

# Chapter 1

# Introduction

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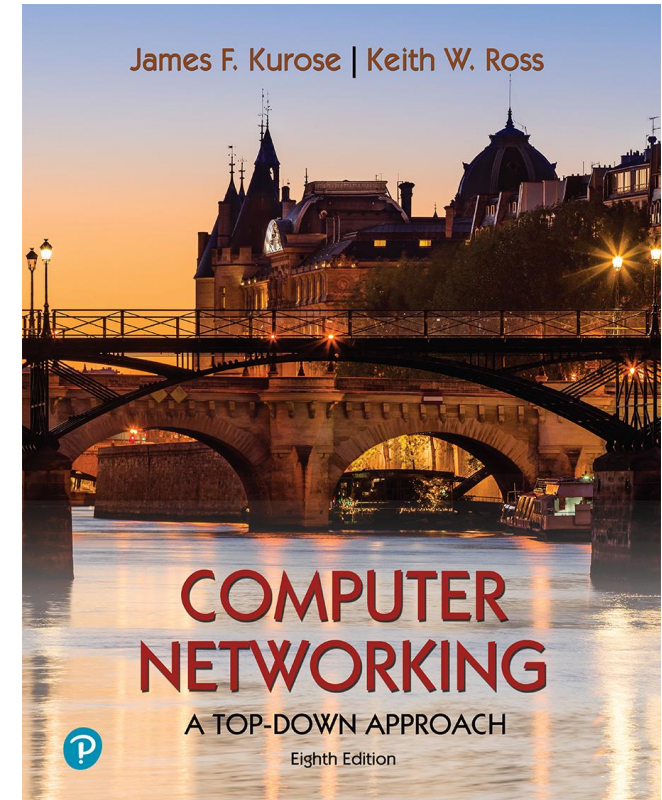
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## *Computer Networking: A Top-Down Approach*

8<sup>th</sup> edition

Jim Kurose, Keith Ross

Pearson, 2020

[http://gaia.cs.umass.edu/kurose\\_ross](http://gaia.cs.umass.edu/kurose_ross)

# 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:*

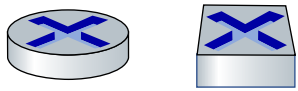
- What *is* the Internet?
- What *is* a protocol?
- **Network edge**: hosts, access network, physical media
- **Network core**: packet/circuit switching, internet structure
- **Performance**: loss, delay, throughput
- Security
- Protocol layers, service models
- History

# 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*

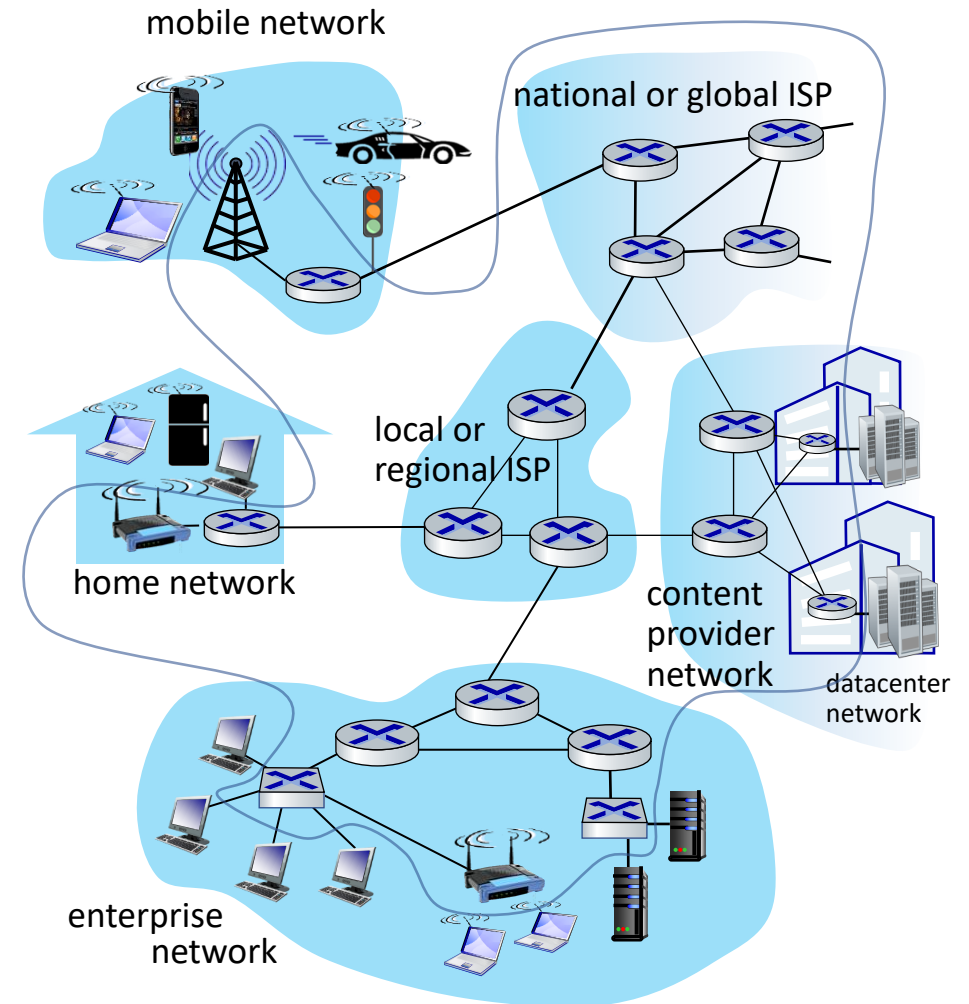
*Communication links*

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



*Networks*

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



# “Fun” Internet-connected devices



Amazon Echo



Internet refrigerator



IP picture frame



Pacemaker & Monitor



Tweet-a-watt:  
monitor energy use



Security Camera



Slingbox: remote  
control cable TV



Web-enabled toaster +  
weather forecaster



AR devices

Internet phones



sensorized,  
bed  
mattress



Fitbit

*Others?*

# The Internet: a “nuts and bolts” view

- *Internet: “network of networks”*

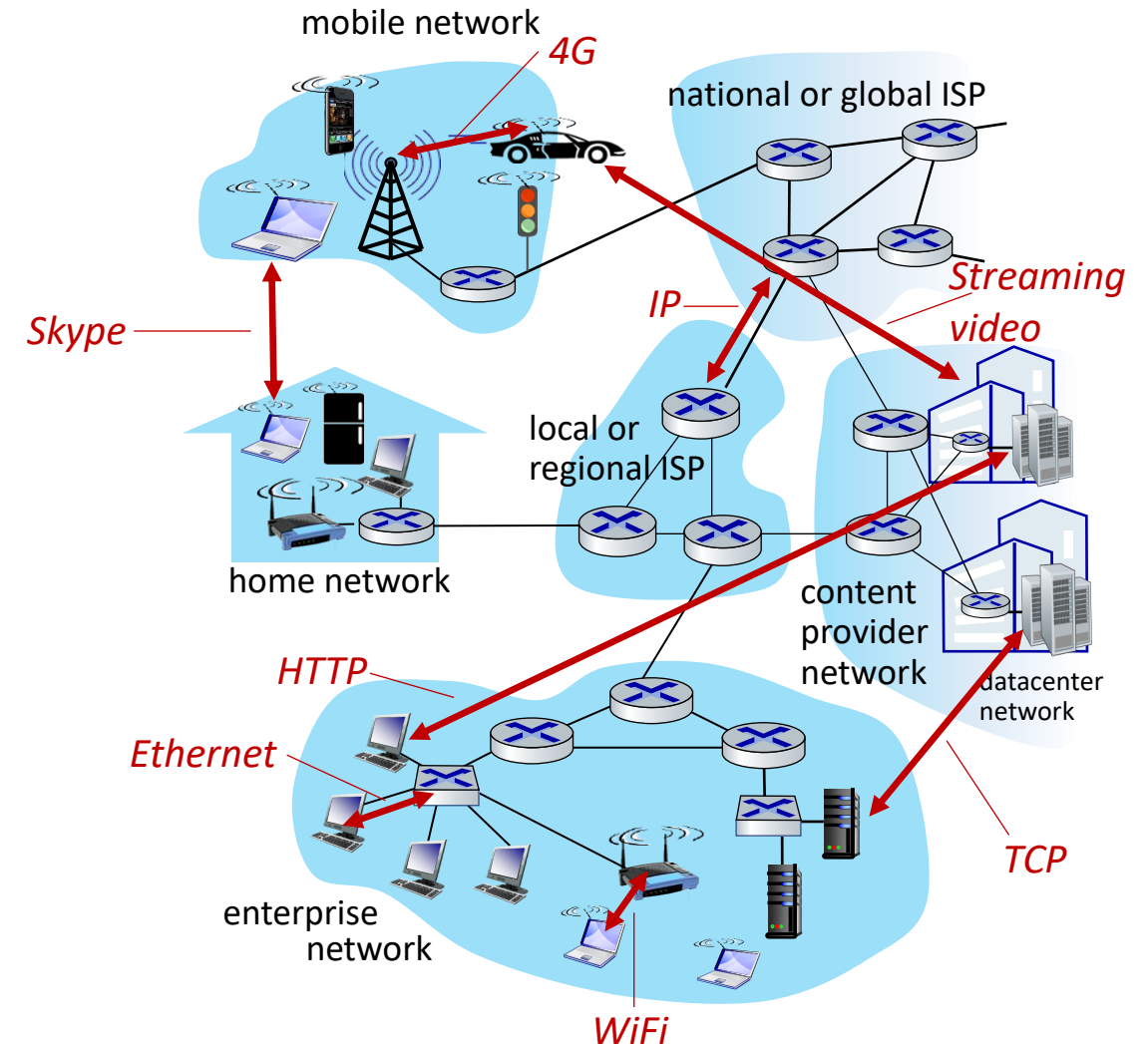
- Interconnected ISPs

- *protocols* are everywhere

- control sending, receiving of messages
- e.g., HTTP (Web), streaming video, Skype, TCP, IP, WiFi, 4G, Ethernet

- *Internet standards*

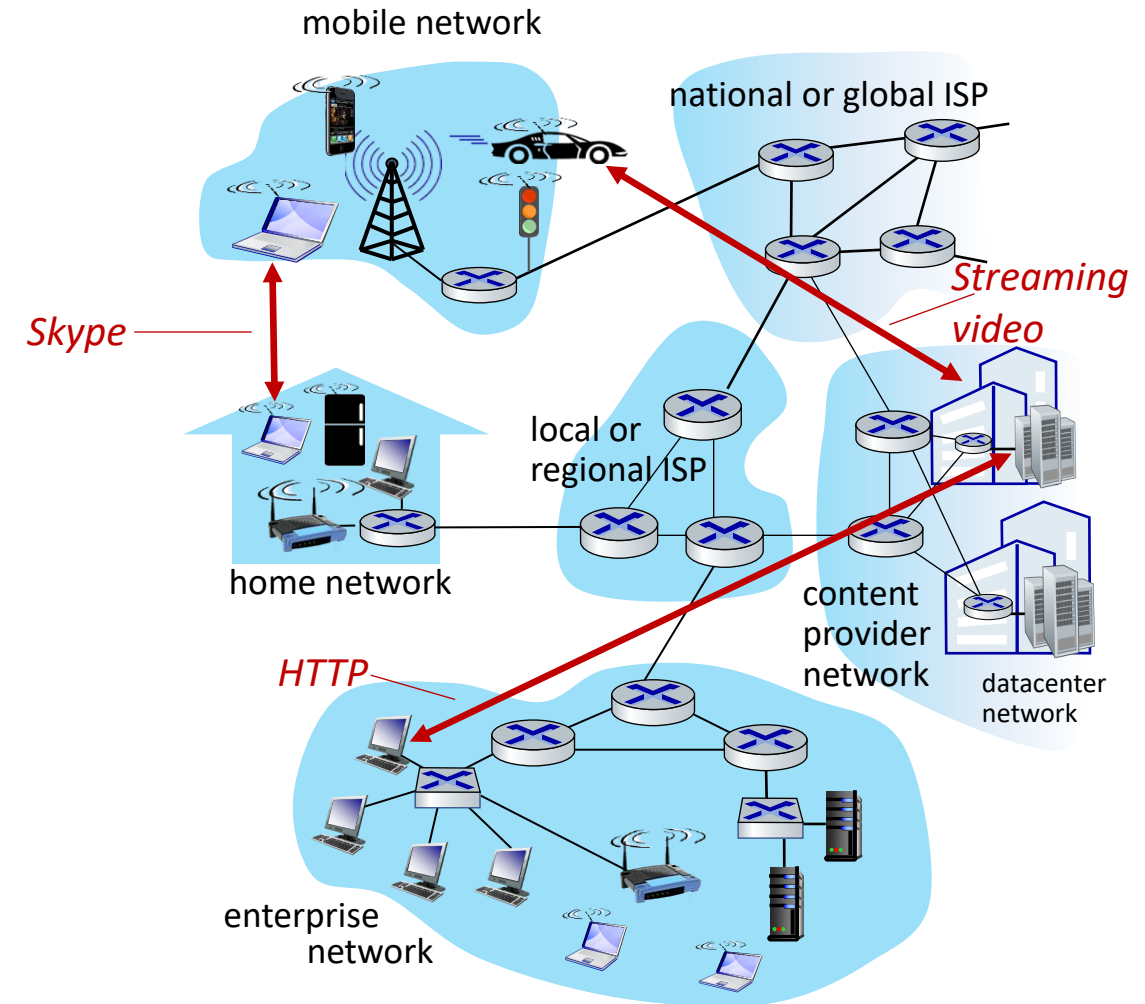
- RFC: Request for Comments
- IETF: Internet Engineering Task Force





# The Internet: a “service” view

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

## *Human protocols:*

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

... specific messages sent

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

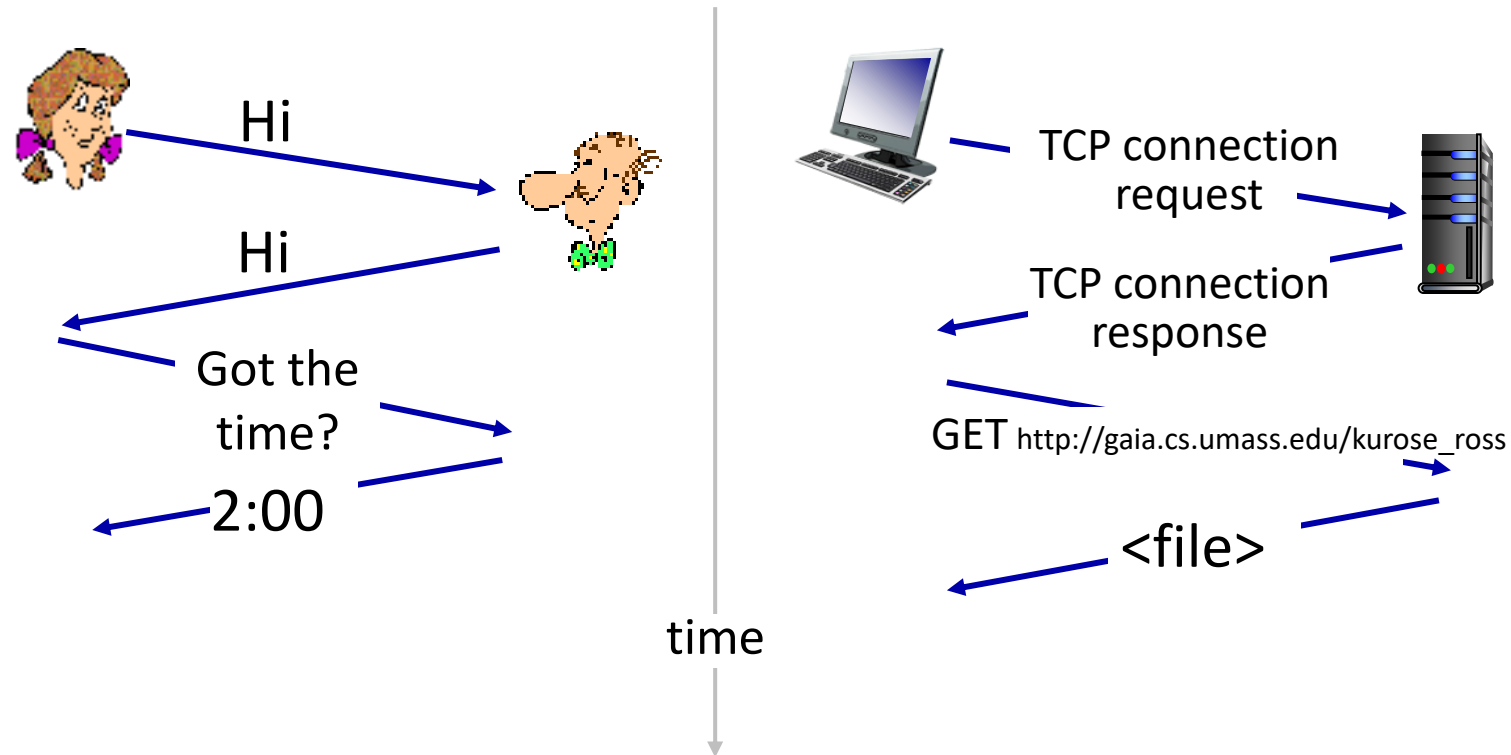
## *Network protocols:*

- 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

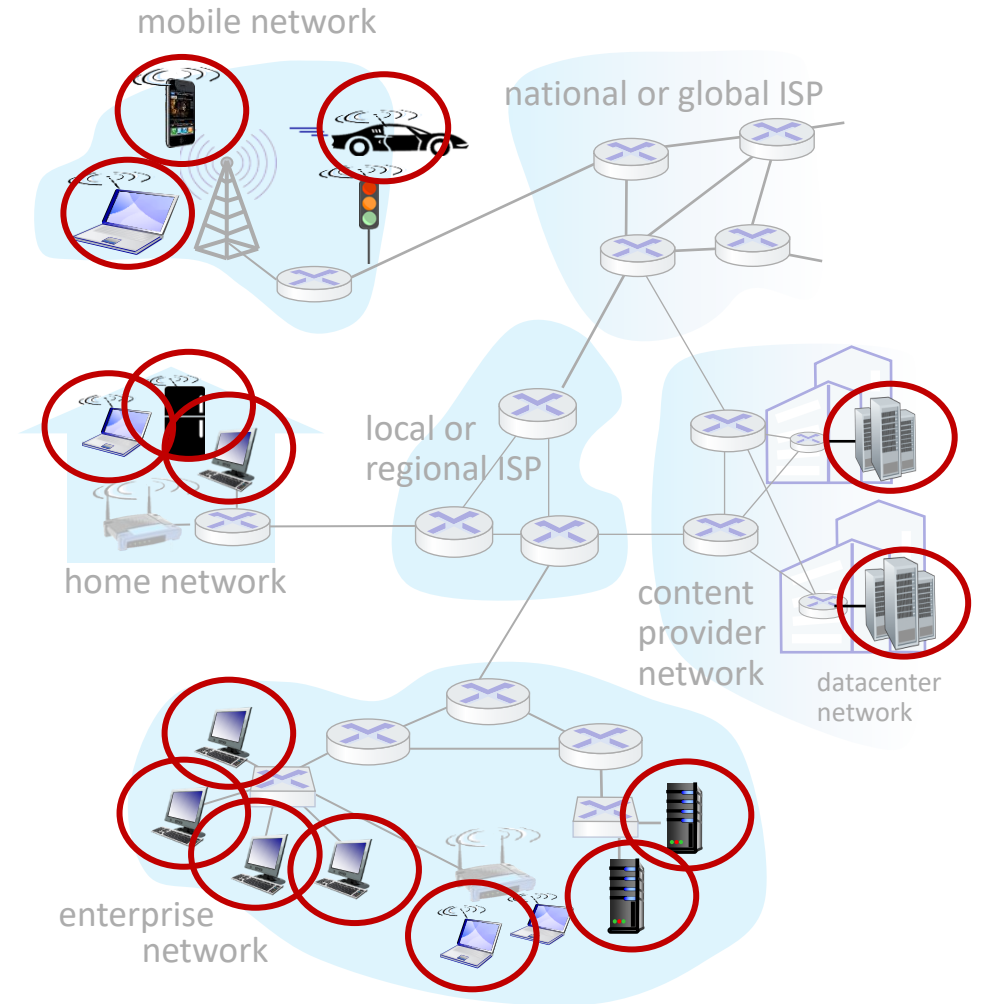
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# A closer look at Internet structure

