

COMP214-21121/21221

Computer Networks

Teacher: Dr. Xu Yang

2020-2021

General Information

- Teacher: Xu Yang
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 - Office: A323, Chi Un Building
 - Telephone: 6353
- Office Hours: Tuesday and Friday Afternoon
- Assessment
 - Assignments, home-based, 30%
 - One Test, class-based, 20%
 - Final exam, class-based, 50%
- Textbook
 - J. F. Kurose and K. W. Ross, Computer Networking-A Top-Down Approach (7th edition). Addison Wesley Higher Education.

General Information

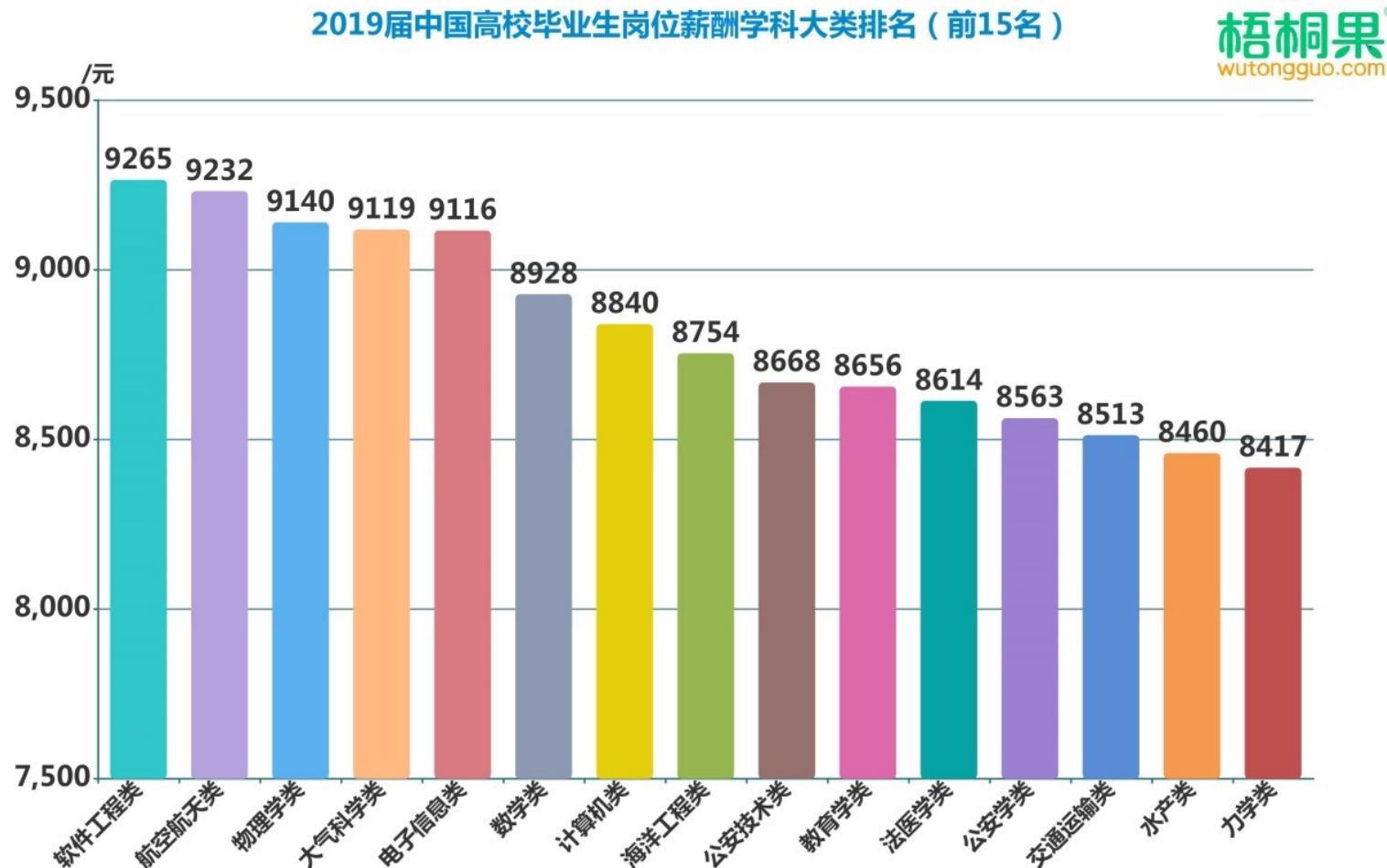
Five Chapters

- Chapter 1: Computer Networks and the Internet (2 weeks).
- Chapter 2: Application Layer (2 weeks)
- Chapter 3: Transport Layer (3 weeks+)
- Chapter 4: The Network Layer (3 weeks+)
- Chapter 5: The Link Layer (2 weeks)

Lab exercises: Wireshark

- 1. Architecture
- 2. Protocols

Why do you need to learn this course?



Why do you need to learn this course?

2019, China

排名	公司	平均综合起薪	最高起薪区间
1	Google 谷歌	46万	60-80万
2	hulu hulu	45万	50-60万
3	pony.ai 小马智行	42万	50-60万
4	Longfor 龙湖地产	40万	50-60万
5	amazon 亚马逊	37万	40-50万
6	Face++ 旷视	32万	40-50万
6	依图 YITU	32万	50-60万
8	SHAREit 茄子快传	31万	35-40万
9	拼多多	30万	50-60万
9	FreeWheel FreeWheel	30万	35-40万
11	BIGO Bigo	29万	50-60万
12	ebay ebay	28万	35-40万
12	猿辅导 猿辅导	28万	40-50万
12	Paradigm 第四范式	28万	30-35万
12	商汤	28万	40-50万
16	字节跳动	27万	60-80万
16	快手	27万	40-50万
16	地平线 Horizon Robotics 地平线机器人技术	27万	40-50万
16	阿里巴巴 Alibaba.com 阿里巴巴	27万	80万及以上
16	趣头条	27万	35-40万

排名	公司	平均综合起薪	最高起薪区间
21	BITMAIN 比特大陆	26万	30-35万
21	Cambricon 寒武纪	26万	35-40万
21	Microsoft 微软	26万	50-60万
21	TRANSWARP 星环科技	26万	35-40万
21	Tencent 腾讯	26万	80万及以上
21	瓜子	26万	35-40万
27	秒针系统	25万	30-35万
27	Win.d 万得	25万	40-50万
27	intel 英特尔	25万	30-35万
27	Sogou 搜狗	25万	40-50万
27	网易 NETEASE www.163.com	25万	40-50万
27	MOMO 陌陌	25万	40-50万
27	DJI 大疆	25万	50-60万
27	TP-LINK TP-LINK	25万	35-40万
27	迅雷	25万	35-40万
36	贝壳	24万	35-40万
36	度小满金融	24万	40-50万
36	滴滴	24万	40-50万
36	融360 Rong360	24万	35-40万
36	中国平安 PINGAN 平安产险	24万	40-50万

2019 Recruitment Salary Ranking (from University)

Chapter 1: introduction

Chapter goal:

- Get “feel,” “big picture,” introduction to terminology
 - more depth, detail *later* in course
- Approach:
 - use Internet as example



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
- Security
- Protocol layers, service models
- History

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)

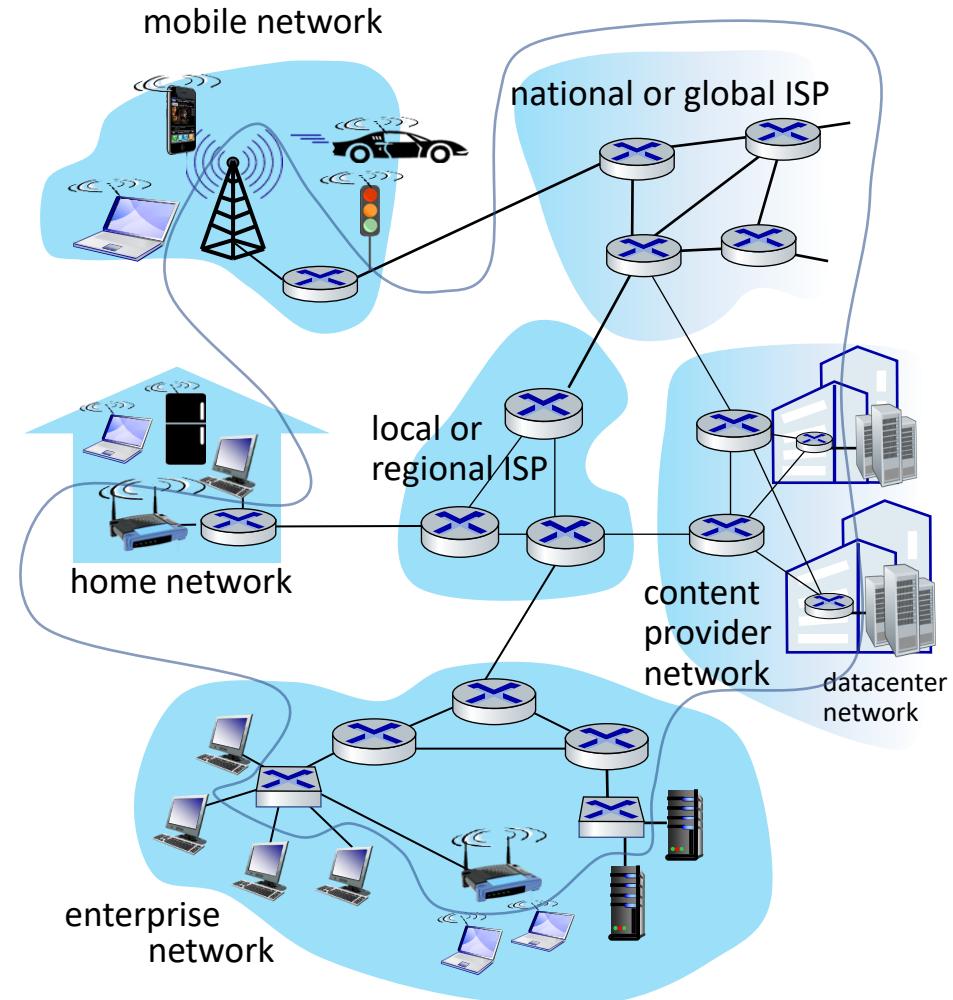
- routers, switches

Communication links

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

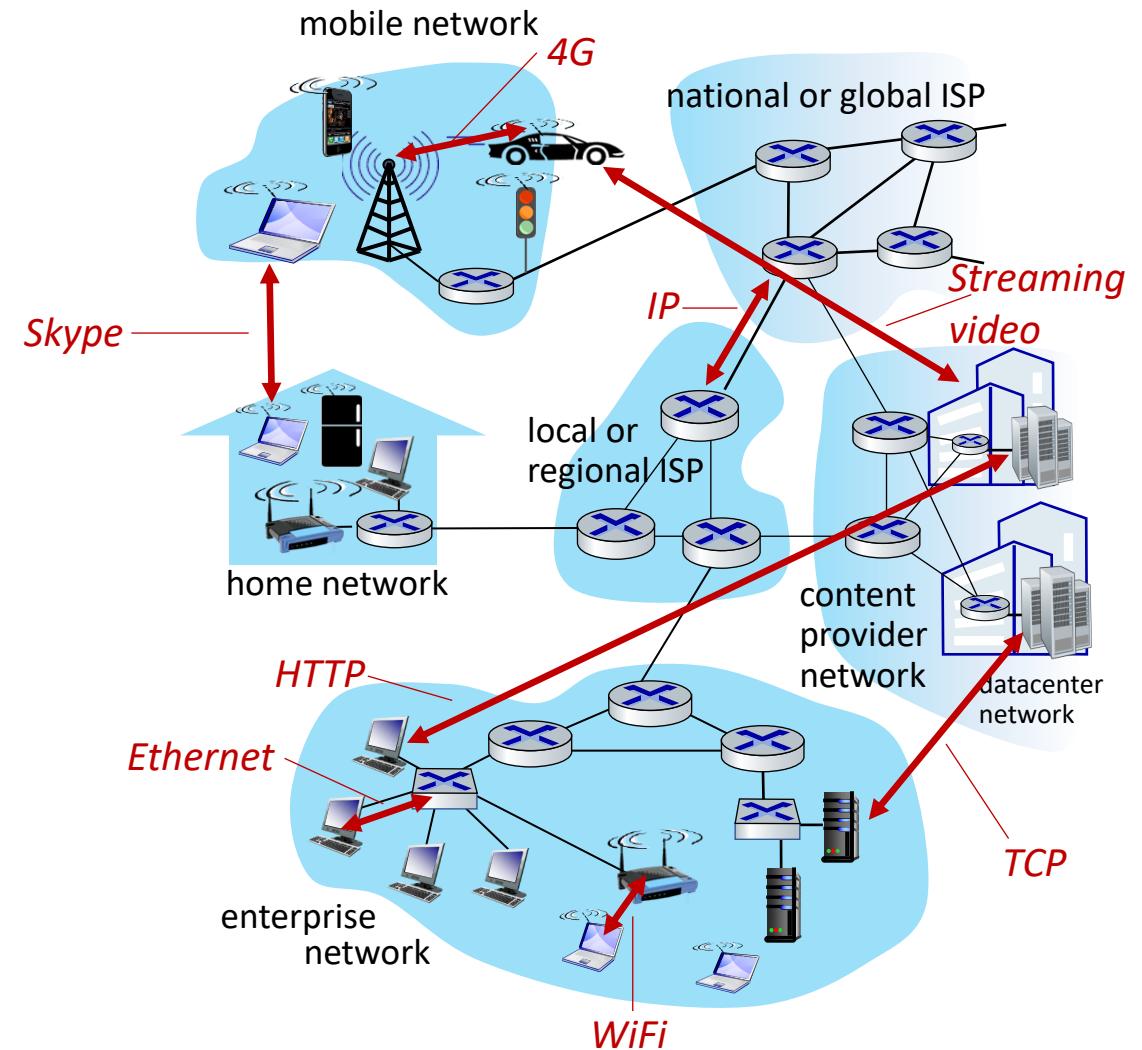
Networks

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



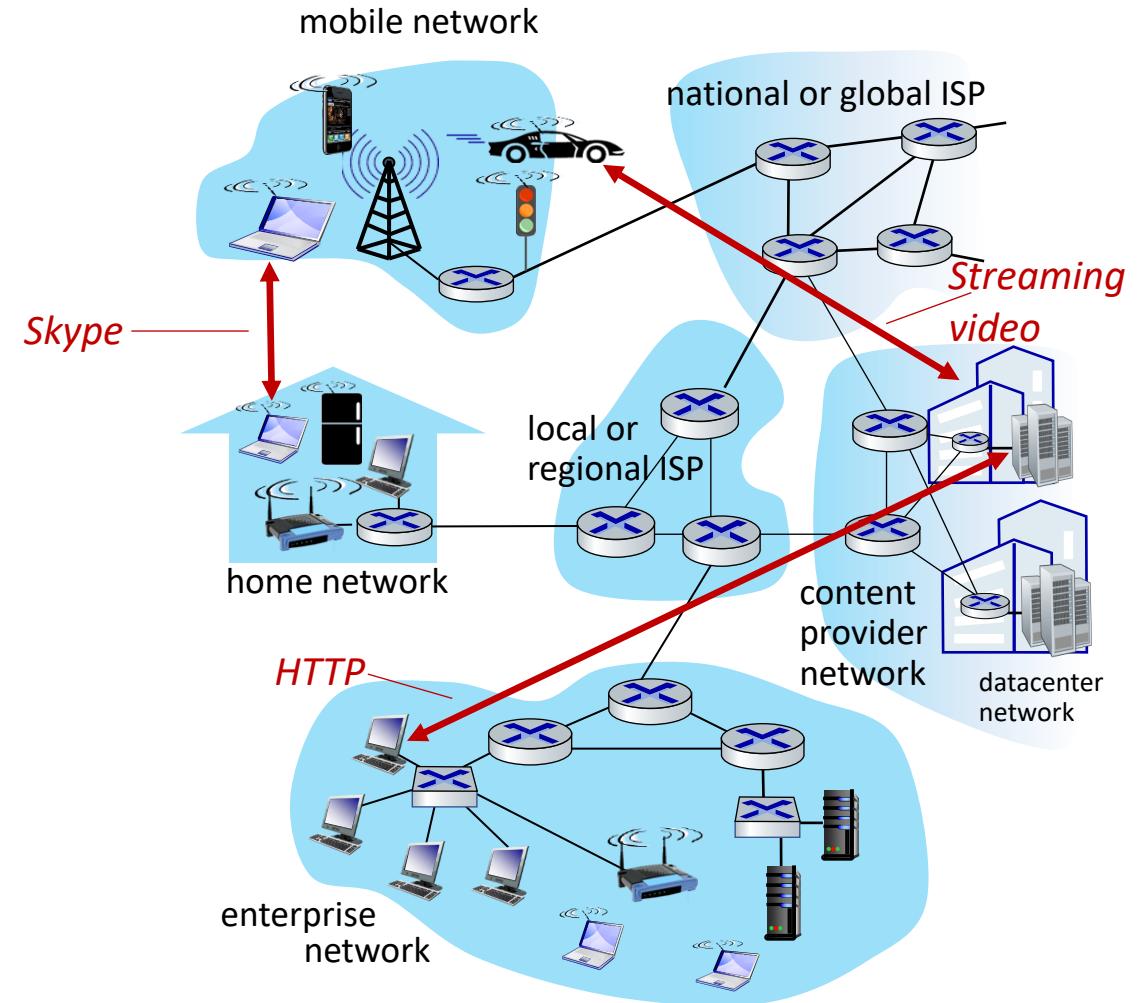
The Internet: a “nuts and bolts” view

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



The Internet: a “service” view

- *Infrastructure* that provides services to applications:
 - Web, streaming video, multimedia teleconferencing, email, games, e-commerce, social media, interconnected 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?

