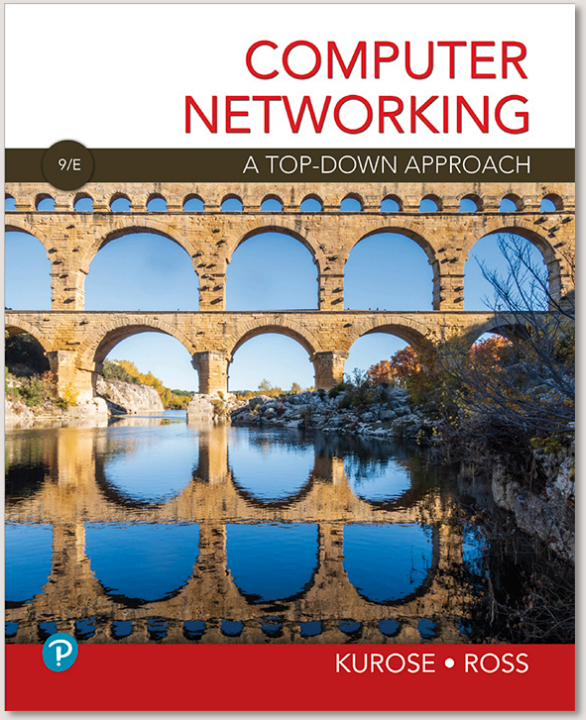


Computer and Communication Networks (2026)

Iordanis Koutsopoulos, Vasilios Siris, George Xylomenos

Professors, Department of Informatics, AUEB

Chapter 1 Introduction



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Computer Networking: A Top-Down Approach

9th edition

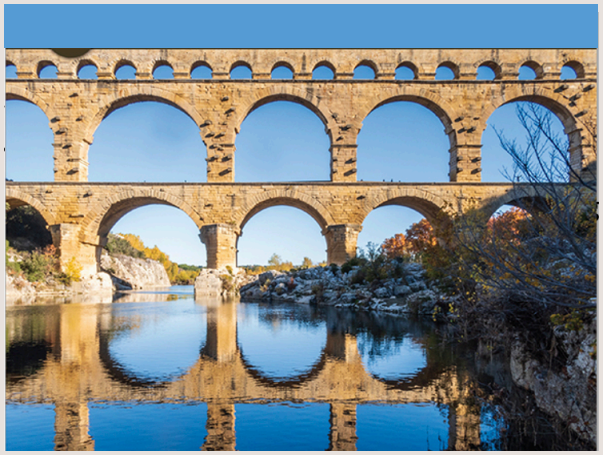
Jim Kurose, Keith Ross

Pearson, 2025

Chapter 1: introduction

Chapter goal:

- Get “feel,” “big picture,” introduction to terminology
  - more depth, detail *later* in course

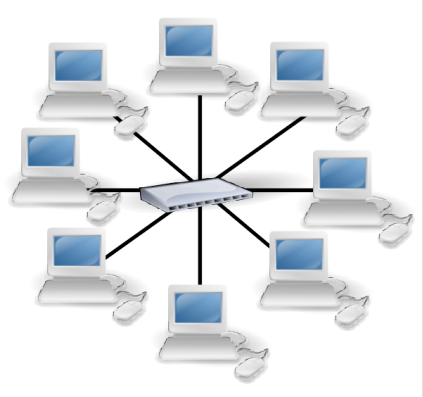


Overview/roadmap:

- What *is* the Internet? What *is* a protocol?
- Network edge: hosts, access network, physical media
- Network core: packet/circuit switching, internet structure
- Performance: loss, delay, throughput
- Protocol layers, service models
- Security
- History

What is a network | a simple definition

- **Network:** A system that enables two or more electronic devices to communicate with each other through wired and/or wireless information transmission media.



- **Focus on Fundamental Principles**
- Technologies change every few years…
- Fundamental principles do not.
- Main goal: To see the forest for the trees — that is, to understand the “big picture.”



The Internet: a "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*

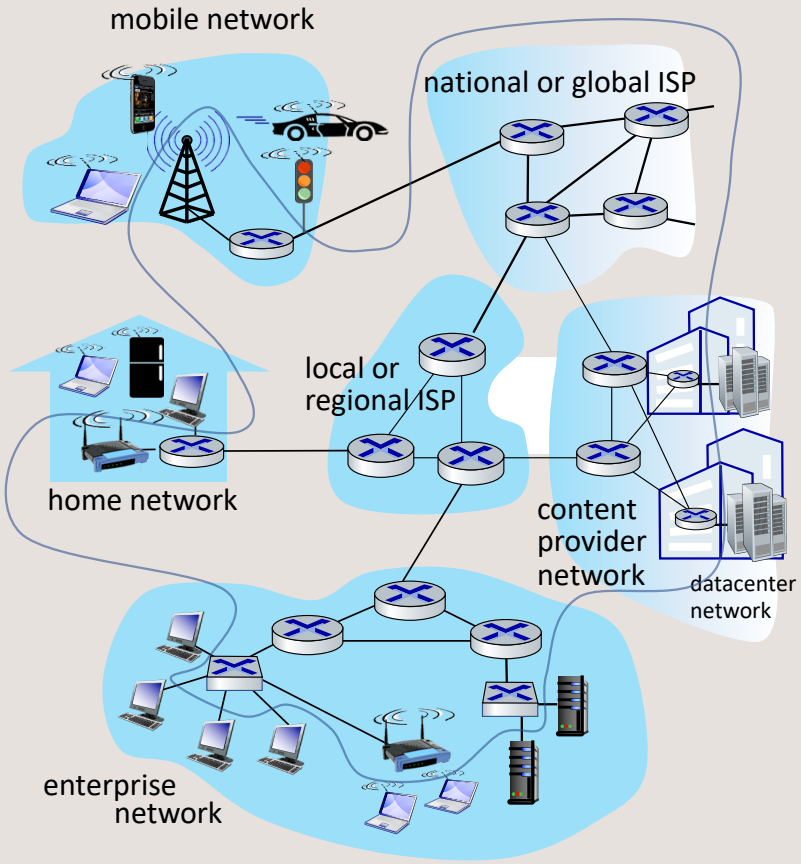


Communication links

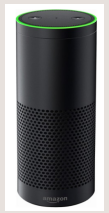
- fiber, copper, radio, satellite
- transmission rate: *bandwidth*

Networks

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



“Fun” Internet-connected devices



Amazon Echo



Internet refrigerator



IP picture frame



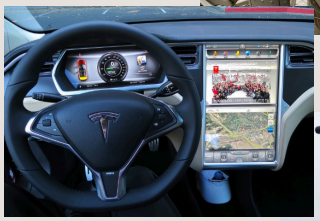
Pacemaker & Monitor



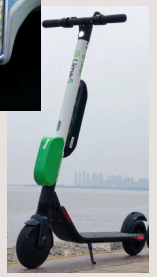
Tweet-a-watt: monitor energy use

bikes





cars



scooters



Web-enabled toaster + weather forecaster



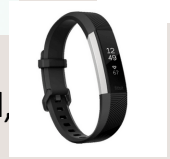
Slingbox: remote control cable TV



Security Camera



AR devices



Fitbit



diapers



Internet phones



Gaming devices

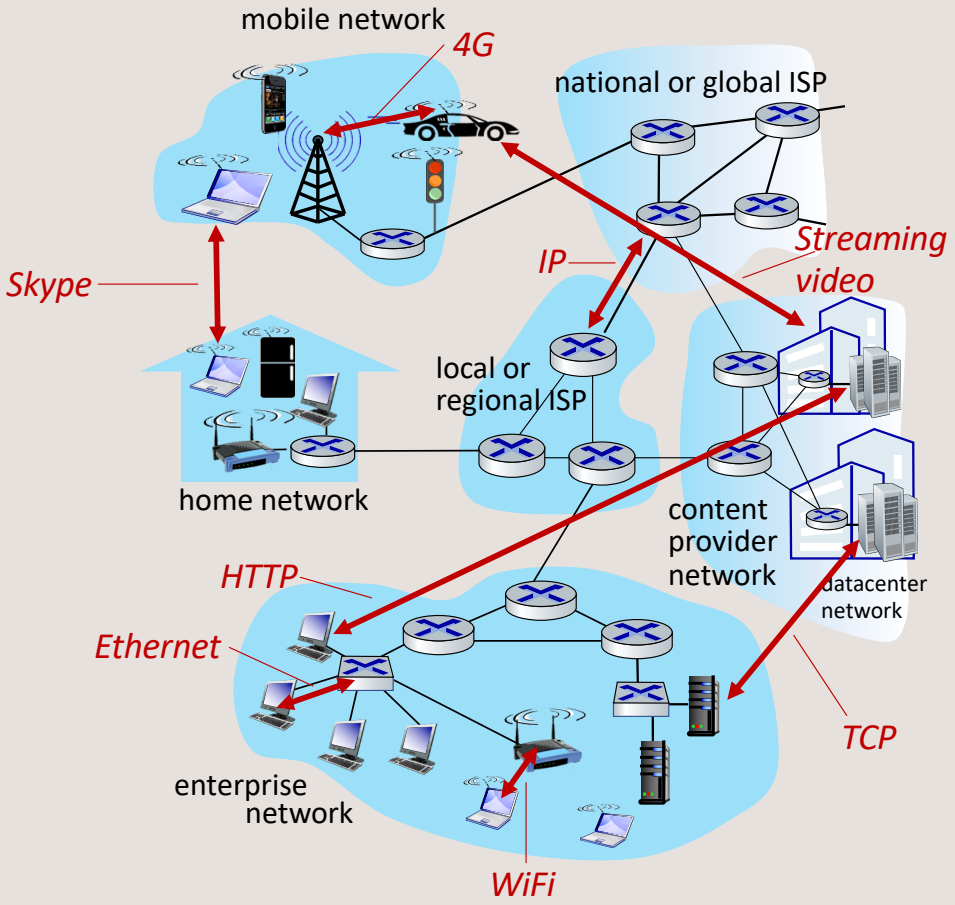


sensorized, bed mattress

Others?

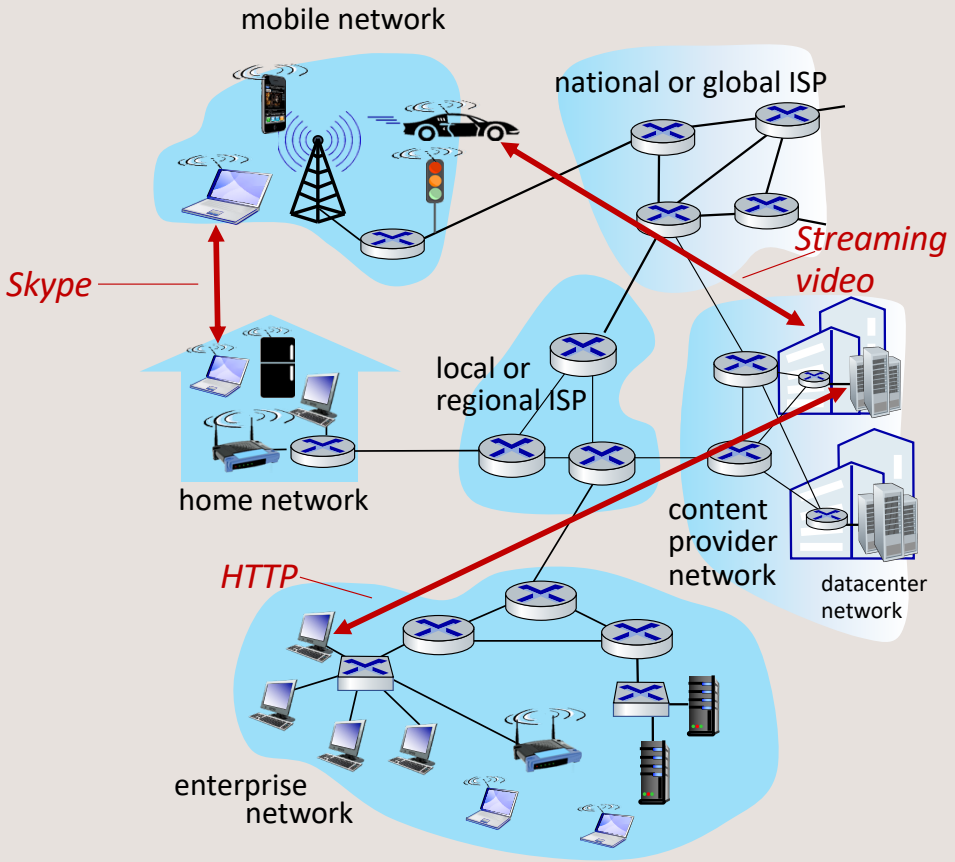
The Internet: a "nuts and bolts" view

- *Internet:* "network of networks"
  - Interconnected ISPs
- *protocols* are *everywhere*
  - control sending, receiving of messages
  - e.g., HTTP (Web), streaming video, Zoom, TCP, IP, WiFi, 4/5G, Ethernet
- *Internet standards*
  - RFC: Request for Comments
  - IETF: Internet Engineering Task Force



The Internet: a "services" view

- *Infrastructure* that provides services to applications:
  - Web, streaming video, multimedia teleconferencing, email, games, e-commerce, social media, inter-connected appliances, …
  - provides *programming interface* to distributed applications:
    - "hooks" allowing sending/receiving apps to "connect" to, use Internet transport service
    - provides service options, analogous to postal service



Similarities with other types of networks

- 1. Goods Transportation Networks (Logistics), e.g., Amazon
  - First mile: from the production facility to a distribution center or large warehouse
  - Middle mile: from one warehouse to another
  - Last mile: from the final warehouse to the customer
- 2. Transportation Networks



First Mile Delivery

↓

Middle Mile Delivery

↓

Last Mile Delivery

What's a protocol?

Human protocols:

- "what's the time?"
- "I have a question"
- introductions

Rules for:

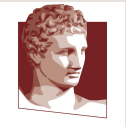
… specific messages sent

… specific actions taken when message received, or other events

Network protocols:

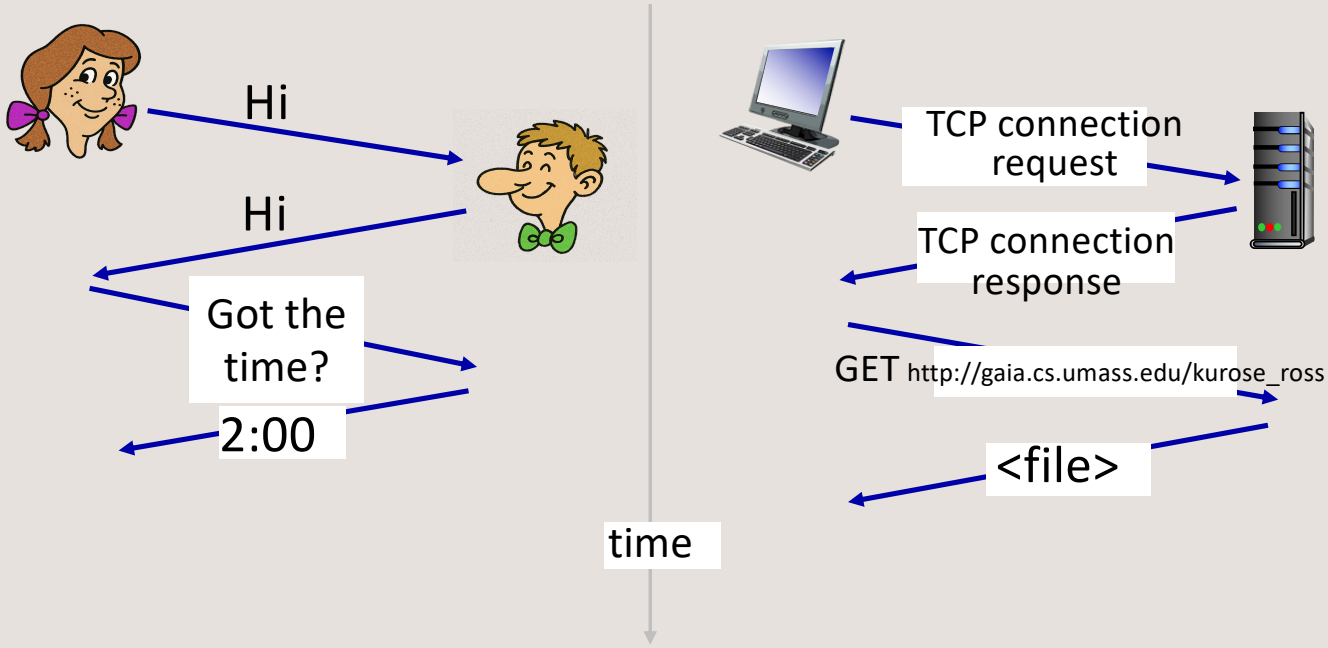
- computers (devices) rather than humans
- all communication activity in Internet governed by protocols

Protocols define the format, order of messages sent and received among network entities, and actions taken on message transmission, receipt



What's a protocol?

A human protocol and a computer network protocol:



Q: other human protocols?

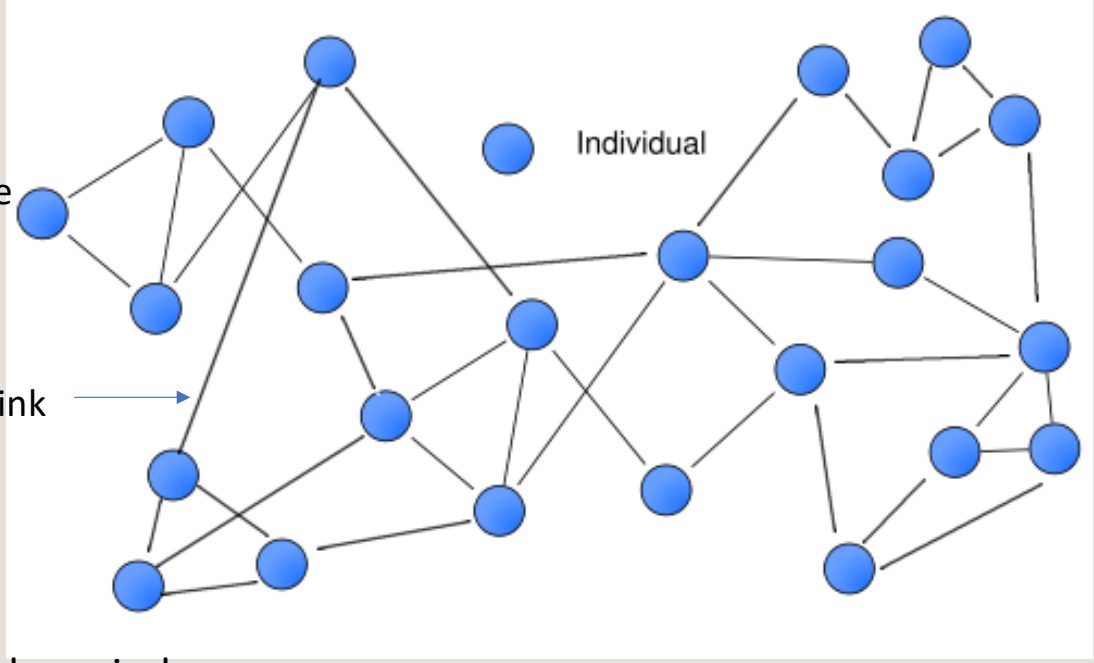
Packets and protocols

- **Link transmission rate, R (bit rate)**
  - **Bits per second (bps):** the number of bits transmitted over the link per second
- **Packet:** a self-contained unit of information carried over the network
  - A group of information bits transmitted together
  - e.g., 1 packet = 1500 bytes in Wi-Fi
- **Network:** a distributed system
  - It requires rules that determine how it operates
  - When a node transmits, whom it transmits to, and at what rate (bits/sec)
- **Protocol:** a set of rules that devices must follow for a specific operation
  - How they interpret incoming messages and how they respond to them
  - What messages they should send to their neighbors / which neighbors to send them to



Mathematical representation: network graph

- Node or vertex
- Link or edge
- Two nodes connect with a link if they can directly transmit packets to each other