## Network edge:

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



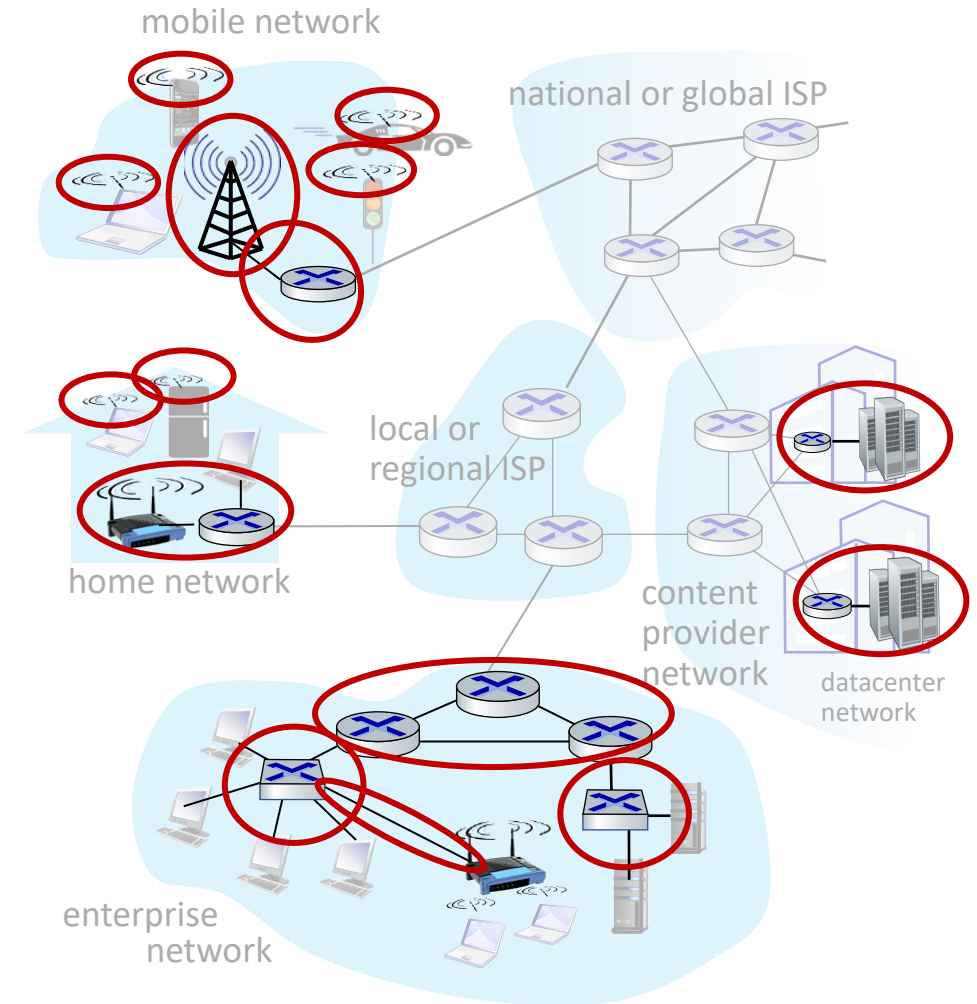
# A closer look at Internet structure

## Network edge:

- 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:

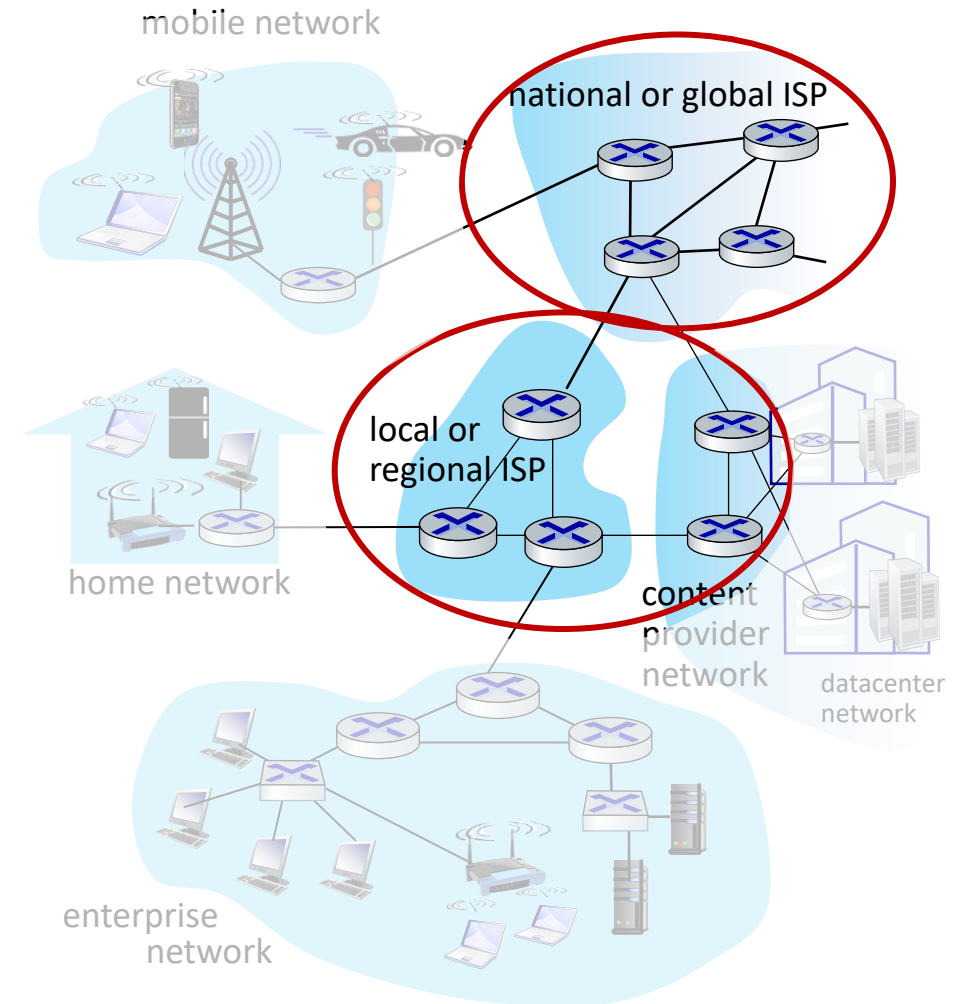
- hosts: clients and servers
- servers often in data centers

## Access networks, physical media:

- wired, wireless communication links

## Network core:

- interconnected routers
- network of networks



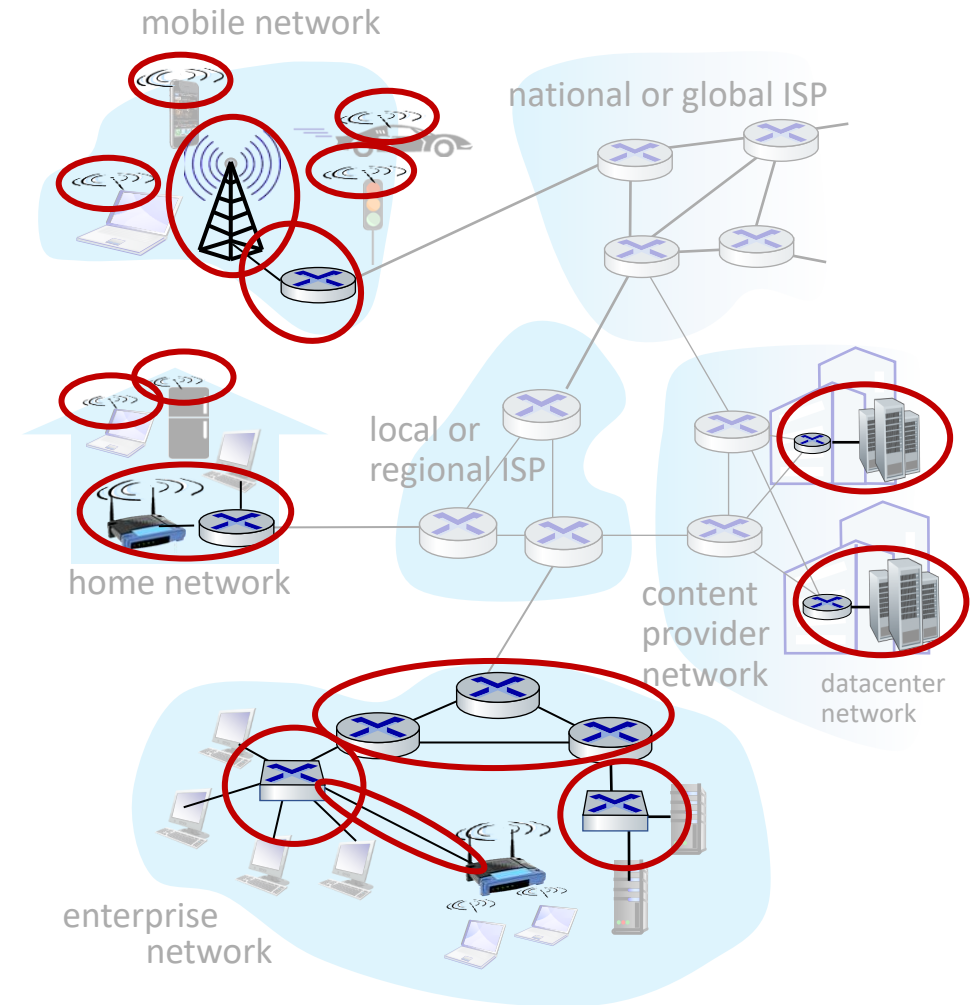
# Access networks and physical media

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

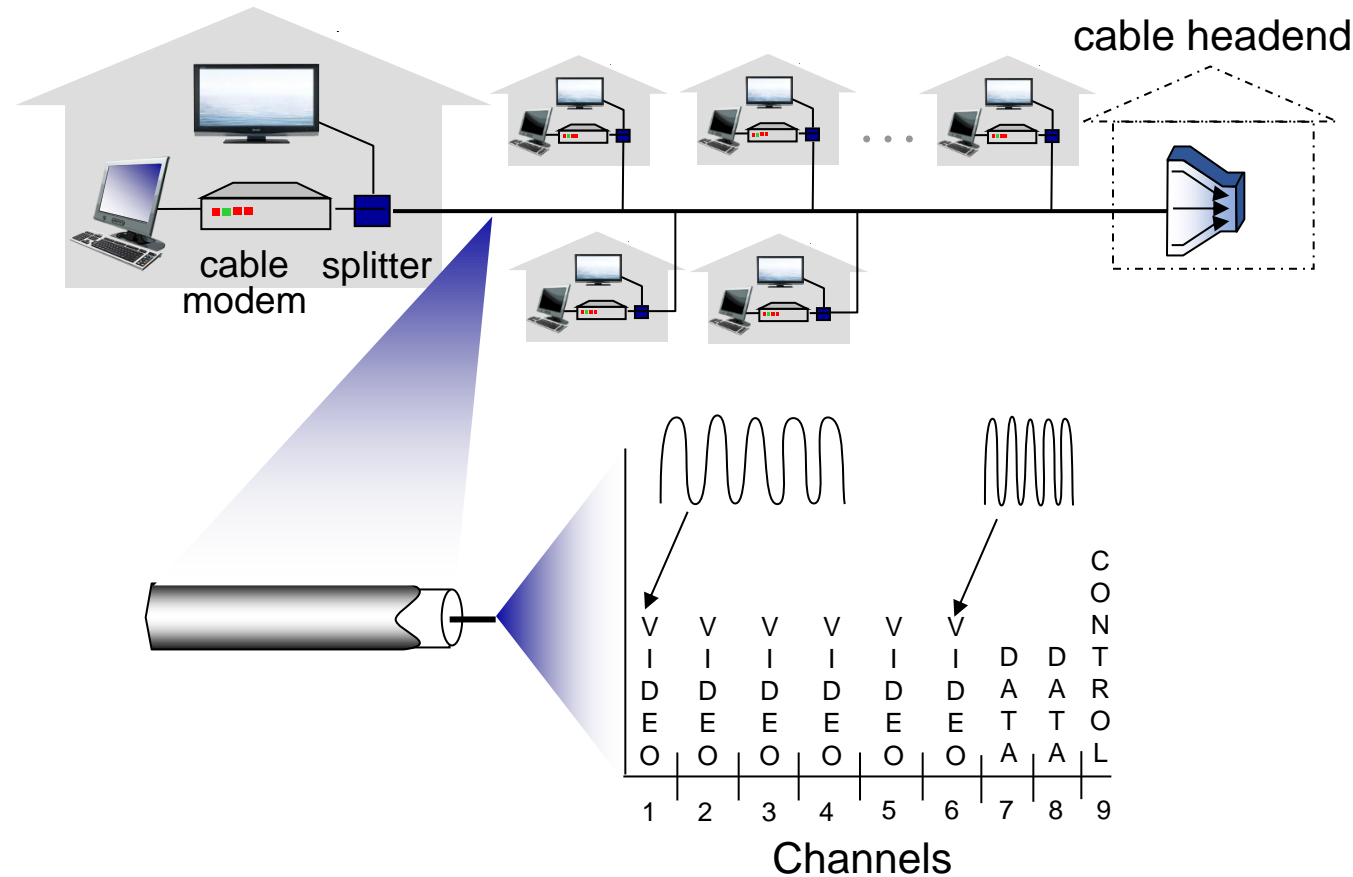
- residential access nets
- institutional access networks (school, company)
- mobile access networks (WiFi, 4G/5G)