Human protocols:

- “what’s the time?”
- “I have a question”
- introductions

... specific messages sent
... specific actions taken
when message received,
or other events

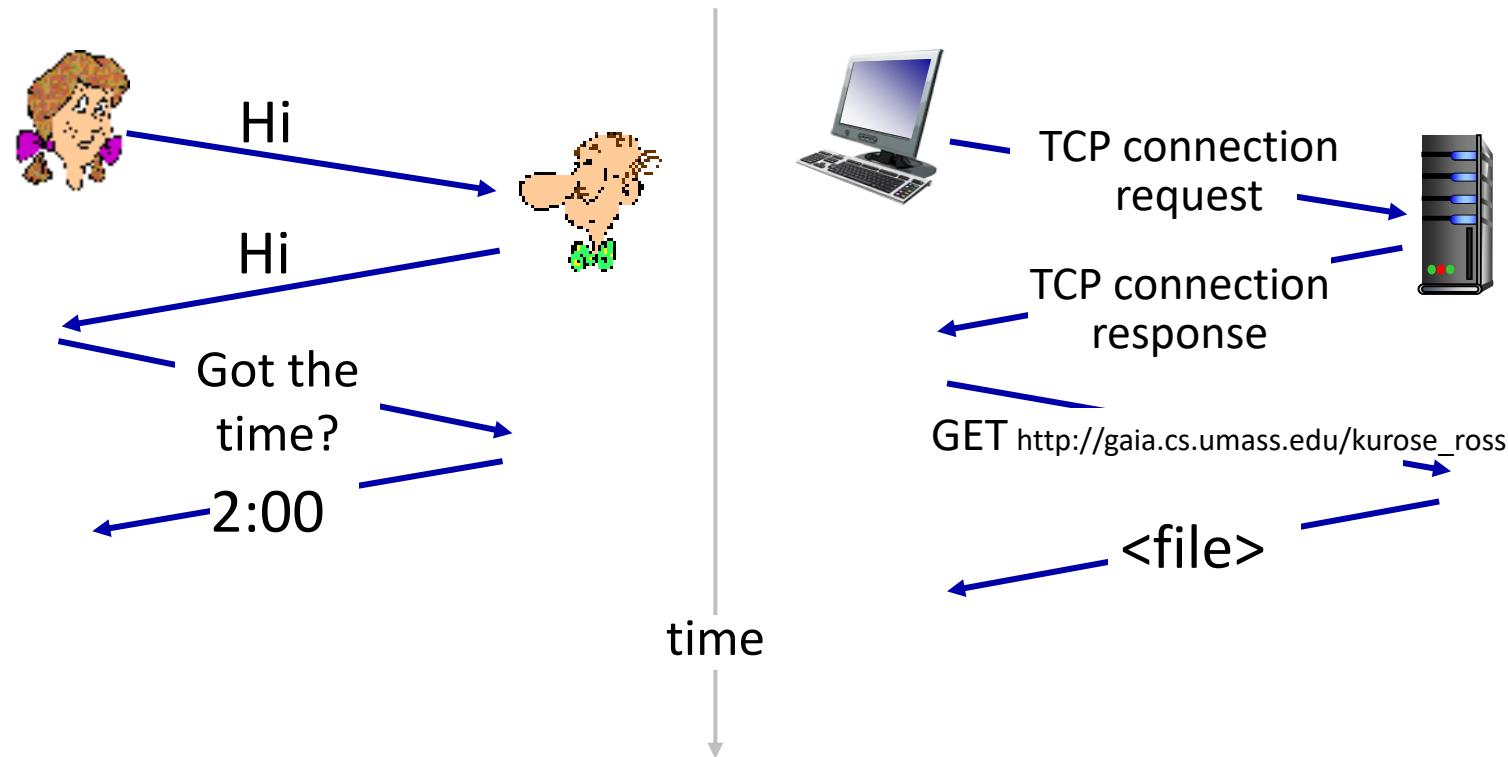
Network protocols:

- 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 msg transmission, receipt*

What's a protocol?

A human protocol and a computer network protocol:



Q: other human protocols?

Chapter 1: roadmap

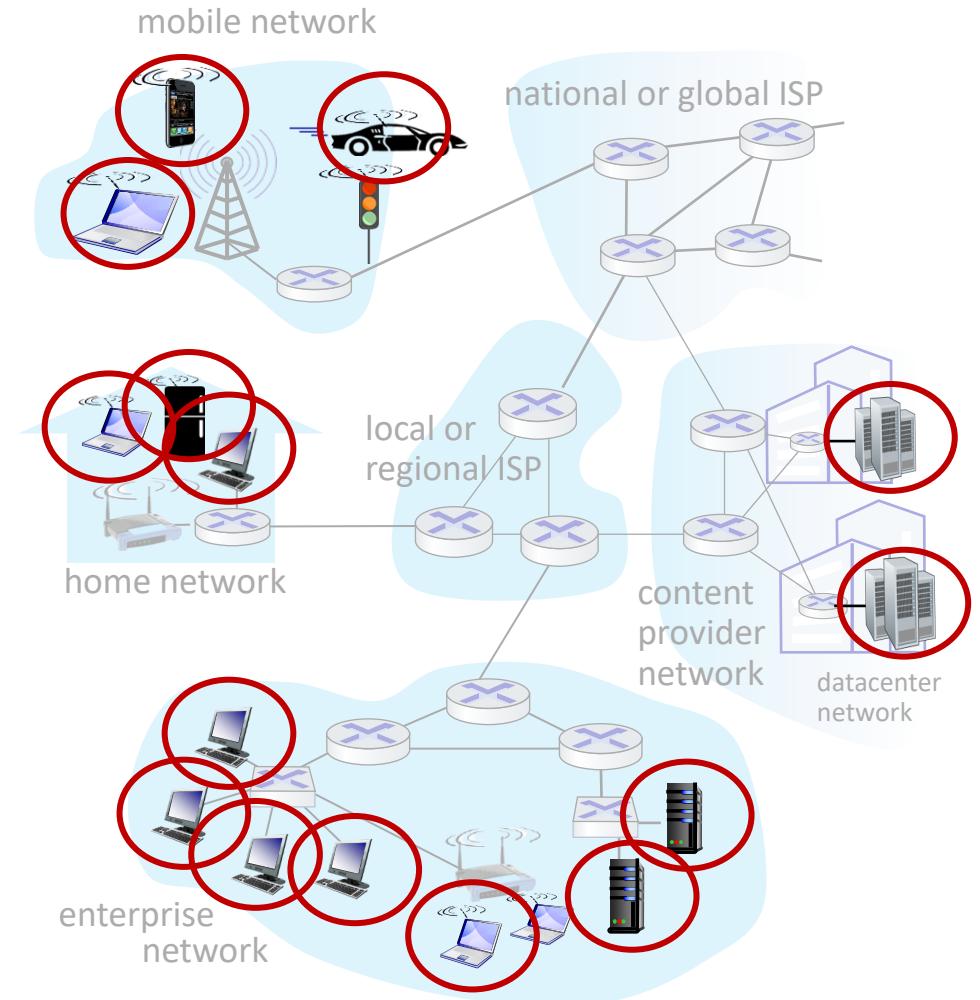
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A closer look at Internet structure

Network edge:

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



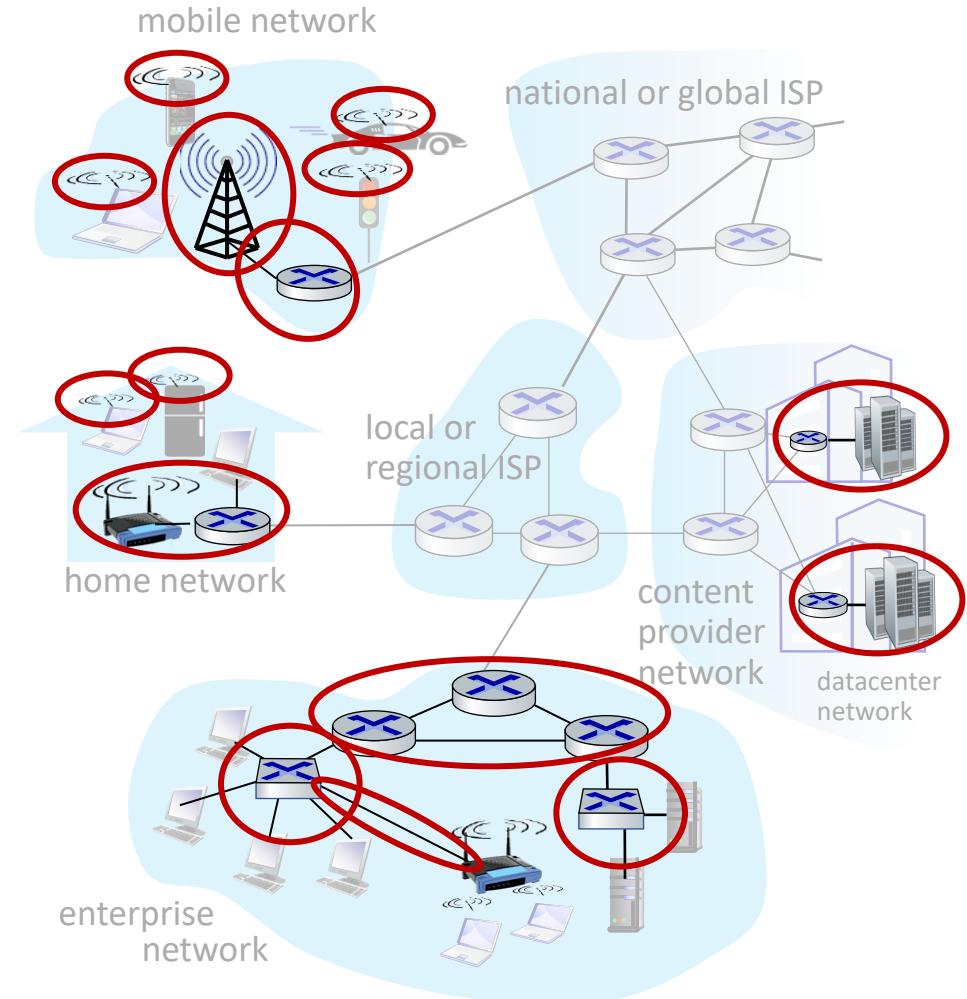
A closer look at Internet structure

Network edge:

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Access networks, physical media:

- wired, wireless communication links



A closer look at Internet structure

Network edge:

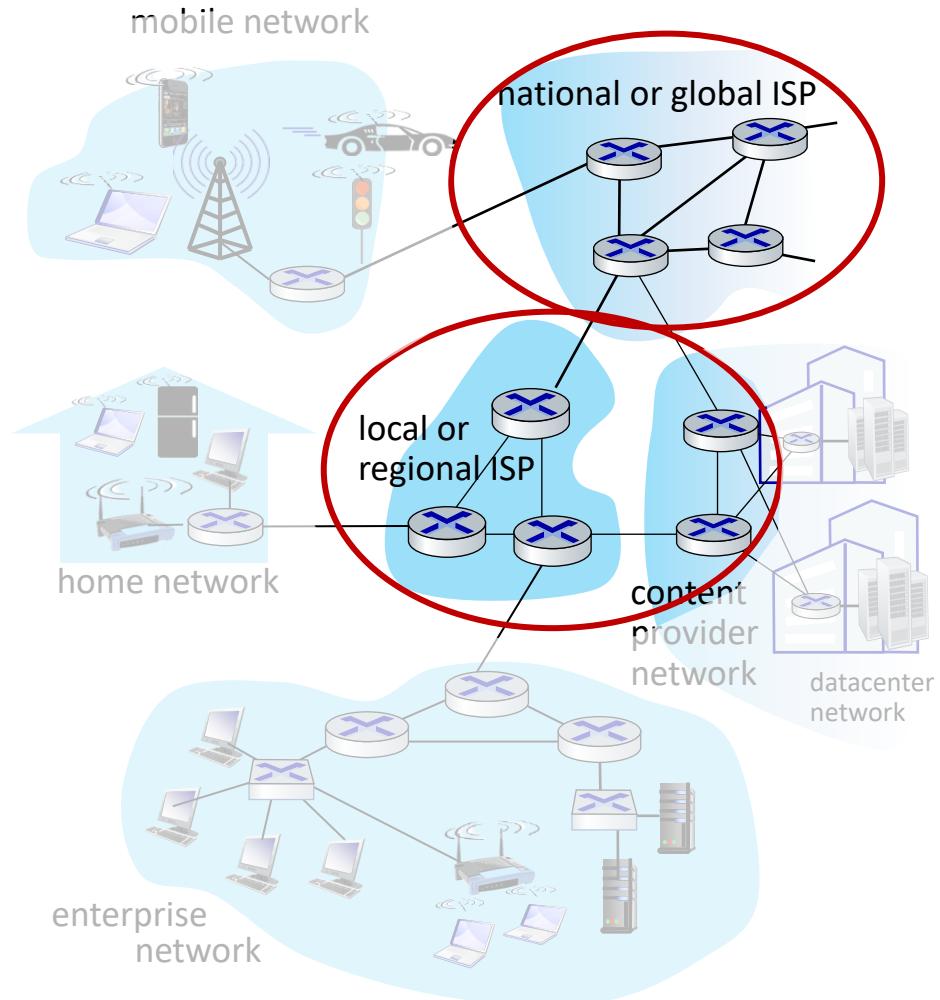
- hosts: clients and servers
- servers often in data centers

Access networks, physical media:

- wired, wireless communication links

Network core:

