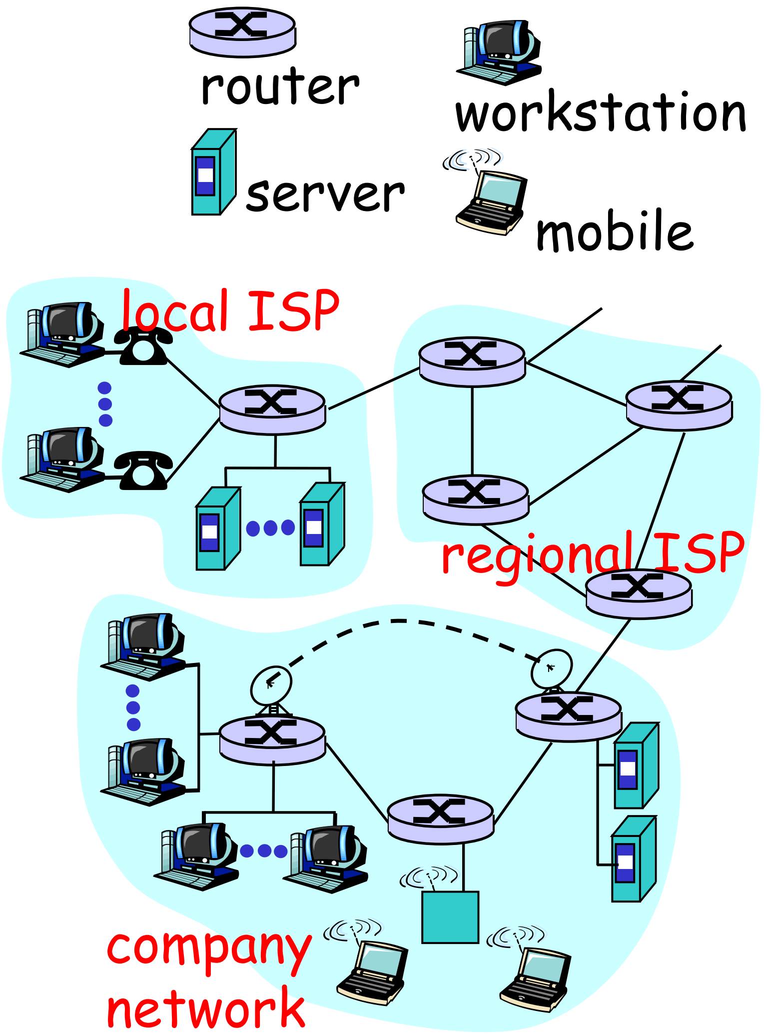
- E.g., https://www.youtube.com/watch?v=w42EsCDAhB4

- 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

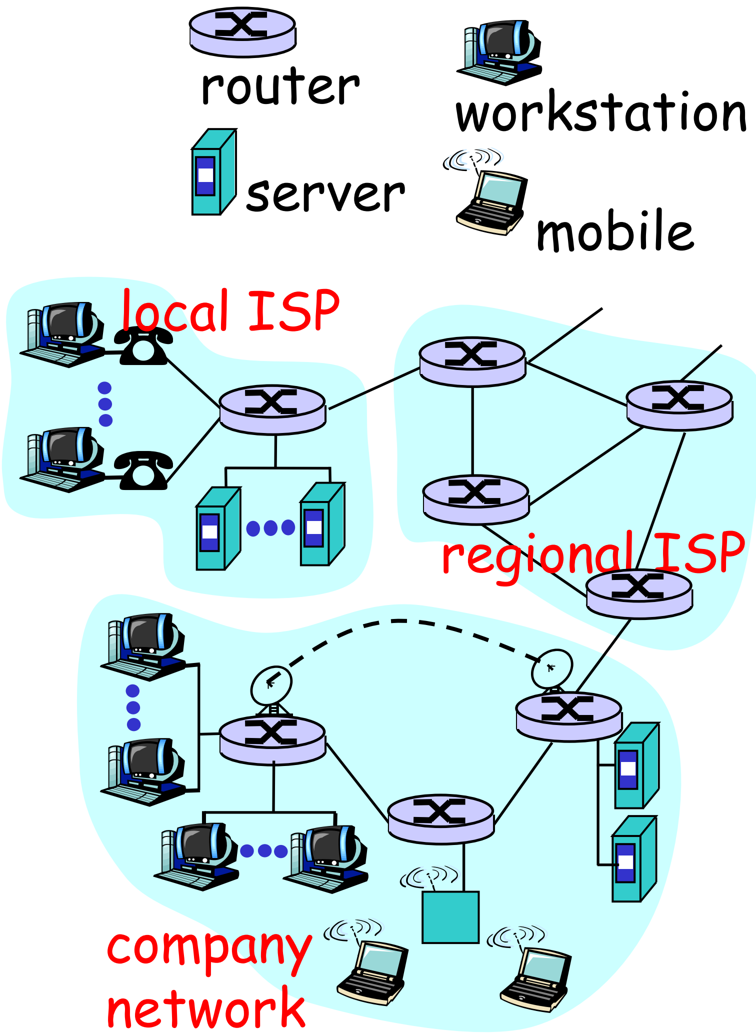
The "nuts and bolts" view of the Internet



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)



Today's service/company landscape include ...

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Equipment manufacturers
(also sell services and help
Operate networks)

Today's service/company landscape include ...

Network operators

Equipment manufacturers (also sell services and help Operate networks)

Today's service/company landscape include ...

Enterprise solutions and network service (e.g., data center solutions and cloud providers)

Today's service/company landscape include ...

Content delivery networks

Enterprise solutions and network service (e.g., data center solutions and cloud providers)

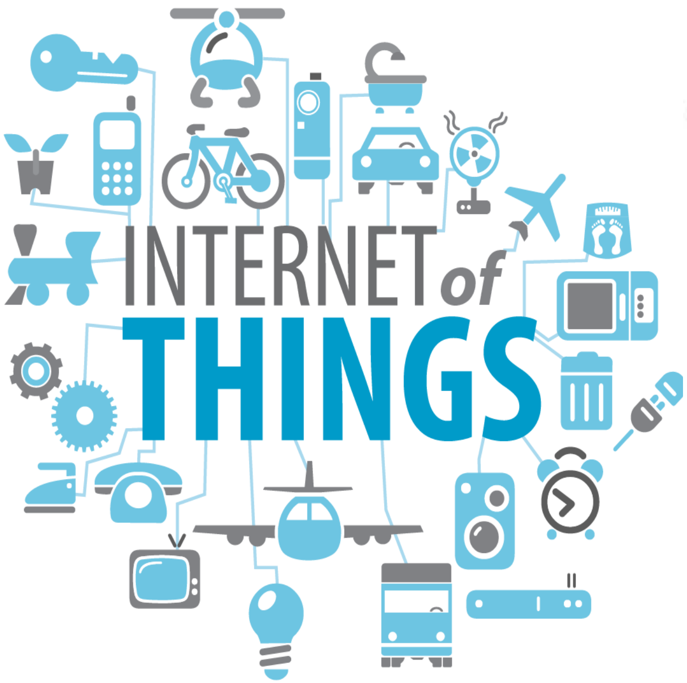
Today's service/company landscape include ...

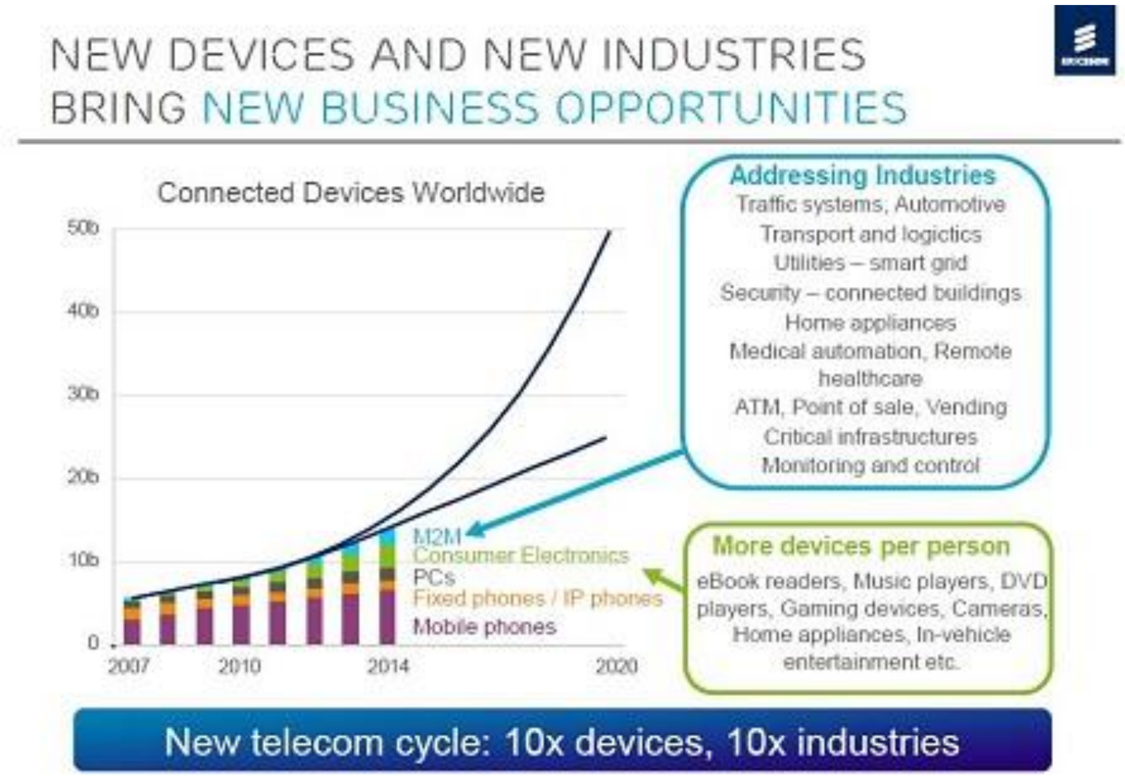
End user services (e.g., web-based social networks, search, communication, and streaming)

Some common applications today …

- World Wide Web (WWW)
- Remote login (telnet, rlogin, ssh)
- File transfer
- Peer-to-peer file sharing
- Cloud computing/services
- Instant messaging (chat, text messaging, etc.)
- Live and video-on-demand streaming
- Internet phone (Voice-Over-IP)
- Distributed games
- …

… and tomorrow



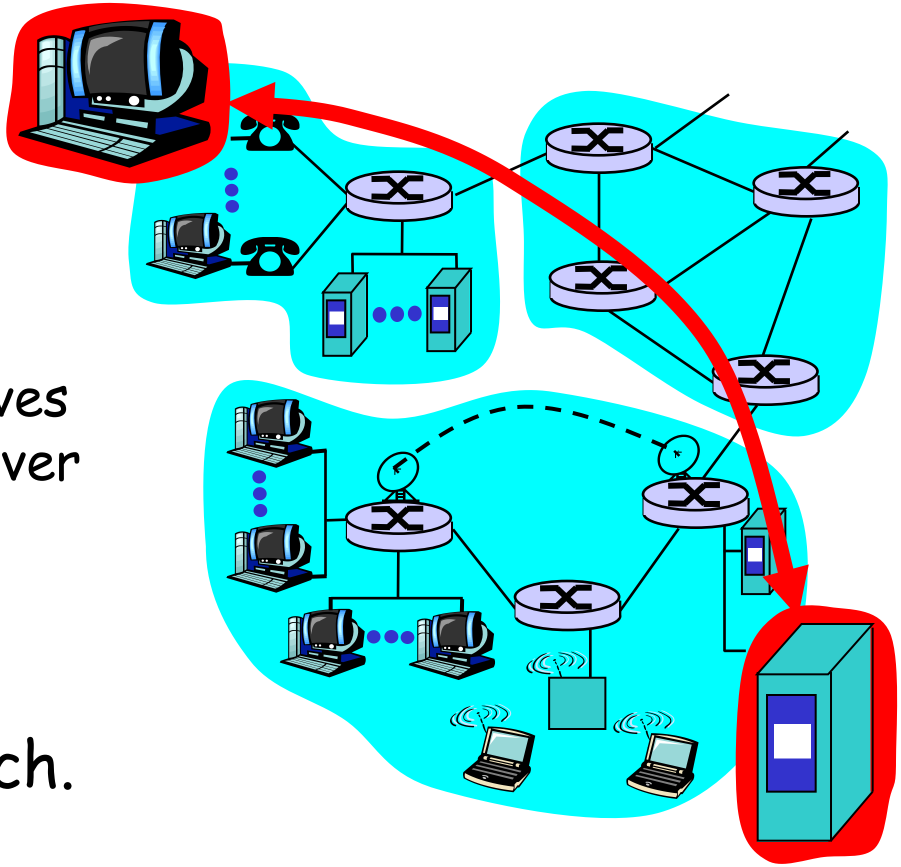


The 2020 vision

- Everything that can be connected will be connected
  - 50B devices (perhaps more like 500B …)
- IoT and smart cities
  - Machine-to-machine
- High-definition 3D streaming to heterogeneous clients

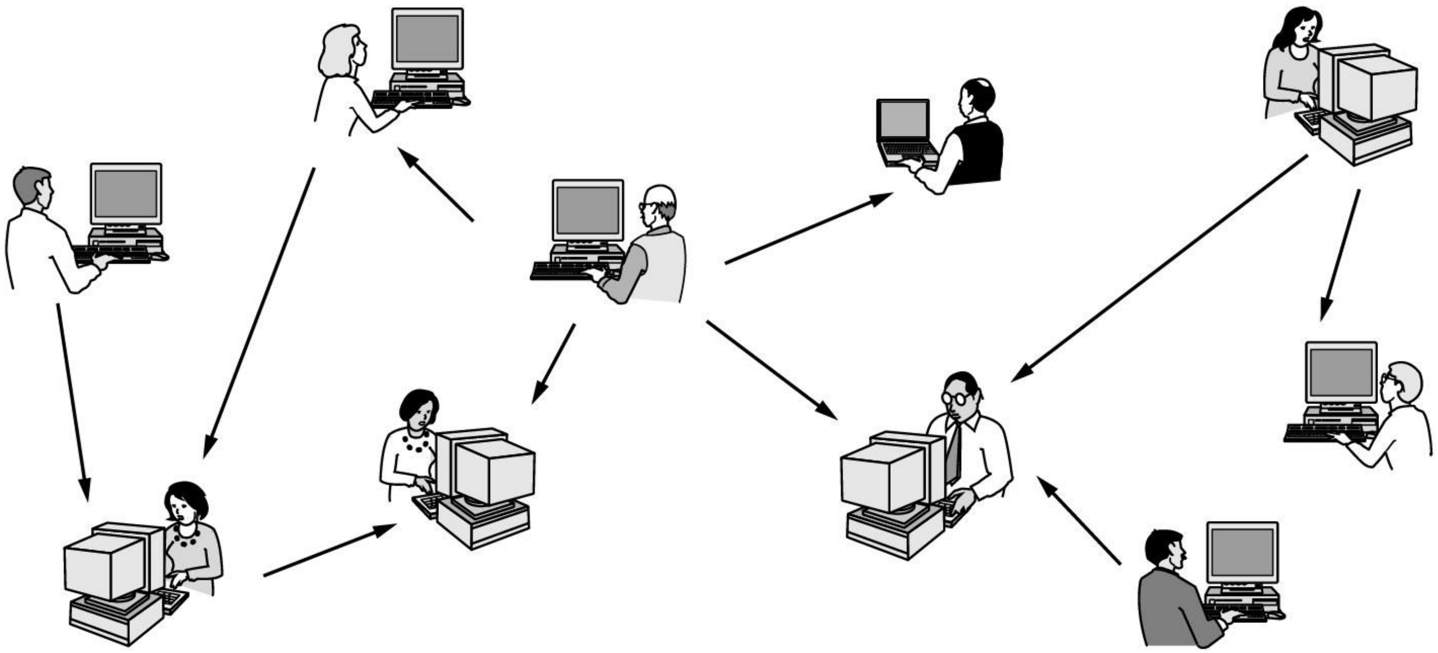
Applications (2)

- 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

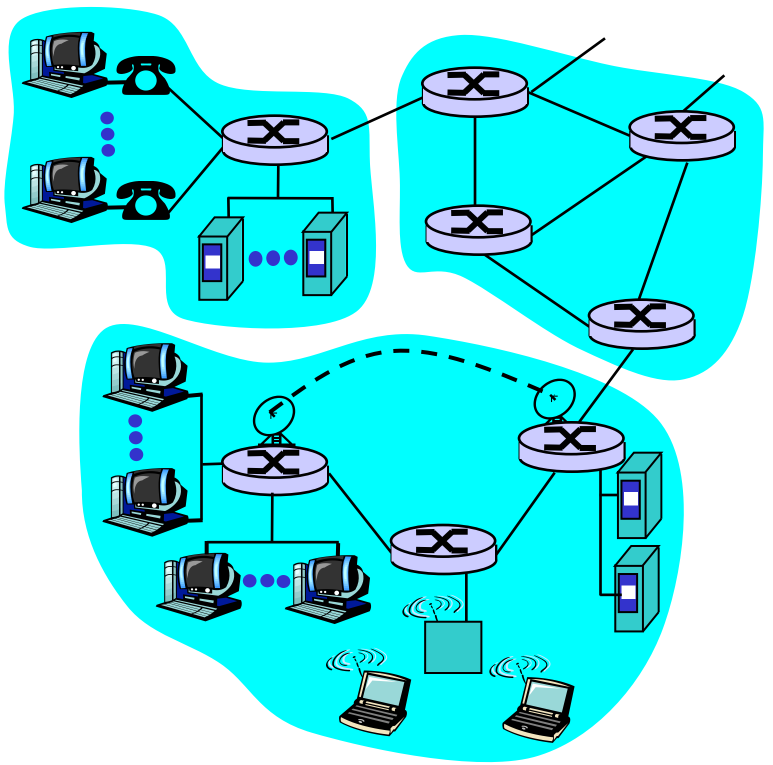
- Wide Area Network (WAN)
- Metropolitan Area Network (MAN)
- Local Area Network (LAN)

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

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

Wide Area Network (WAN)