*What to look for:*

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



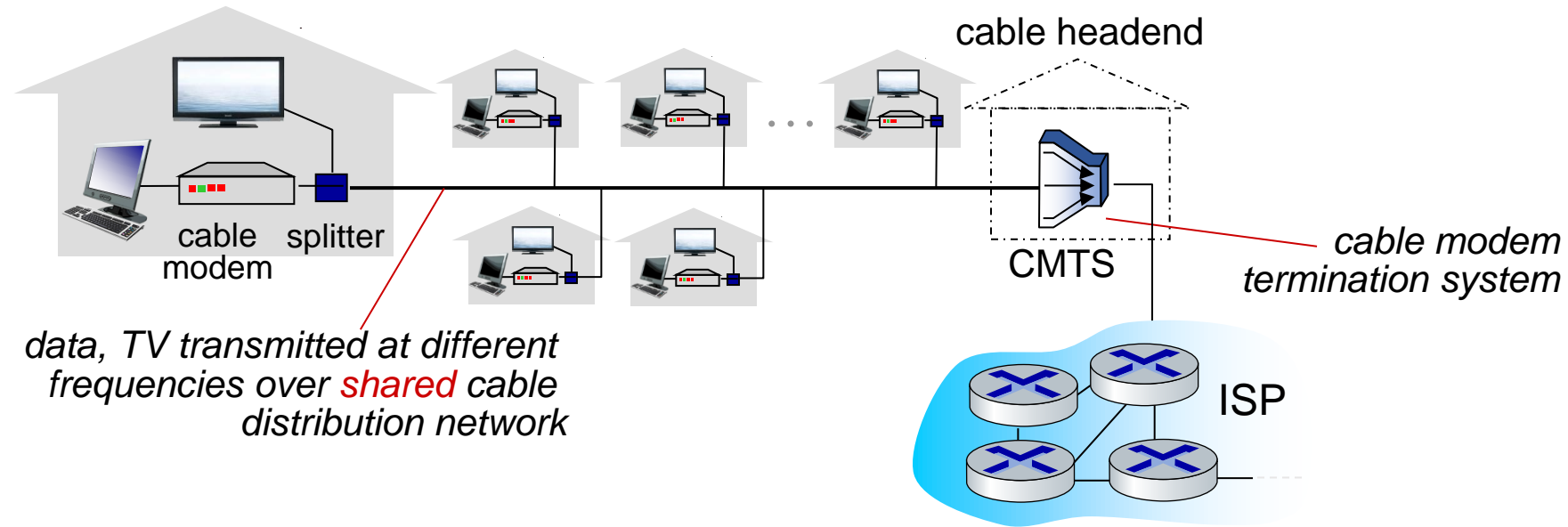
# Access networks: cable-based access



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



# Access networks: cable-based access



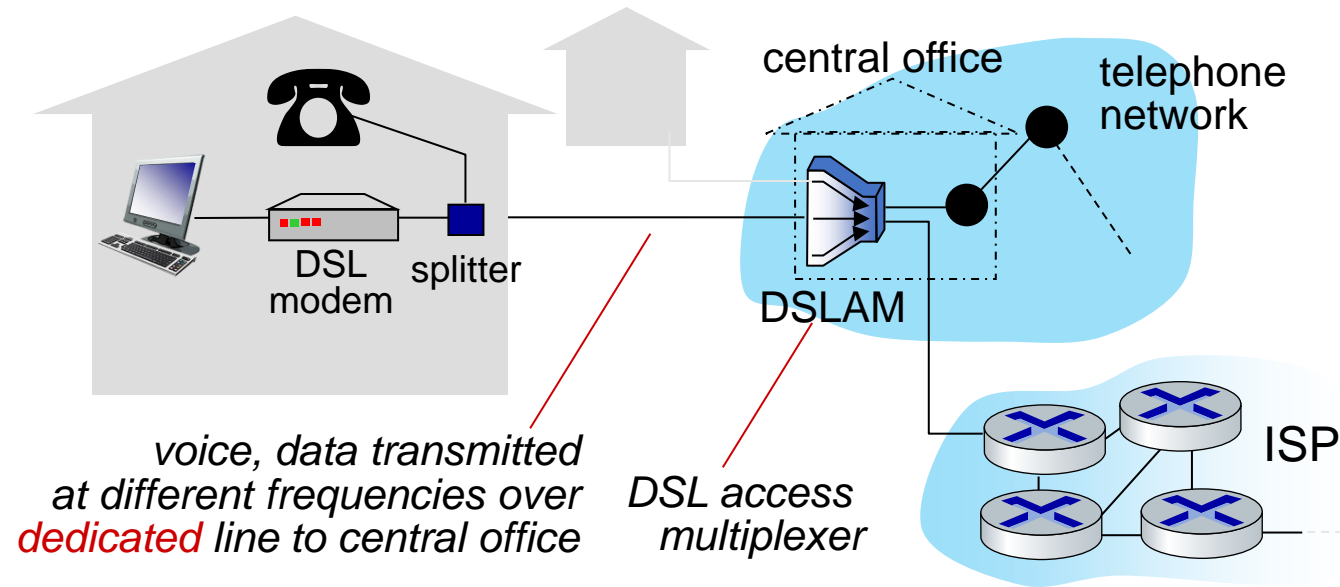
## ■ HFC: hybrid fiber coax

- 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

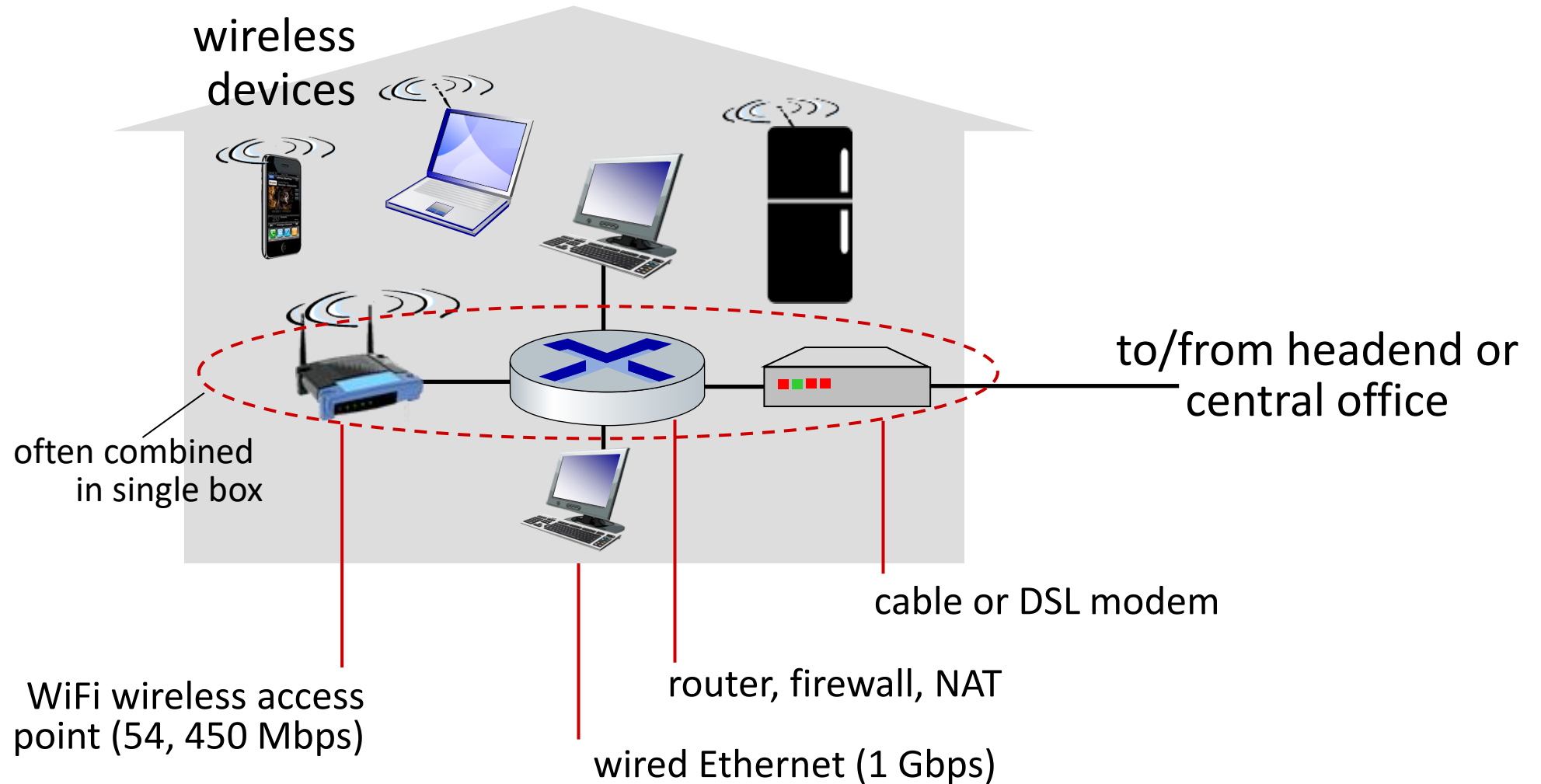
- homes *share access network* to cable headend

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

# Access networks: home networks



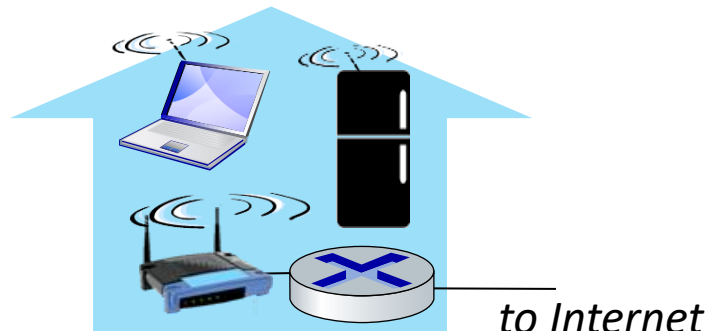
# Wireless access networks

Shared *wireless* access network connects end system to router

- via base station aka “access point”

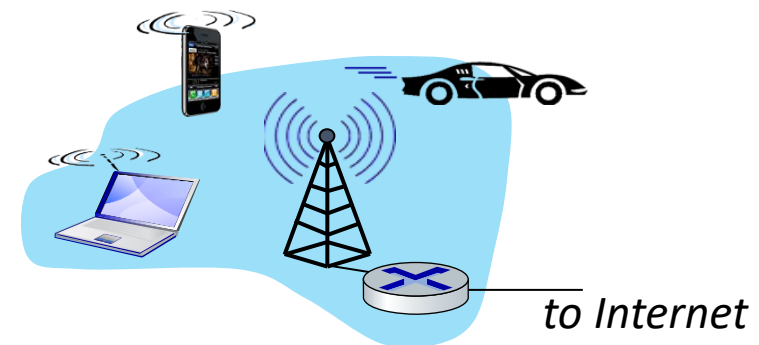
## Wireless local area networks (WLANs)

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

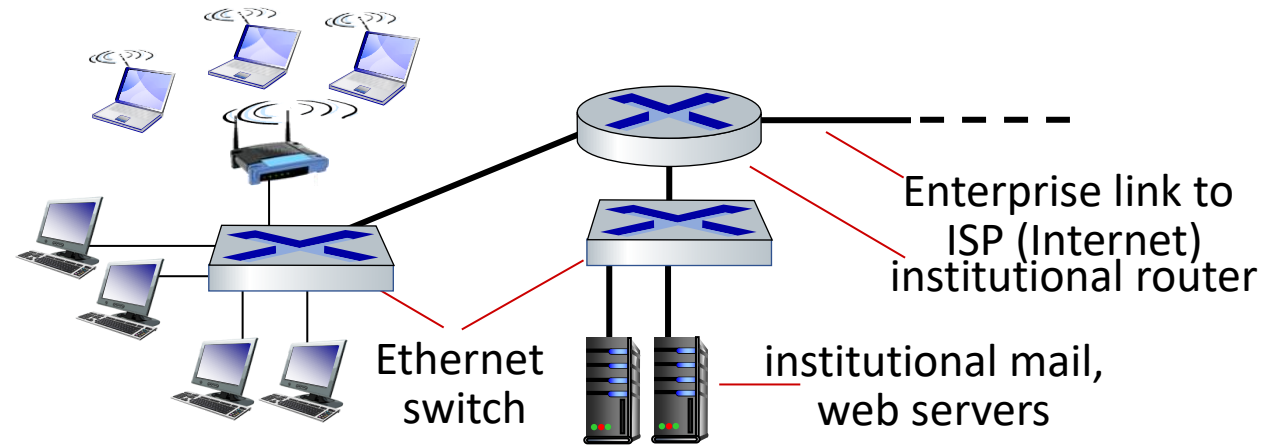


## Wide-area cellular access networks

- provided by mobile, cellular network operator (10's km)
- 10's Mbps
- 4G/5G cellular networks (6G coming)



# Access networks: enterprise networks

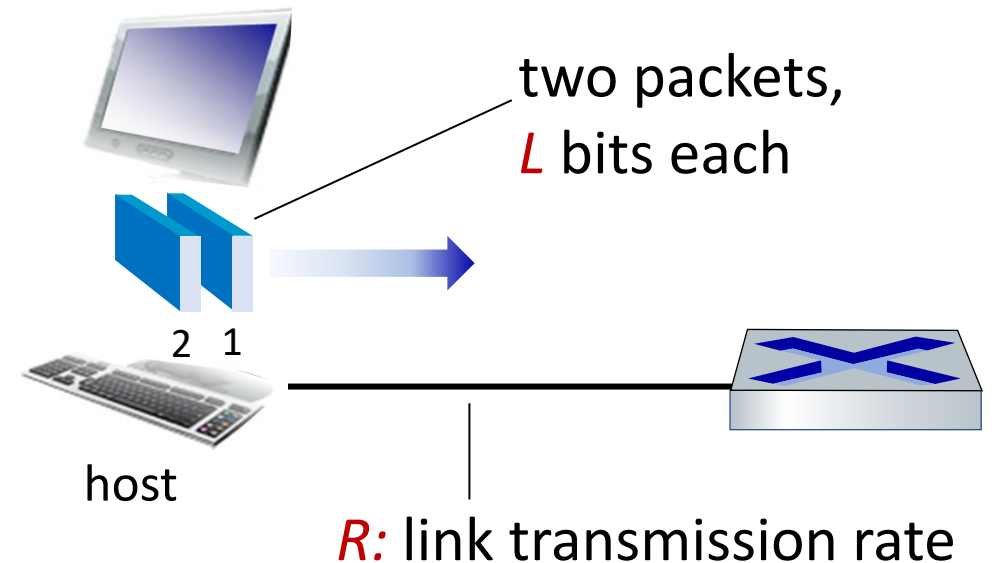


- companies, universities, etc.
- mix of wired, wireless link technologies, connecting a mix of switches and routers (we'll cover differences shortly)
  - Ethernet: wired access at 100Mbps, 1Gbps, 10Gbps
  - WiFi: wireless access points at 11, 54, 450 Mbps

# 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*



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

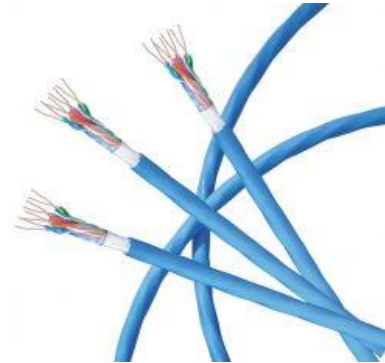


# Links: physical media

- **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

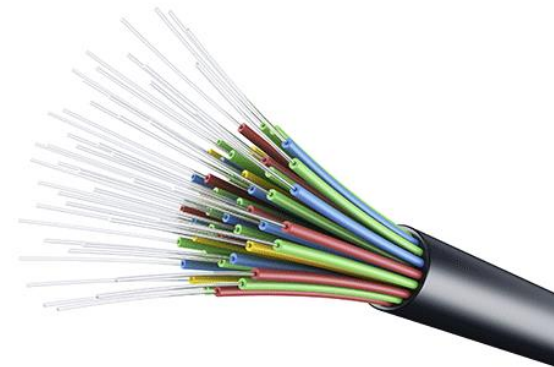
## Coaxial cable:

- 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/noise

## Radio link types:

- Wireless LAN (WiFi)
  - 10-100's Mbps; 10's of meters
- wide-area (e.g., 4G cellular)
  - 10's Mbps over ~10 Km
- Bluetooth: cable replacement
  - short distances, limited rate
- terrestrial microwave
  - point-to-point; up to 45 Mbps channels
- satellite
  - up to 45 Mbps per channel
  - 270 msec end-end delay
  - geosynchronous versus low-earth-orbit

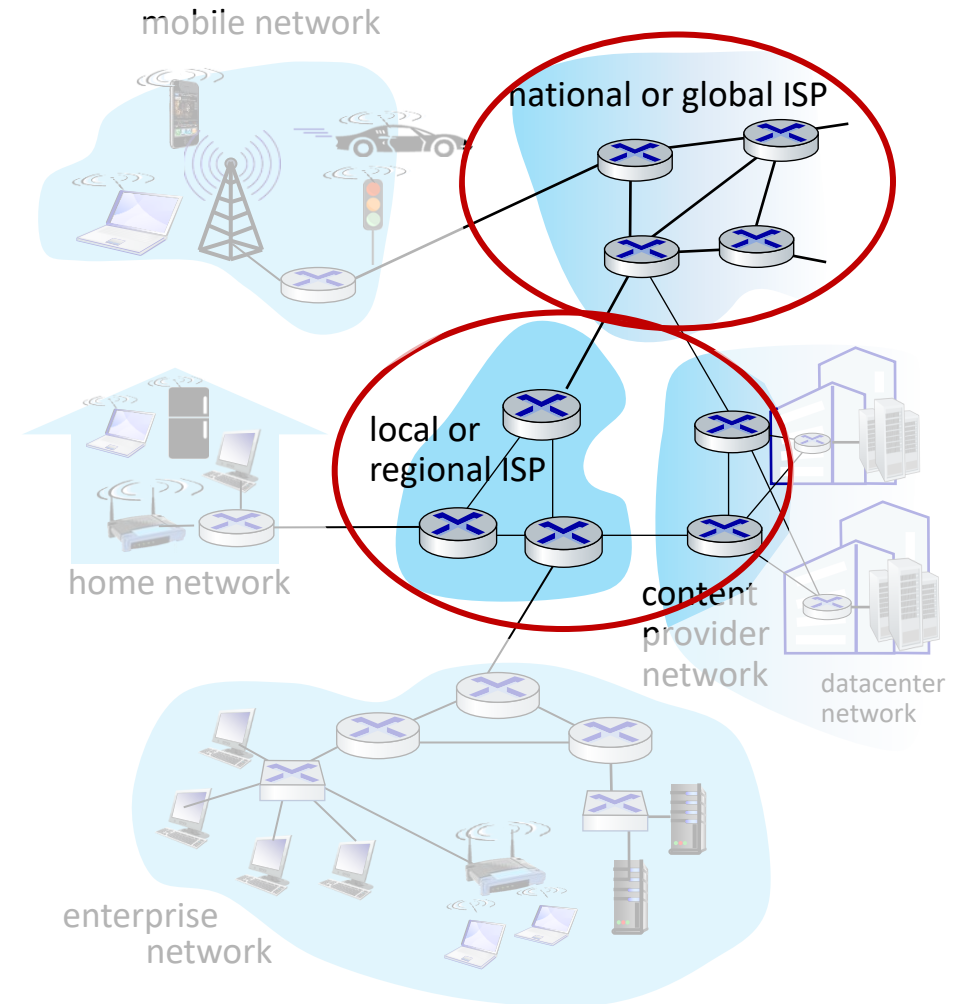
# Chapter 1: roadmap

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# The network core

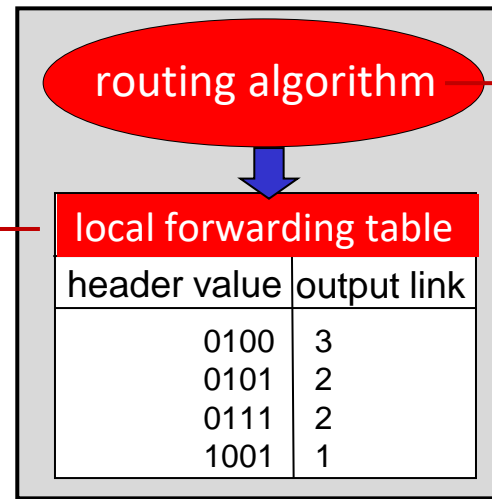
- mesh of interconnected routers
- **packet-switching**: hosts break application-layer messages into *packets*
  - network **forward** packets from one router to the next, across links on **path** from **source** to **destination**
  - each packet transmitted at full link capacity



# Two key network-core functions

## Forwarding:

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



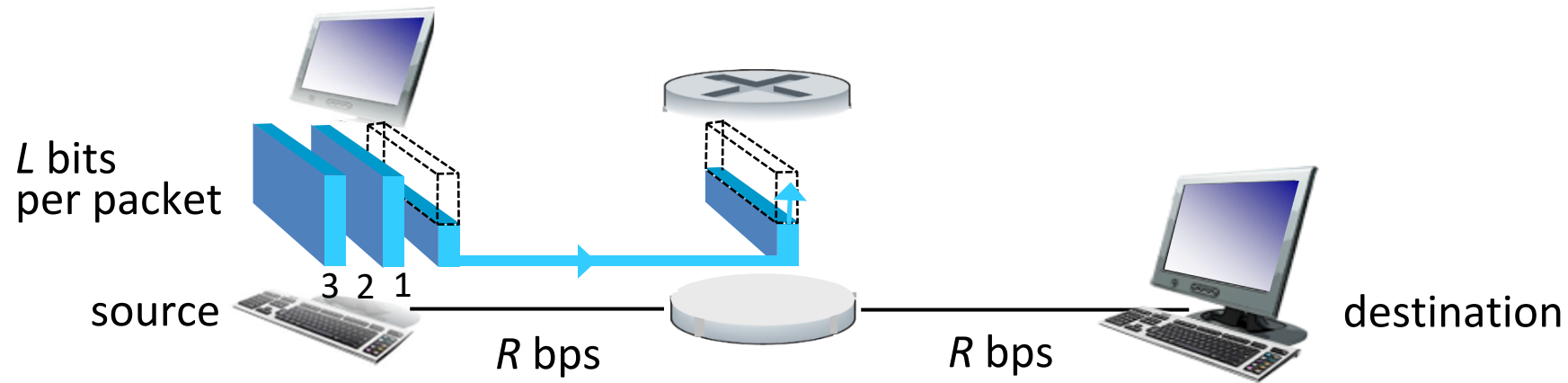
destination address in arriving packet's header