Link: wired or wireless

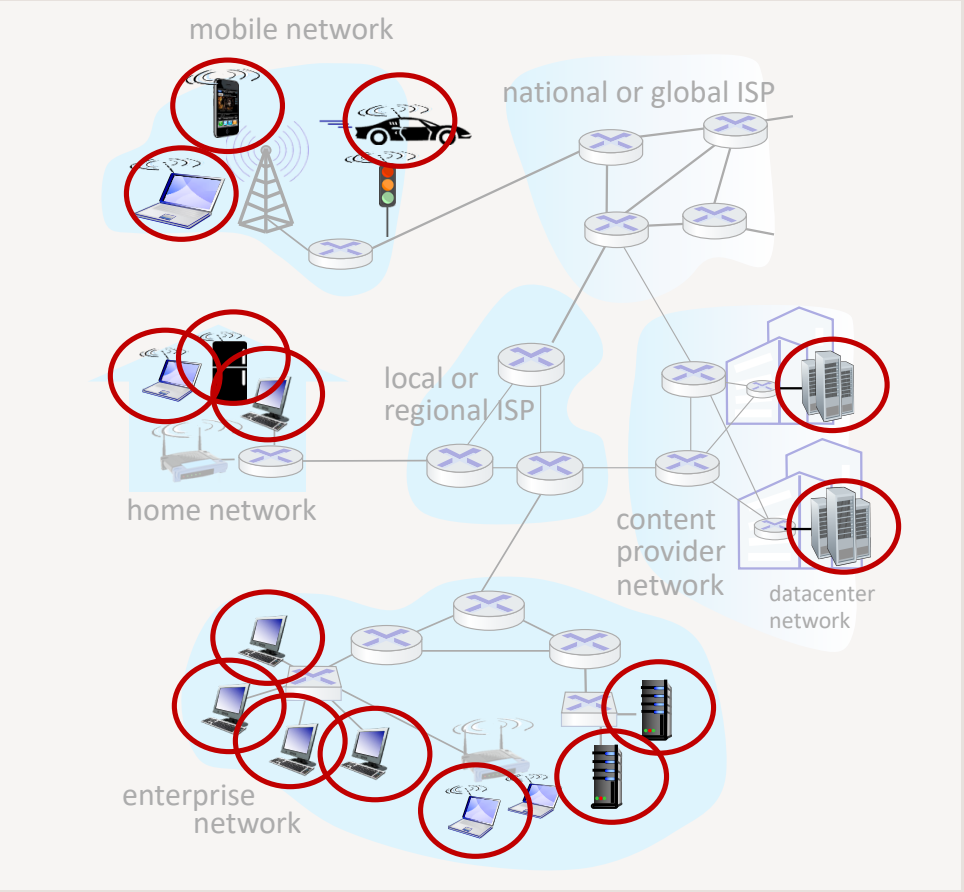
Chapter 1: roadmap

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- History

A closer look at Internet structure

Network edge:

- hosts: clients and servers
- servers often in data centers



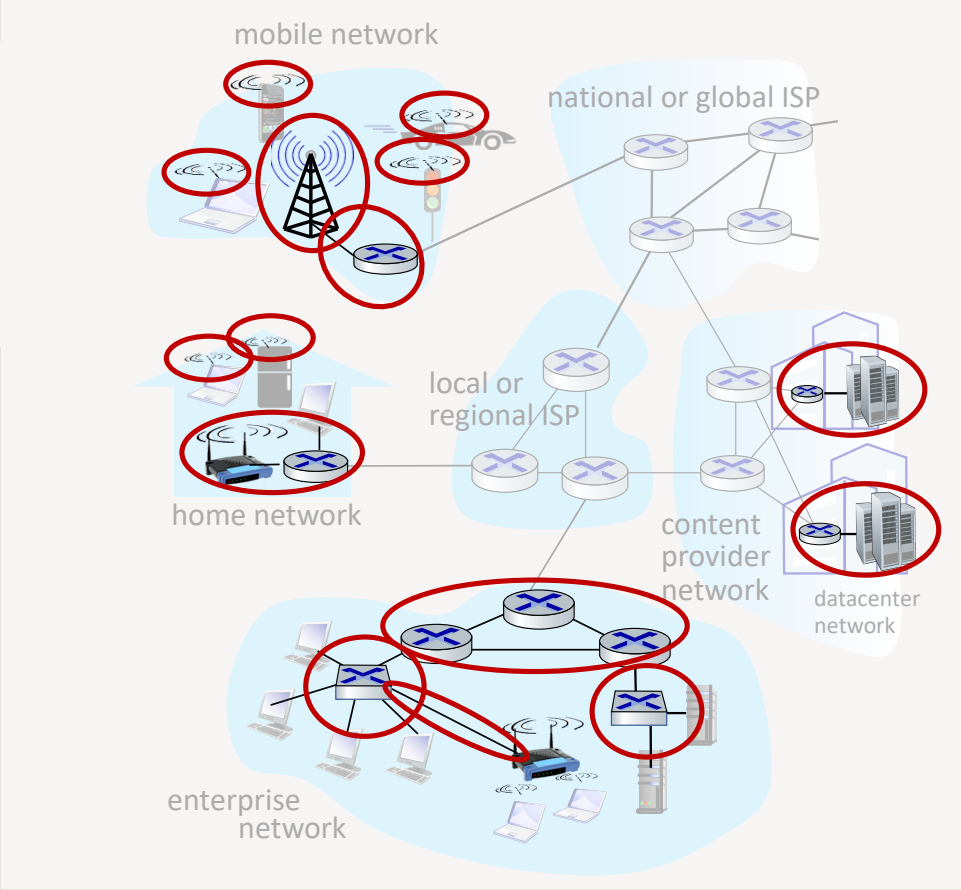
A closer look at Internet structure

Network edge:

- hosts: clients and servers
- servers often in data centers

Access networks, physical media:

- wired, wireless communication links



A closer look at Internet structure

Network edge:

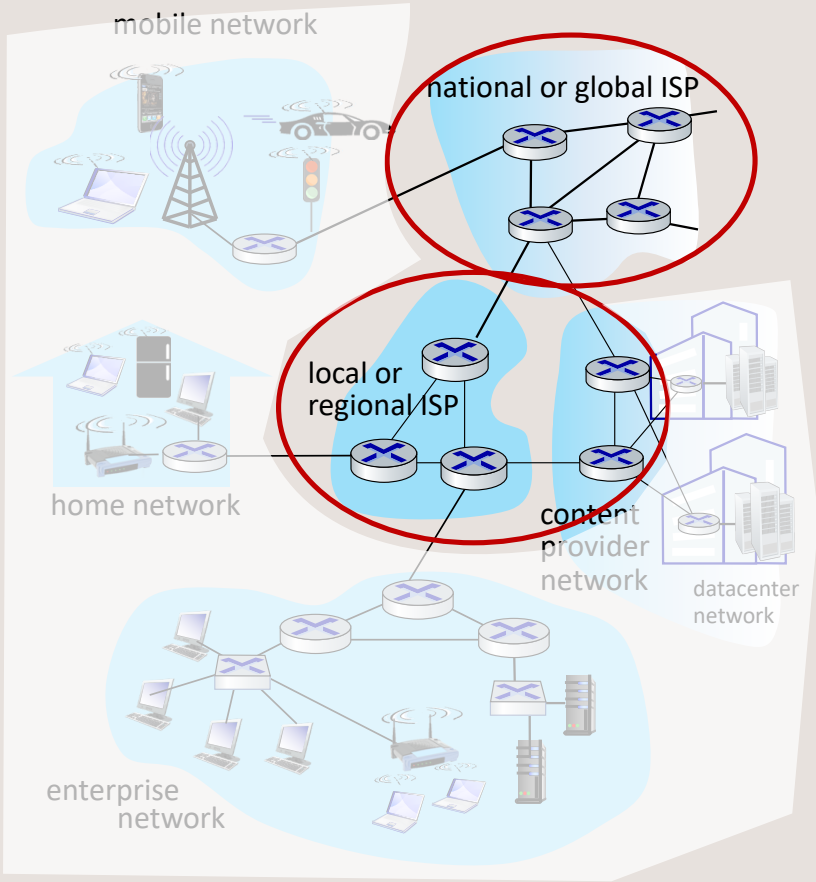
- hosts: clients and servers
- servers often in data centers

Access networks, physical media:

- wired, wireless communication links

Network core:

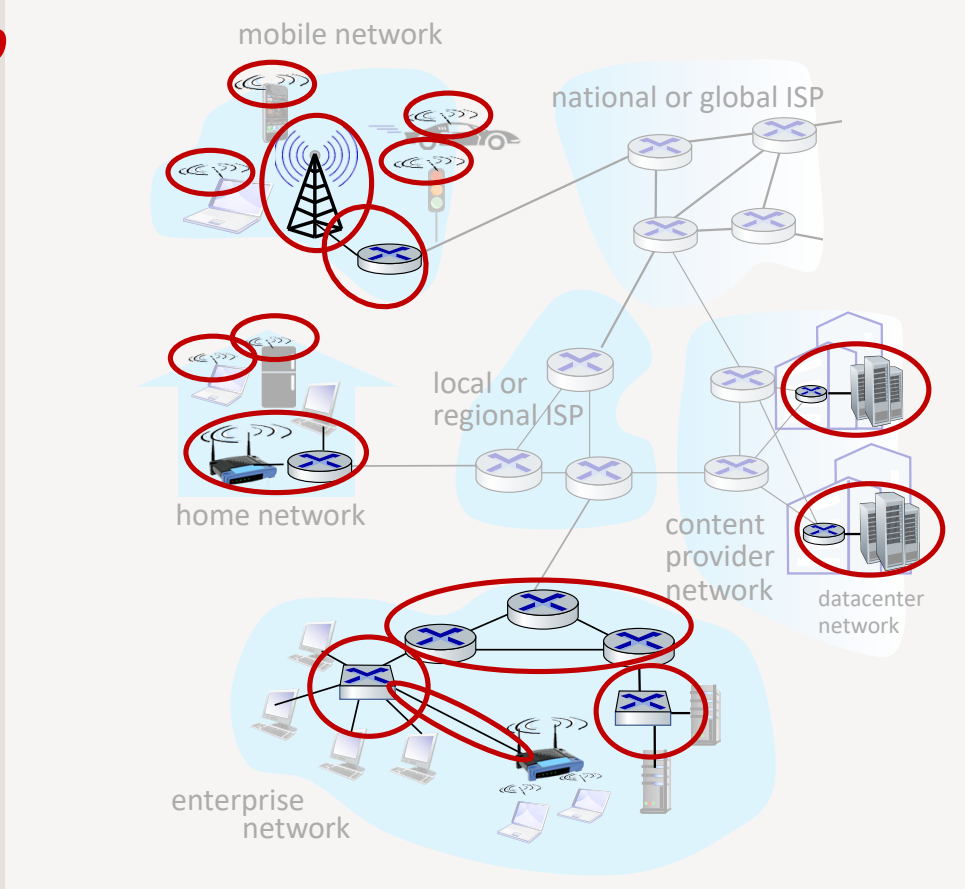
- interconnected routers
- network of networks



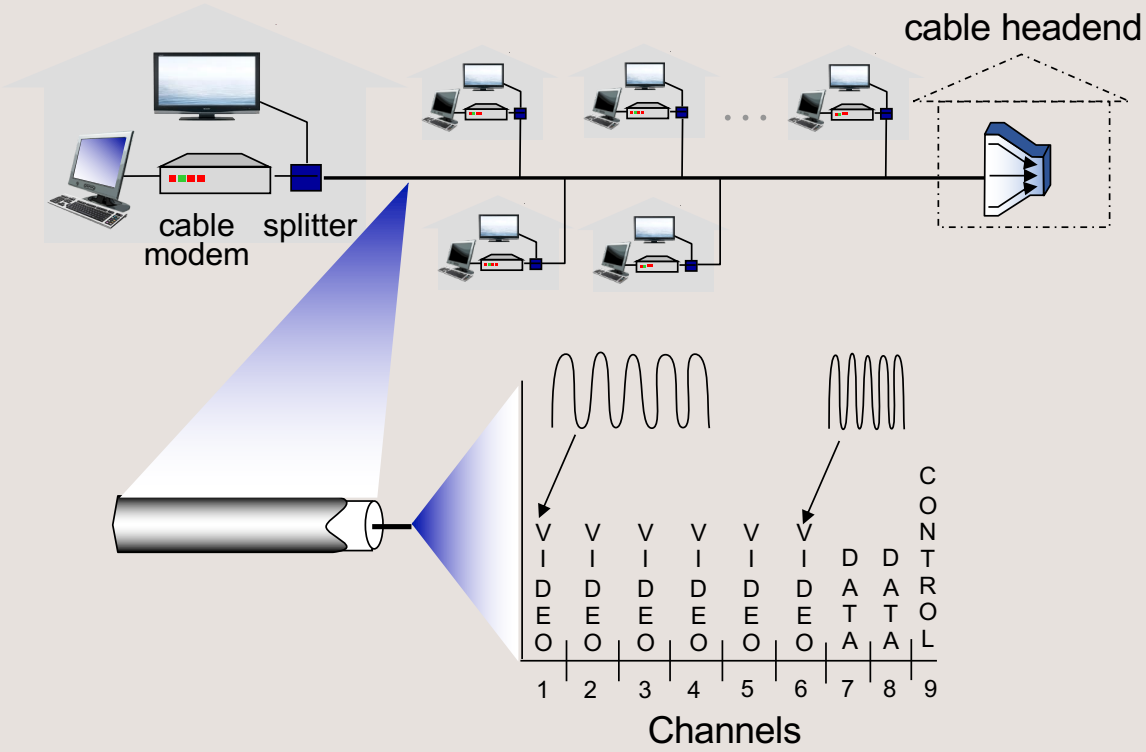
Access networks and physical media

Q: How to connect end systems to edge router?

- residential access nets
- institutional access networks (school, company)
- mobile access networks (WiFi, 4G/5G)

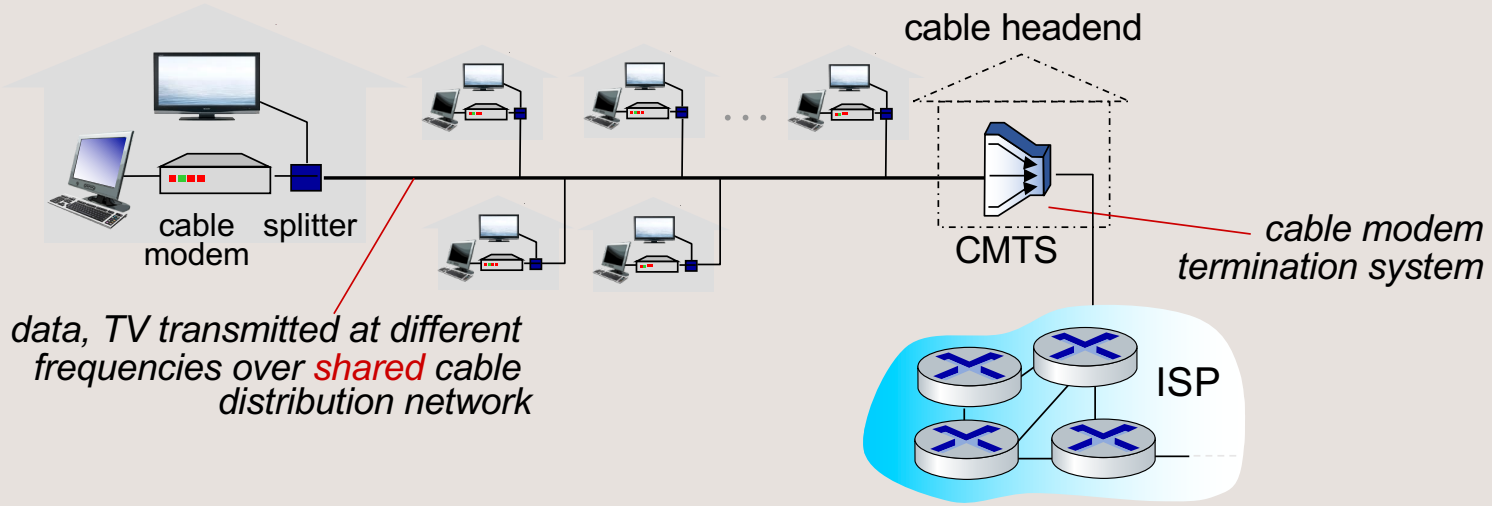


Access networks: cable-based access



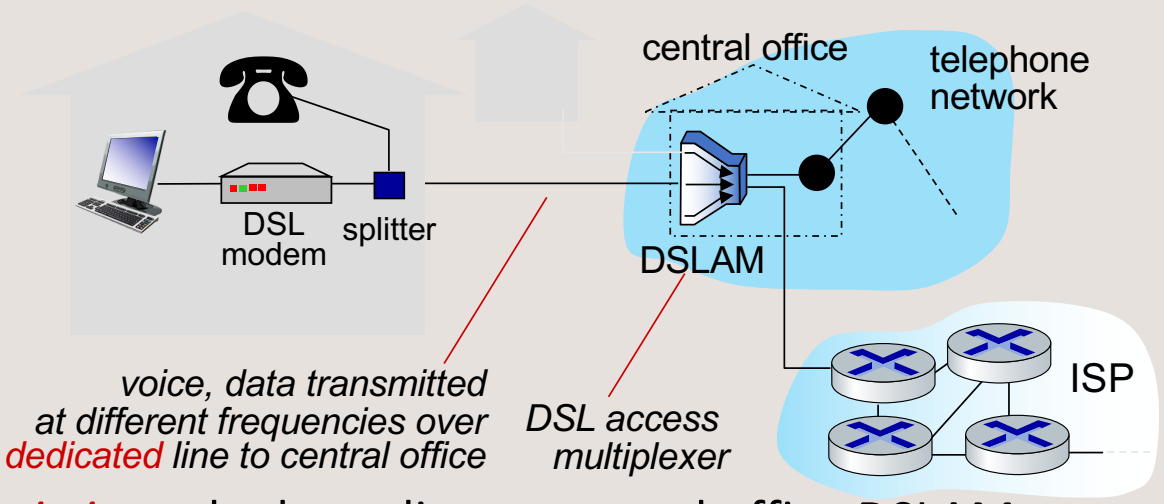
frequency division multiplexing (FDM): different channels transmitted in different frequency bands

Access networks: cable-based access



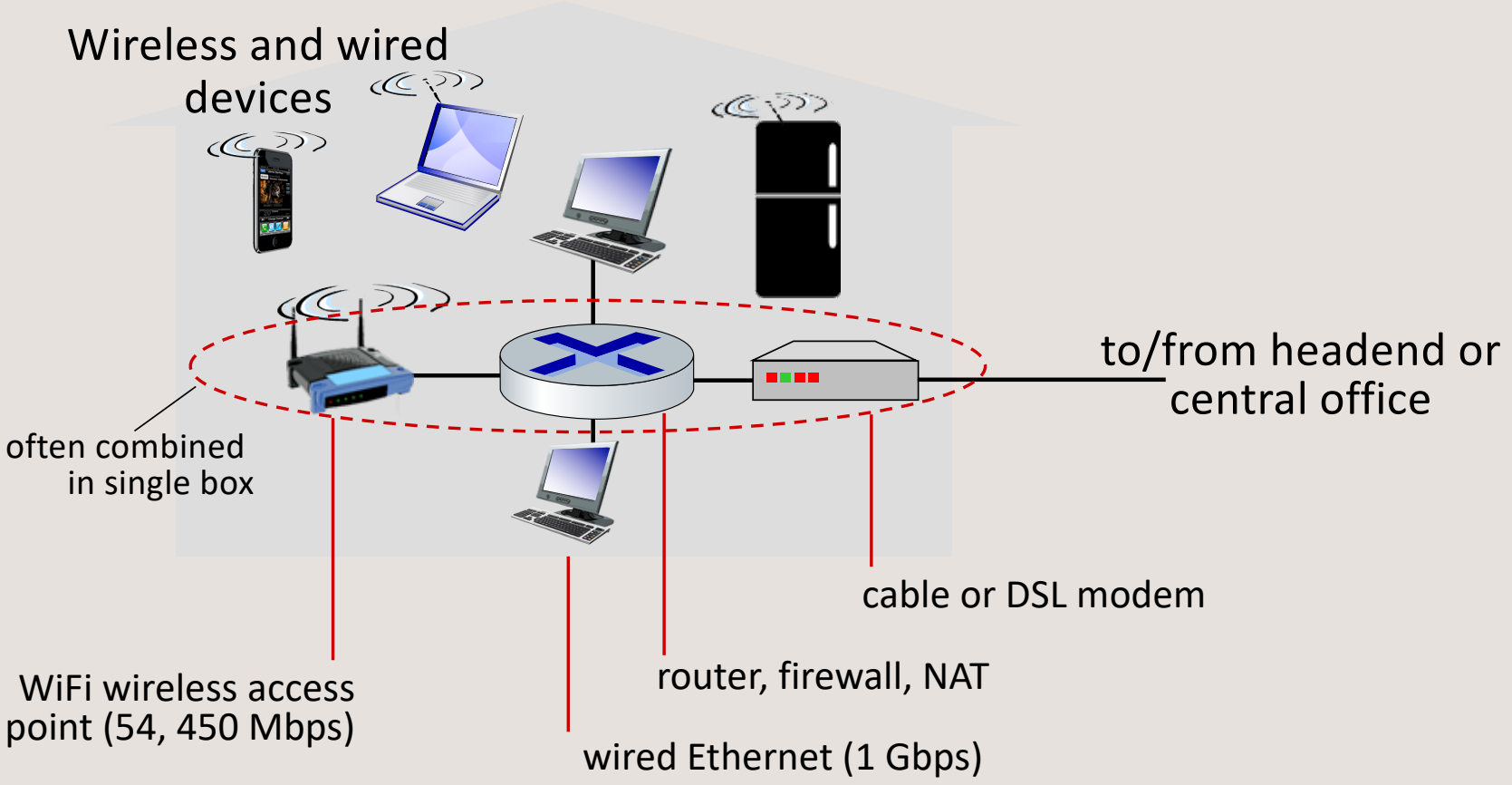
- HFC: hybrid fiber coax
  - asymmetric: up to 40 Mbps – 1.2 Gbps downstream transmission rate, 30-100 Mbps upstream transmission rate
- network of cable, fiber attaches homes to ISP router
  - homes *share access network* to cable headend