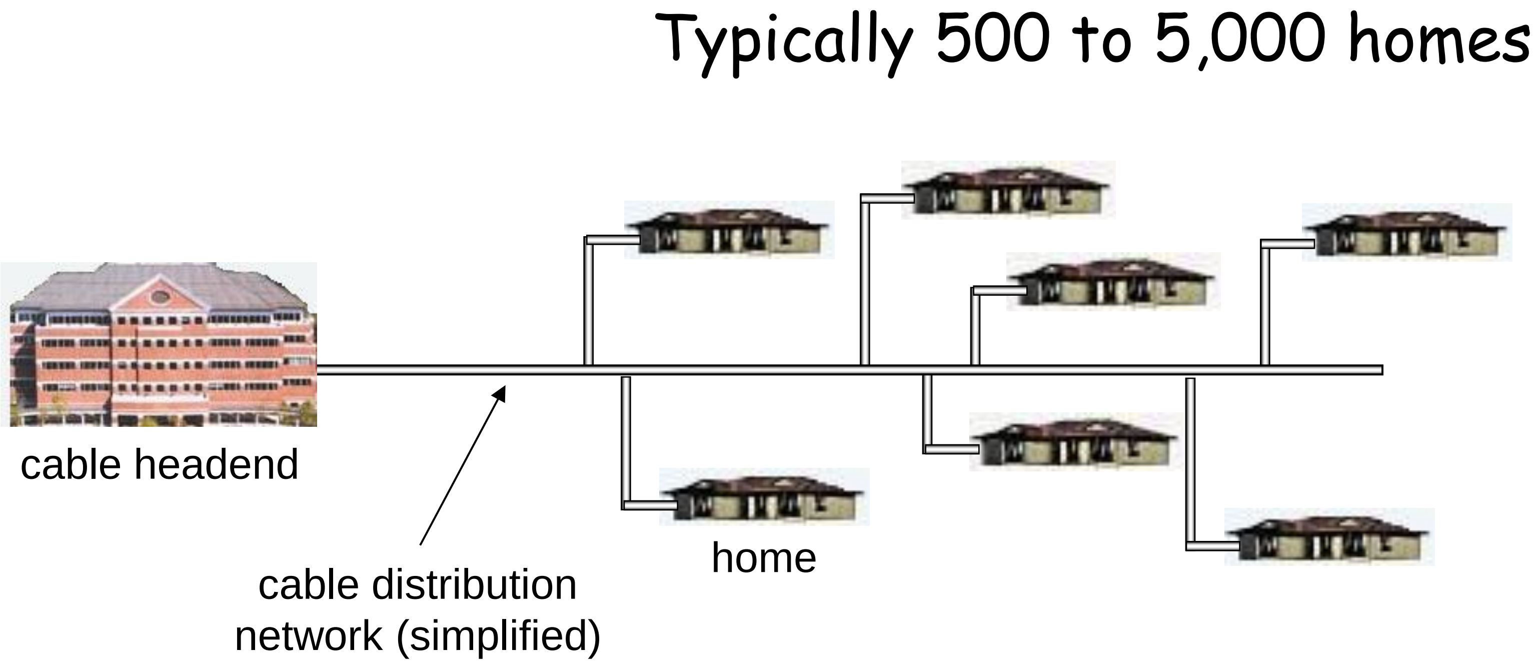
- Spans a large geographic area, e.g., a country or a continent
- A WAN consists of several transmission lines and routers
- Internet is an example of a WAN



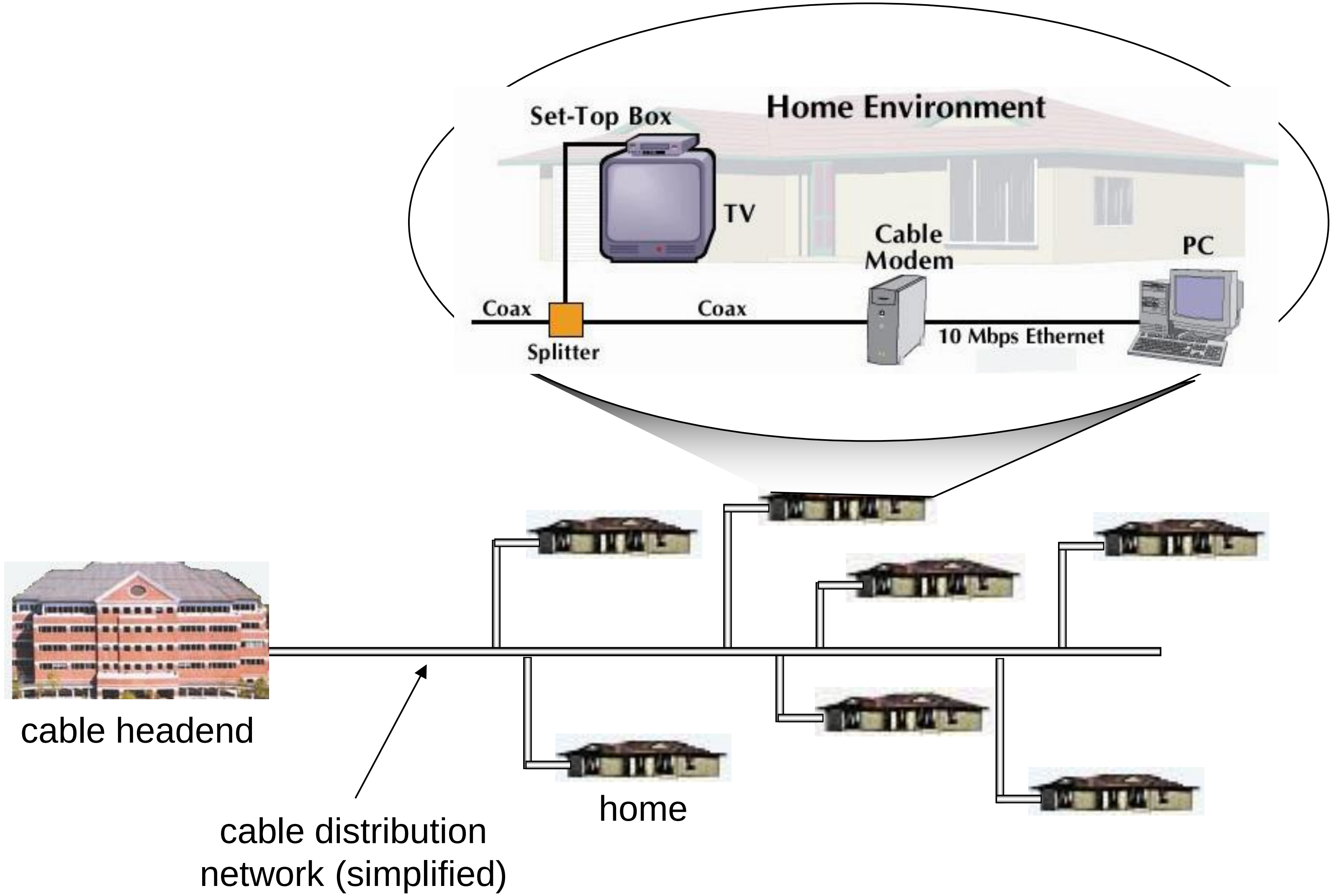
Metropolitan Area Network (MAN)

"City sized": tens of kilometers

A Cable TV Network is an example of a MAN



Cable Network Architecture: Overview



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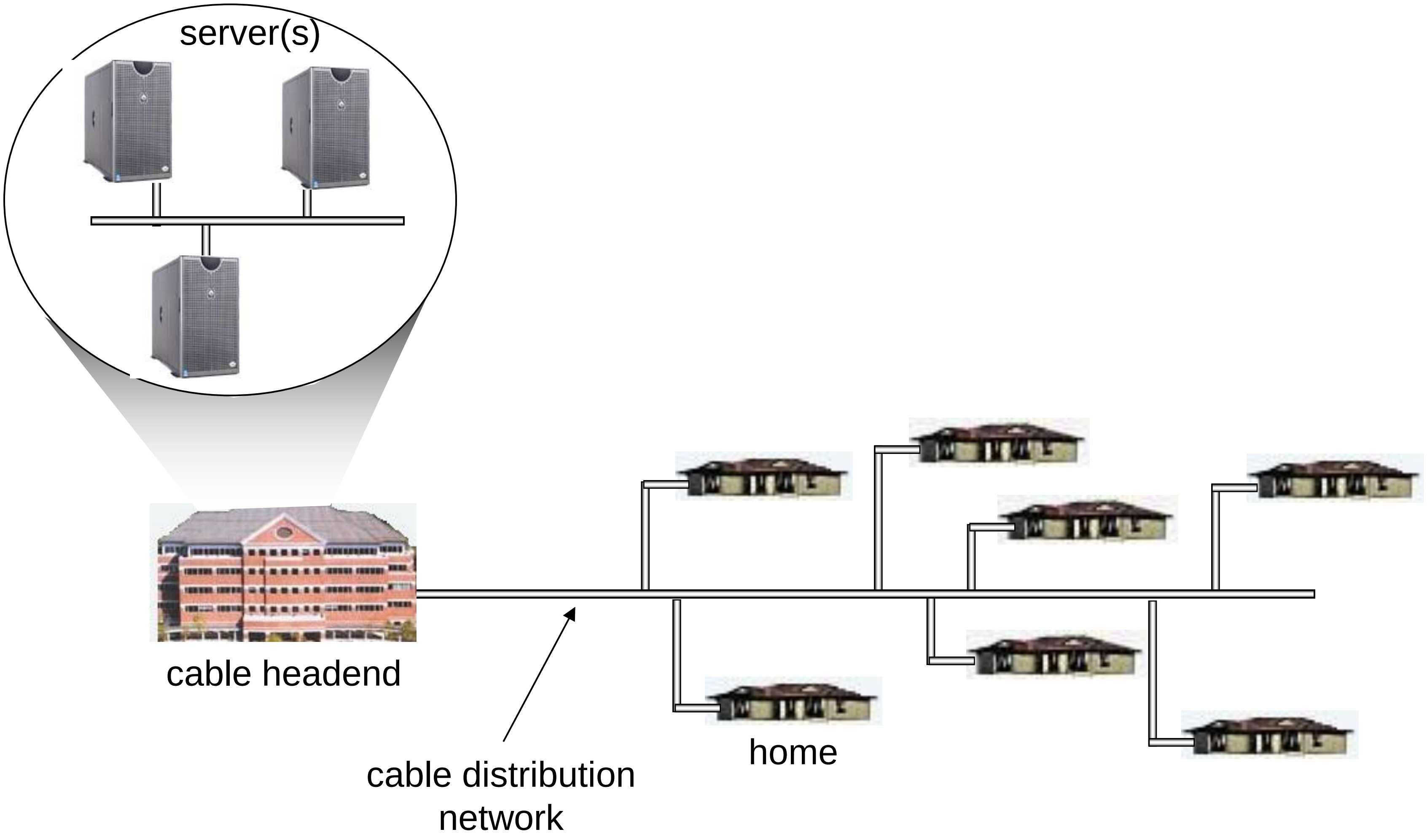
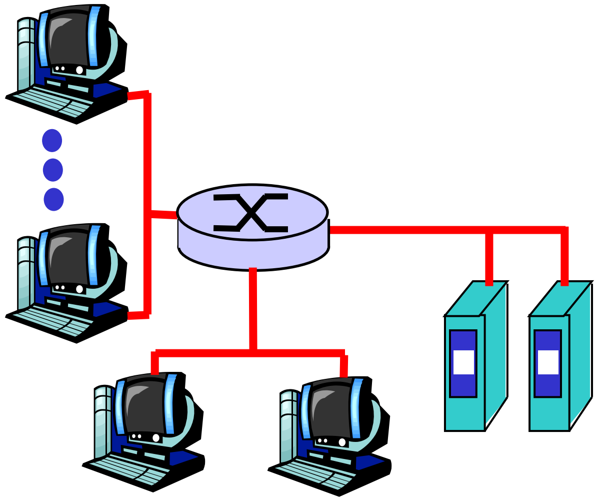


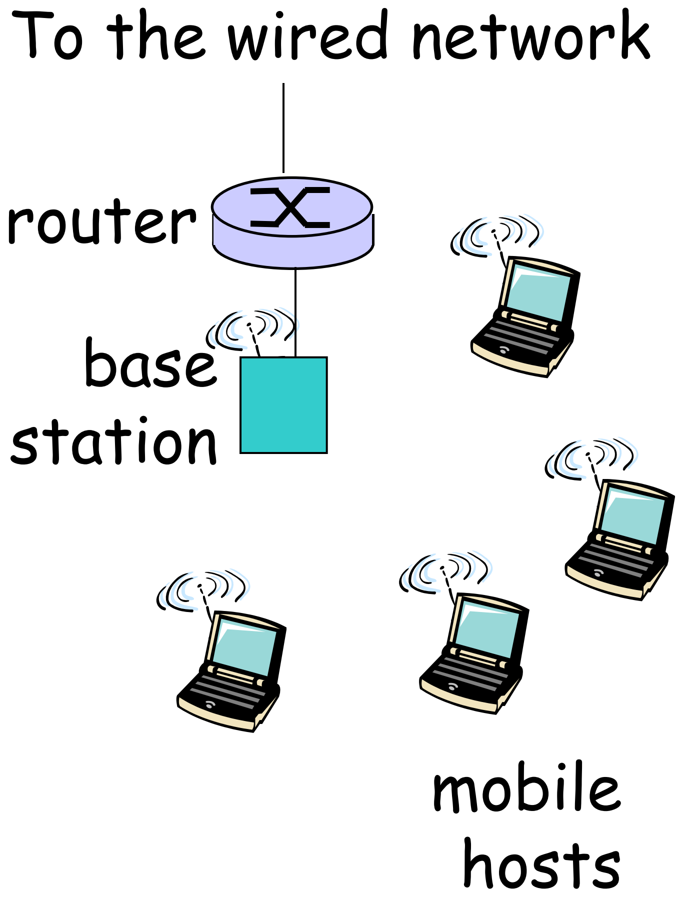
Local Area Network (LAN)

- 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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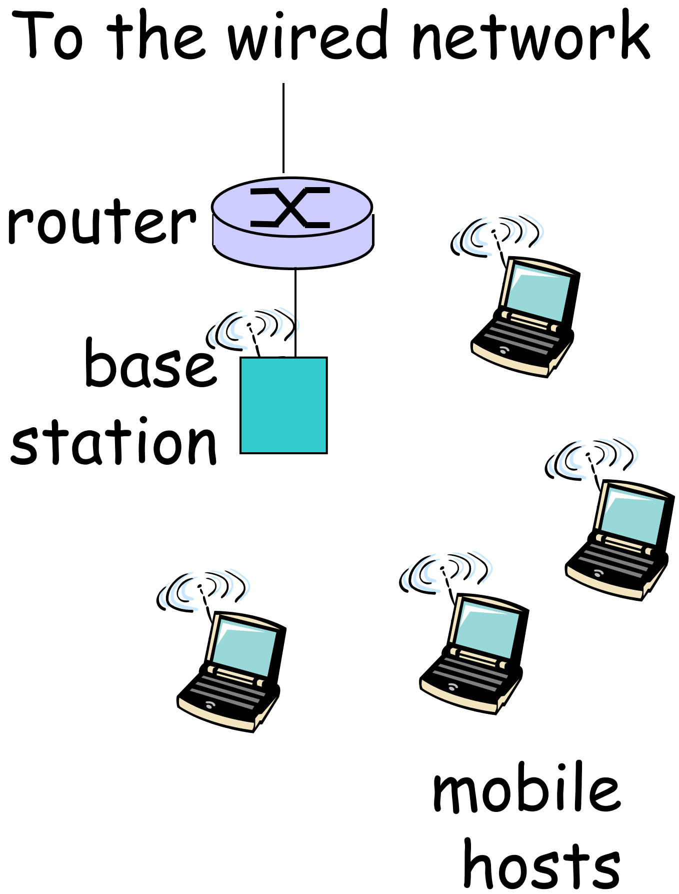
  - 802.11b (WiFi)

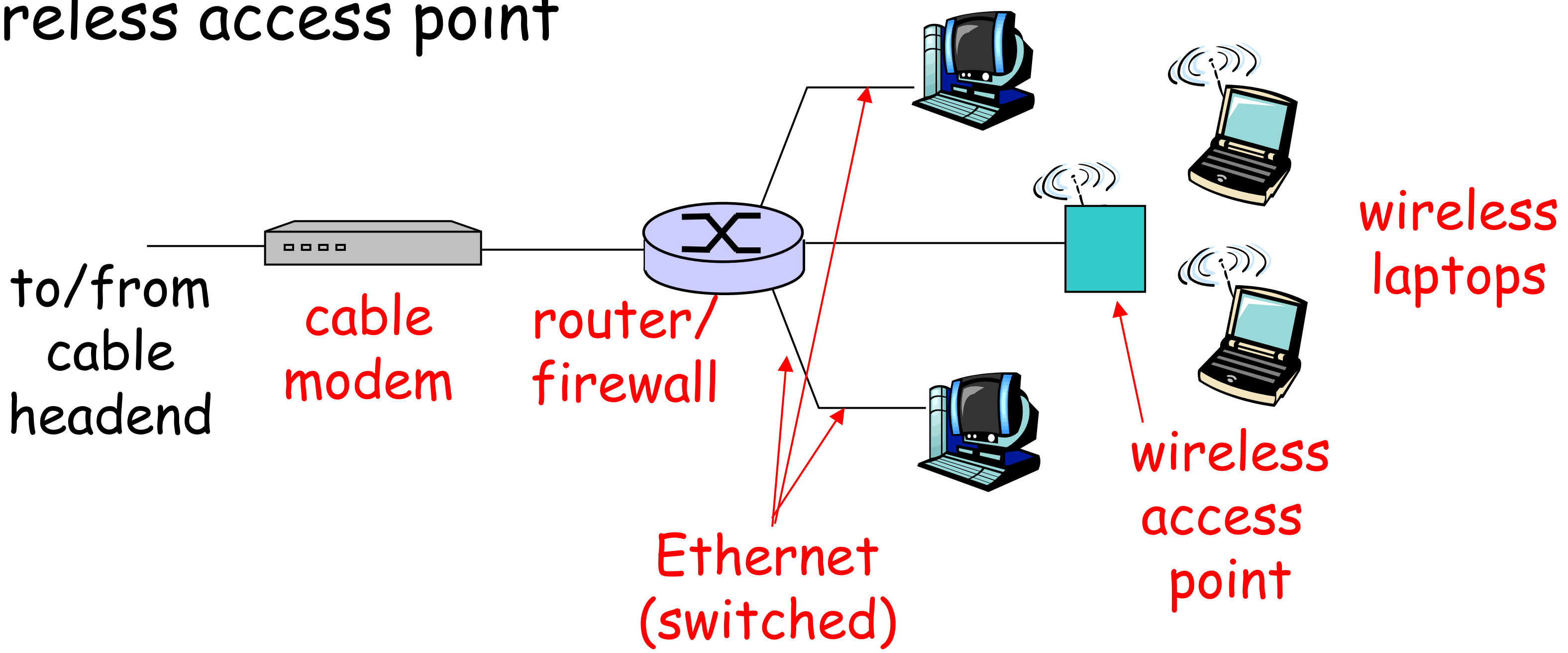
- wider-area wireless access
  - provided by telco operator
  - 3G, 4G
  - WAP/GPRS in Europe
  - WiMax



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?

