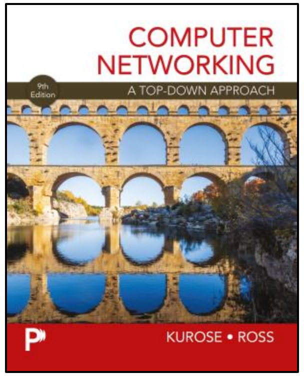


CSC 361
Computer Networks
Overview

Wenjun Yang

Summer 2026

Chapter 1: Introduction

Chapter goal:

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

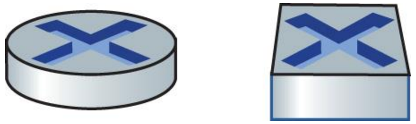
Overview/roadmap:

- 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

The Internet: a "Nuts and Bolts" View (1 of 2)

Billions of connected computing **devices**:

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

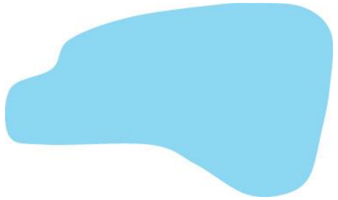


Packet switches: forward packets (chunks of data)

- **routers**, **switches**

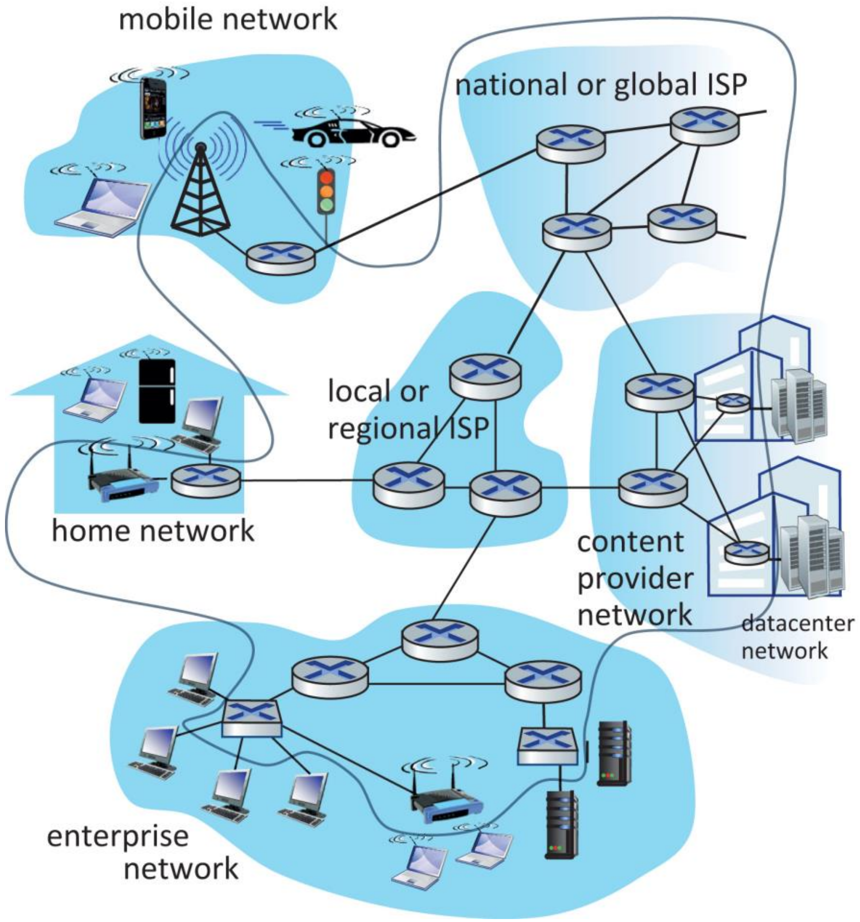
Communication links

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

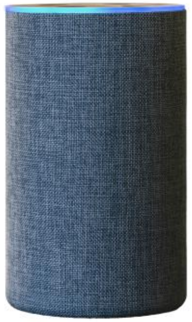


Networks

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



“Fun” Internet-Connected Devices (1 of 2)



Amazon Echo

Security Camera

Internet phones

Internet refrigerator

Gaming devices

IP picture frame

Slingbox: remote control cable TV

Pacemaker & Monitor

Web-enabled toaster + Weather forecaster

"Fun" Internet-Connected Devices (2 of 2)

sensorized, bed mattress

Fitbit

AR devices

diapers

Tweet-a-watt: monitor energy use

bikes

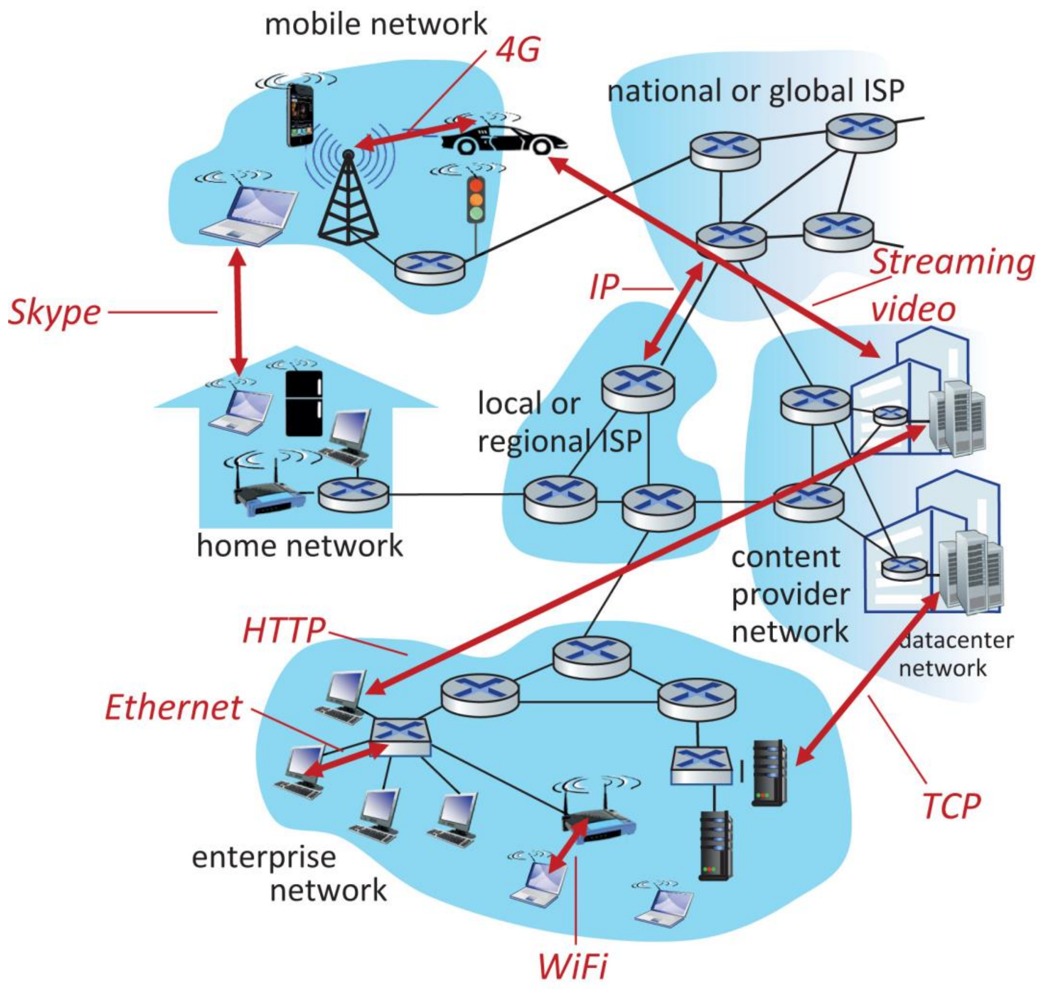
cars

scooters

Others?

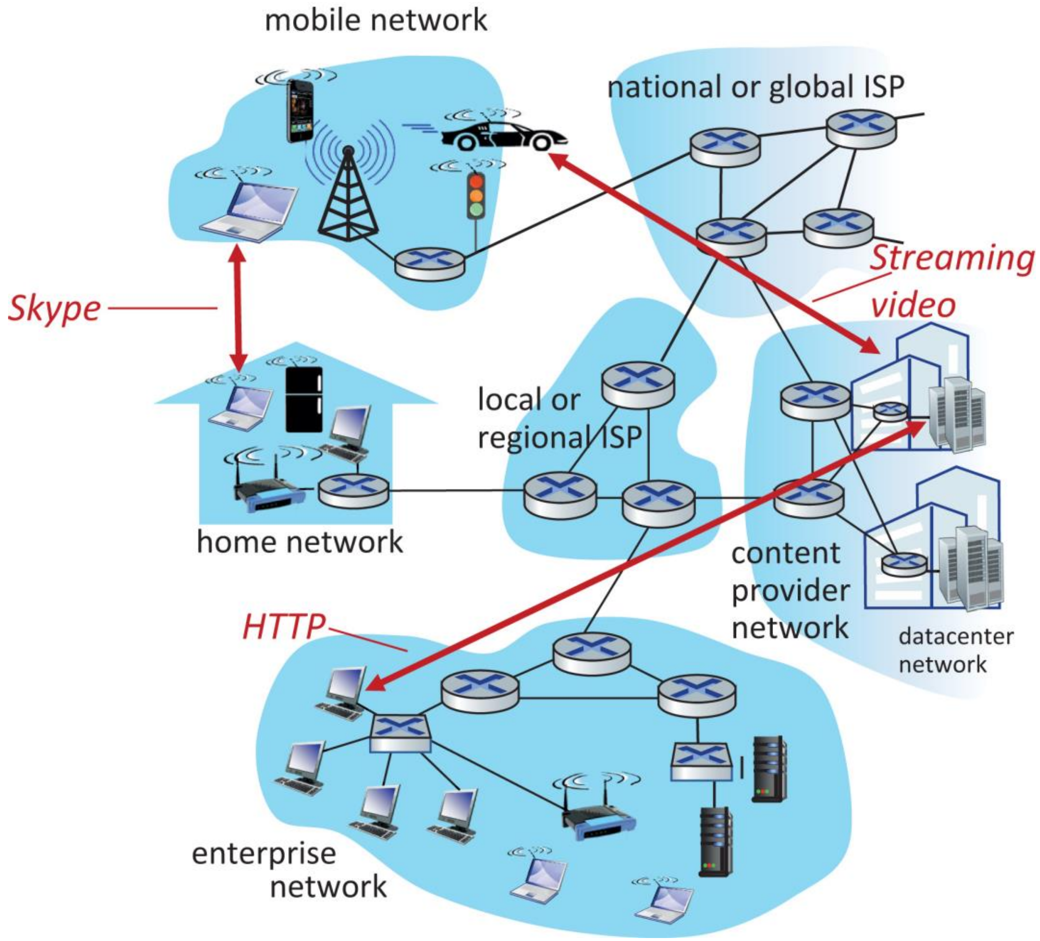
The Internet: a "Nuts and Bolts" View (2 of 2)

- 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



What’s a Protocol? (1 of 2)

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

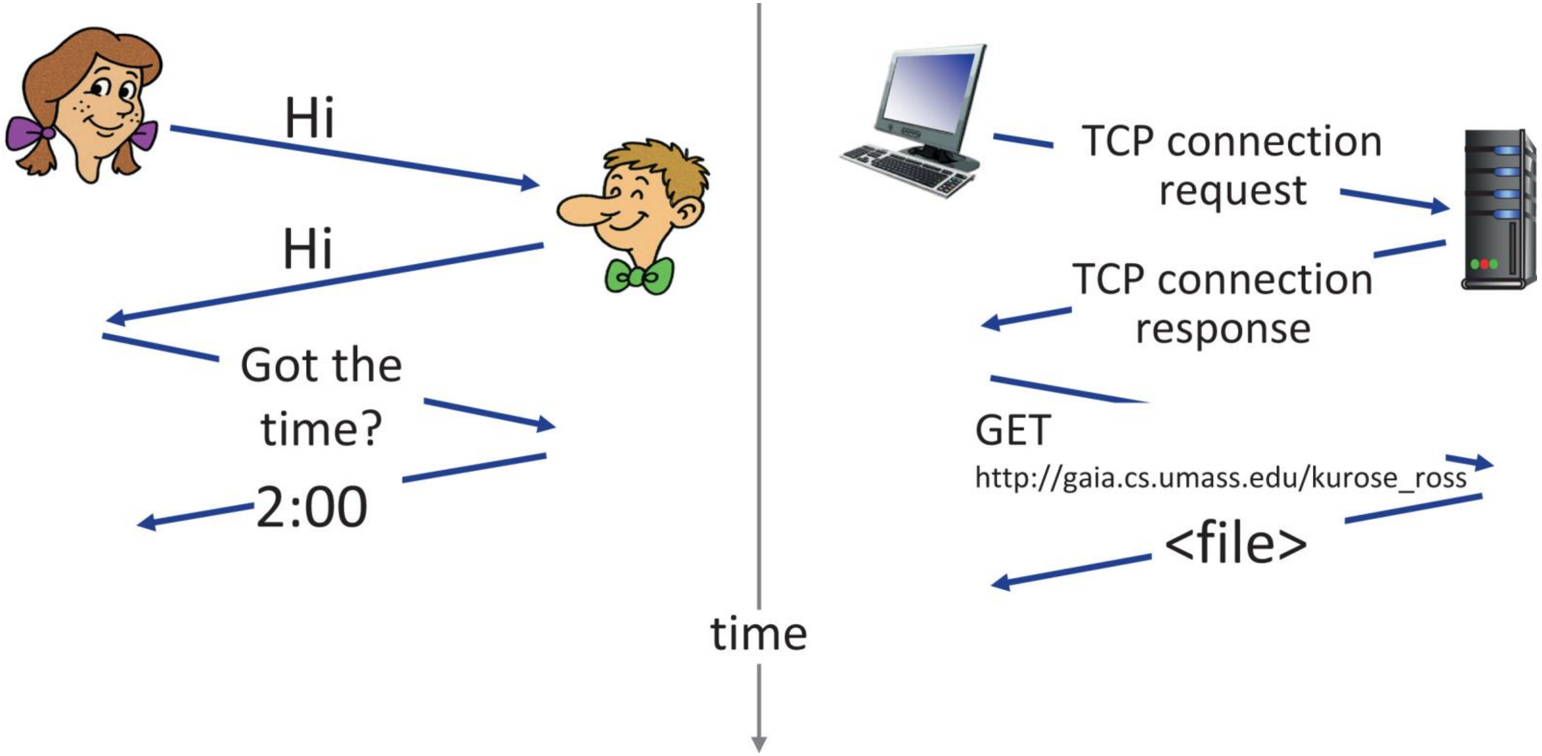
Network protocols:

- 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? (2 of 2)

A human protocol and a computer network protocol:



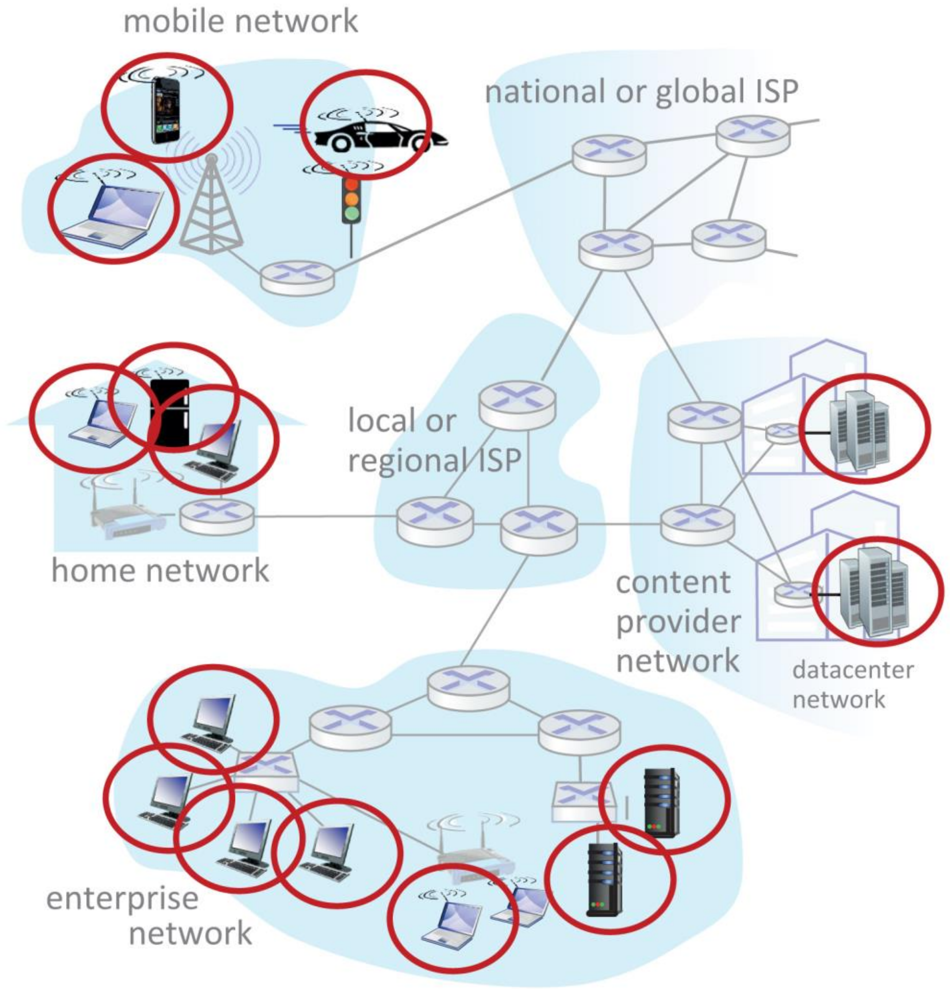
Chapter 1: Roadmap (1 of 6)

- 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

A Closer look at Internet Structure (1 of 3)

Network edge:

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



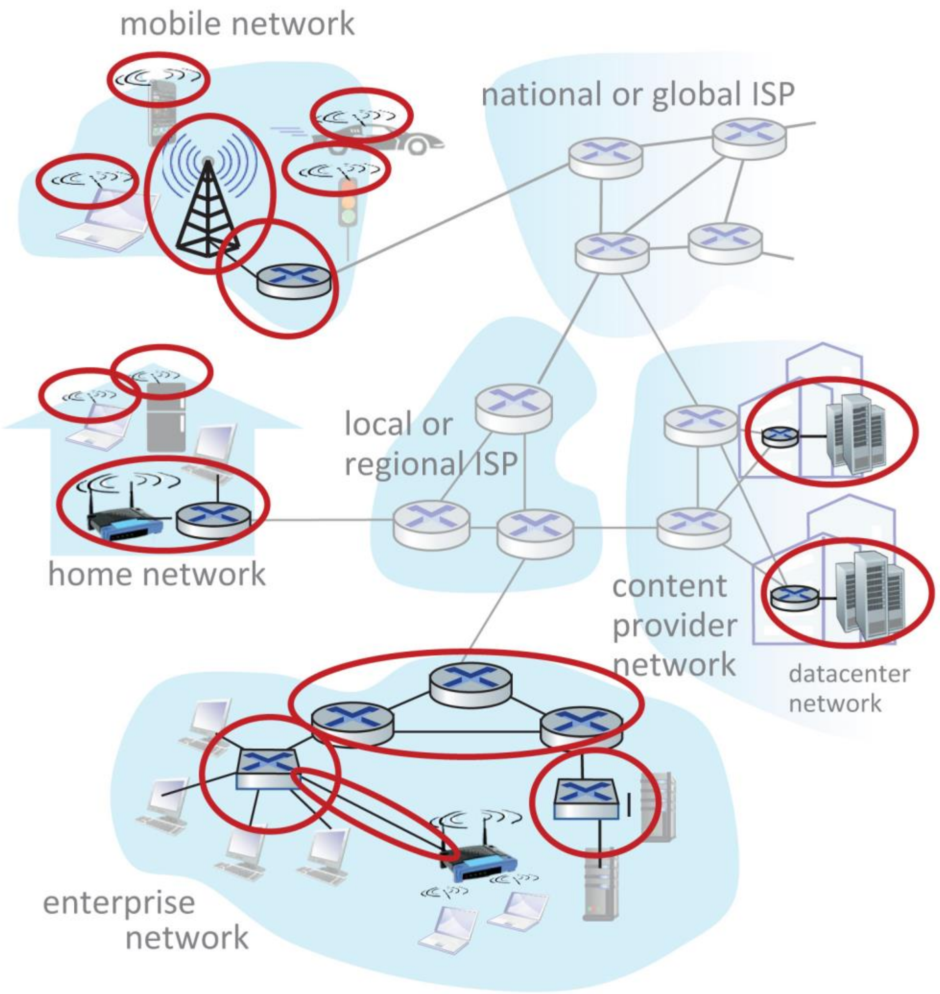
A Closer look at Internet Structure (2 of 3)

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 (3 of 3)

Network edge:

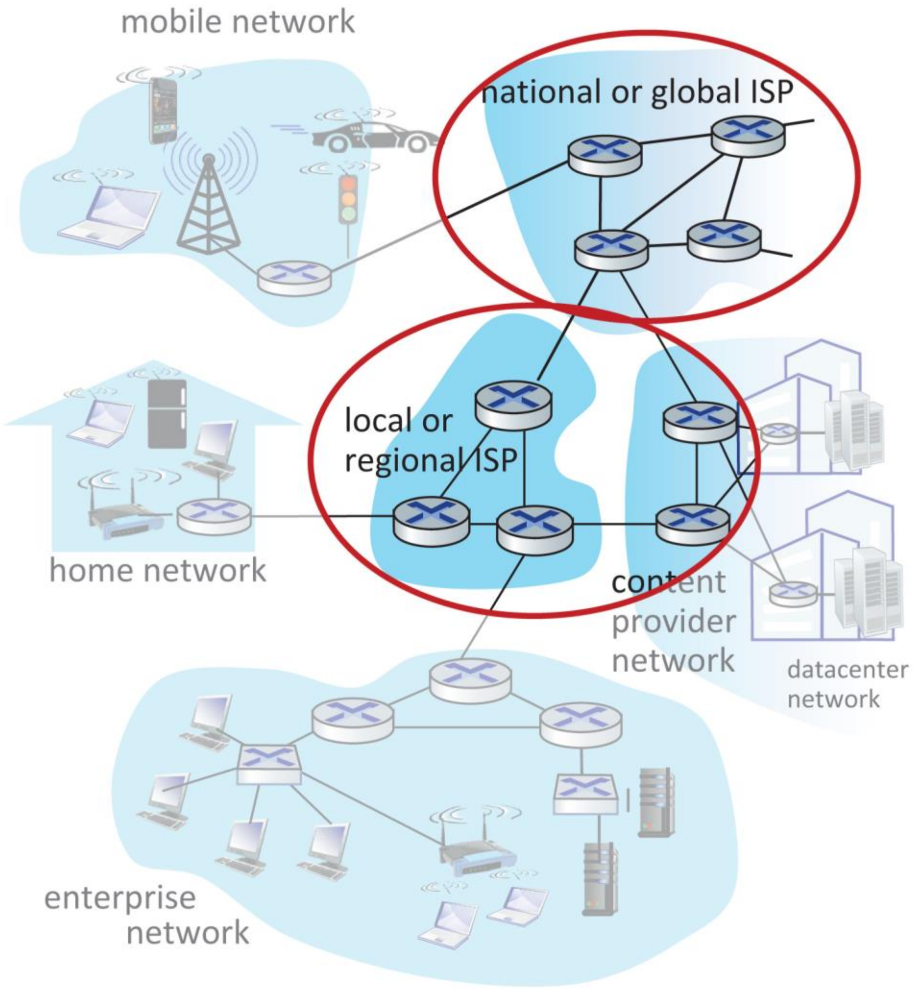
- hosts: clients and servers
- servers often in data centers

Access networks, physical media:

- wired, wireless communication links

Network core:

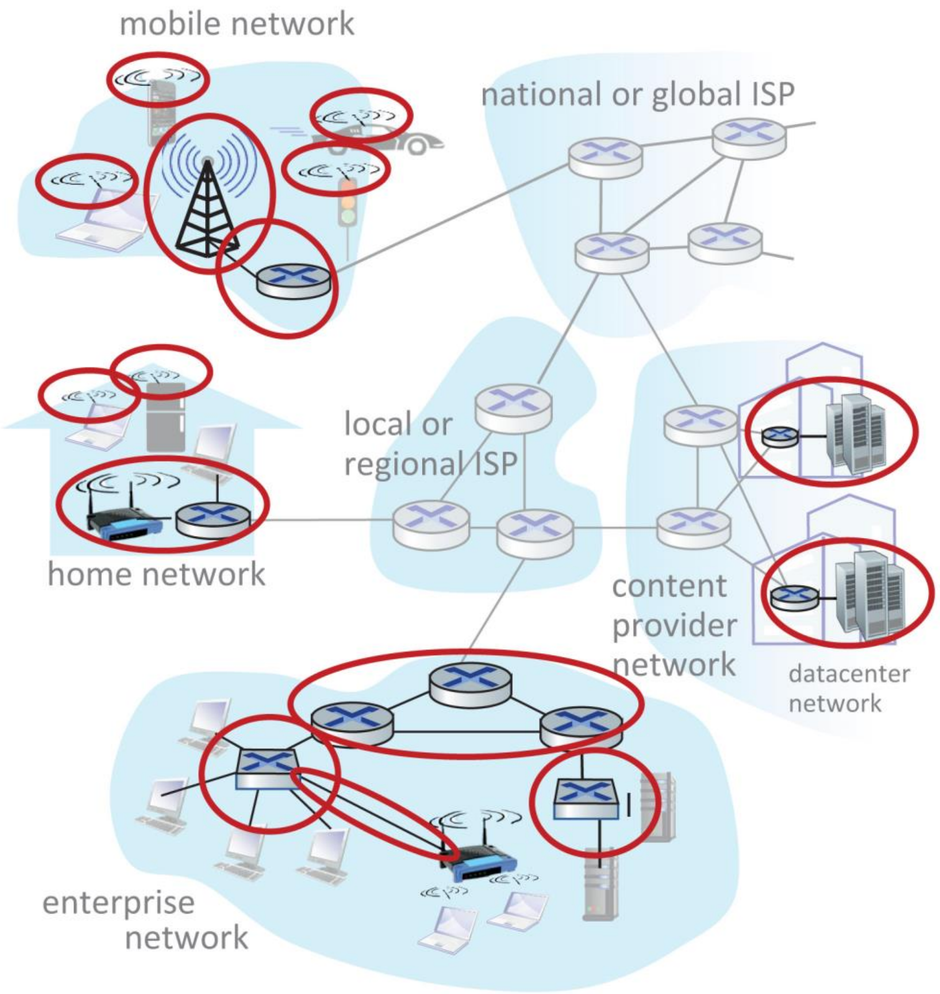
- interconnected routers
- network of networks



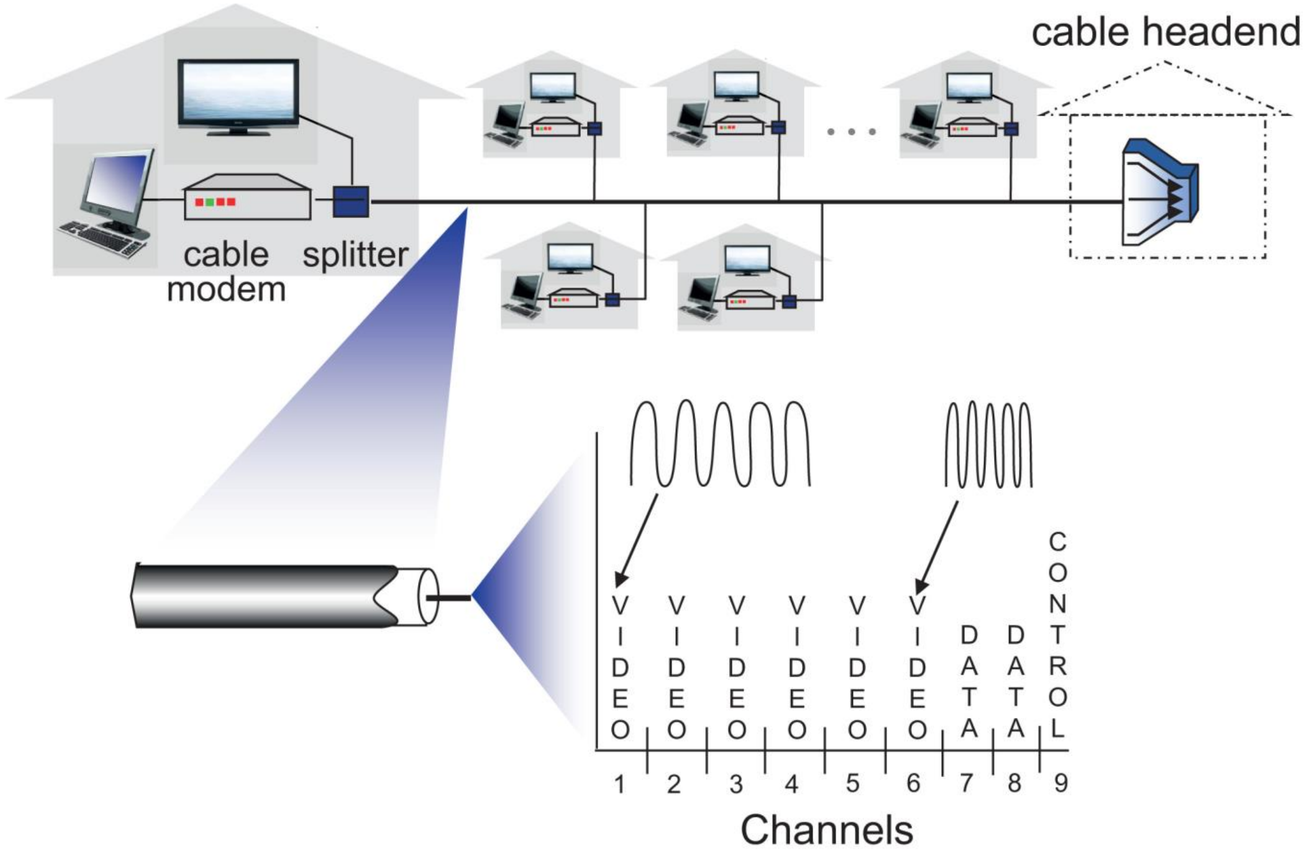
Access Networks and Physical Media

Q: How to connect end systems to edge router?

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

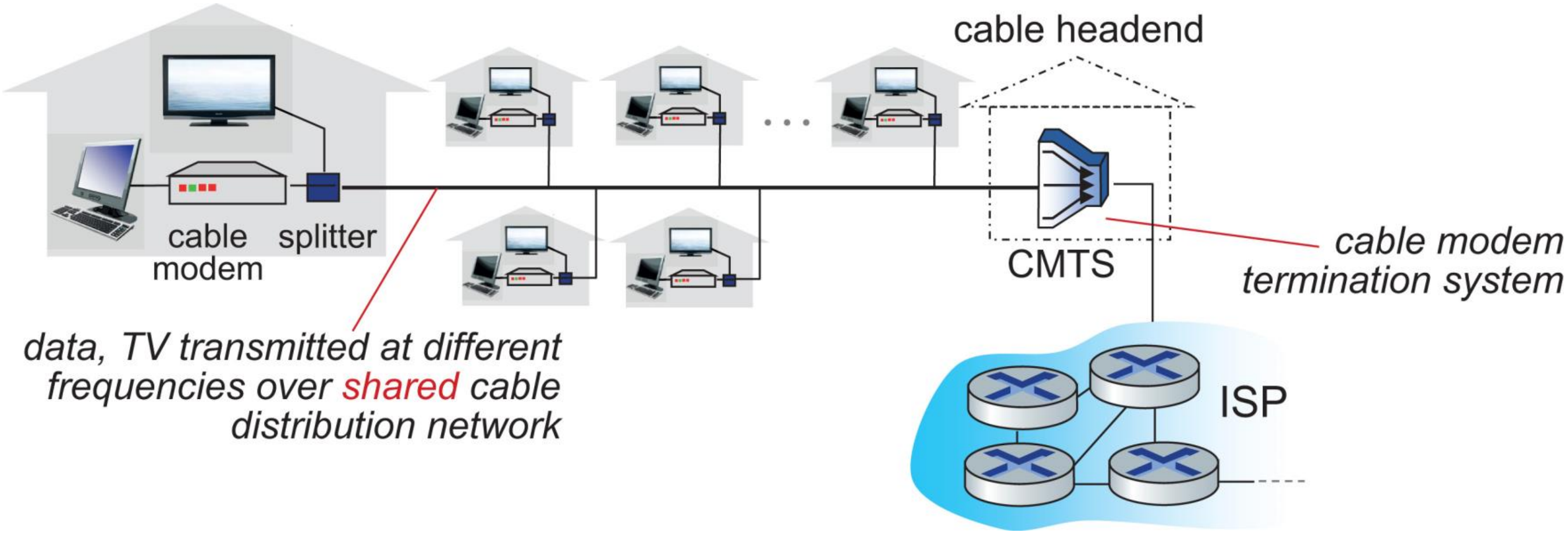


Access Networks: Cable-Based Access (1 of 2)



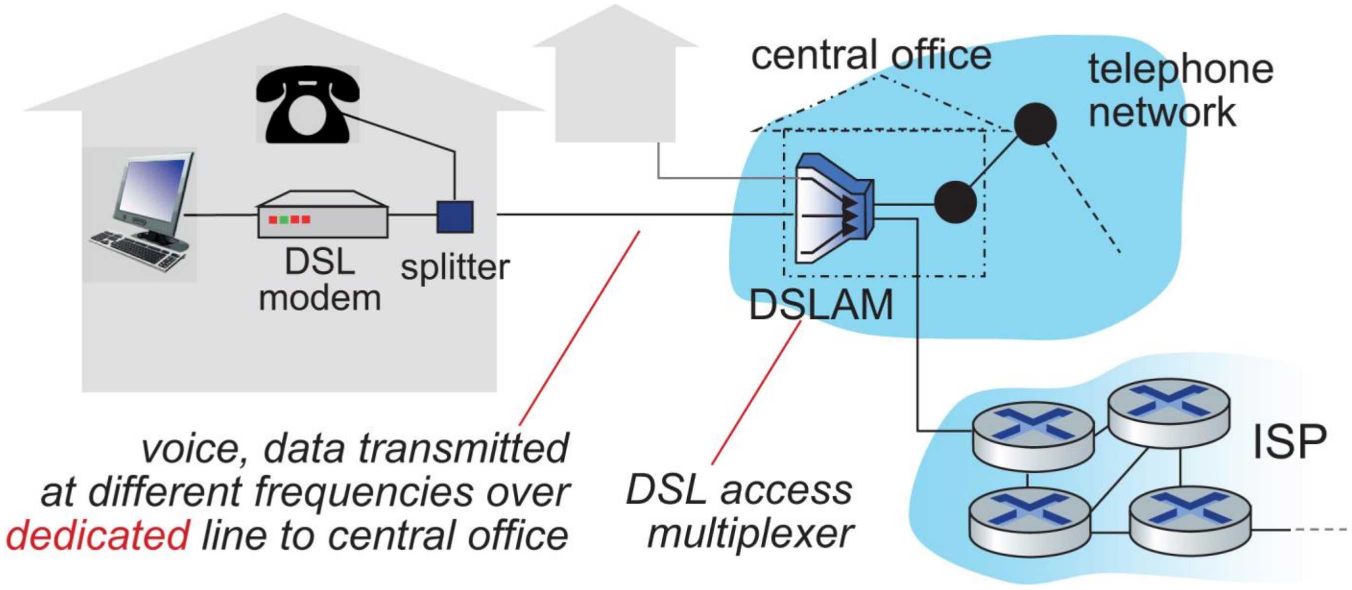
frequency division multiplexing (FDM): different channels transmitted in different frequency bands

Access Networks: Cable-Based Access (2 of 2)



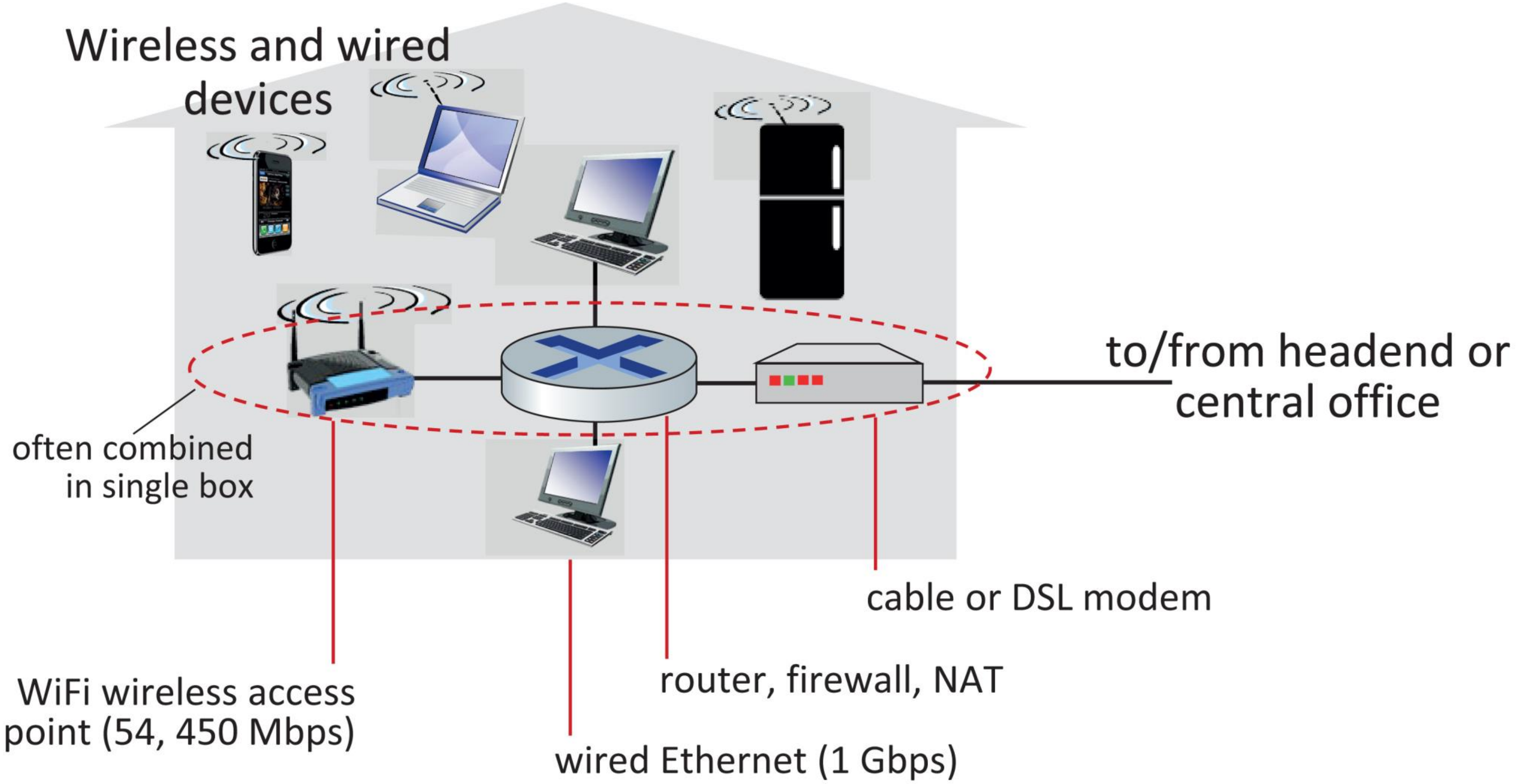
- HFC: hybrid fiber coax
  - asymmetric: up to 40 Mbps – 1.2 Gbps downstream transmission rate, 30-100 Mbps upstream transmission rate
- network of cable, fiber attaches homes to ISP router
  - homes **share access network** to cable headend