- interconnected routers
- network of networks



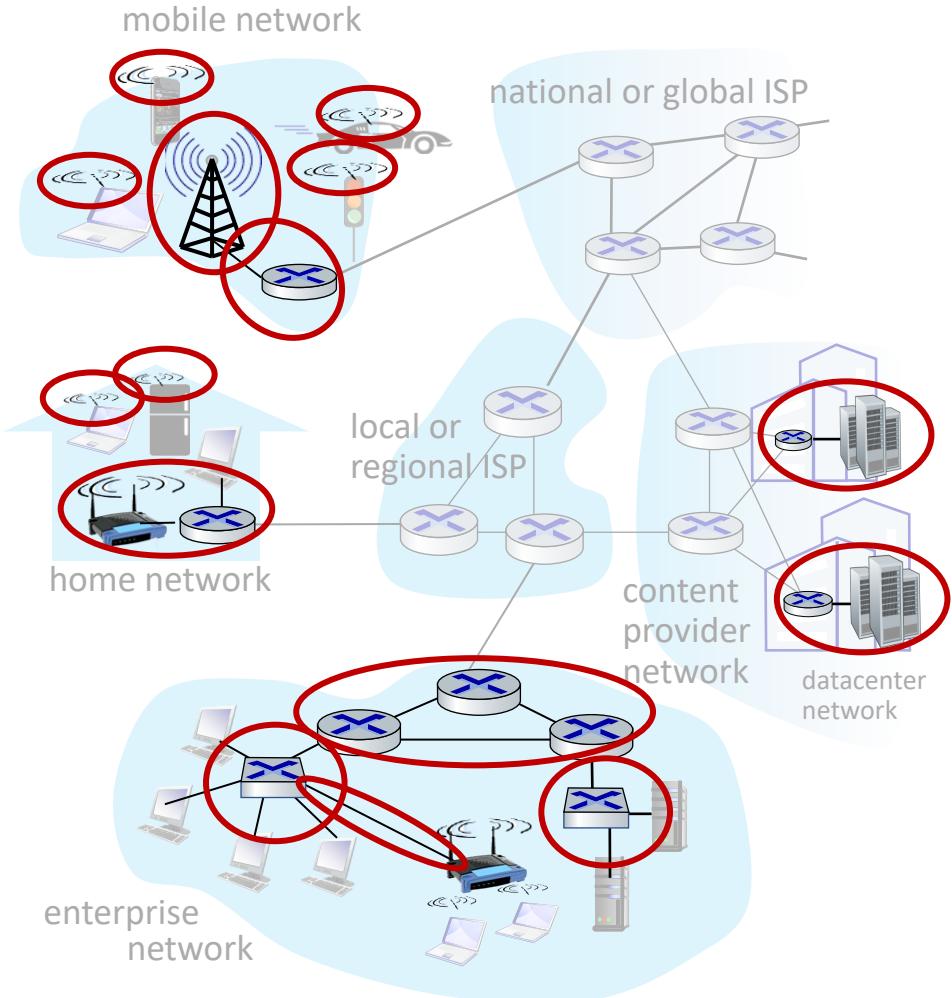
Access networks and physical media

*Q: How to connect end systems
to edge router?*

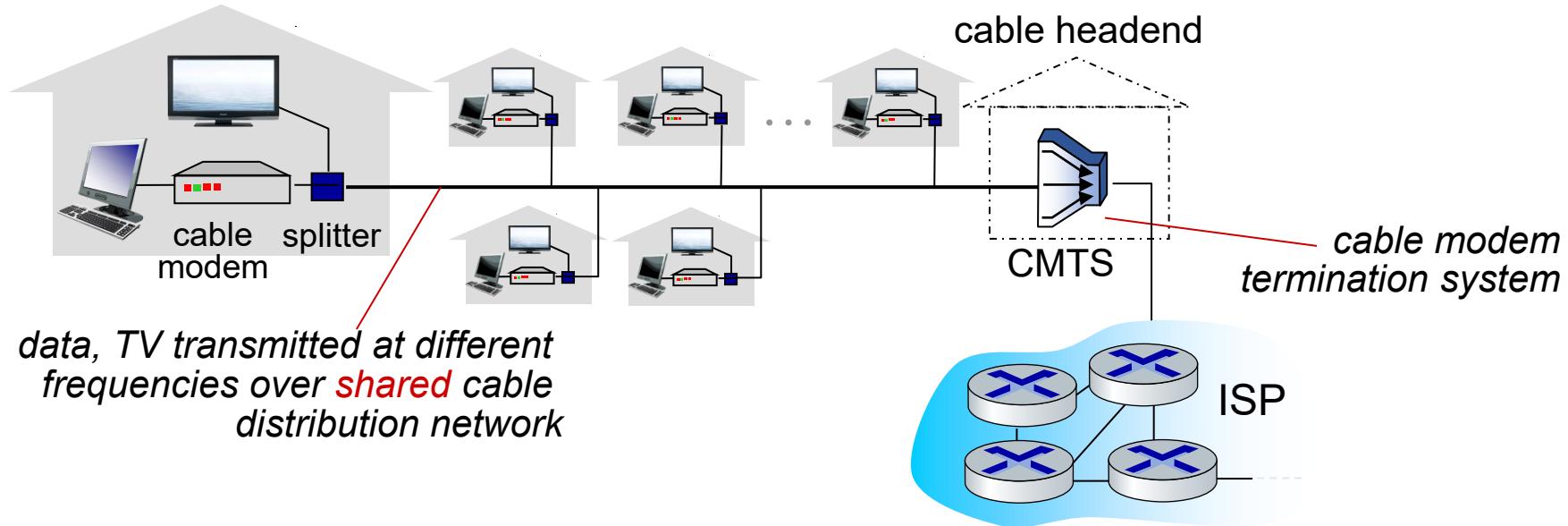
- residential access nets
- institutional access networks (school, company)
- mobile access networks (WiFi, 4G/5G)

What to look for:

- transmission rate (bits per second) of access network?
- shared or dedicated access among users?

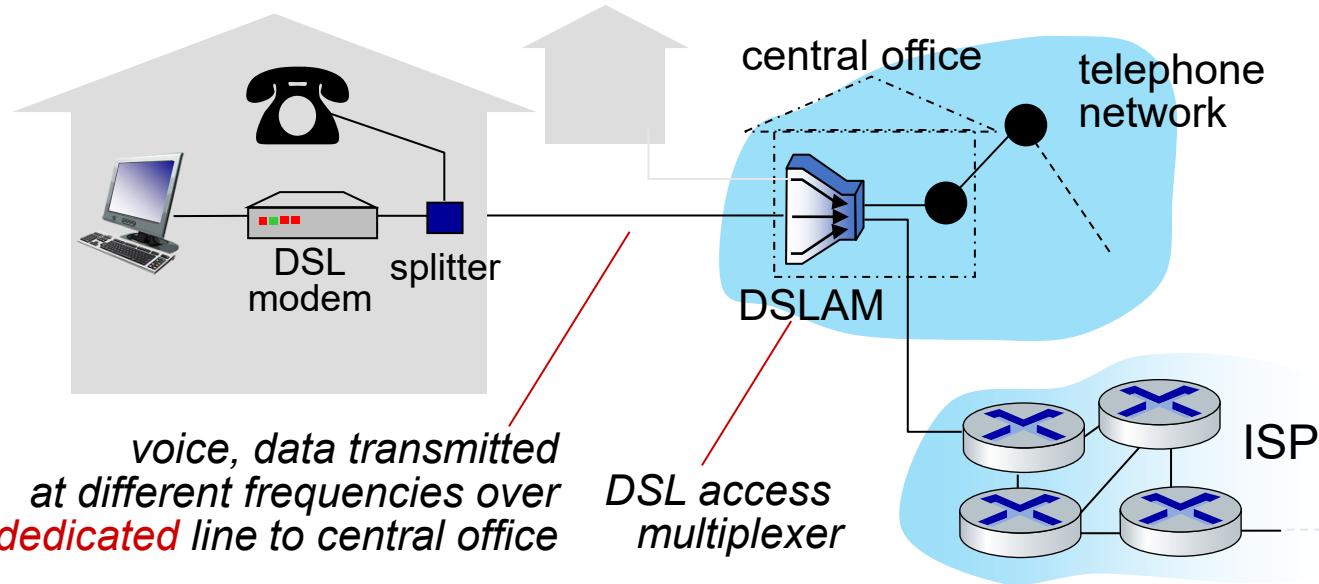


Access networks: cable-based access



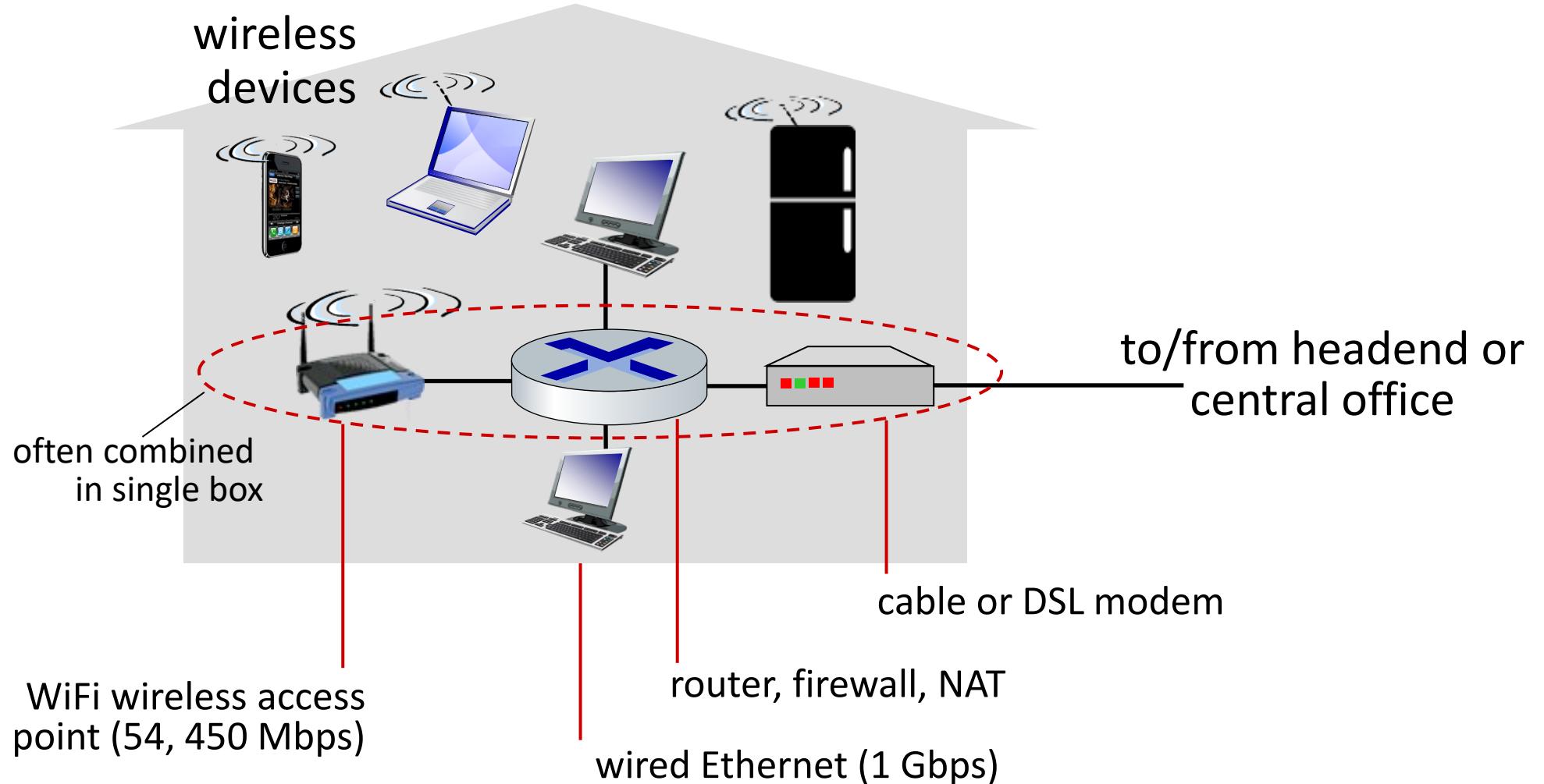
- HFC: hybrid fiber coax
 - asymmetric: up to 40 Mbps – 1.2 Gbs downstream transmission rate, 30-100 Mbps upstream transmission rate
- network of cable, fiber attaches homes to ISP router
 - homes **share access network** to cable headend

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



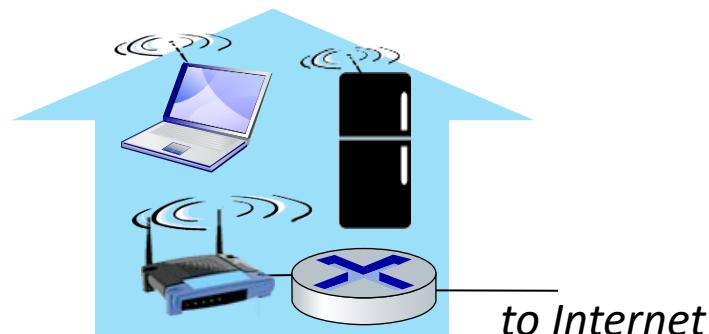
Wireless access networks

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

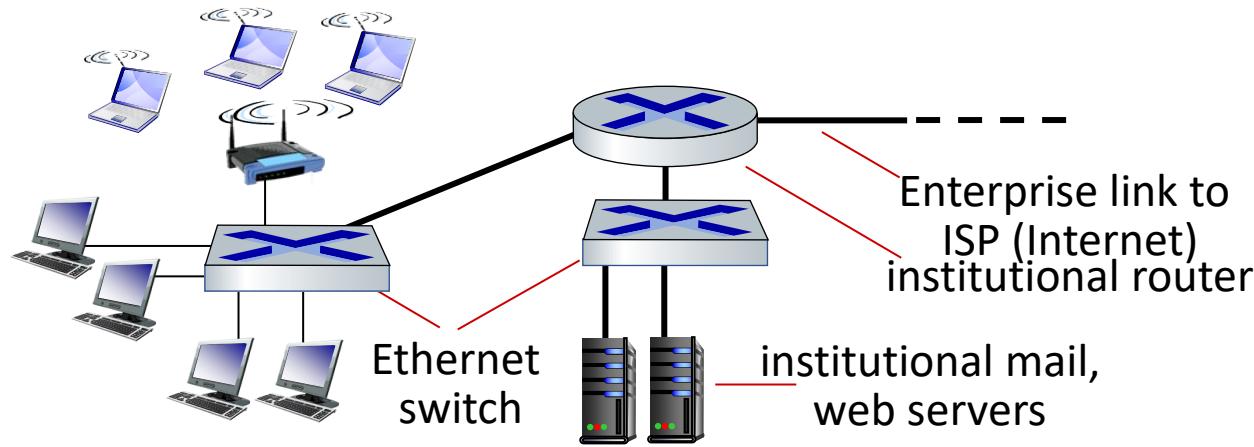


Wide-area cellular access networks

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



Access networks: enterprise networks

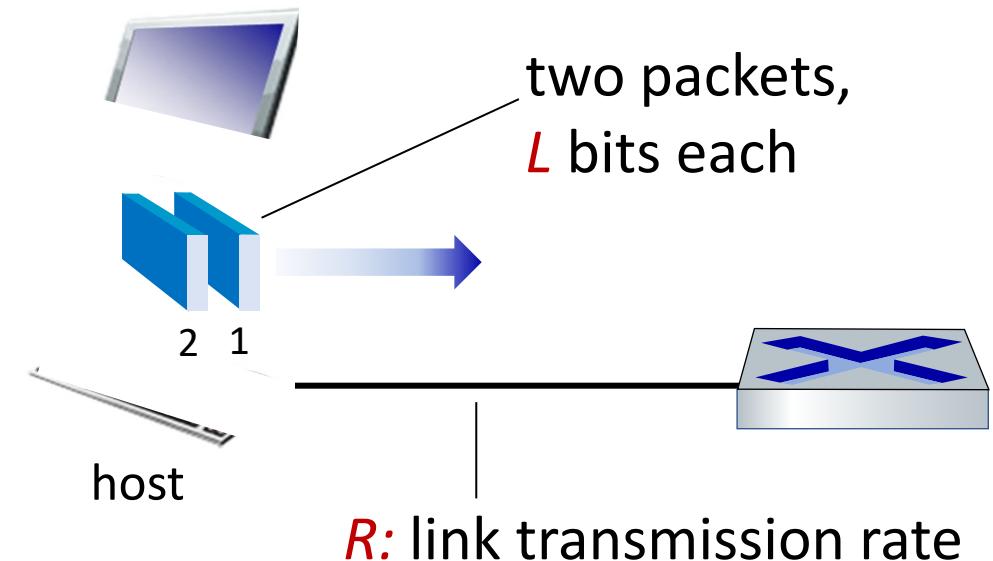


- companies, universities, etc.
- mix of wired, wireless link technologies, connecting a mix of switches and routers (we'll cover differences shortly)
 - Ethernet: wired access at 100Mbps, 1Gbps, 10Gbps
 - WiFi: wireless access points at 11, 54, 450 Mbps

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*



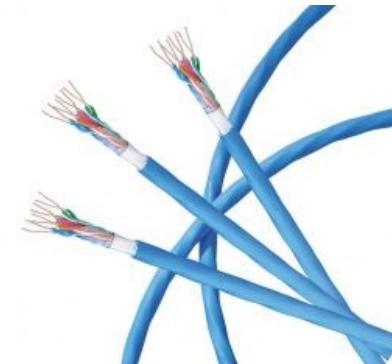
$$\text{packet transmission delay} = \frac{\text{time needed to transmit } L\text{-bit packet into link}}{R \text{ (bits/sec)}} = \frac{L \text{ (bits)}}{R \text{ (bits/sec)}}$$