## Routing:

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



# Packet-switching: store-and-forward

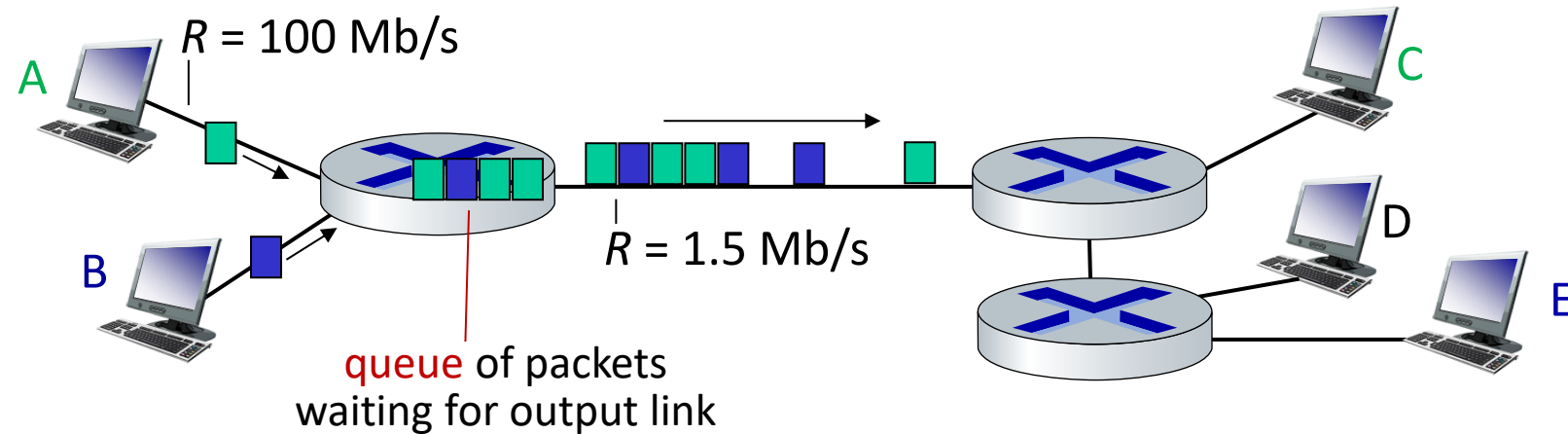


- **Transmission delay:** takes  $L/R$  seconds to transmit (push out)  $L$ -bit packet into link at  $R$  bps
- **Store and forward:** entire packet must arrive at router before it can be transmitted on next link
- **End-end delay:**  $2L/R$  (above), assuming zero propagation delay (more on delay shortly)

## *One-hop numerical example:*

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

# Packet-switching: queueing delay, loss



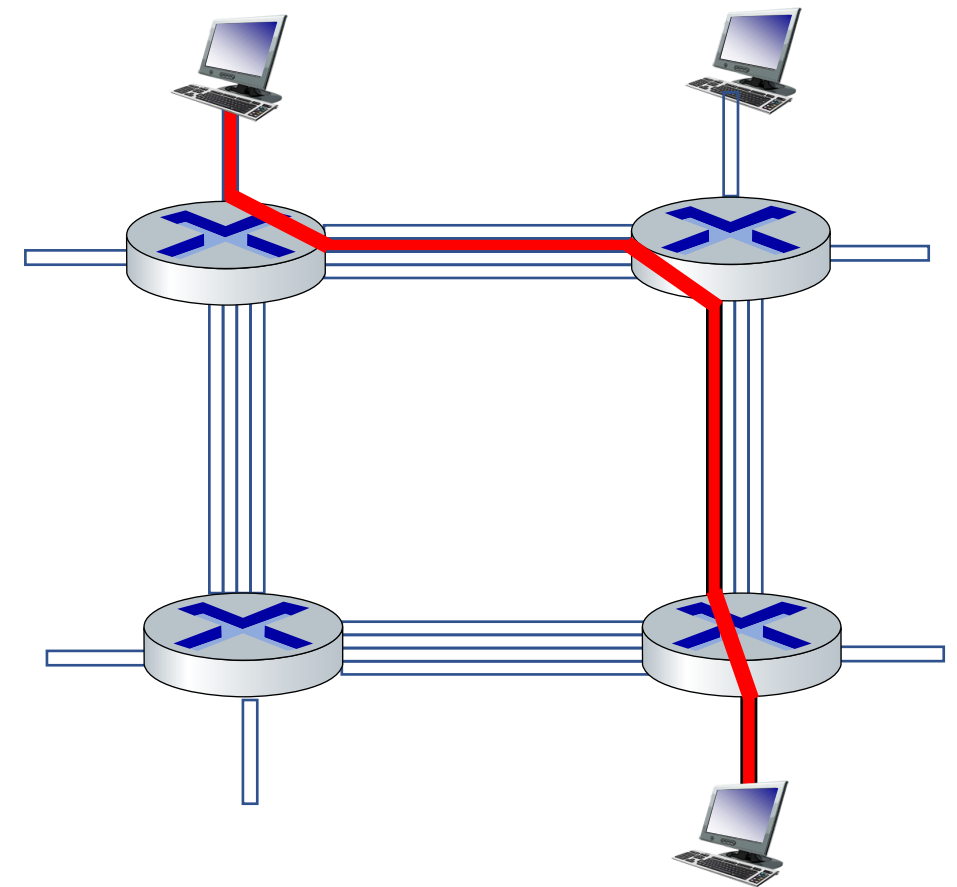
***Packet queuing and loss:*** if arrival rate (in bps) to link exceeds transmission rate (bps) of link for some period of time:

- 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

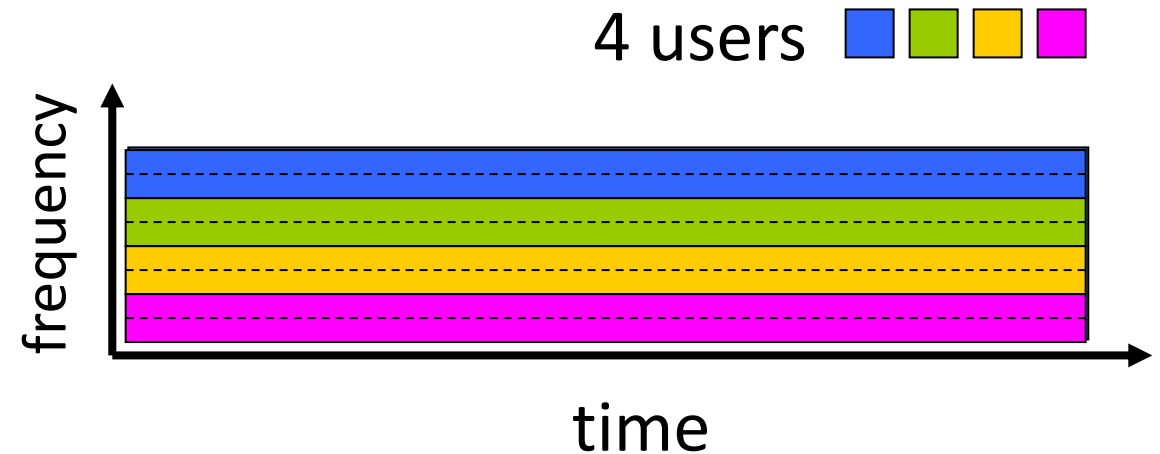
- in diagram, each link has four circuits.
  - call gets 2<sup>nd</sup> circuit in top link and 1<sup>st</sup> circuit in right link.
- dedicated resources: no sharing
  - circuit-like (guaranteed) performance
- circuit segment idle if not used by call (no sharing)
- commonly used in traditional telephone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



# Circuit switching: FDM and TDM

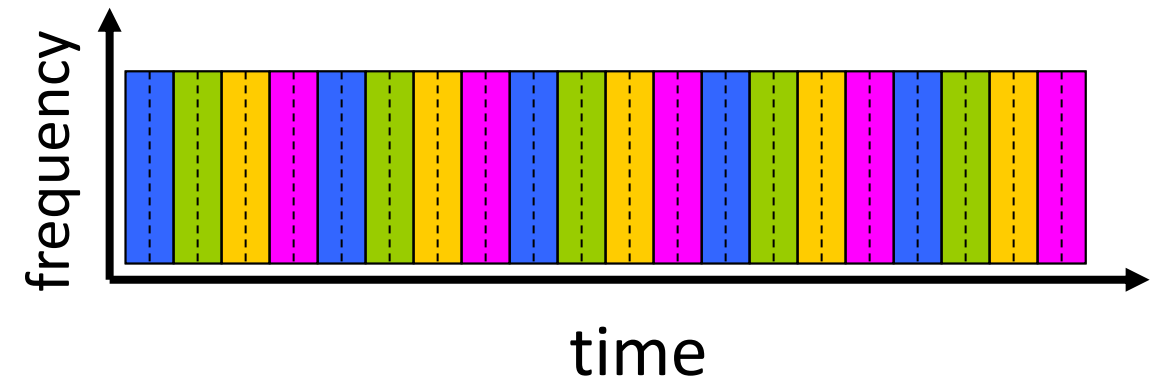
## Frequency Division Multiplexing (FDM)

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

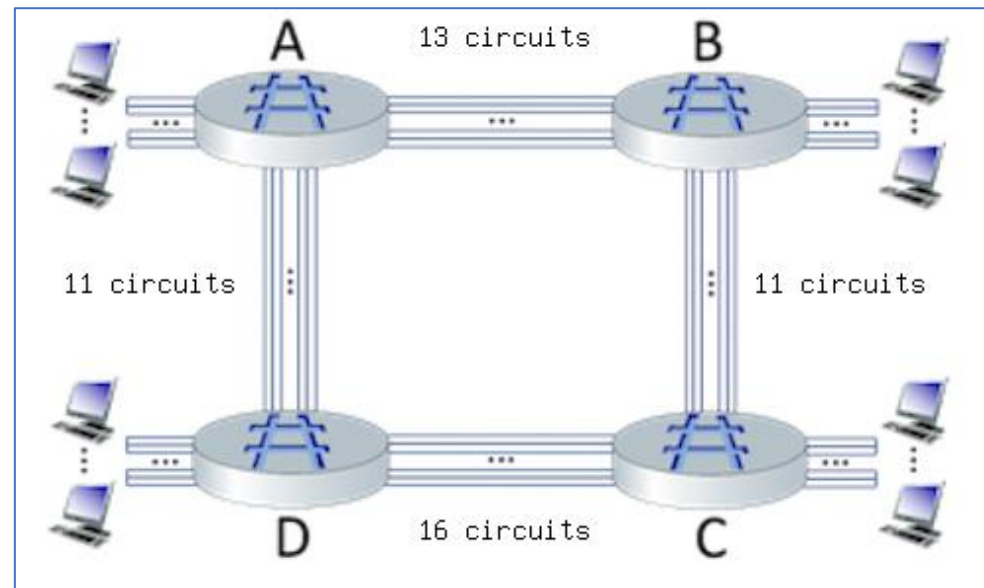


## Time Division Multiplexing (TDM)

- 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)



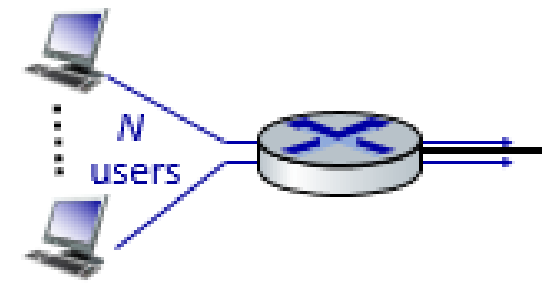
# Example:



Suppose there are **13 circuits between A and B, 11 circuits between B and C, 16 circuits between C and D, and 11 circuits between D and A.**

- What is the maximum number of connections that can be ongoing in the network at any one time? **51 connections.**
- Suppose that these maximum number of connections are all ongoing. What happens when another call connection request arrives to the network, will it be accepted? **No.**
- Suppose that every connection requires 2 consecutive hops, and calls are connected clockwise. For example, a connection can go from A to C, from B to D, from C to A, and from D to B. With these constraints, what is the maximum number of connections that can be ongoing in the network at any one time? **22 connections.**

# Packet switching Vs. circuit switching

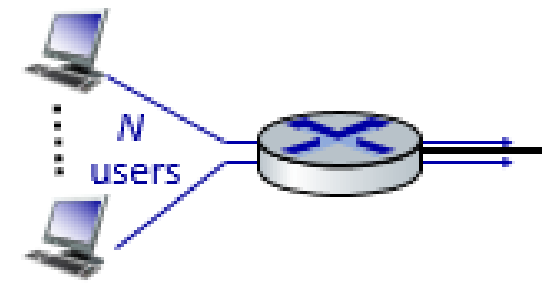


- **Problem:** users share a 1.5 Mbps link. Also suppose each user requires 250 Kbps when transmitting, but each user transmits only 10% of the time.
  - When circuit switching is used, how many users can be supported?  
 $1.5 \text{ Mbps} / 250 \text{ Kbps per user} = 6 \text{ users.}$
  - Packet switching is used. Find the probability that a given user is transmitting.  
 $P(\text{a given user is transmitting}) = p = 0.10$
  - Suppose there are 20 users. Find the probability that at any given time, exactly  $n$  users are transmitting simultaneously.  
 $P(\text{exactly } n \text{ users are transmitting simultaneously}) = \binom{20}{n} p^n (1 - p)^{20-n}$

\* Check out the online interactive exercises for more examples: [http://gaia.cs.umass.edu/kurose\\_ross/interactive](http://gaia.cs.umass.edu/kurose_ross/interactive)



# Packet switching Vs. circuit switching



- Find the probability when 7 or more users transmitting simultaneously.

P(7 or more users are transmitting simultaneously)

=  $1 - P(6 \text{ or less users are transmitting simultaneously})$

=  $1 - [P(6 \text{ users are transmitting simultaneously}) + P(5 \text{ users are transmitting simultaneously}) + \dots + P(1 \text{ user is transmitting simultaneously}) + P(\text{no user is transmitting})]$

=  $1 - \sum_{n=0}^6 \binom{20}{n} p^n (1-p)^{20-n}$

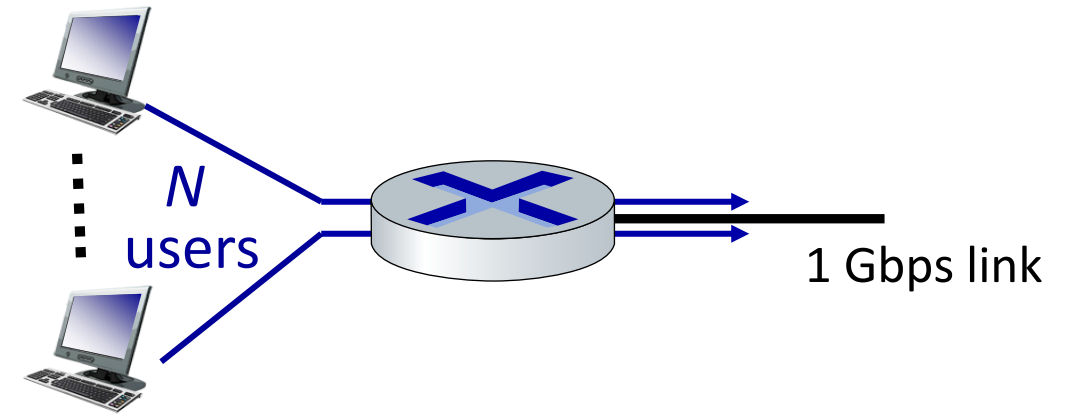
→  $P(7 \text{ or more users are transmitting simultaneously}) = 0.0023861$

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# Packet switching versus circuit switching

Example:

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



**Question:** 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 0.0004 \*

**Q:** how did we get value 0.0004?

**Q:** what happens if  $> 35$  users ?

*packet switching allows more users to use network!*

\* Check out the online interactive exercises for more examples: [http://gaia.cs.umass.edu/kurose\\_ross/interactive](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

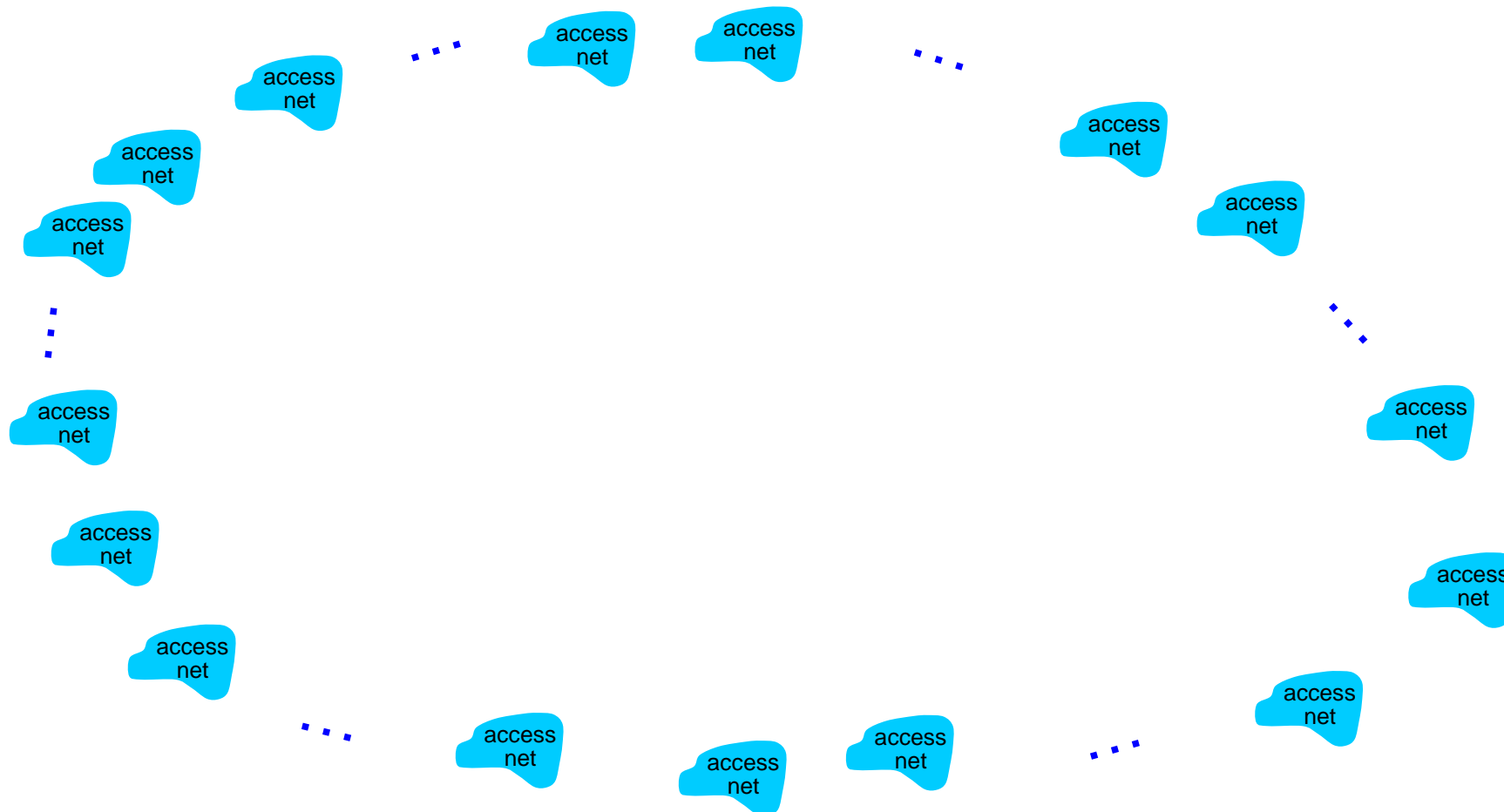
**Q:** human analogies of reserved resources (circuit switching) versus on-demand allocation (packet switching)?