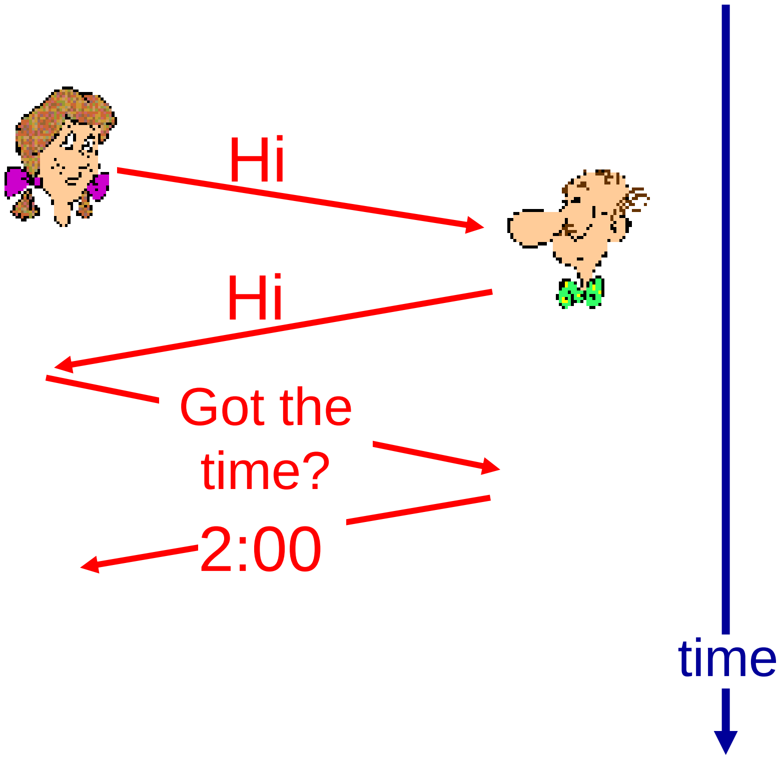
Protocols:

- 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



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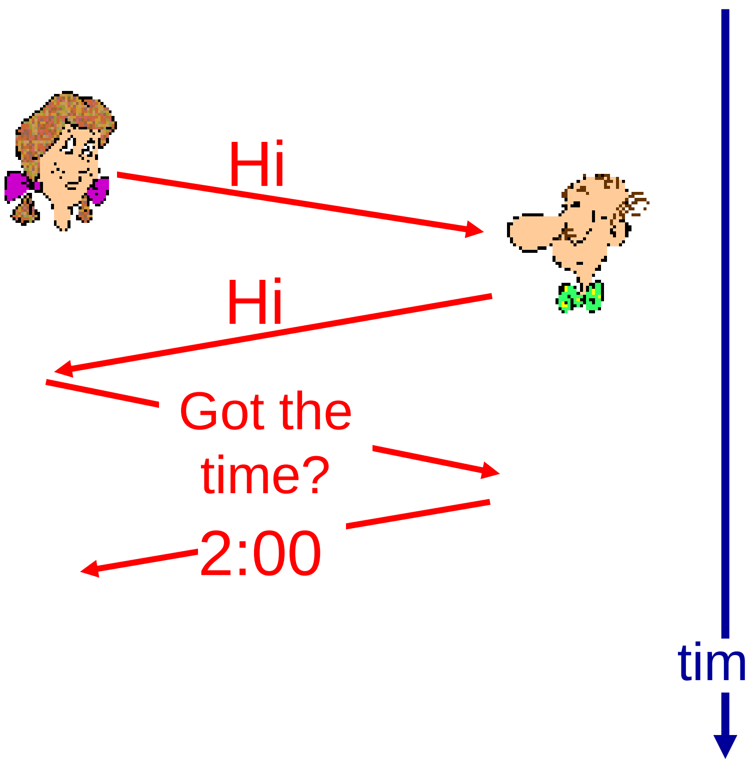
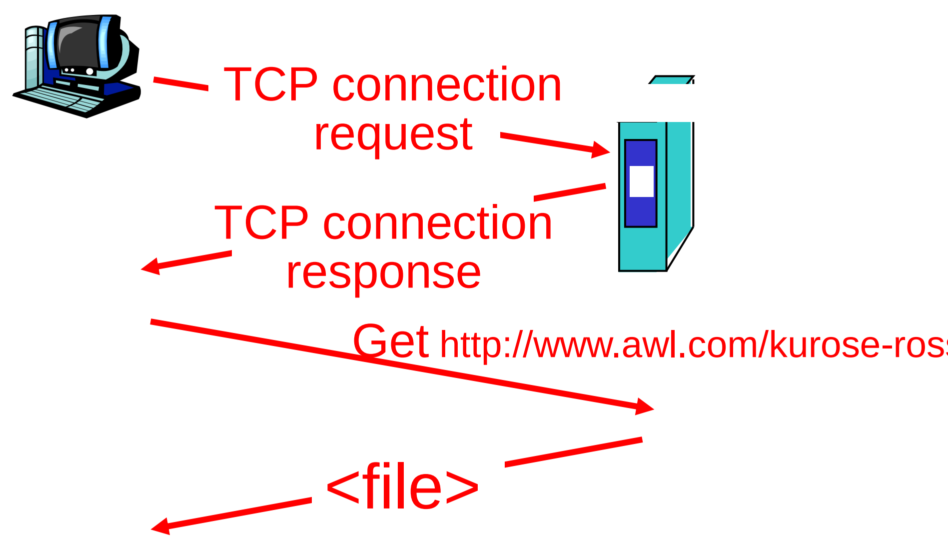
network protocols:

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





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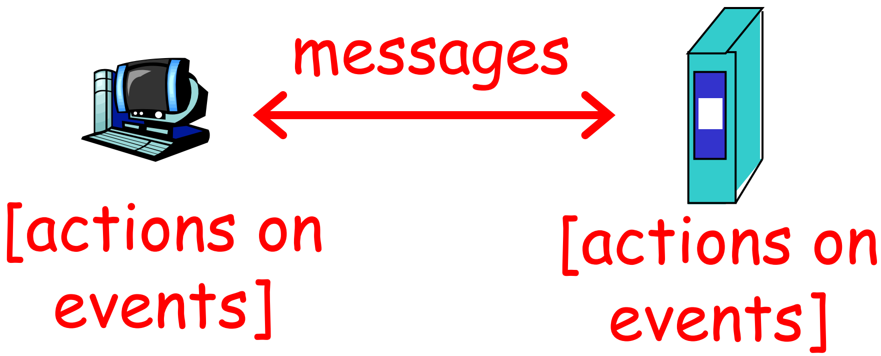
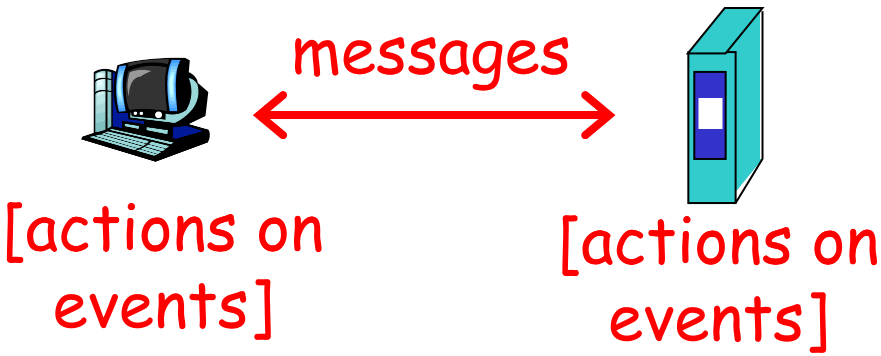


Need:

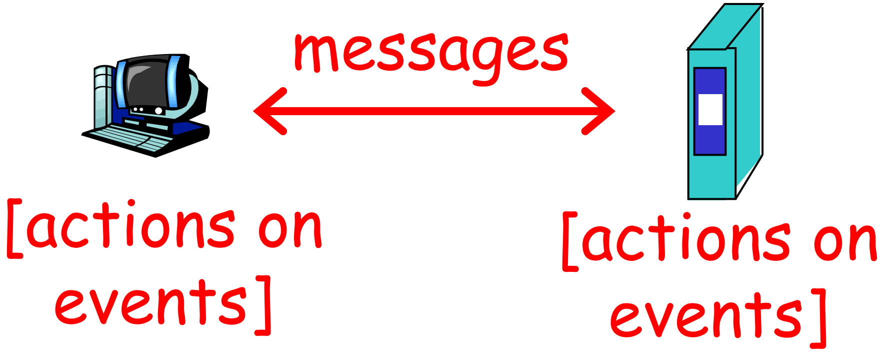
But first ...What's a protocol?



Need:

... specific msgs sent

But first ...What's a protocol?

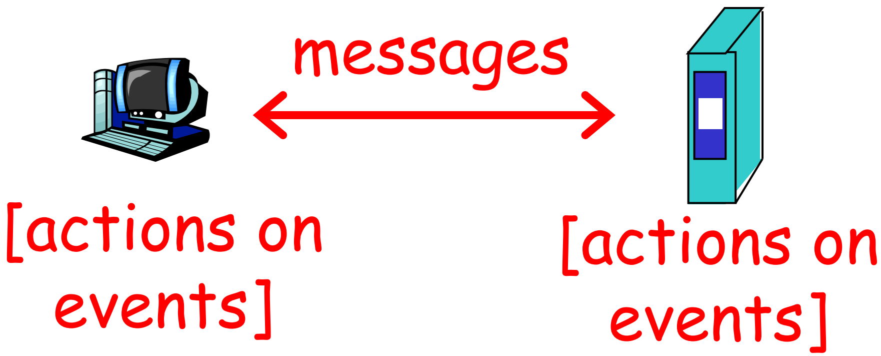


Need:

... 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)

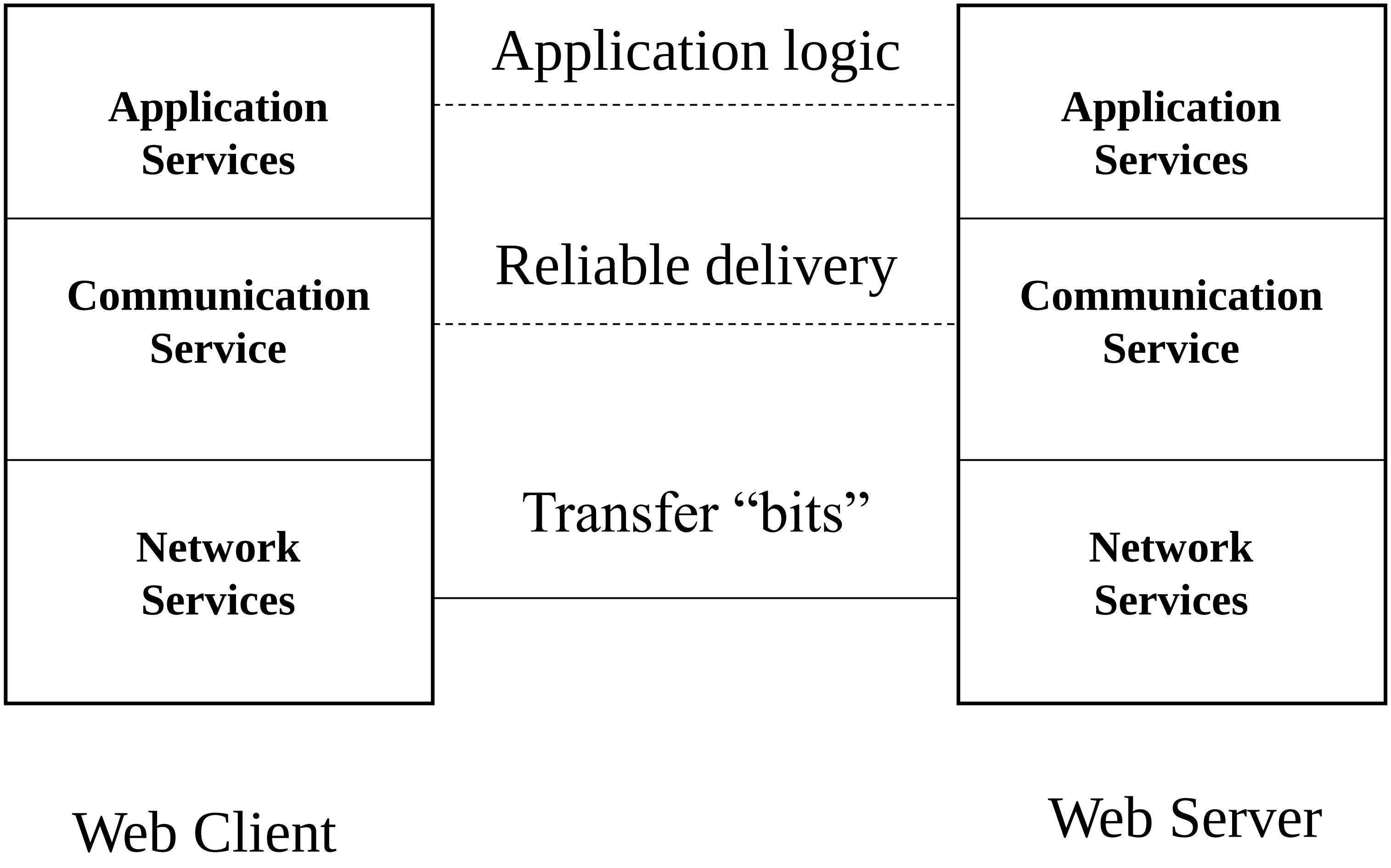
Layered Architecture: Why?

- 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:

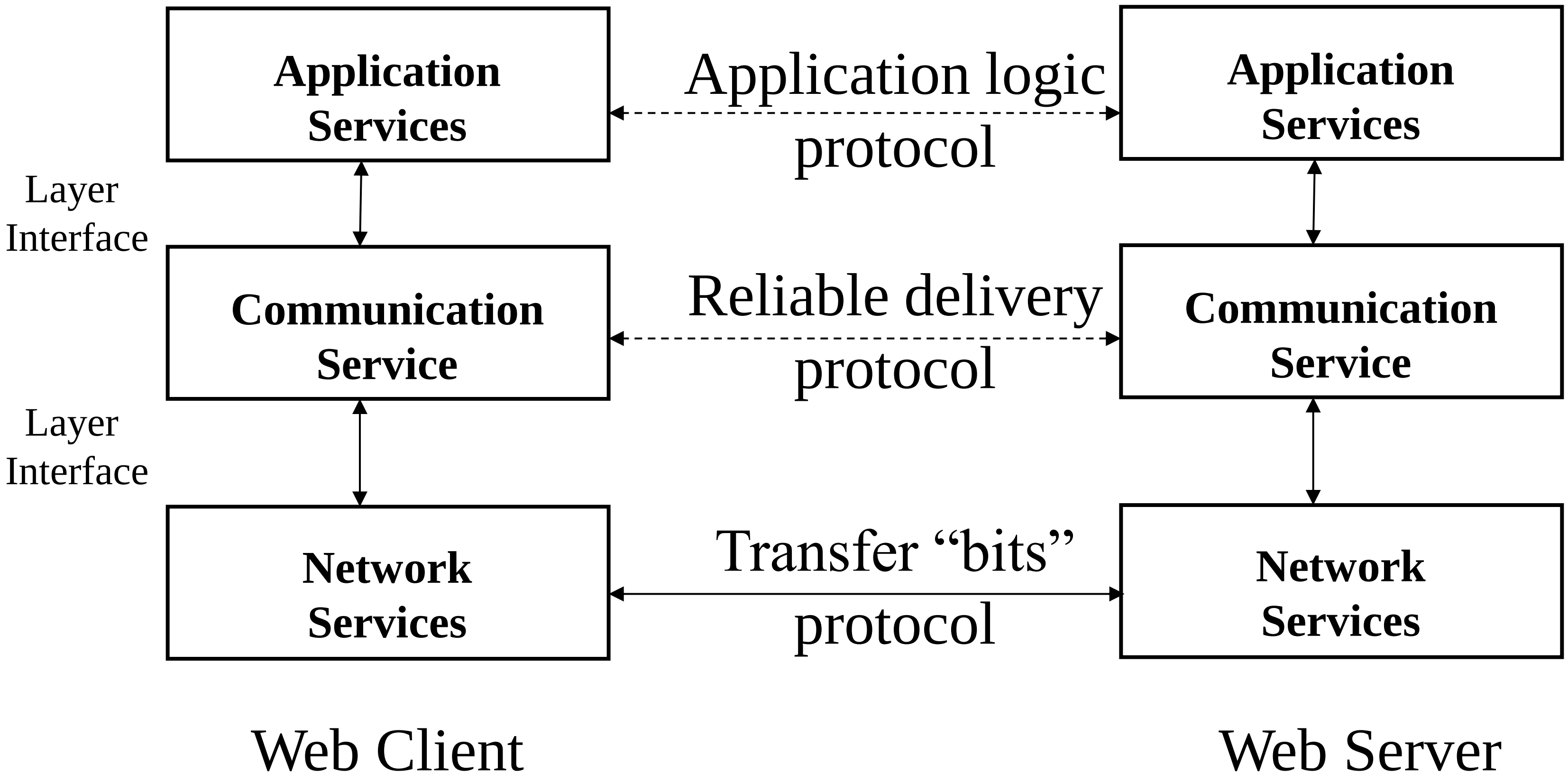
- explicit structure allows identification, relationship of complex system's pieces
  - layered reference model for discussion
- modularization eases maintenance, updating of system
  - change of implementation of layer's service transparent to rest of system
  - e.g., change in network technology doesn't 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



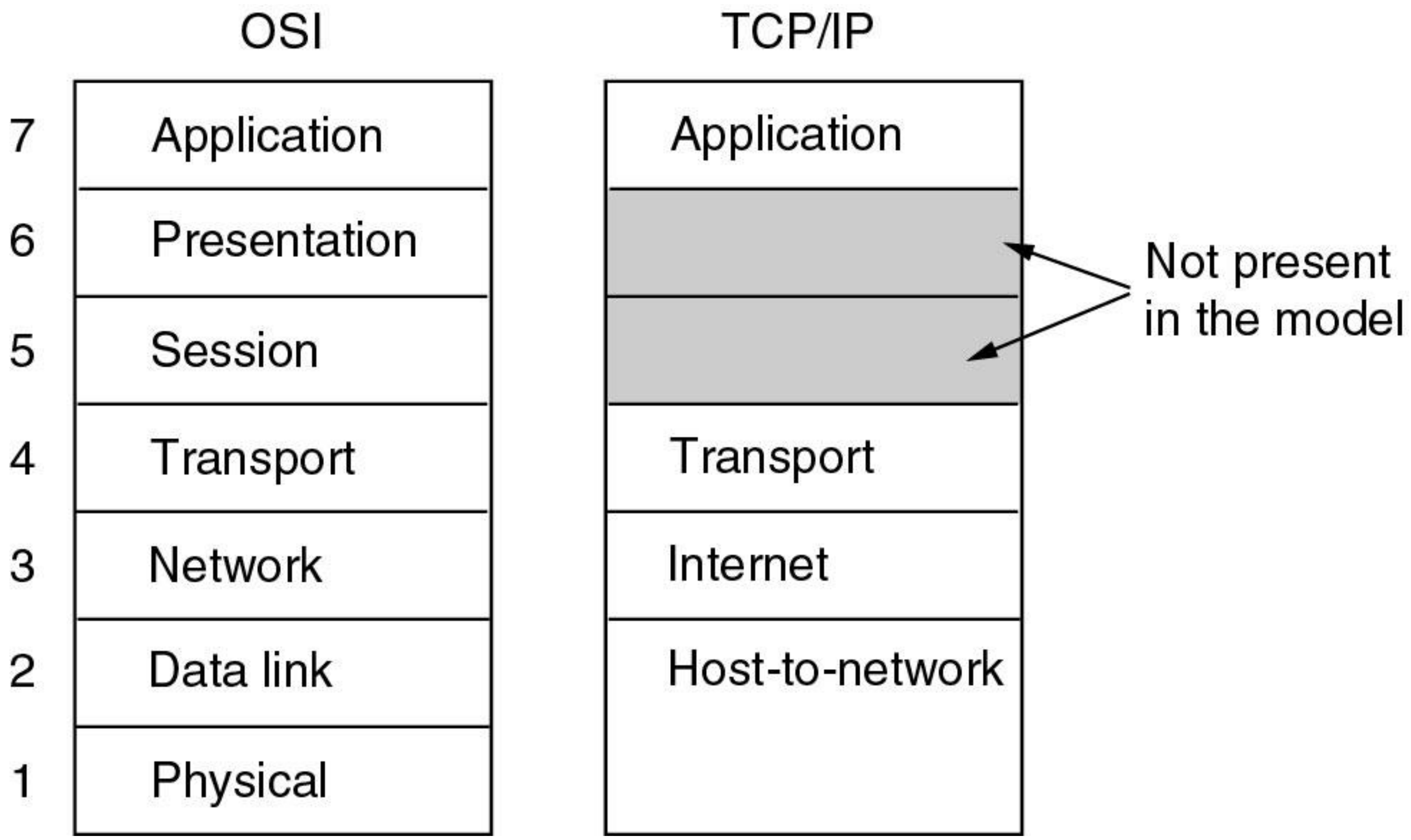
Layered Architecture (cont'd)