Links: physical media

- **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

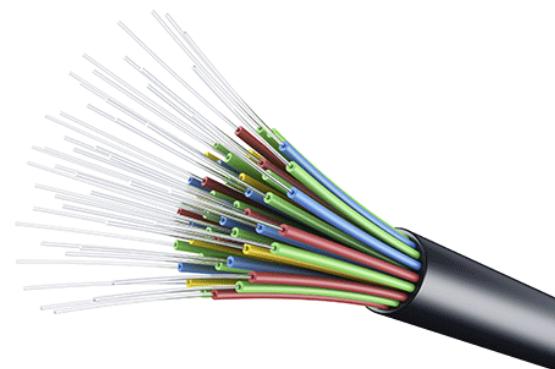
Coaxial cable:

- 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

Wireless radio

- signal carried in electromagnetic spectrum
- no physical “wire”
- broadcast and “half-duplex” (sender to receiver)
- propagation environment effects:
 - reflection
 - obstruction by objects
 - interference

Radio link types:

- terrestrial microwave
 - up to 45 Mbps channels
- Wireless LAN (WiFi)
 - Up to 100's Mbps
- wide-area (e.g., cellular)
 - 4G cellular: ~ 10's Mbps
- satellite
 - up to 45 Mbps per channel
 - 270 msec end-end delay
 - geosynchronous versus low-earth-orbit

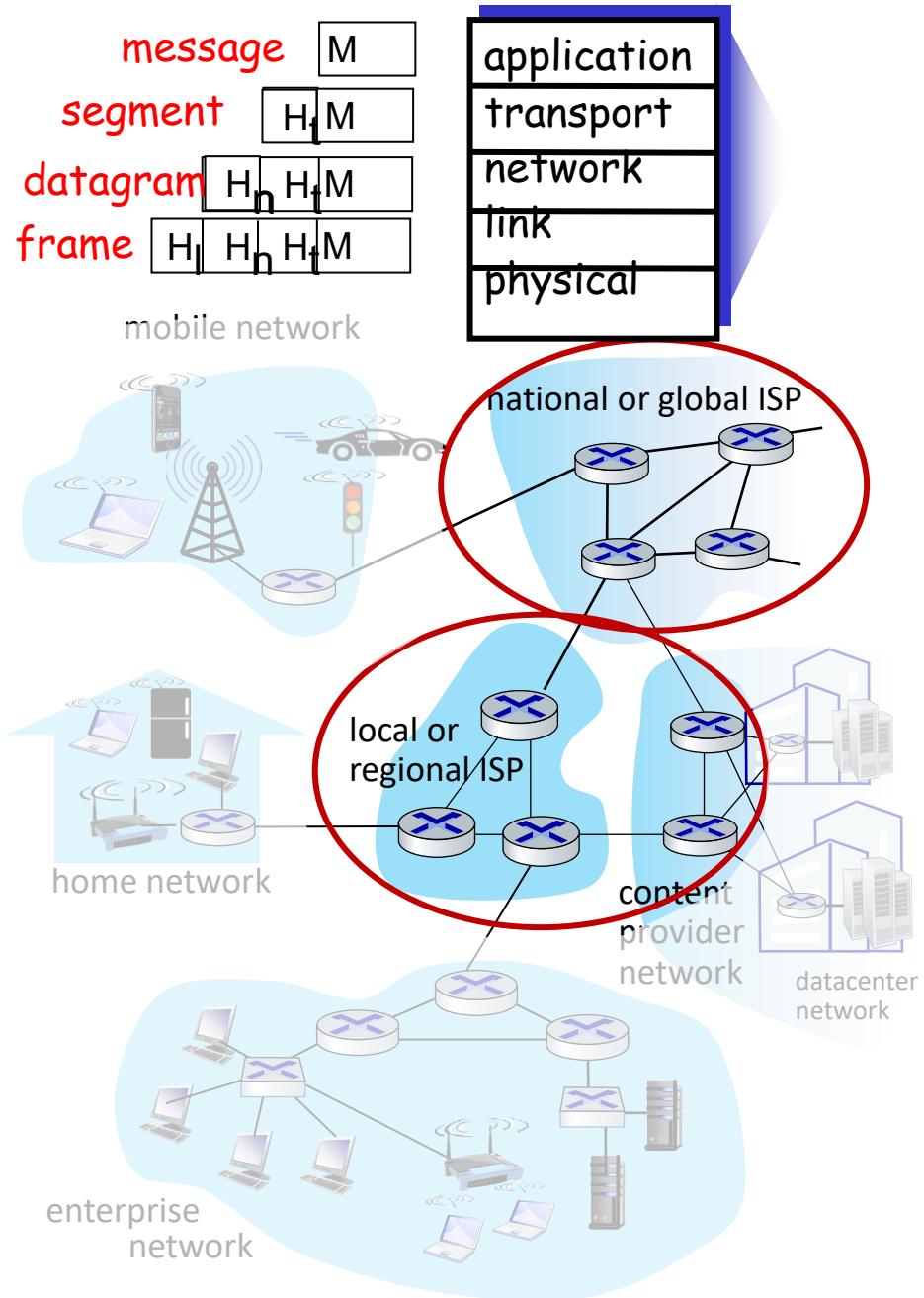
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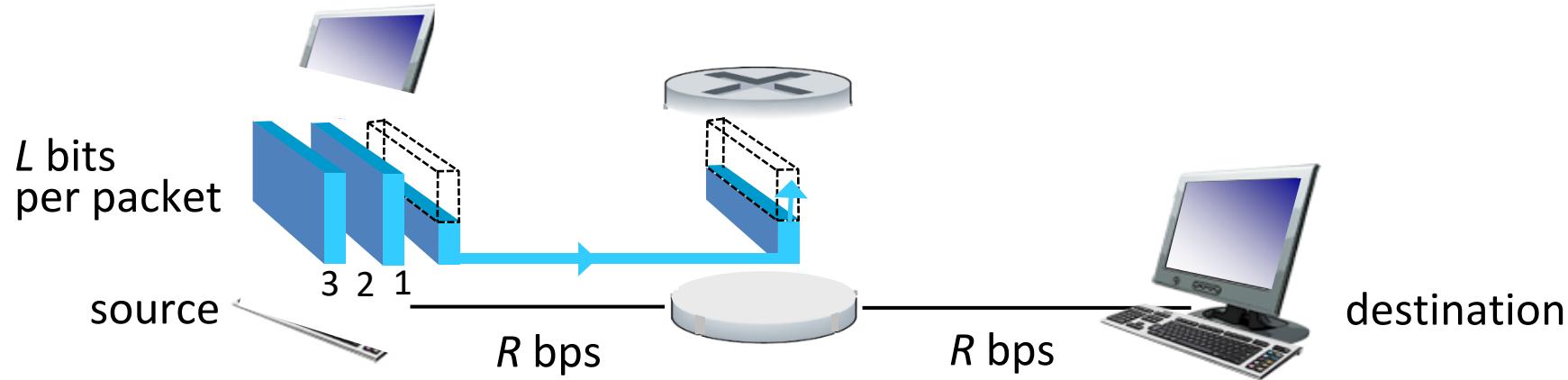


The network core

- mesh of interconnected routers
- **packet-switching:** hosts break application-layer messages into *packets*
 - forward packets from one router to the next, across links on path from source to destination
 - each packet transmitted at full link capacity



Packet-switching: store-and-forward

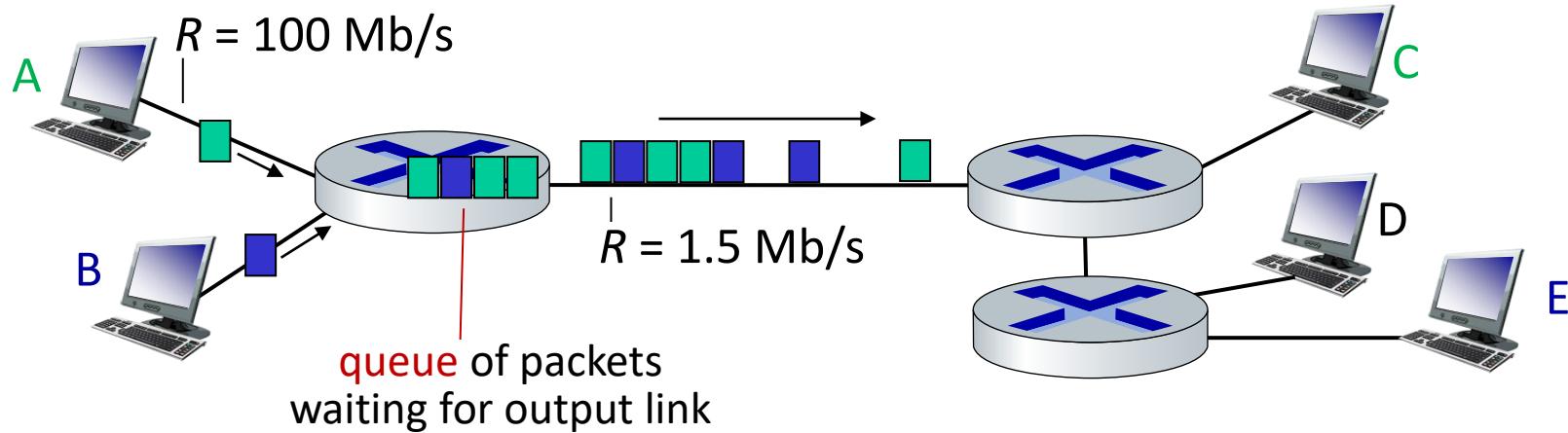


- **Transmission delay:** takes L/R seconds to transmit (push out) L -bit packet into link at R bps
- **Store and forward:** entire packet must arrive at router before it can be transmitted on next link
- **End-end delay:** $2L/R$ (above), assuming zero propagation delay (more on delay shortly)

One-hop numerical example:

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

Packet-switching: queueing delay, loss



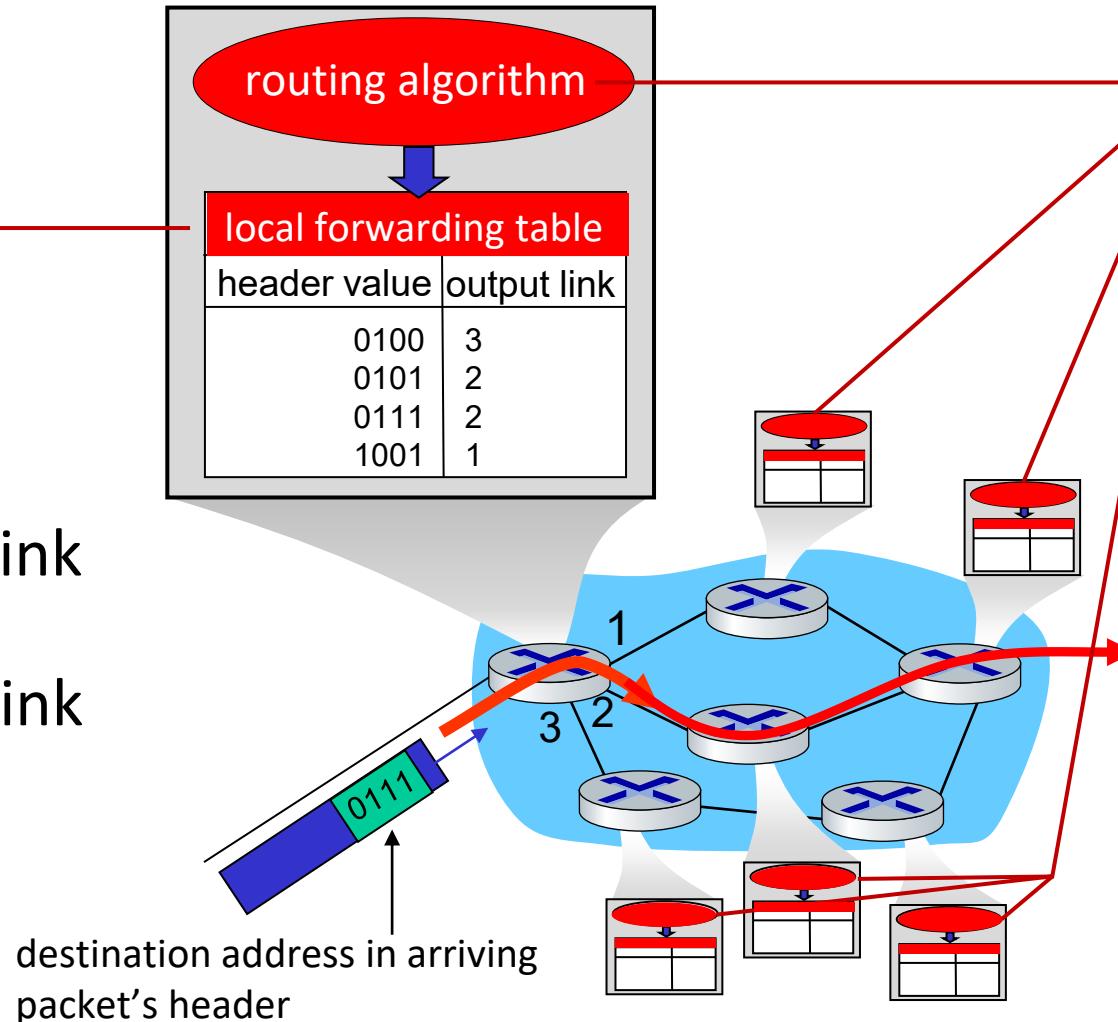
Packet queuing and loss: if arrival rate (in bps) to link exceeds transmission rate (bps) of link for a period of time:

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

Two key network-core functions

Forwarding:

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



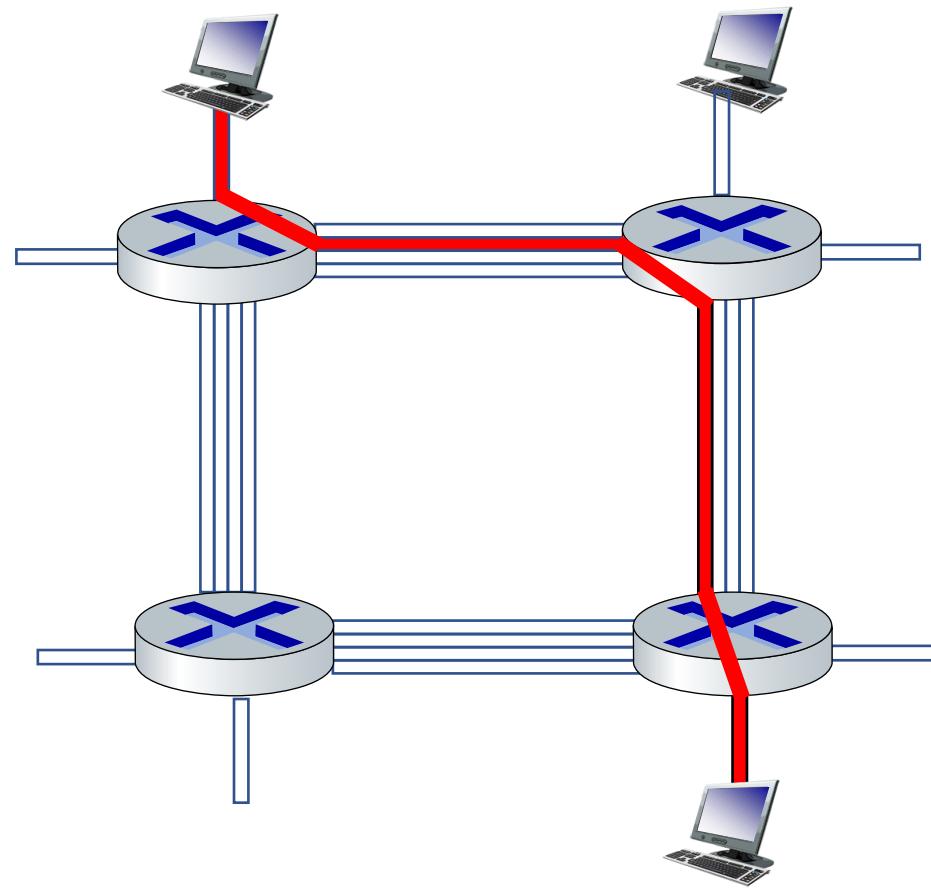
Routing:

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

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



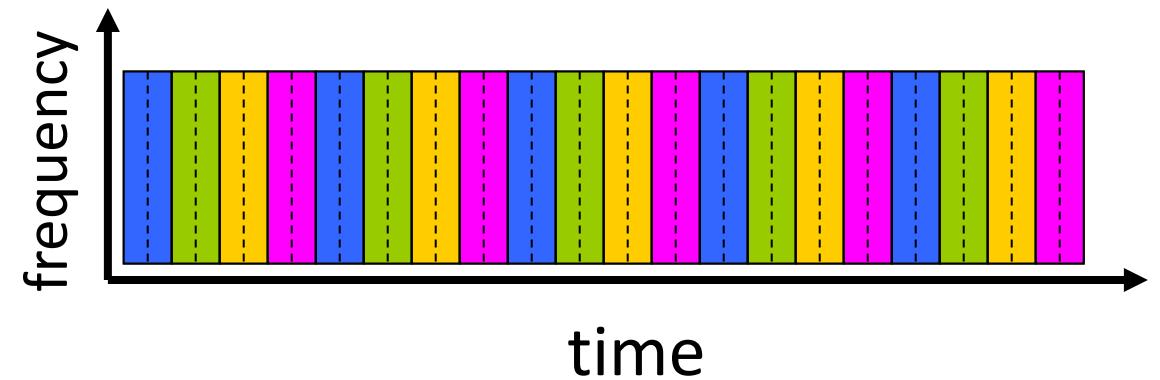
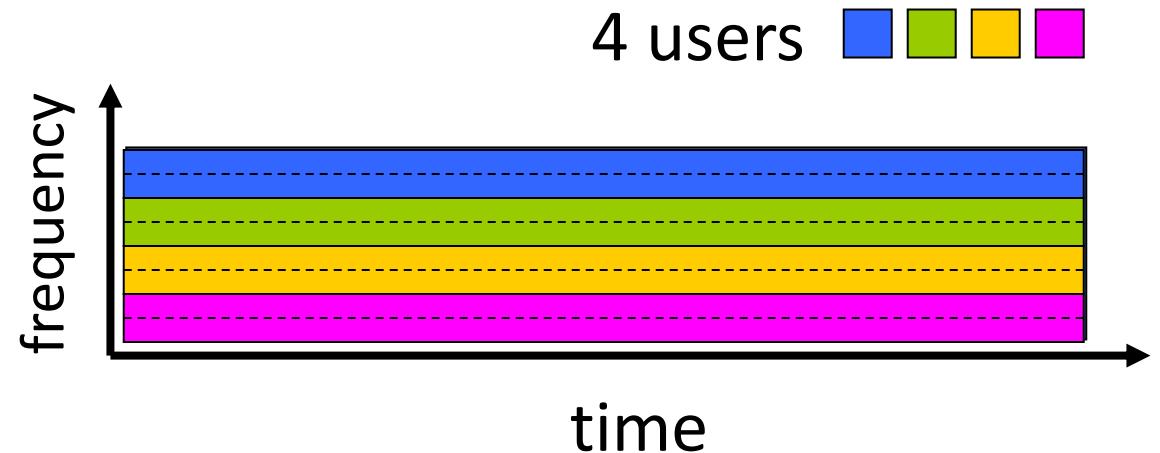
Circuit switching: FDM and TDM

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, but only during its time slot(s)

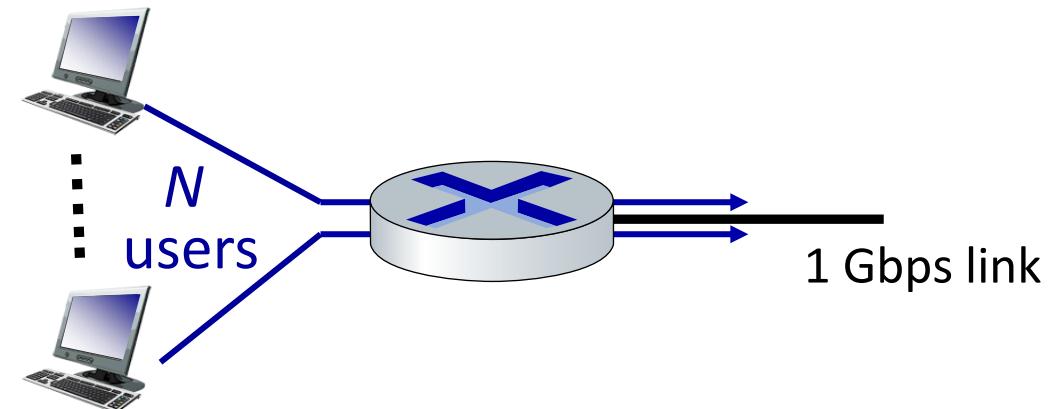


Packet switching versus circuit switching

packet switching allows more users to use network!

Example:

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

Q: what happens if > 35 users ?

* 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?**
 - bandwidth guarantees traditionally used for audio/video applications

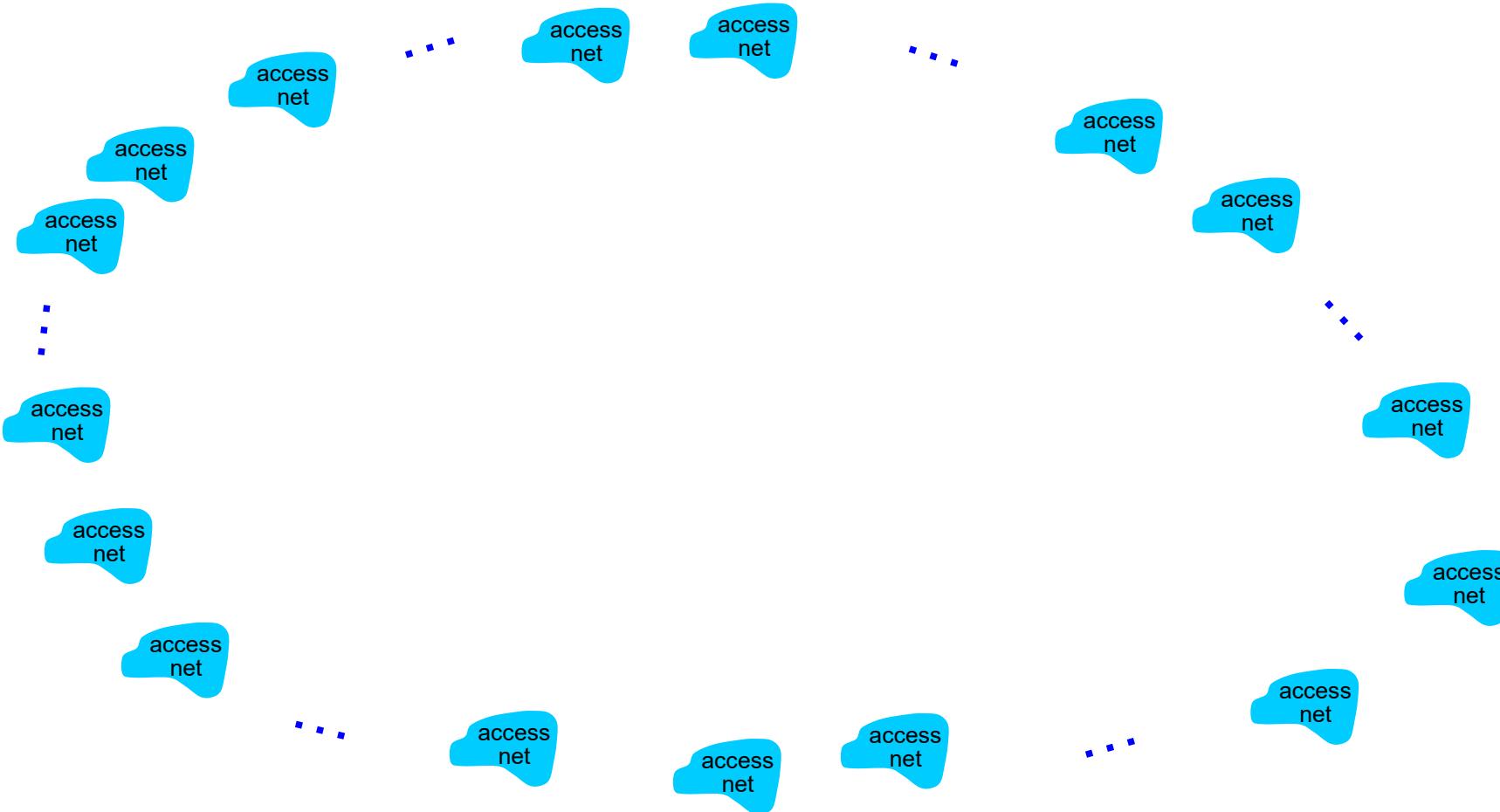
Q: human analogies of reserved resources (circuit switching) versus on-demand allocation (packet switching)?

Internet structure: a “network of networks”

- Hosts connect to Internet via **access** Internet Service Providers (ISPs)
 - residential, enterprise (company, university, commercial) ISPs
- Access ISPs in turn must be interconnected
 - so that any two hosts can send packets to each other
- Resulting network of networks is very complex
 - evolution was driven by **economics** and **national policies**
- Let's take a stepwise approach to describe current Internet structure

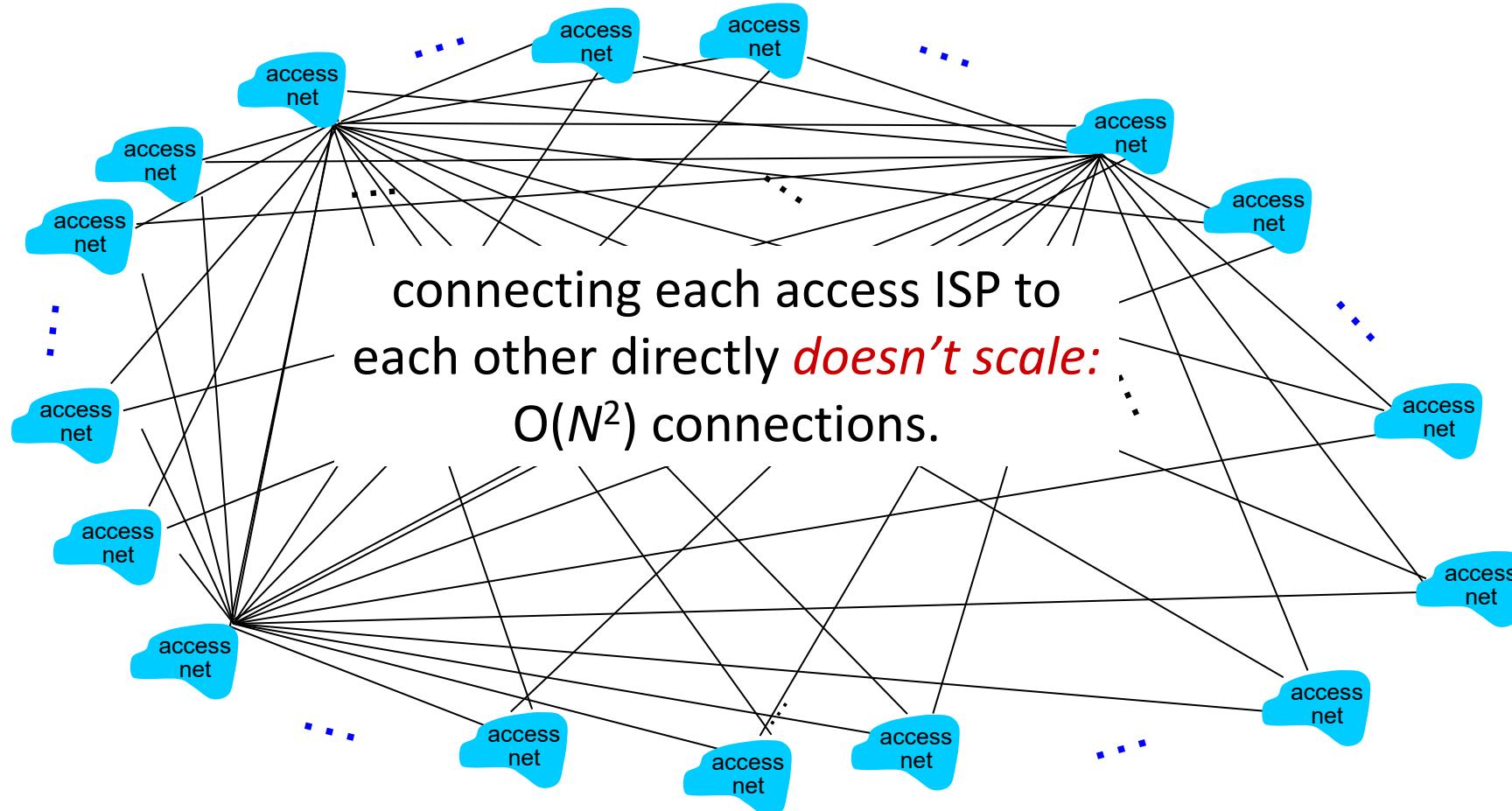
Internet structure: a “network of networks”

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



Internet structure: a “network of networks”