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
- 24-52 Mbps dedicated downstream transmission rate
- 3.5-16 Mbps dedicated upstream transmission rate

Access Networks: Home Networks



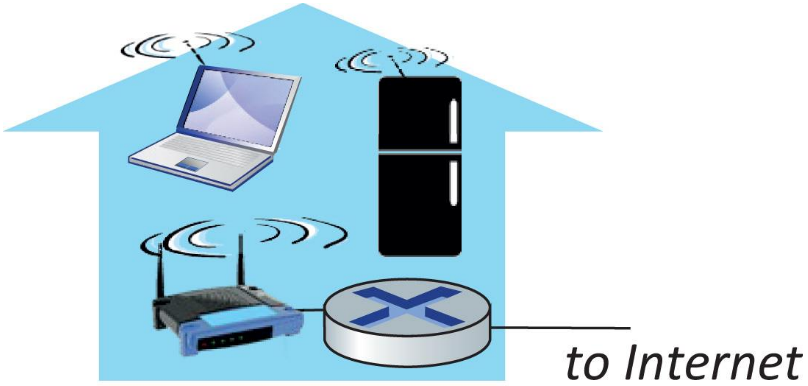
Wireless Access Networks

Shared **wireless** access network connects end system to router

- via base station aka "access point"

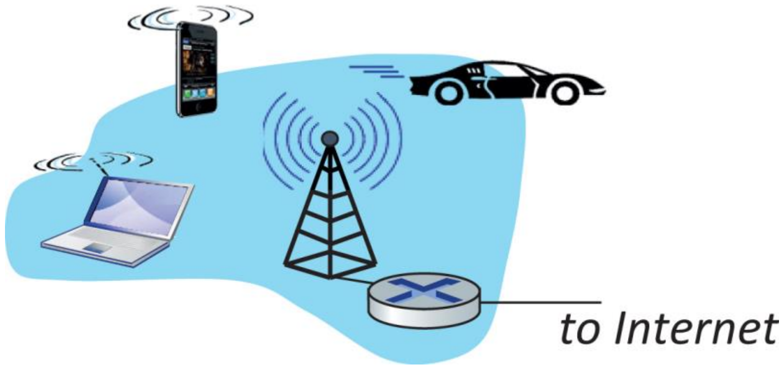
Wireless local area networks (WLANs)

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

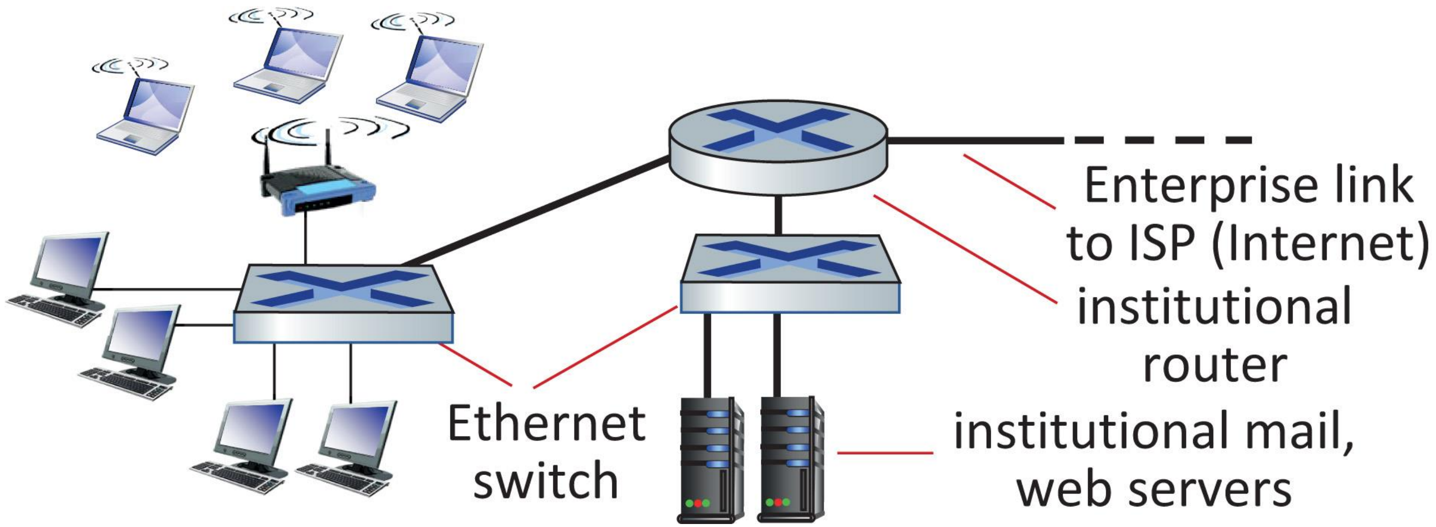


Wide-area cellular access networks

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



Access Networks: Enterprise Networks

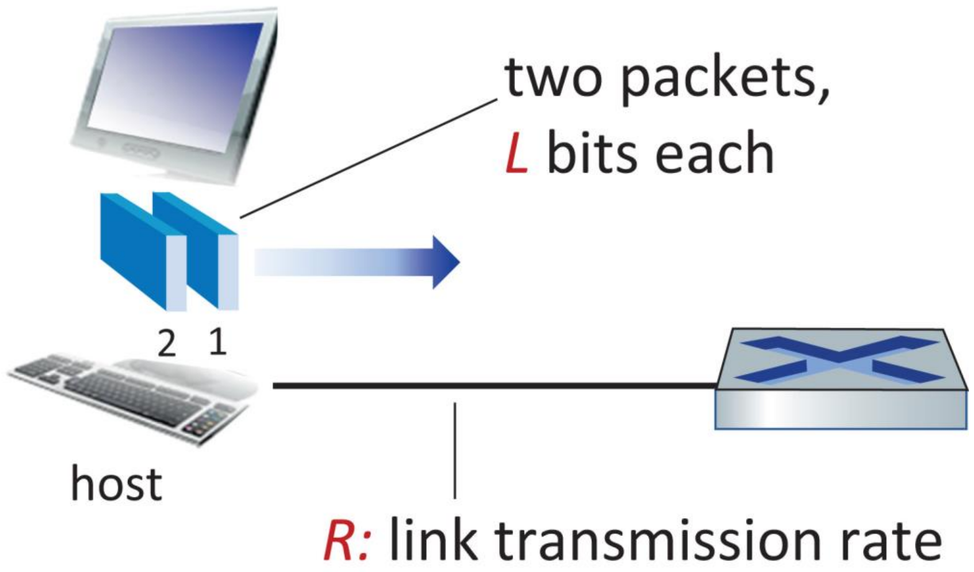


- companies, universities, etc.
- mix of wired, wireless link technologies, connecting a mix of switches and routers (we'll cover differences shortly)
  - Ethernet: wired access at 100Mbps, 1Gbps, 10Gbps
  - WiFi: wireless access points at 11, 54, 450 Mbps

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**



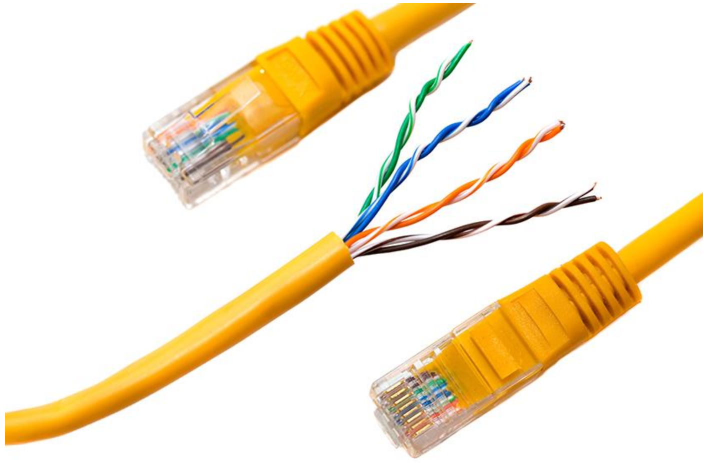
$$\text{packet transmission delay} = \text{time needed to transmit } L\text{-bit packet into link} = \frac{L(\text{bits})}{R(\text{bits/sec})}$$

Links: Physical Media (1 of 3)

- bit: propagates between transmitter/receiver pairs
- physical link: what lies between transmitter & receiver
- guided media:
  - signals propagate in solid media: copper, fiber, coax
- unguided media:
  - signals propagate freely, e.g., radio

Twisted pair (TP)

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



Links: Physical Media (2 of 3)

Coaxial cable:

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

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 (3 of 3)

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)

Chapter 1: Roadmap (2 of 6)

- What **is** the Internet?
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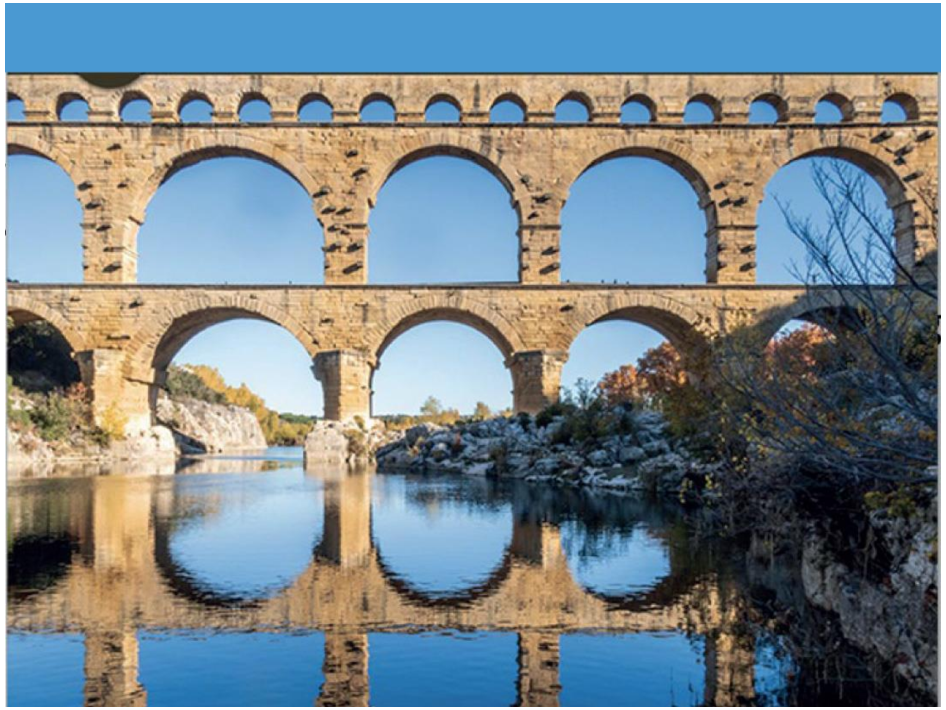
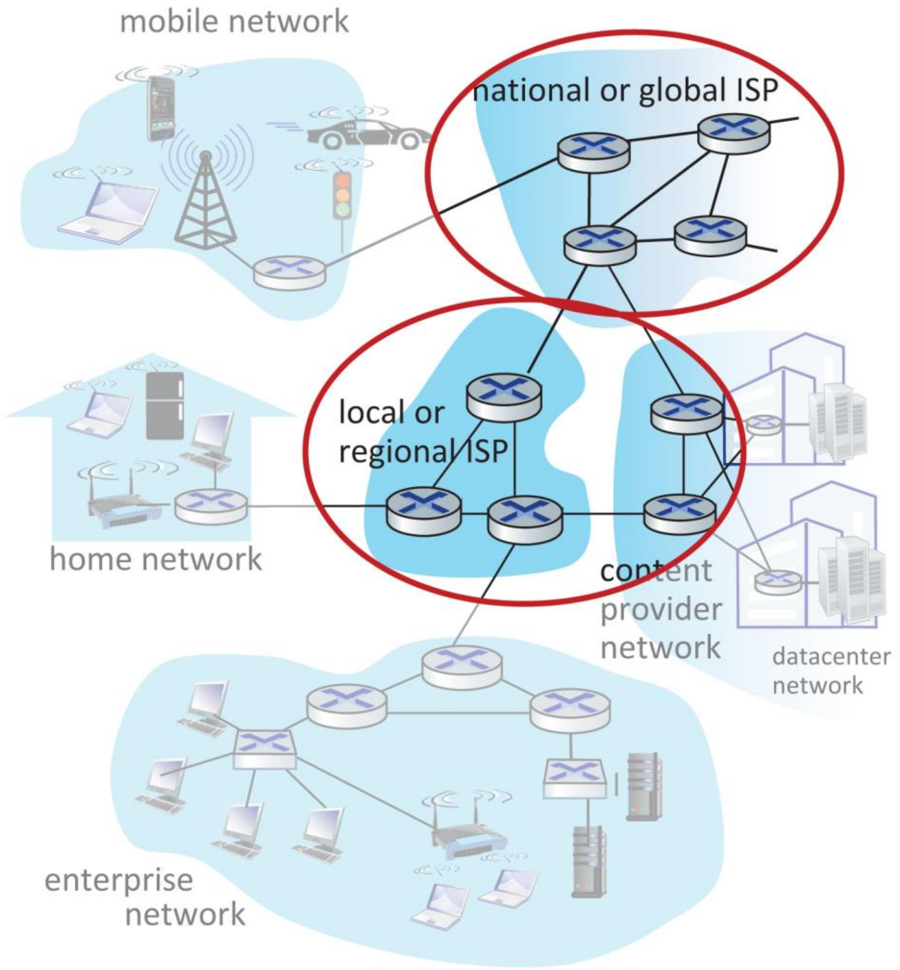
- Protocol layers, service models