# 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

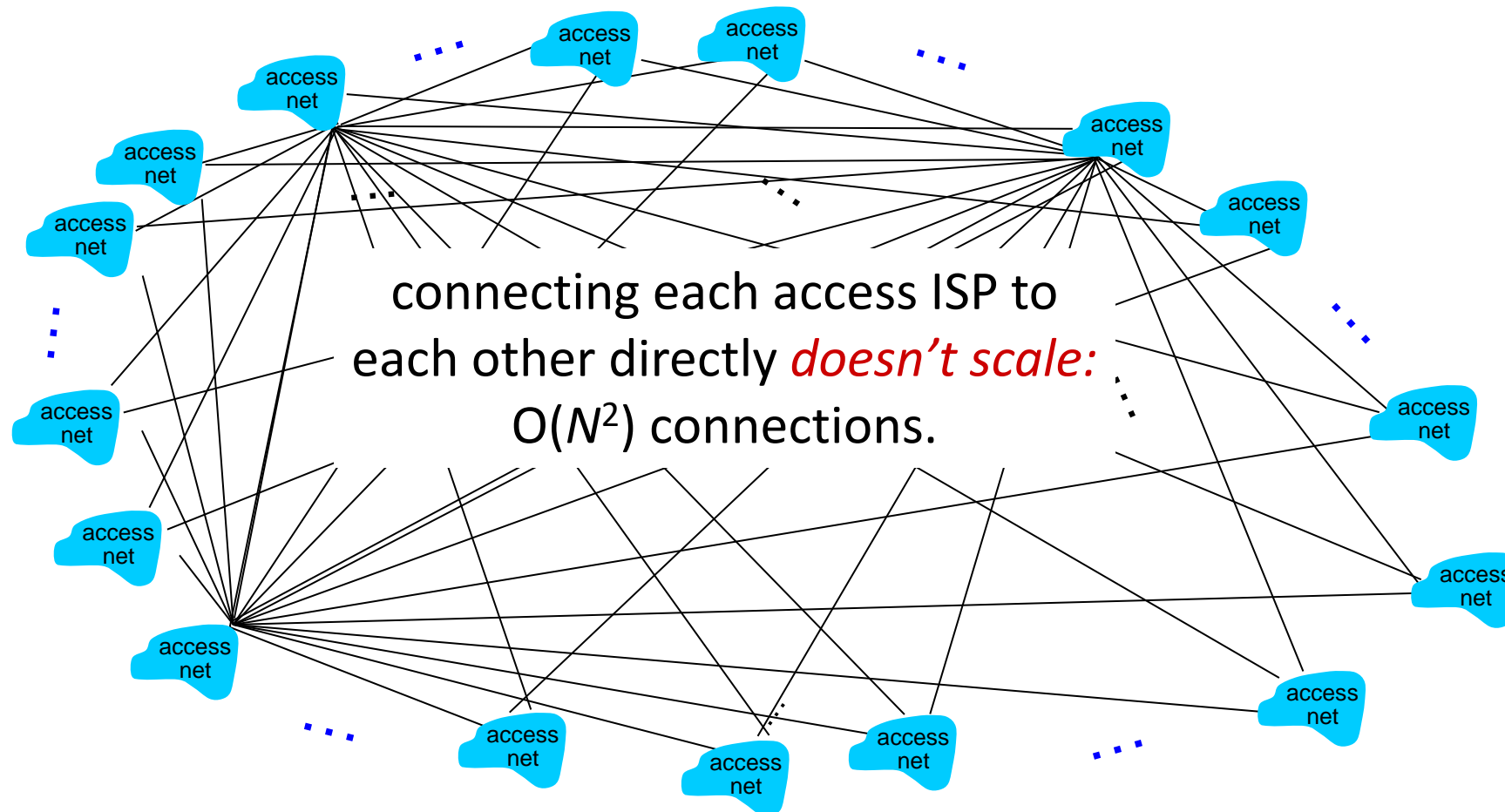
# Internet structure: a “network of networks”

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



# Internet structure: a “network of networks”

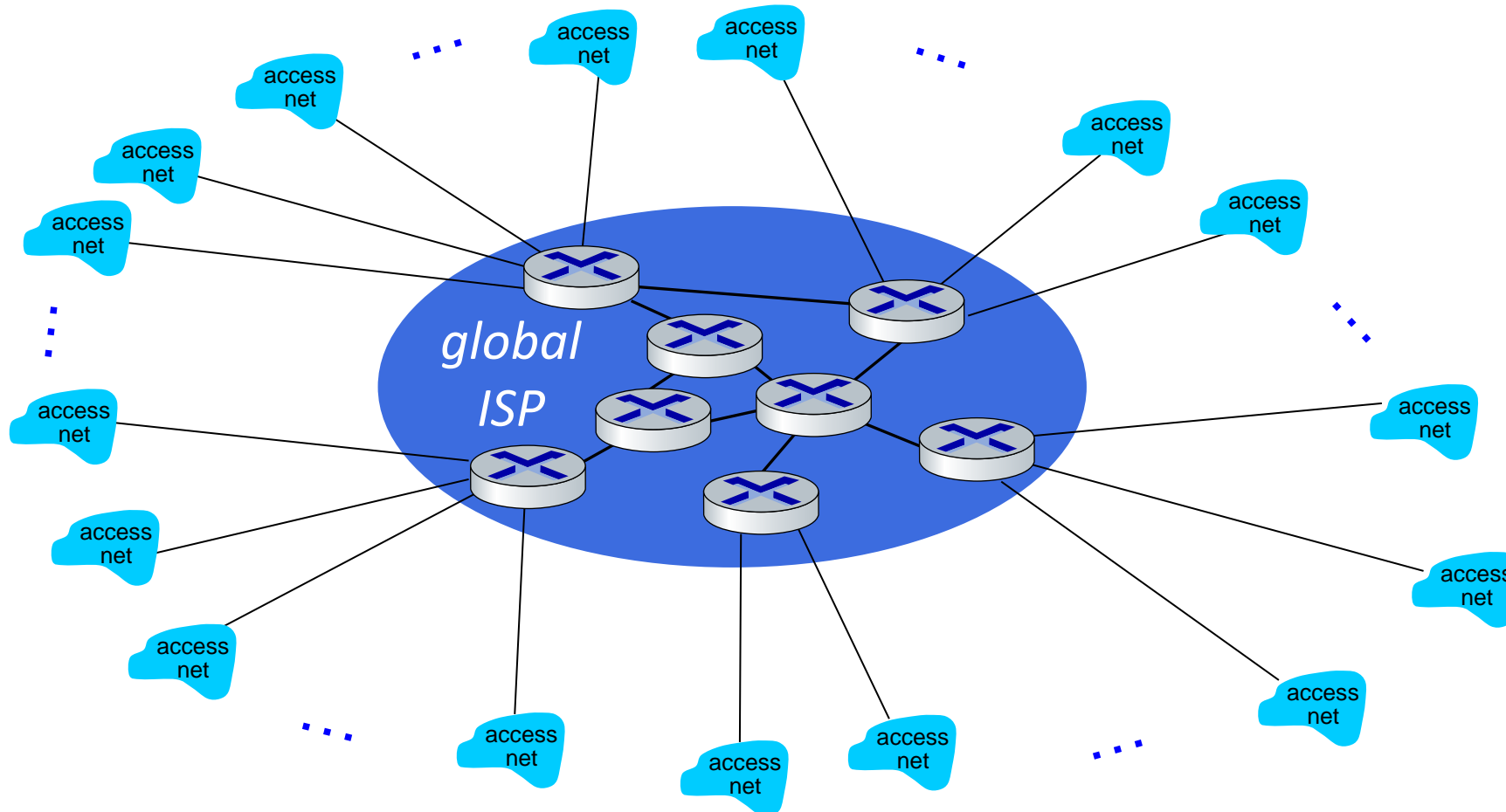
*Question:* given *millions* of access ISPs, how to connect them together?



# Internet structure: a “network of networks”

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

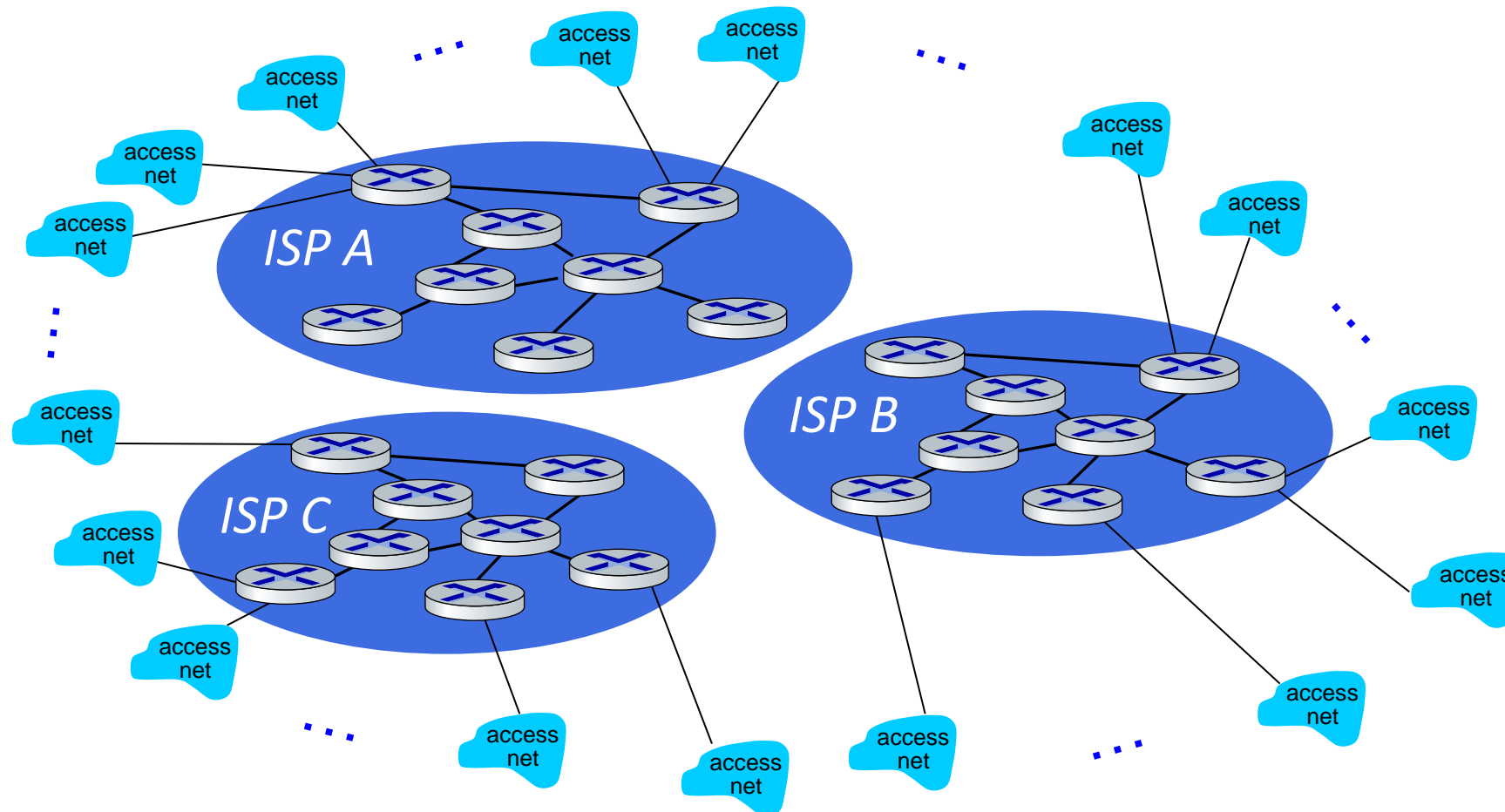
*Customer and provider ISPs have economic agreement.*





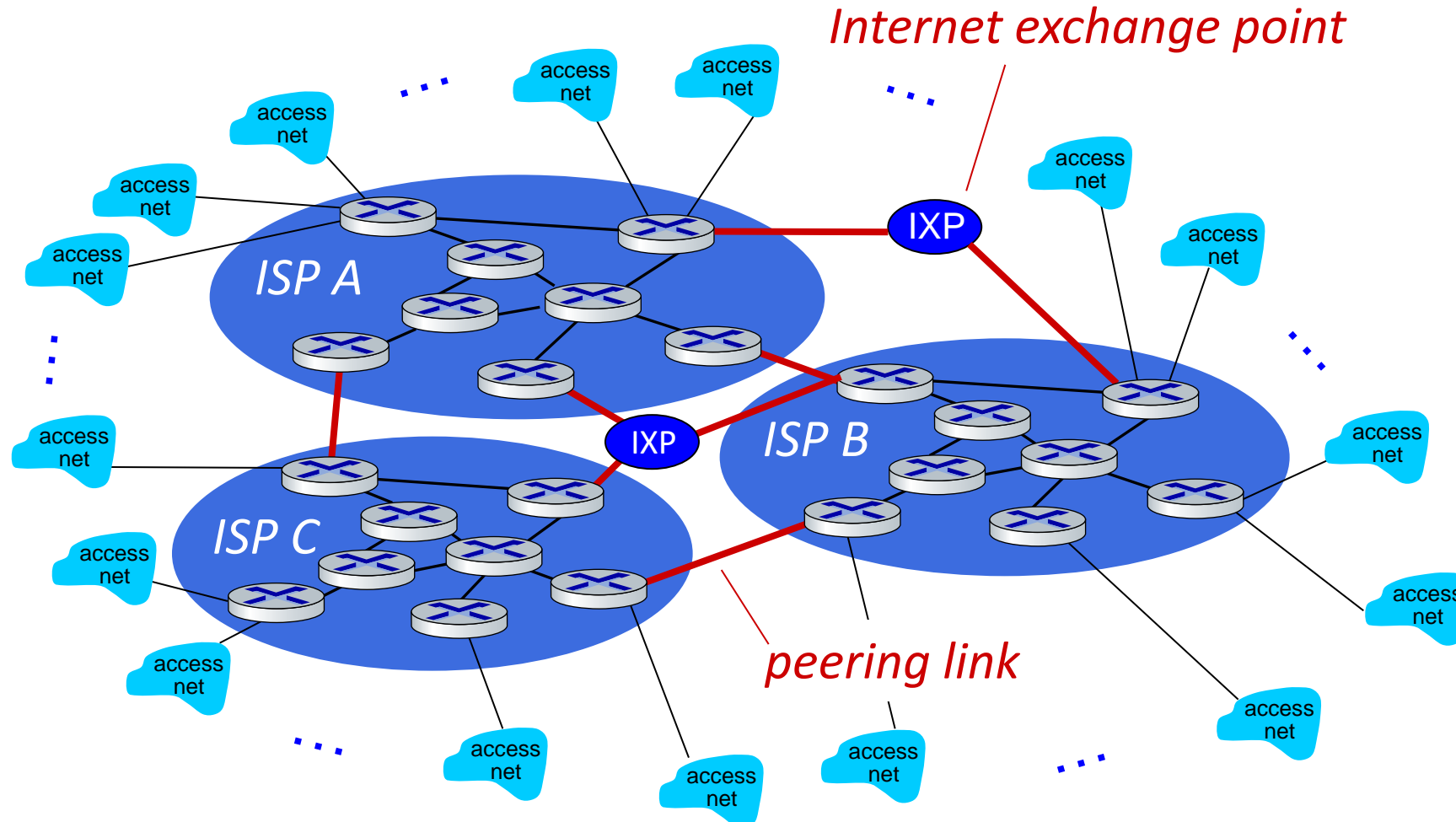
# Internet structure: a “network of networks”