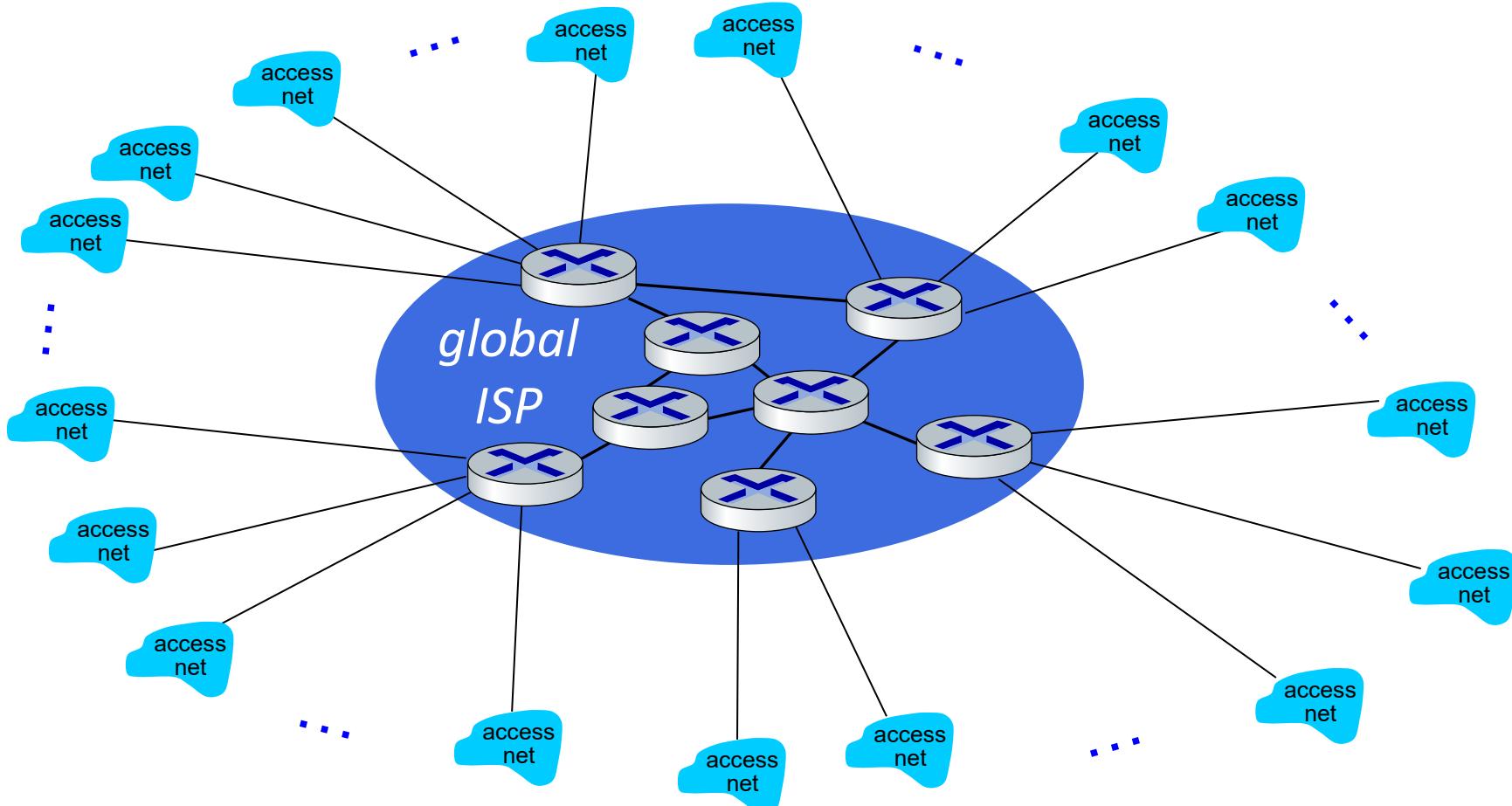
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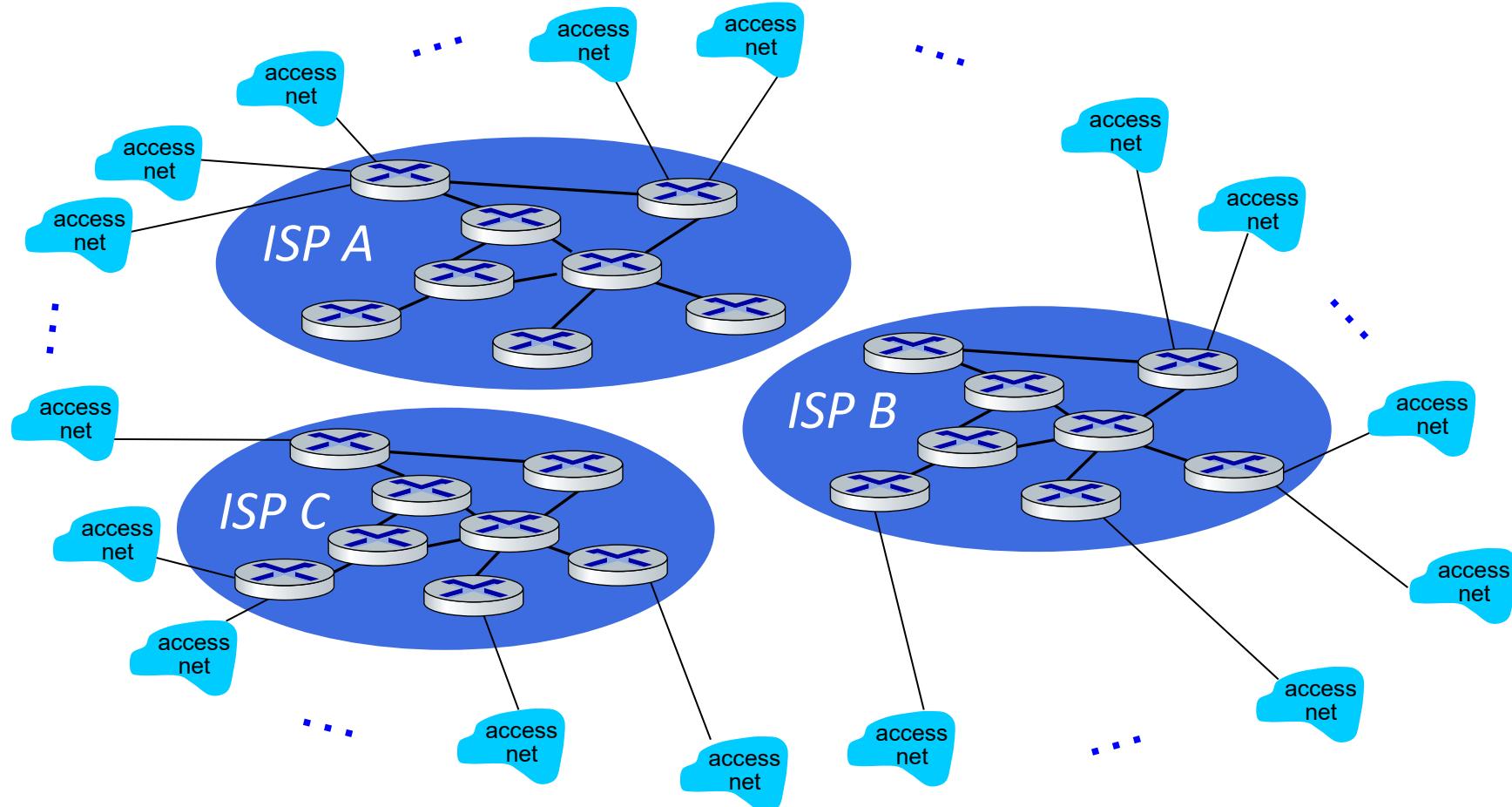
Option: connect each access ISP to one global transit ISP?

Customer and provider ISPs have economic agreement.



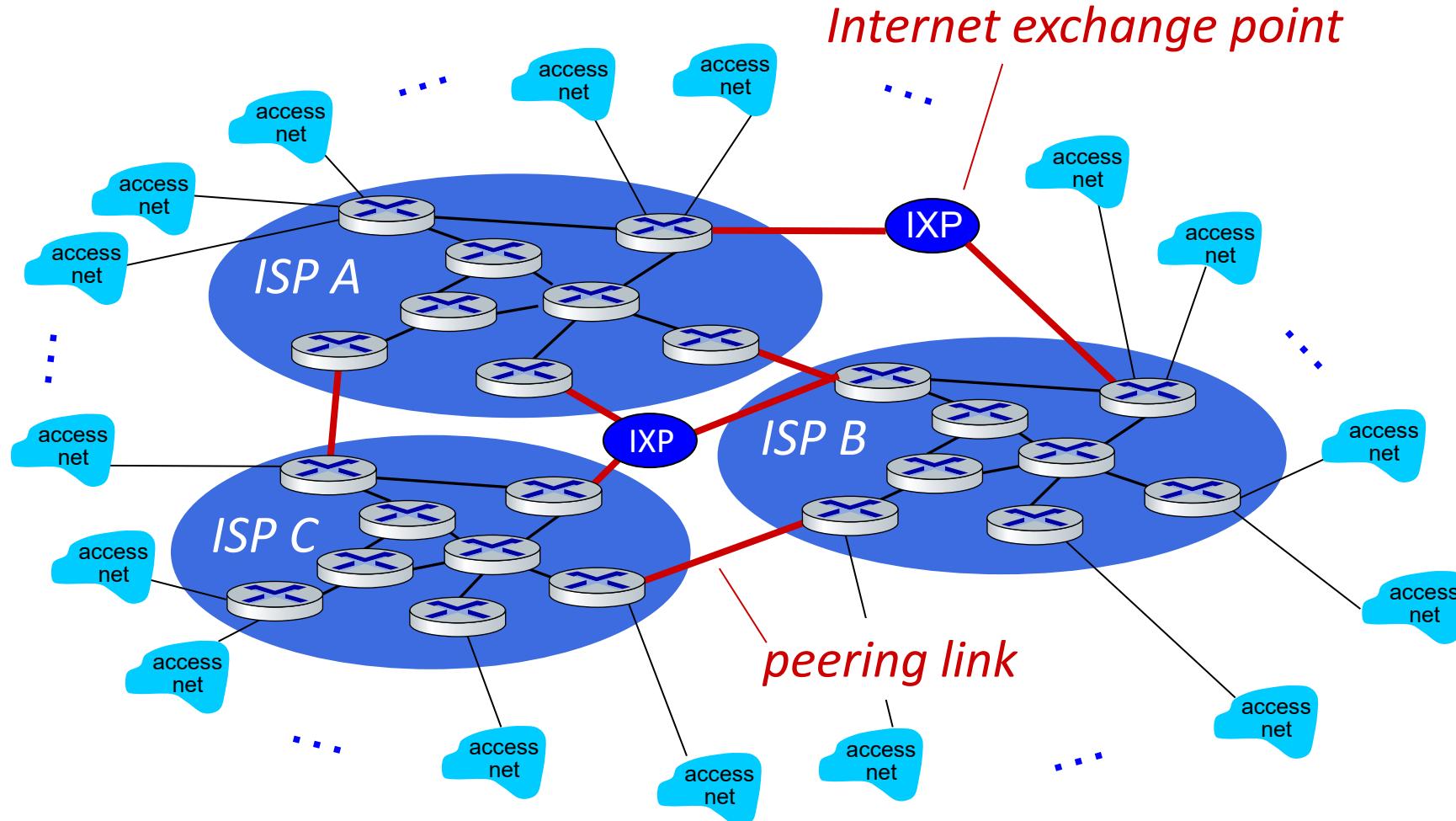
Internet structure: a “network of networks”

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



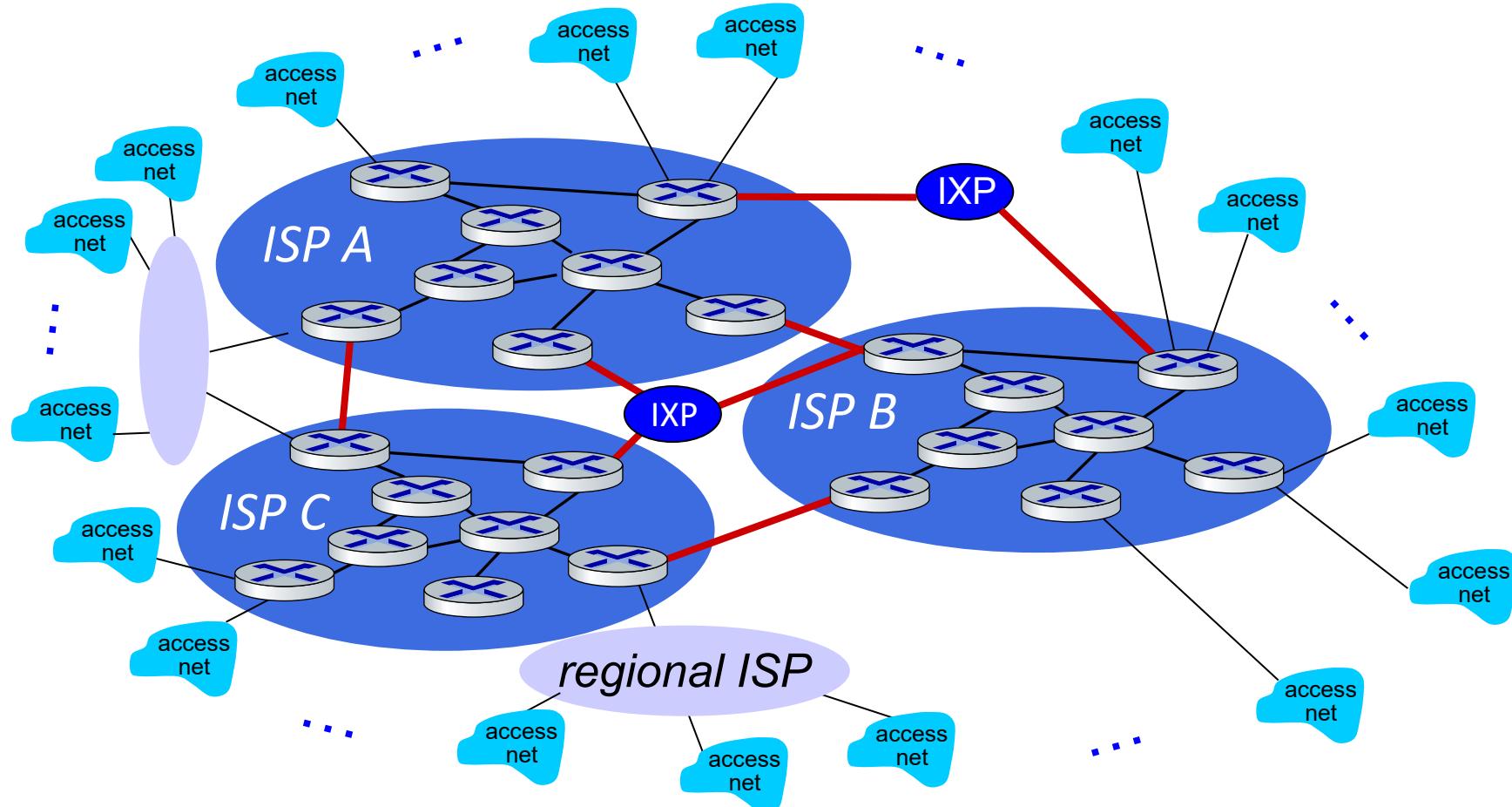
Internet structure: a “network of networks”

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



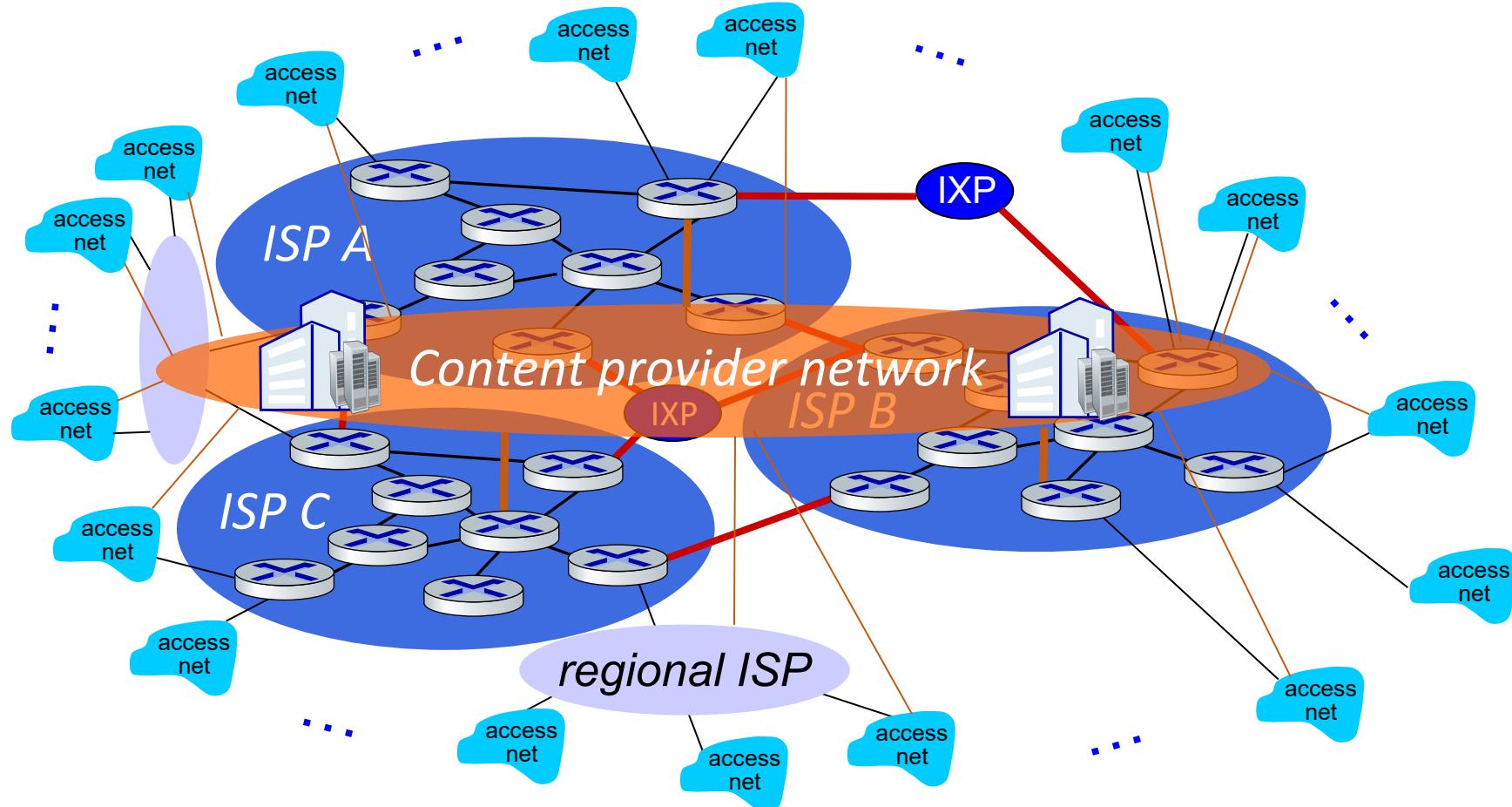
Internet structure: a “network of networks”