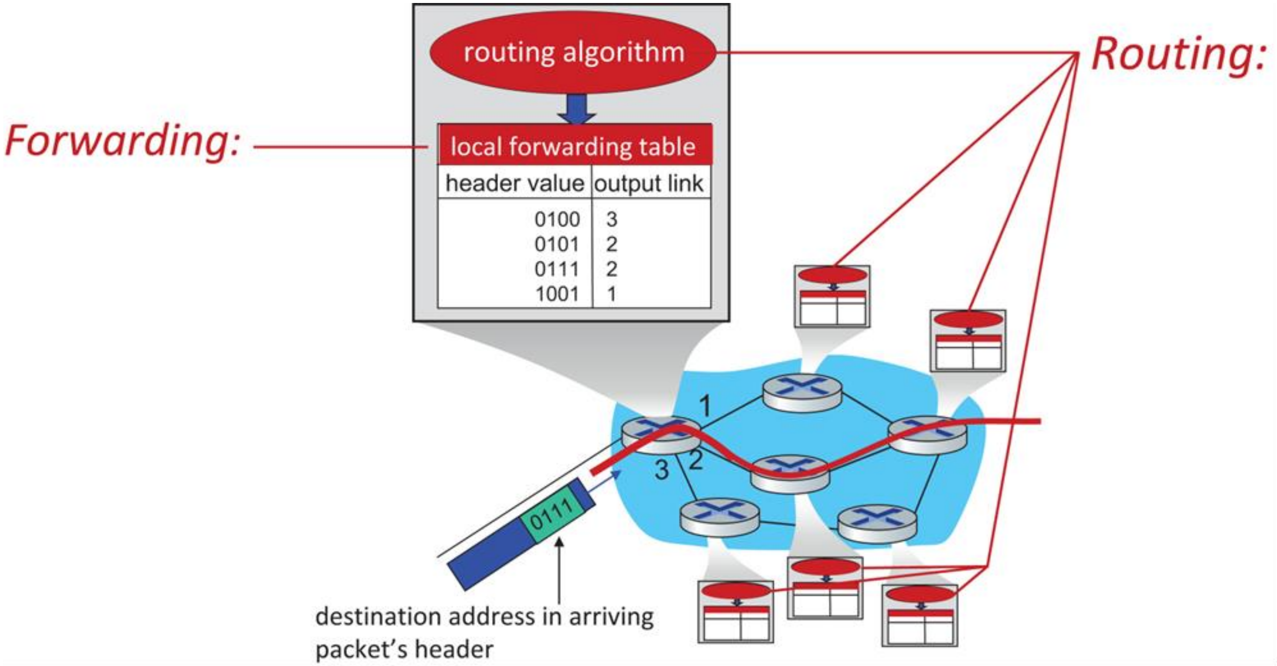
The Network Core

- 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

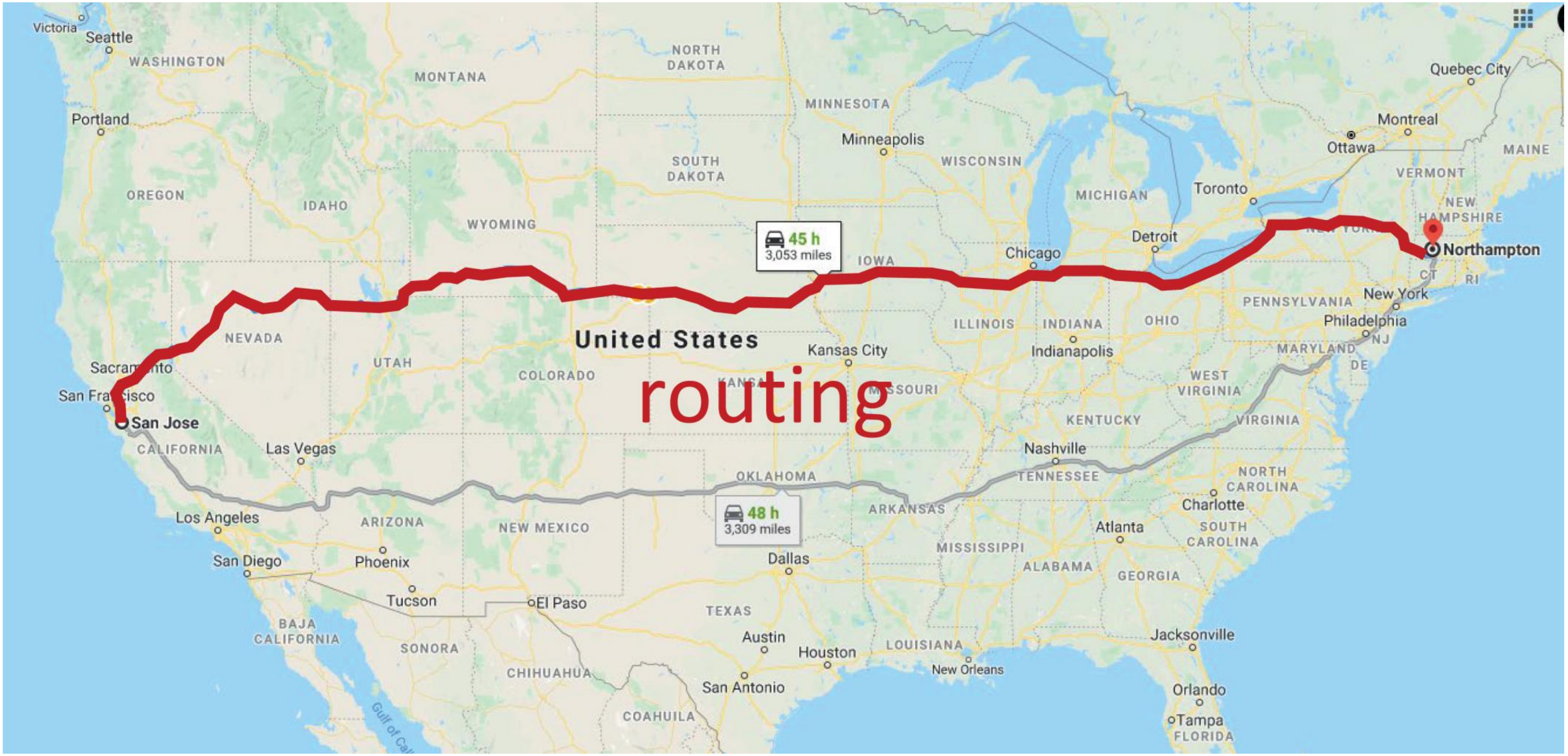


Two Key Network-Core Functions

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

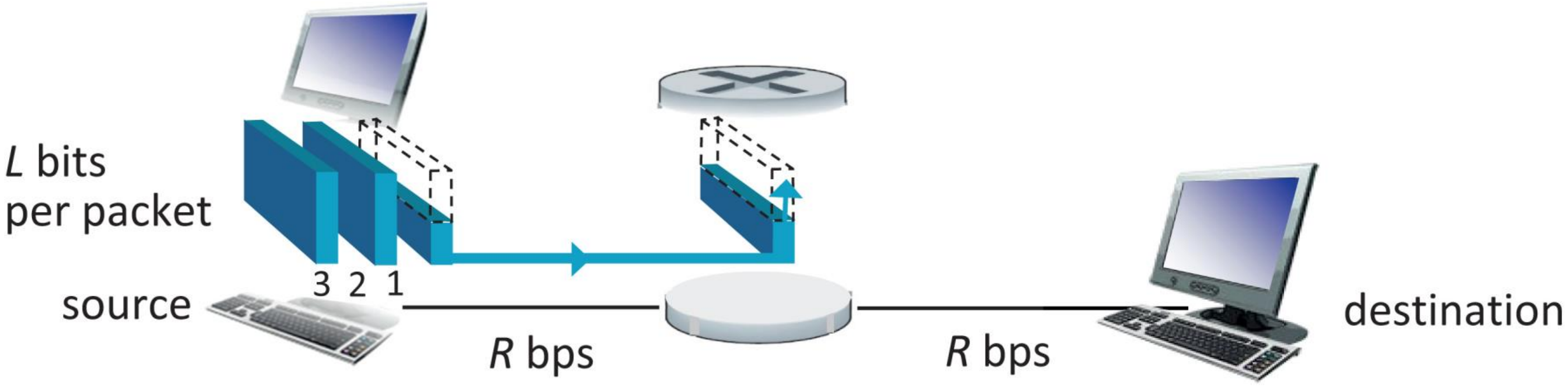


- **global** action: determine source-destination paths taken by packets
- routing algorithms


45 h
3,053 miles
48 h
3,309 miles
San Jose
Northampton
United States
routing


forwarding
forwarding
45 h
3,053 miles
48 h
3,309 miles
United States
San Jose
Northampton
Cleveland
Sacramento
Seattle
Portland
San Francisco
Las Vegas
Los Angeles
San Diego
Phoenix
Tucson
El Paso
Dallas
Austin
Houston
San Antonio
Kansas City
Minneapolis
Chicago
Detroit
Toronto
Indianapolis
Nashville
Atlanta
New Orleans
Tampa
Ottawa
Montreal
Quebec City
Victoria

Packet-Switching: Store-and-Forward

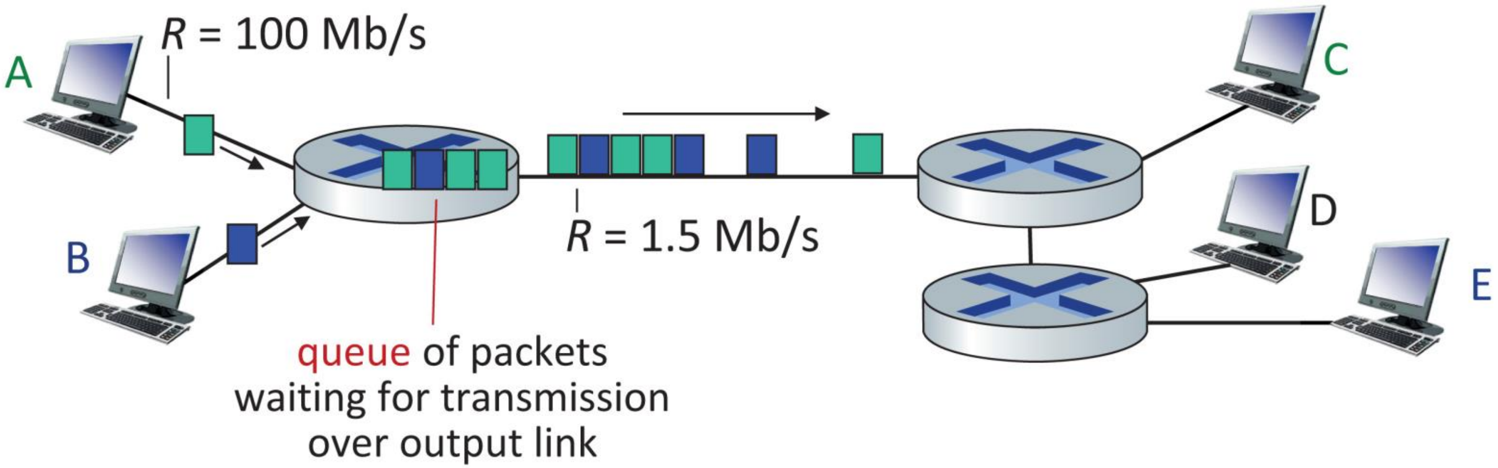


- packet transmission delay: takes *L*/*R* seconds to transmit (push out) *L*-bit packet into link at *R* bps
- store and forward: **entire** packet must arrive at router before it can be transmitted on next link

One-hop numerical example:

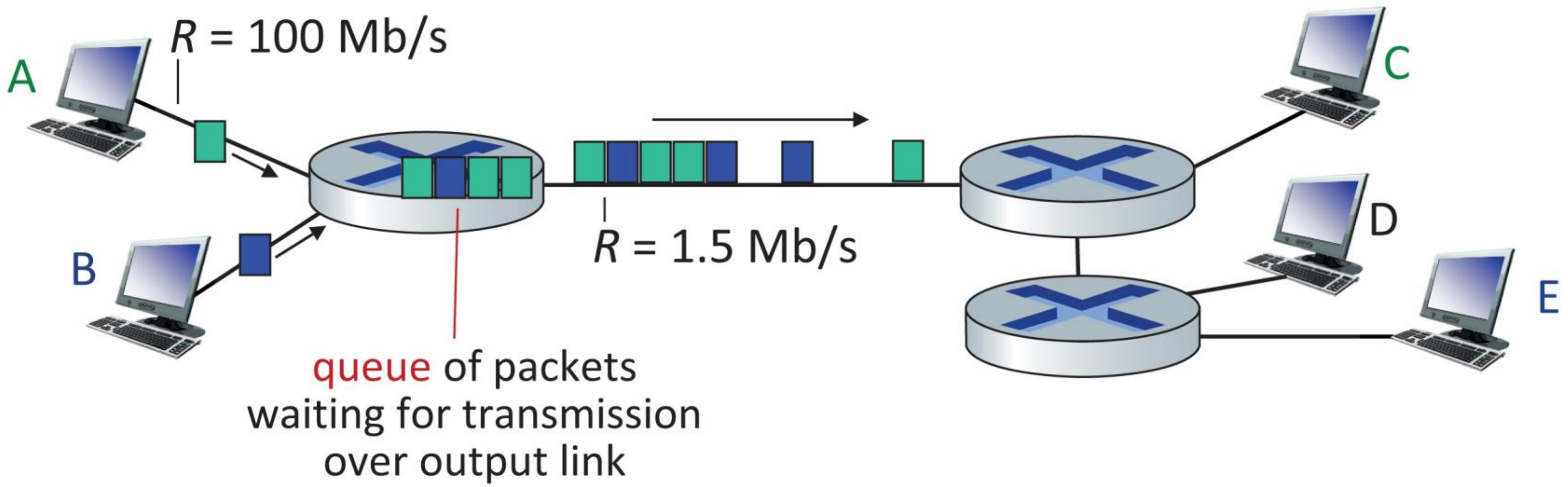
- *L* = 10 Kbits
- *R* = 100 Mbps
- one-hop transmission delay = 0.1 msec

Packet-Switching: Queueing (1 of 2)



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

Packet-Switching: Queueing (2 of 2)



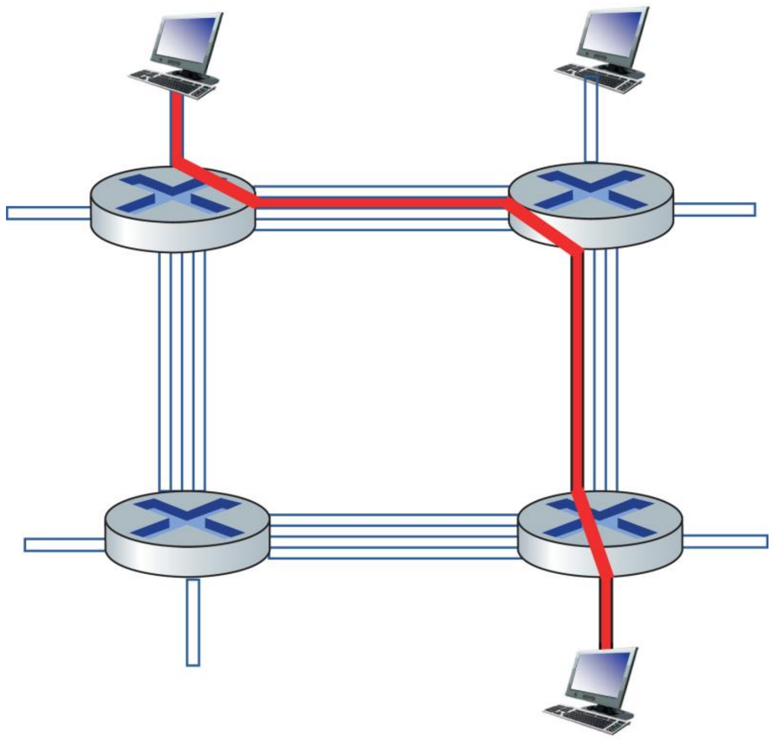
Packet queuing and loss: if arrival rate (in bps) to link exceeds transmission rate (bps) of link for some period of time:

- packets will queue, waiting to be transmitted on output link
- packets can be dropped (lost) if memory (buffer) in router fills up

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



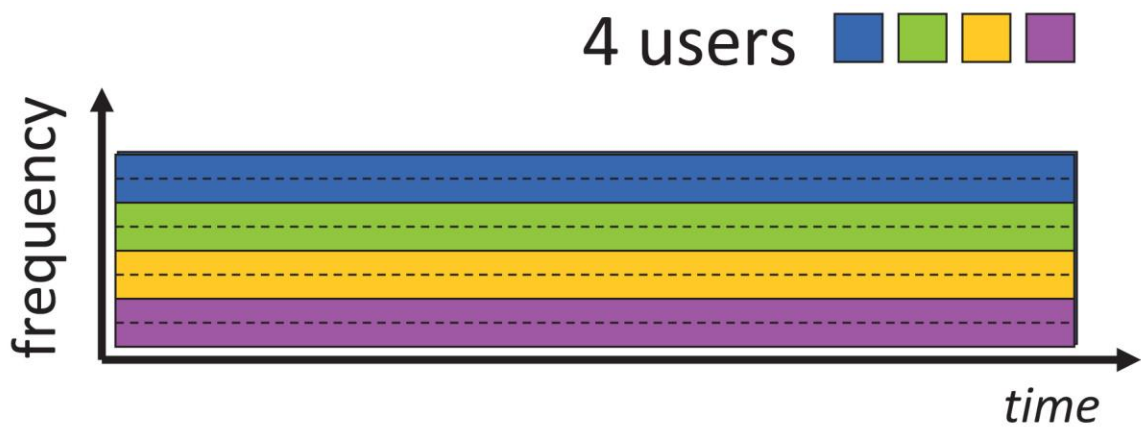
* Check out the online interactive exercises for more examples:

http://gaia.cs.umass.edu/kurose_ross/interactive

Circuit Switching: FDM and TDM

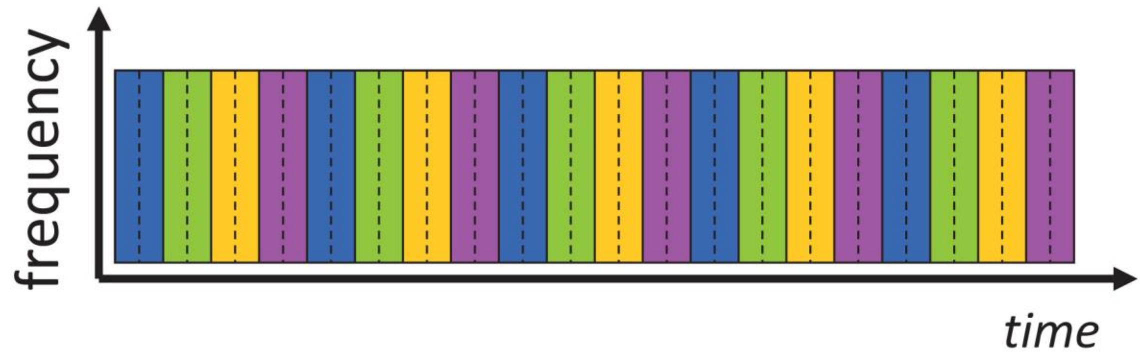
Frequency Division Multiplexing (FDM)

- 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)

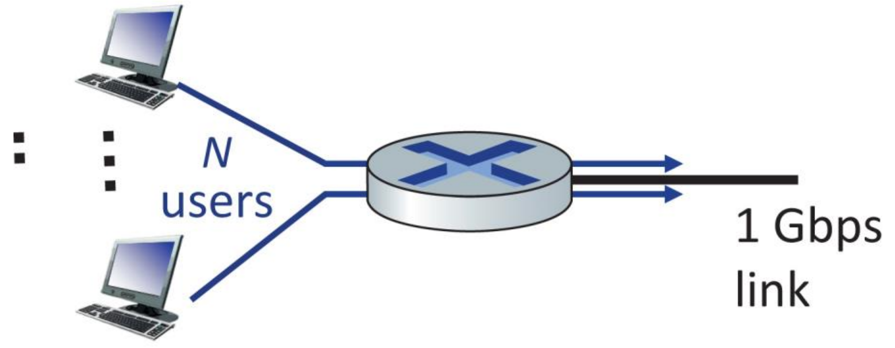
- time divided into slots
- each call allocated periodic slot(s), can transmit at maximum rate of (wider) frequency band (only) during its time slot(s)



Packet Switching versus Circuit Switching (1 of 2)

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 *

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 (2 of 2)

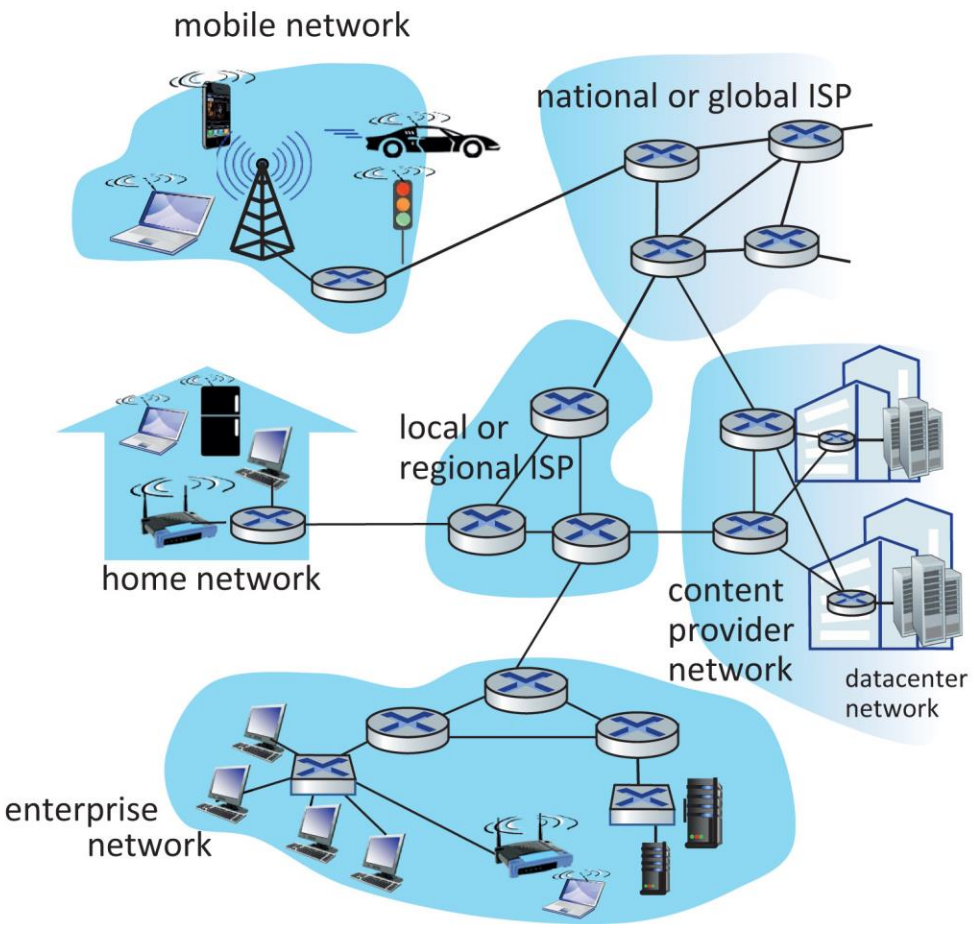
Is packet switching a "slam dunk winner"?