Access networks: digital subscriber line (DSL)



- use *existing* telephone line to central office DSLAM
  - data over DSL phone line goes to Internet
  - voice over DSL phone line goes to telephone net
  - Frequency Division Multiplexing)
  - Share link time in upsteam and downstream
- 24-52 Mbps dedicated downstream, 3.5-16 Mbps dedicated upstream transmission rate

Access networks: home networks



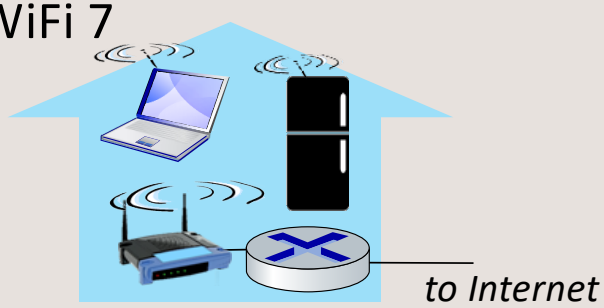
Wireless access networks

Shared *wireless* access network connects end system to router

- via base station aka “access point”

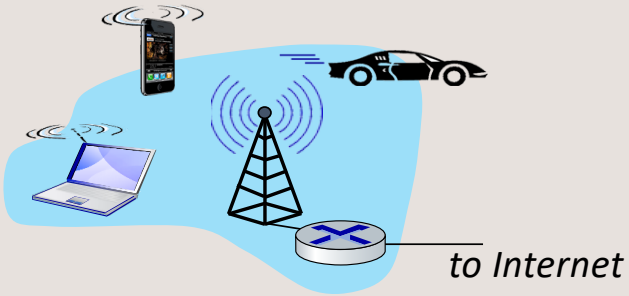
Wireless local area networks (WLANs)

- typically within or around building (~100 ft)
- 802.11b/g/n (WiFi): 11, 54, 450 Mbps transmission rate
- WiFi 7

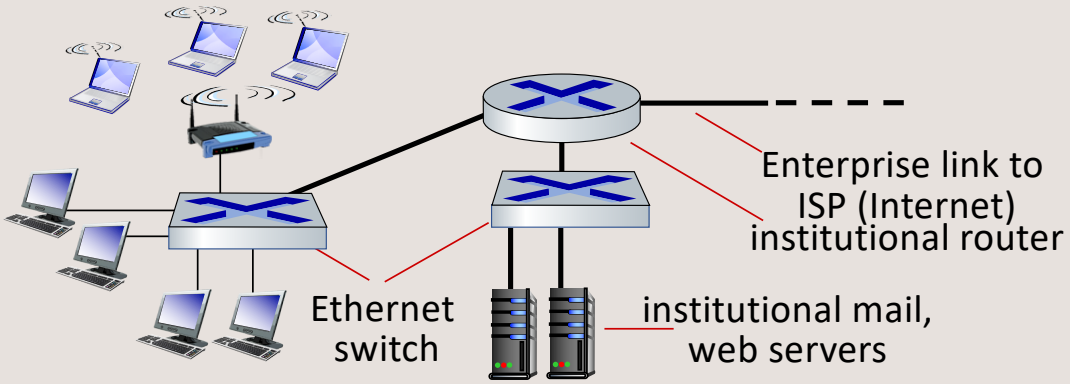


Wide-area cellular access networks

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



Access networks: enterprise networks



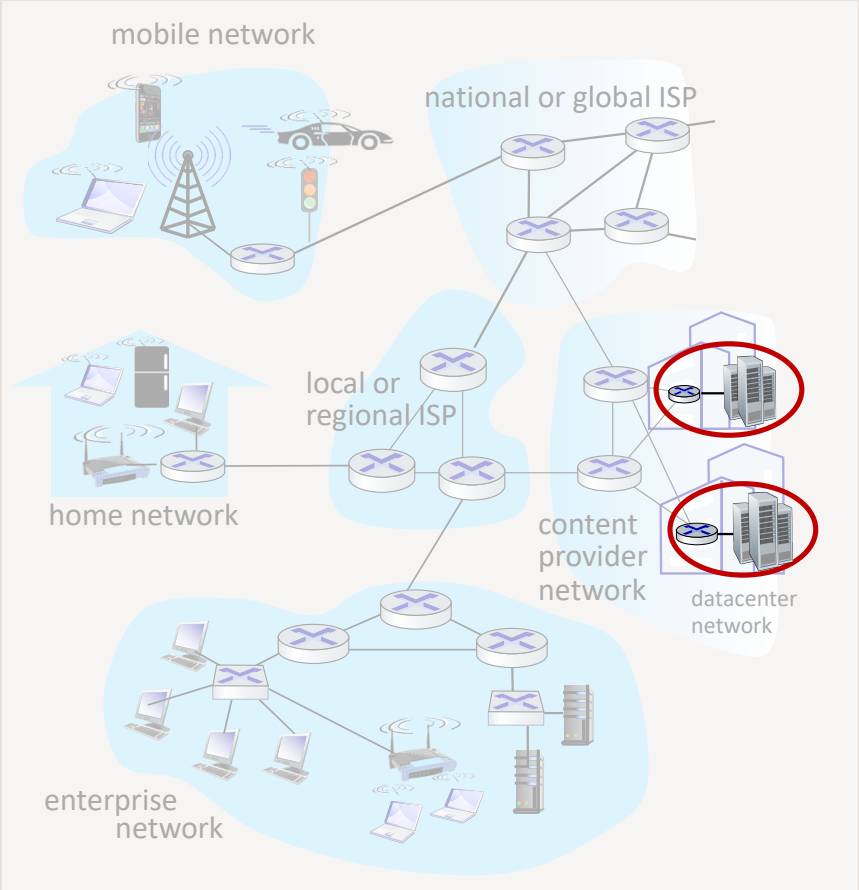
- Companies, universities, etc.
- Mix of wired, wireless link technologies, connecting a mix of switches and routers (we'll cover differences shortly)
  - Ethernet: wired access at 100Mbps, 1Gbps, 10Gbps
  - WiFi: wireless access points at 11, 54, 450 Mbps

Access networks: data center networks

- High-bandwidth links (10s to 100s Gbps) connect hundreds to thousands of servers together, and to Internet



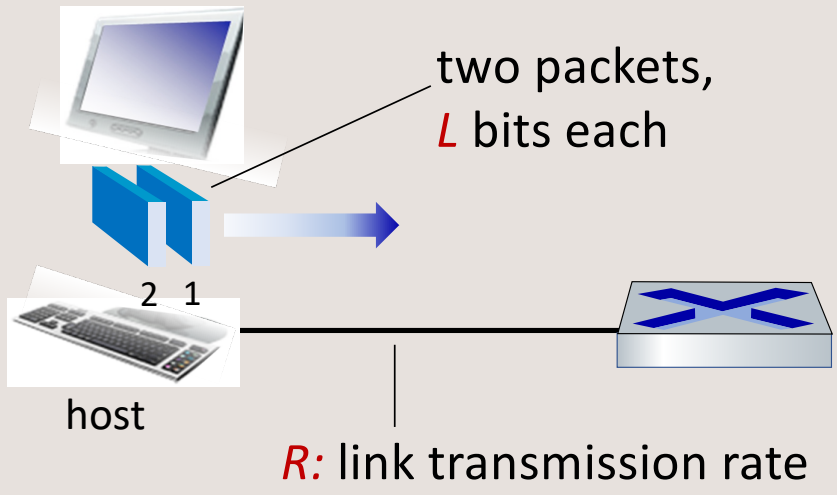
Courtesy: Massachusetts Green High Performance Computing Center (mghpcc.org)



Host: sends *packets* of data

host sending function:

- takes application message
- breaks into smaller chunks, known as *packets*, of length *L* bits
- transmits packet into access network at *transmission rate R*
  - link transmission rate, aka link *capacity, aka link bandwidth*

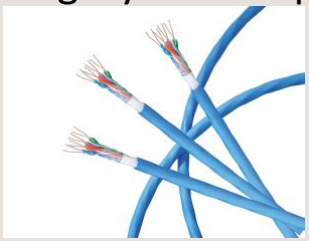


$$\text{packet transmission delay} = \text{time needed to transmit } L\text{-bit packet into link} = \frac{L \text{ (bits)}}{R \text{ (bits/sec)}}$$

Links: physical media

Twisted pair (TP):

- two insulated copper wires
  - Category 5: 100 Mbps, 1 Gbps Ethernet
  - Category 6: 10Gbps Ethernet





Coaxial cable:

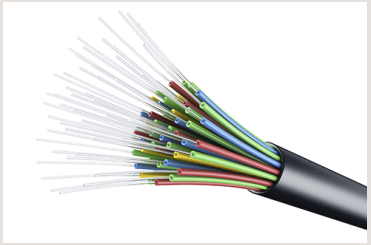
- two concentric copper conductors
- bidirectional
- broadband:
  - multiple frequency channels on cable
  - 100's Mbps per channel



- bit: propagates between transmitter/receiver pairs
- physical link: what lies between transmitter & receiver

Fiber optic cable:

- glass fiber carrying light pulses, each pulse a bit
- high-speed operation:
  - high-speed point-to-point transmission (10's-100's Gbps)
- low error rate:
  - repeaters spaced far apart
  - immune to electromagnetic noise



Links: physical media

Wireless radio

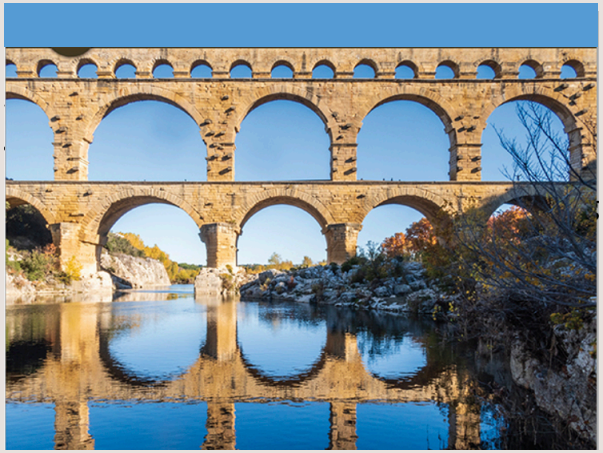
- signal carried in various "bands" in electromagnetic spectrum
- no physical "wire"
- broadcast, "half-duplex" (sender to receiver)
- propagation environment effects:
  - reflection
  - obstruction by objects
  - Interference/noise

Radio link types:

- Wireless LAN (WiFi)
  - 10-100's Mbps; 10's of meters
- wide-area (e.g., 4G/5G cellular)
  - 100's Mbps (4G/5G) over ~10 Km
- Bluetooth: cable replacement
  - short distances, limited rates
- terrestrial microwave
  - point-to-point; 45 Mbps channels
- satellite
  - up to < 100 Mbps (Starlink) downlink
  - 270 msec end-end delay (geostationary)

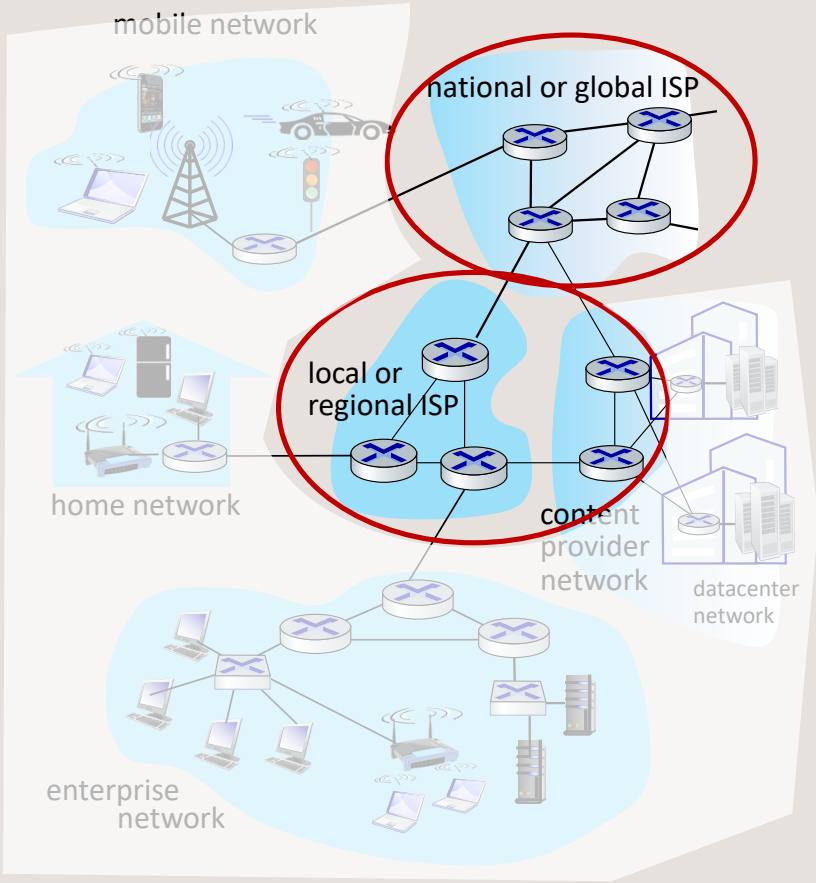
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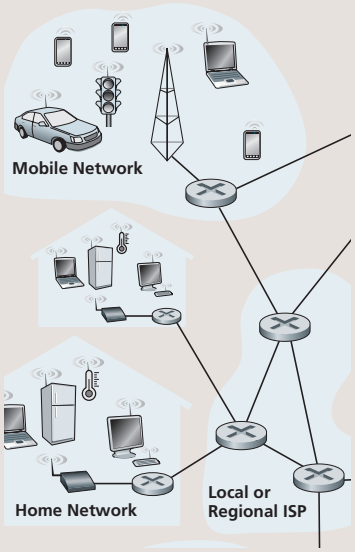
The network core

- mesh of interconnected routers
- packet-switching: hosts break application-layer messages into *packets*
  - network forwards packets from one router to the next, across links on path from source to destination



Packet Transmission (briefly)

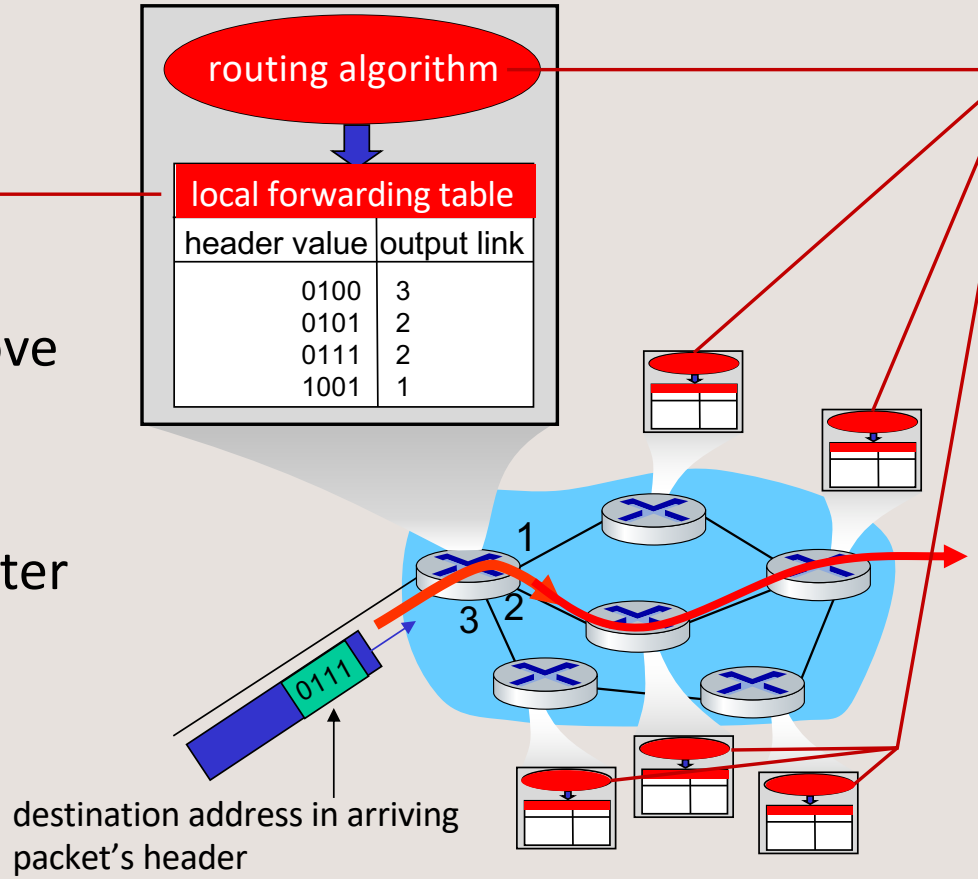
- When a host has data to send to another host, it divides the data into data packets.
  - It adds a header to each packet.
- Packets are transmitted to their destination over a single link or a sequence of links.
- Packets are transmitted over each link at a transmission rate R
  - packets/sec → bits/sec
- A sequence of links between the source and destination of a packet is called a route or path.
- Switch: receives packets on an incoming link and forwards them to an outgoing link.



