COMP3234B
Computer and Communication Networks

2nd semester 2023-2024
Introduction to Computer Networks

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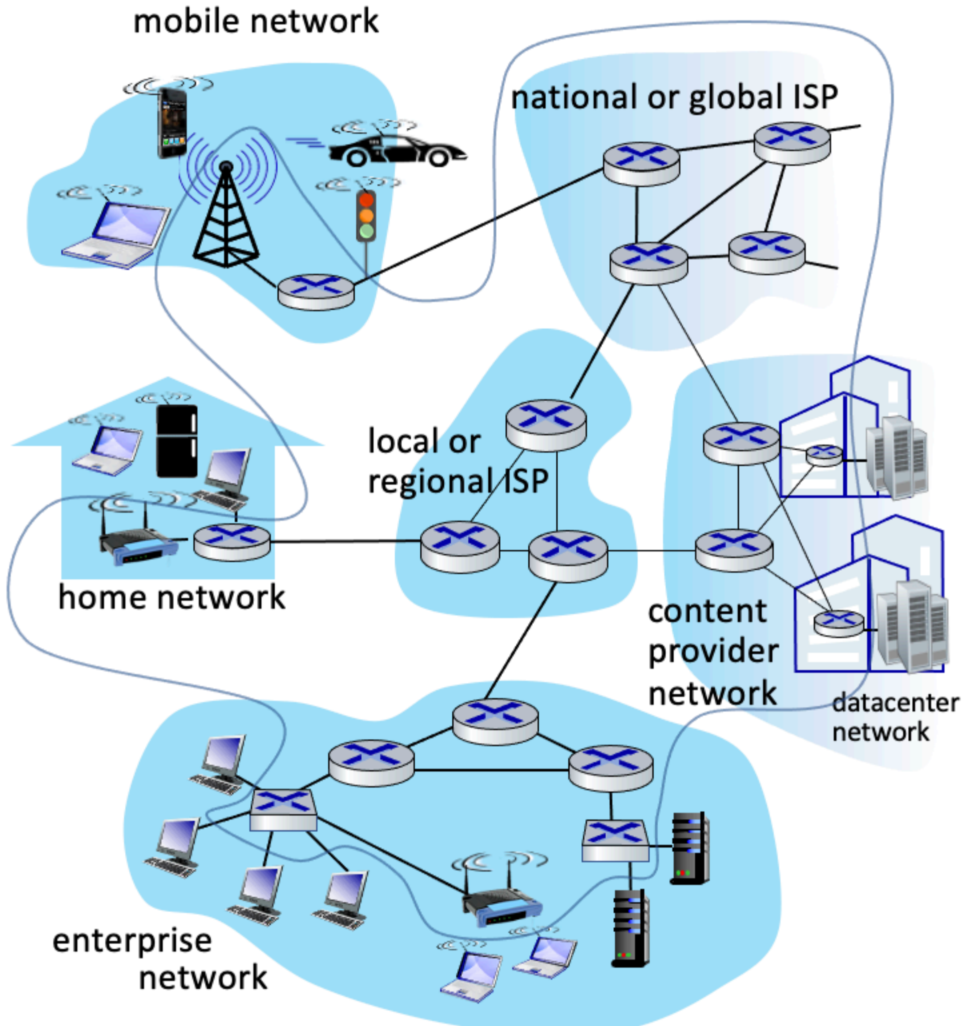
- Internet [Learning outcome 1]
- Protocol [Learning outcome 1]
- Layering [Learning outcome 1]
- Network edge - access networks [Learning outcome 1]
- Network core - circuit vs. packet switching [Learning outcomes 1, 2]
- Key performance metrics [Learning outcomes 1, 3]

What is the Internet?



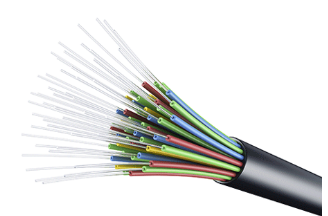
- A global system of interconnected computer networks linking billions of computing devices throughout the world

  - hosts == end systems running network applications

    e.g. Web, email, WhatsApp, Zoom,...

  - communication links: the media by which data travel

Twisted pair
copper wire



Fiber optic cable

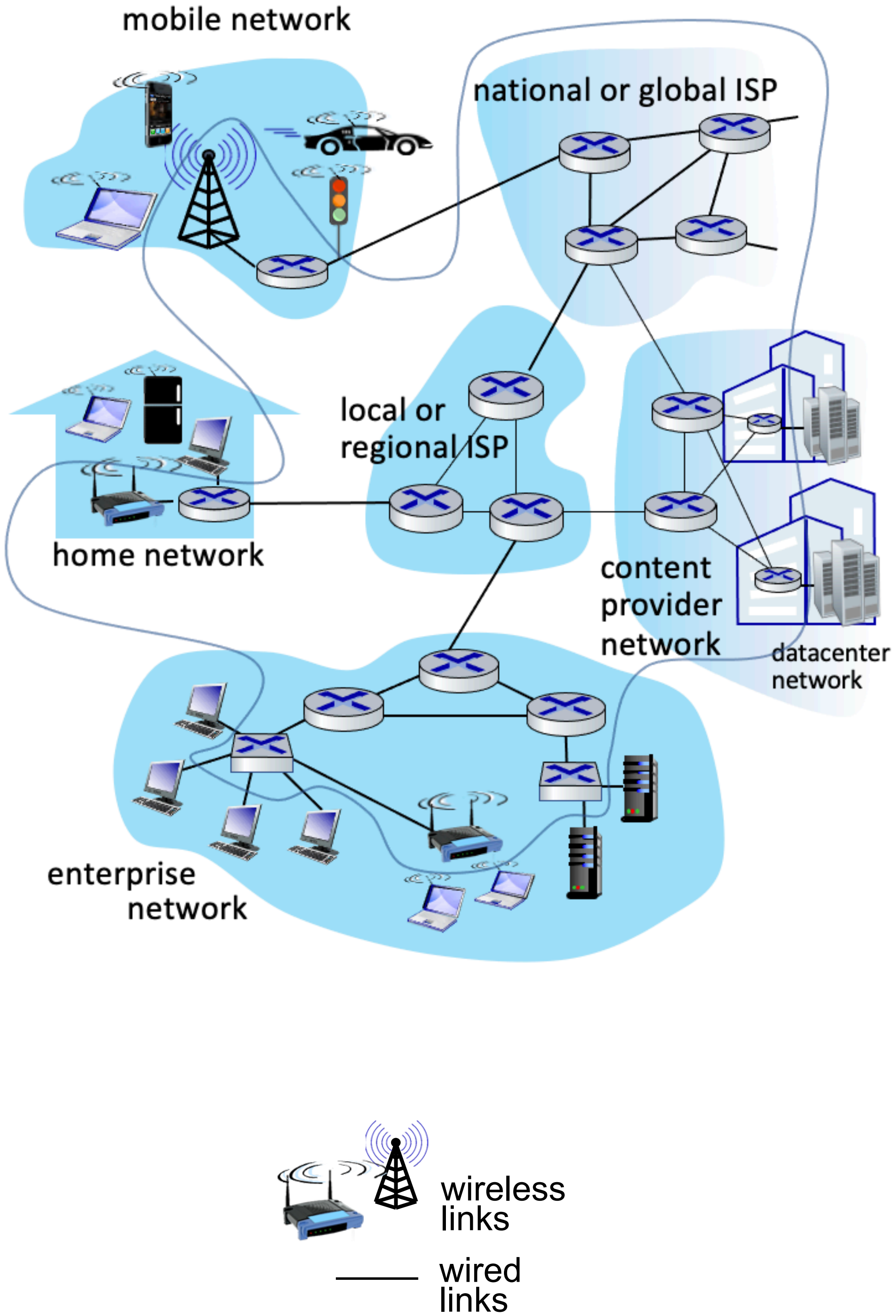
radio

satellite

  - routers and switches

    switching devices that end systems are connected to, for forwarding data from one host to another

What is the Internet? (cont'd)

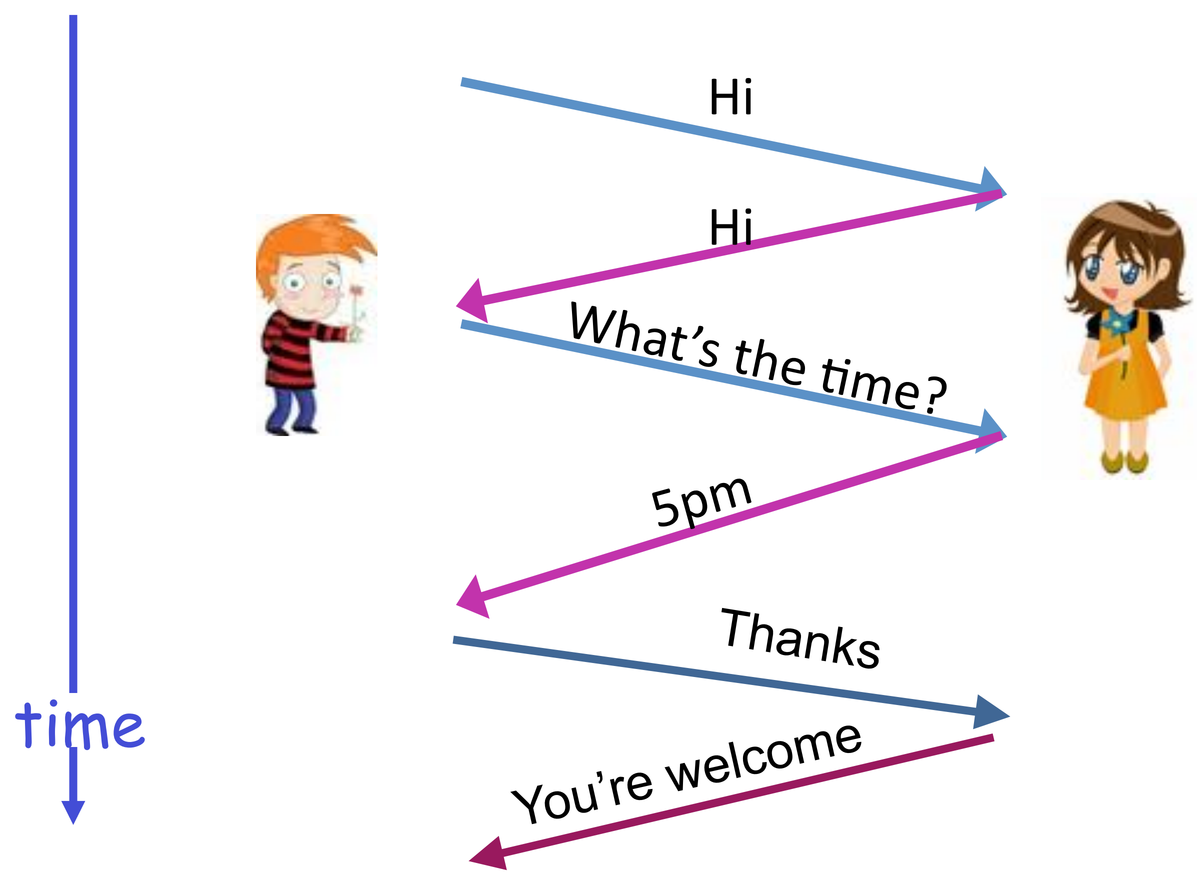


- A network of networks
  - interconnected ISP (Internet service provider) networks
- A communication infrastructure
  - to support network applications
  - to provide different types of services
    reliable data delivery vs. unreliable data delivery (best effort)
  - end systems and routers/switches run protocols to send and receive data to/from each other

Network Protocol

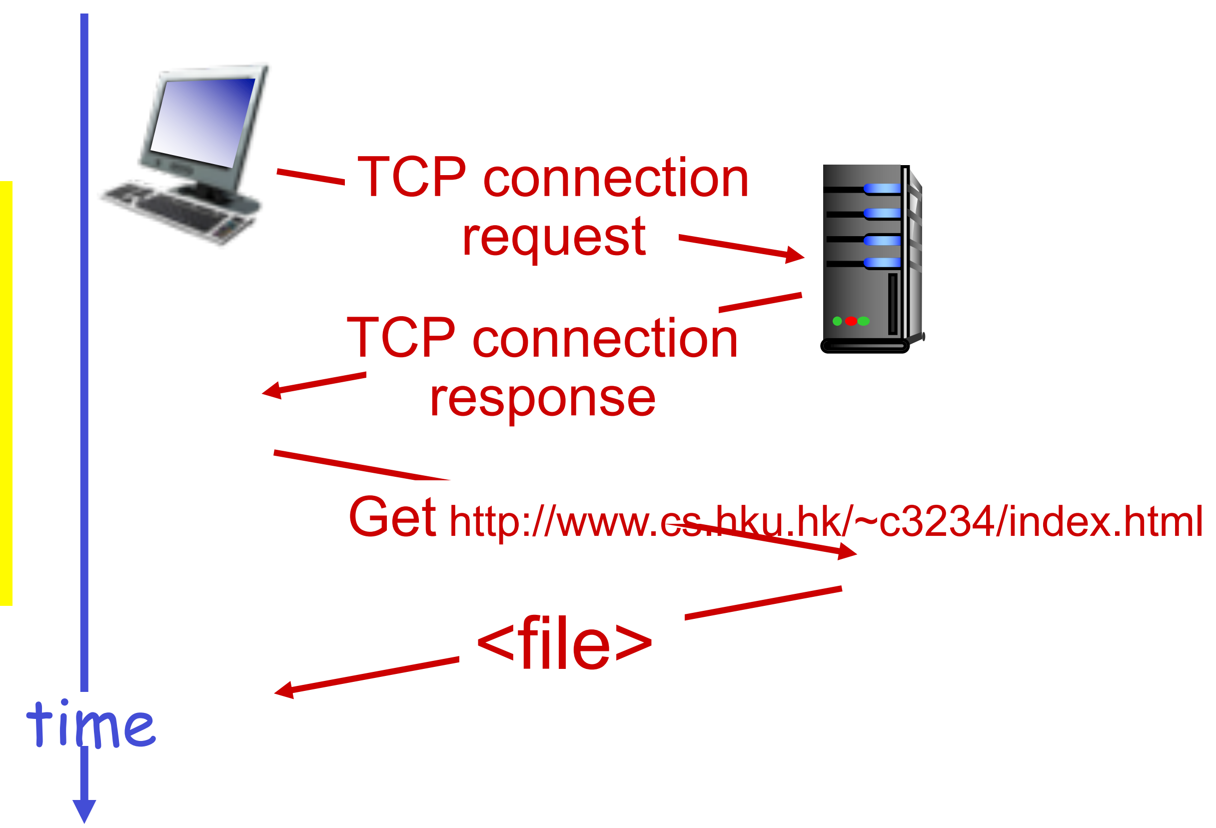
- Oxford Dictionary
  - a system of fixed rules and formal behaviour used at official meetings, usually between governments

- A human protocol

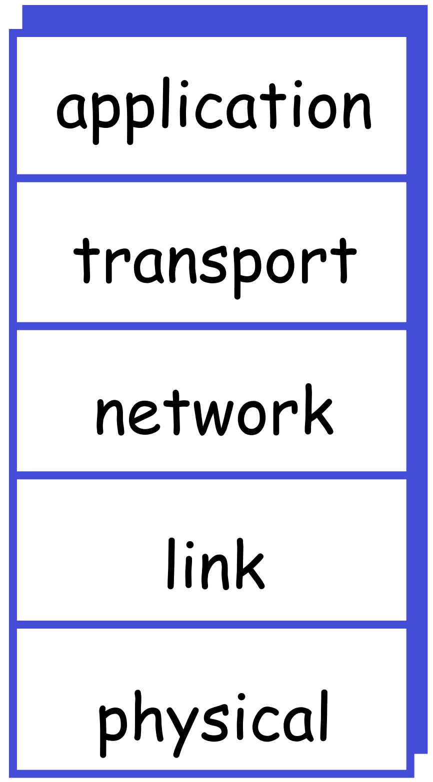


Network Protocol (cont'd)