- 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” (1 of 9)

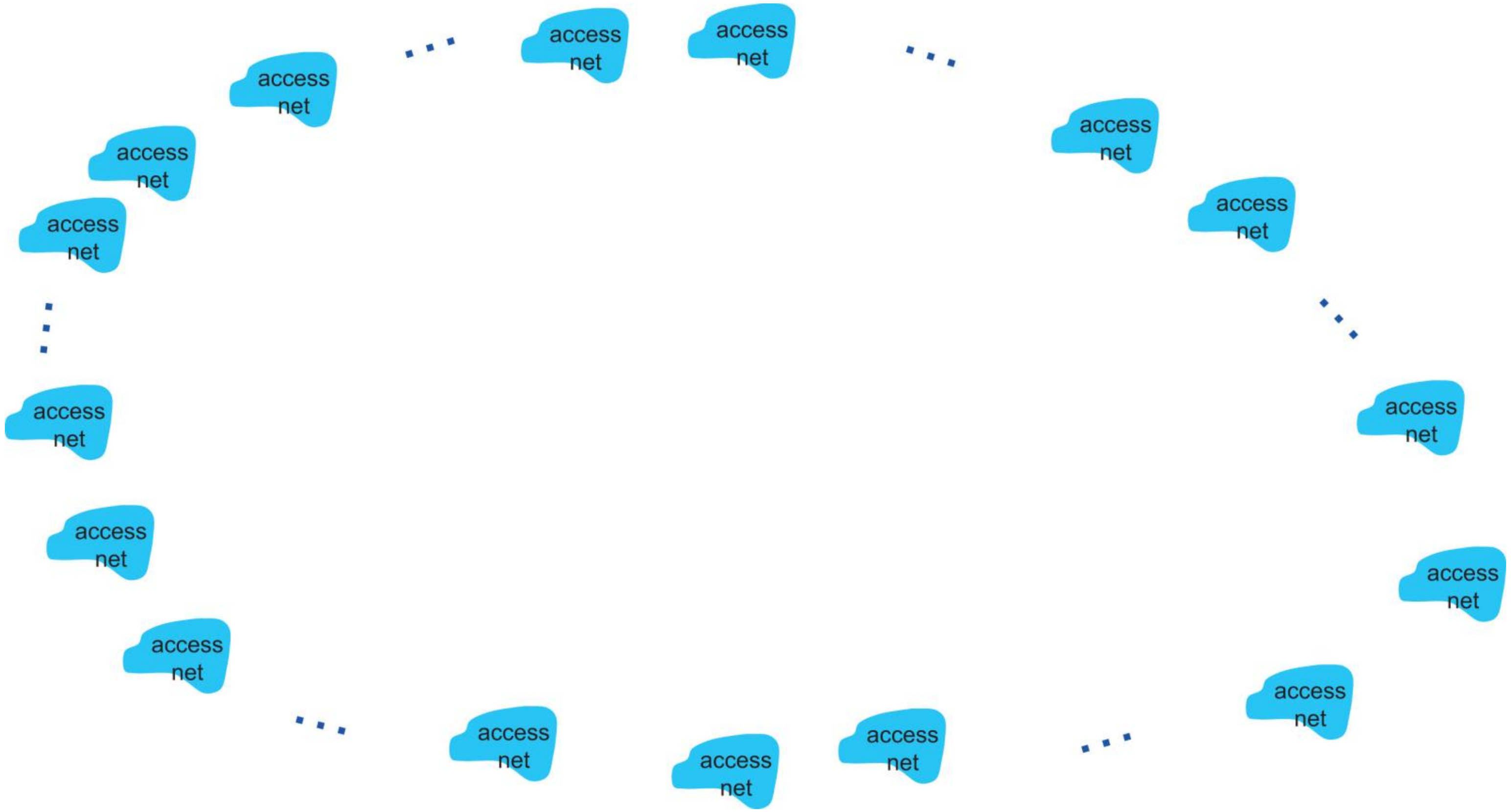
- hosts connect to Internet via access Internet Service Providers (ISPs)
- access ISPs in turn must be interconnected
  - so that **any** two hosts *(***anywhere!***)* can send packets to each other
- resulting network of networks is very complex
  - evolution driven by economics, national policies



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

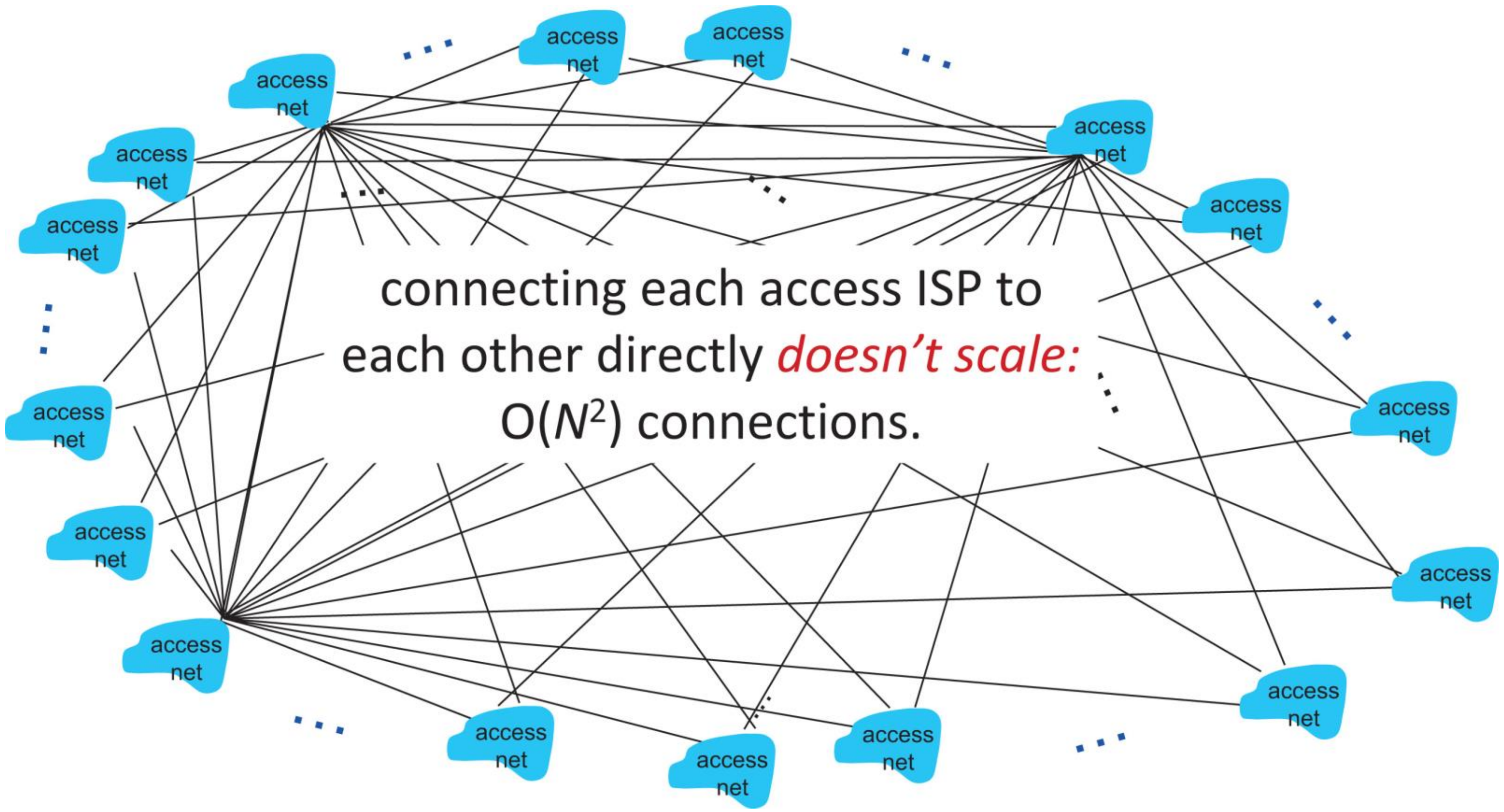
Internet Structure: a "Network of Networks" (2 of 9)

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



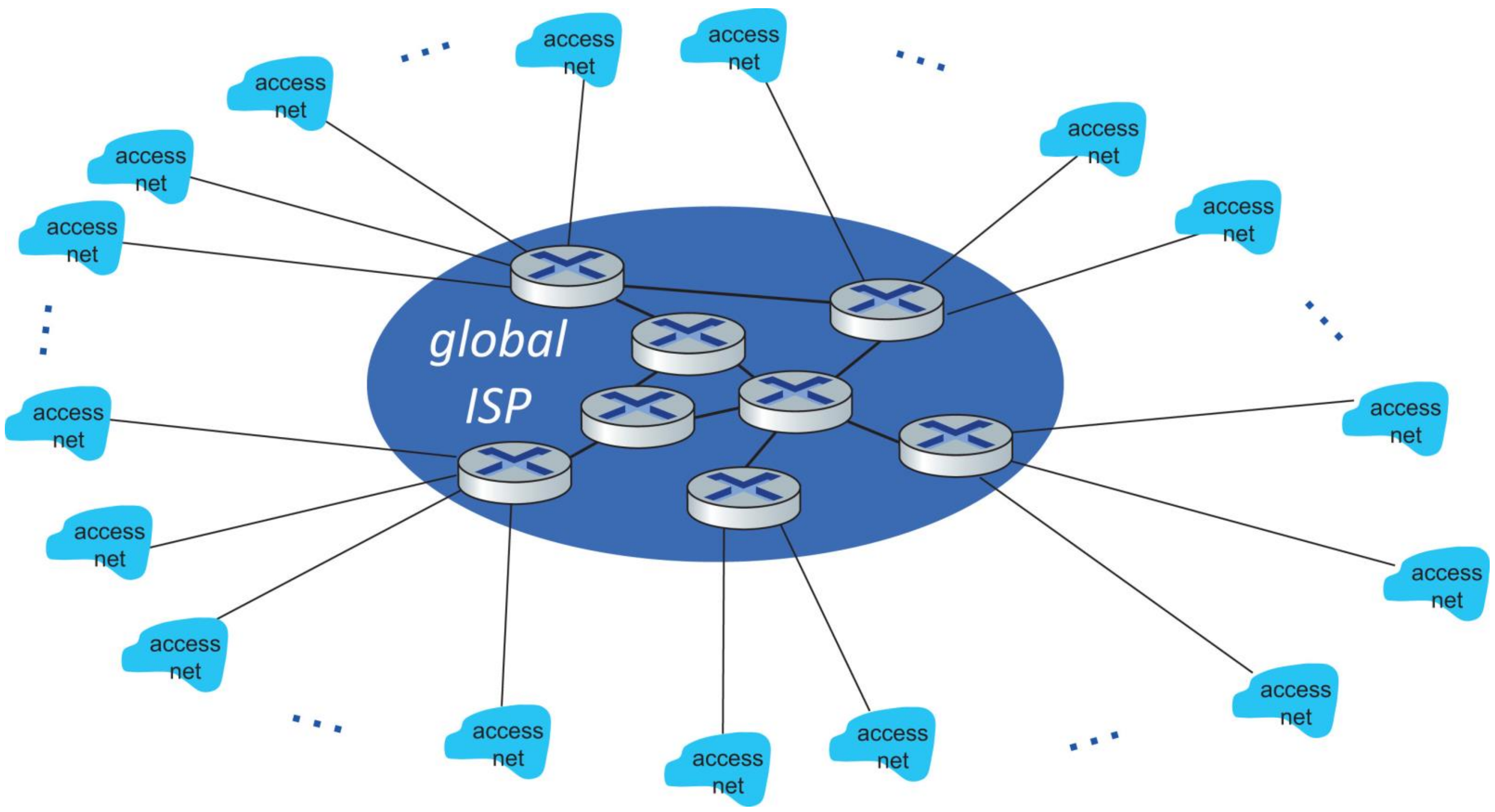
Internet Structure: a “Network of Networks” (3 of 9)

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



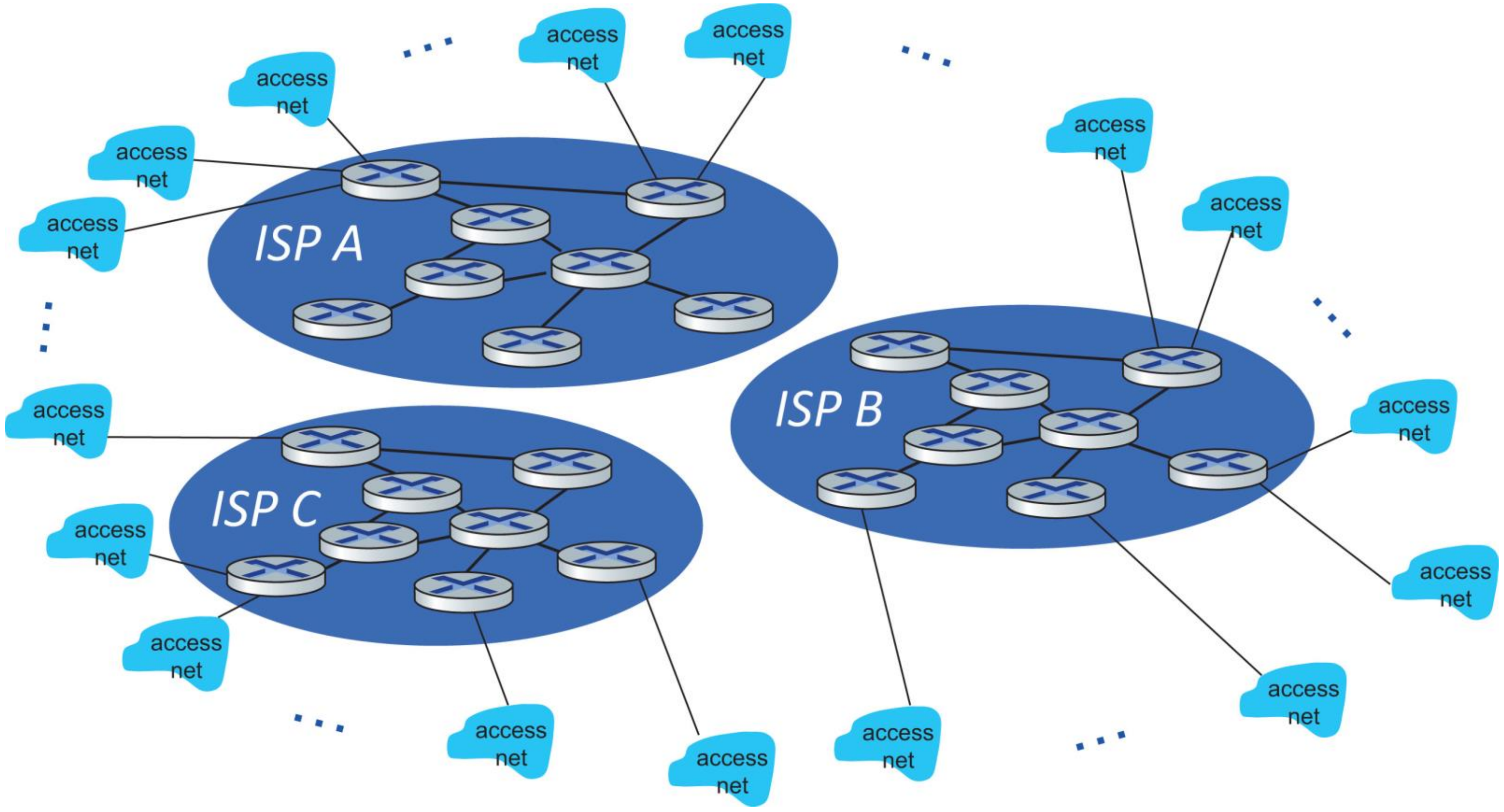
Internet Structure: a “Network of Networks” (4 of 9)

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



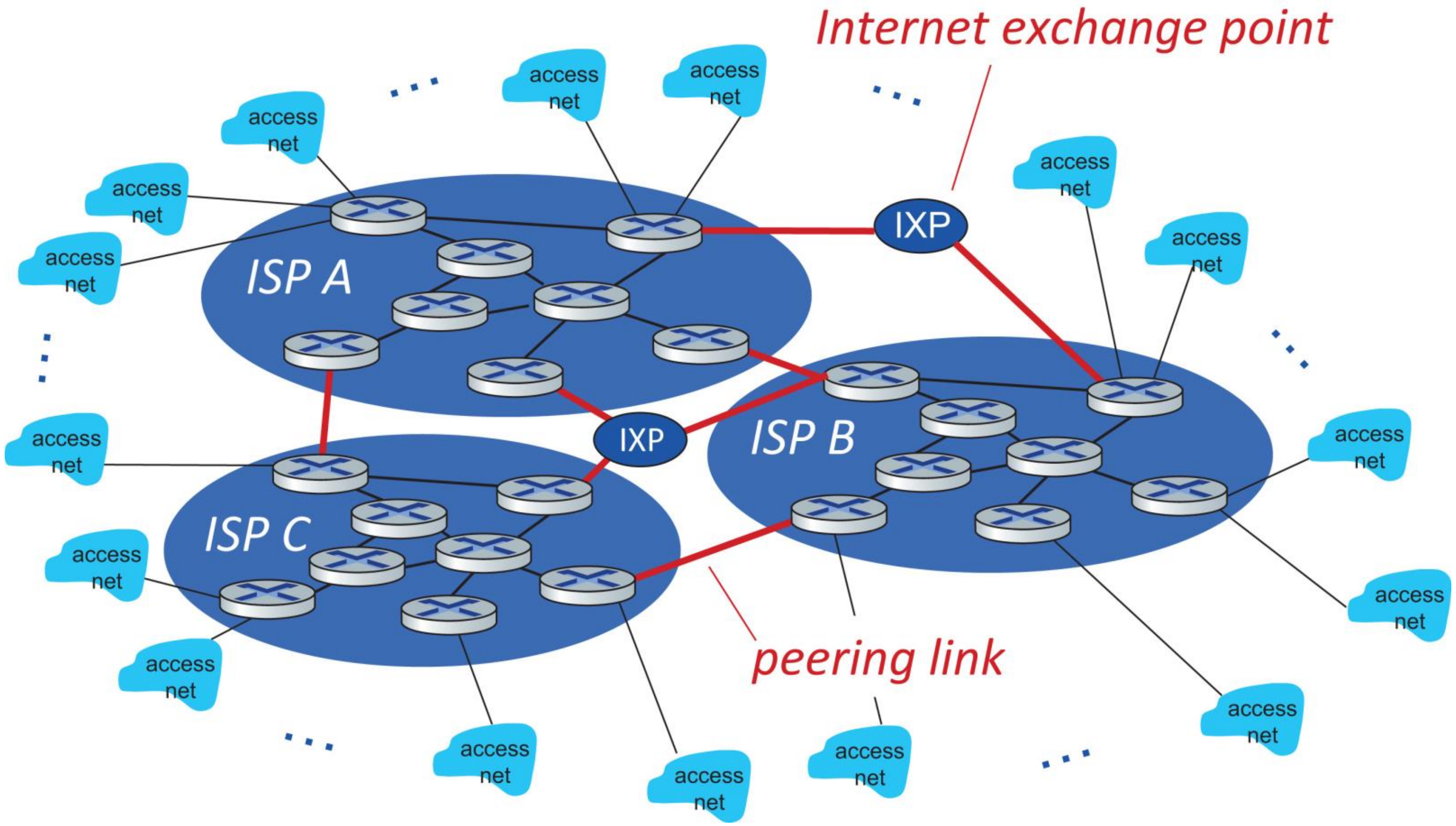
Internet Structure: a “Network of Networks” (5 of 9)