Two key network-core functions

Forwarding:

- aka "switching"
- *local* action: move arriving packets from router's input link to appropriate router output link



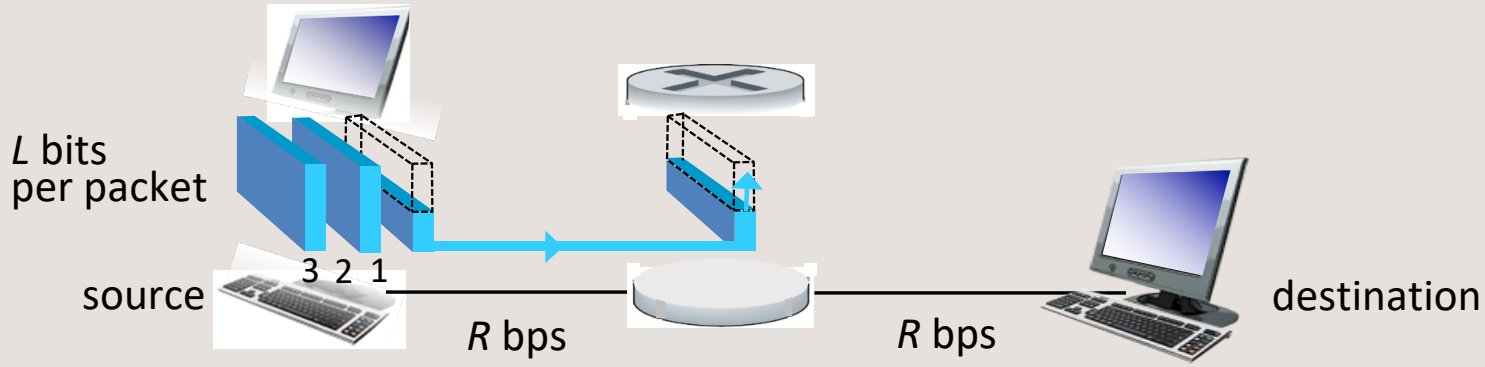
Routing:

- *global* action: determine source-destination paths taken by packets
- routing algorithms


routing
45 h
3,053 miles
48 h
3,309 miles
San Jose
Northampton
United States
Victoria
Seattle
Portland
San Francisco
Sacramento
Los Angeles
San Diego
Las Vegas
Phoenix
Tucson
El Paso
Dallas
Austin
Houston
San Antonio
New Orleans
Kansas City
Minneapolis
Chicago
Detroit
Toronto
Ottawa
Montreal
Quebec City
New York
Philadelphia
Indianapolis
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Atlanta
Charlotte
Jacksonville
Orlando
Tampa
WASHINGTON
OREGON
CALIFORNIA
NEVADA
IDAHO
MONTANA
WYOMING
UTAH
COLORADO
ARIZONA
NEW MEXICO
NORTH DAKOTA
SOUTH DAKOTA
NEBRASKA
KANSAS
OKLAHOMA
TEXAS
MINNESOTA
IOWA
MISSOURI
ARKANSAS
LOUISIANA
WISCONSIN
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OHIO
KENTUCKY
TENNESSEE
MISSISSIPPI
ALABAMA
GEORGIA
FLORIDA
SOUTH CAROLINA
NORTH CAROLINA
VIRGINIA
WEST VIRGINIA
PENNSYLVANIA
NEW YORK
MARYLAND
DE
NJ
CT
RI
VERMONT
NEW HAMPSHIRE
MAINE
BAJA CALIFORNIA
SONORA
CHIHUAHUA
COAHUILA


forwarding
forwarding
45 h
3,053 miles
48 h
3,309 miles
United States
Victoria
Seattle
WASHINGTON
Portland
NORTH DAKOTA
MINNESOTA
Minneapolis
SOUTH DAKOTA
WISCONSIN
MICHIGAN
Toronto
Quebec City
Montreal
Ottawa
MAINE
VERMONT
NEW HAMPSHIRE
Northampton
WYOMING
Chicago
Detroit
IOWA
ILLINOIS
INDIANA
OHIO
Indianapolis
Kansas City
COLORADO
KANSAS
MISSOURI
KENTUCKY
Nashville
TENNESSEE
San Francisco
San Jose
CALIFORNIA
Las Vegas
OKLAHOMA
ARKANSAS
Atlanta
Los Angeles
ARIZONA
NEW MEXICO
MISSISSIPPI
ALABAMA
San Diego
Phoenix
Dallas
Tucson
El Paso
TEXAS
BAJA CALIFORNIA
SONORA
Austin
Houston
LOUISIANA
New Orleans
CHIHUAHUA
San Antonio
COAHUILA
Tampa
FLORIDA
Cleveland
DOWNTOWN
CENTRAL
OHIO CITY

Packet-switching: store-and-forward



- packet transmission delay: takes L/R seconds to transmit (push out) L-bit packet into link at R bps
- *store and forward: entire* packet must arrive at router before it can be transmitted on next link

One-hop numerical example:

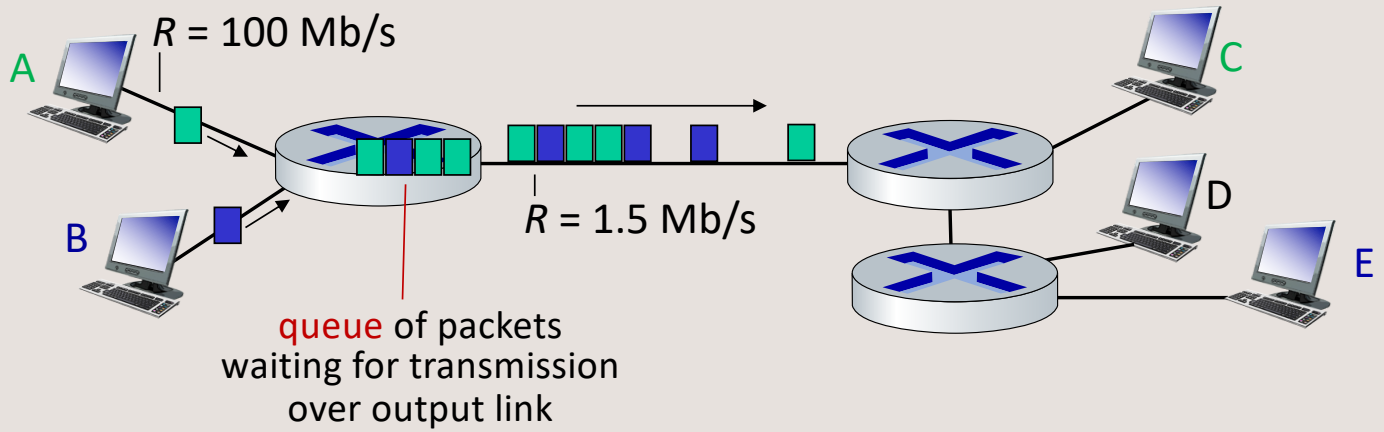
- L = 10 Kbits
- R = 100 Mbps
- one-hop transmission delay = 0.1 msec

Store-and-Forward (2): Example

- Suppose the source has K packets to transmit to a destination through a router (see previous figure)
  - At what time will the destination receive all K packets?
  - Answer: ((K+1)L/R). Why?
- Suppose the source has one packet and wants to transmit it to the destination through N links
  - At what time will the destination receive the packet?
  - Answer: (NL/R). Why?
- Suppose the source has K packets and wants to transmit them to the destination through N links
  - At what time will the destination receive all the packets?
  - Answer: ((K+N-1)L/R). Why?



Packet-switching: queueing



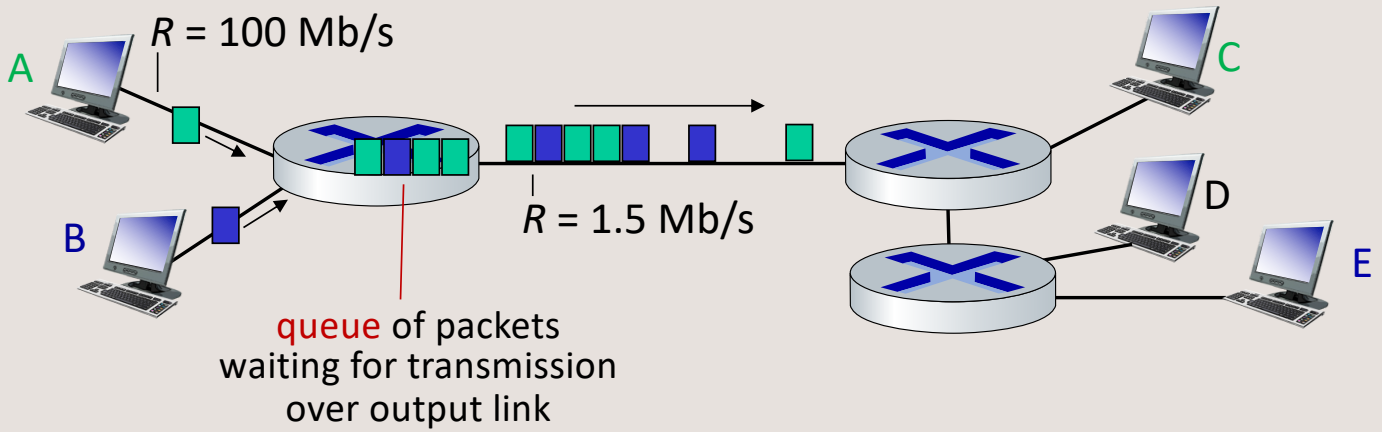
Queueing occurs when work arrives faster than it can be serviced:







Packet-switching: queueing



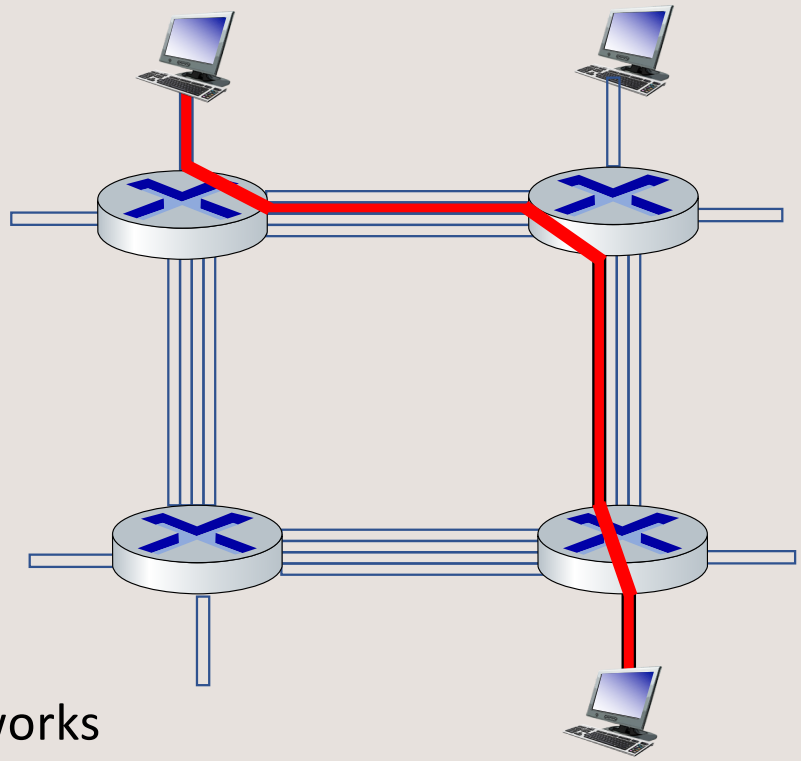
Packet queuing and loss: if arrival rate (in bps) to link exceeds transmission rate (bps) of link for some period of time:

- packets will queue, waiting to be transmitted on output link
- packets can be dropped (lost) if memory (buffer) in router fills up
- Example: Suppose the packet size = L bits
- Packet arrival rate λ = number of packets arriving per second
- Packet transmission rate: 15 Mbps/ L bits/packet
  - When do packets start accumulating in the queue?

Alternative to packet switching: circuit switching

end-end resources allocated to, reserved for "call" between source and destination

- in diagram, each link has four circuits.
  - call gets 2nd circuit in top link and 1st circuit in right link.
- dedicated resources: no sharing
  - circuit-like (guaranteed) performance
- circuit segment idle if not used by call (no sharing)
  - commonly used in traditional telephone networks



* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/interactive

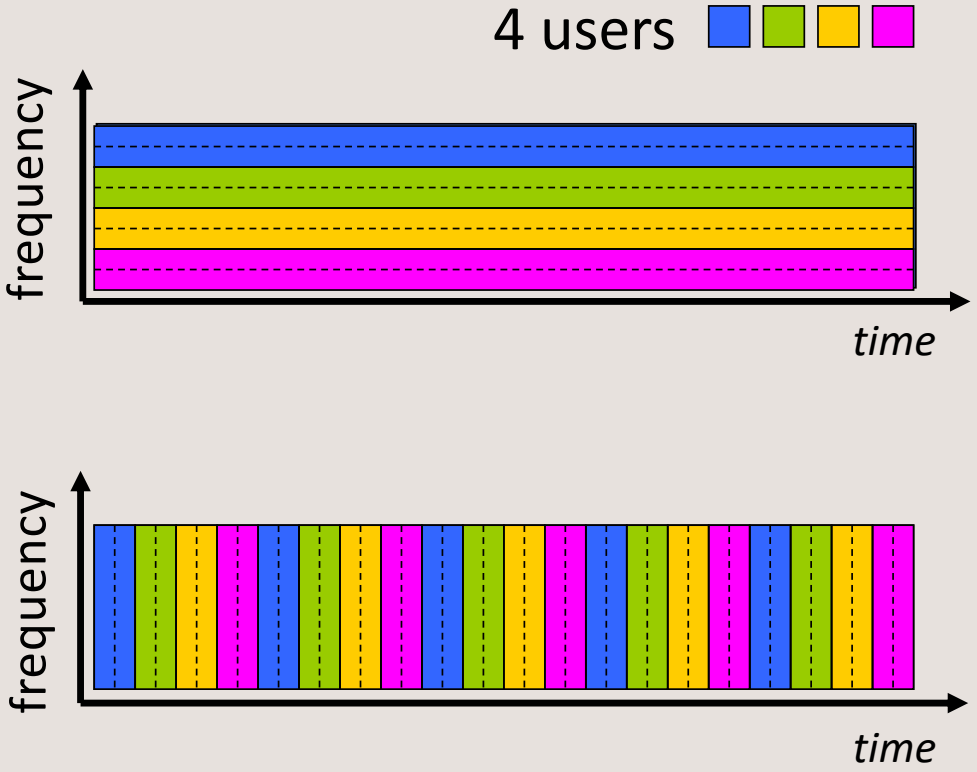
Circuit switching: FDM and TDM

Frequency Division Multiplexing (FDM)

- optical, electromagnetic frequencies divided into (narrow) frequency bands
  - each call allocated its own band, can transmit at max rate of that narrow band

Time Division Multiplexing (TDM)

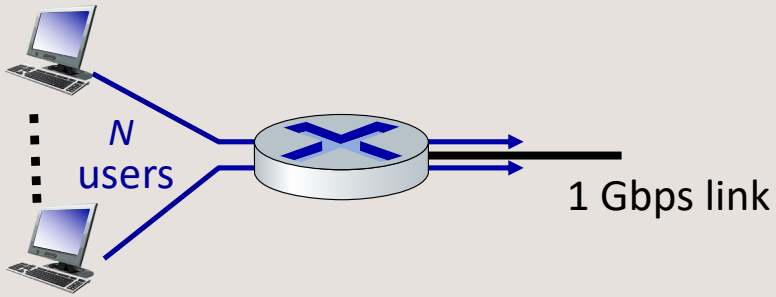
- time divided into slots
- each call allocated periodic slot(s), can transmit at maximum rate of (wider) frequency band (only) during its time slot(s)



Packet switching versus circuit switching

example:

- 1 Gb/s link
- each user:
  - 100 Mb/s when “active”
  - active 10% of time



Q: how many users can use this network under circuit-switching and packet switching?

- *circuit-switching:* 10 users
- *packet switching:* with 35 users, probability > 10 active at same time is less than .0004 *
- With prob. 0.9996, the total traffic is <1Gbps and is serviced without delay! Just as in CS!

Q: how did we get value 0.0004?

A: HW problem (for those with course in probability only)

* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/interactive

Packet switching versus circuit switching

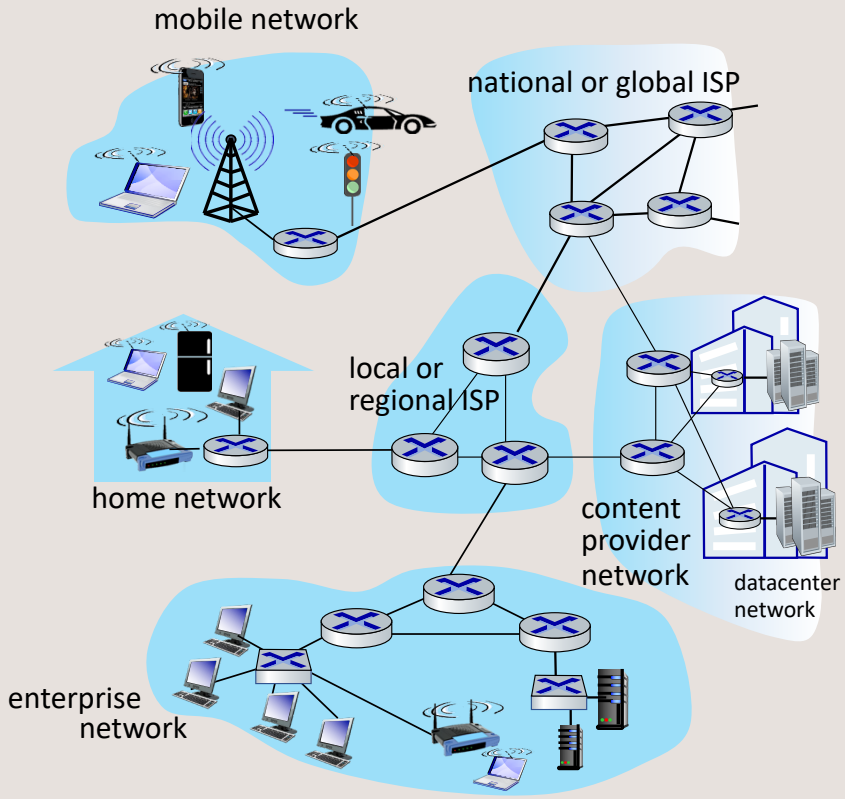
Is packet switching a "slam dunk winner"?

- great for "bursty" data – sometimes has data to send, but at other times not
  - resource sharing
  - simpler, no call setup
- excessive congestion possible: packet delay and loss due to buffer overflow
  - protocols needed for reliable data transfer, congestion control
- *Q:* How to provide circuit-like behavior with packet-switching?
  - "It's complicated." We'll study various techniques that try to make packet switching as "circuit-like" as possible.

Q: human analogies of reserved resources (circuit switching) versus on-demand allocation (packet switching)?

Internet structure: a "network of networks"

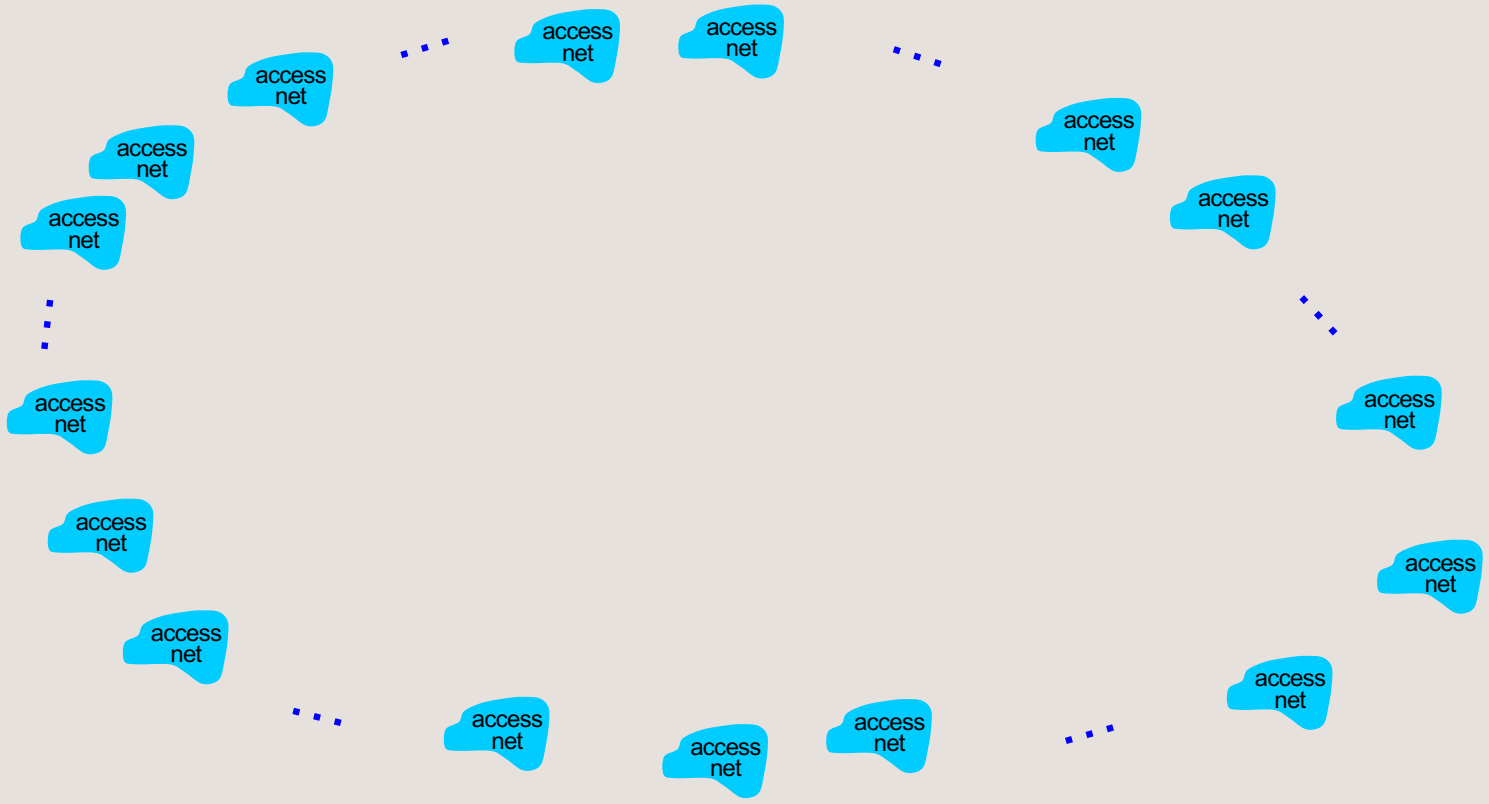
- hosts connect to Internet via access Internet Service Providers (ISPs)
- access ISPs in turn must be interconnected
  - so that *any* two hosts *(anywhere!)* can send packets to each other
- resulting network of networks is very complex
  - evolution driven by economics, national policies