- A network protocol defines
  - format, order of msgs sent and received between network entities
  - actions taken upon msg transmission/receipt



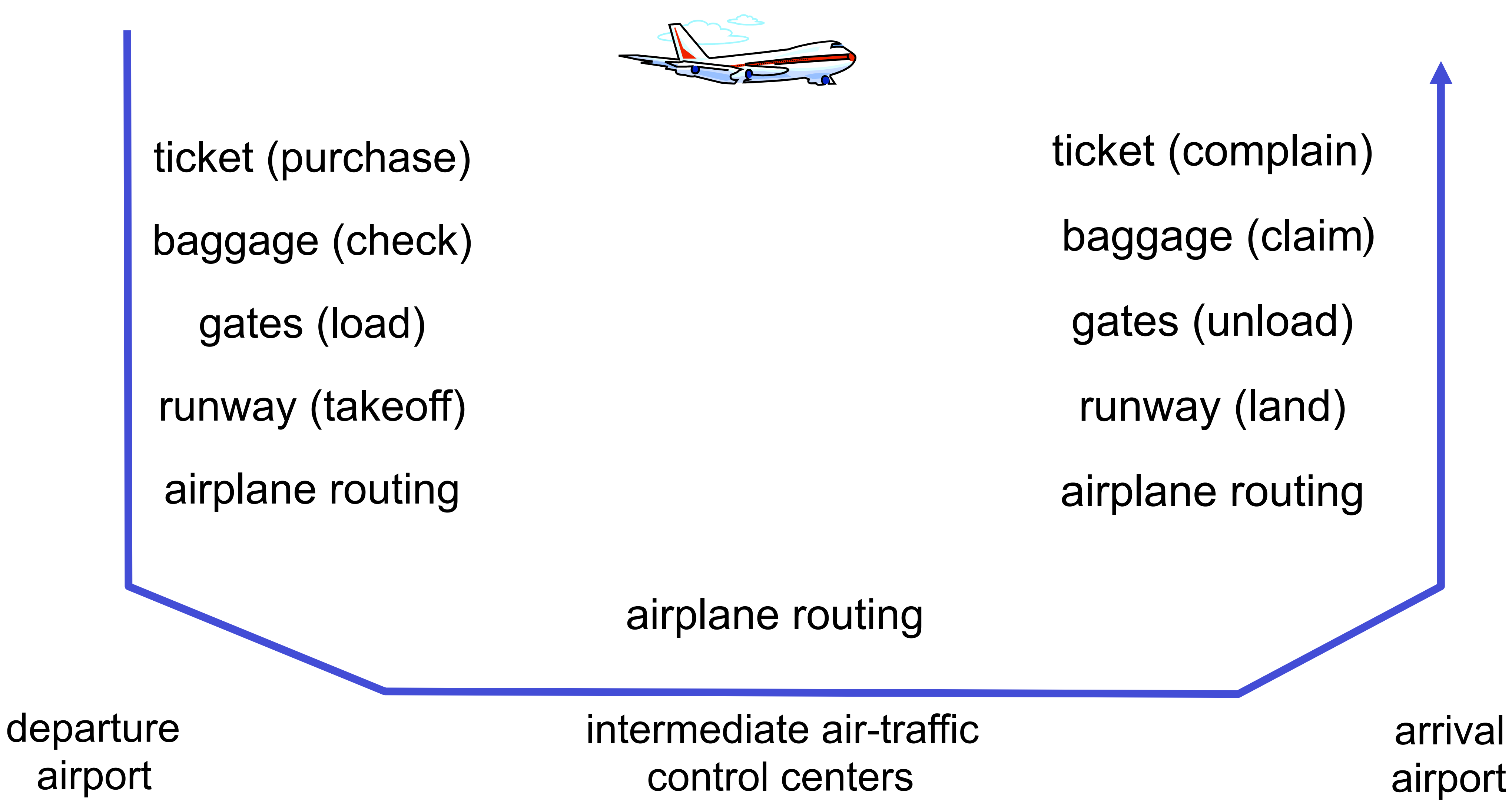
- Internet is complex with many protocols implementing different services



Is there a way to organize the protocols of network?

Layering

- A computer network
  - basic function: transmit data from source to destination
- An airline system (an analogy)
  - basic function: transfer passenger from one place to another



Layering (cont'd)

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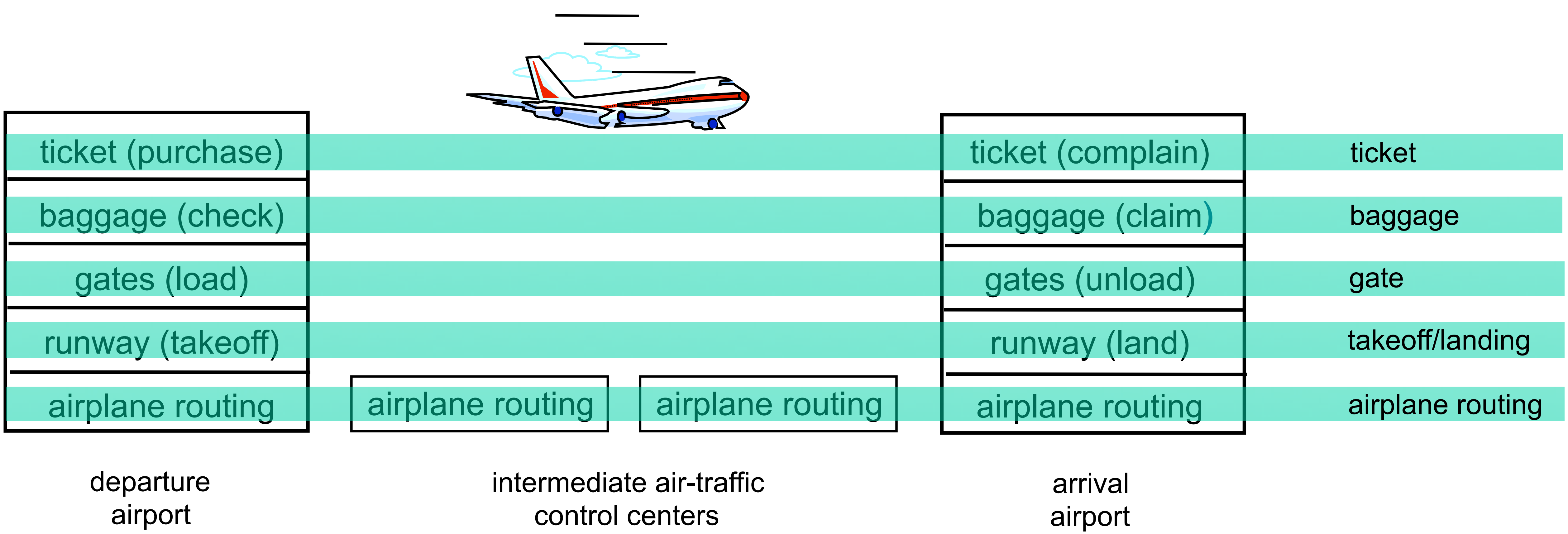


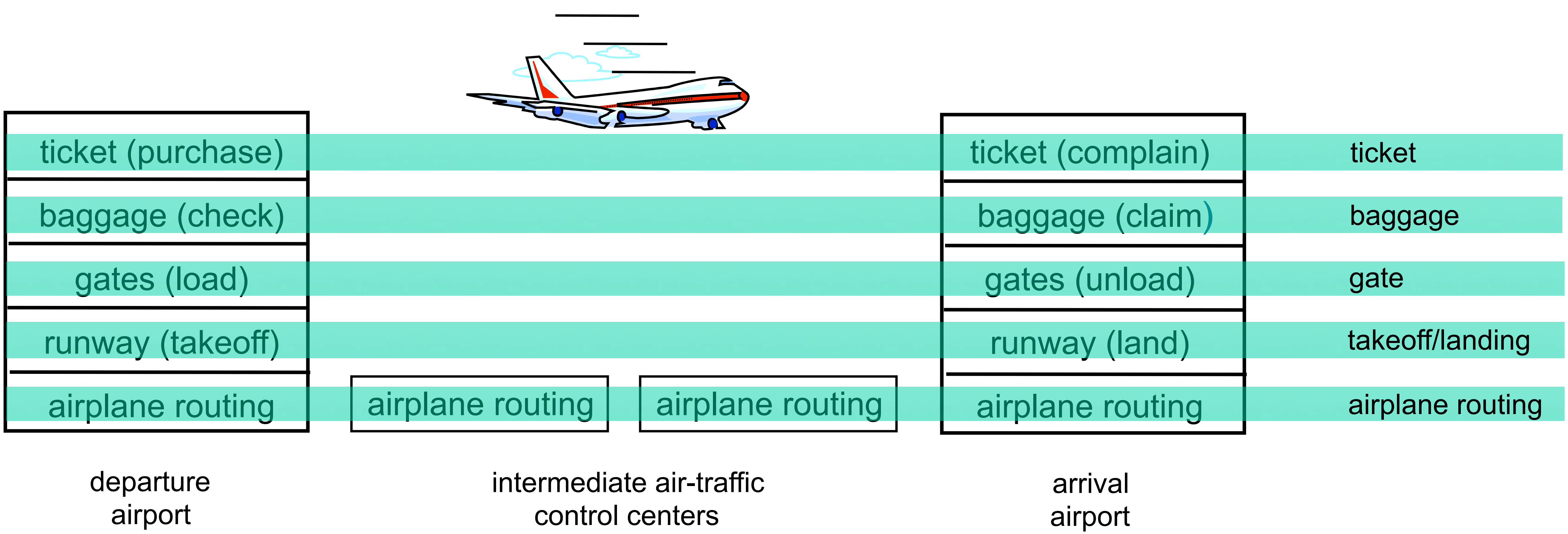
Layering (cont'd)

A layer is a collection of conceptual similar functions that provide services to the layer above it and receives services from the layer below it.

Why layering?

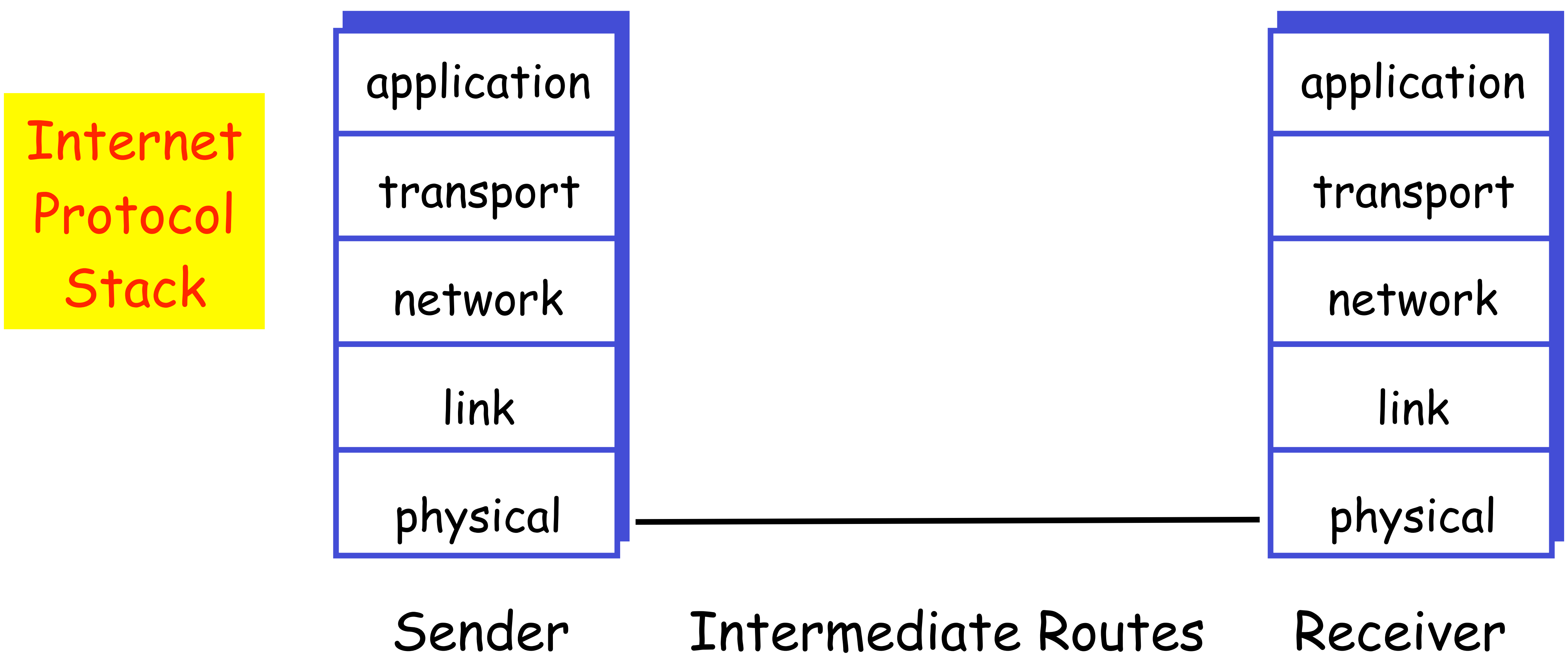
- modulation of complex systems
- easier maintenance and update of systems

  change of *implementation* of one layer's service is transparent to the rest



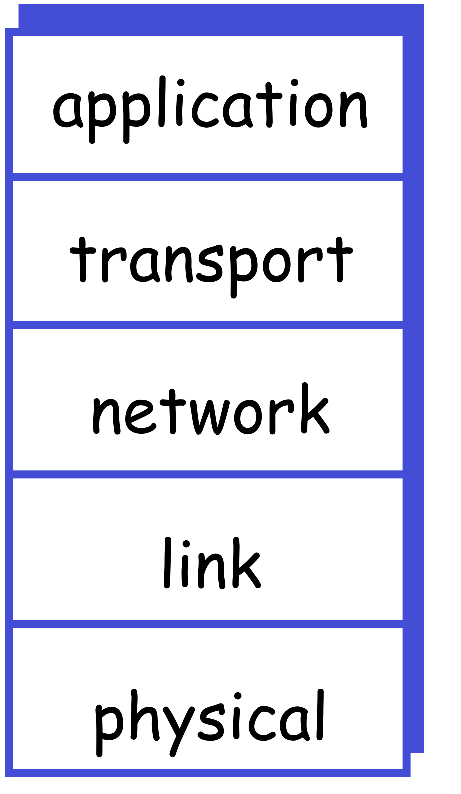
Network protocol layers

- Network protocols — and the hardware and software that implement the protocols — are organized in layers
  - There are 5 layers in the Internet protocol stack
  - Each layer
    - performs certain actions within that layer
    - uses the service provided by the layer directly below it