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

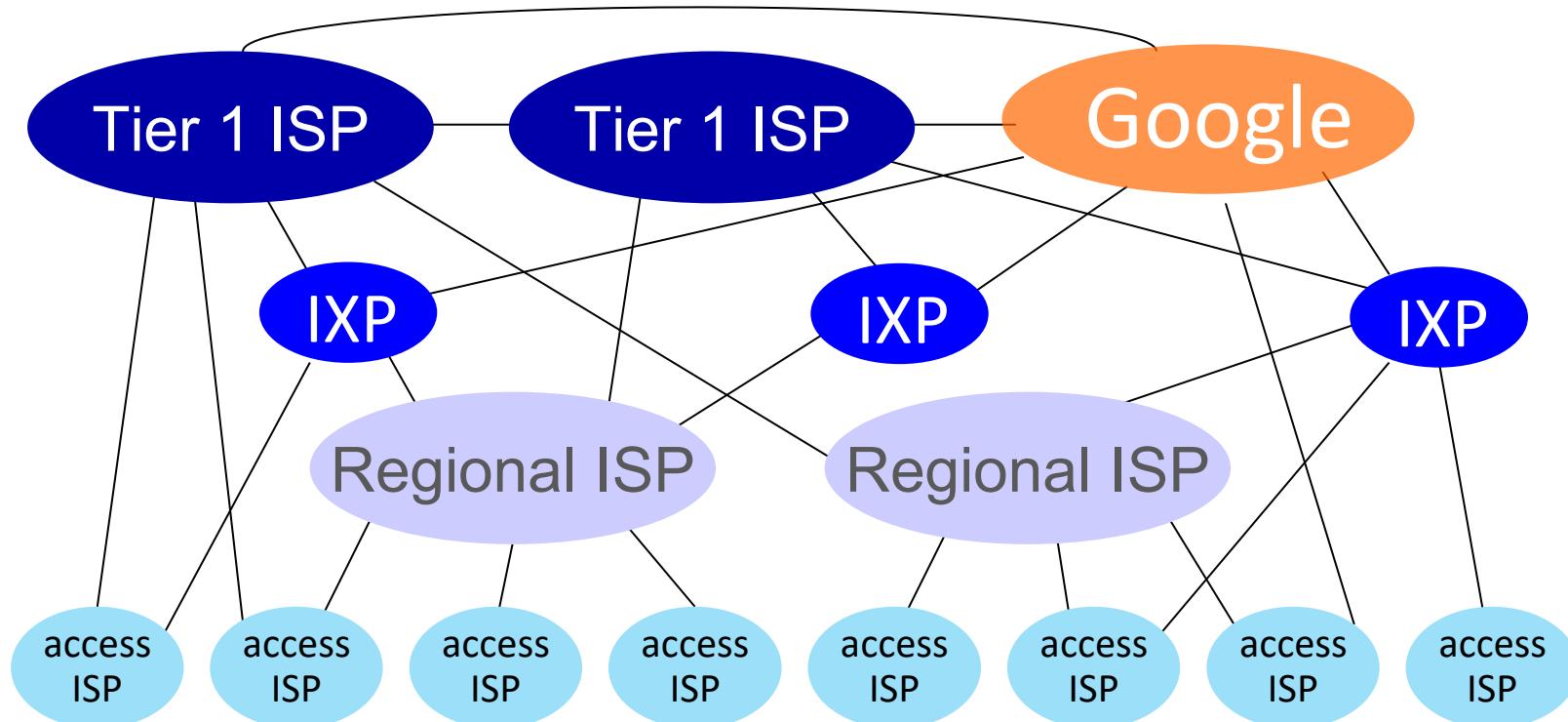


Internet structure: a “network of networks”

... 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

Tier-1 ISP Network map: Sprint (2019)



Chapter 1: roadmap

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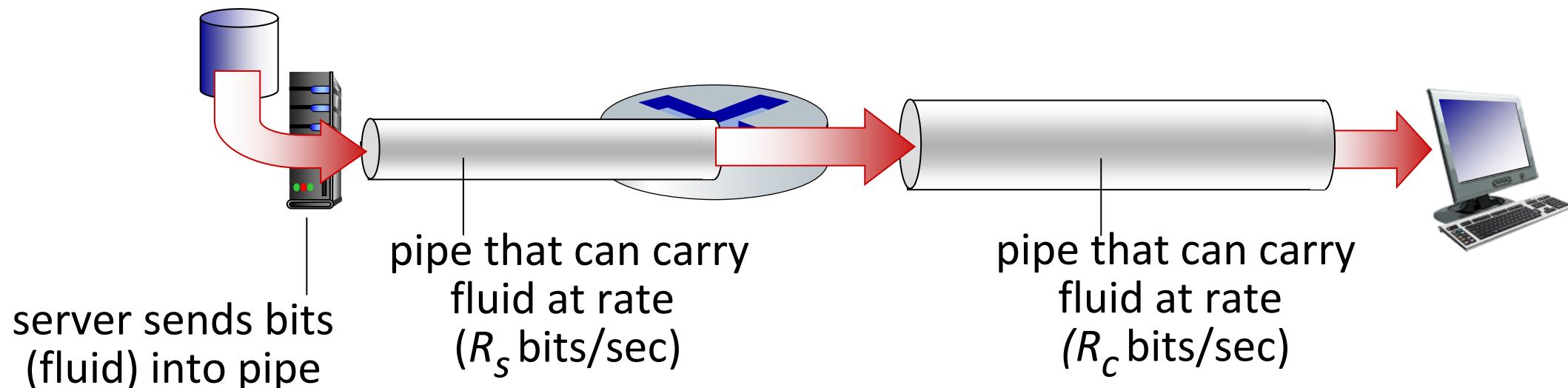


Bandwidth

- In computer networking, we use the term bandwidth in two contexts:
 - The first, **bandwidth in hertz**, which refers to the range of frequencies in composite signal or the range of frequencies that a link or a channel can pass.
 - The second, **bandwidth in bits per second (bps)**, which refers to the speed of bit transmission in a link or channel. In this case, it is also called as **capacity or link transmission rate**.
- For example,
 - The bandwidth of a subscriber line is 4 kHz for voice data.
 - The bandwidth of a link for data transmission is 56 kbps.

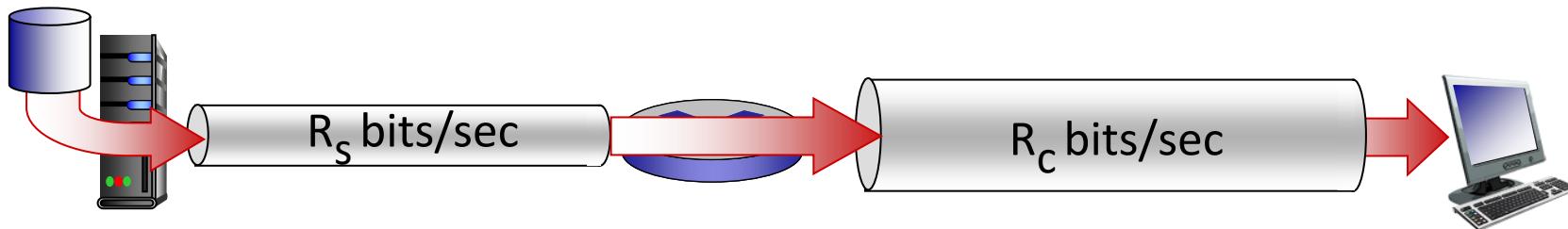
Throughput

- *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

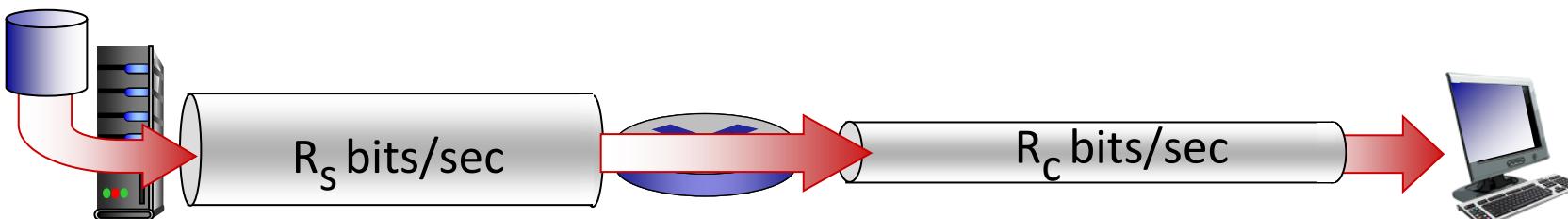


Throughput

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



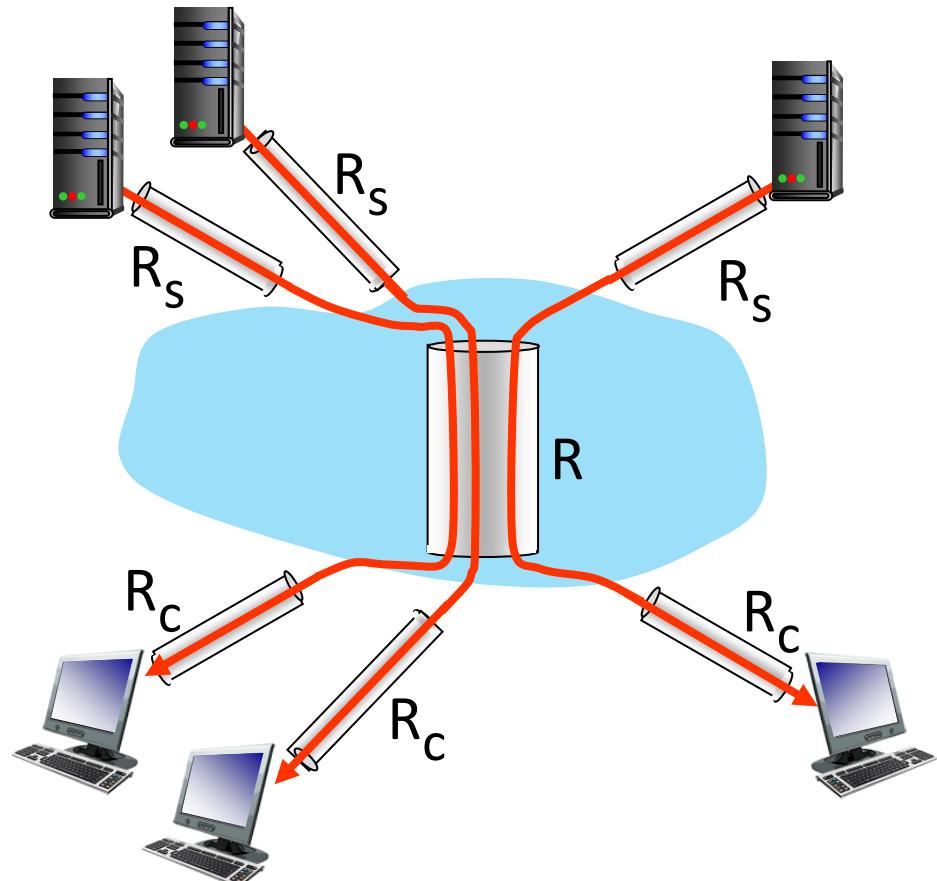
$R_s > R_c$ What is average end-end throughput?



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

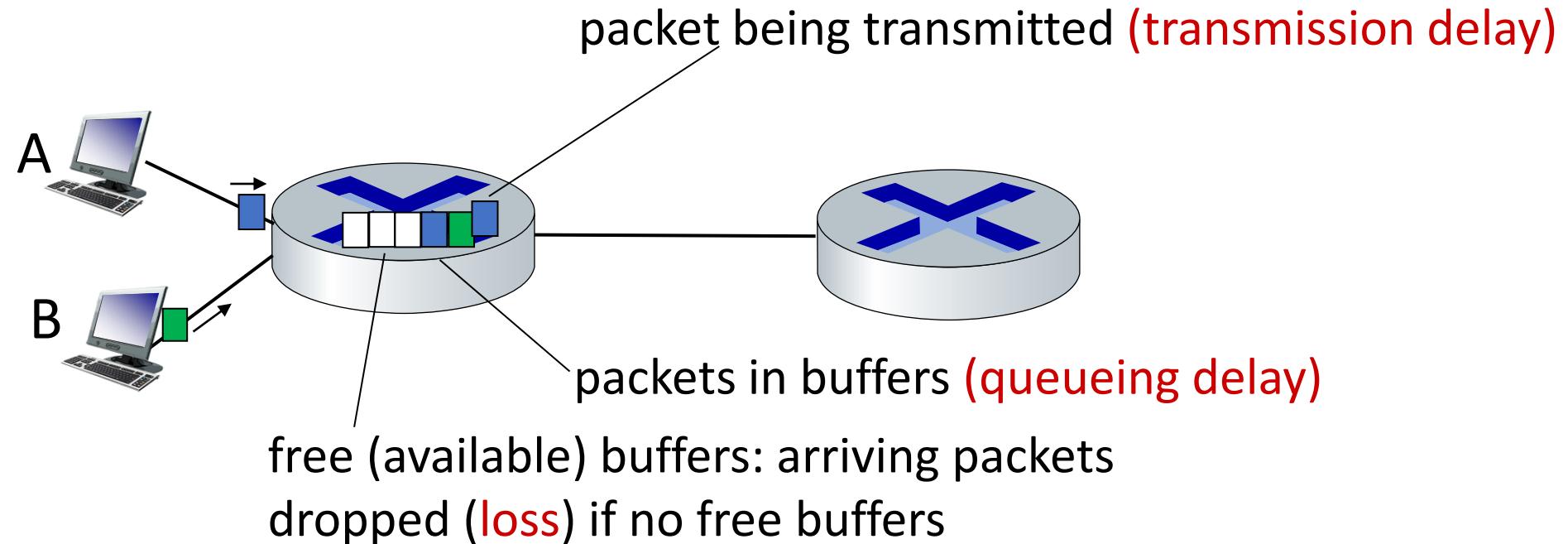
- per-connection end-end throughput: $\min(R_c, R_s, R/10)$
- in practice: R_c or R_s is often bottleneck

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

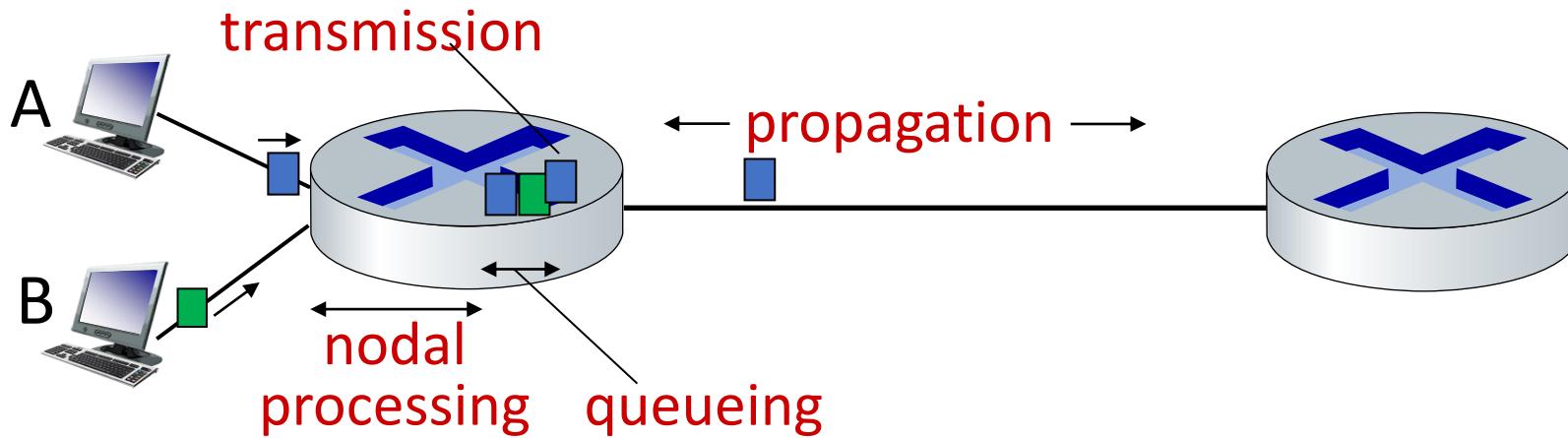
How do packet loss and delay occur?

packets *queue* in router buffers

- packets queue, wait for turn
- arrival rate to link (temporarily) exceeds output link capacity: packet loss