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



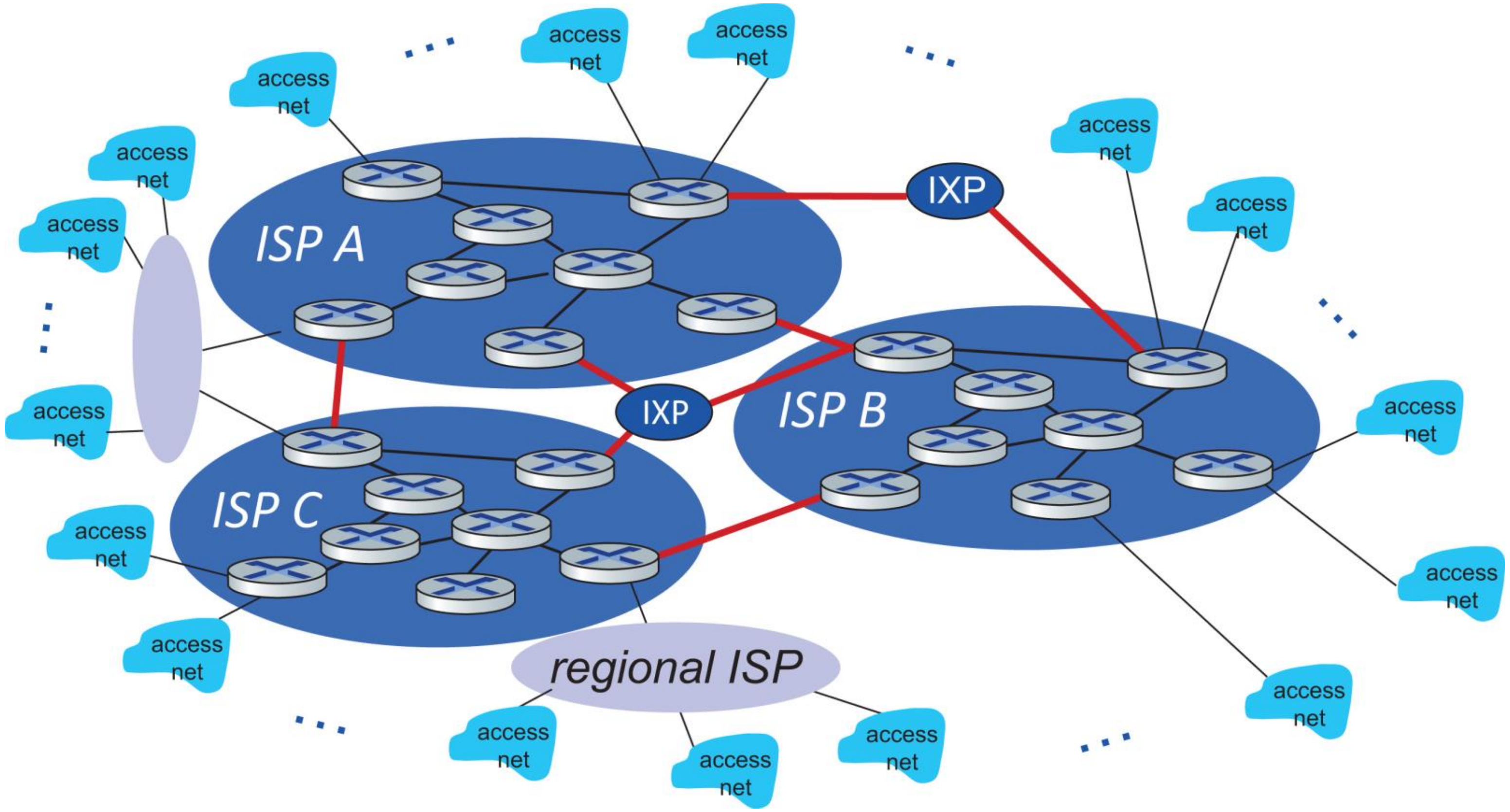
Internet Structure: a "Network of Networks" (6 of 9)

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



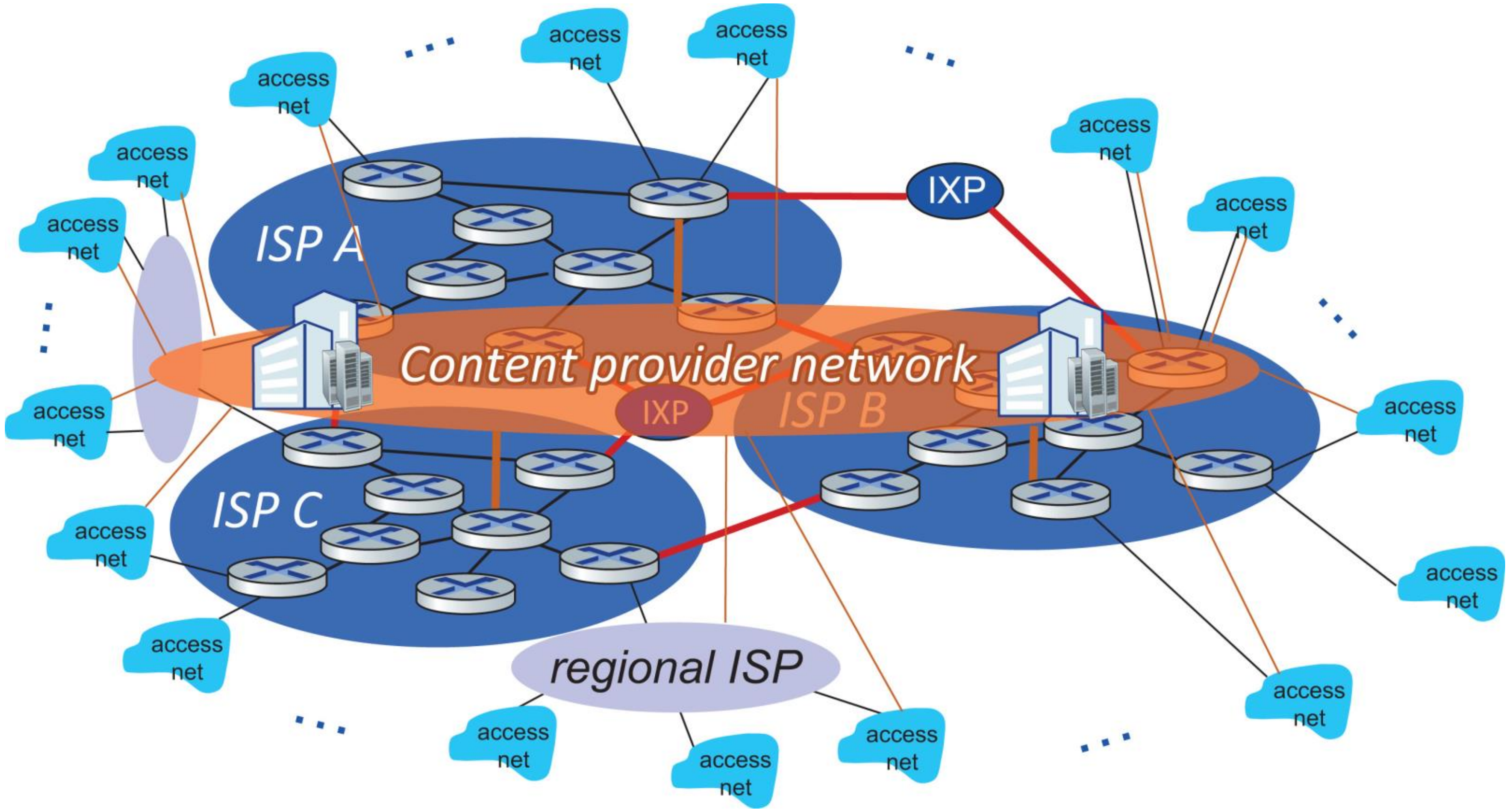
Internet Structure: a "Network of Networks" (7 of 9)

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

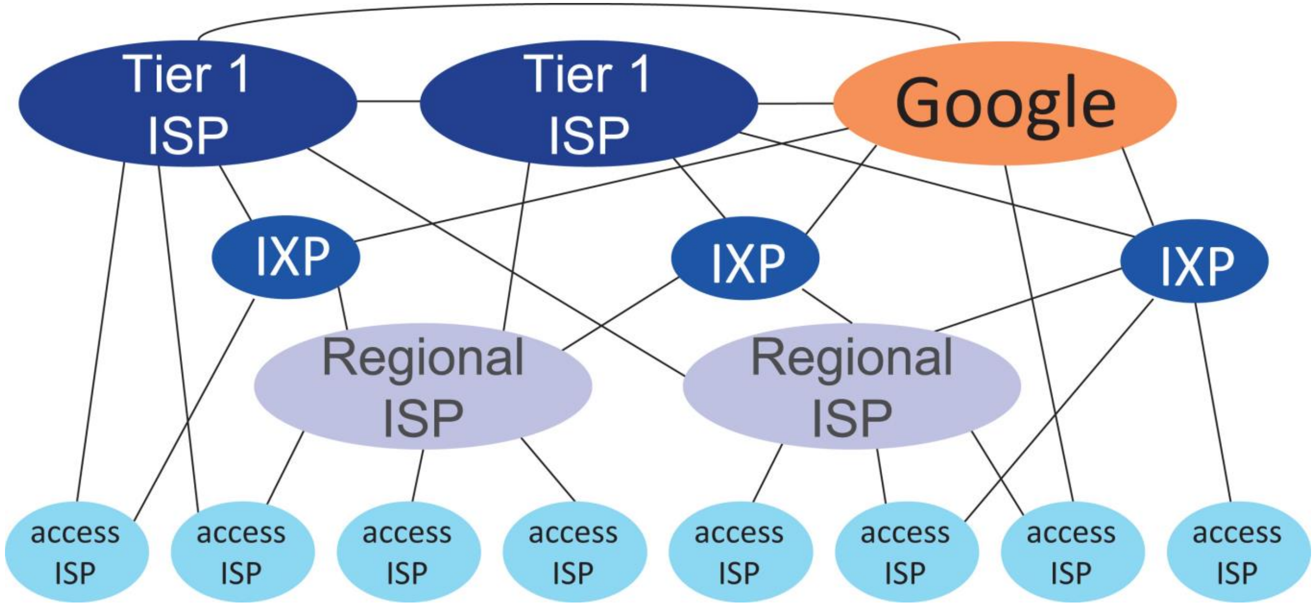


Internet Structure: a “Network of Networks” (8 of 9)

… 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” (9 of 9)



At “center”: small # of well-connected large networks

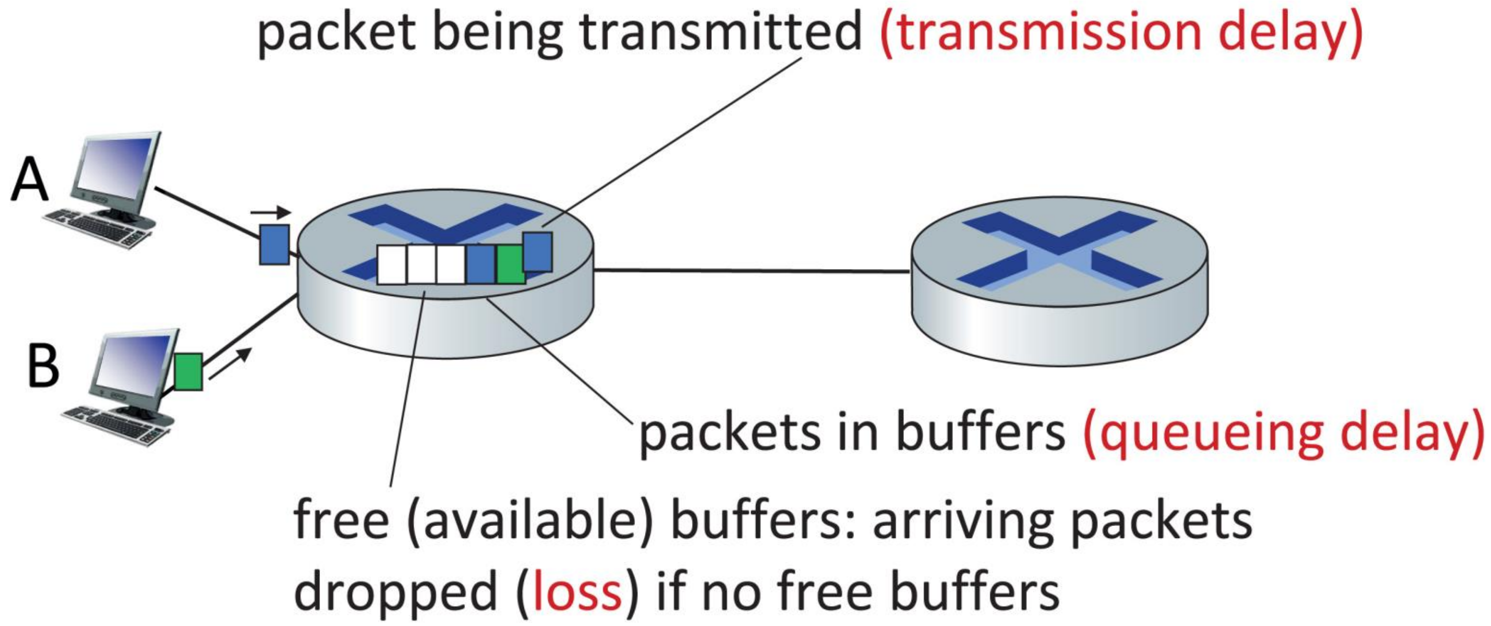
- “tier-1” commercial ISPs (e.g., Level 3, Sprint, AT&T, NTT), national & international coverage
- content provider networks (e.g., Google, Facebook): private network that connects its data centers to Internet, often bypassing tier-1, regional ISPs

Chapter 1: Roadmap (3 of 6)

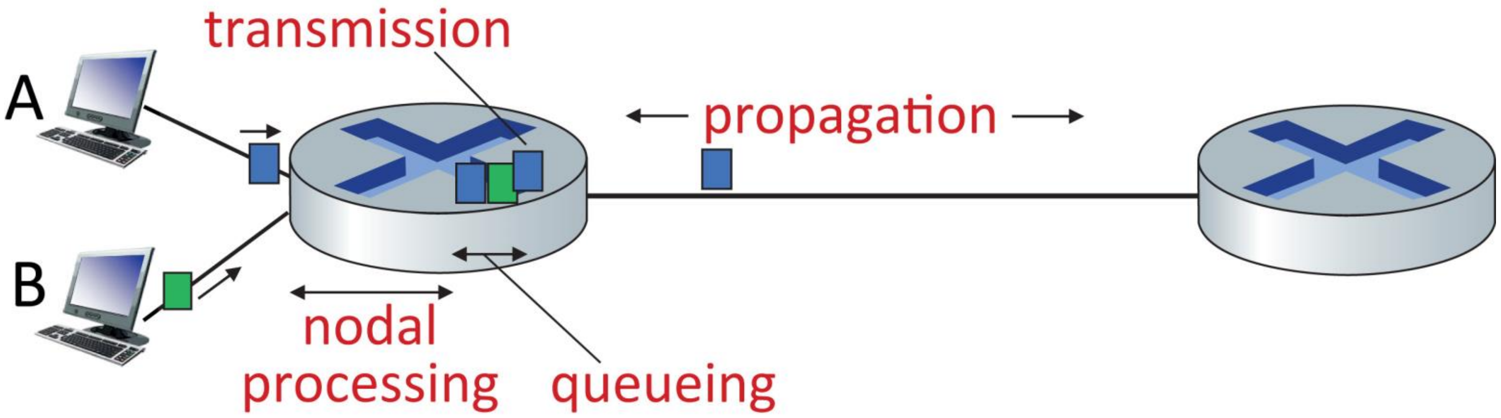
- What is the Internet?
- What is a protocol?
- Network edge: hosts, access network, physical media
- Network core: packet/circuit switching, internet structure
- **Performance: loss, delay, throughput**
- Protocol layers, service models

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 (1 of 2)



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

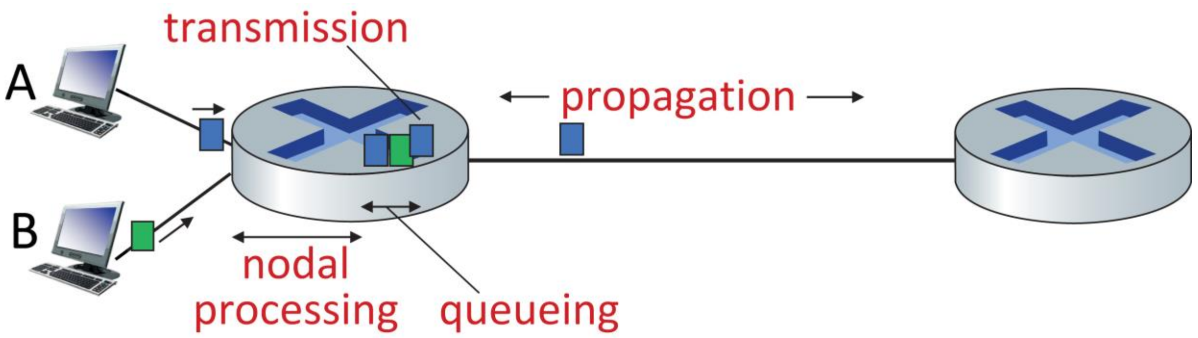
d_{proc} :nodal processing

- 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 (2 of 2)



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

d_{trans} : transmission delay:

- L: packet length (bits)
- R: link **transmission rate (bps)**

- $d_{trans} = L/R$

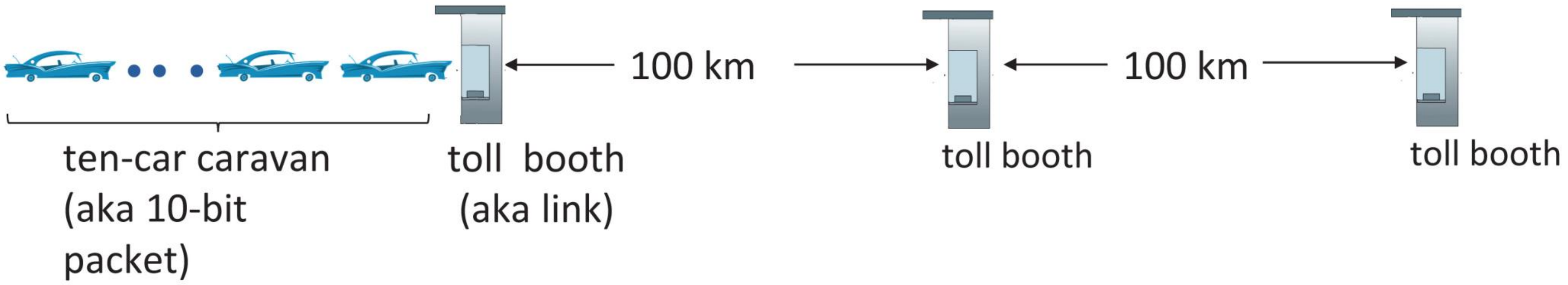
d_{proc} : propagation delay:

- d: length of physical link
- s: propagation speed $(\tilde{}2 \times 10^8 \text{m/sec})$

- $d_{proc} = d/s$

d_{trans} and d_{prop} very different

Caravan Analogy (1 of 2)



- 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

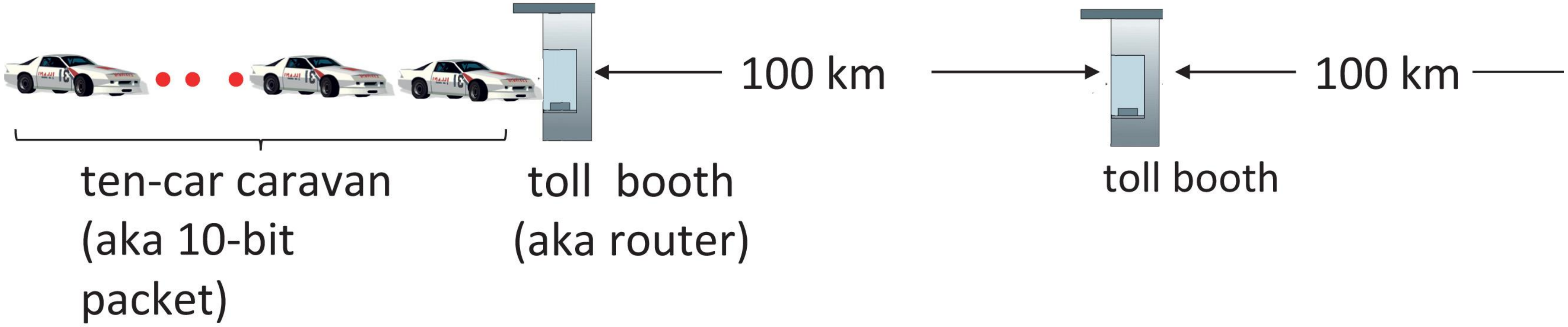
  $= 12 * 10 = 120 \text{ sec}$

- time for last car to propagate from 1st to 2nd toll both:

  $100 \text{ km} / (100 \text{ km/hr}) = 1 \text{hr}$

- A: 62 minutes

Caravan Analogy (2 of 2)



- 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?