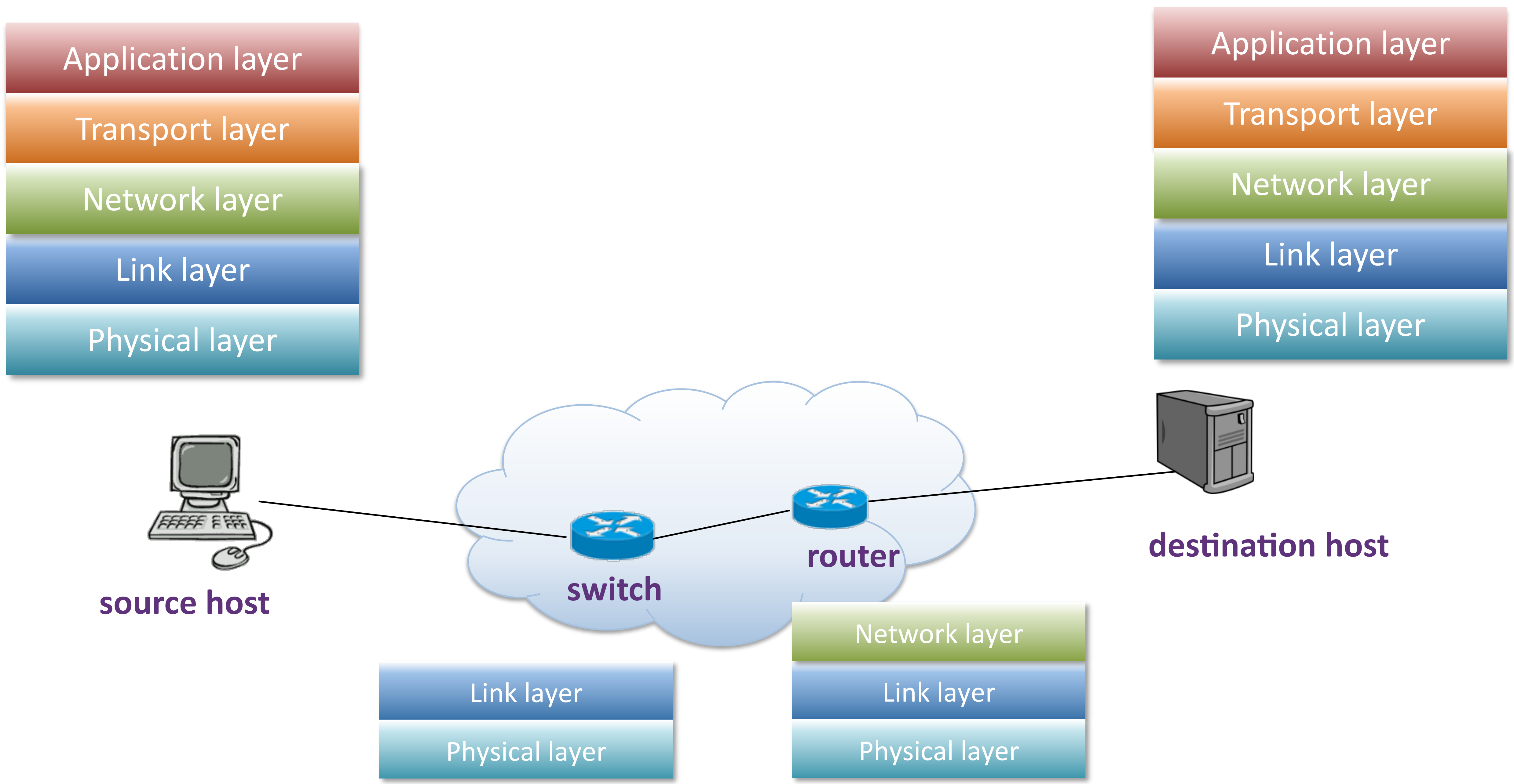
Internet protocol stack

- Application
  - service: supporting network applications
  - protocols: HTTP, SMTP, DNS
- Transport
  - service: process-to-process data transfer
  - protocols: TCP, UDP
- Network
  - service: data routing from source host to destination host
  - protocols: IP, routing protocols
- Link
  - service: data transfer between neighboring network devices
  - protocol: Ethernet, WiFi
- Physical
  - service: bit transfer on the transmission medium



Internet protocol stack (cont'd)

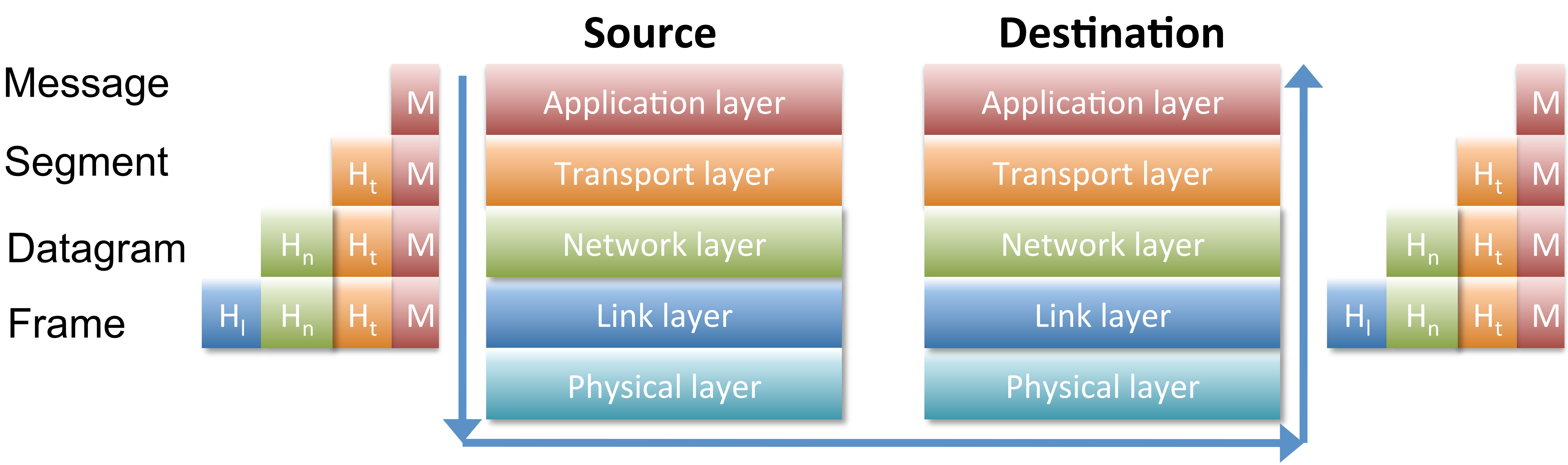
Different network devices implement different numbers of layers



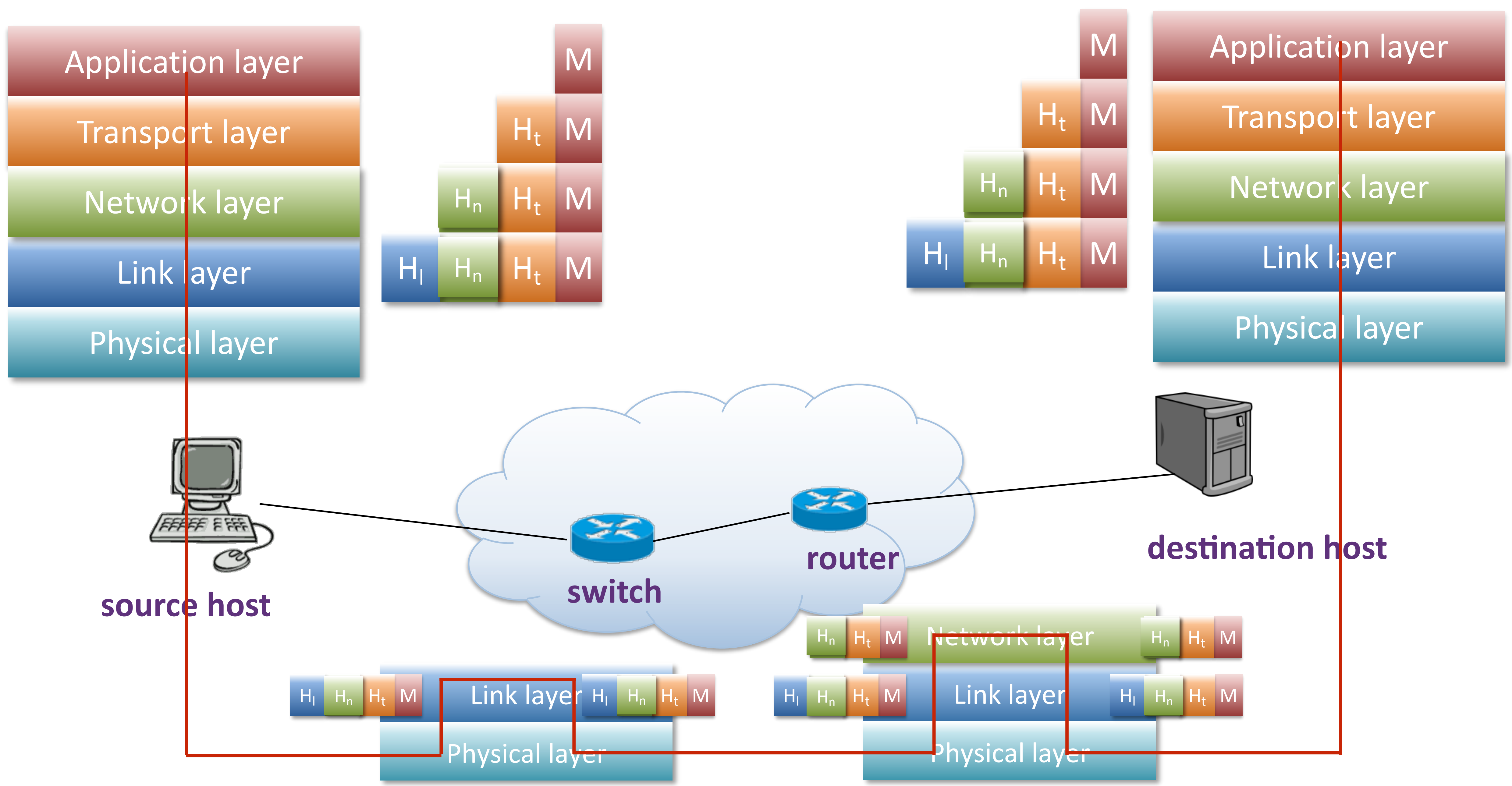
Data encapsulation and decapsulation

Different layers have different data formats

- At each layer, the data packet can be divided into two parts: header and data (or payload)
- Encapsulation: upon receiving a data packet from the upper layer, the whole packet is encapsulated in data part of a packet in this layer, and header is added over the data for control information at this layer
- Decapsulation: for each data packet of this layer, remove header of this layer and extract data part for passing to the upper layer



Data encapsulation and decapsulation (cont'd)



Who define network protocols?

- IETF (Internet Engineering Task Force): RFC (Request for Comments)

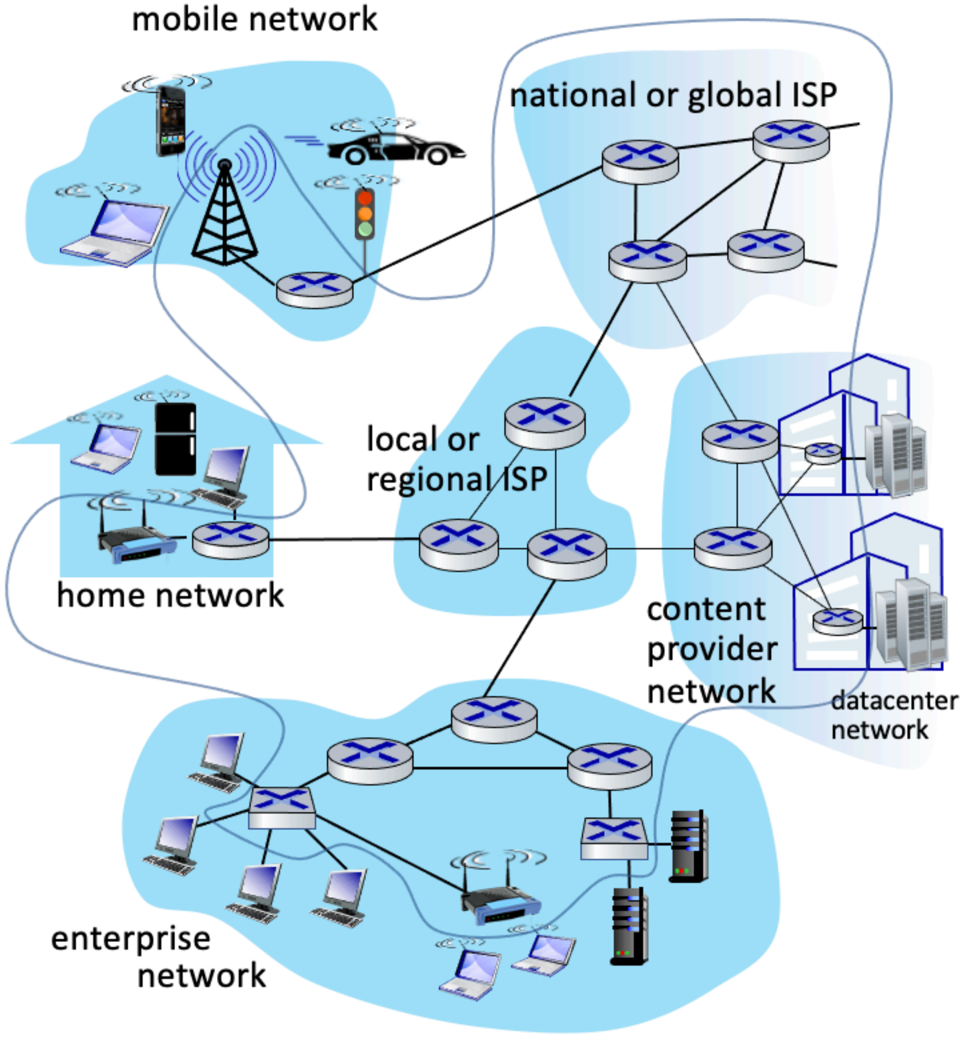
  HTTP (for the Web), SMTP (for email), TCP, IP, etc.