Let's take a stepwise approach to describe current Internet structure

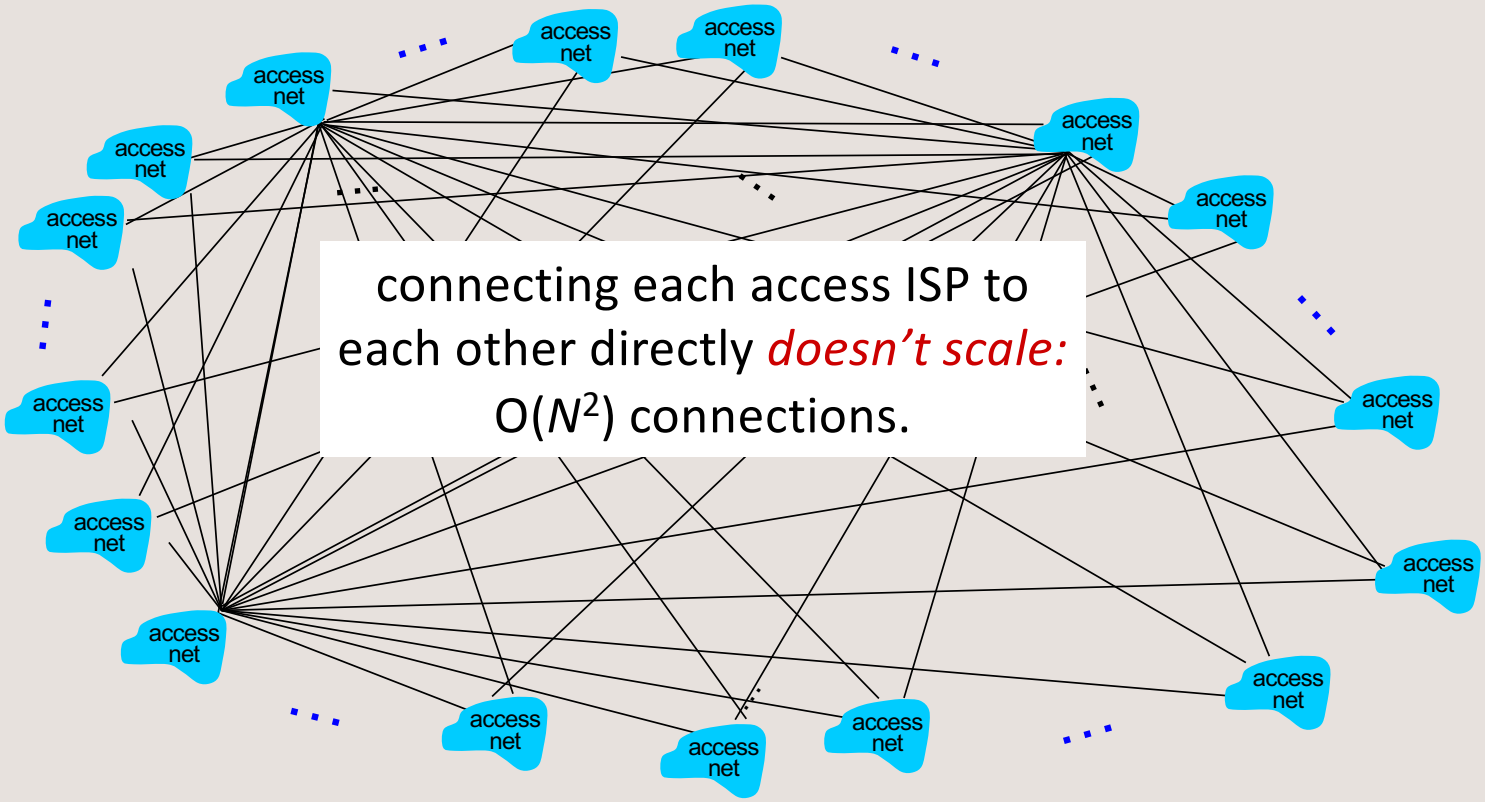
Internet structure: a "network of networks"

Question: given *millions* of access ISPs, how to connect them together?



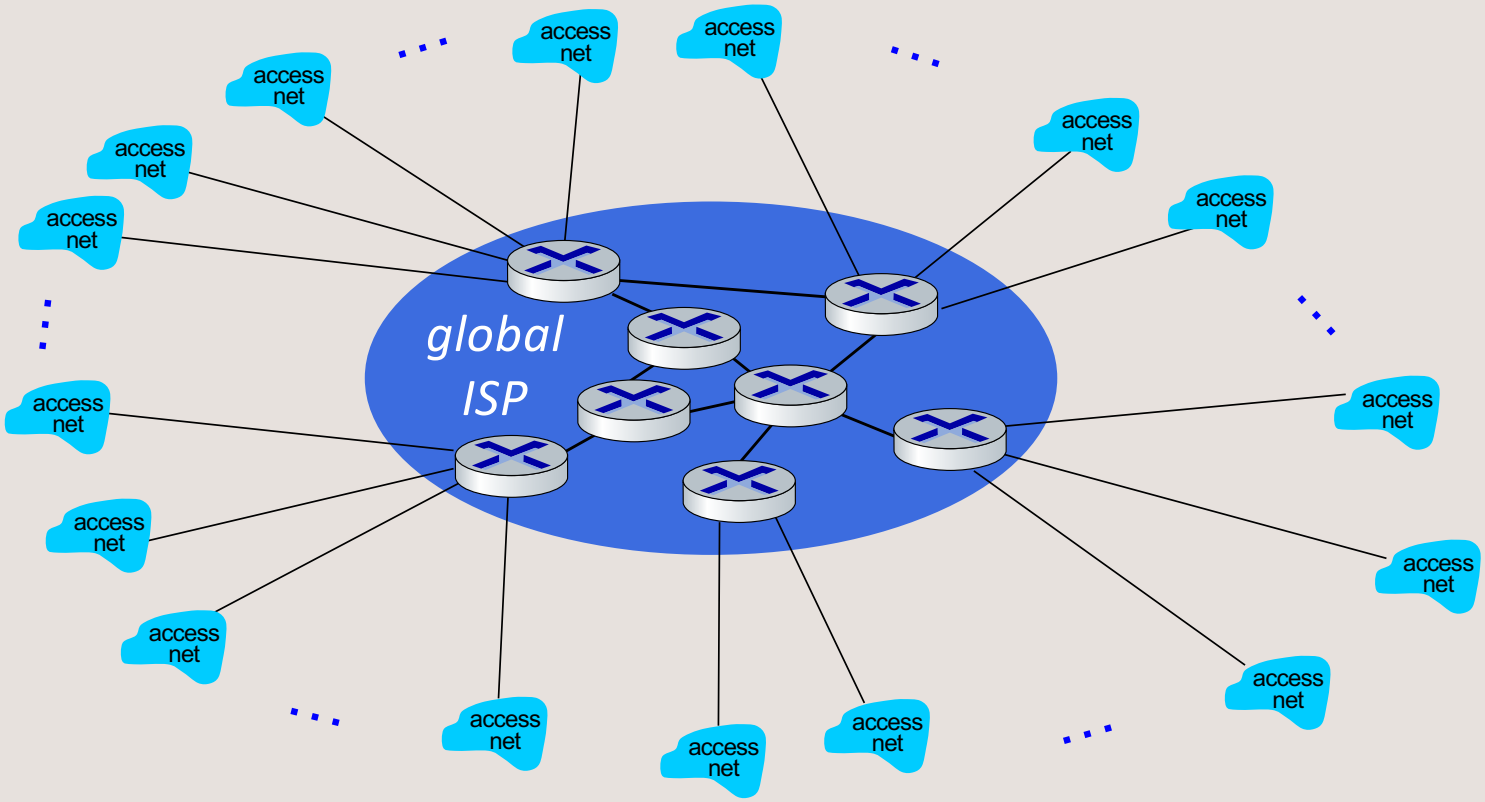
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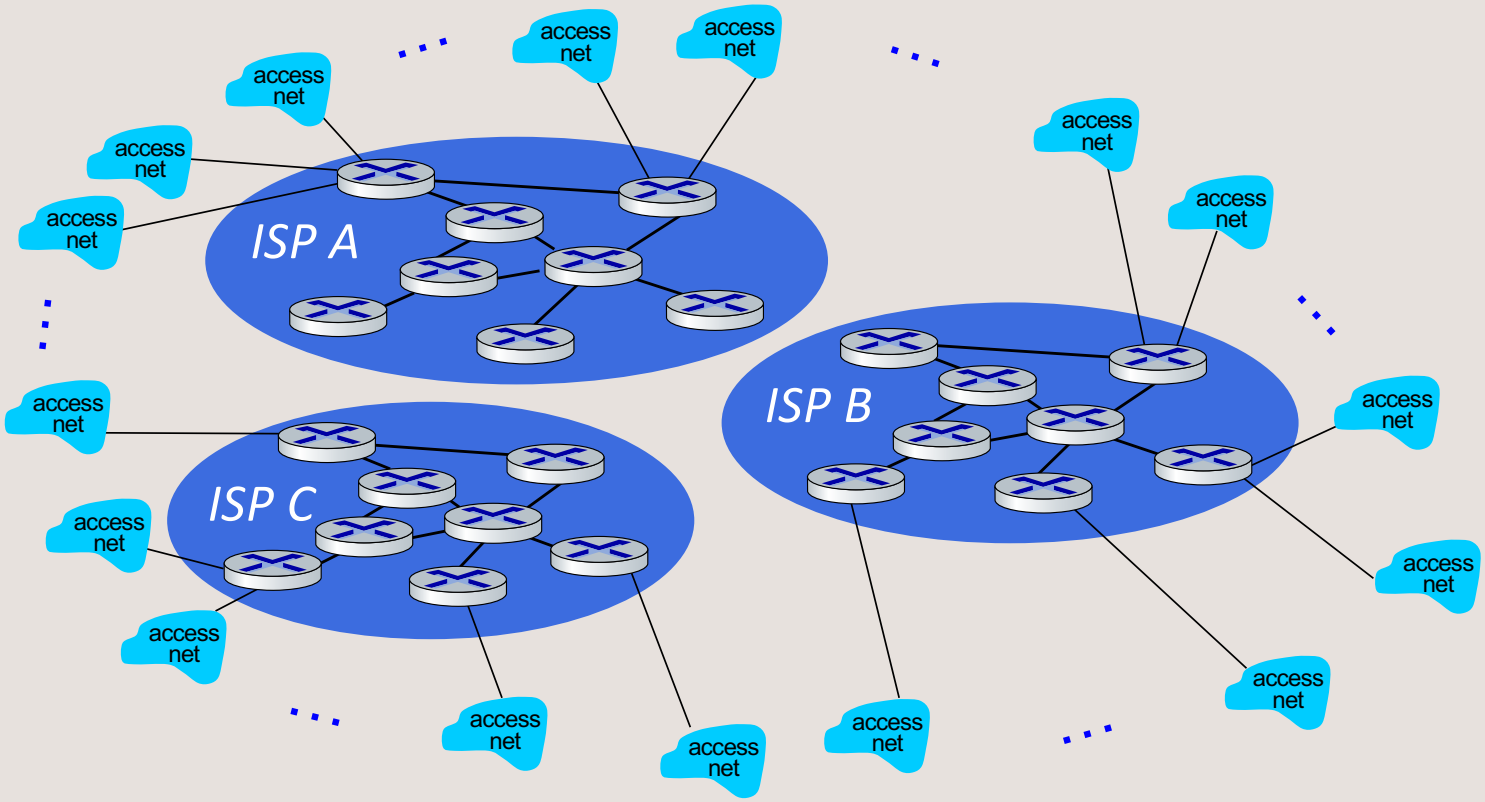
Internet structure: a "network of networks"

Option: connect each access ISP to one global transit ISP?
Customer and provider ISPs have economic agreement.



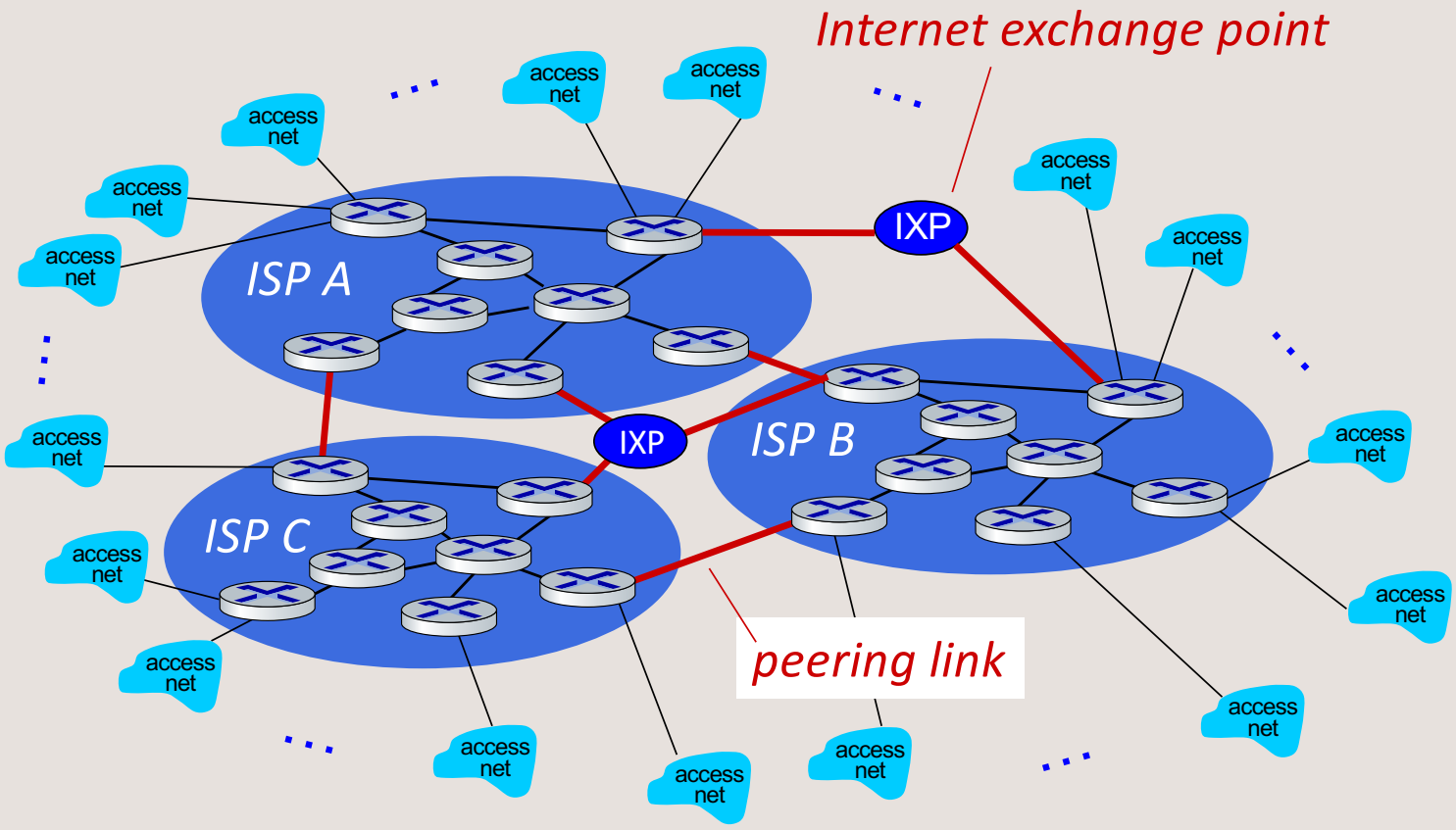
Internet structure: a “network of networks”

But if one global ISP is viable business, there will be competitors ….



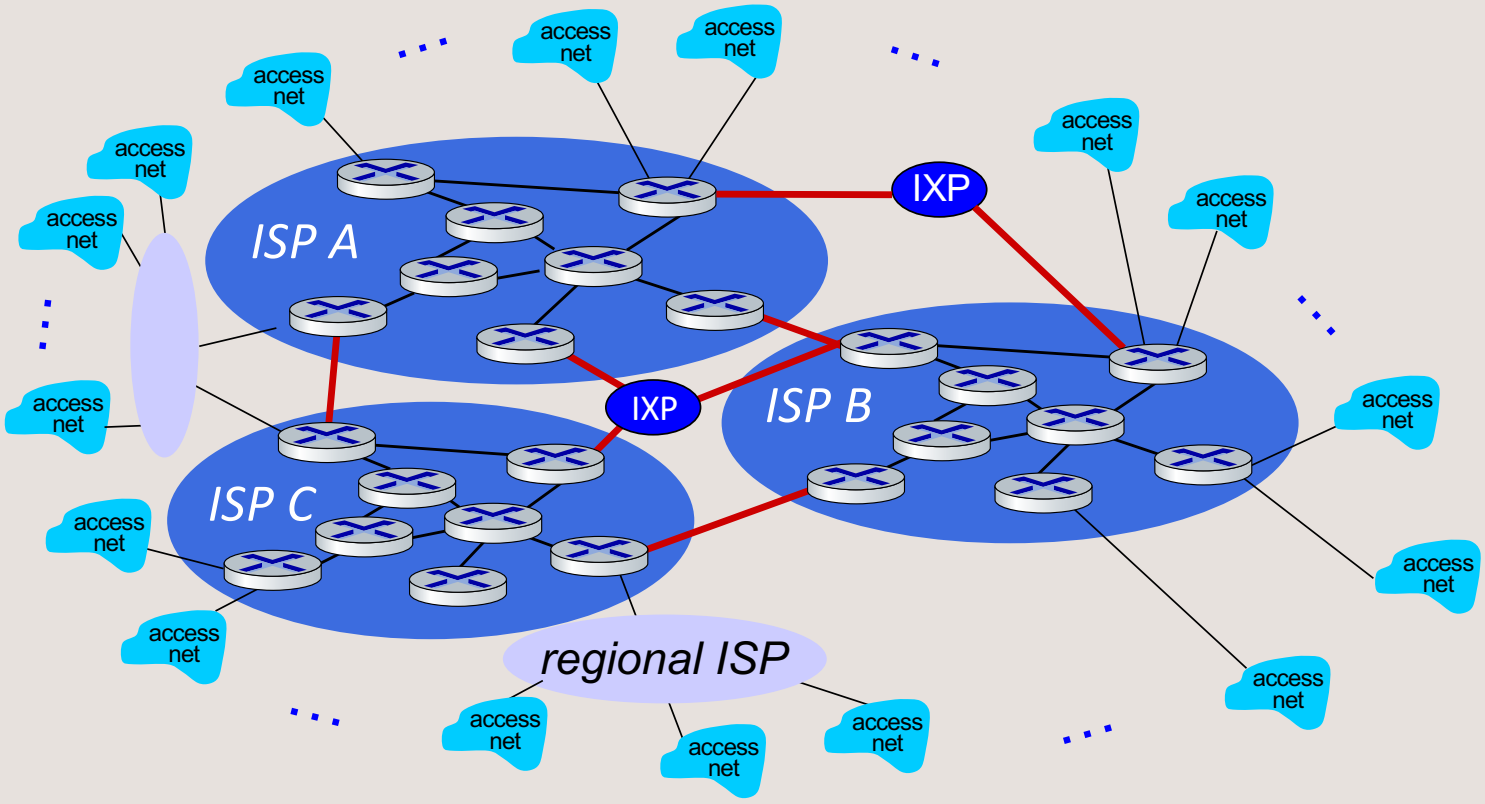
Internet structure: a "network of networks"

But if one global ISP is viable business, there will be competitors …. who will want to be connected