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



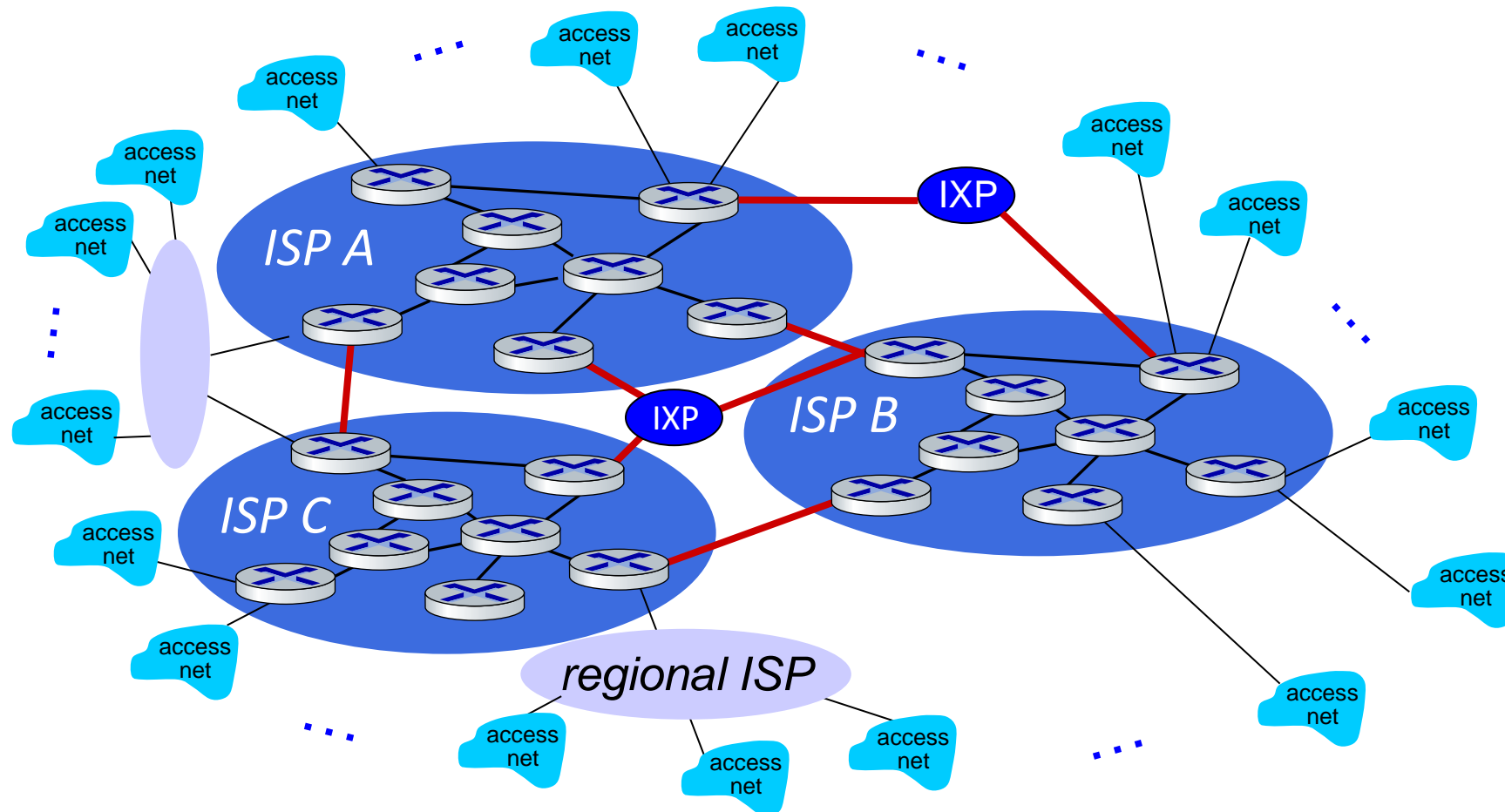
# Internet structure: a “network of networks”

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



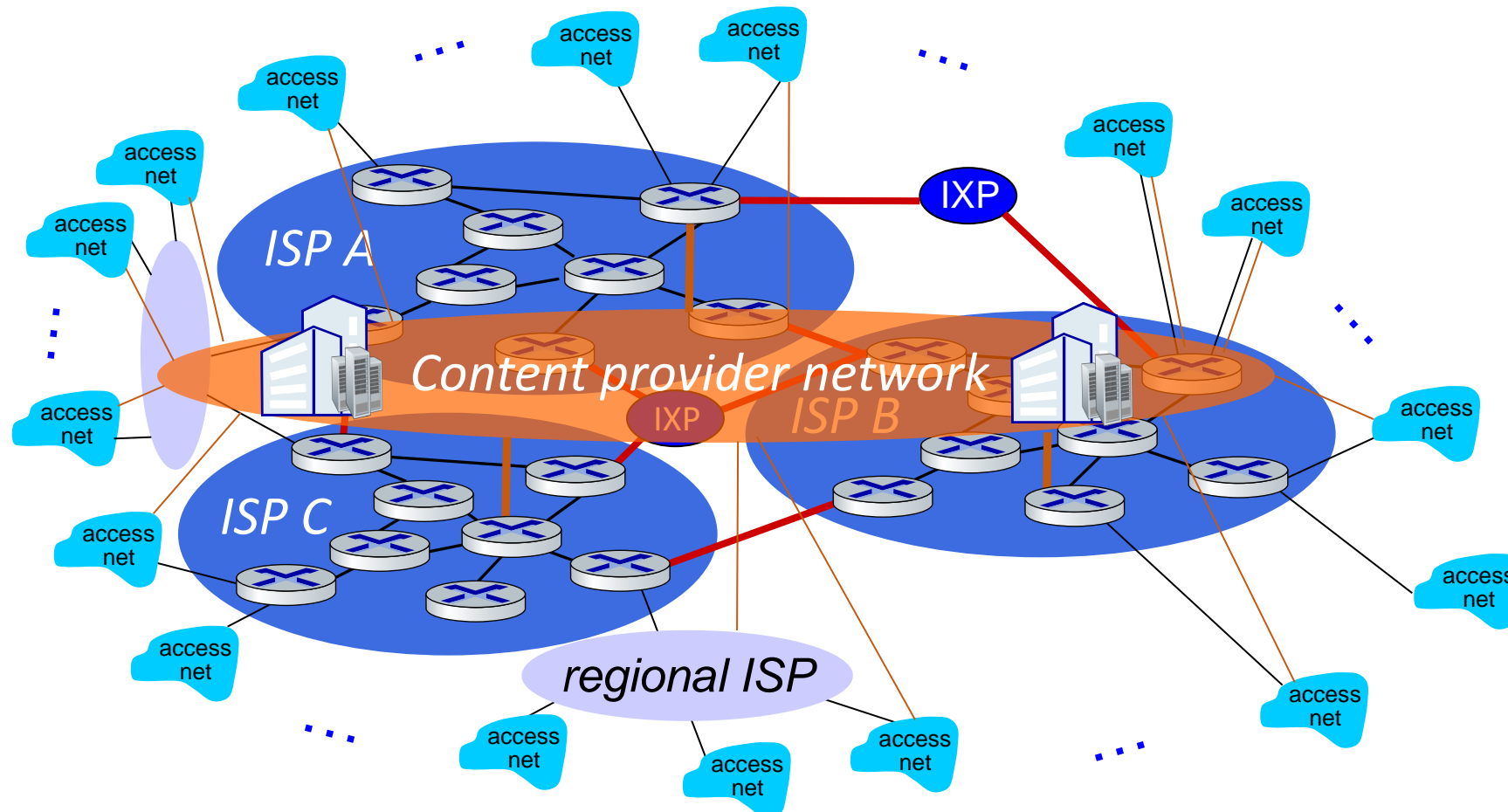
# Internet structure: a “network of networks”

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

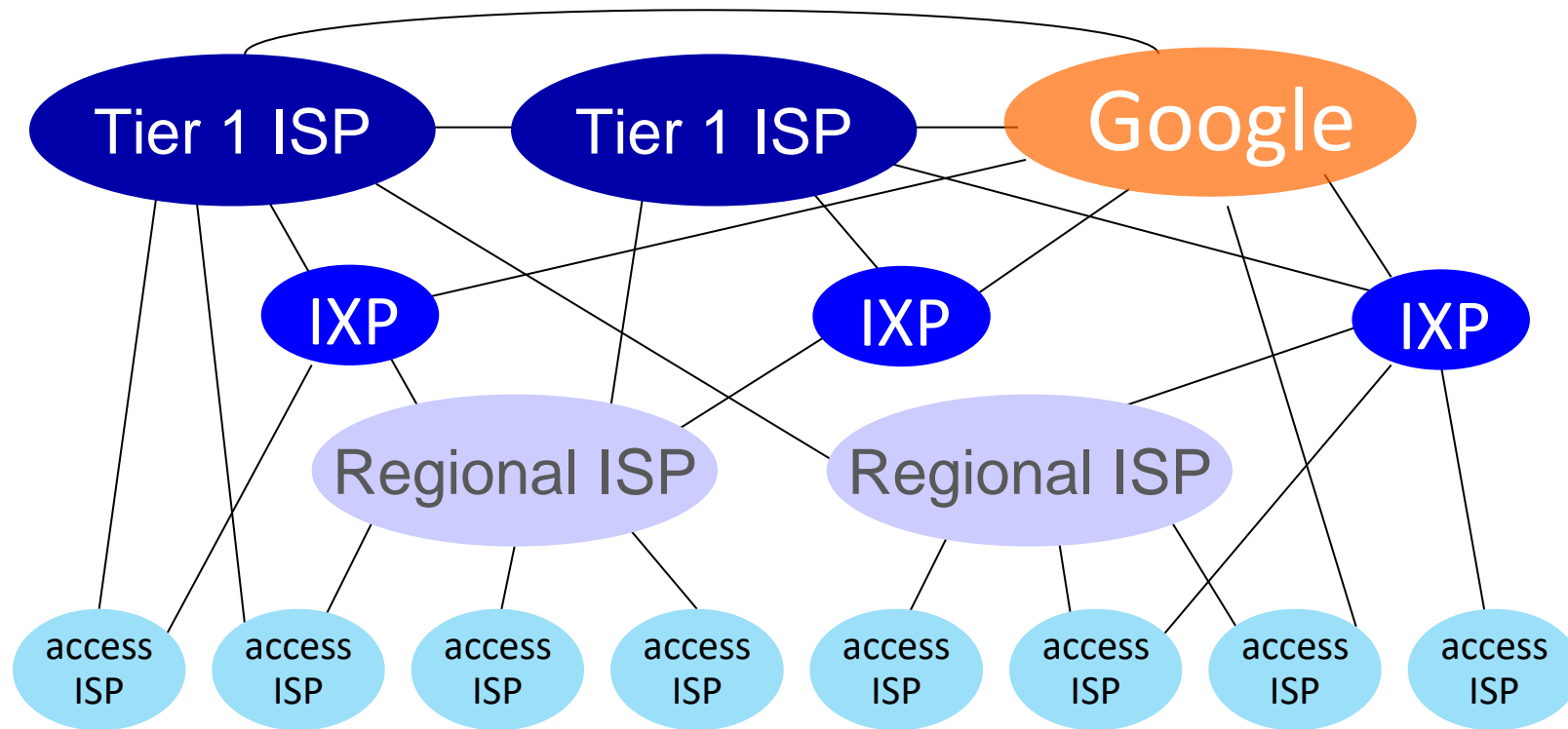


# Internet structure: a “network of networks”

... 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

# Tier-1 ISP Network map: Sprint (2019)



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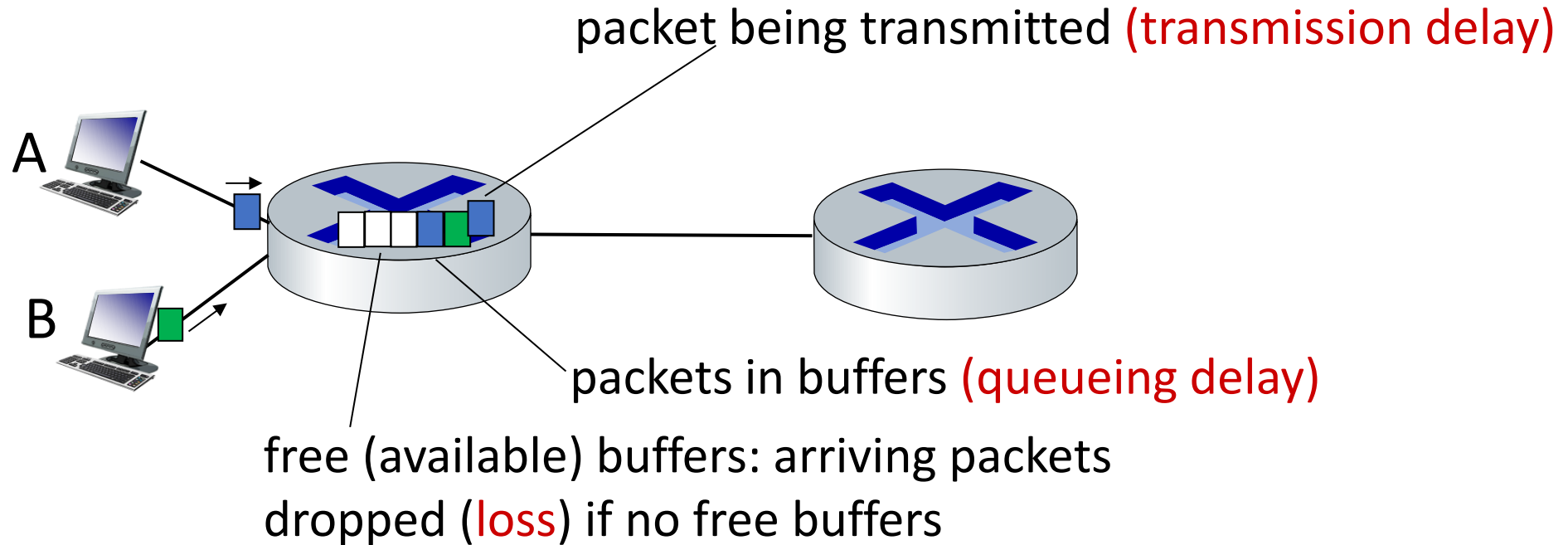




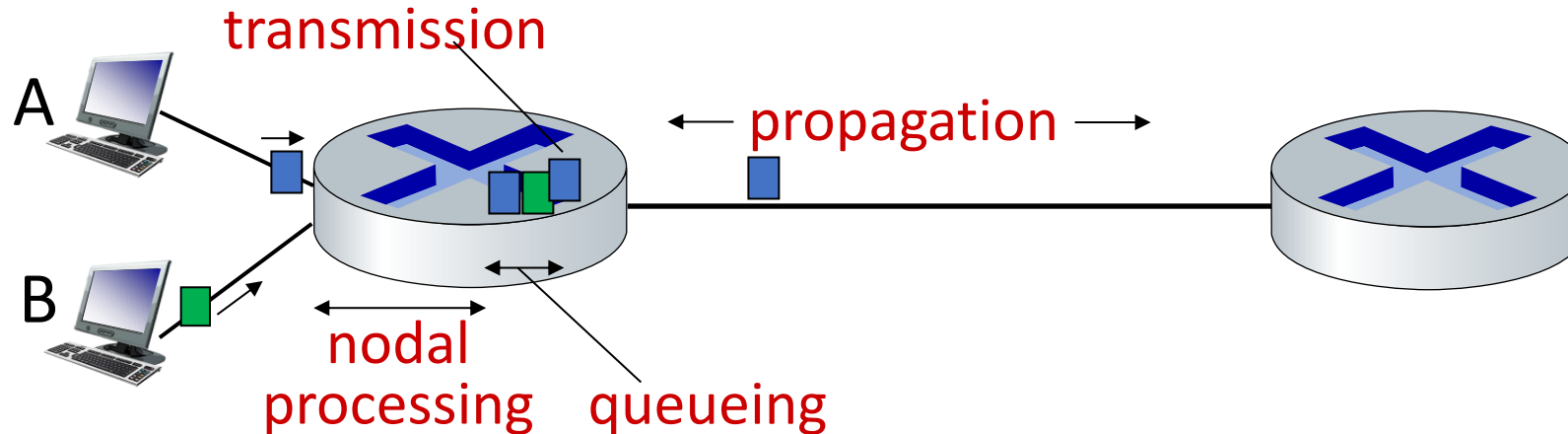
# How do packet loss and delay occur?

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



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

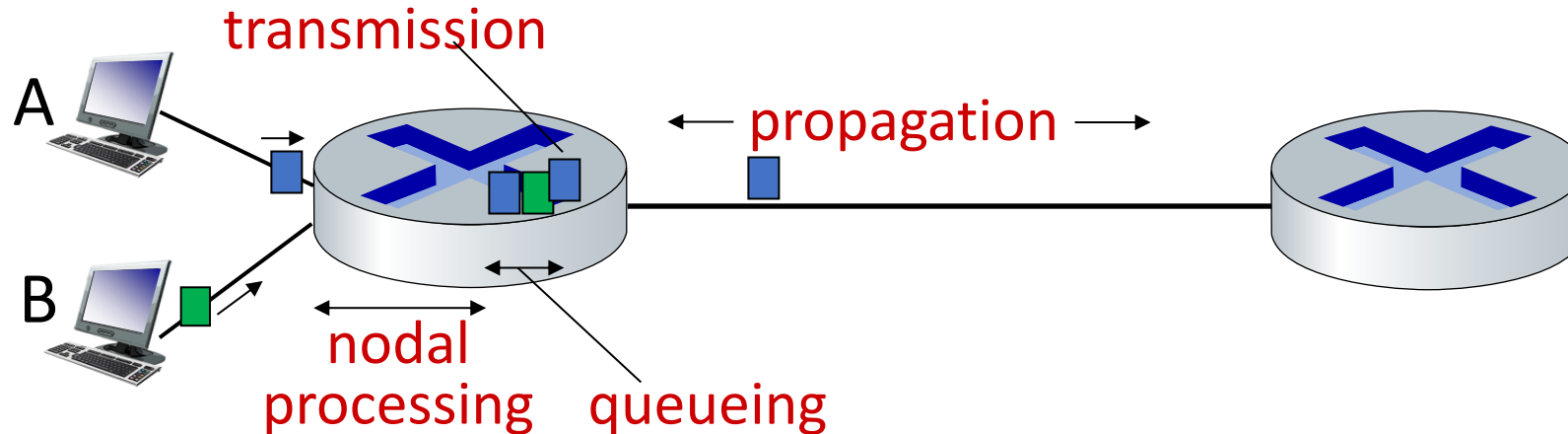
$d_{\text{proc}}$ : nodal processing

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

$d_{\text{queue}}$ : queueing delay

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

# Packet delay: four sources



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

$d_{\text{trans}}$ : transmission delay:

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

▪  $d_{\text{trans}} = L/R$

$d_{\text{prop}}$ : propagation delay:

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

▪  $d_{\text{prop}} = d/s$

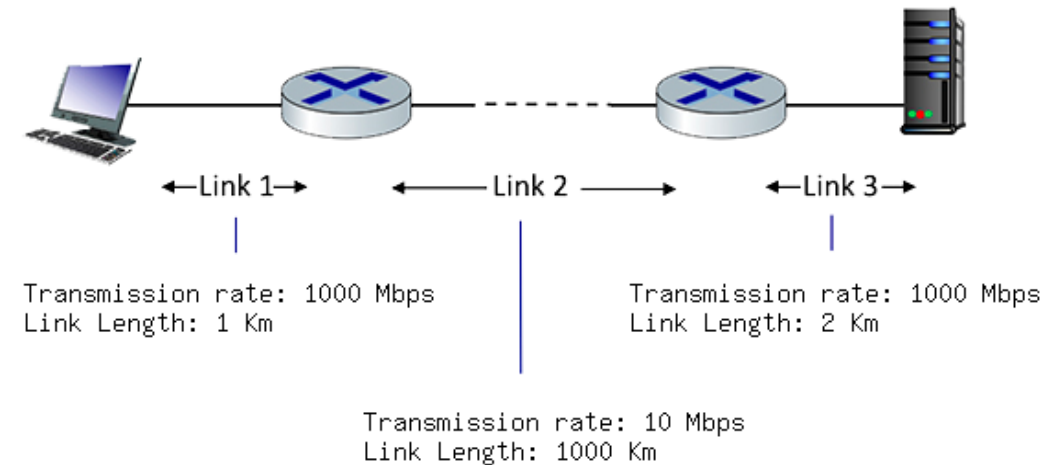
$d_{\text{trans}}$  and  $d_{\text{prop}}$   
very different

\* Check out the online interactive exercises:  
[http://gaia.cs.umass.edu/kurose\\_ross](http://gaia.cs.umass.edu/kurose_ross)

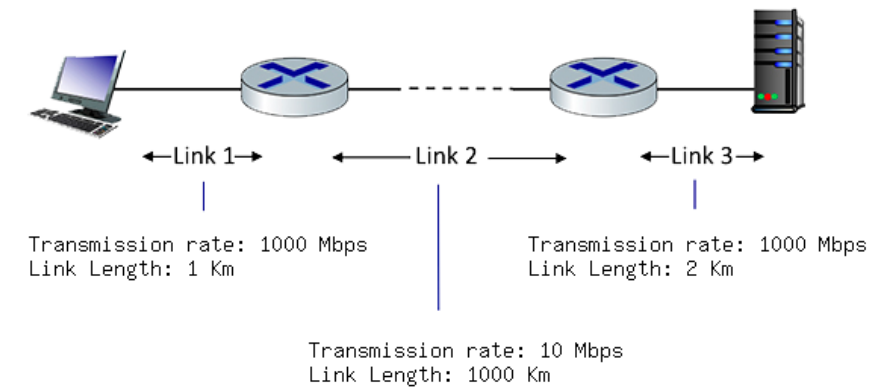
# Example:

Assume the length of a packet is 12000 bits. The speed of light propagation delay on each link is  $3 \times 10^8$  m/sec.