- Other organizations, e.g.,IEEE 802 LAN Standards Committee

  Ethernet, WiFi

Components of the Internet

- Network edge
  - end systems (running network applications)
- Access network
  - wired, wireless communication links
- Network core
  - inter-connected routers and switches



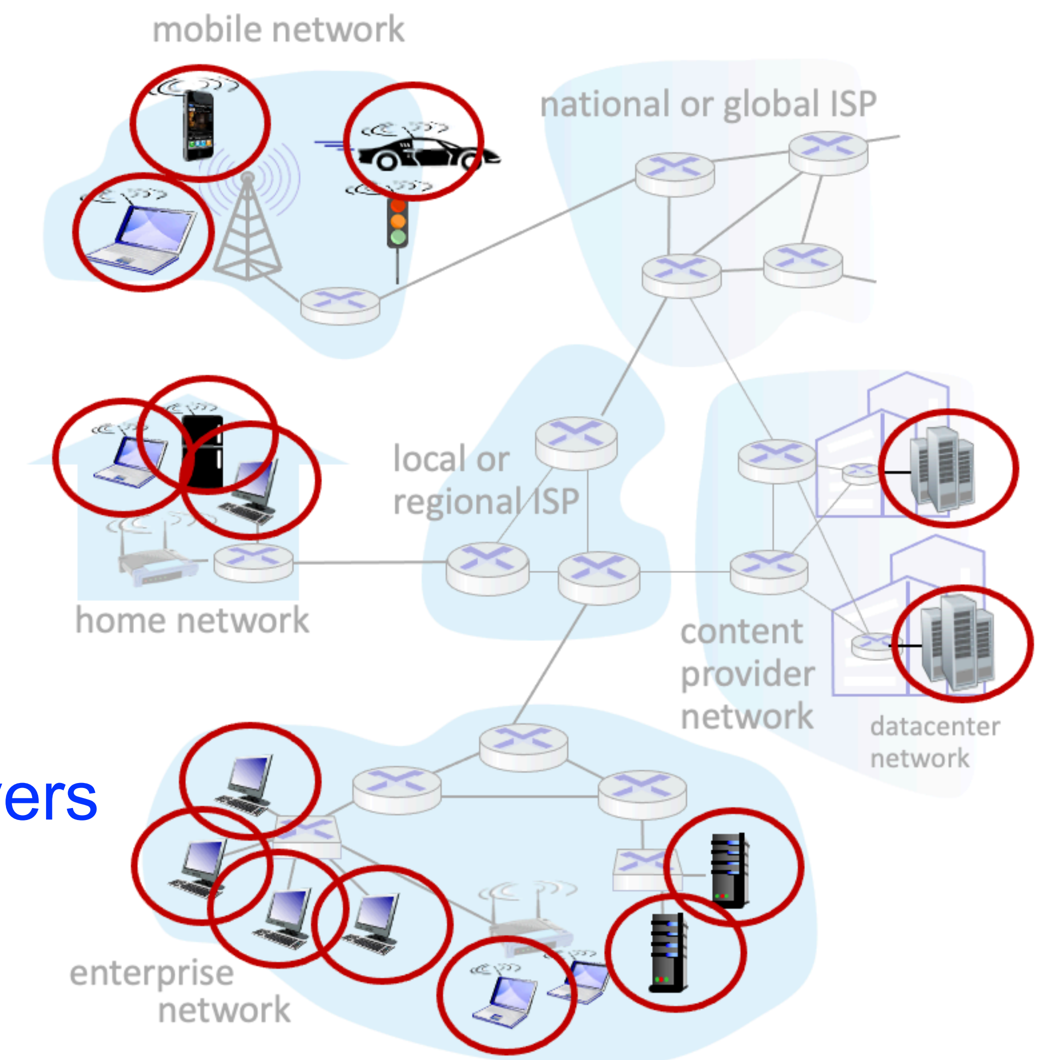
Network edge

- End systems (hosts): categorized based on functionality
  - Server: provides services/data

    always on
    permanent IP addresses
    runs server process to wait to be connected
    e.g., web server, email server

  - Client: requests/receives services/data from servers

    may be intermittently connected (on and off)
    may have dynamic IP addresses
    runs client process to initiate the connection
    e.g., web browser, email client



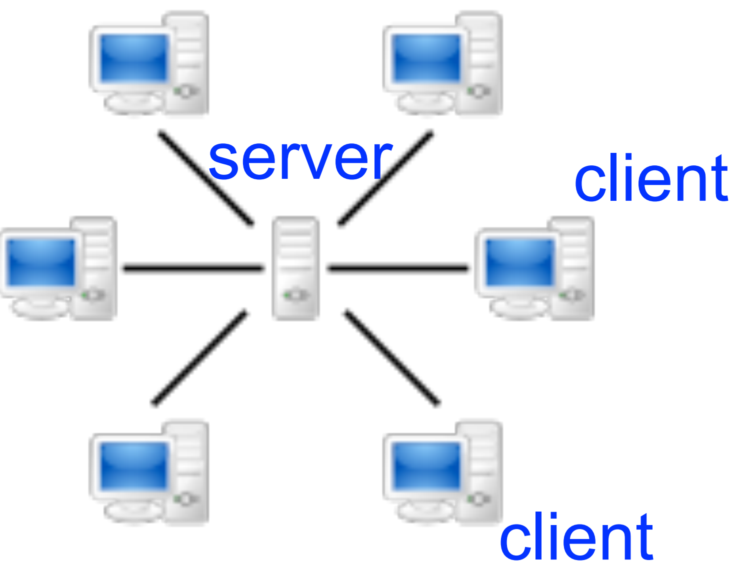
Network edge (cont’d)

- Applications

  Client-server model

  Client requests/receives services/data from servers

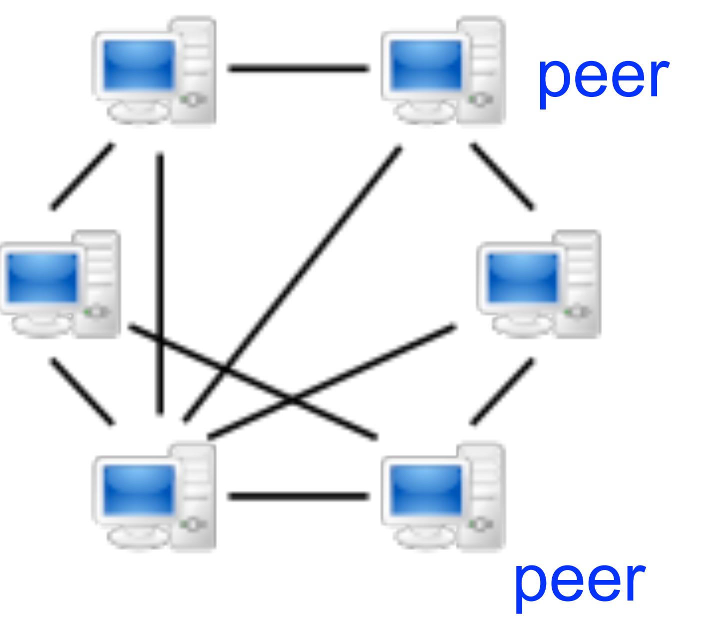
  e.g., Web browser/server, Email client/server



  Peer-to-peer model

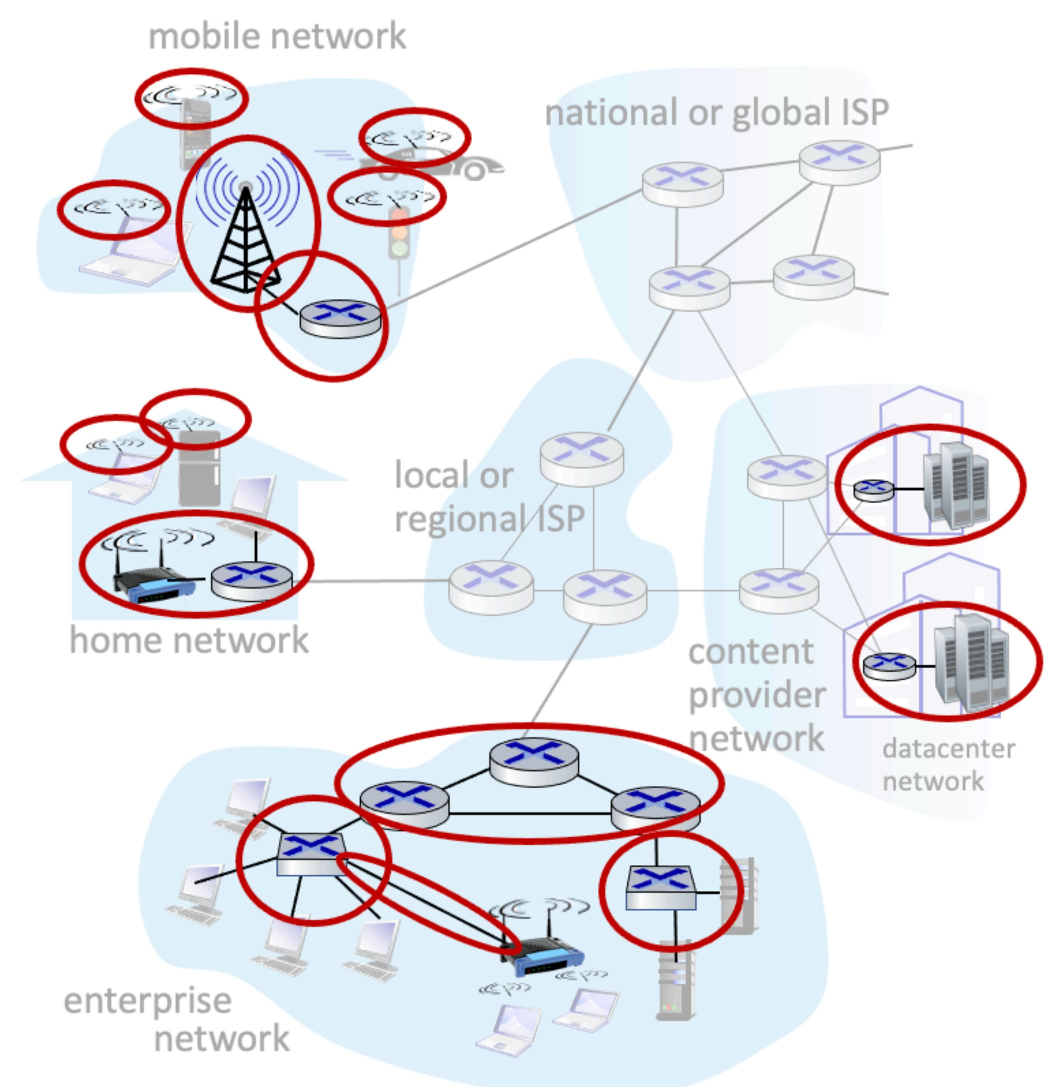
  Participating hosts (peers) are both servers and clients; run both server and client processes

  e.g., BitTorrent, Blockchain systems

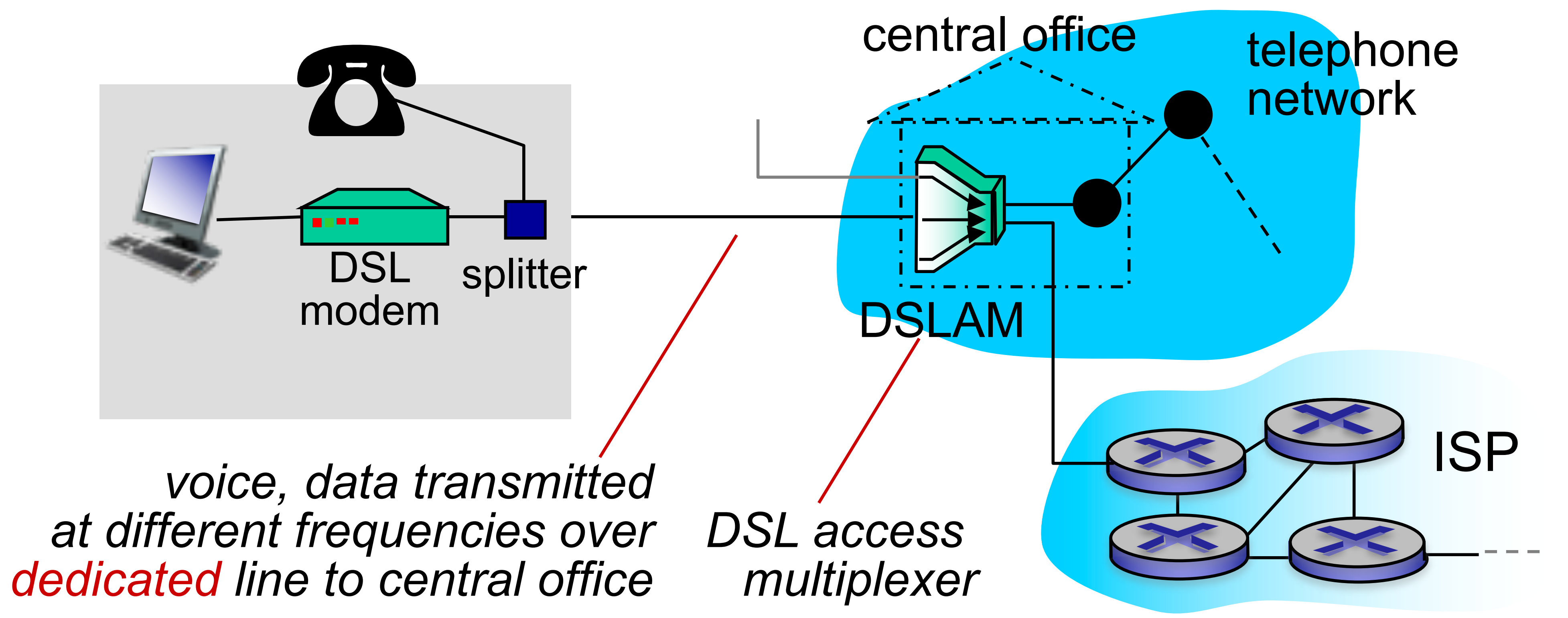


Access network

- Communication links connecting hosts to edge routers/switches
  - Residential access networks
  - Institutional access networks (school, company)
  - Mobile access networks (WiFi, 4G/5G)

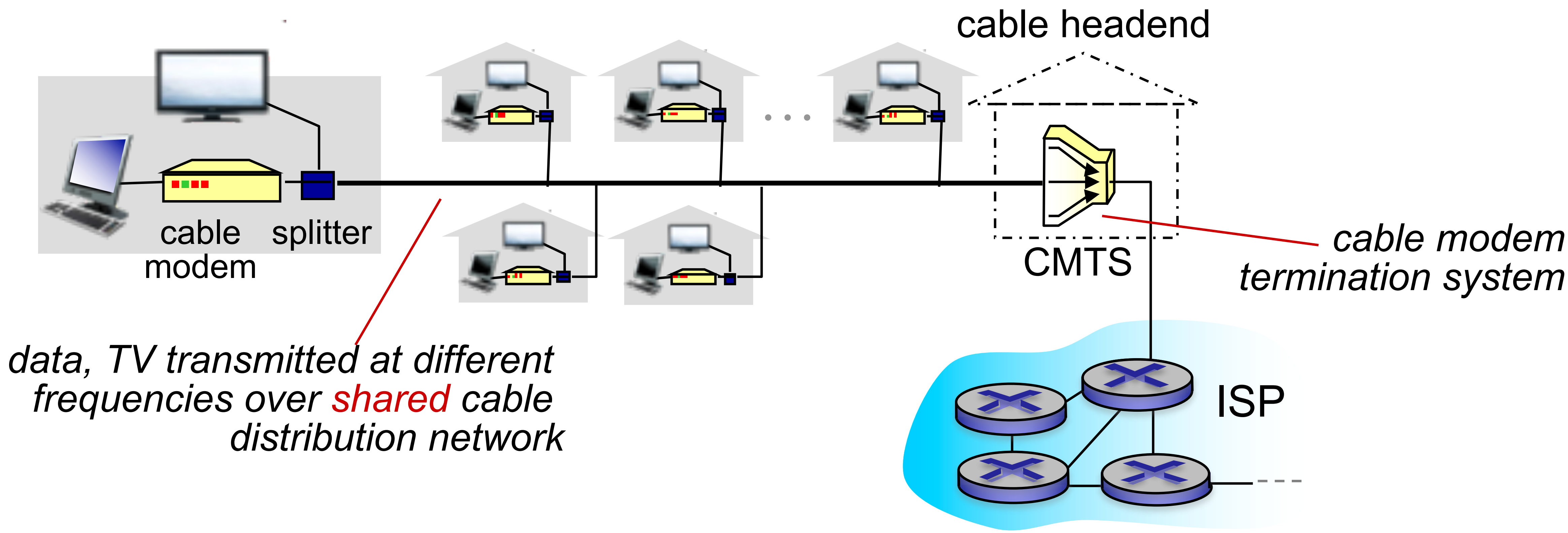


Residential access network: digital subscriber line (DSL)