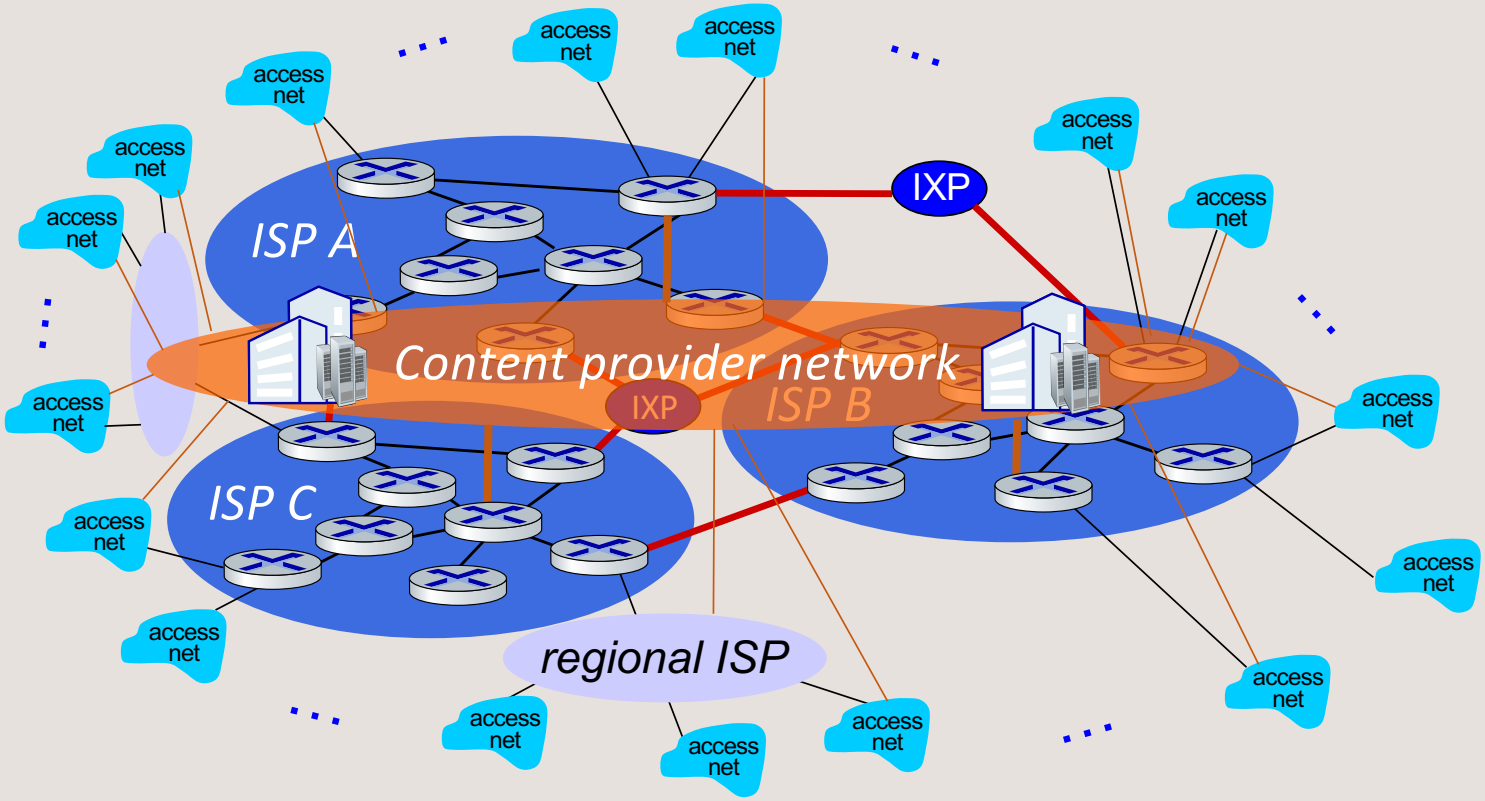
Internet structure: a “network of networks”

… and regional networks may arise to connect access nets to ISPs

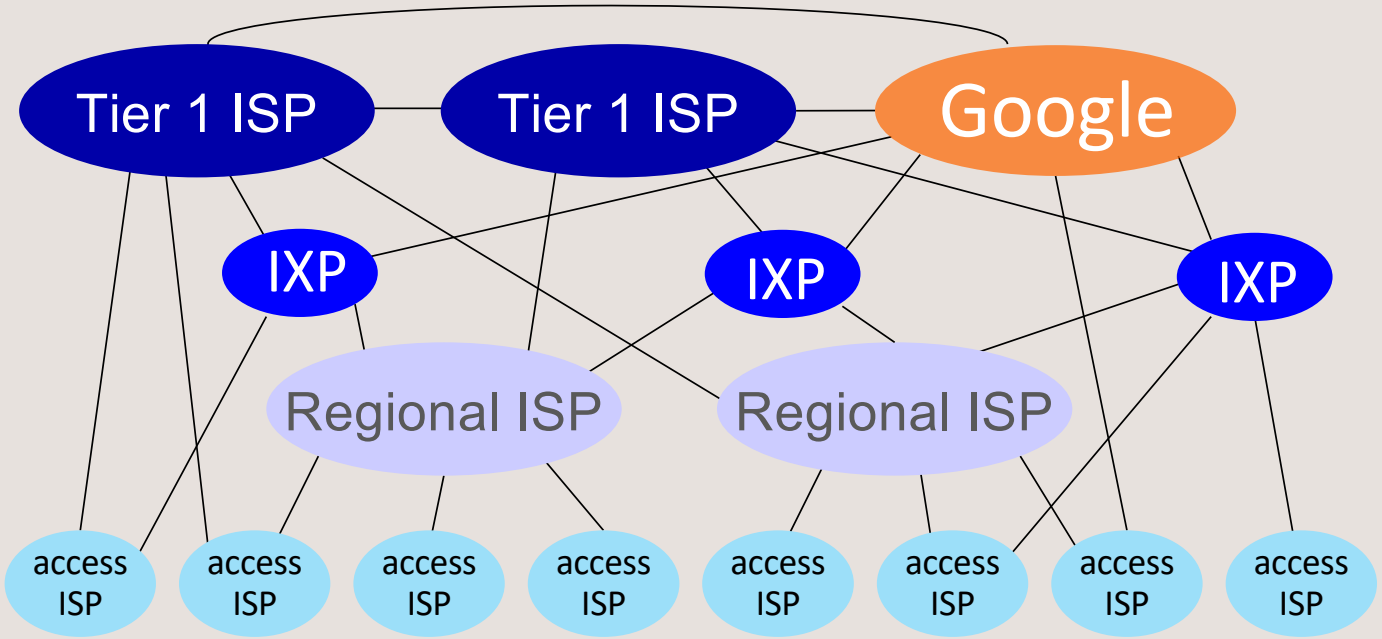


Internet structure: a "network of networks"

… and content provider networks (e.g., Google, Microsoft, Akamai) may run their own network, to bring services, content close to end users



Internet structure: a "network of networks"

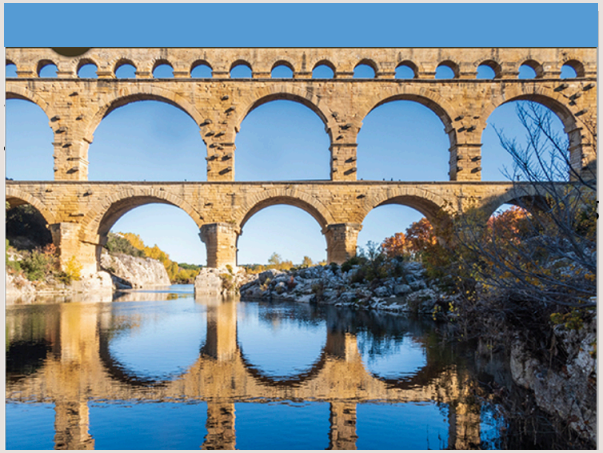


At "center": small # of well-connected large networks

- "tier-1" commercial ISPs (e.g., Level 3, Sprint, AT&T, NTT), national & international coverage
- content provider networks (e.g., Google, Facebook): private network that connects its data centers to Internet, often bypassing tier-1, regional ISPs

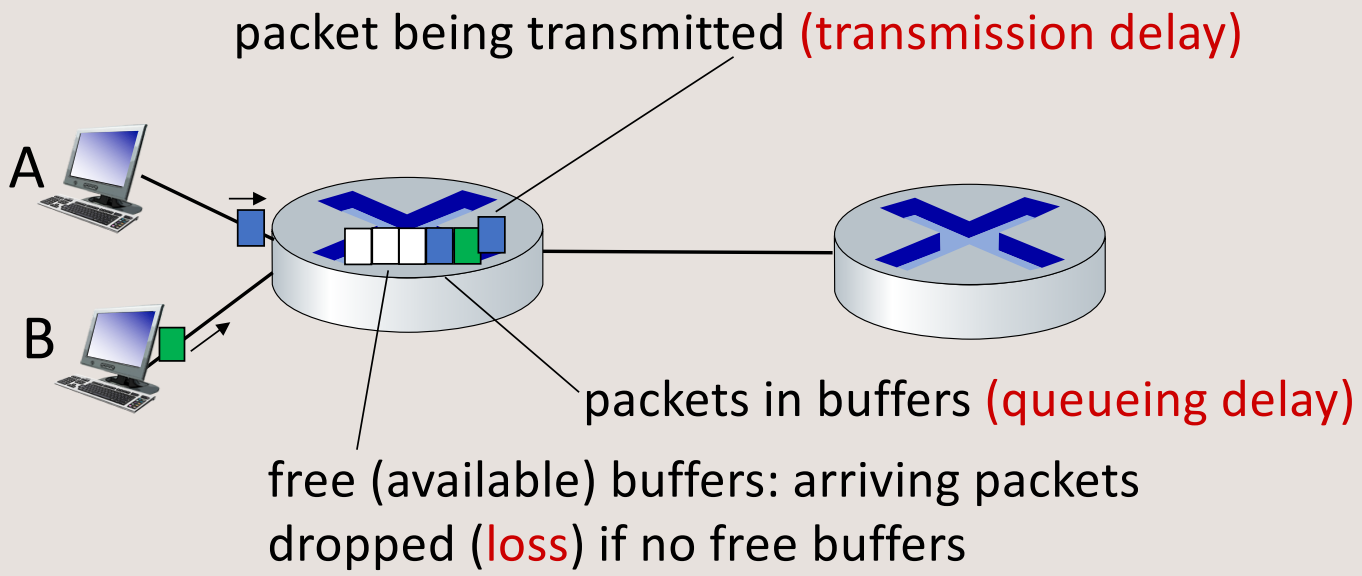
Chapter 1: roadmap

- What *is* the Internet?
- What *is* a protocol?
- Network edge: hosts, access network, physical media
- Network core: packet/circuit switching, internet structure
- **Performance: loss, delay, throughput**
- Security
- Protocol layers, service models
- History

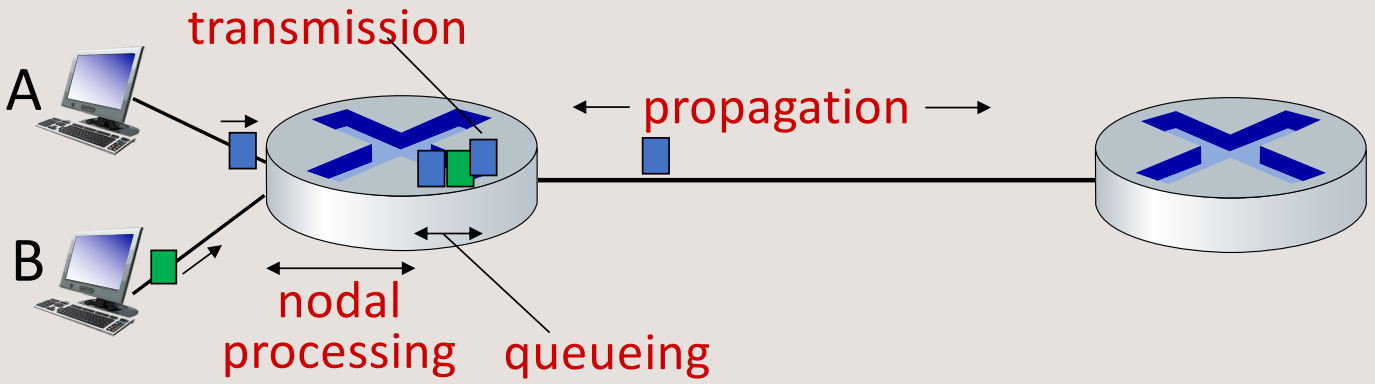


How do packet delay and loss occur?

- packets *queue* in router buffers, waiting for turn for transmission
  - queue length grows when arrival rate to link (temporarily) exceeds output link capacity
- packet *loss* occurs when memory to hold queued packets fills up



Packet delay: four sources



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

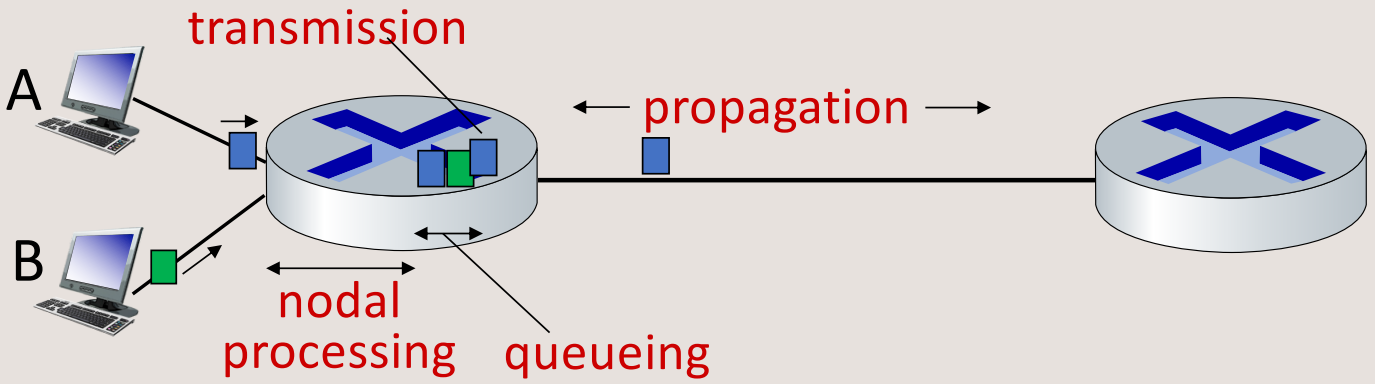
d_{proc}: nodal processing

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

d_{queue}: queueing delay

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

Packet delay: four sources



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

d_{trans}: transmission delay:

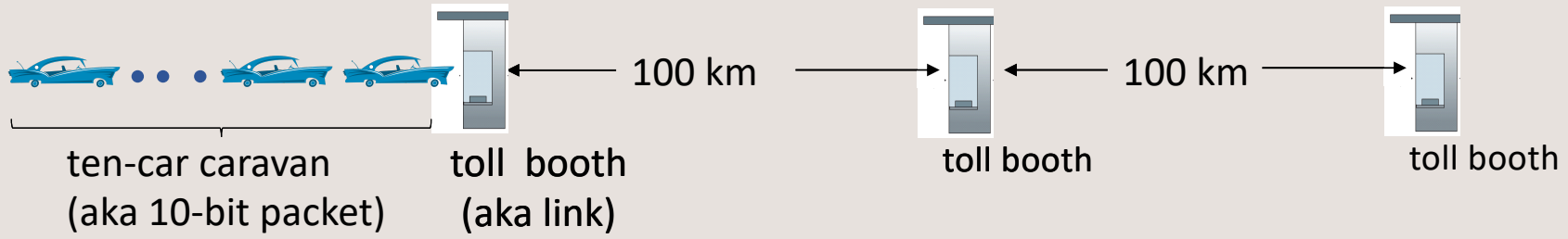
- L: packet length (bits)
- R: link *transmission rate (bps)*
- $d_{trans} = L/R$

d_{prop}: propagation delay:

- d: length of physical link
- s: propagation speed (~2×10^8 m/sec)
- $d_{prop} = d/s$

d_{trans} and d_{prop} *very* different

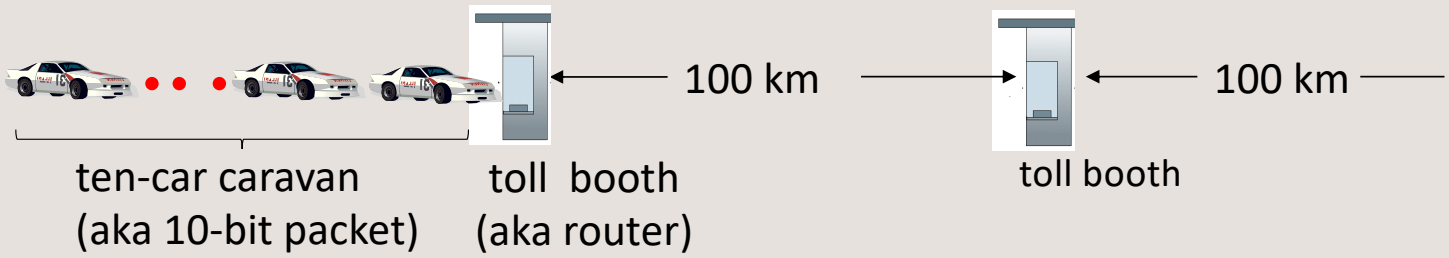
Caravan analogy



- car ~ bit; caravan ~ packet; toll service ~ link transmission
- toll booth takes 12 sec to service car (bit transmission time)
- "propagate" at 100 km/hr
- *Q:* How long until caravan is lined up before 2nd toll booth?

- time to "push" entire caravan through toll booth onto highway = 12*10 = 120 sec
- time for last car to propagate from 1st to 2nd toll both: 100km/(100km/hr) = 1 hr
- *A:* 62 minutes

Caravan analogy



- suppose cars now "propagate" at 1000 km/hr
- and suppose toll booth now takes one min to service a car
- *Q:* Will cars arrive to 2nd booth before all cars serviced at first booth?

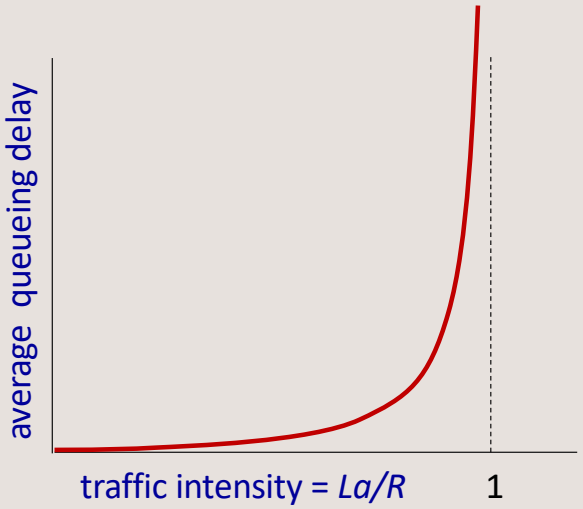
  A: Yes! after 7 min, first car arrives at second booth; three cars still at first booth

Packet queueing delay (revisited)

- *a:* average packet arrival rate
- *L:* packet length (bits)
- *R:* link bandwidth (bit transmission rate)

$$\frac{L \cdot a}{R} : \frac{\text{arrival rate of bits}}{\text{service rate of bits}}$$

"traffic intensity"

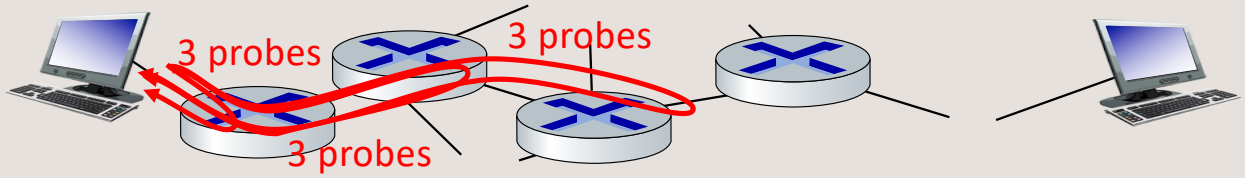


- *La/R* ~ 0: avg. queueing delay small
- *La/R* -> 1: avg. queueing delay large
- *La/R* > 1: more "work" arriving is more than can be serviced - average delay infinite!