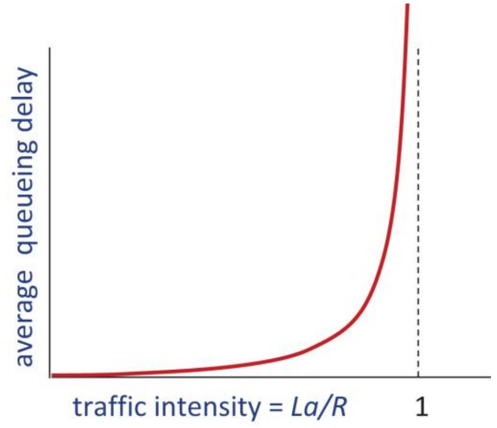
A: Yes! after 7 min, first car arrives at second booth; three cars still at first booth

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!

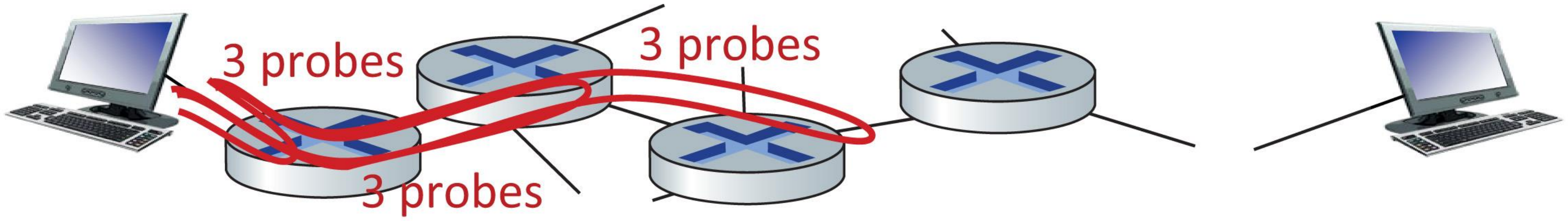


La/R ~ 0

La/R -> 1

"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



Real Internet Delays and Routes

traceroute: gaia.cs.umass.edu to www.eurecom.fr

3 delay measurements from gaia.cs.umass.edu to cs-gw.cs.umass.edu

```
1  cs-gw (128.119.240.254)  1 ms  1 ms  2 ms
2  border1-rt-fa5-1-0.gw.umass.edu (128.119.3.145)  1 ms  1 ms  2 ms
3  cht-vbns.gw.umass.edu (128.119.3.130)  6 ms 5 ms 5 ms
4  jn1-at1-0-0-19.wor.vbns.net (204.147.132.129)  16 ms 11 ms 13 ms
5  jn1-so7-0-0-0.wae.vbns.net (204.147.136.136)  21 ms 18 ms 18 ms
6  abilene-vbns.abilene.ucaid.edu (198.32.11.9)  22 ms  18 ms  22 ms
7  nycm-wash.abilene.ucaid.edu (198.32.8.46)  22 ms  22 ms  22 ms
8  62.40.103.253 (62.40.103.253)  104 ms 109 ms 106 ms
9  de2-1.de1.de.geant.net (62.40.96.129)  109 ms 102 ms 104 ms
10  de.fr1.fr.geant.net (62.40.96.50)  113 ms 121 ms 114 ms
11  renater-gw.fr1.fr.geant.net (62.40.103.54)  112 ms  114 ms  112 ms
12  nio-n2.cssi.renater.fr (193.51.206.13)  111 ms  114 ms  116 ms
13  nice.cssi.renater.fr (195.220.98.102)  123 ms  125 ms  124 ms
14  r3t2-nice.cssi.renater.fr (195.220.98.110)  126 ms  126 ms  124 ms
15  eurecom-valbonne.r3t2.ft.net (193.48.50.54)  135 ms  128 ms  133 ms
16  194.214.211.25 (194.214.211.25)  126 ms  128 ms  126 ms
17  * * *
18  * * *
19  fantasia.eurecom.fr (193.55.113.142)  132 ms  128 ms  136 ms
```

3 delay measurements to border1-rt-fa5-1-0.gw.umass.edu

trans-oceanic link (hops 7 → 8)

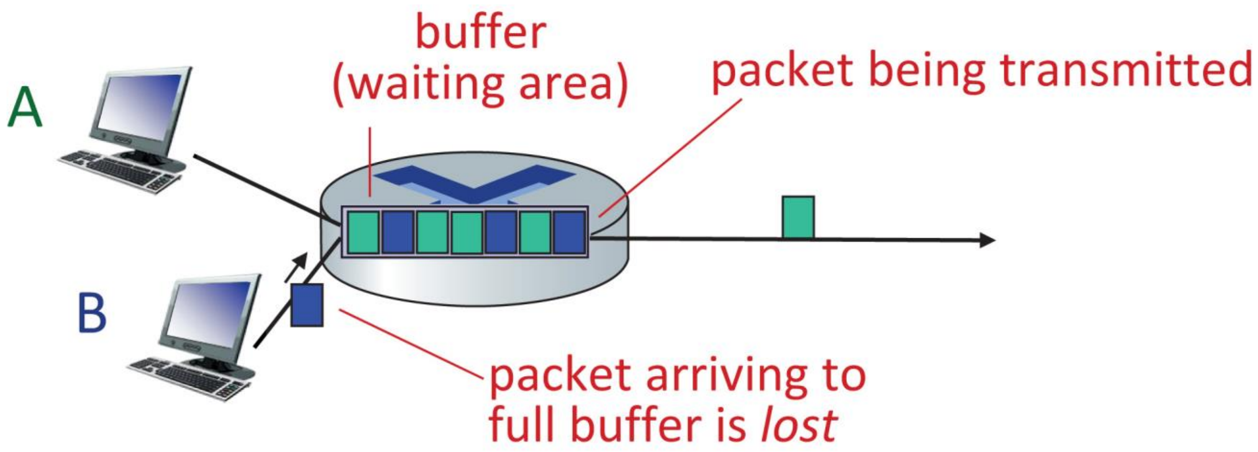
looks like delays *decrease*! Why? (hops 11 → 12)

* means no response (probe lost, router not replying)

* Do some traceroutes from exotic countries at www.traceroute.org

Packet Loss

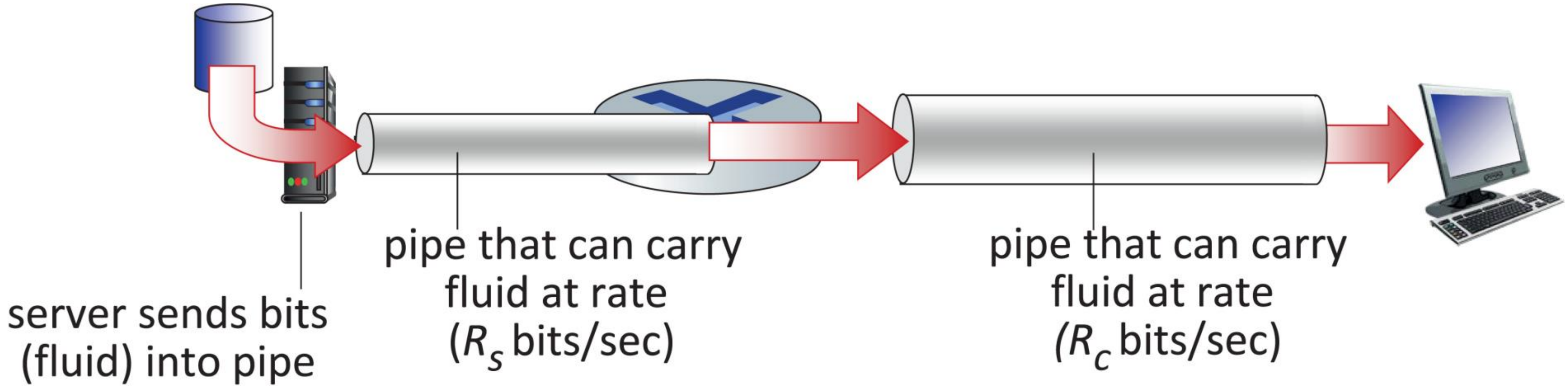
- queue (aka buffer) preceding link in buffer has finite capacity
- packet arriving to full queue dropped (aka lost)
- lost packet may be retransmitted by previous node, by source end system, or not at all



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

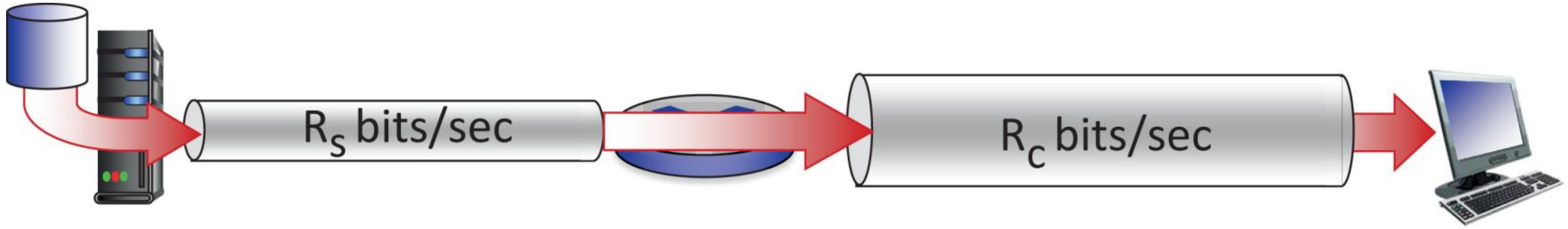
Throughput (1 of 2)

- **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

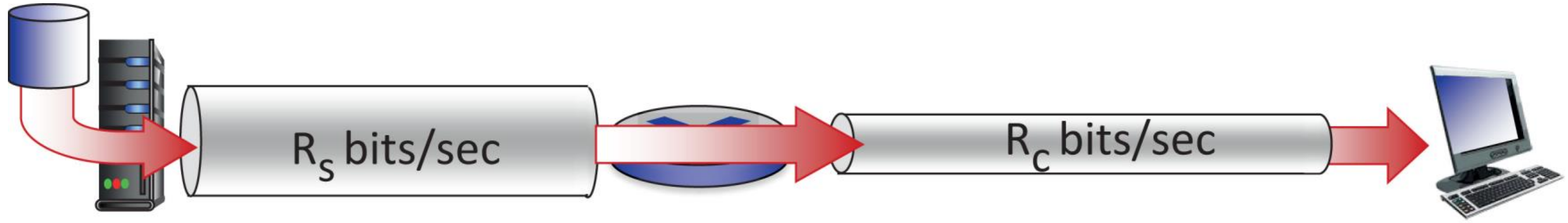


Throughput (2 of 2)

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



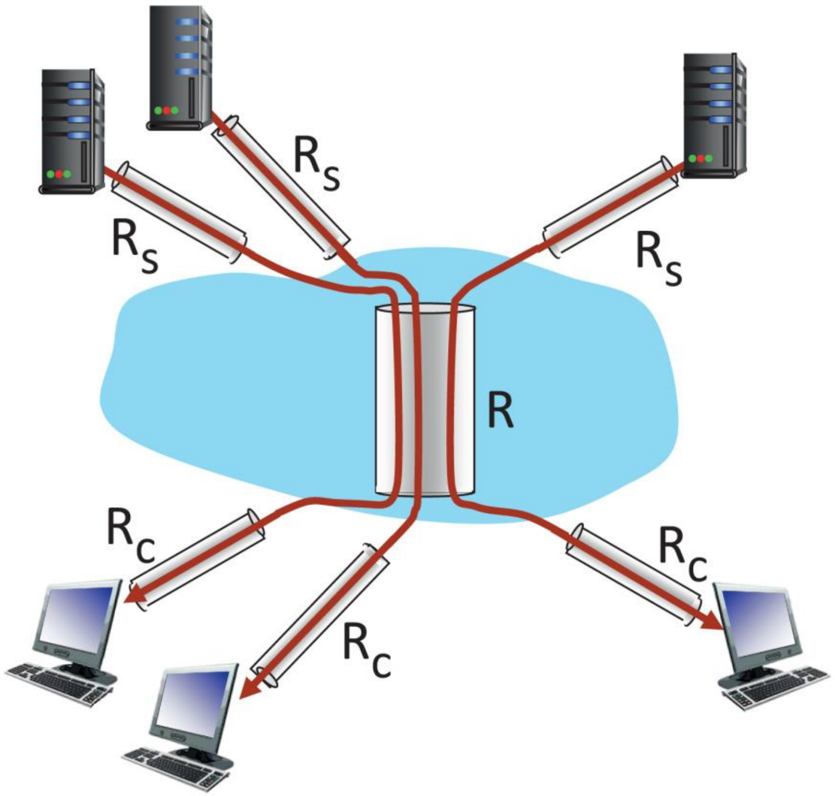
$R_s > R_c$ What is average end-end throughput?



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

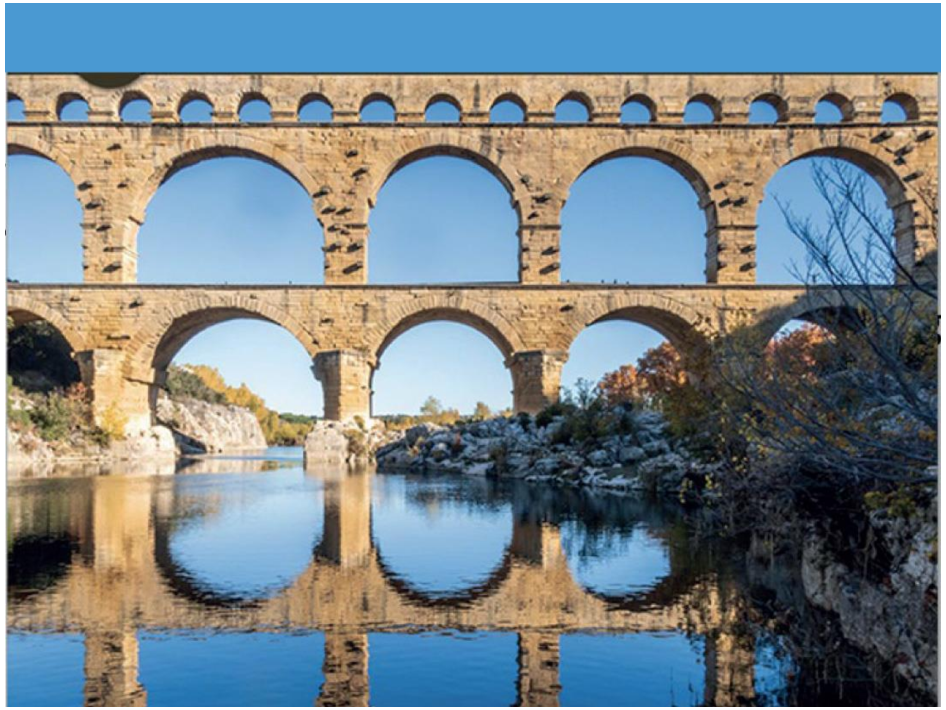
- per-connection end-end throughput:
  $min(R_c, R_s, R/10)$
- in practice: R_c or R_s is often bottleneck

* Check out the online interactive exercises for more examples:

http://gaia.cs.umass.edu/kurose_ross/

Chapter 1: Roadmap (5 of 6)

- 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**



Protocol "Layers" and Reference Models

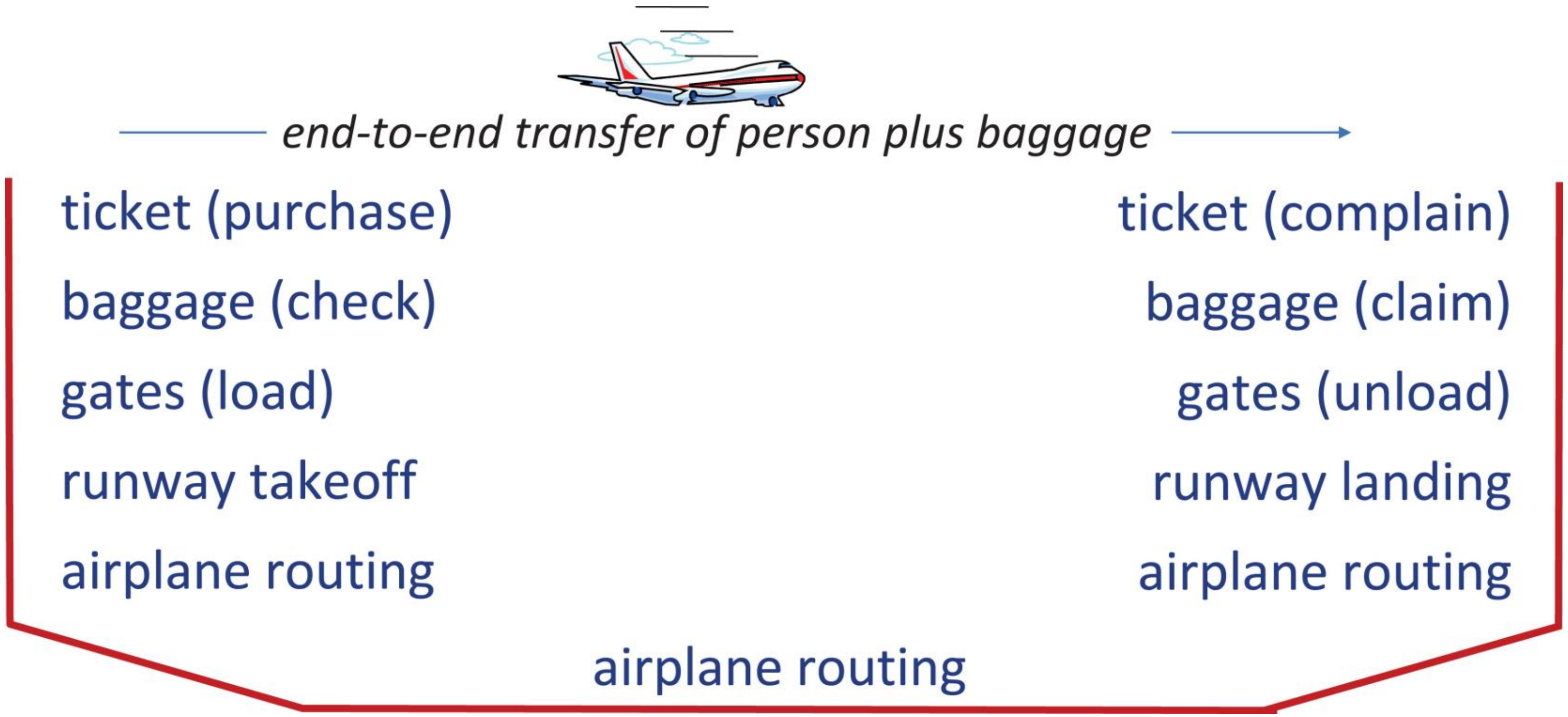
Networks are complex, with many "pieces":

- hosts
- routers
- links of various media
- applications
- protocols
- hardware, software

Question: is there any hope of **organizing** structure of network?