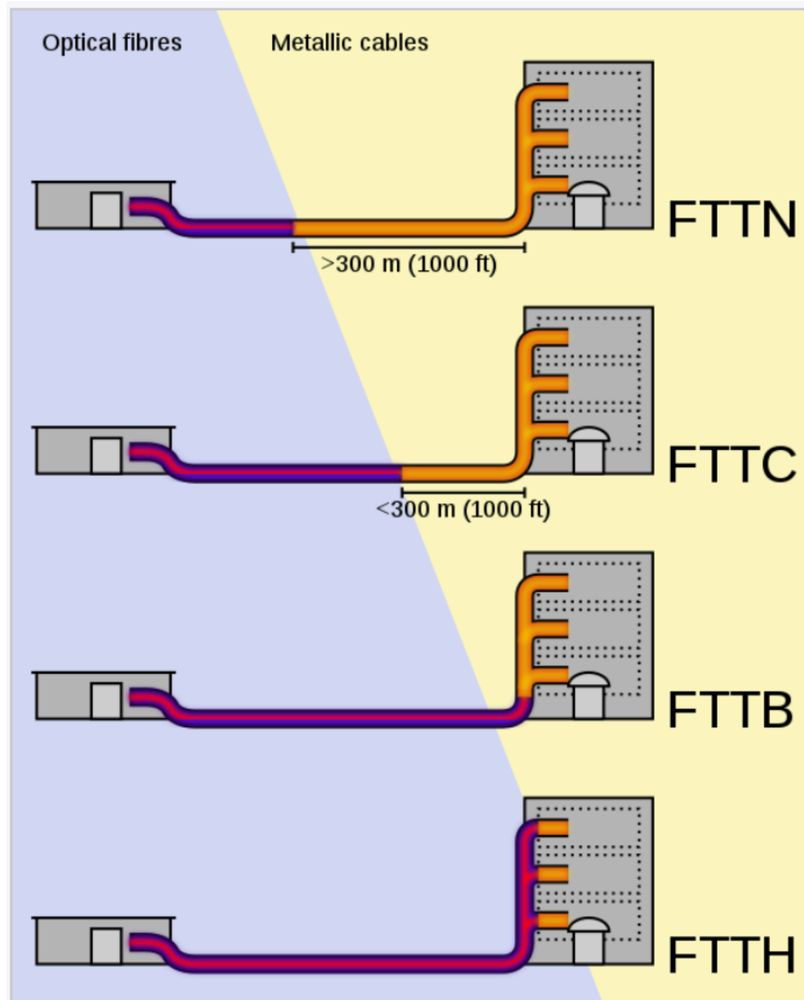
- Use existing telephone line to central office DSLAM (**DSL access multiplexer**)
  - data over DSL phone line goes to Internet; voice over DSL phone line goes to telephone network
  - typically a few Mbps (megabits per second) upstream transmission rate, and tens of Mbps downstream transmission rate

Residential access network: cable network



- Use hybrid fiber coaxial (HFC) cables to connect to ISP router
  - typically tens of Mbps to a few Gbps downstream and tens to hundreds of Mbps upstream transmission rates
  - homes share cable TV network to connect to cable headend (using DSL, each home has dedicated access to central office)

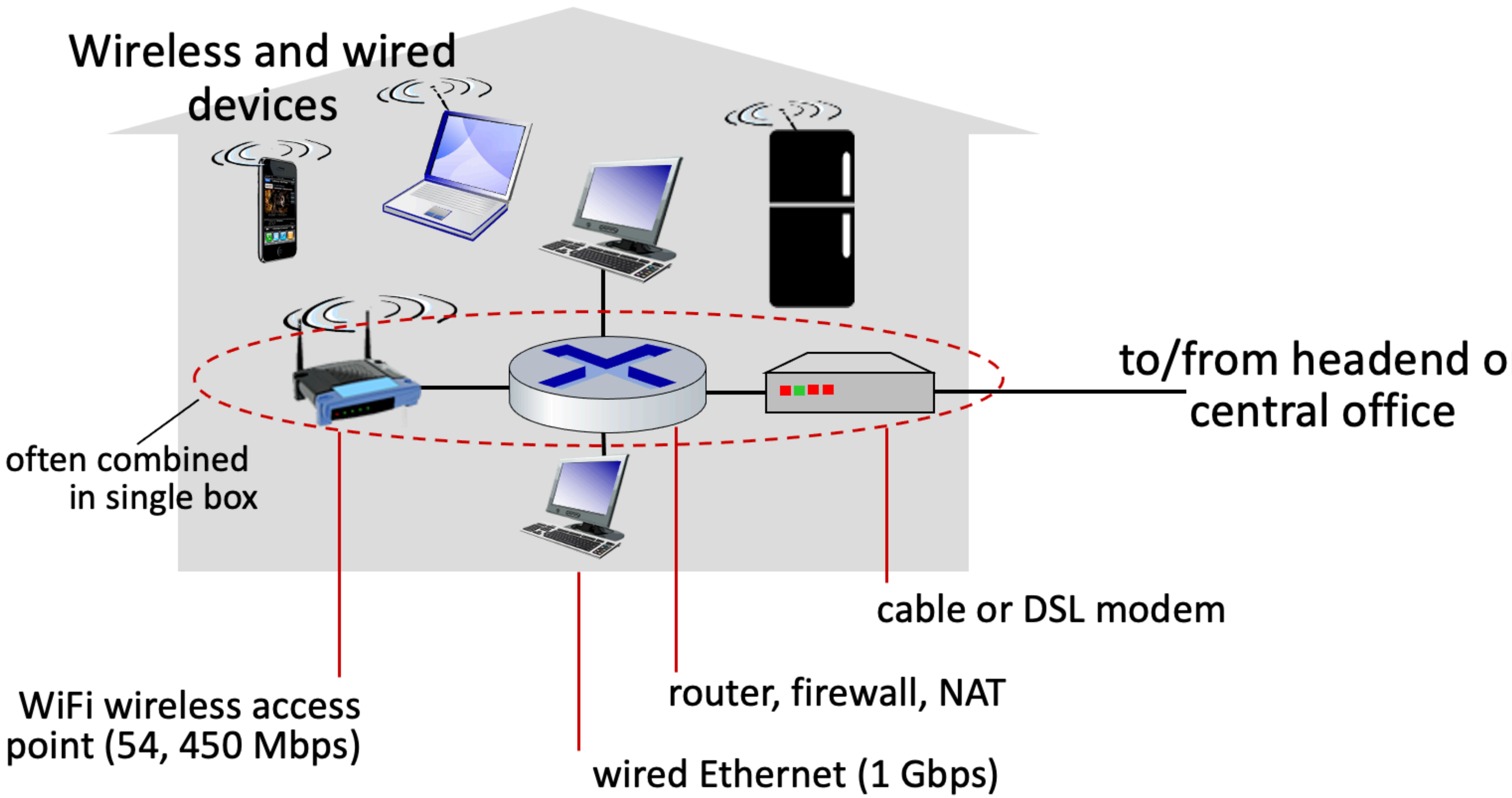
Residential access network: fiber to the x



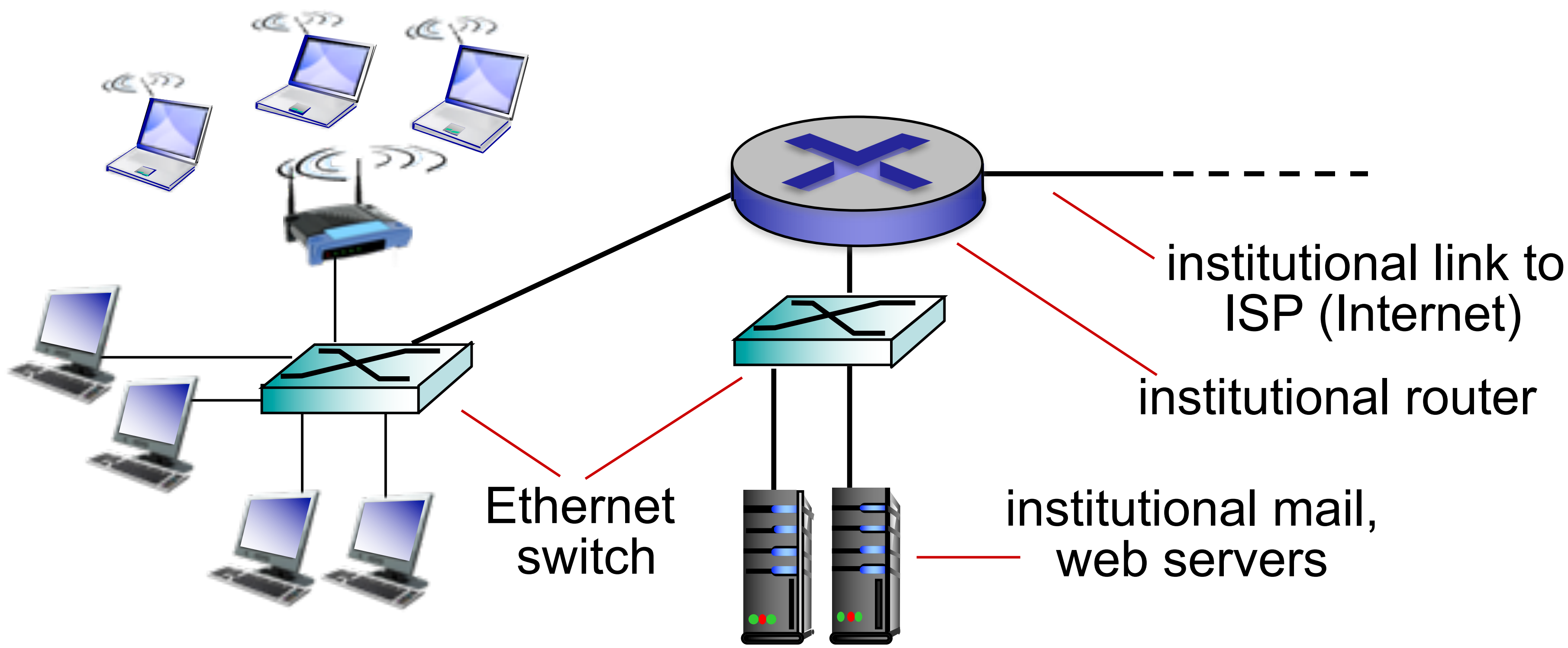
(Image from https://en.wikipedia.org/wiki/Fiber_to_the_x)

- Use optical fiber to provide all or part of the last-mile telecommunication network for connecting user homes/premises to the ISP's router
  - x: Node, Curb, Building, Home, etc.
  - FTTH (Fiber To The Home): typically a few Gbps upstream and downstream transmission rates

Home network



Institutional access network: Ethernet



- Ethernet is most prevalent LAN (local area network) technology, typically used in companies, universities, etc.: 1Gbps, 10Gbps, 25Gbps, 50Gbps, 100Gbps transmission rates

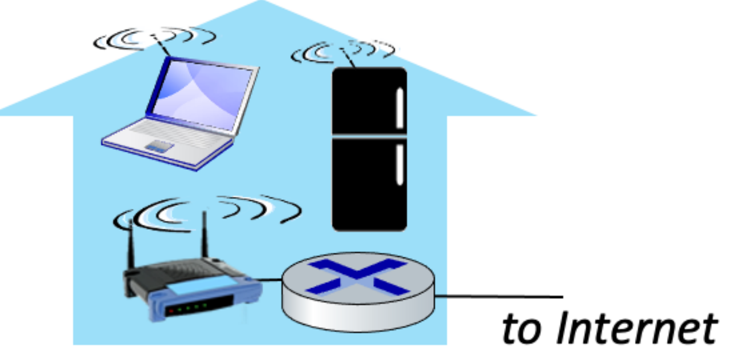
Wireless access network

- Shared wireless access network connects end systems to routers via base stations (aka access points)