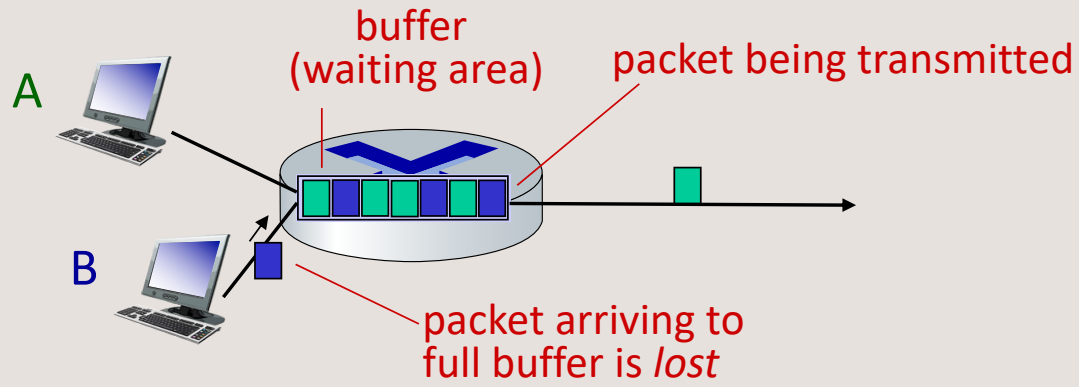
“Real” Internet delays and routes

- what do “real” Internet delay & loss look like?
- **traceroute** program: provides delay measurement from source to router along end-end Internet path towards destination. For all *i:*
  - sends three packets that will reach router *i* on path towards destination (with time-to-live field value of *i*)
  - router *i* will return packets to sender
  - sender measures time interval between transmission and reply



Packet loss

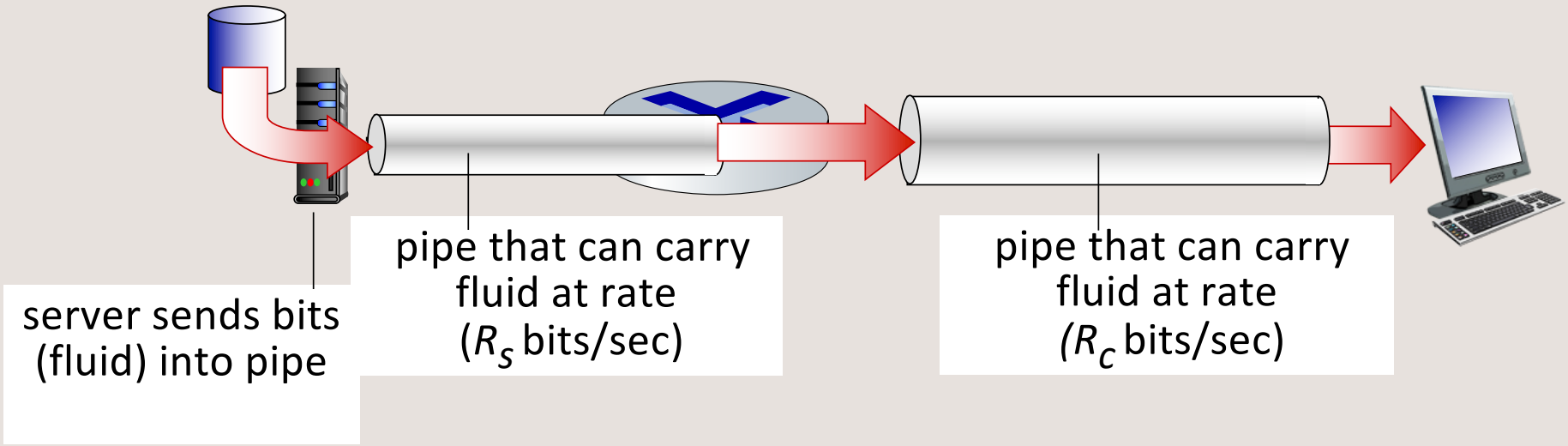
- queue (aka buffer) preceding link in buffer has finite capacity
- packet arriving to full queue dropped (aka lost)
- lost packet may be retransmitted by previous node, by source end system, or not at all



* Check out the Java applet for an interactive animation (on publisher's website) of queuing and loss

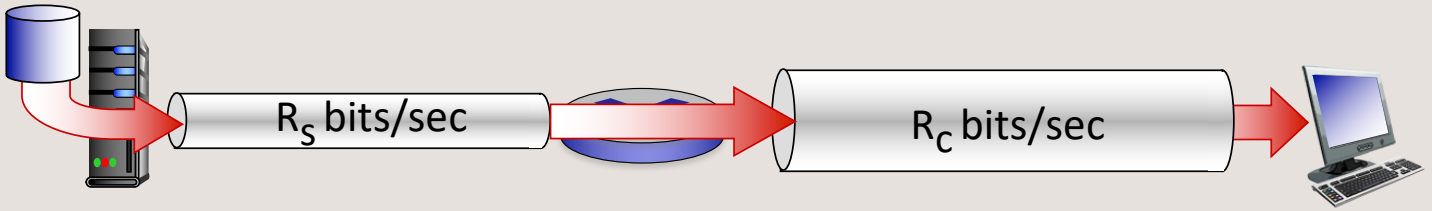
Throughput

- *throughput:* rate (bits/time unit) at which bits are being sent from sender to receiver
  - *instantaneous:* rate at given point in time
  - *average:* rate over longer period of time

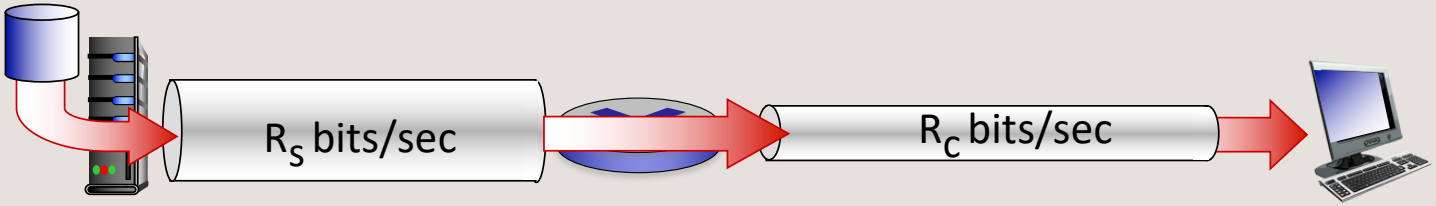


Throughput

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



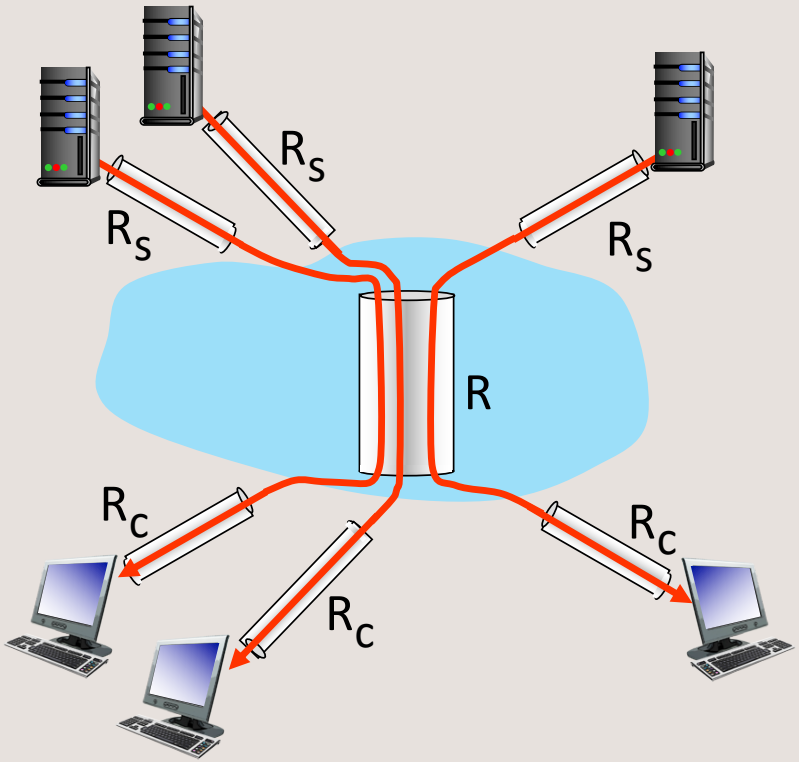
$R_s > R_c$ What is average end-end throughput?



bottleneck link

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

Throughput: network scenario



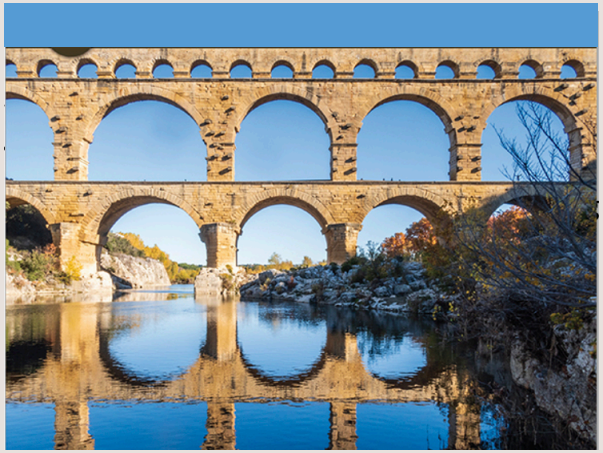
10 connections (fairly) share backbone bottleneck link *R* bits/sec

- per-connection end-end throughput: $min(R_c, R_s, R/10)$
- in practice: R_c or R_s is often bottleneck

* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/

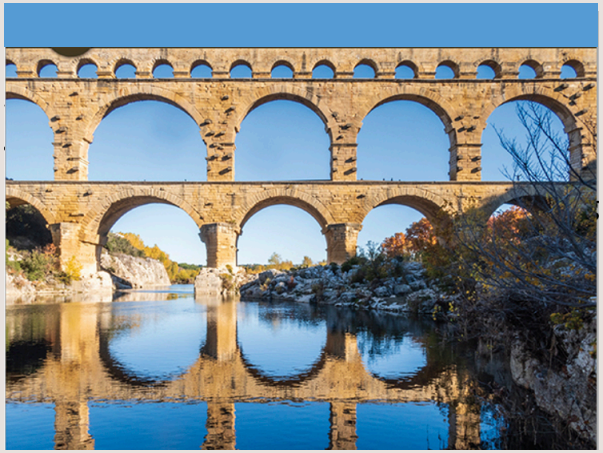
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- What *is* a protocol?
- Network edge: hosts, access network, physical media
- Network core: packet/circuit switching, internet structure
- Performance: loss, delay, throughput
- Security (later in class)
- Protocol layers, service models
- History

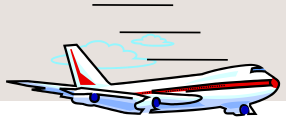


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Example: organization of air travel



end-to-end transfer of person plus baggage

ticket (purchase)

baggage (check)

gates (load)

runway takeoff

airplane routing

ticket (complain)

baggage (claim)

gates (unload)

runway landing

airplane routing

airplane routing

How would you *define/discuss* the *system* of airline travel?

- a series of steps, involving many services

Example: organization of air travel



layers: each layer implements a service

- via its own internal-layer actions
- relying on services provided by layer below

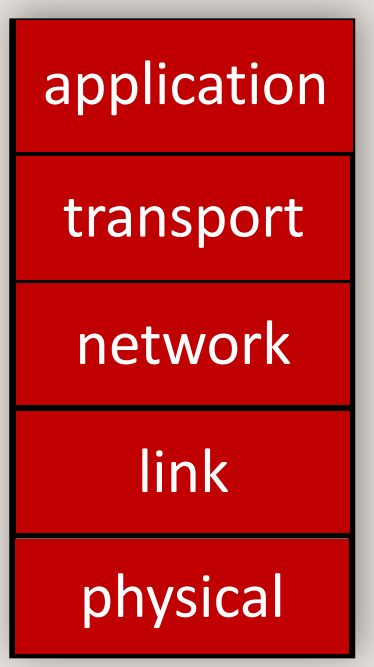
Why layering?

Approach to designing/discussing complex systems:

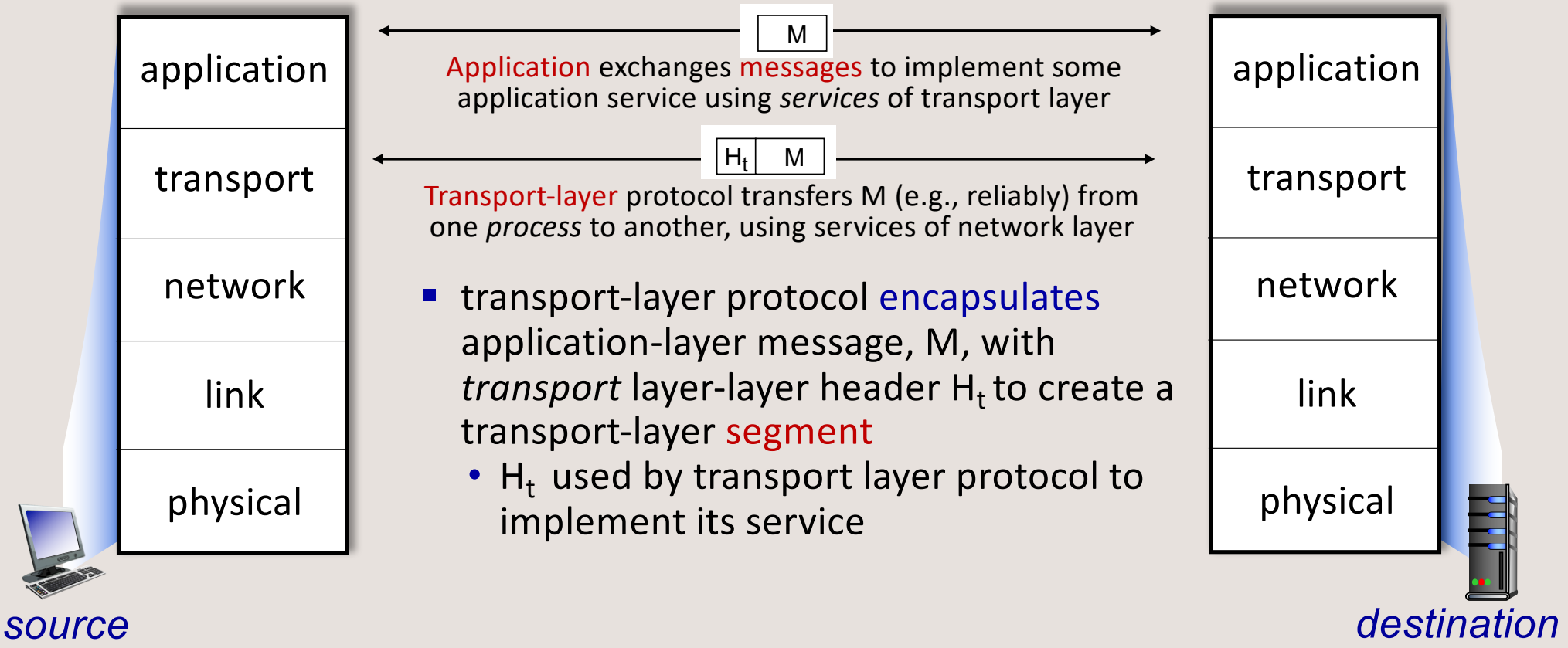
- explicit structure allows identification, relationship of system's pieces
  - layered *reference model* for discussion
- modularization eases maintenance, updating of system
  - change in layer's service *implementation*: transparent to rest of system
  - e.g., change in gate procedure doesn't affect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

Layered Internet protocol stack

- *application:* supporting network applications
  - HTTP, IMAP, SMTP, DNS
- *transport:* process-process data transfer
  - TCP, UDP
- *network:* routing of datagrams from source to destination
  - IP, routing protocols
- *link:* data transfer between neighboring network elements
  - Ethernet, 802.11 (WiFi), PPP
- *physical:* bits “on the wire”

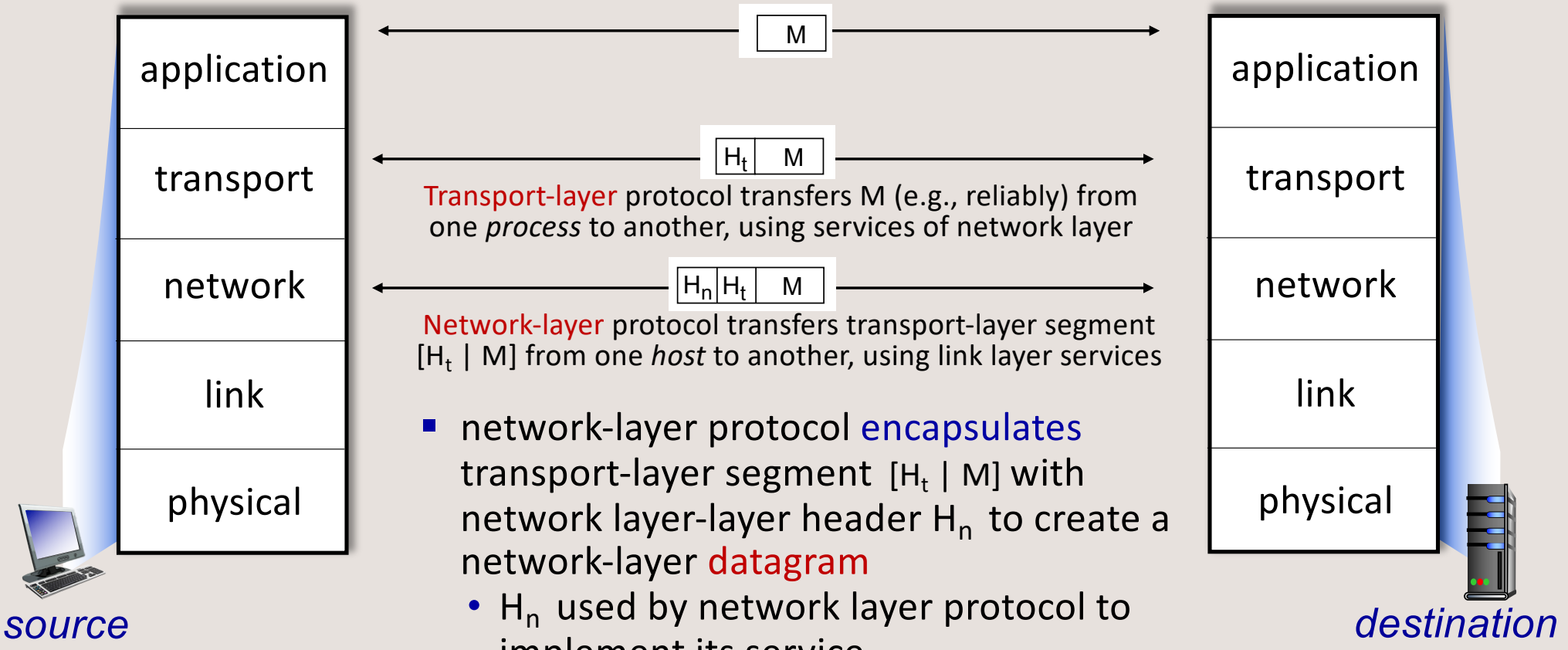


Services, Layering and Encapsulation



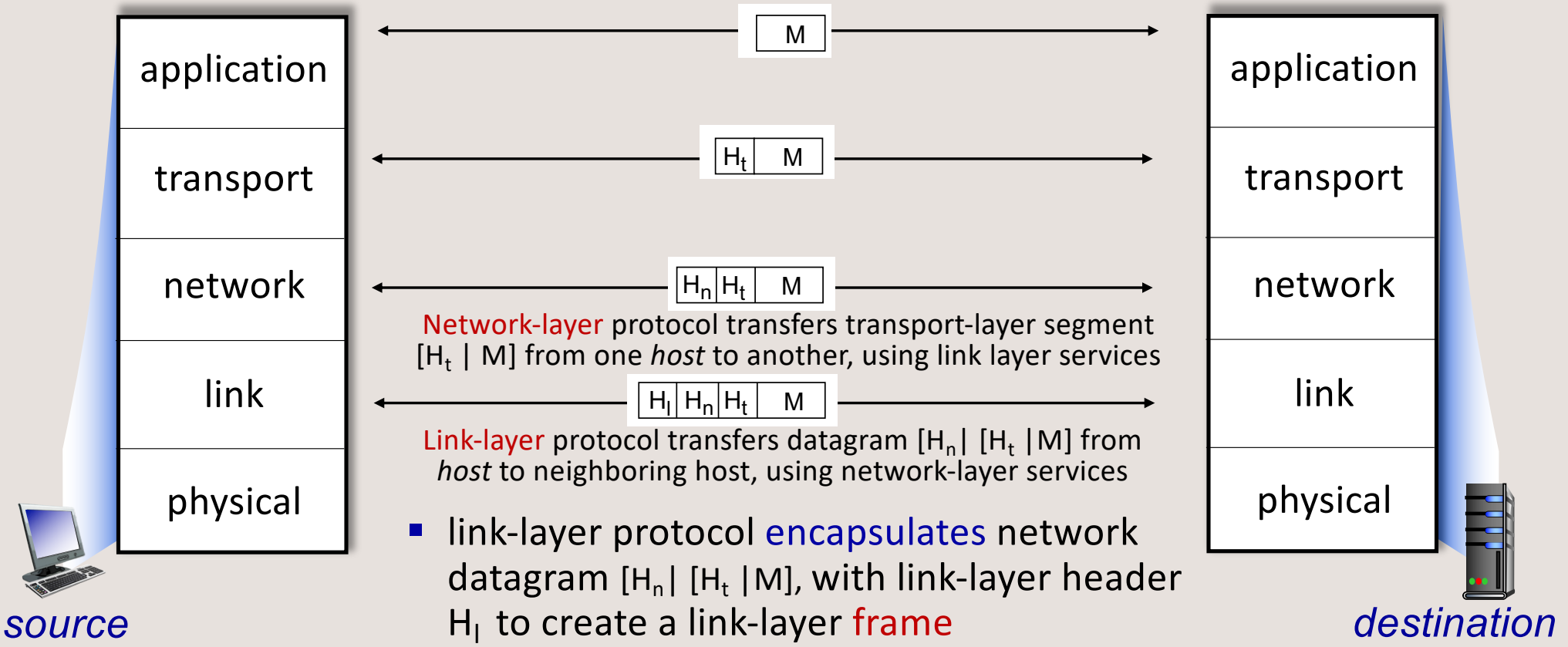
- transport-layer protocol encapsulates application-layer message, M, with *transport* layer-layer header H_t to create a transport-layer segment
  - H_t used by transport layer protocol to implement its service