- 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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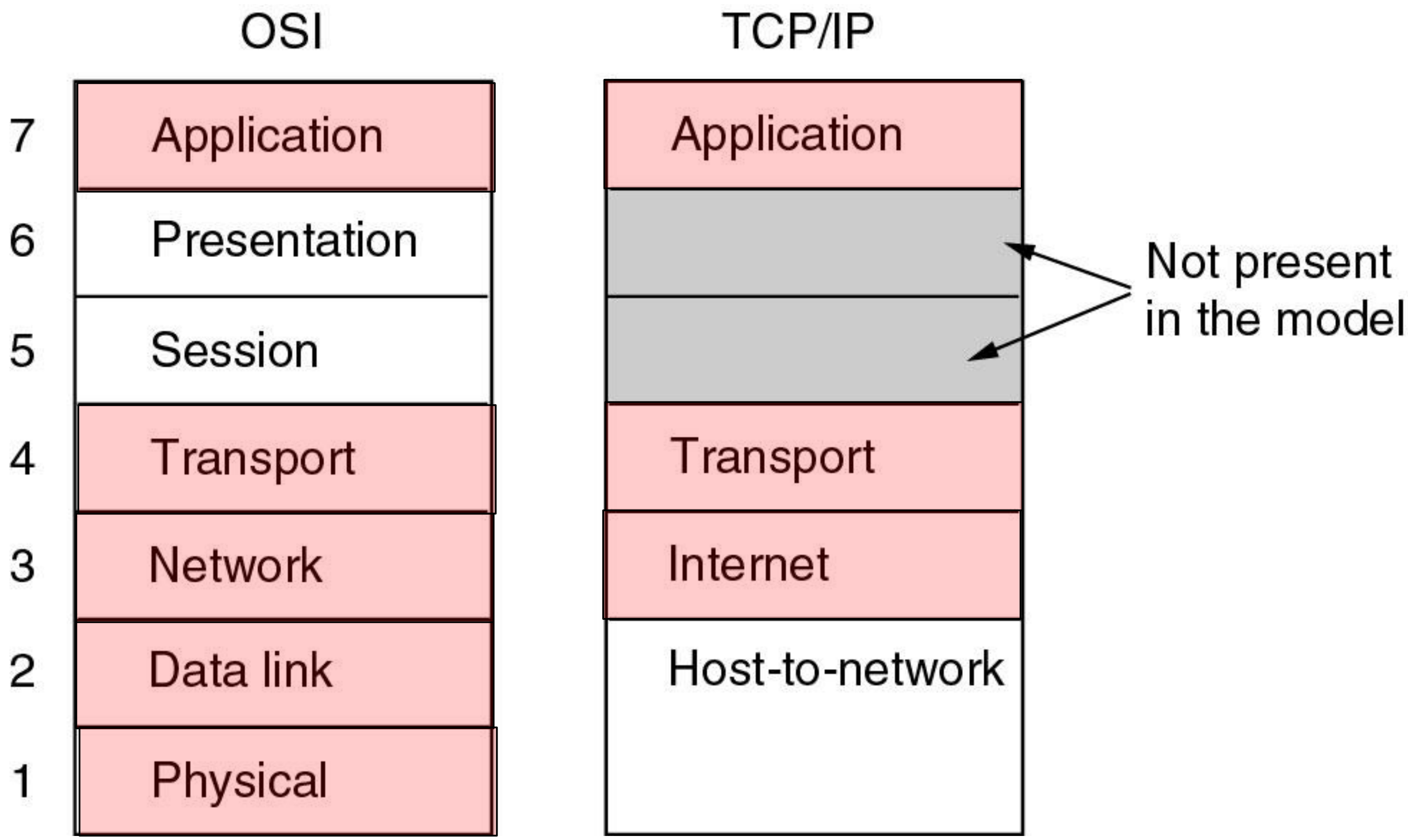
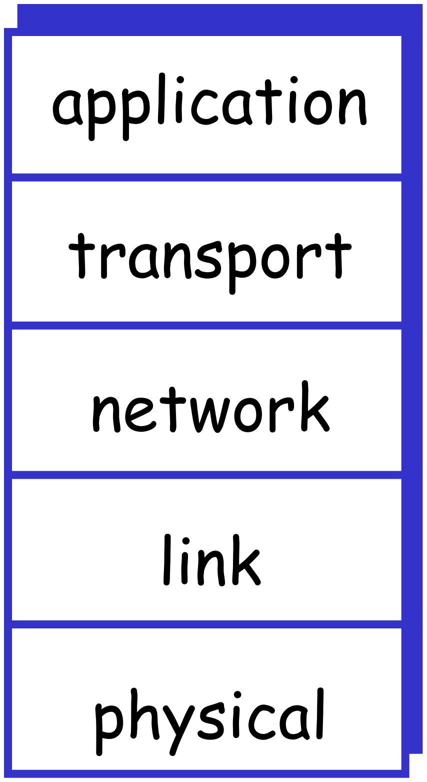


Internet protocol stack

- application: supporting network applications
  - FTP, SMTP, HTTP
- 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
- Applications typically sends messages
- 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 segment
- 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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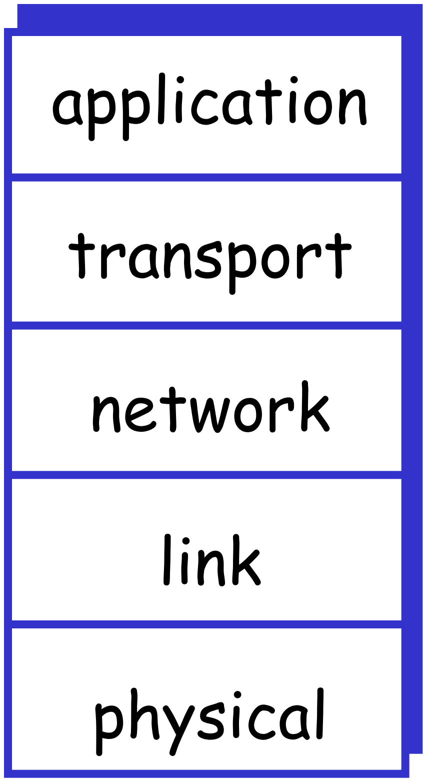
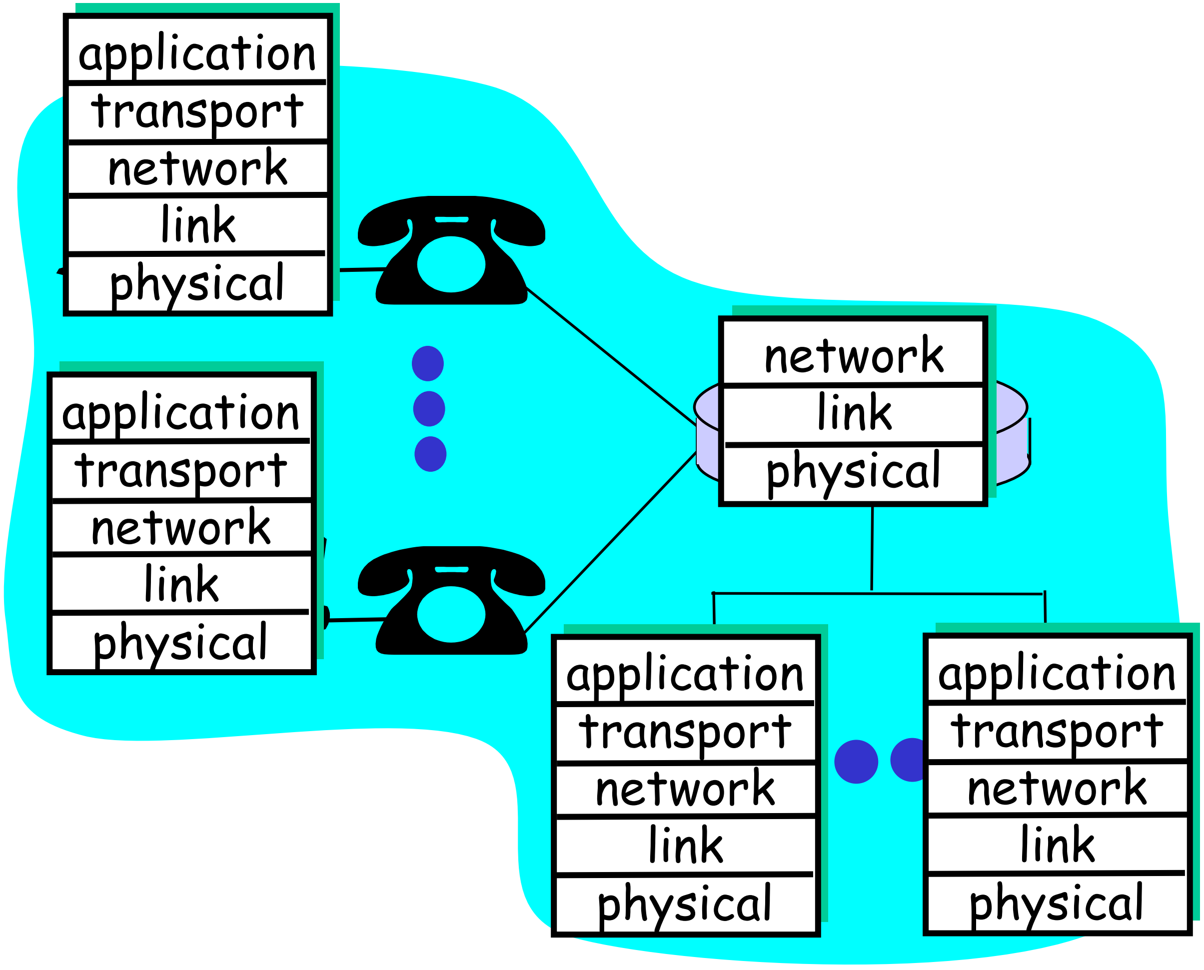
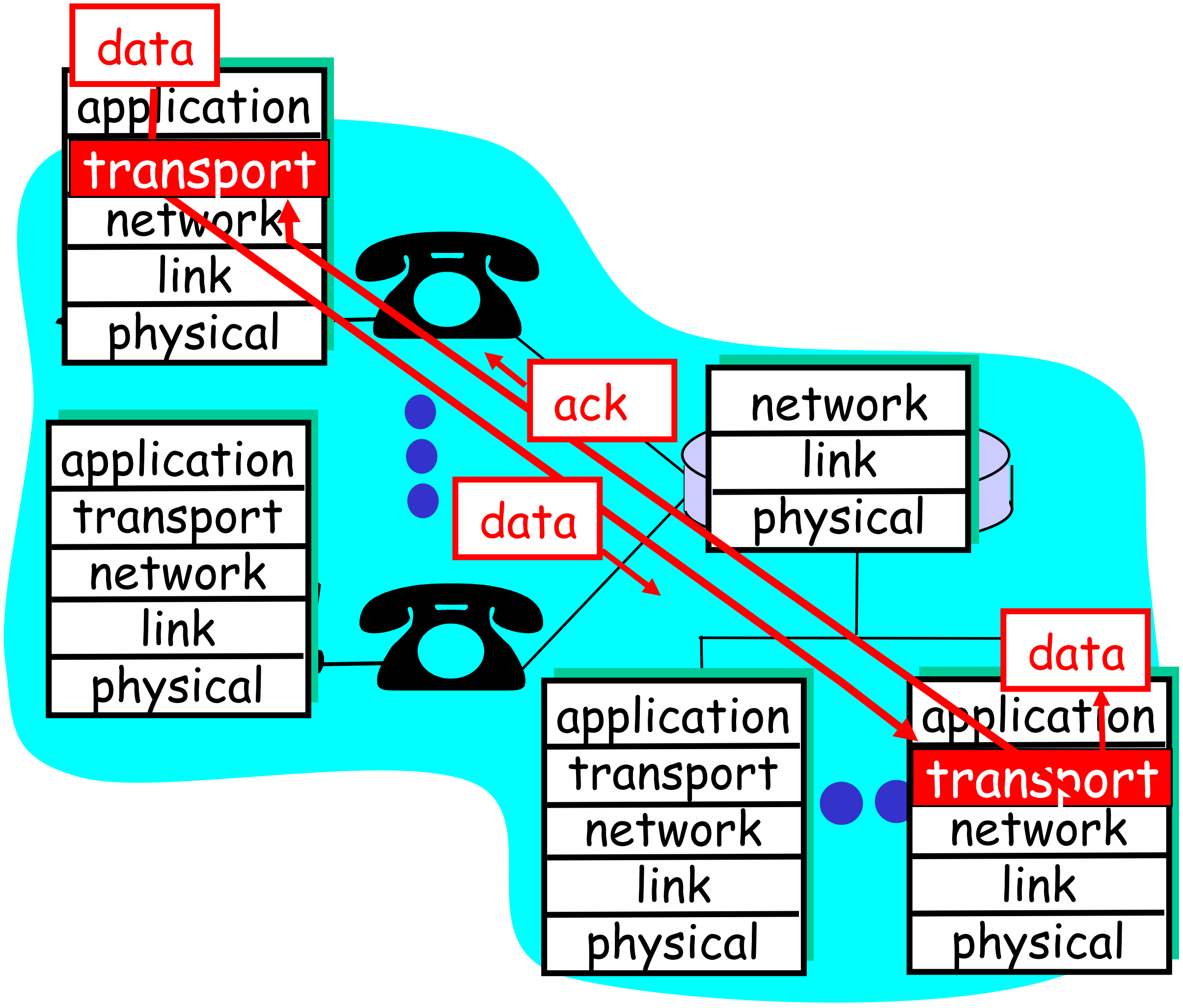