- Q1: What is the transmission delay of link 1?
- Q2: What is the propagation delay of link 1?
- Q3: What is the total delay of link 1?
- Q4: What is the transmission delay of link 2?
- Q5: What is the propagation delay of link 2?
- Q6: What is the total delay of link 2?
- Q7: What is the total delay?



# Example:



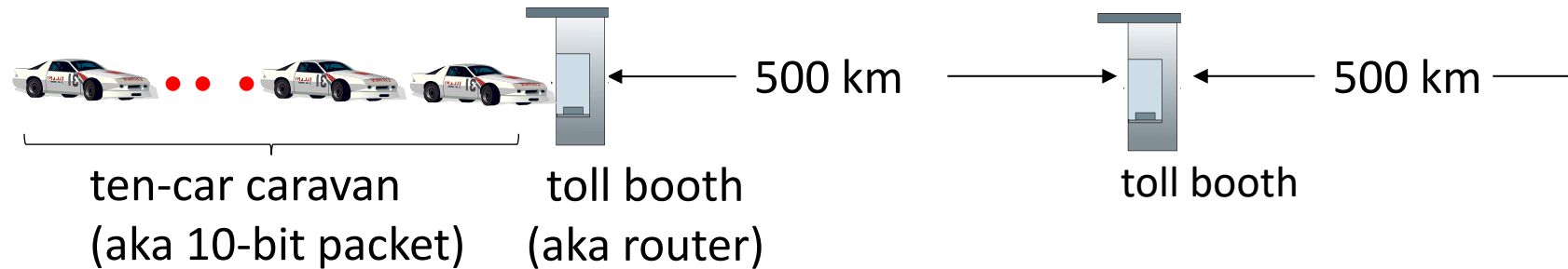
Assume the length of a packet is 12000 bits. The speed of light propagation delay on each link is  $3 \times 10^8$  m/sec.

- Q1: What is the transmission delay of link 1?  **$1.2 \times 10^{-5}$**
- Q2: What is the propagation delay of link 1?  **$3.33 \times 10^{-6}$**
- Q3: What is the total delay of link 1?  **$15.33 \times 10^{-6}$**
- Q4: What is the transmission delay of link 2? **0.0012**
- Q5: What is the propagation delay of link 2? **0.0033**
- Q6: What is the total delay of link 2? **0.0045**
- Q7: What is the total delay?  **$15.33 \times 10^{-6} + 0.0045 + 18.67 \times 10^{-6} = 0.004534$**

# Example:

- Assume we want to send an image from mars to earth
- 1920X1080 pixels, assume true color (each pixel is 3 bytes), using 100Mbps
- Distance to mars 213.85 million km
- $D_{\text{prop}} = \text{Propagation delay} = \text{distance} / \text{speed of light}$
- $D_{\text{prop}} = 213.85 * 10^9 / (3 * 10^8) = 712 \text{ sec} = 11.8 \text{ min}$
- File size =  $1920 * 1080 * 3 * 8$
- Assume packet size is equal file size
- $\text{Transmission delay} = 1920 * 1080 * 3 * 8 / (100 * 10^6) = 0.5 \text{ sec}$
- Total Time =  $712 + 0.5 = 712.5 \text{ sec}$

# Example: caravan analogy

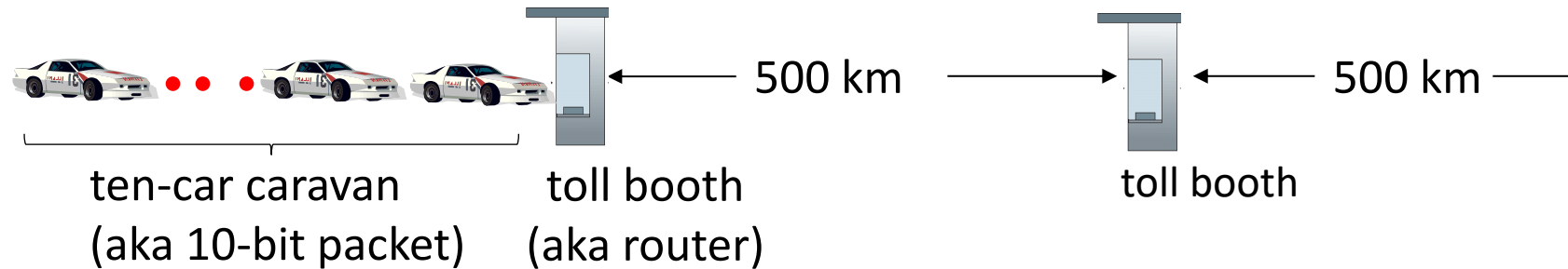


Suppose the caravan has 10 cars, and that the tollbooth services (that is, transmits) a car at a rate of one car per 1 seconds. Once receiving serving a car proceeds to the next tool both, which is 500 kilometers away at a rate of 20 kilometers per second. Also assume that whenever the first car of the caravan arrives at a tollbooth, it must wait at the entrance to the tollbooth until all of the other cars in its caravan have arrived, and lined up behind it before being serviced at the toll booth.

- Once a car enters service at the tollbooth, how long does it take until it leaves service?
- How long does it take for the entire caravan to receive service at the tollbooth (that is the time from when the first car enters service until the last car leaves the tollbooth)?
- Once the first car leaves the tollbooth, how long does it take until it arrives at the next tollbooth?
- Once the first car leaves the tollbooth, how long does it take until it enters service at the next tollbooth?



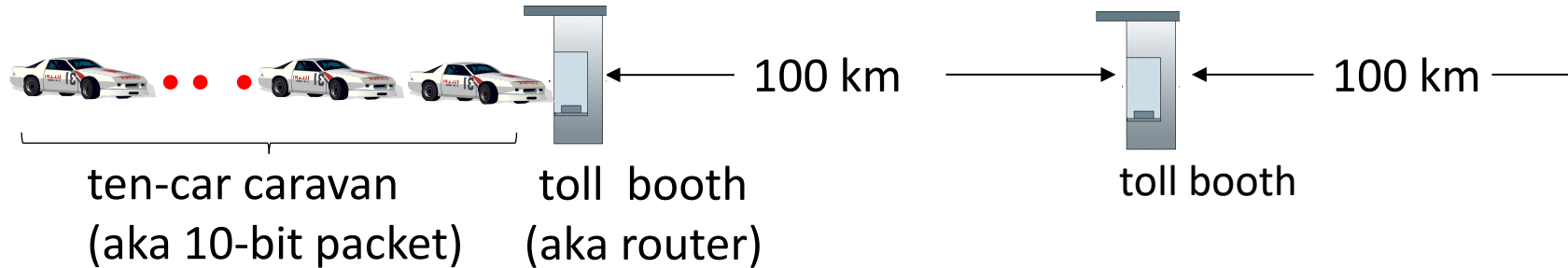
# Example: caravan analogy



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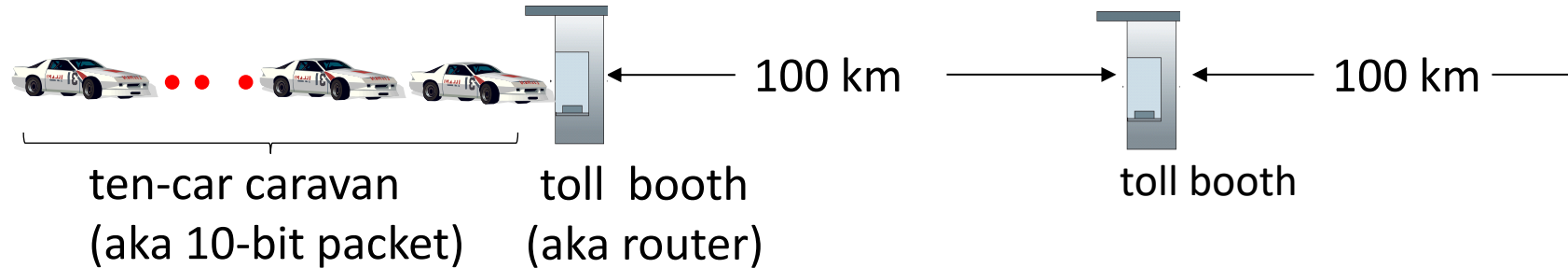
- Once a car enters service at the tollbooth, how long does it take until it leaves service? **1 sec.**
- How long does it take for the entire caravan to receive service at the tollbooth (that is the time from when the first car enters service until the last car leaves the tollbooth)? **10 sec.**
- Once the first car leaves the tollbooth, how long does it take until it arrives at the next tollbooth? **25 sec.**
- Once the first car leaves the tollbooth, how long does it take until it enters service at the next tollbooth? **34 sec.**

# Caravan analogy



- cars “propagate” at 100 km/hr
- toll booth takes 12 sec to service car (bit transmission time)
- car  $\sim$  bit; caravan  $\sim$  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**

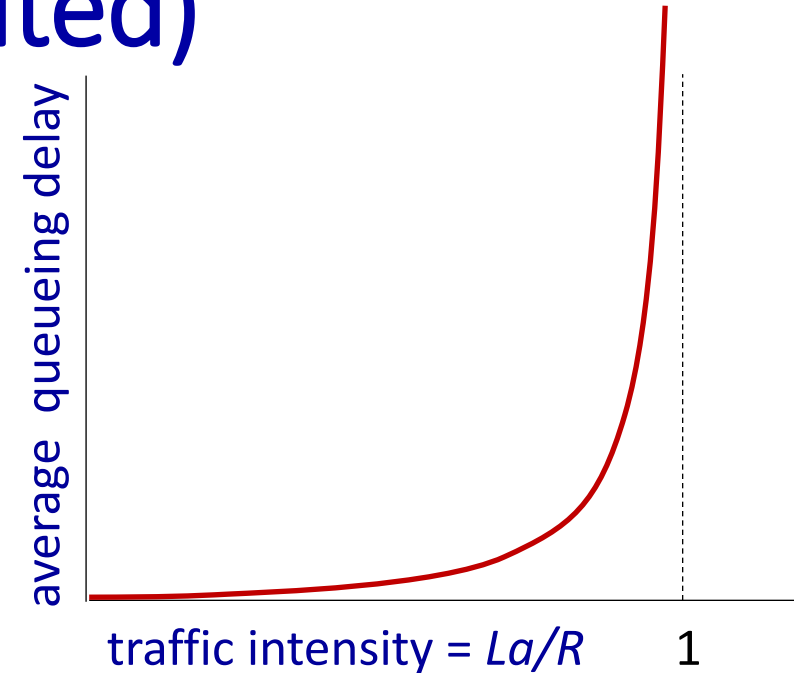
# Caravan analogy



- 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

# 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!



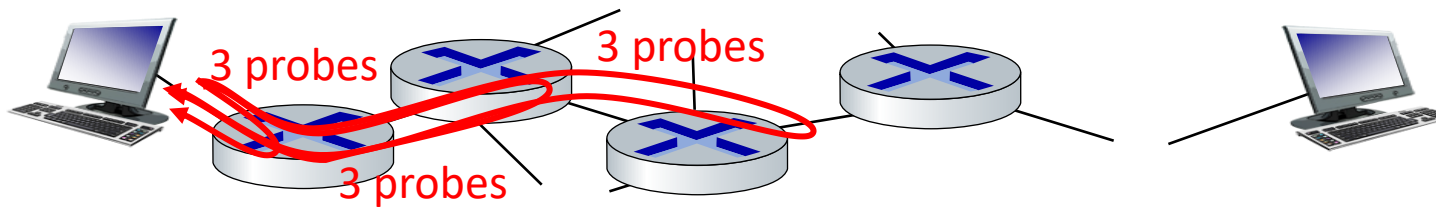
# Packet queueing delay

Assume a constant transmission rate of  $R = 700000$  bps, a constant packet-length  $L = 4600$  bits, and  $a$  is the average rate of packets/second. Traffic intensity  $I = La/R$ , and the queuing delay is calculated as  $I(L/R)(1 - I)$  for  $I < 1$ .

- In practice, does the queuing delay tend to vary a lot? **Yes.**
- Assuming that  $a = 34$ , what is the queuing delay? **1.1401 ms**
- Assuming that  $a = 90$ , what is the queuing delay? **1.588 ms**
- Assuming the router's buffer is infinite, the queuing delay is 1.588 ms, and 860 packets arrive. How many packets will be in the buffer 1 second later?  
**231 packets**  $860 - ((1 \div 1.588) * 1000)$
- If the buffer has a maximum size of 792 packets, how many of the 860 packets would be dropped upon arrival from the previous question? **68**  
 $860 - 792 =$

# “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

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

trans-oceanic link

looks like delays  
decrease! Why?

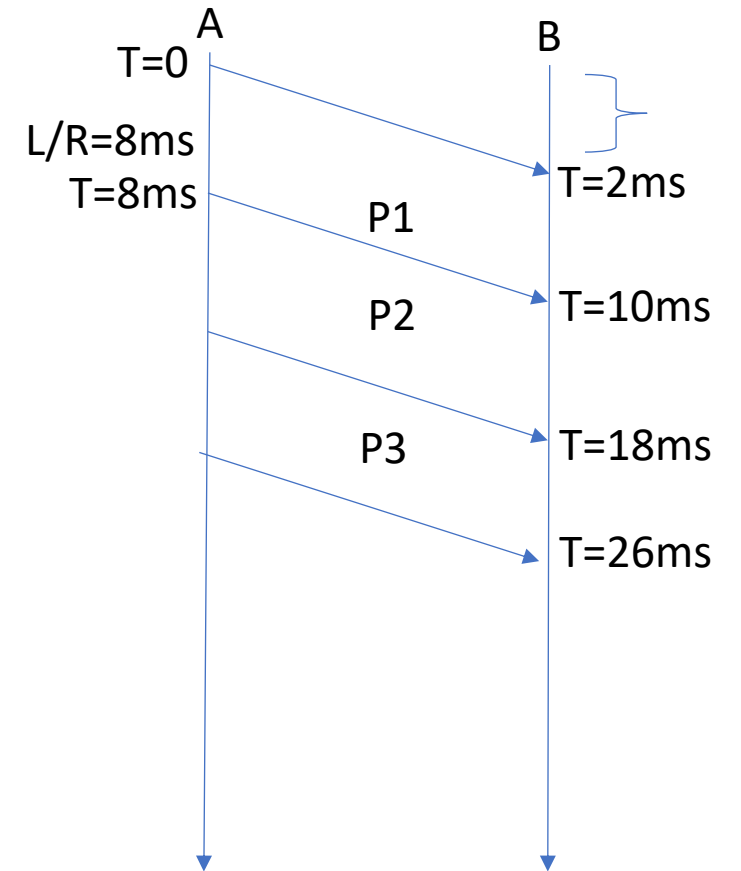
\* means no response (probe lost, router not replying)

| hop | hostname (ip)                                   | 1st probe | 2nd probe | 3rd probe |
|-----|---|-----------|-----------|-----------|
| 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    |

\* Do some traceroutes from exotic countries at [www.traceroute.org](http://www.traceroute.org)