Services, Layering and Encapsulation



- network-layer protocol encapsulates transport-layer segment [H_t | M] with network layer-layer header H_n to create a network-layer datagram
  - H_n used by network layer protocol to implement its service

Services, Layering and Encapsulation

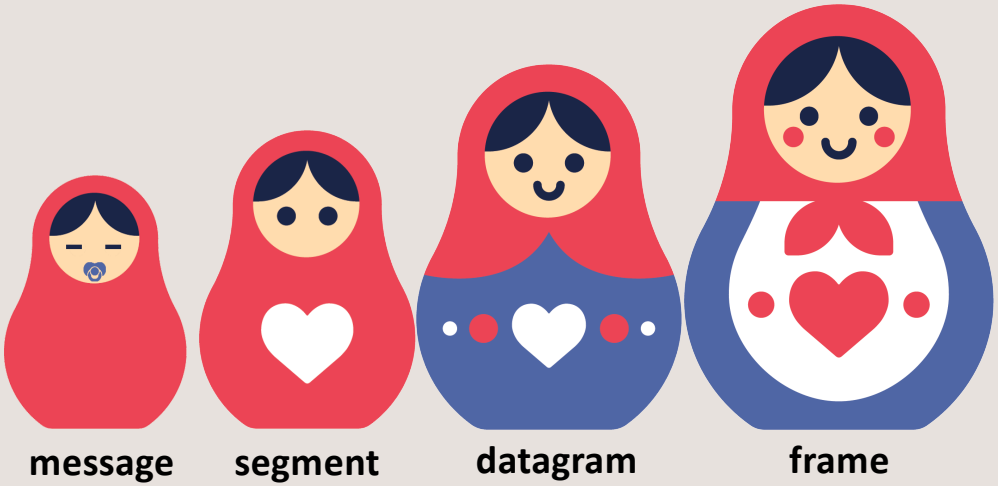


- link-layer protocol encapsulates network datagram [H_n| [H_t |M], with link-layer header H_l to create a link-layer frame

Encapsulation

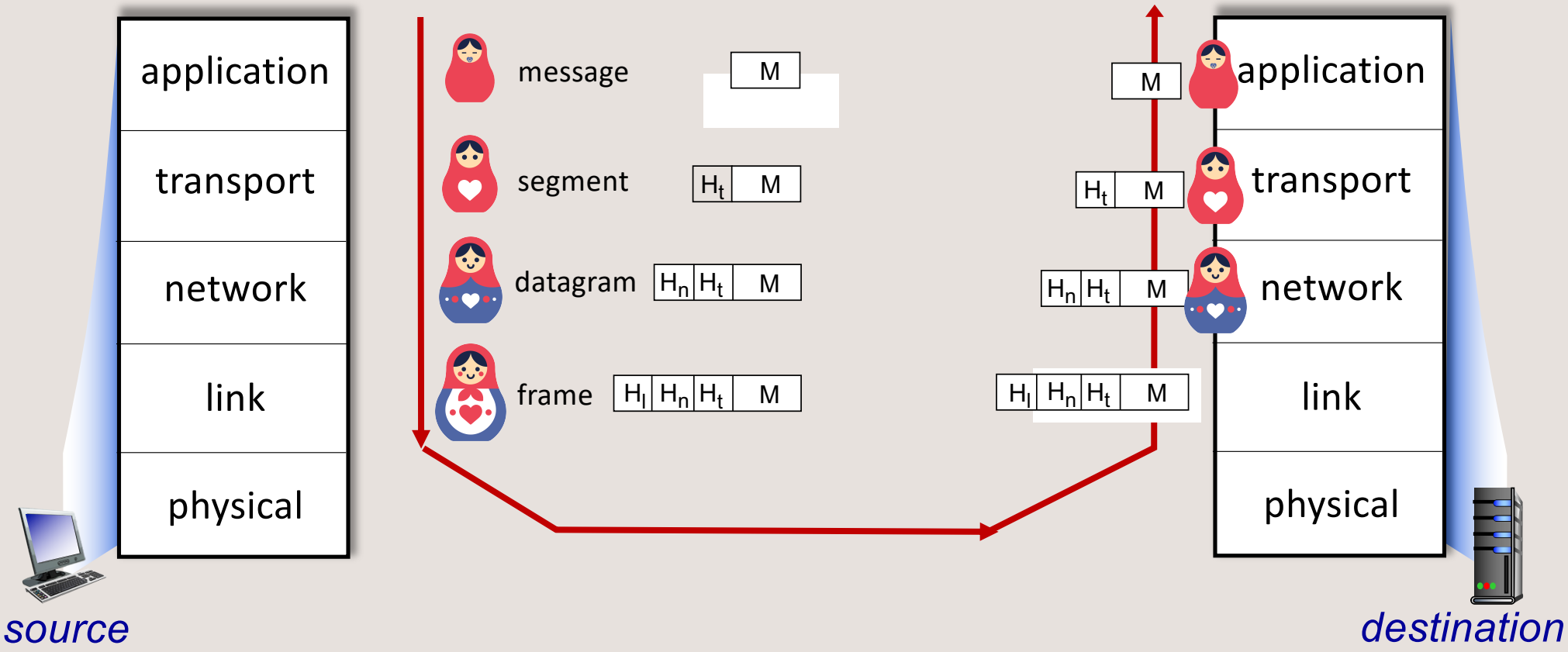
Matryoshka dolls (stacking dolls)



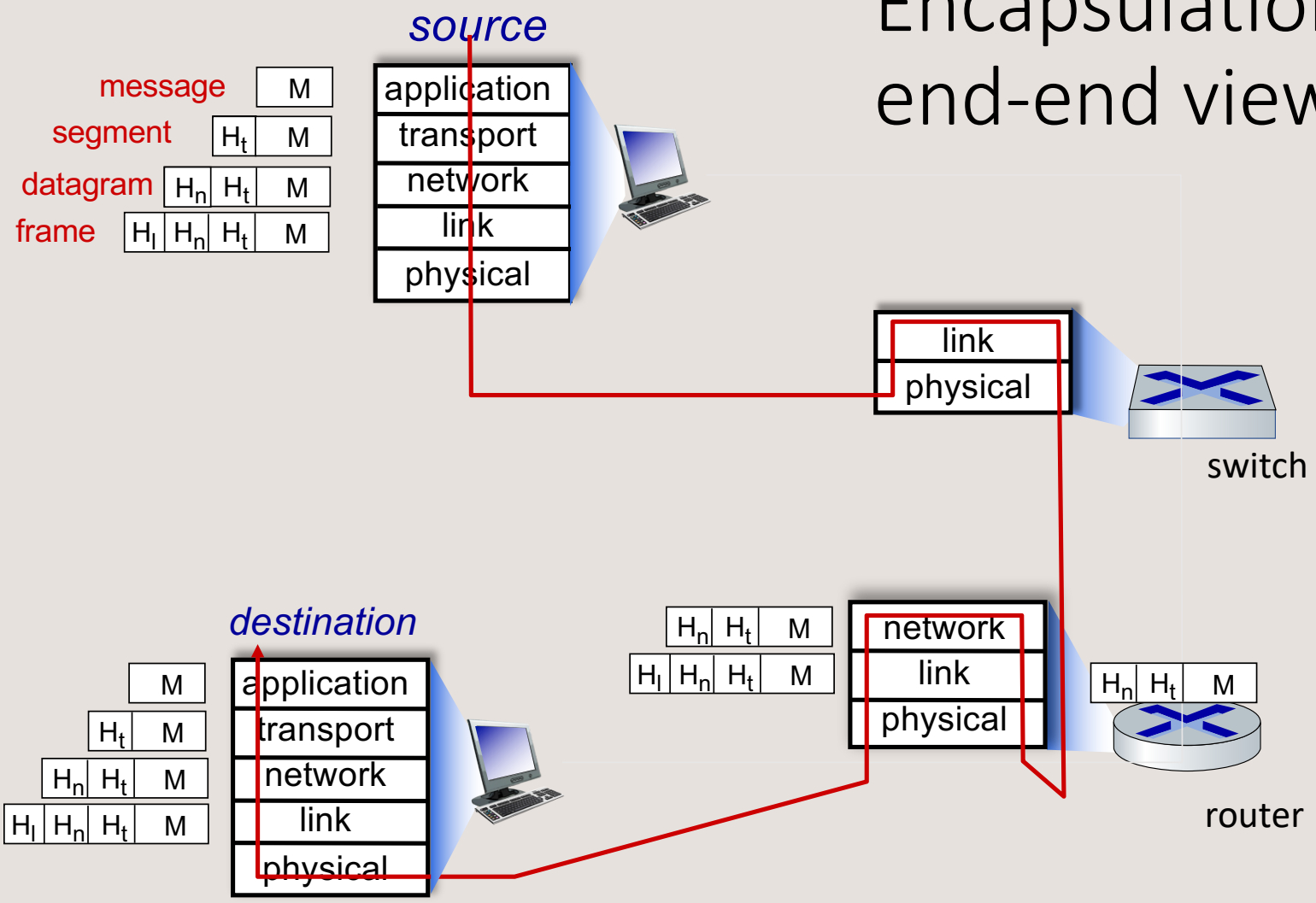


Credit: https://dribbble.com/shots/7182188-Babushka-Boi

Services, Layering and Encapsulation

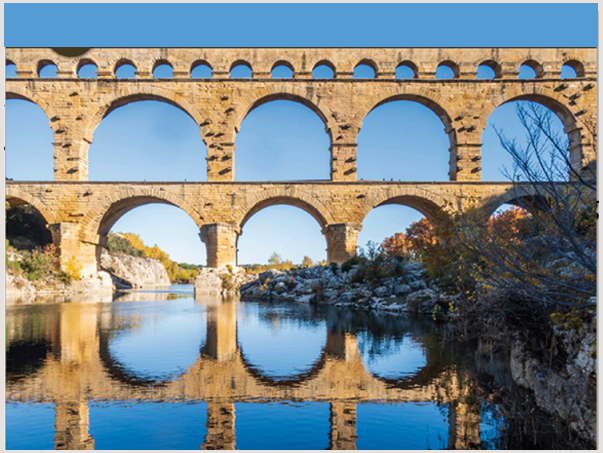


Encapsulation: an end-end view



Chapter 1: roadmap

- What *is* the Internet?
- What *is* a protocol?
- Network edge: hosts, access network, physical media
- Network core: packet/circuit switching, internet structure
- Performance: loss, delay, throughput
- Security
- Protocol layers, service models
- History

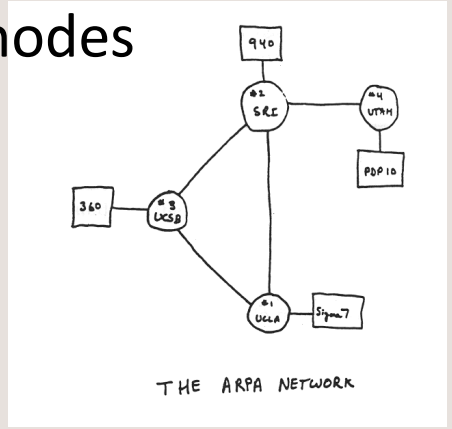


Internet history

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 demo
  - NCP (Network Control Protocol) first host-host protocol
  - first e-mail program
  - ARPAnet has 15 nodes



Internet history

1972-1980: Internetworking, new and proprietary networks

- 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
- 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 routing
- decentralized control

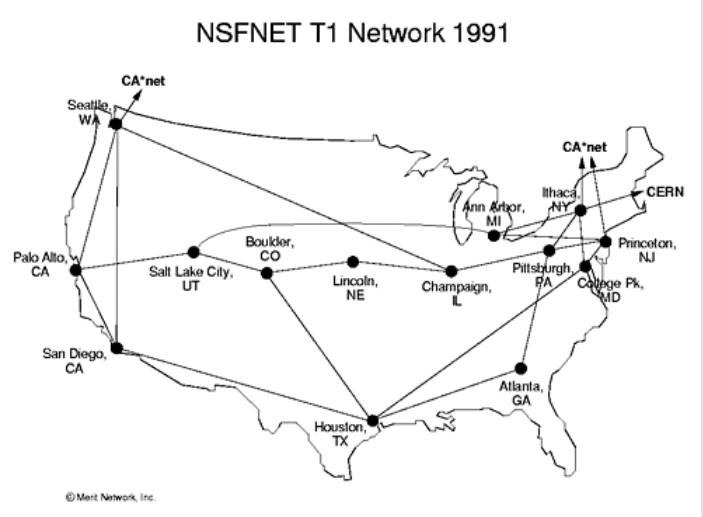
define today's Internet architecture

Internet history

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



Internet history

1990, 2000s: commercialization, the Web, new applications

- early 1990s: 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 1990s: commercialization of the Web

late 1990s – 2000s:

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

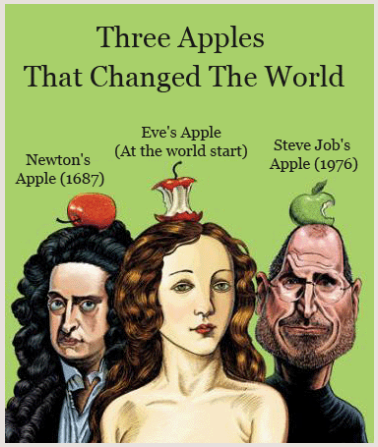
Internet history

2005-present: scale, SDN, mobility, cloud

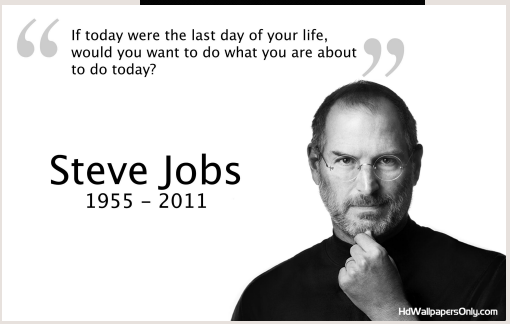
- aggressive deployment of broadband home access (10-100's Mbps)
- 2008: software-defined networking (SDN)
- increasing ubiquity of high-speed wireless access: 4G/5G, WiFi
- service providers (Google, FB, Microsoft) create their own networks
  - bypass commercial Internet to connect "close" to end user, providing "instantaneous" access to social media, search, video content, …
- enterprises run their services in "cloud" (e.g., Amazon Web Services, Microsoft Azure)
- rise of smartphones: more mobile than fixed devices on Internet (2017)
- ~15B devices attached to Internet (2023, statista.com)
- Rise of Social Networks - Facebook, Instagram, Twitter (X) and more recent

Milestones for PCs

- 1976: Apple
- 1997-2011







- "3 Apples changed the world: the one that Eve ate, the one that fell on Newton's head and the one that Steve built. "
- Microsoft, 1975

Microsoft

Milestones for PCs

- 1994

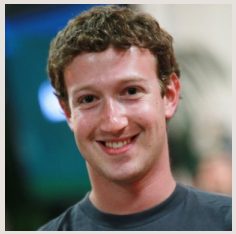


- 1998

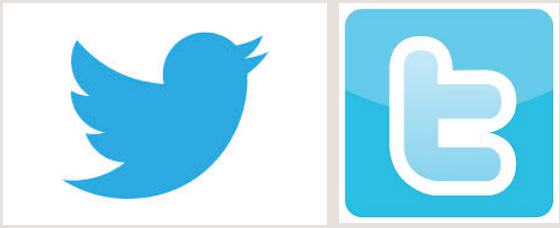


- 2003





- 2006





Industries

- NetFlix
- LinkedIn
- Qualcomm
- TikTok

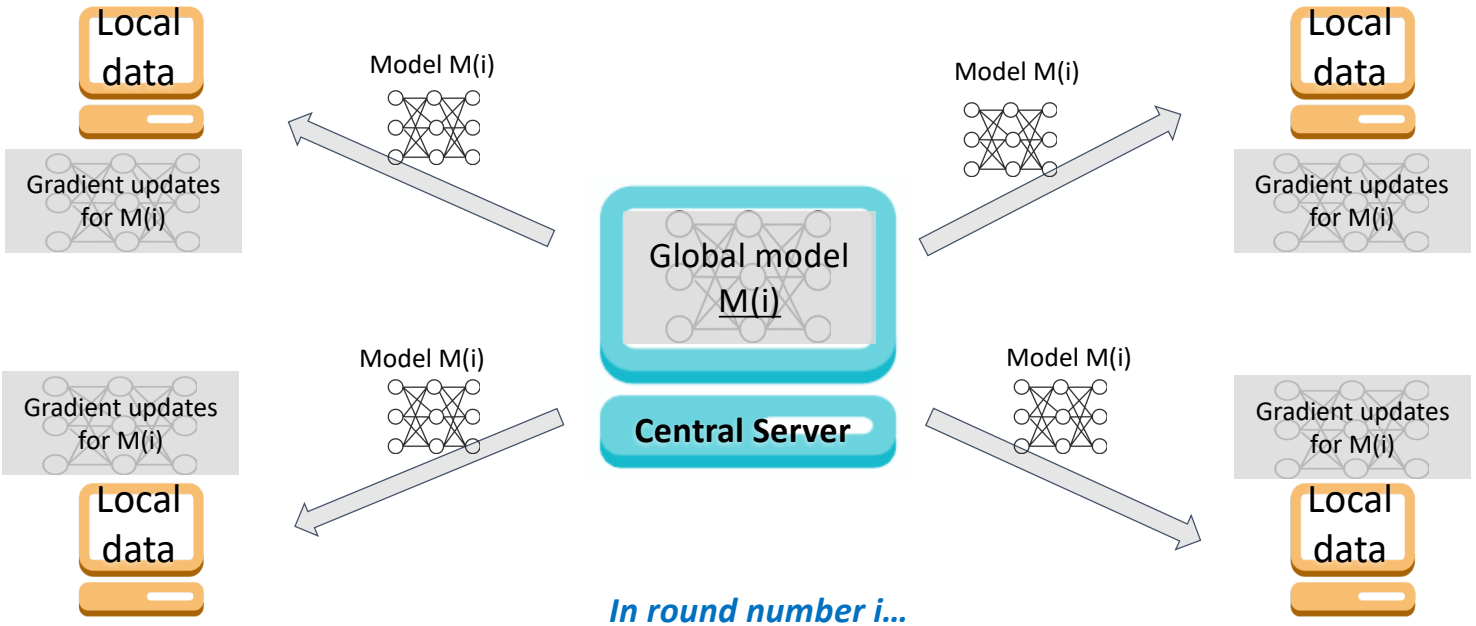


- Samsung, Huawei, Nokia, Ericsson → 5G/6G
  - And “Beyond 5G”
- See: https://www.youtube.com/watch?v=T6ubRoZCeVw



Federated Learning (2017)

Federated learning – overview



Deployed by Google, Apple, etc.



Sky is the limit for the next decades…

- 6G/7G Wireless
  - Towards 7G Mobile Wireless
- Quantum Internet
- Internet of Agents