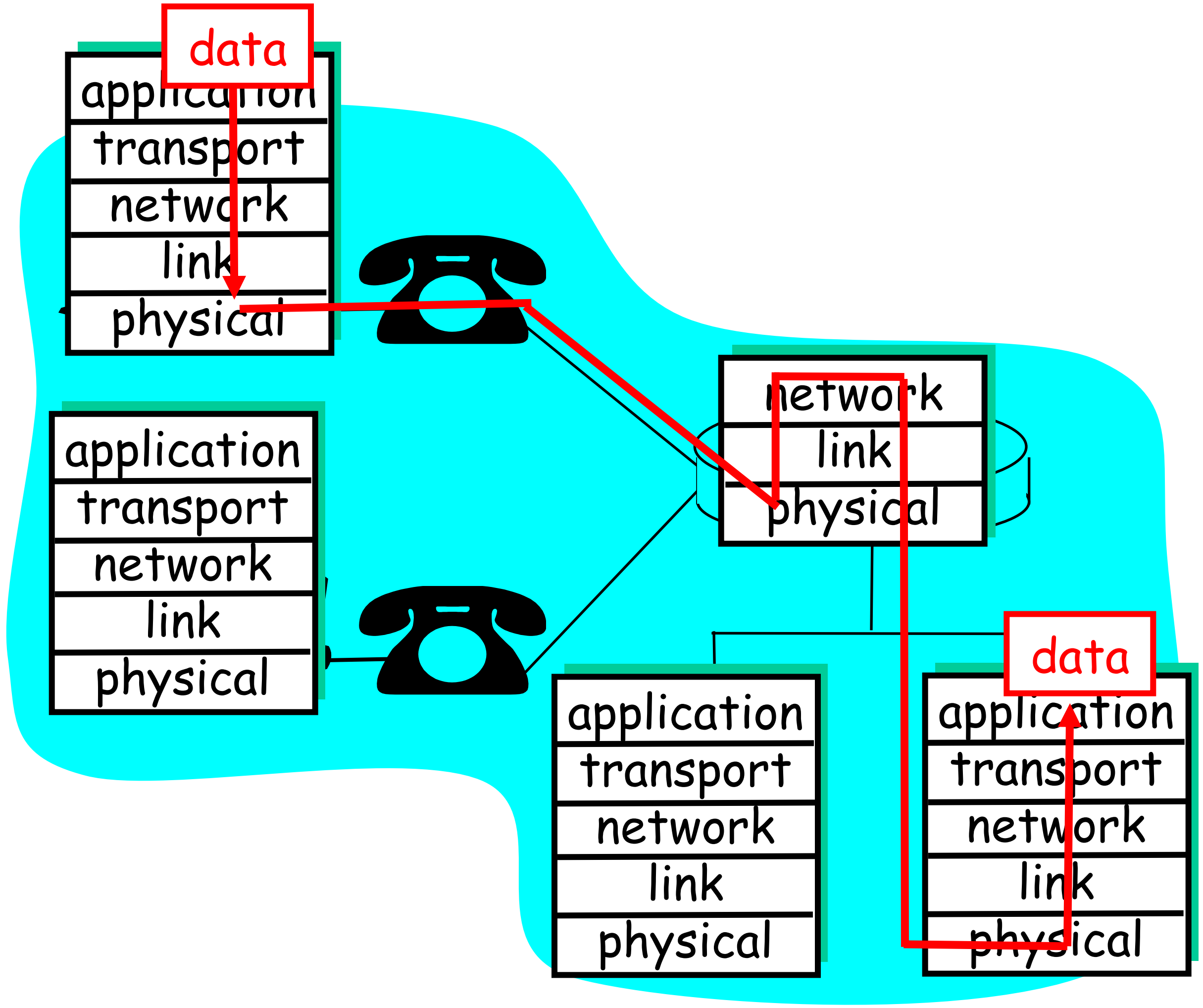
Layering: logical communication



Layering: *logical* communication



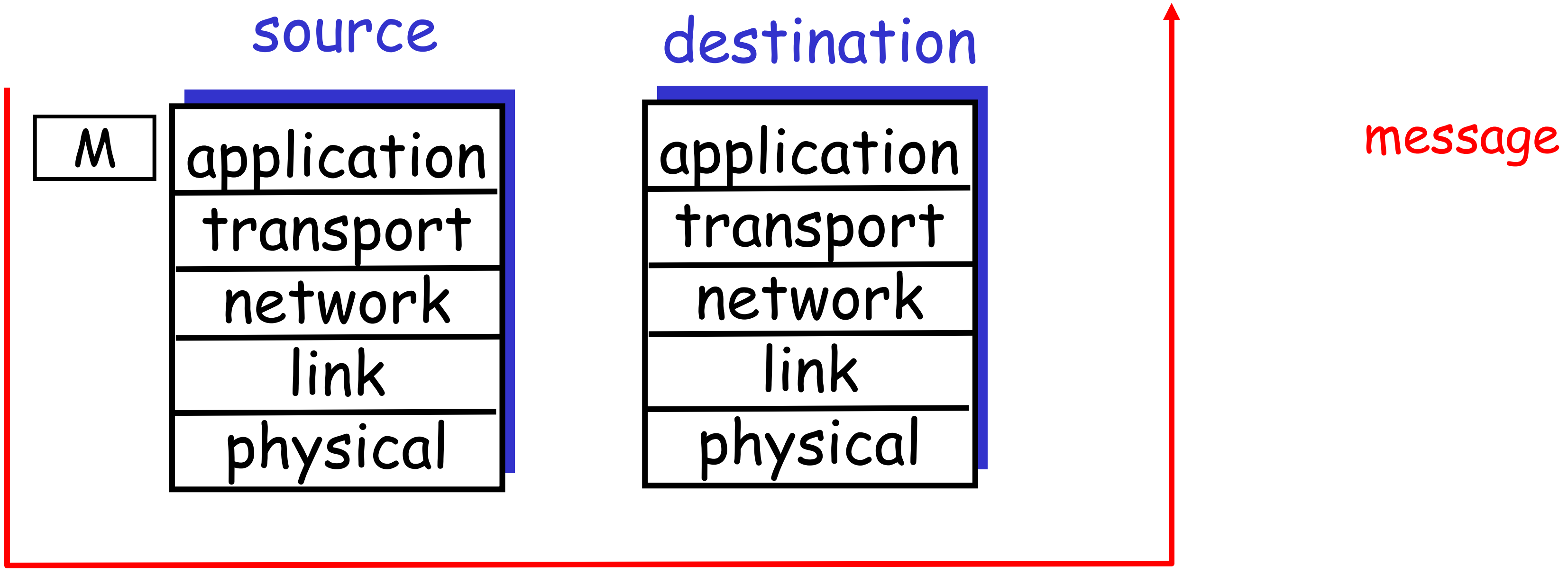
Layering: *physical* communication



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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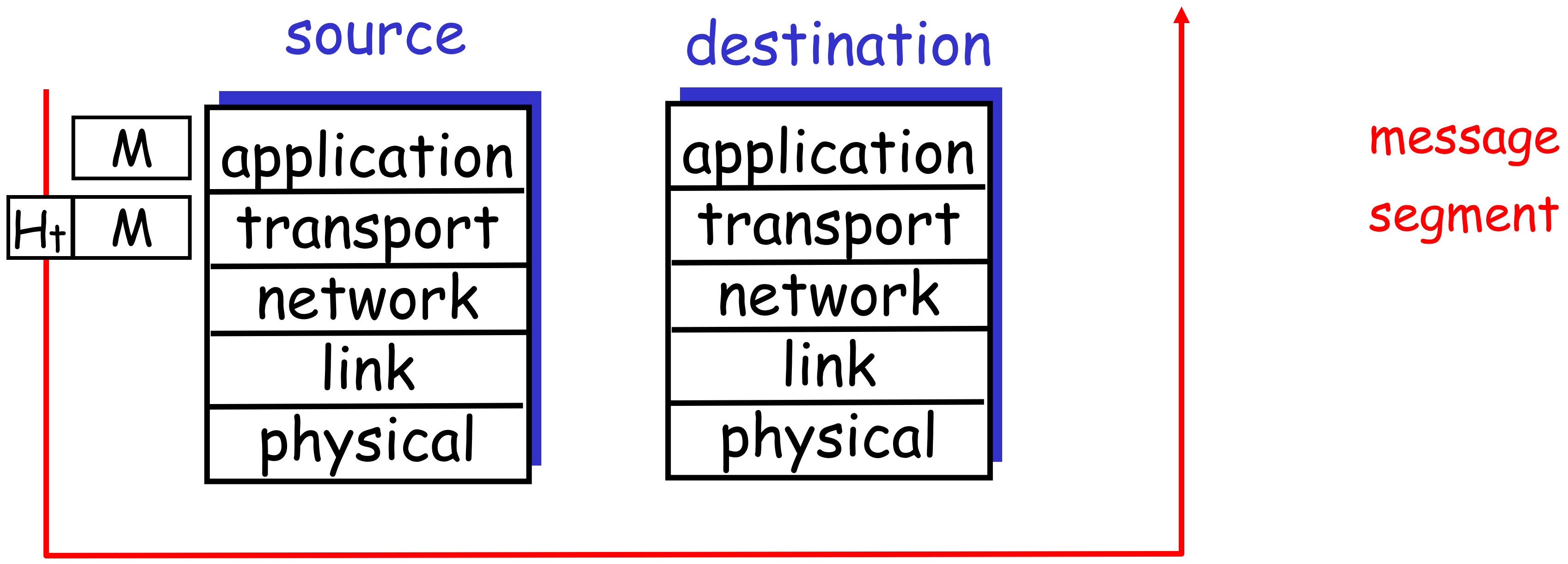

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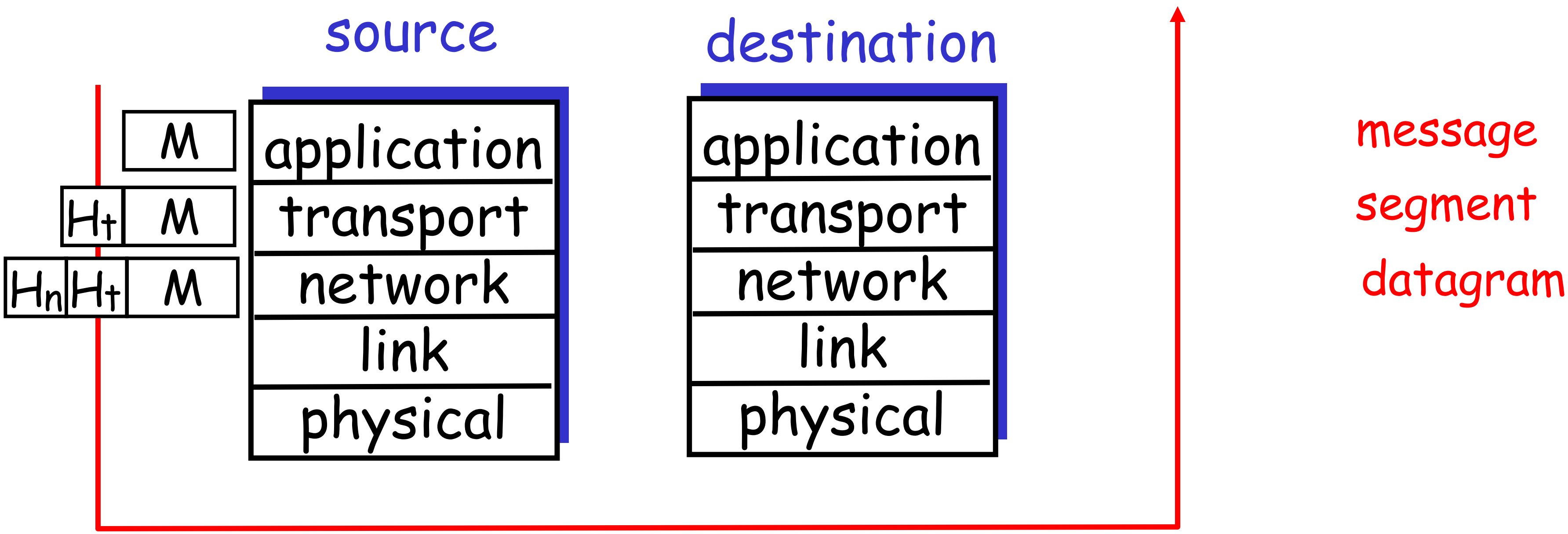

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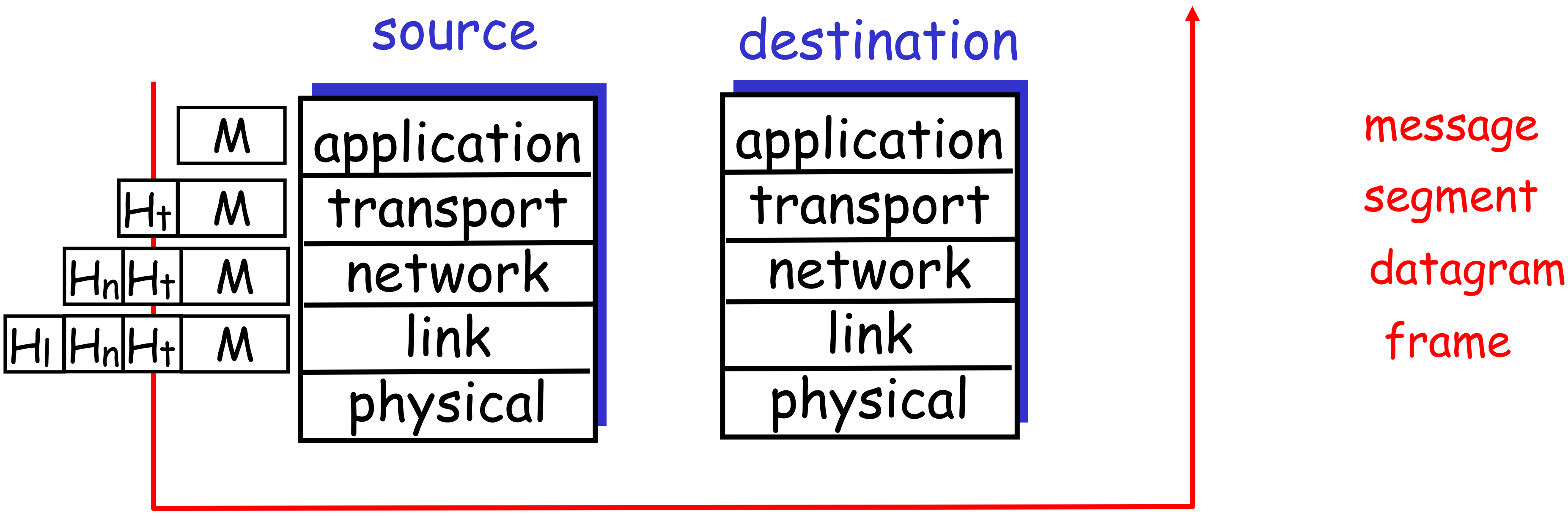

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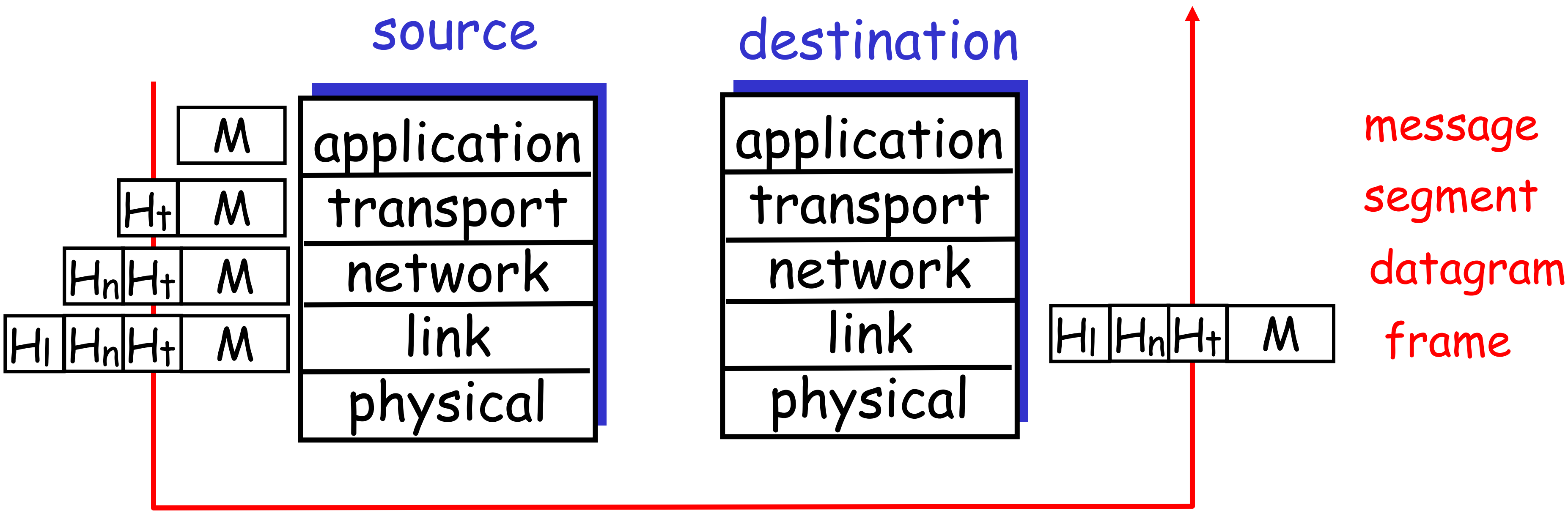

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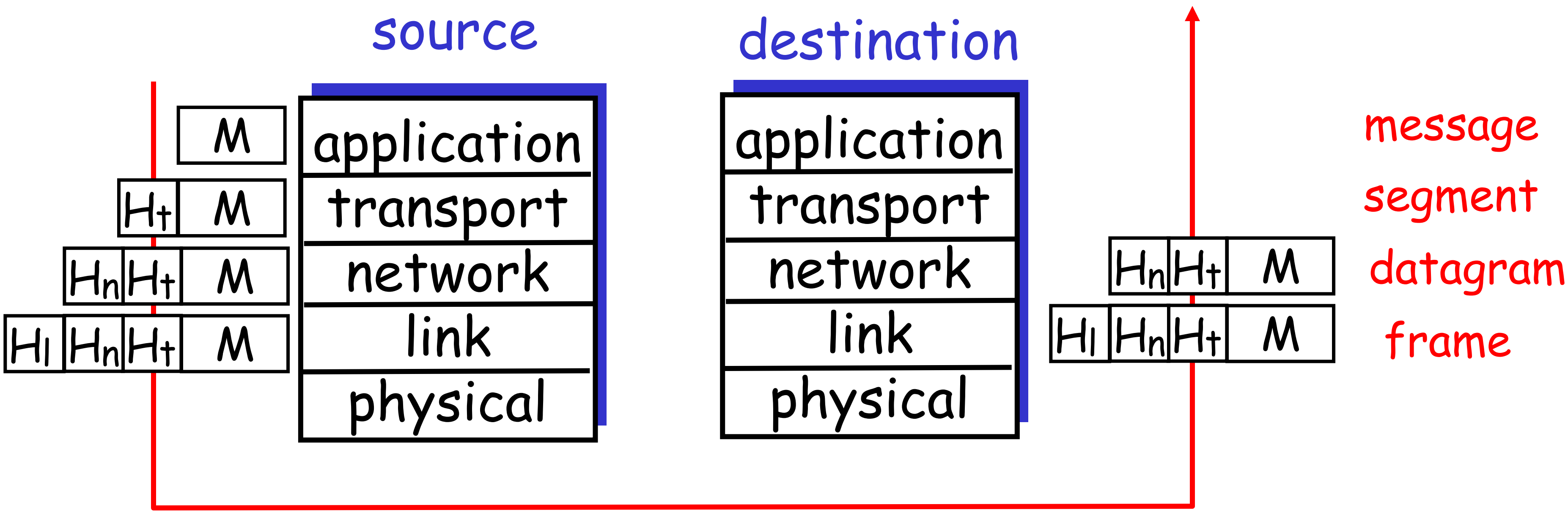

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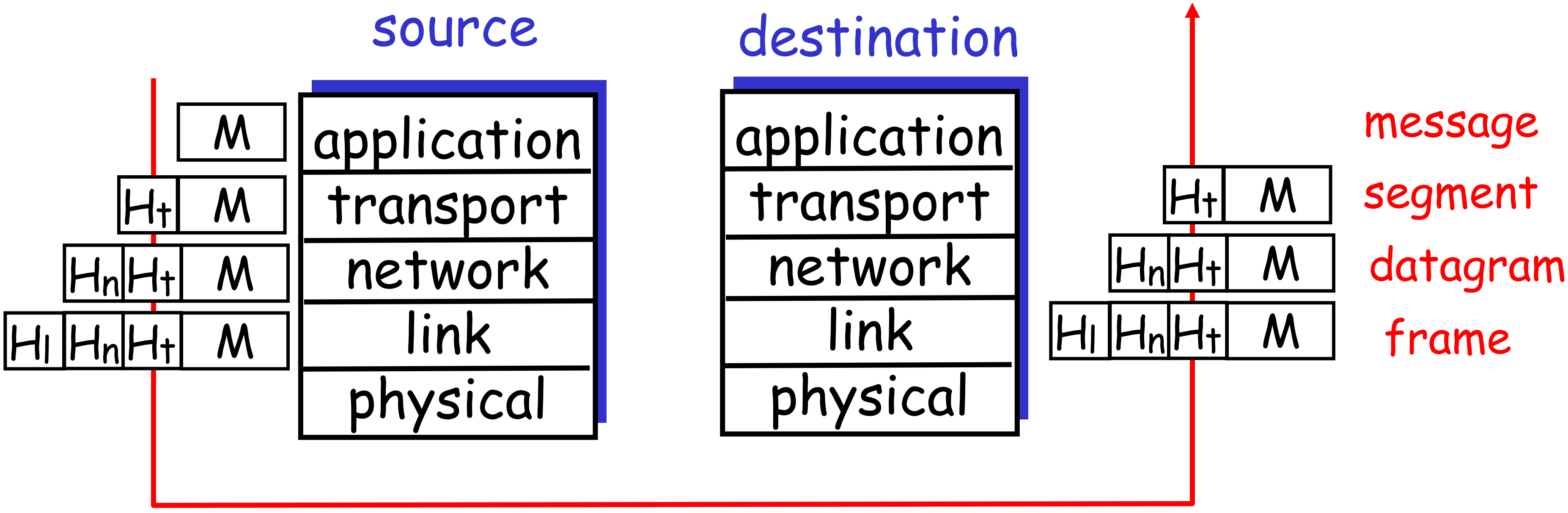