Packet delay: four sources



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

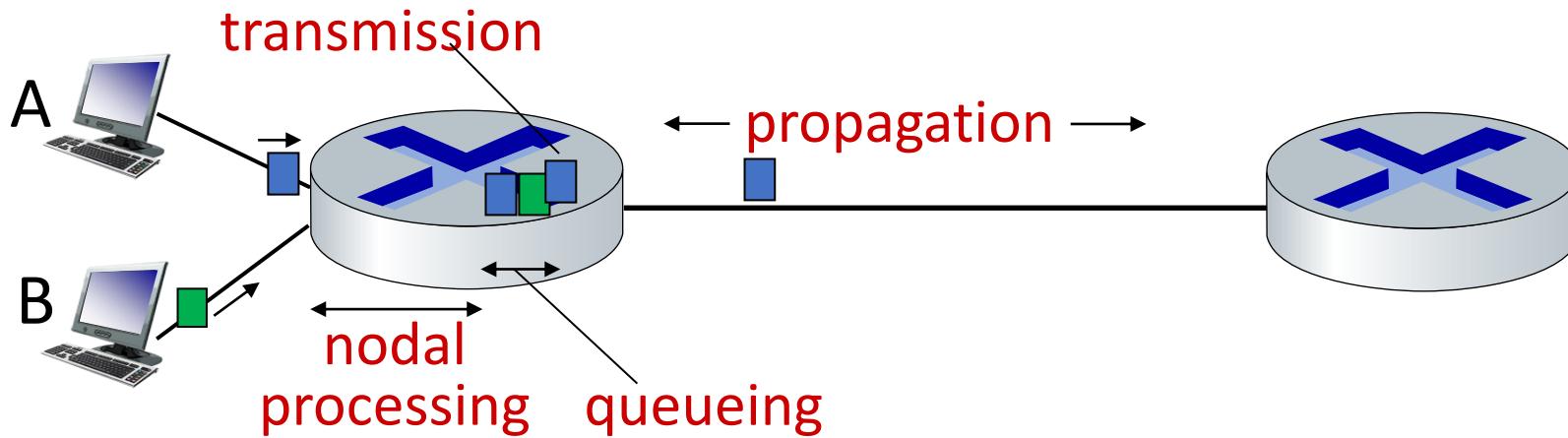
d_{proc} : nodal processing

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

d_{queue} : queueing delay

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

Packet delay: four sources



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

d_{trans} : transmission delay:

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

$$\boxed{d_{\text{trans}} = L/R}$$

d_{trans} and d_{prop}
very different

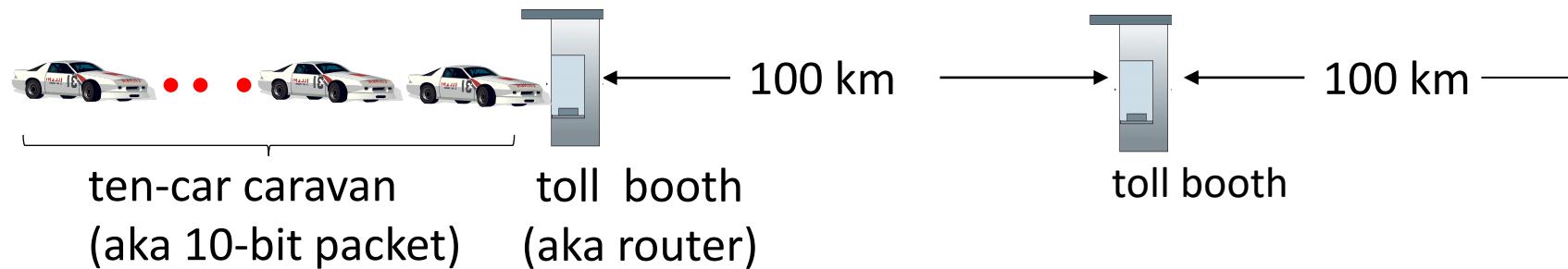
d_{prop} : propagation delay:

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

$$\boxed{d_{\text{prop}} = d/s}$$

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

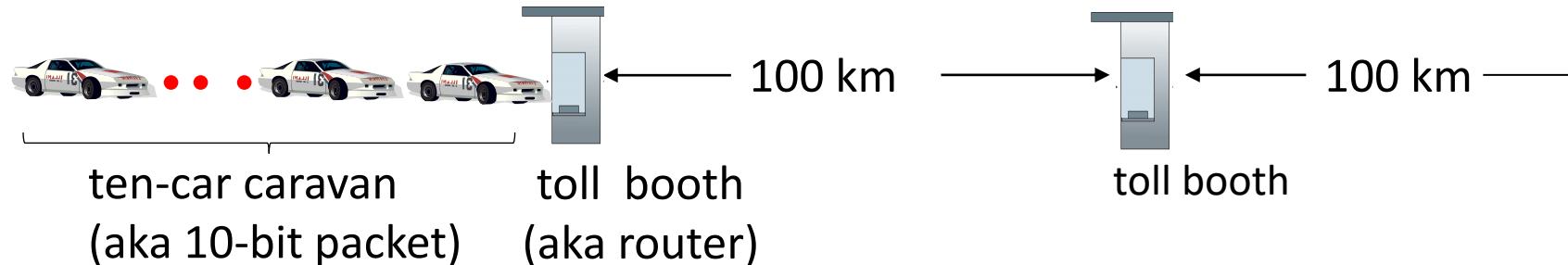
Caravan analogy



- cars “propagate” at 100 km/hr
- toll booth takes 12 sec to service car (bit transmission time)
- car ~ bit; caravan ~ packet
- **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: $100\text{km}/(100\text{km/hr}) = 1$ 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

Examples

- The distance between two routers is 12,000km and propagation speed is 2.4×10^8 m/s in cable. The propagation delay is

$$\text{Propagation time} = \frac{12,000 \times 1000}{2.4 \times 10^8} = 50 \text{ ms}$$

- The example shows that a bit can go over the Atlantic Ocean in only **50 ms** if there is a direct cable.

Examples

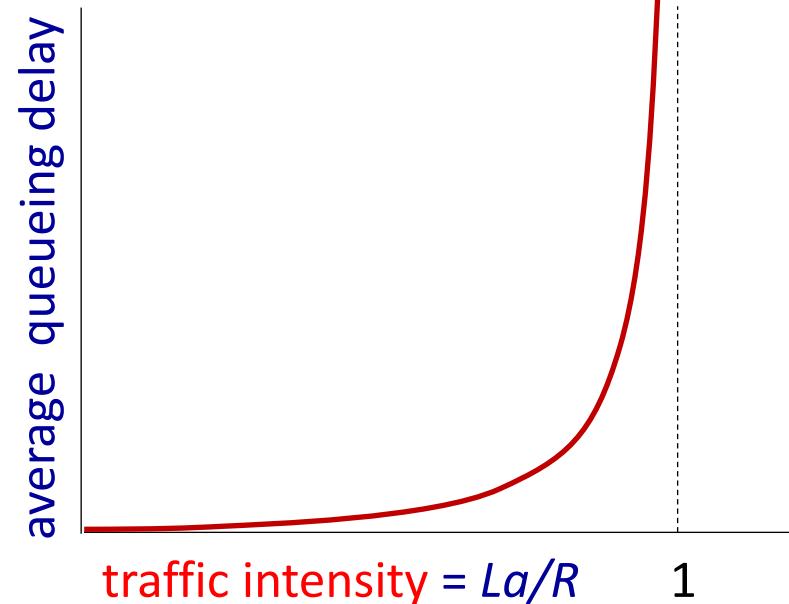
- The **bandwidth** of a link is **1Gbps**. The transmission time for a 2.5-kbyte message (an e-mail) is

$$\text{Transmission time} = \frac{2500 \times 8}{10^9} = 0.020 \text{ ms}$$

- Comparing the **propagation time (50ms)** and **transmission time (0.02ms)**, we note that because the **message is short and the bandwidth is high**, the dominant factor is the propagation time, not the transmission time.

Packet queueing delay (revisited)

- R : link bandwidth (bps)
- L : packet length (bits)
- a : average packet arrival rate
- $La/R \sim 0$: avg. queueing delay small
- $La/R \rightarrow 1$: avg. queueing delay large
- $La/R > 1$: more “work” arriving is more than can be serviced - average delay infinite!

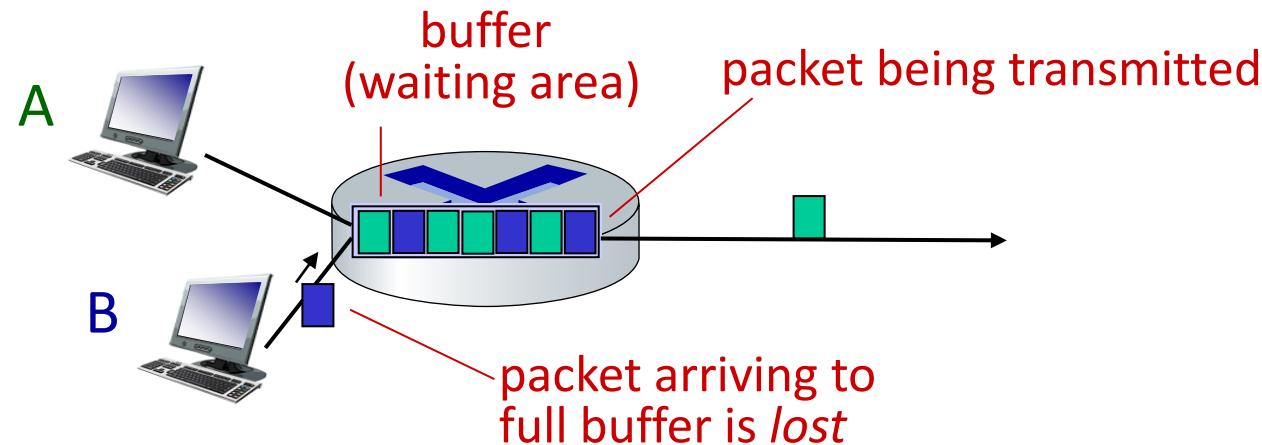


$La/R \sim 0$

Introduction: 1-57

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 queuing and loss

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
- **Protocol layers, service models**
- History



Protocol “layers” and reference models

*Networks are complex,
with many “pieces”:*

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

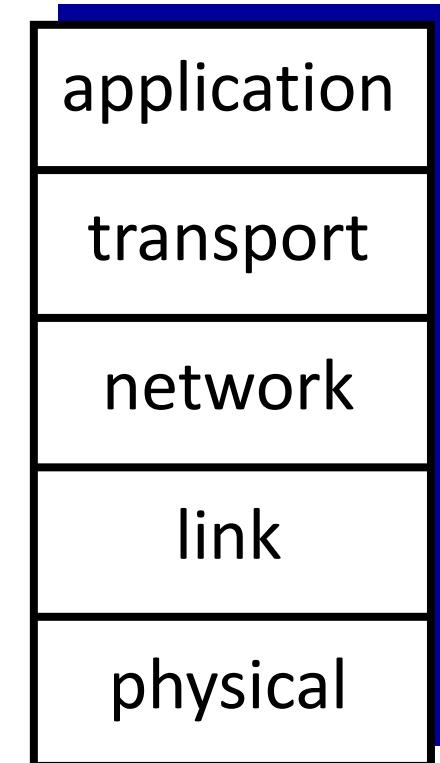
Question:

is there any hope of
organizing structure of
network?

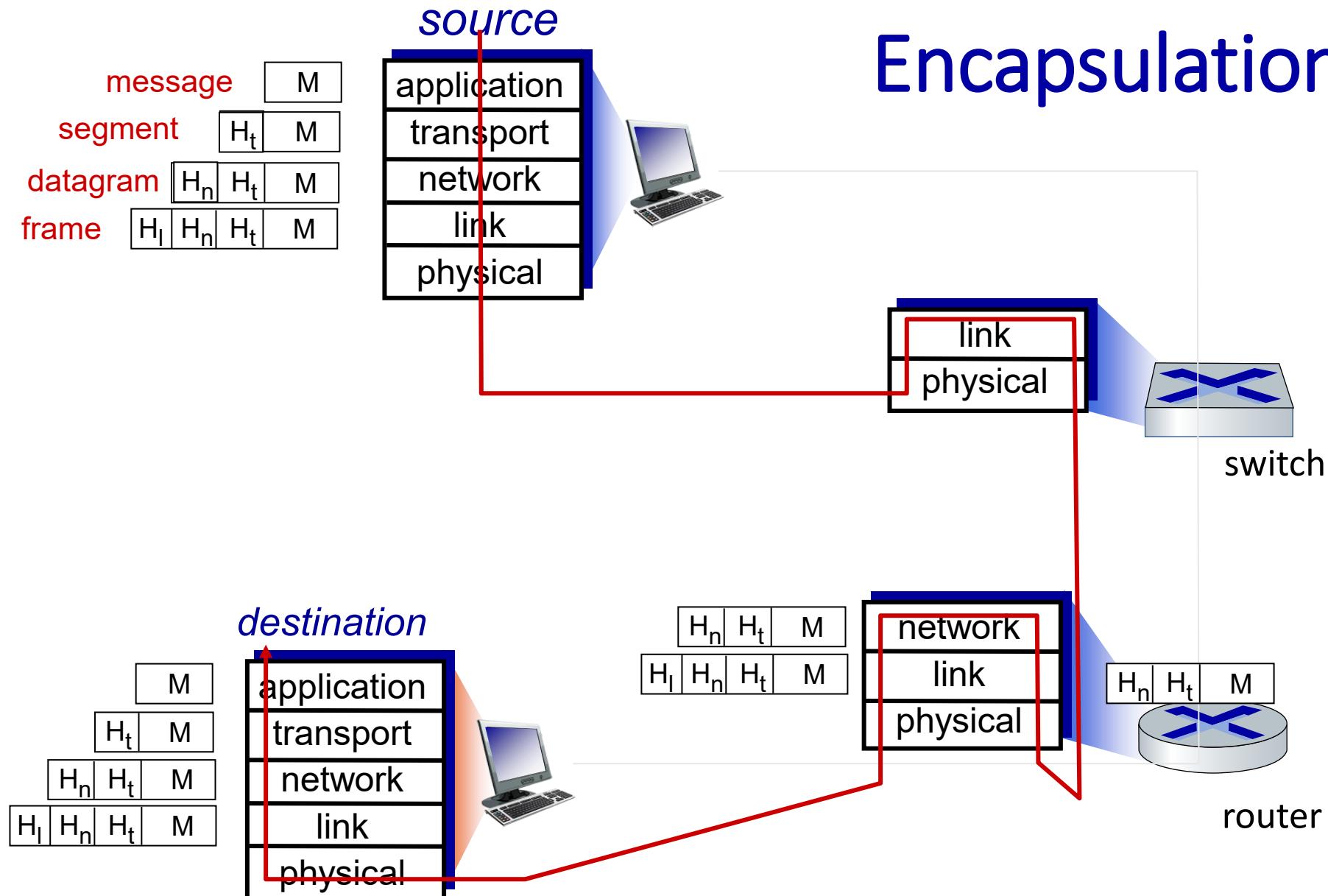
.... or at least our
discussion of networks?

Internet protocol stack

- *application*: supporting network applications
 - IMAP, SMTP, HTTP
- *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”



Encapsulation



Chapter 1: summary

We've covered a "ton" of material!

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

You now have:

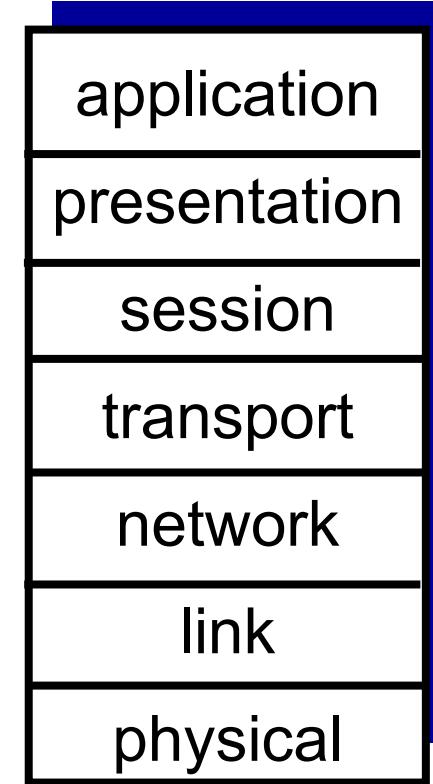
- context, overview, vocabulary, "feel" of networking
- more depth, detail, *and fun* to follow!

Additional Chapter 1 slides

ISO/OSI reference model

Two layers not found in Internet protocol stack!

- *presentation*: allow applications to interpret meaning of data, e.g., encryption, compression, machine-specific conventions
- *session*: synchronization, checkpointing, recovery of data exchange
- Internet stack “missing” these layers!
 - these services, *if needed*, must be implemented in application
 - needed?



The seven layer OSI/ISO reference model

Wireshark