  - wireless LANs

    within building

    WiFi: up to a few Gbps transmission rate

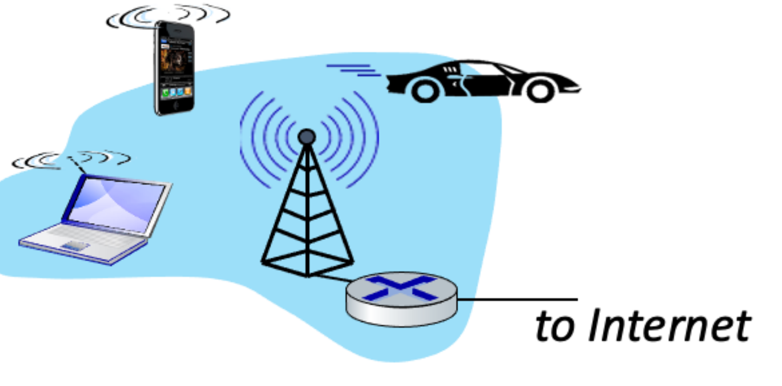


  - wide-area wireless access network

    provided by telco (cellular) operator

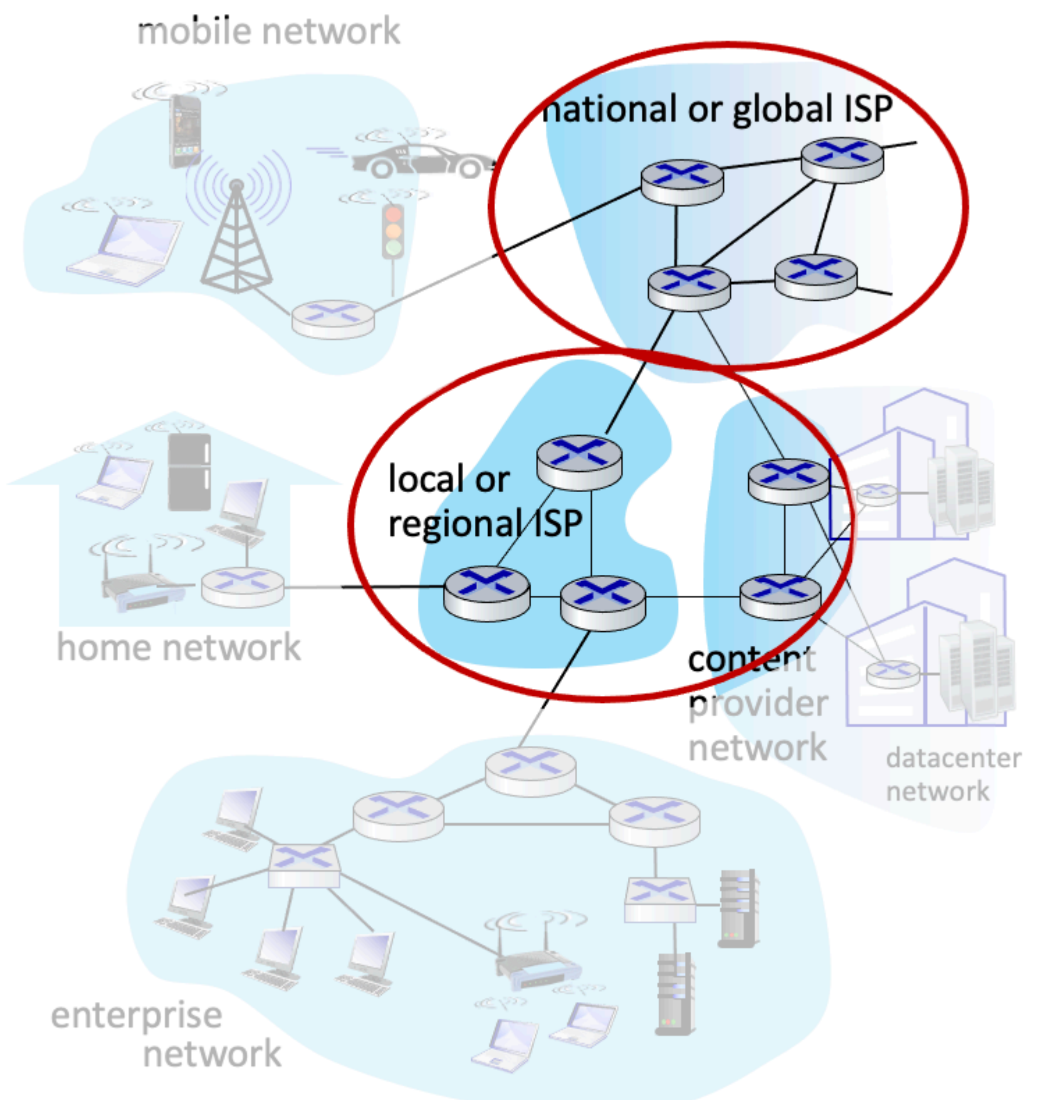
    range within tens of km

    4G, 5G: up to a few tens of Gbps



Network core

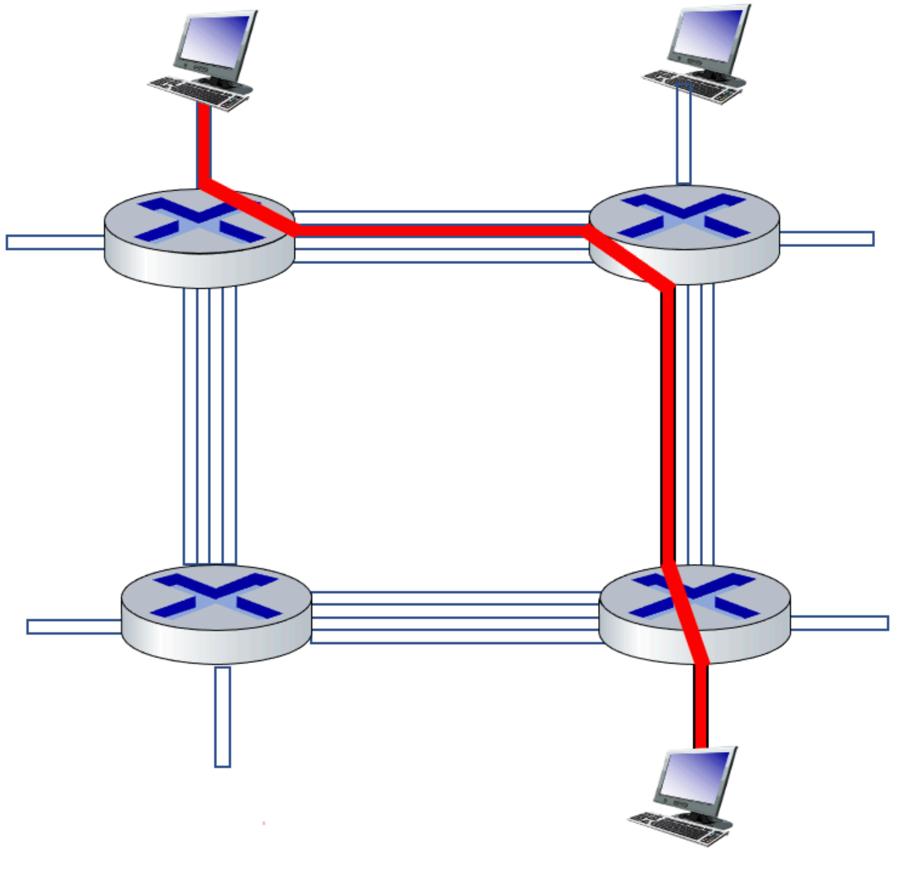
- Inter-connected routers
- Many communication sessions are sharing the same network
- Two fundamental approaches to move data through a shared network
  - circuit switching: dedicated circuit per communication session
  - packet switching: data sent in discrete “chunks” from one router to the next



Circuit switching

- End-to-end resources reserved along a path between the source/sender host and the destination/receiver host for the duration of the communication session
  - Resources: link bandwidth, buffer space at switches/routers, etc.
  - Guaranteed performance: transmission rate, end-to-end delay
  - example of circuit-switched network: traditional telephone network

    Communication session <=> call
  - Need to first set up the connection between source and destination (circuit)

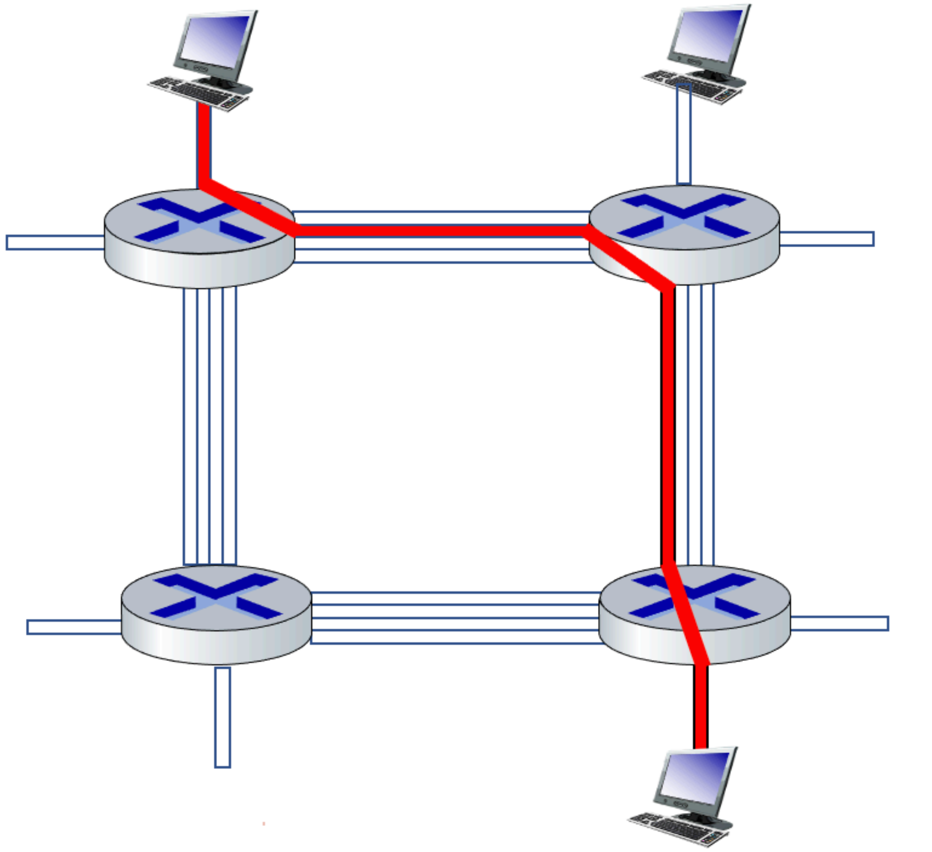


Circuit switching (cont'd)

Q: How do multiple concurrent communication sessions share the network?

A: Bandwidth of each link divided into pieces to allocate to different sessions

- Frequency division multiplexing (FDM)
- Time division multiplexing (TDM)

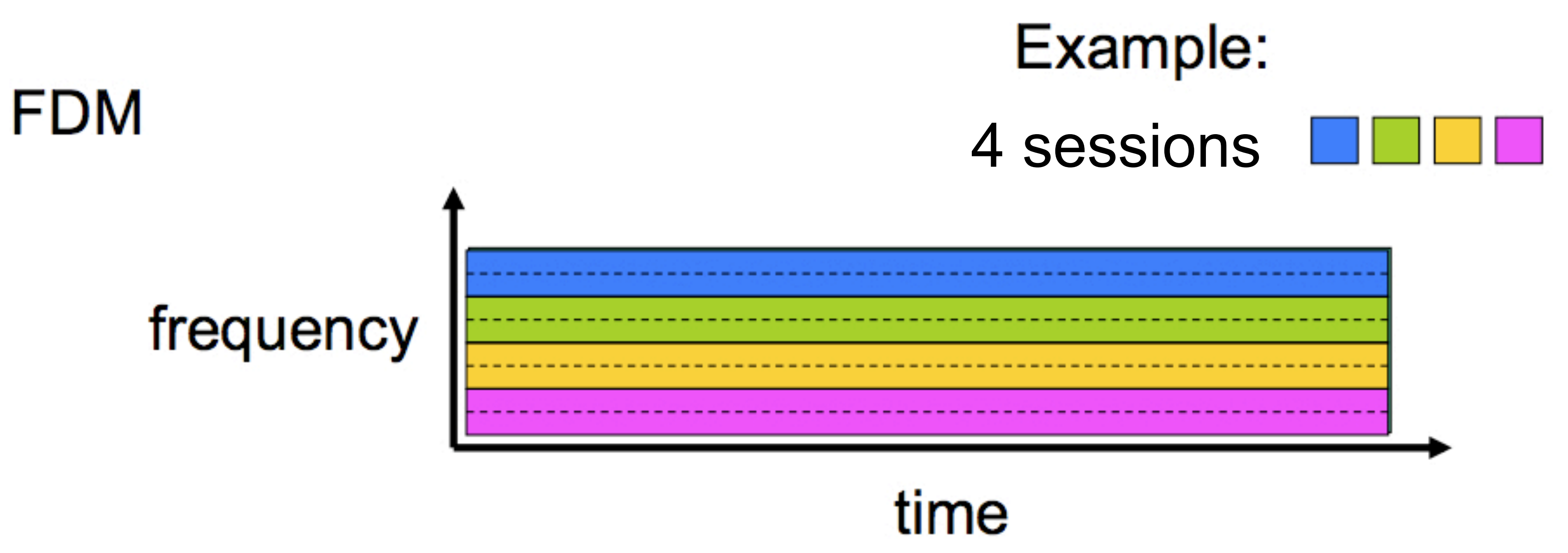


FDM

- Frequency division multiplexing
  - Frequency spectrum of a link is divided into frequency bands
  - Frequency band allocated to different sessions using the link
  - Width of the frequency band == bandwidth ==Transmission rate (bits/second)

  e.g., FM radio stations use FDM to share frequencies among radio channels (88MHz-108MHz)

  e.g., Transmissions of 26 TV channels share the cable using FDM (47MHz-300MHz)



TDM

- Time division multiplexing
  - Time divided into frames of fixed duration; each frame is divided into a fixed number of time slots
  - One time slot in each frame is dedicated to a session

    (like CPU task scheduling in an operating system)

  - Numerical example

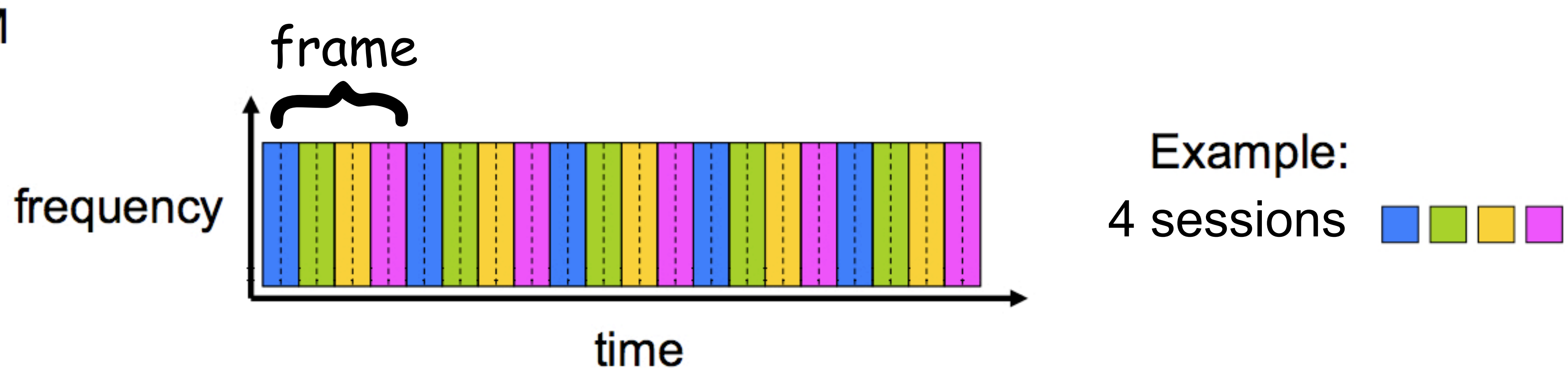
    How long does it take to send a file of 4M bits from host A to host B over a circuit-switched network?