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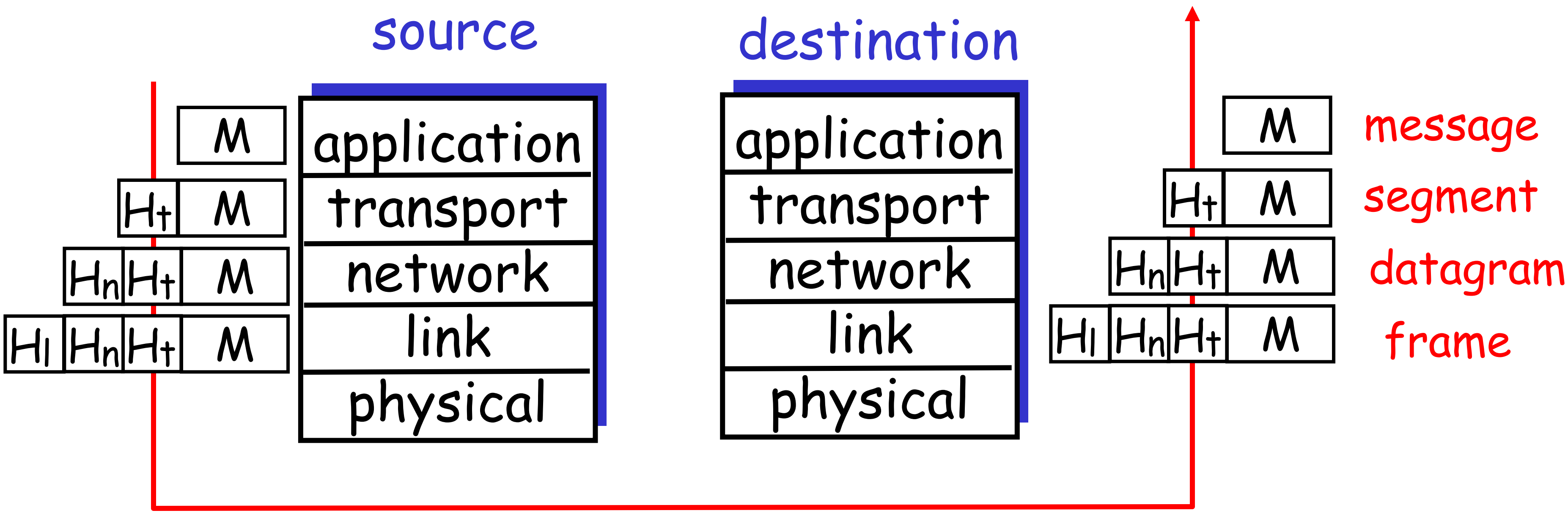

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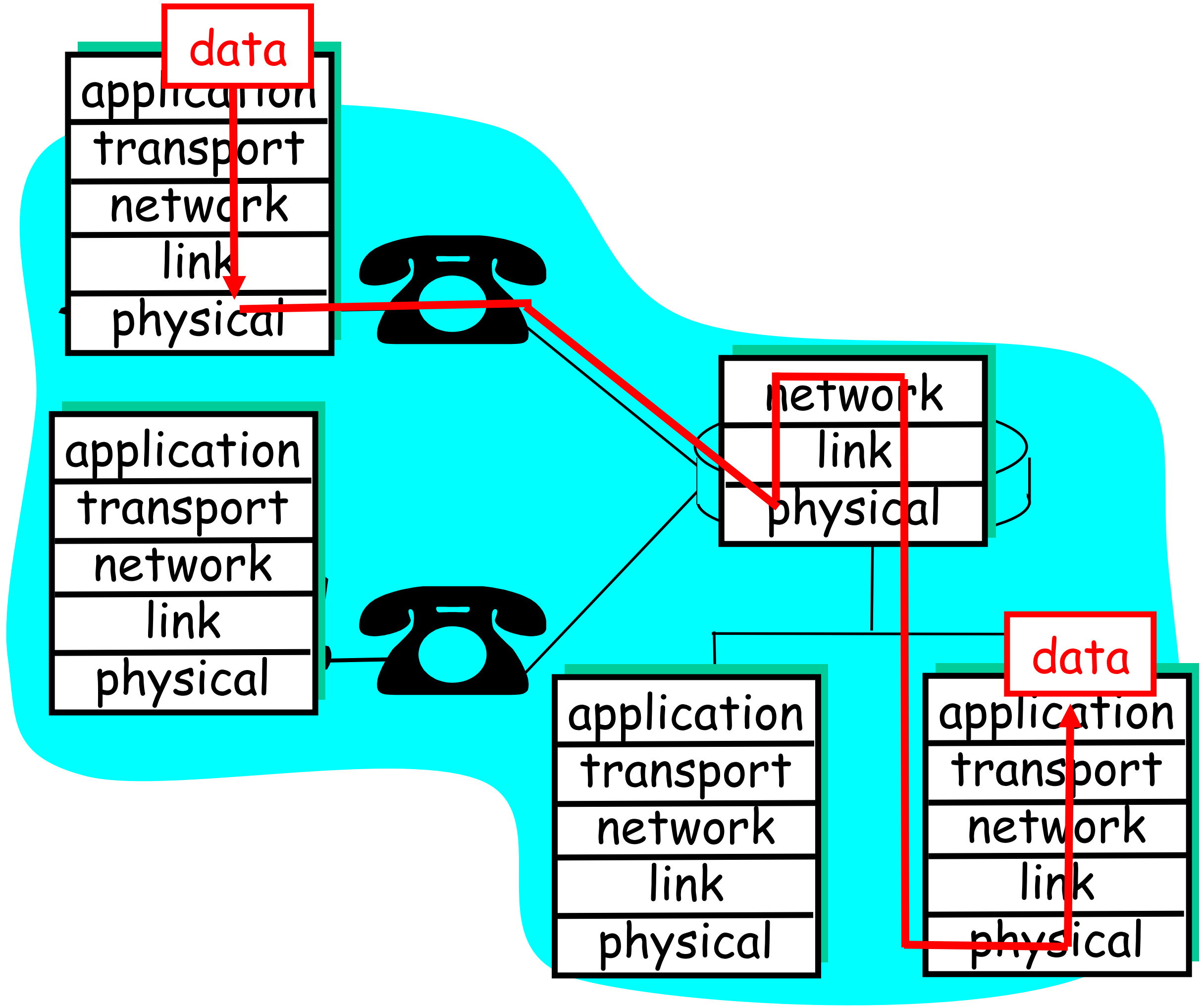

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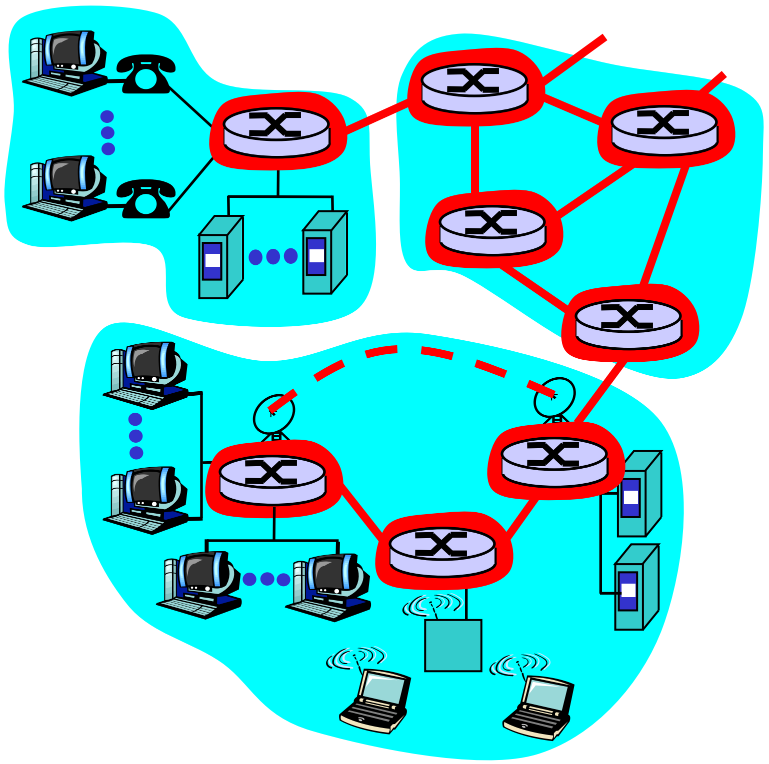
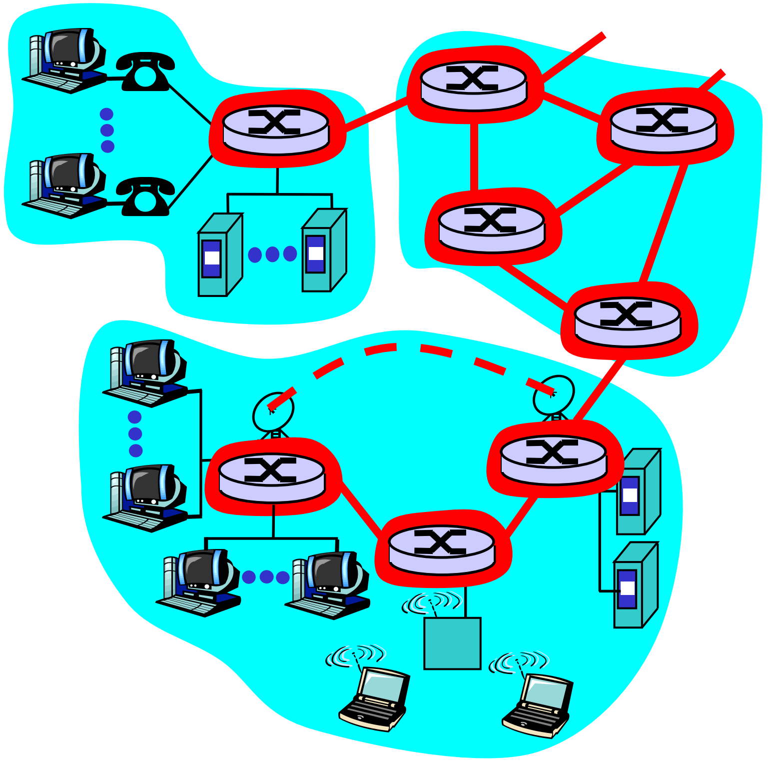
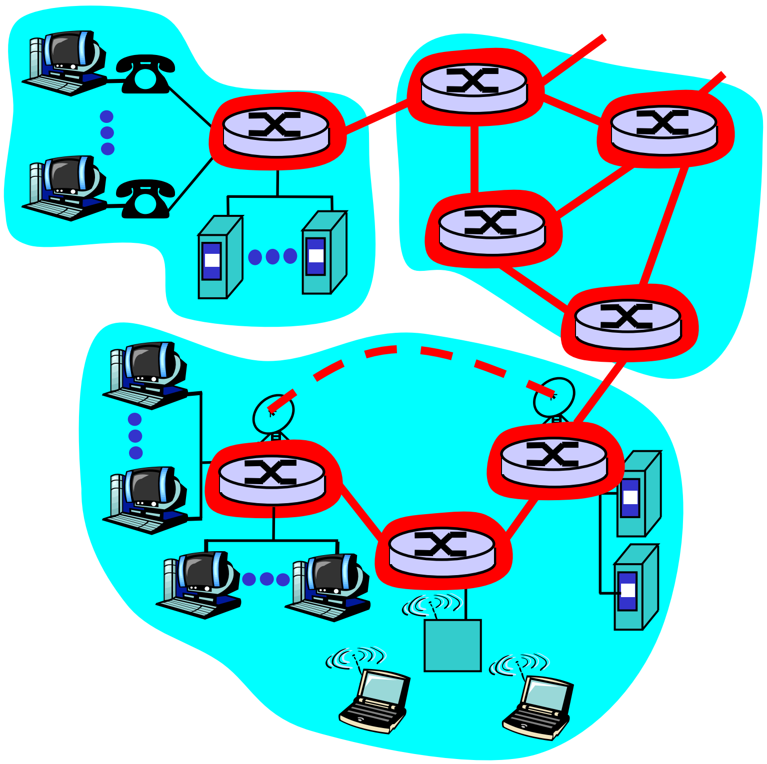
- mesh of interconnected routers



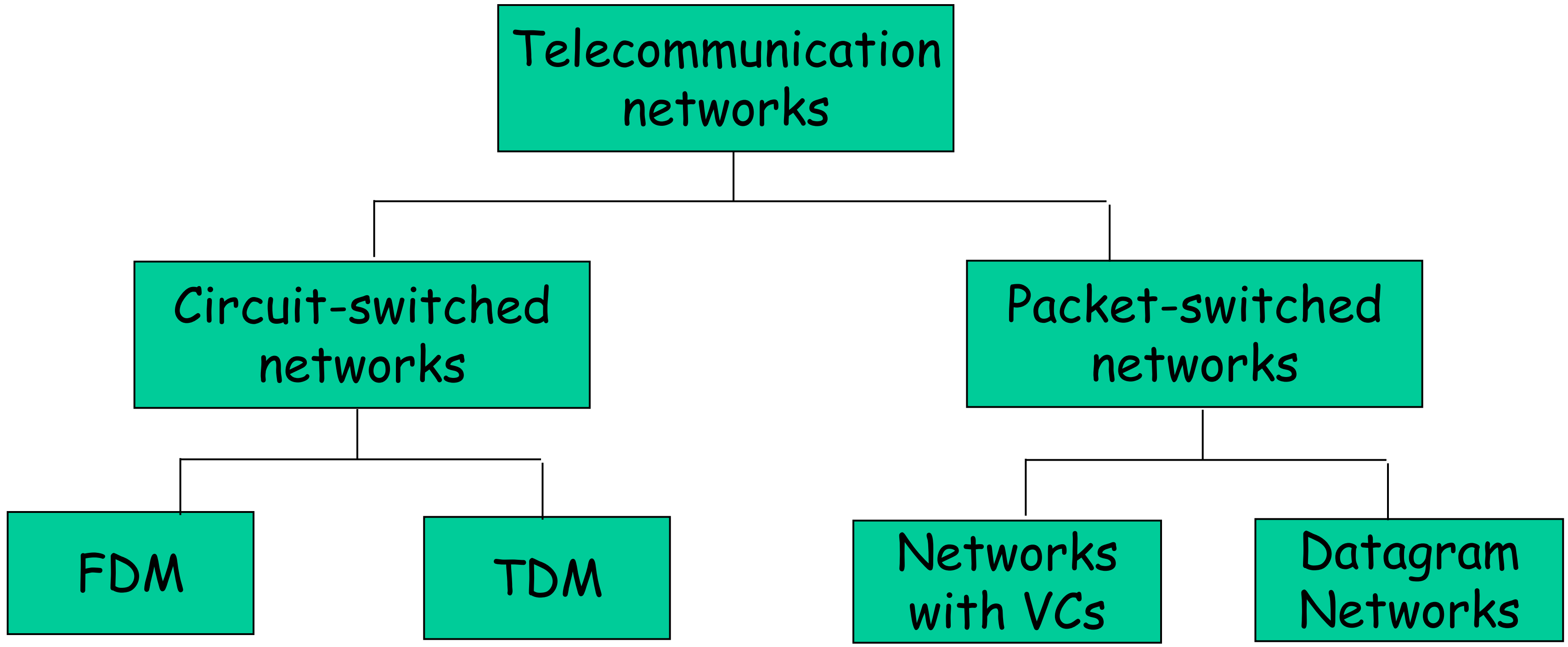
- mesh of interconnected routers
- *the* fundamental question: how is data transferred through net?



- 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"



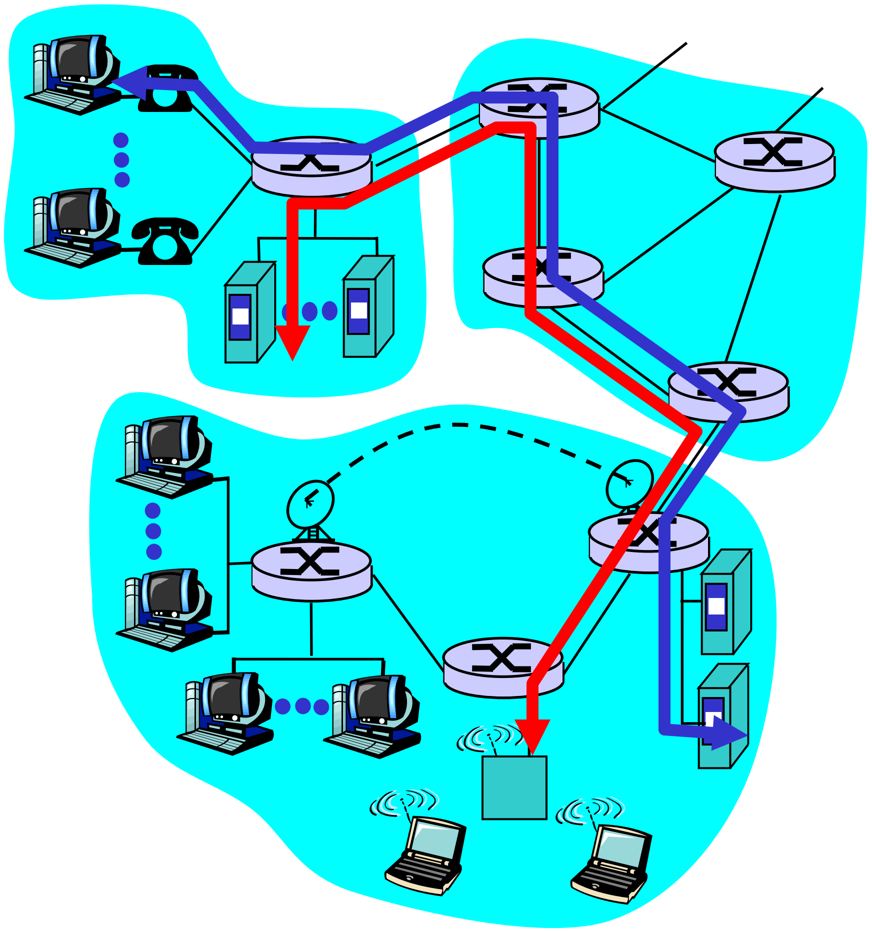
Network Taxonomy



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.