- and/or our **discussion** of networks?

Example: Organization of Air Travel (1 of 2)



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

- a series of steps, involving many services

Example: Organization of Air Travel (2 of 2)

layers: each layer implements a service

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

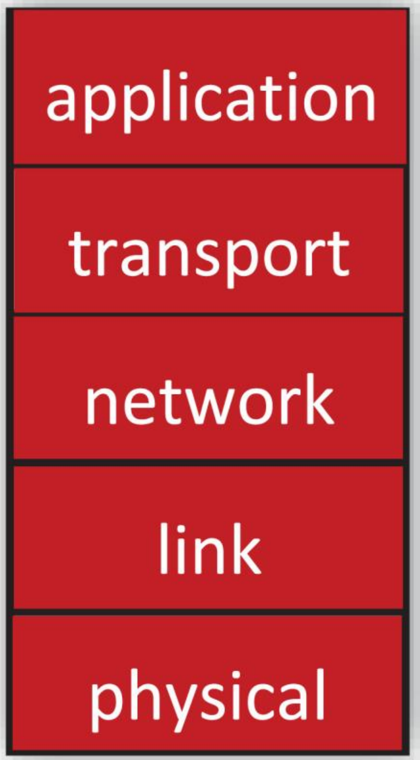
Why Layering?

Approach to designing/discussing complex systems:

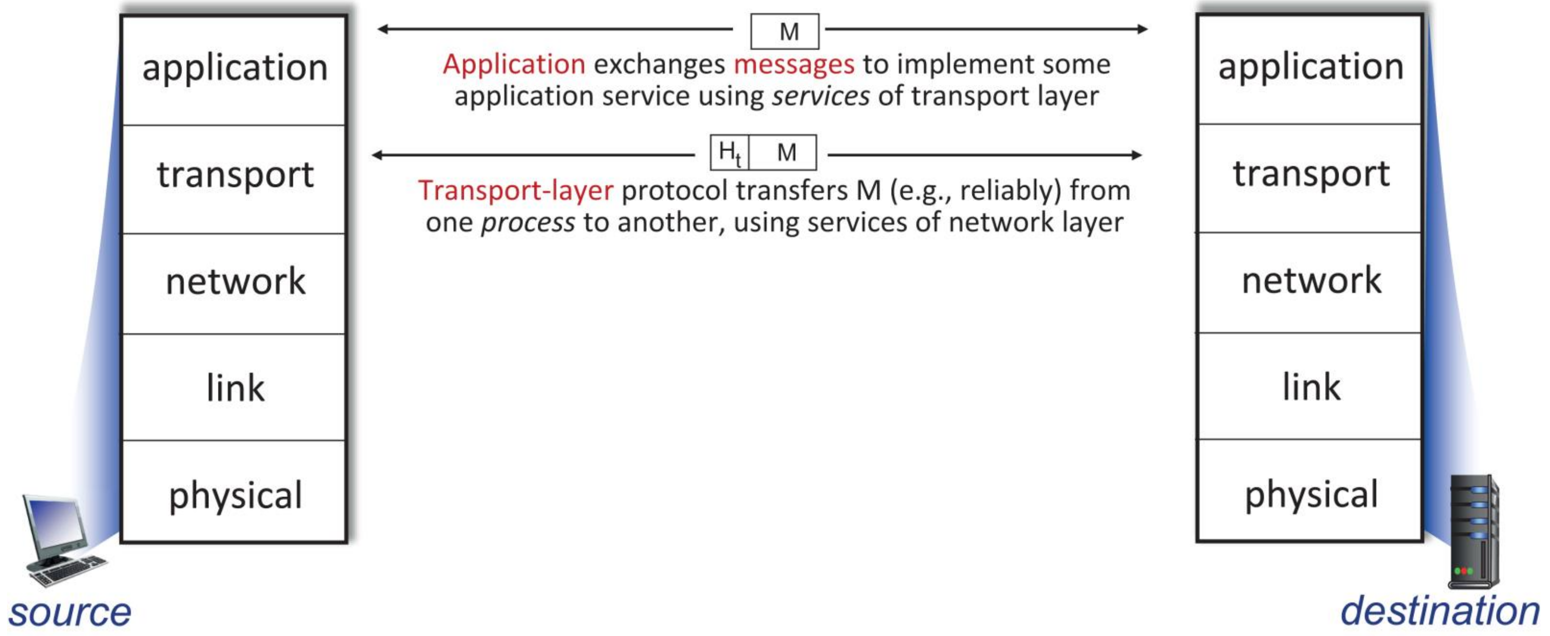
- explicit structure allows identification, relationship of system's pieces
  - layered reference model for discussion
- modularization eases maintenance, updating of system
  - change in layer's service **implementation**: transparent to rest of system
  - e.g., change in gate procedure doesn't affect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

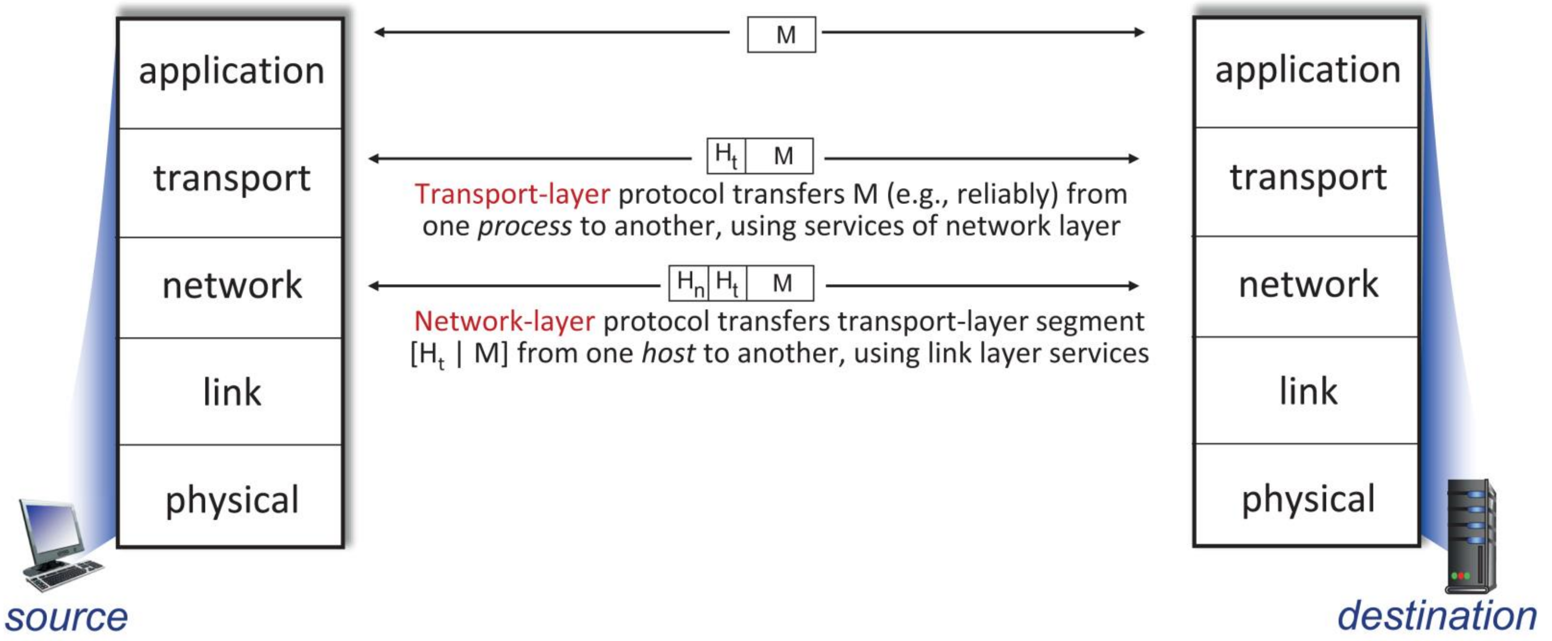


Services, Layering and Encapsulation (1 of 5)



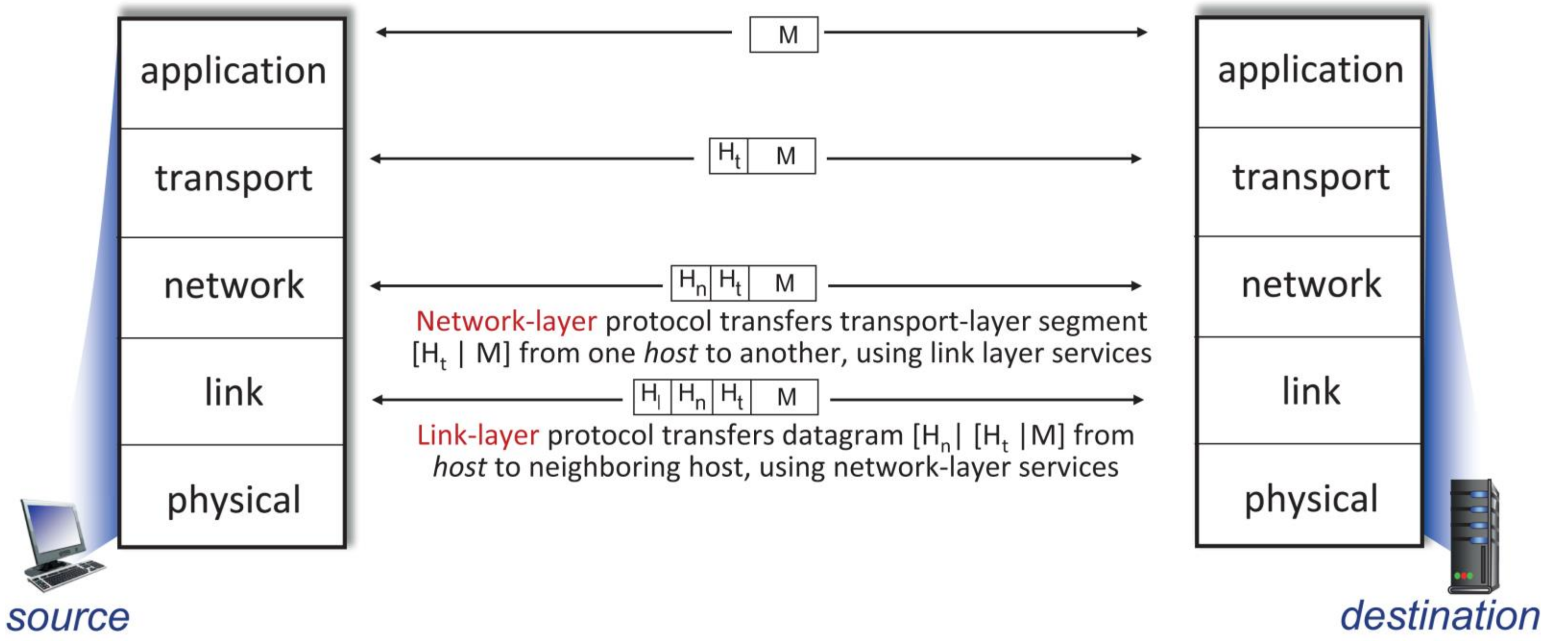
- transport-layer protocol encapsulates application-layer message, M, with **transport** layer-layer header
  H_t to create a transport-layer segment
- H_t used by transport layer protocol to implement its service

Services, Layering and Encapsulation (2 of 5)



- 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 (3 of 5)

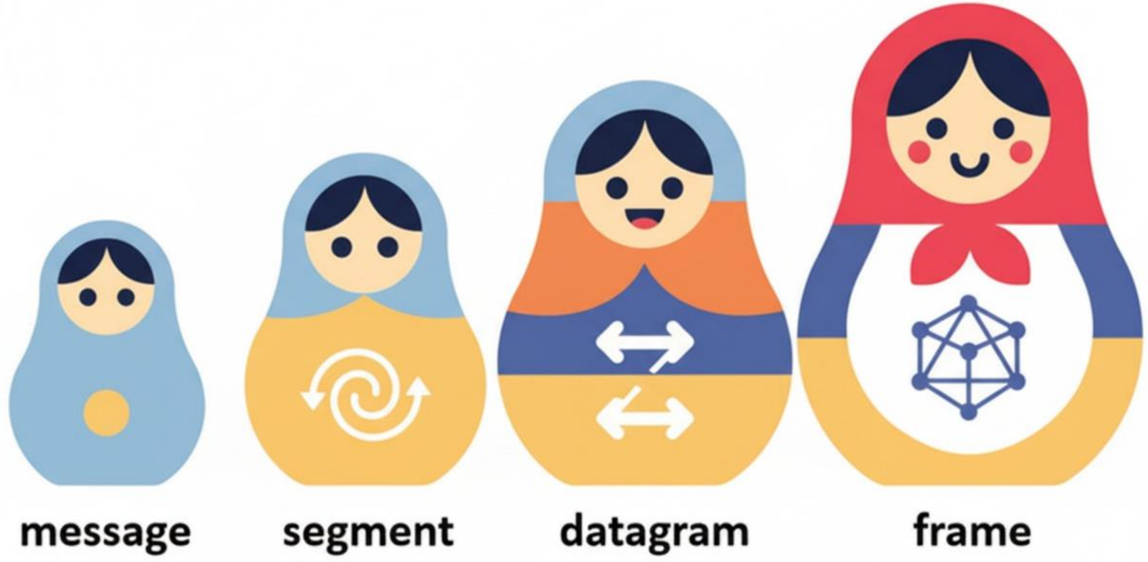


- link-layer protocol encapsulates network datagram

  $[H_n |[H_t |M]$ with link-layer header H_l to create a link-layer frame

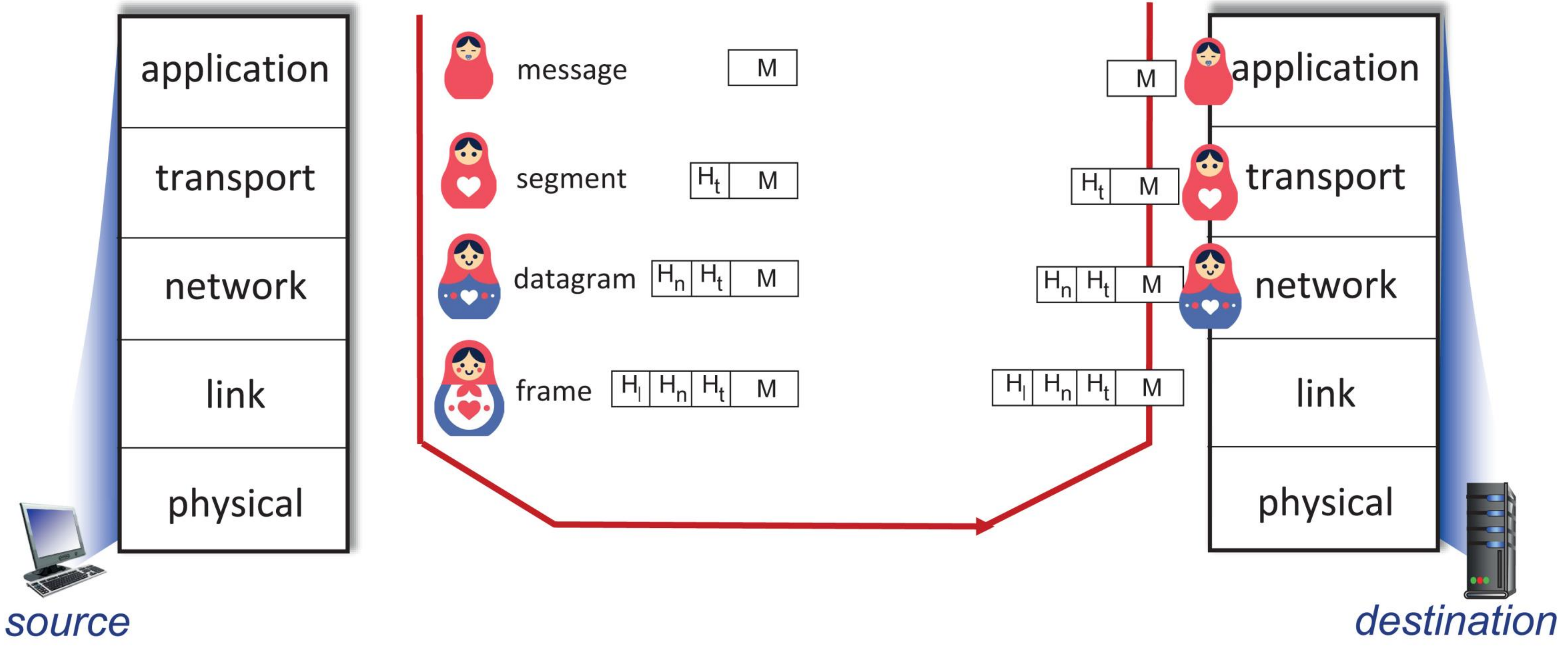
Encapsulation

Matryoshka dolls (stacking dolls)



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

Services, Layering and Encapsulation (4 of 5)



Encapsulation: an End-End View