    all links are 1.536 Mbps

    each link uses TDM with frame length = 1 second

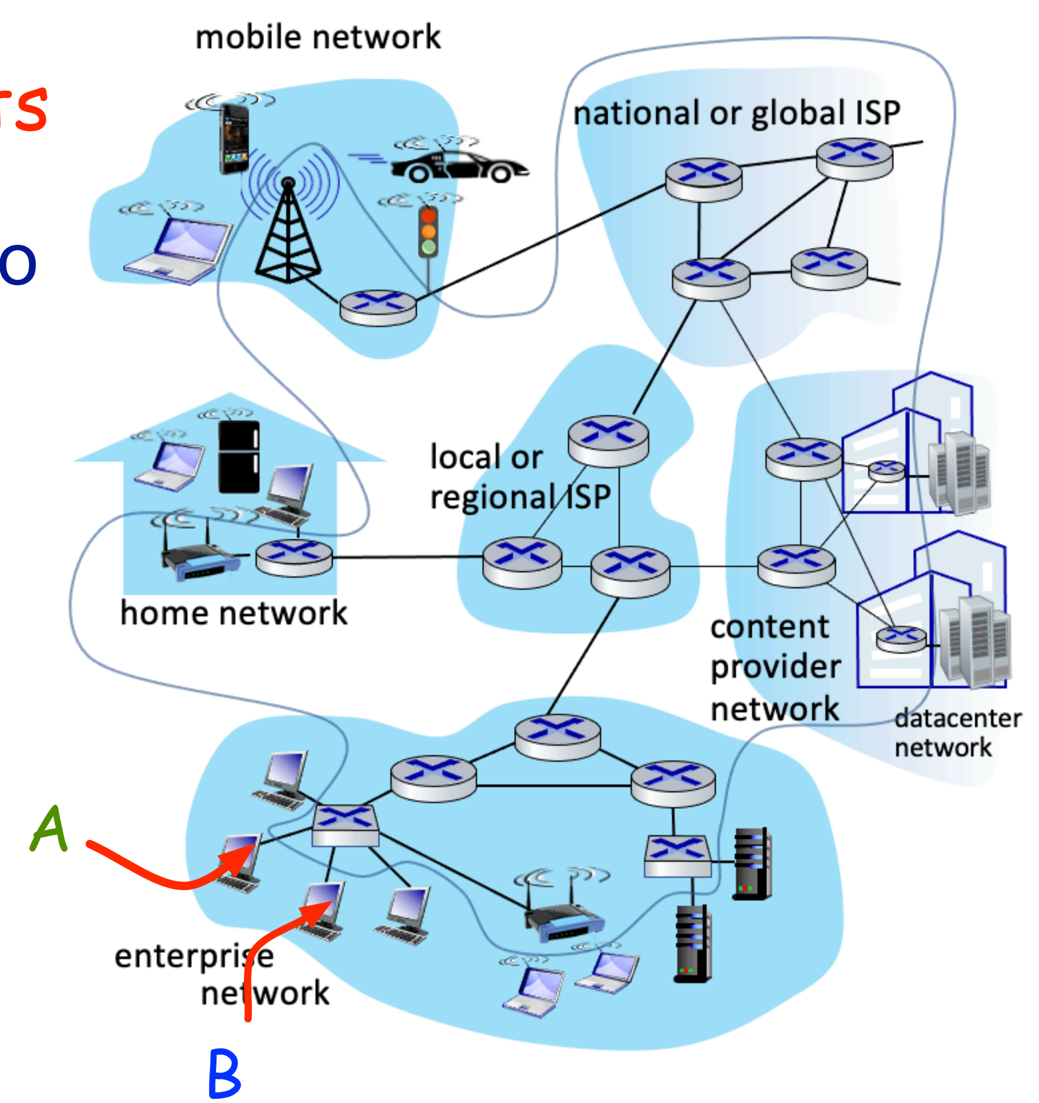
    and 4 time slots in each frame

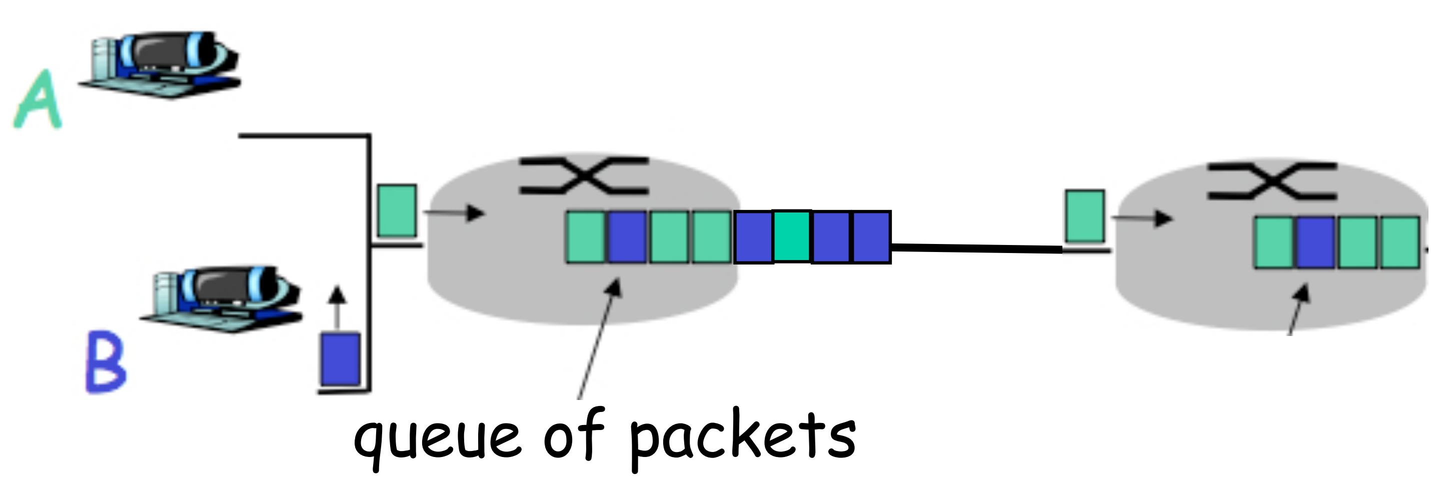
TDM



Packet switching

- Data stream (between a source and a destination) divided into small chunks: packets
- No reservation of resources along the path, no need for call setup
  - Packets from different sender hosts use resources along the path as needed

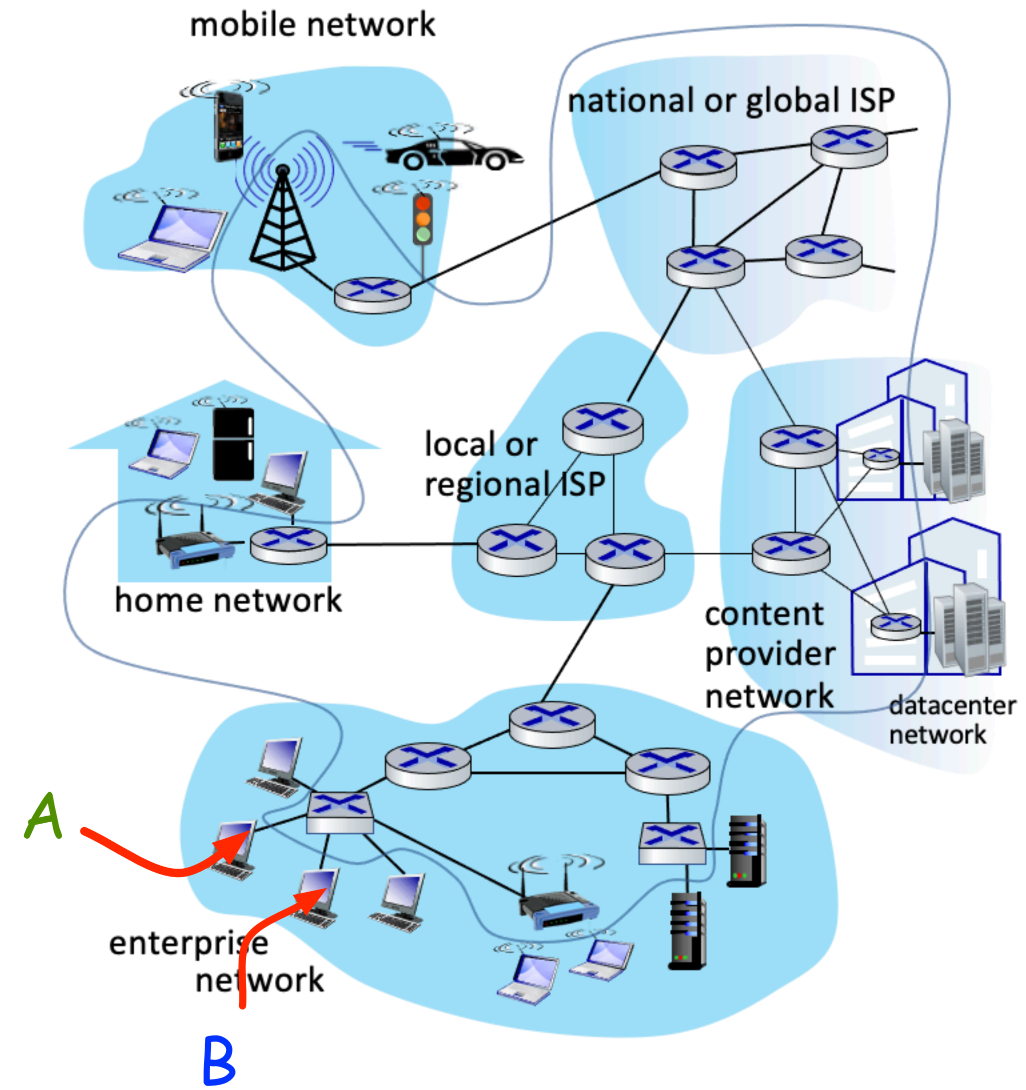


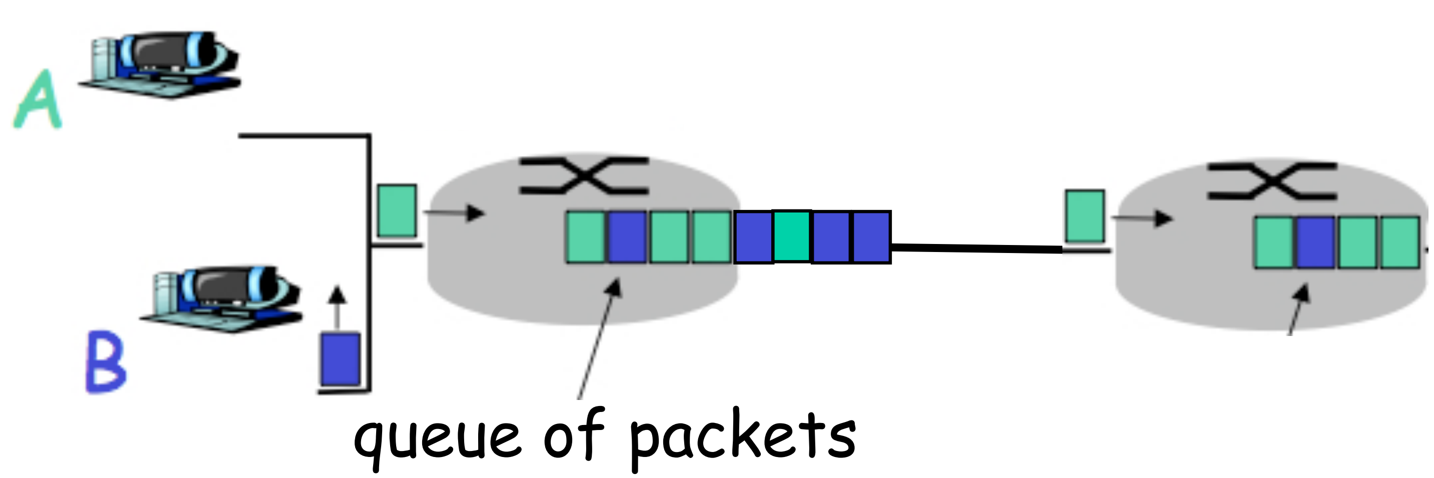


Packet switching

- Store and forward
  - switches/routers must receive the complete packet and then forward it
  - packet moves one hop at a time

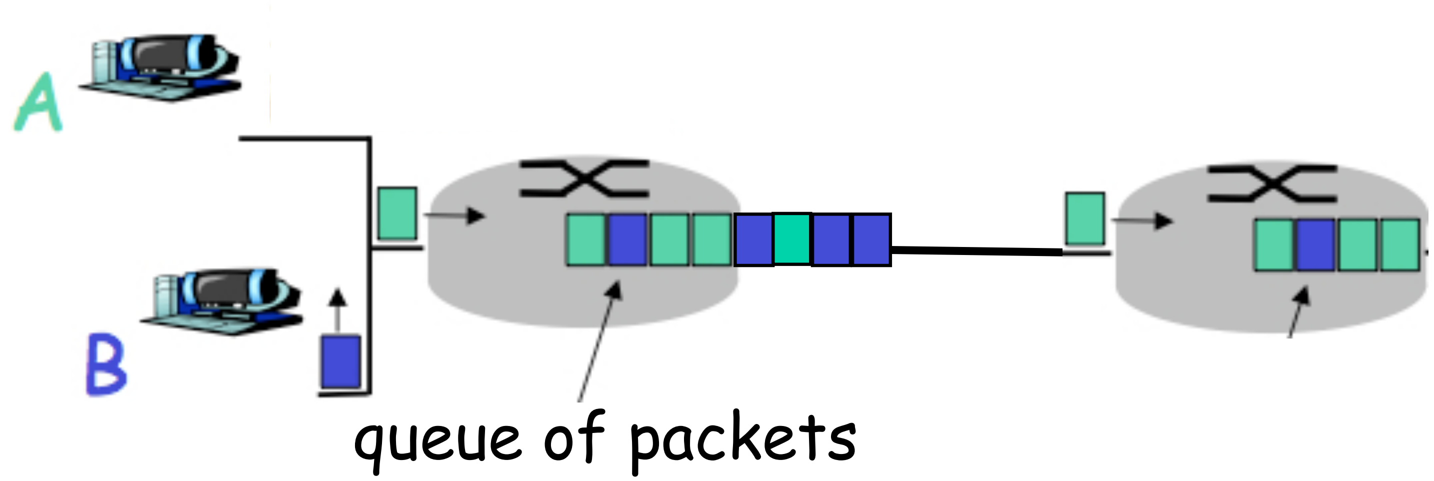
- No guarantee of bandwidth, delay
- An example: Internet is largely based on packet switching





Statistical multiplexing

- The on-demand sharing of a communication link among packets from different senders in a packet-switched network is called statistical multiplexing
  - time-domain multiplexing, but without division of fixed-length time slots and preallocation of time slots
  - sequence of A and B packets does not have fixed pattern



Packet switching vs circuit switching

- Advantages
  - Simpler: no call setup needed
  - More efficient: allow more users to use network

Each user alternates between

- "active" period (10% of the time): generates data at 100 kb/s
- "inactive" period (90% of the time): no data generation

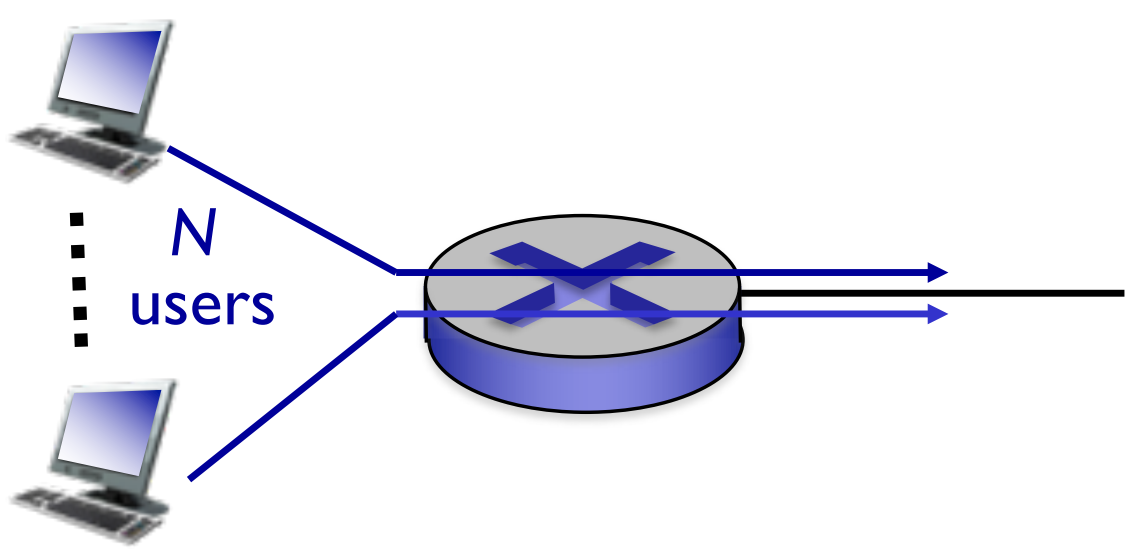
Circuit switching with TDM

- support 10 simultaneous users (1 Mbps/100 Kbps)

Packet switching

- if there are 35 users, probability that there are > 10 active users is

  less than 0.0004



Calculation of the probability >10 active users among 35 (packet switching)

at any given time

prob. that a given user is transmitting: $p = 0.1$

prob. that exactly n users are transmitting: $\binom{35}{n} p^n (1-p)^{35-n}$

prob. that 11 or more users are transmitting:

$$\sum_{n=11}^{35} \binom{35}{n} p^n (1-p)^{35-n}$$

$$= 1 - \sum_{n=0}^{10} \binom{35}{n} p^n (1-p)^{35-n}$$

Packet switching vs circuit switching (cont'd)