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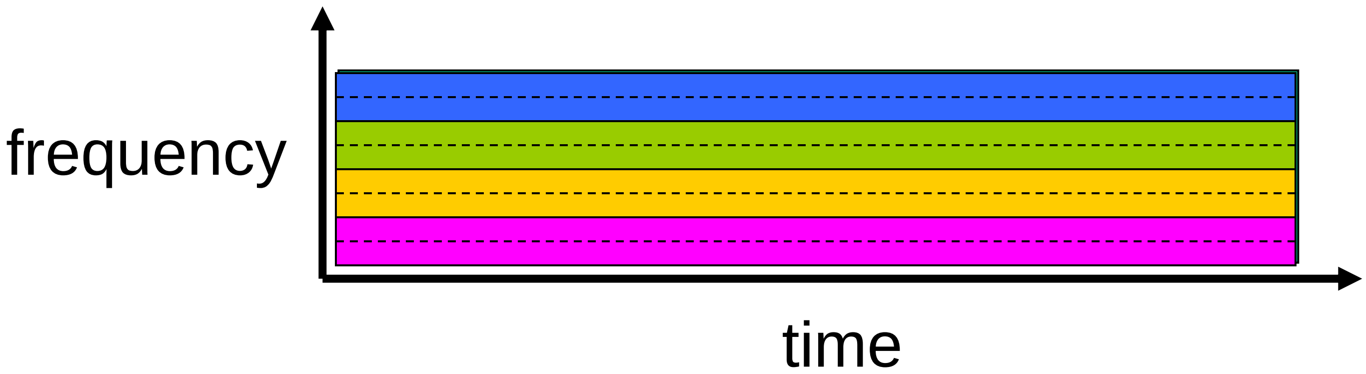
- Capacity of medium exceeds the capacity required for transmission of a single signal
  - How can we improve "efficiency"? Let's multiplex.
- Divide link bandwidth into "pieces":
  - frequency division - FDMA
  - time division – TDMA
  - code division - CDMA (cellular networks)
  - wavelength division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

Circuit-Switching: FDMA and TDMA

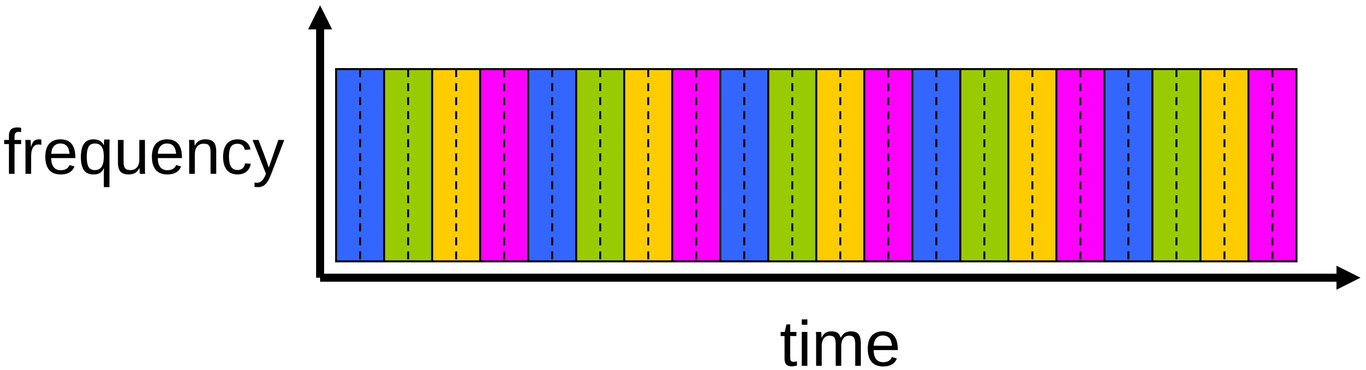
Example:

4 users

FDMA



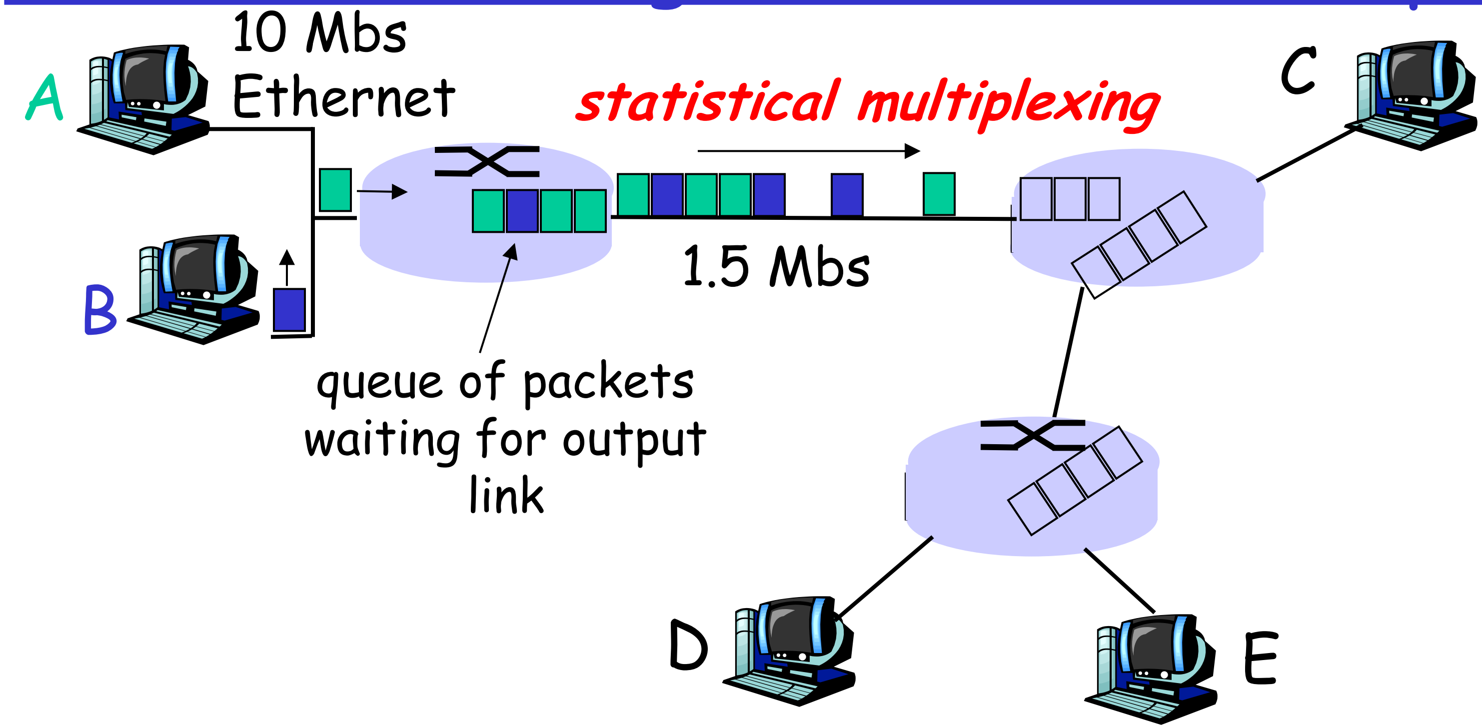
TDMA



Alt. 2: Packet-Switching

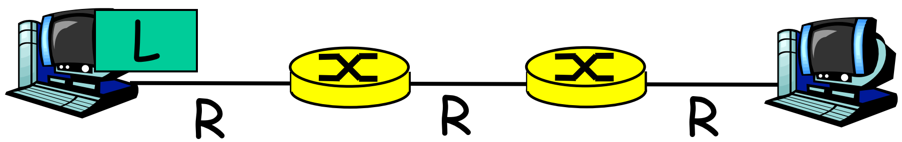
- source breaks long messages into smaller "packets"
- "store-and-forward" transmission
  - packets *share* network resources
  - each packet briefly uses full link bandwidth
- resource contention
  - aggregate resource demand can exceed amount available
  - congestion: packets queue, wait for link use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

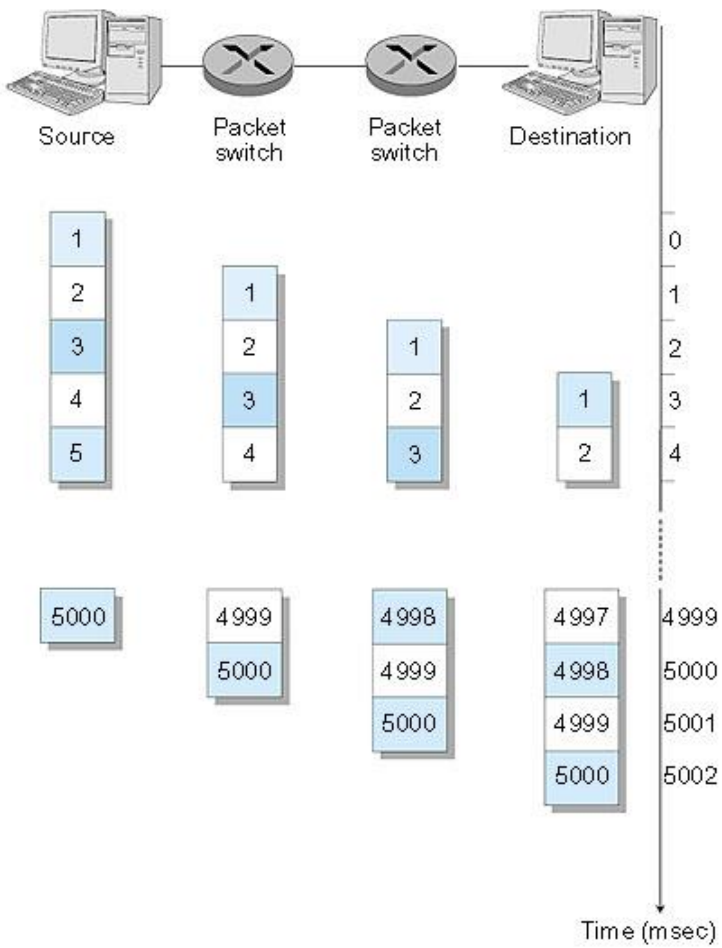


- Takes L/R seconds to transmit (push out) packet of L bits on to link or R bps
- Entire packet must arrive at router before it can be transmitted on next link: *store and forward*
- delay = 3L/R

Example:

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

Packet-Switching: Message Segmenting



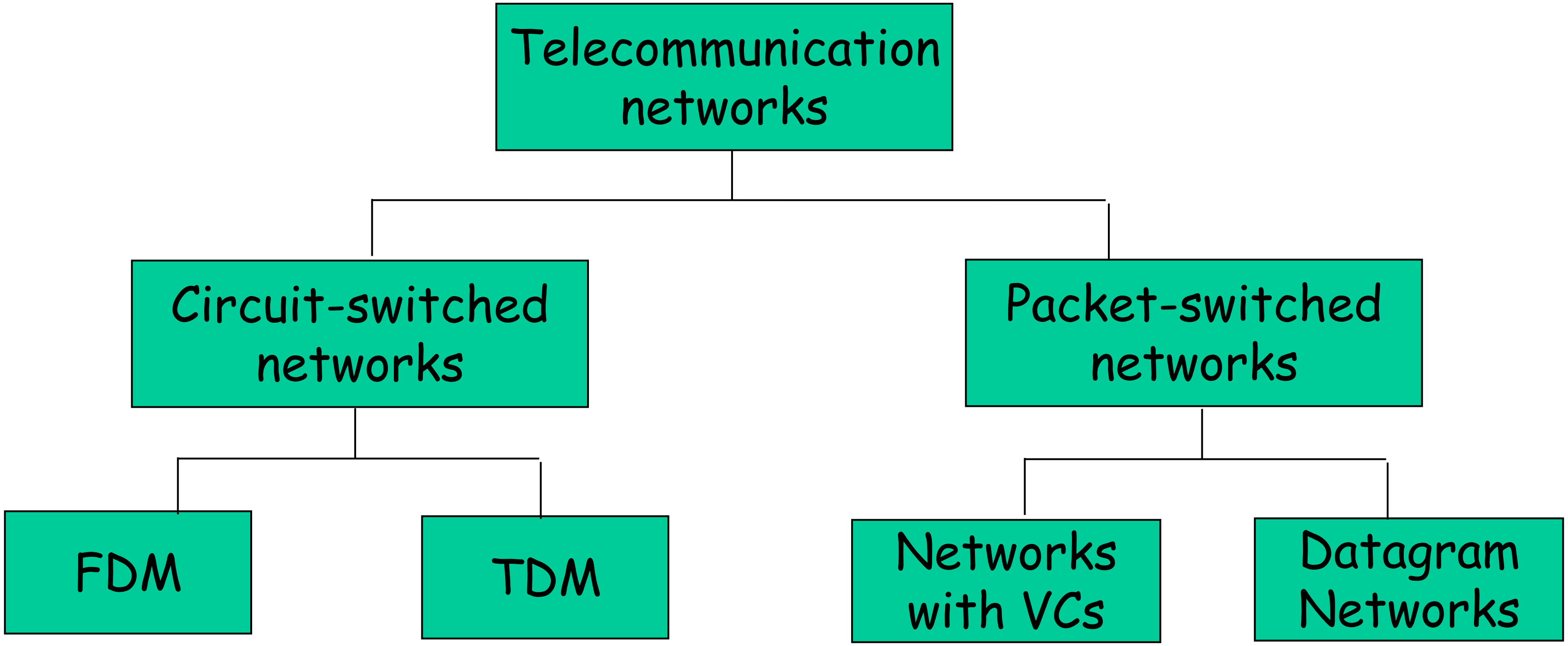
Now break up the message into 5000 packets

- 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



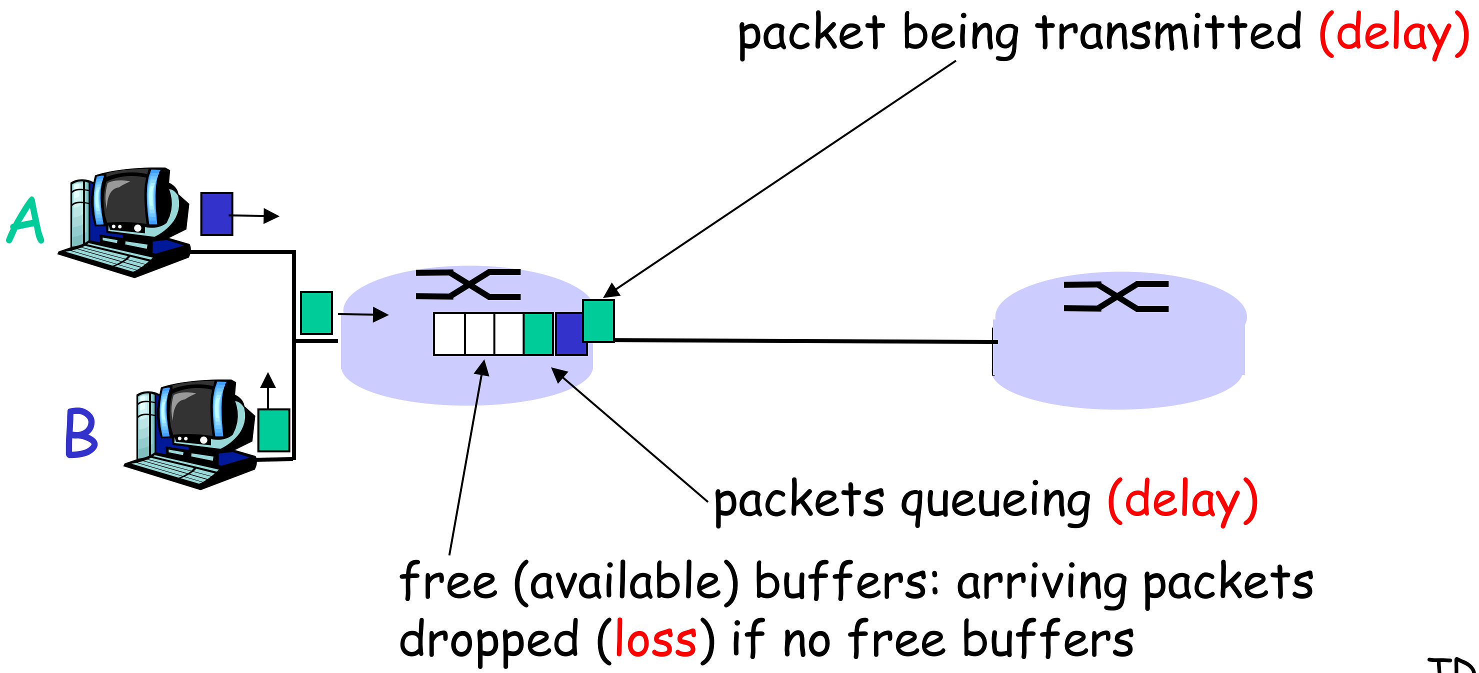
Roadmap

- 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?

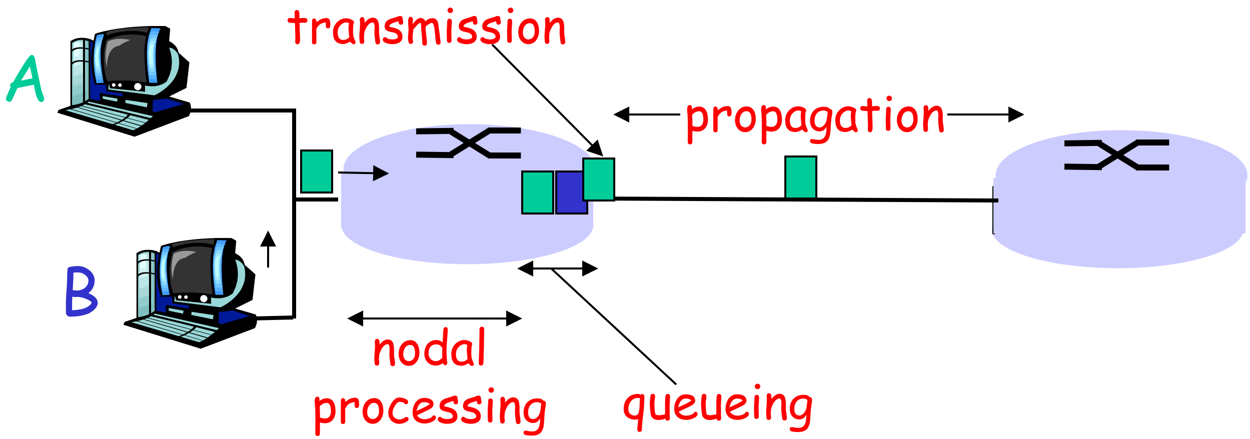
packets *queue* in router buffers

- 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

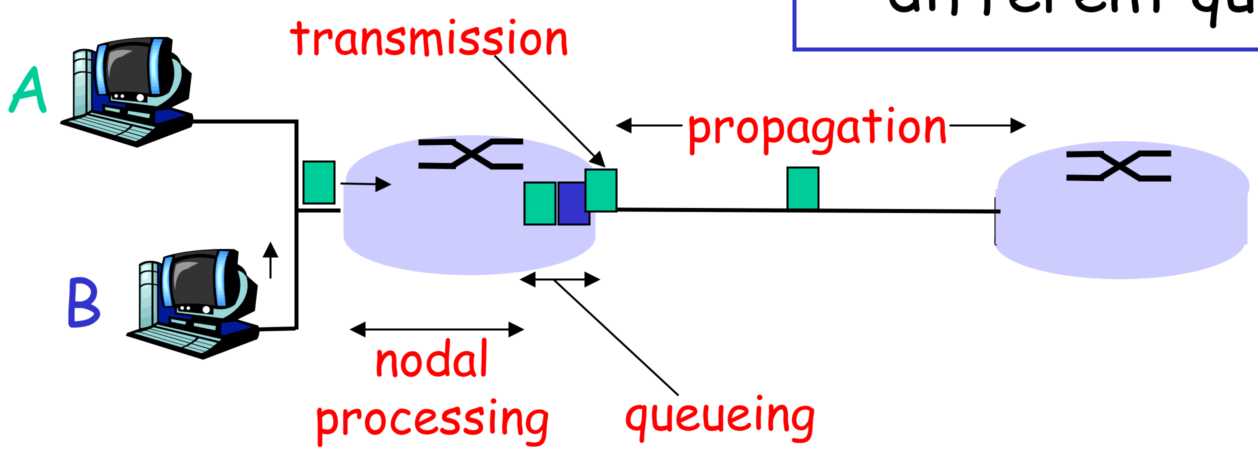
3. Transmission delay:

- 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 (~2×10^8 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