- Challenges
  - Congestion - if arrival rate to link exceeds transmission rate of link for a period of time:

    packets will queue in router buffers, waiting to be transmitted on link

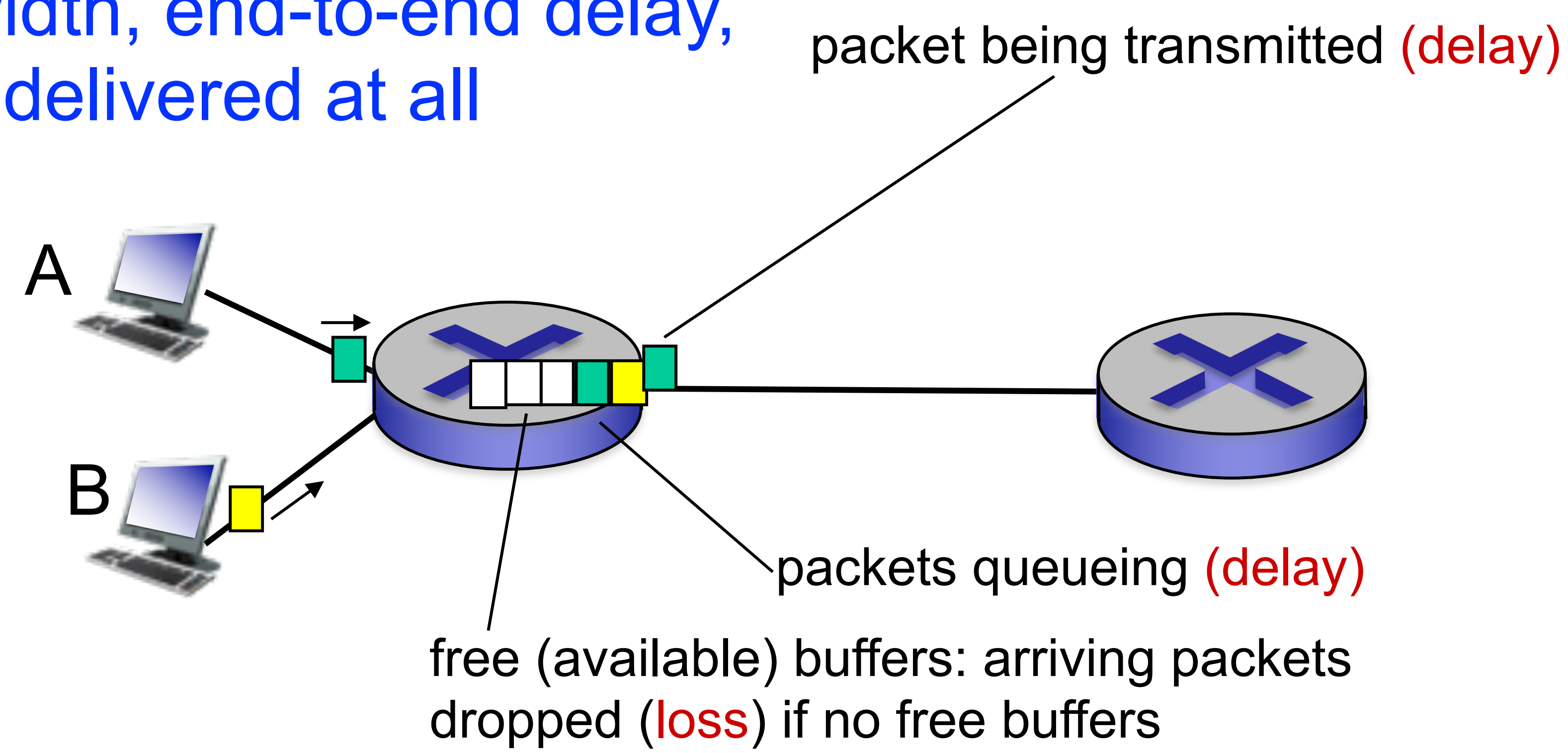
    packets can be dropped (lost) if buffer fills up

    =>packet delay and loss

  - No guaranteed on bandwidth, end-to-end delay, and whether packets are delivered at all

Protocols needed to achieve reliable data transfer and congestion control

Tasks for transport layer



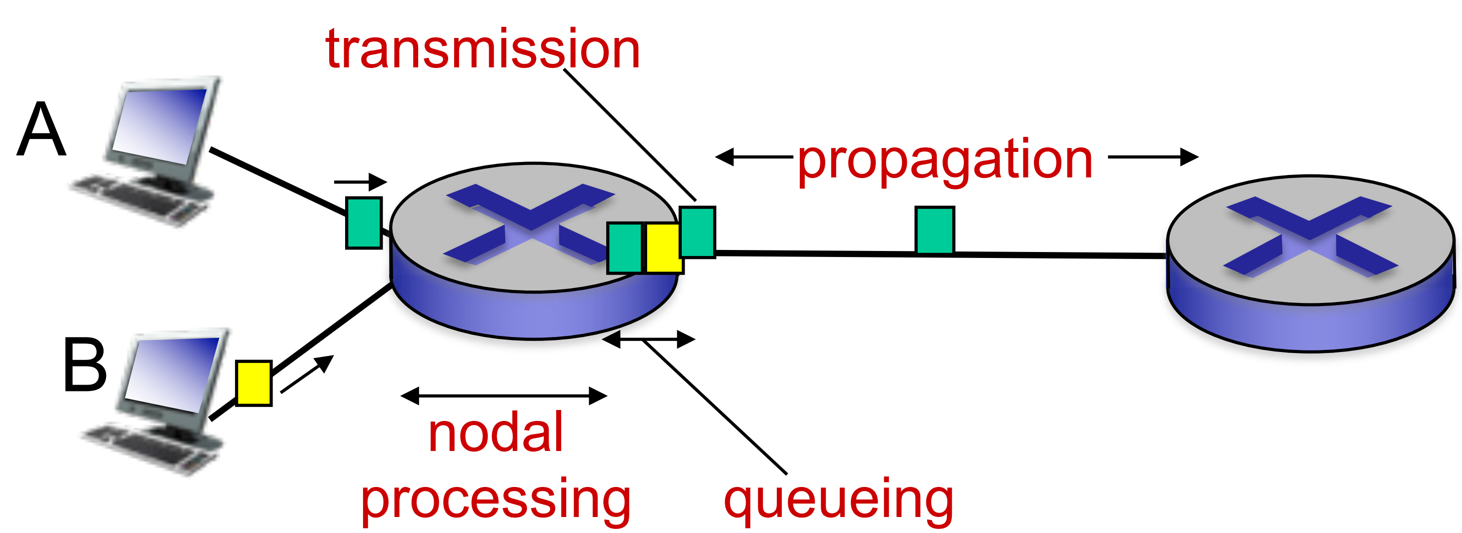
Performance metrics in packet-switched networks

- Delay
- Loss
- Throughput

Delay

Four sources of packet delays

- **Nodal processing delay**
  packet processing at a node: decide output link, bit error check, etc.
- **Transmission delay**
  R=link bandwidth (bps)
  L=packet length (bits)
  transmission delay
  =time to send bits into link
  = L/R
- **Queueing delay**
  time waiting at output link for transmission
- **Propagation delay**
  d=length of physical link (m)
  s=propagation speed in medium (m/s)
  propagation delay = d/s

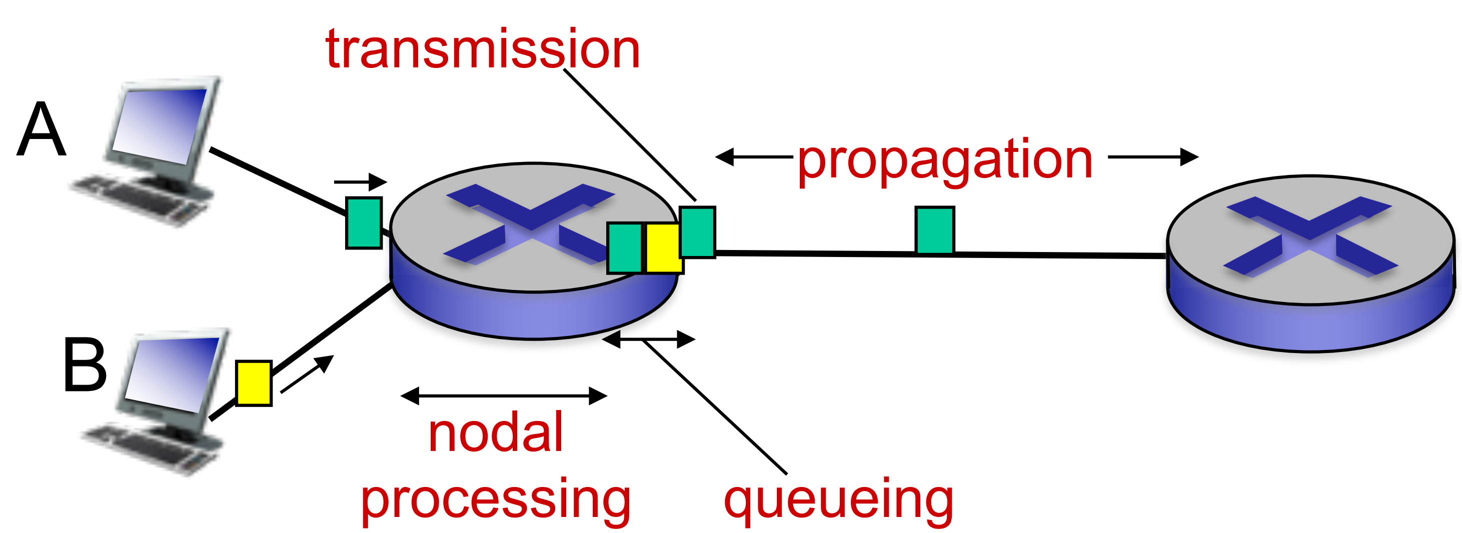


Delay (cont'd)

Nodal delay

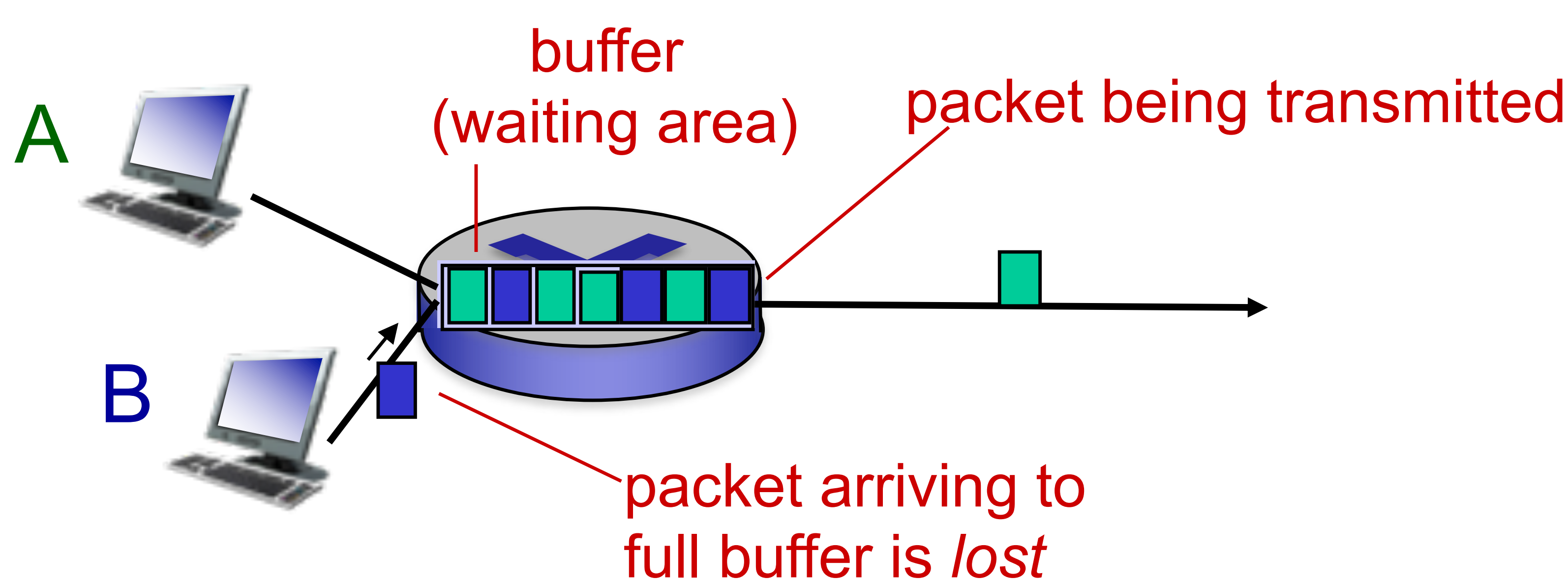
$$d_{\text{nodal}} = d_{\text{proc}} + d_{\text{queue}} + d_{\text{trans}} + d_{\text{prop}}$$

- 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



Packet loss

- Cause
  - transmission link has limited bandwidth
  - buffer has limited space
- Packet loss
  - packets arriving to a full buffer (queue) are dropped (lost)

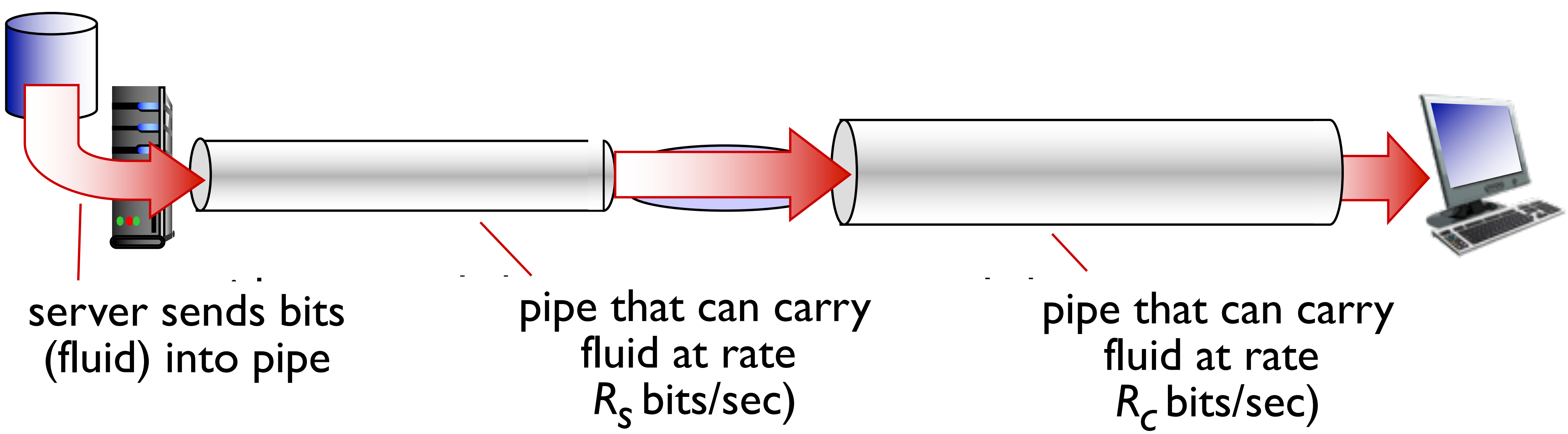


Throughput

- Rate (bits/second) at which data are transferred end-to-end from *sending host* to *receiving host*
  - Instantaneous throughput: rate at given point in time
  - Average throughput: rate over longer period of time

$R_s < R_c$ 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

- **Required reading:**
  - Chapters 1.1, 1.2, 1.3, 1.4, 1.5 in *Computer Networking: A Top Down Approach* (8th Edition)

- Acknowledgement:
  - Some materials are extracted from the slides created by Prof. Jim F. Kurose and Prof. Keith W. Ross for the textbook.