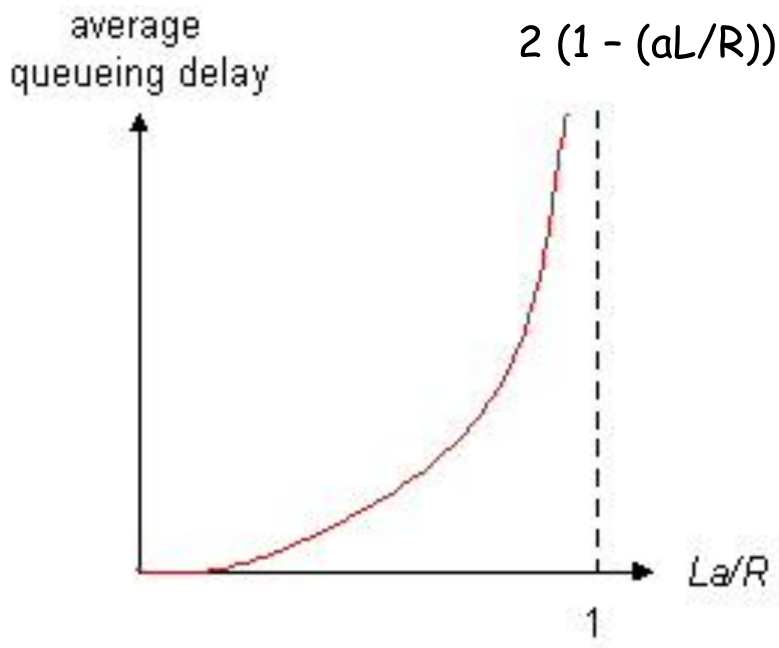
E.g., Assume M/D/1

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

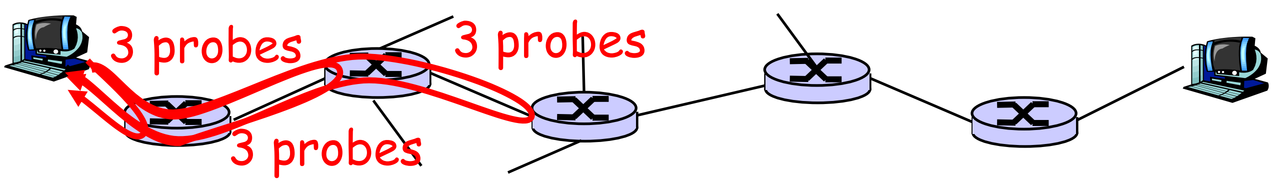
traffic intensity = aL/R



- 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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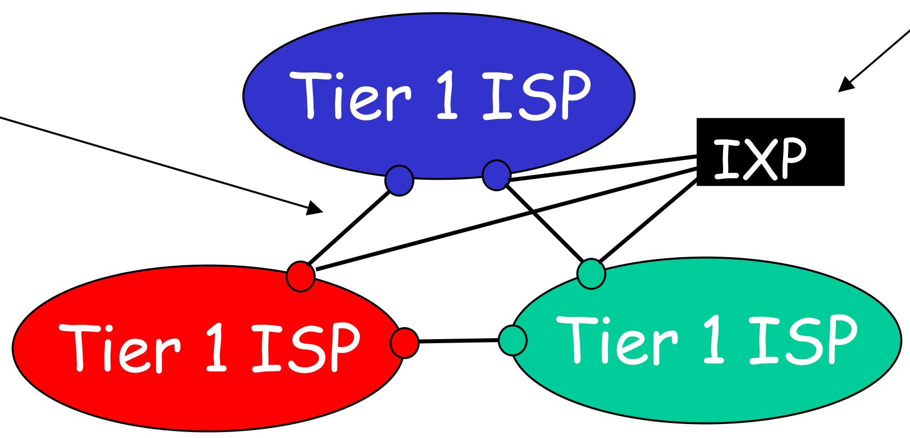
Internet structure: network of networks

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

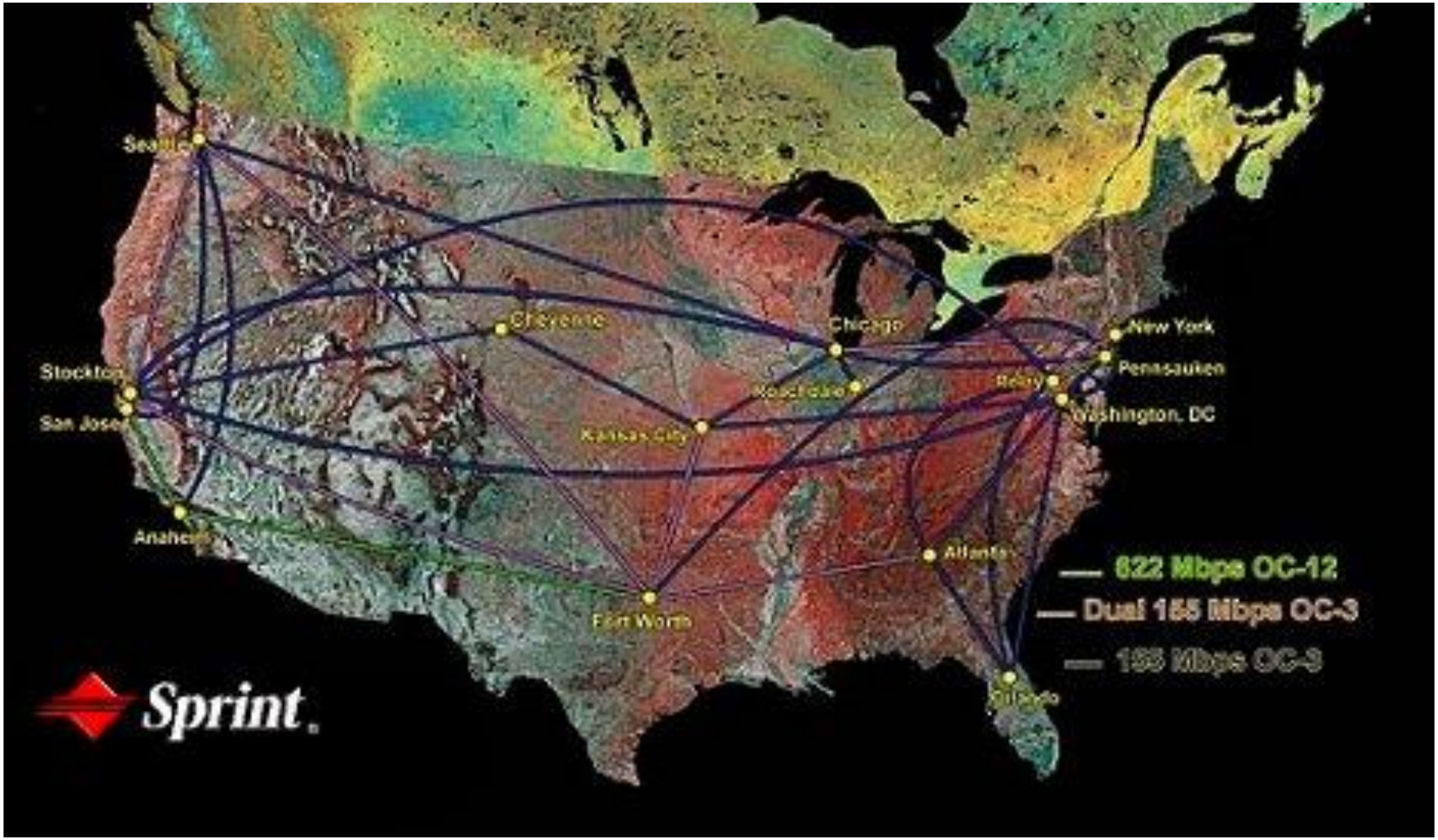
Tier-1 providers interconnect (peer) privately



Tier-1 providers also interconnect at public internet exchange points (IXPs)

Tier-1 ISP: e.g., Sprint

Sprint US backbone network

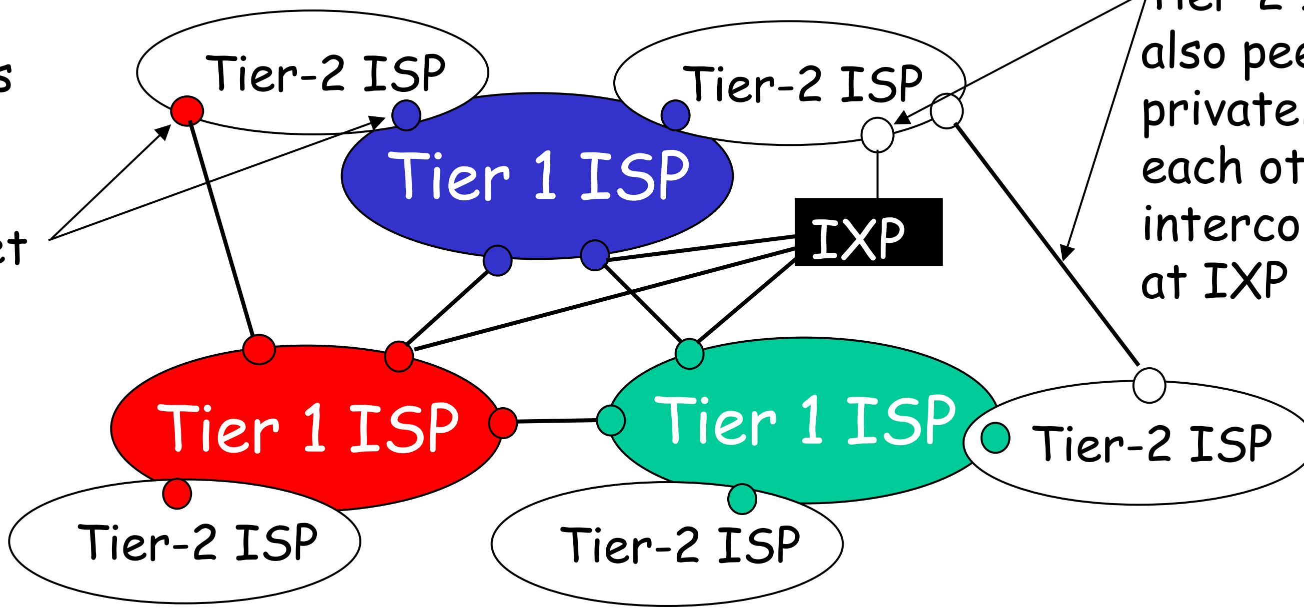


Internet structure: network of networks

- "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

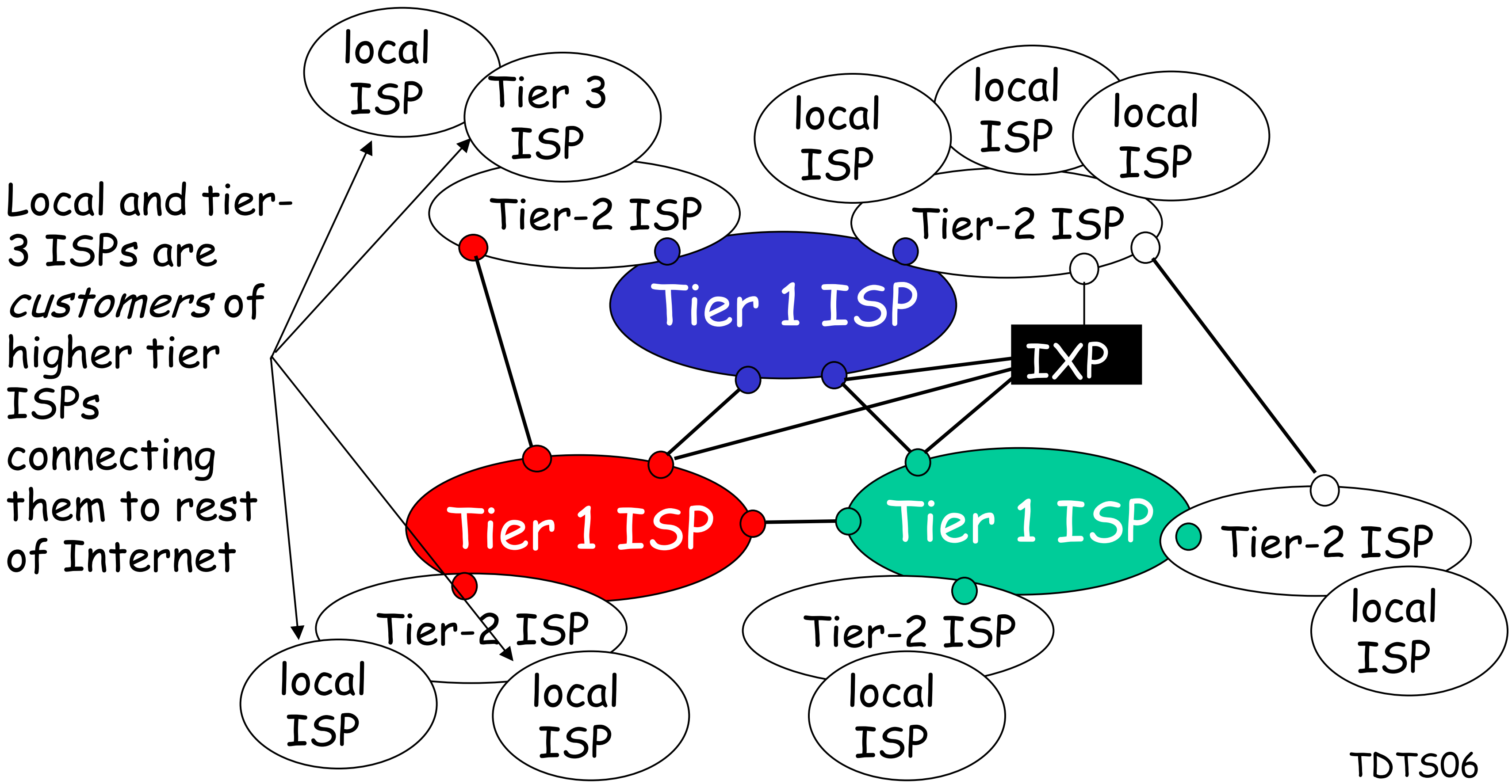
- tier-2 ISP is *customer* of tier-1 provider



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

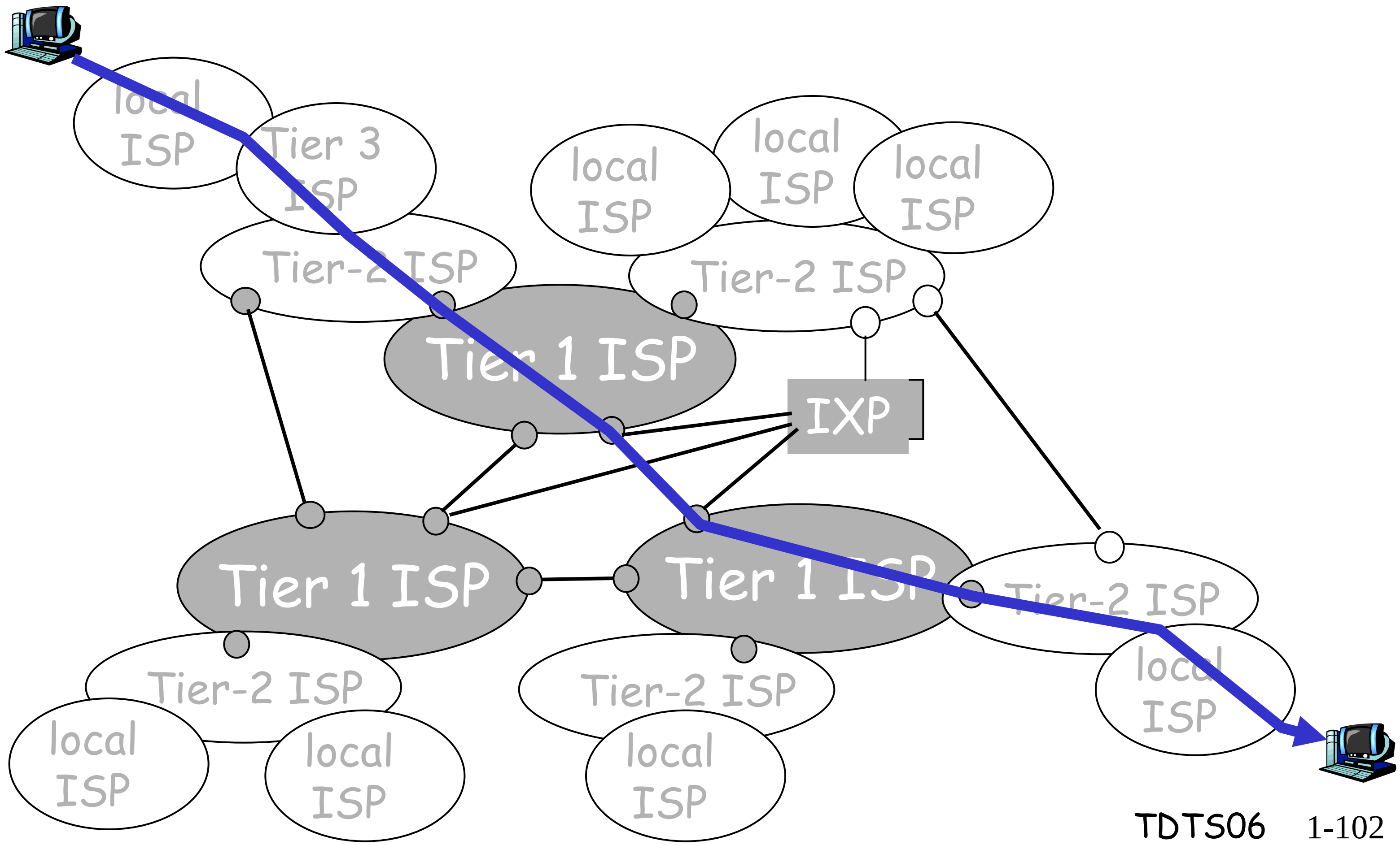
Internet structure: network of networks

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



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 vs. circuit-switching
- Internet/ISP structure
- Performance: loss, delay
- Layering and service models
- Internet history

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- more depth, detail *to follow!*

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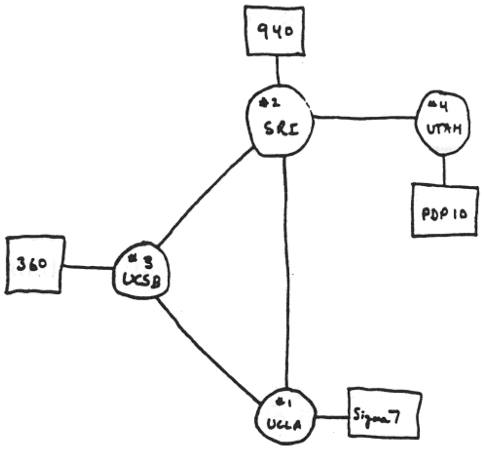
Ohh, and the history …

- …

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



THE ARPA NETWORK

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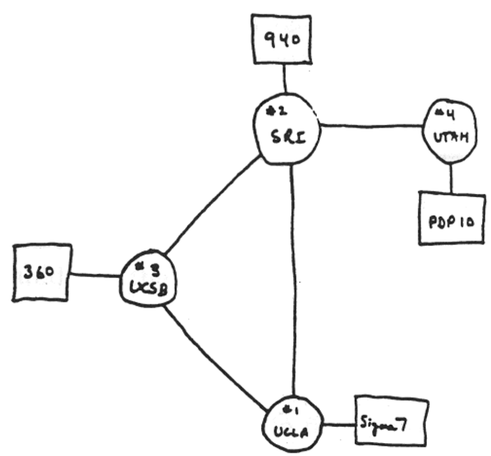

THE ARPA NETWORK

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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
- wireless, mobility
- smart grid, sustainable ICT, ...

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The future is yours to write