# Example

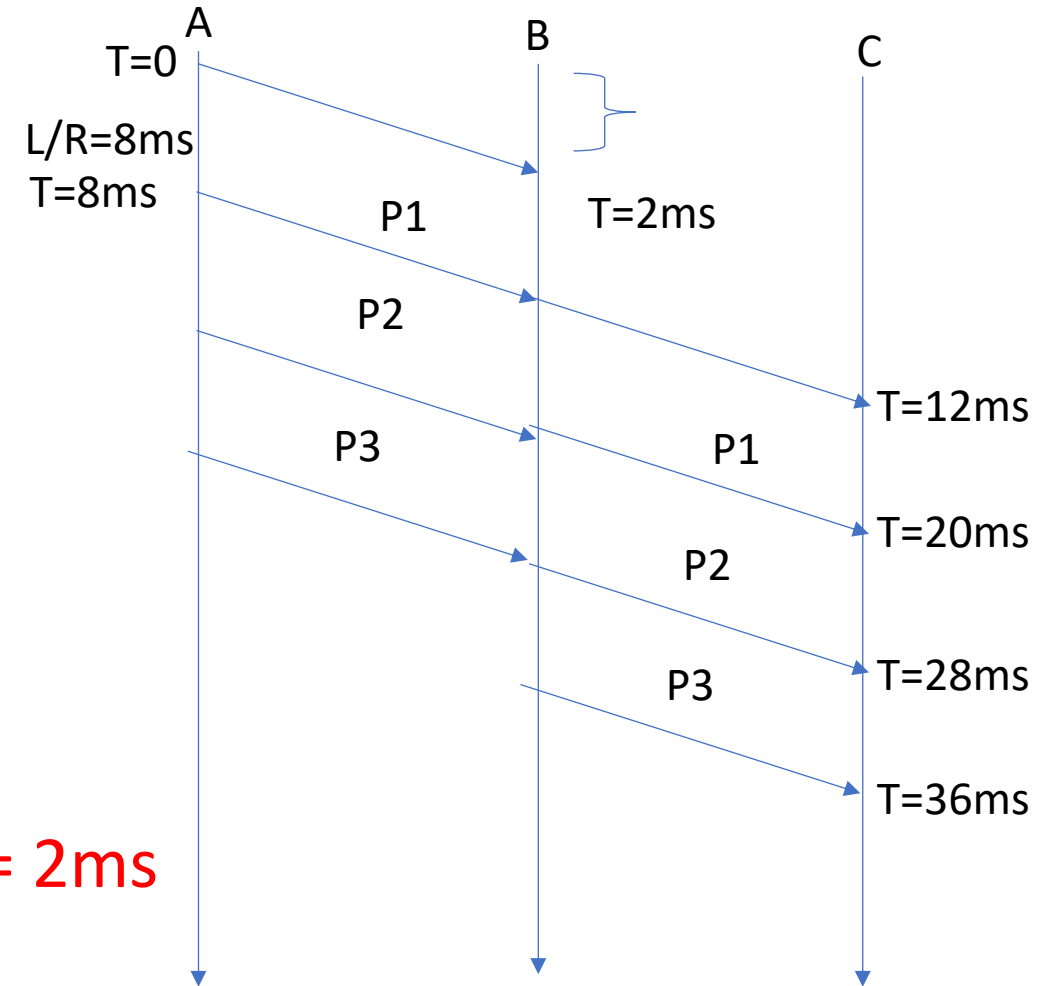
- Consider sending one file from A to B
- File 3 kbyte
- Packet length  $L=1\text{kbyte}$
- Data Rate  $R=1\text{ Mbps}$
- Distance between A and B is 500 km
- Assume speed of light is  $2.5 \times 10^8\text{ m/s}$
- Propagation Delay  $d_{\text{prop}}$ ?
- $d_{\text{prop}} = d/s = 500 * 1000 / (2.5 * 10^8) = 2\text{ms}$
- Transmission Delay ( $d_{\text{trans}}$ )?
- $d_{\text{trans}} = L/R = 1\text{kbyte} / 1\text{Mbps} = 1 * 1000 * 8\text{ bits} / 1\text{M bits/sec} = 8\text{ms}$





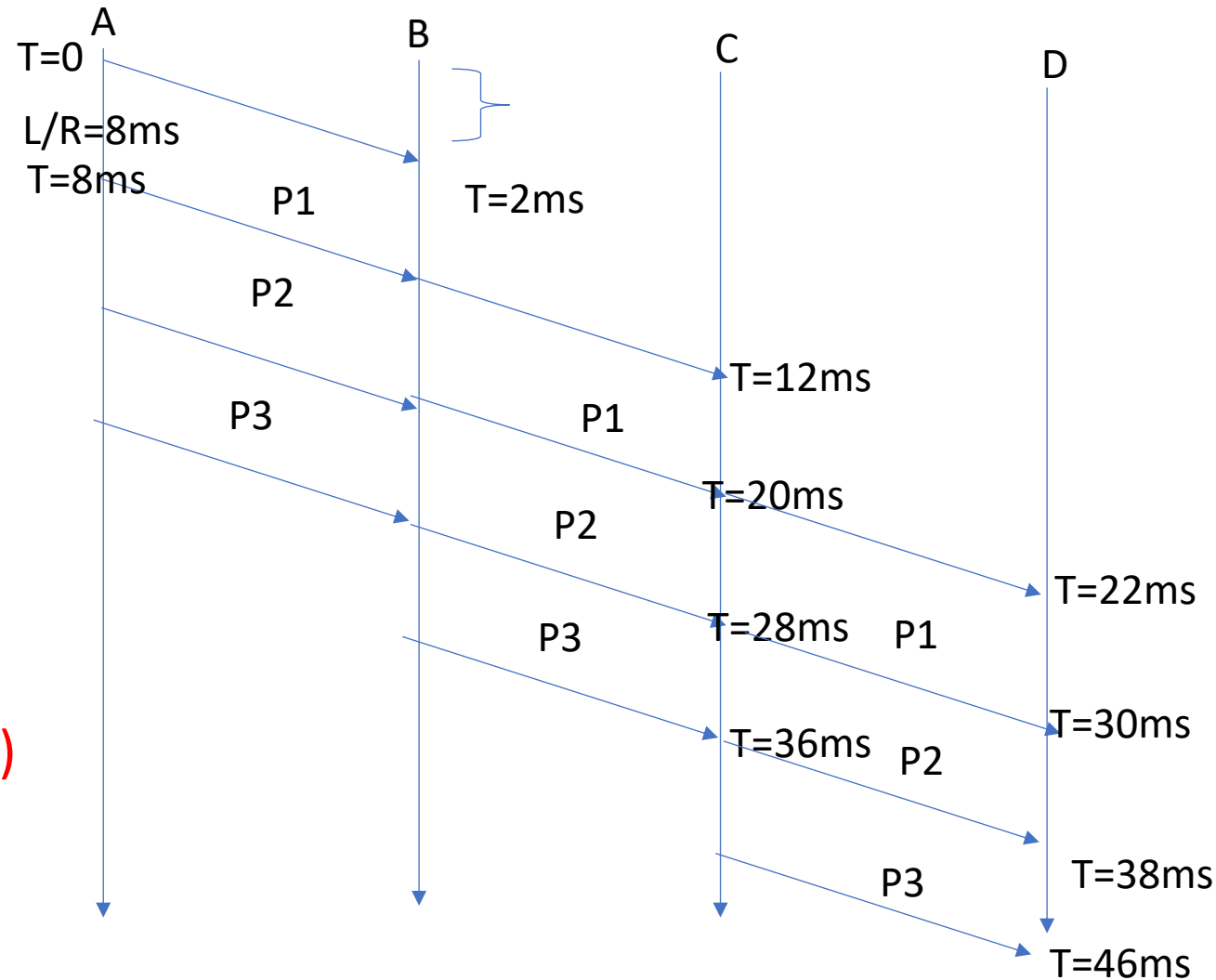
# Example

- Consider sending one file from A to C
- File 3 kbyte
- Packet length  $L=1\text{kbyte}$
- Data Rate  $R=1\text{ Mbps}$
- Distance between A and B is 500 km
- Assume speed of light is  $2.5 \times 10^8\text{ m/s}$
- Propagation Delay  $d_{\text{prop}}$ ?
- $d_{\text{prop}} = d/s = 500 * 1000 / (2.5 * 10^8) = 2\text{ms}$
- Transmission Delay ( $d_{\text{trans}}$ )?
- $d_{\text{trans}} = L/R = 1\text{kbyte} / 1\text{Mbps} = 1 * 1000 * 8\text{ bits} / 1\text{M bits/sec} = 8\text{ms}$



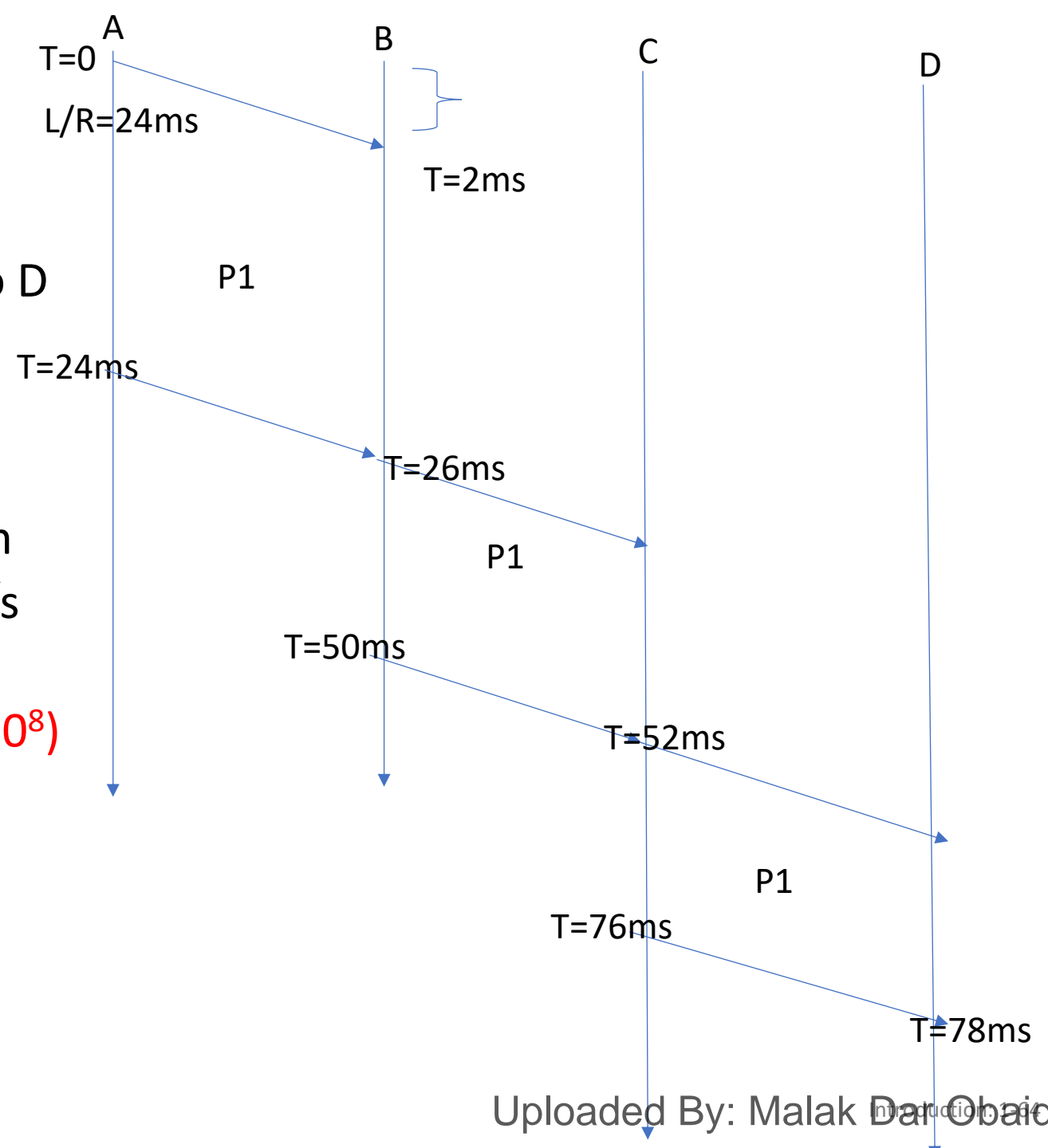
# Example

- Consider sending one file from A to D
- File 3 kbyte
- Packet length  $L=1\text{kbyte}$
- Data Rate  $R=1\text{ Mbps}$
- Distance between A and B is 500 km
- Assume speed of light is  $2.5 \times 10^8\text{ m/s}$
- Propagation Delay  $d_{\text{prop}}$ ?
- $d_{\text{prop}} = d/s = 500 * 1000 / (2.5 * 10^8) = 2\text{ms}$
- Transmission Delay ( $d_{\text{trans}}$ )?
- $d_{\text{trans}} = L/R = 1\text{kbyte} / 1\text{Mbps} = 1 * 1000 * 8 \text{ bits} / 1\text{M bits/sec} = 8\text{ms}$



# Example

- Consider sending one file from A to D
- File 3 kbyte
- Packet length  $L=3\text{kbyte}$
- Data Rate  $R=1\text{ Mbps}$
- Distance between A and B is 500 km
- Assume speed of light is  $2.5 \times 10^8\text{ m/s}$
- Propagation Delay  $d_{\text{prop}}$ ?
- $d_{\text{prop}} = d/s = 500 * 1000 / (2.5 * 10^8) = 2\text{ms}$
- Transmission Delay ( $d_{\text{trans}}$ )?
- $d_{\text{trans}} = L/R = 3\text{kbyte} / 1\text{Mbps} = 3 * 1000 * 8 \text{ bits} / 1\text{M bits/sec} = 24\text{ms}$



# Example

Consider sending a file of 6 Mbits over a path of  $X$  links. Each link transmits at a rate of 4 Mbps. Suppose that a packet-switched datagram network is used, and it segments the file into 450 packets with each packet having a 500 bits header. Assume that there are no queuing delays, the processing delay is negligible, and each of the  $X$  links has a propagation delay of 7 milliseconds. Calculate the maximum number of links,  $X$ , that is along the path such that the total time to deliver the file is less than or equal to 2.107 seconds.

$$t_{\text{trans.}} = (6 \text{ Mbits}/450 + 500 \text{ bits})/4 \text{ Mbps} = 0.00346 \text{ seconds}$$

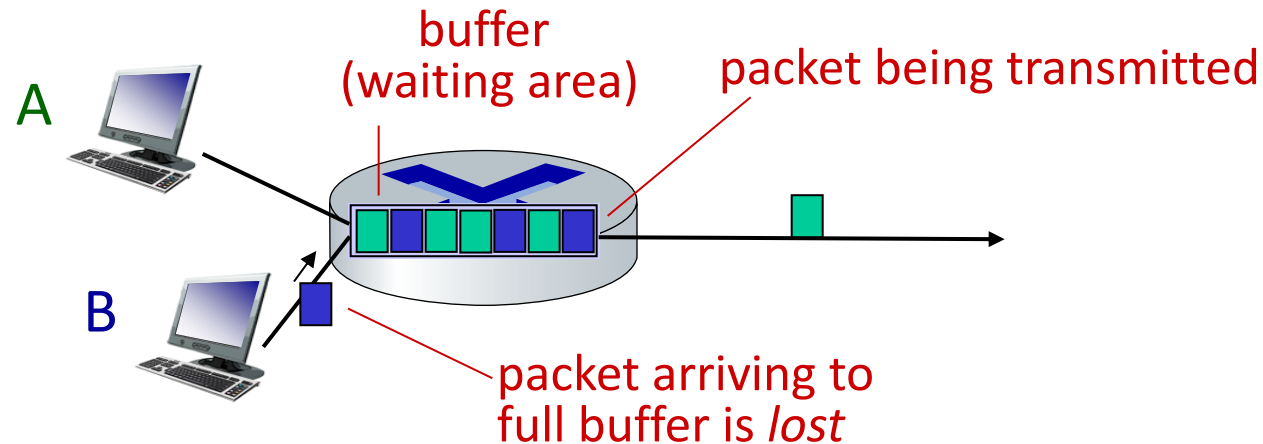
$$\begin{aligned} \text{Total time} = 2.107 \text{ s} &\geq X \times (t_{\text{trans.}} + t_{\text{prop.}}) \text{ (1st packet)} + 449 \text{ packets} \times t_{\text{trans.}} \\ &\geq (X + 449) \times 0.00346 + X \times 0.007 \end{aligned}$$

$$\rightarrow X \leq (2.107 - 1.55354)/0.01046 = 52.9$$

$$\rightarrow \text{Maximum number of links } X = 52 \text{ links}$$

# Packet loss

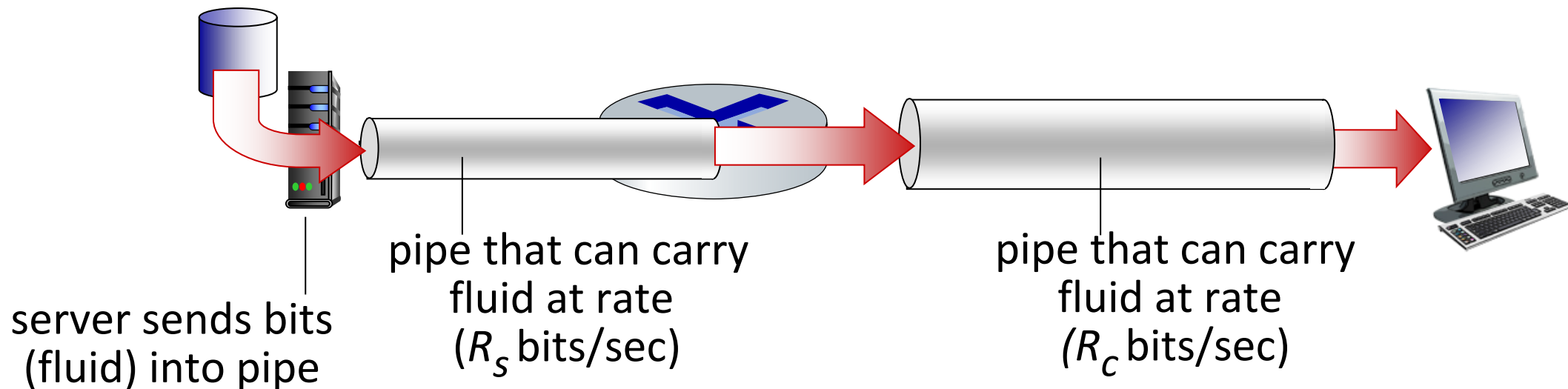
- queue (aka buffer) preceding link in buffer has finite capacity
- packet arriving to full queue dropped (aka lost)
- lost packet may be retransmitted by previous node, by source end system, or not at all



\* Check out the Java applet for an interactive animation on queuing and loss

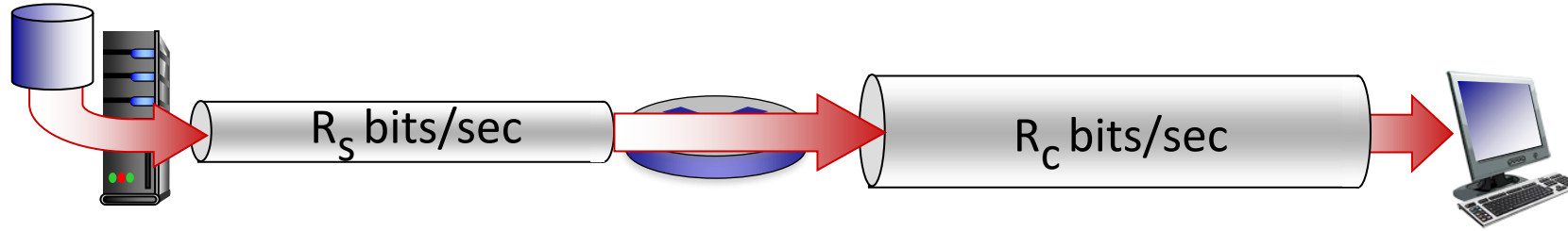
# Throughput

- *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

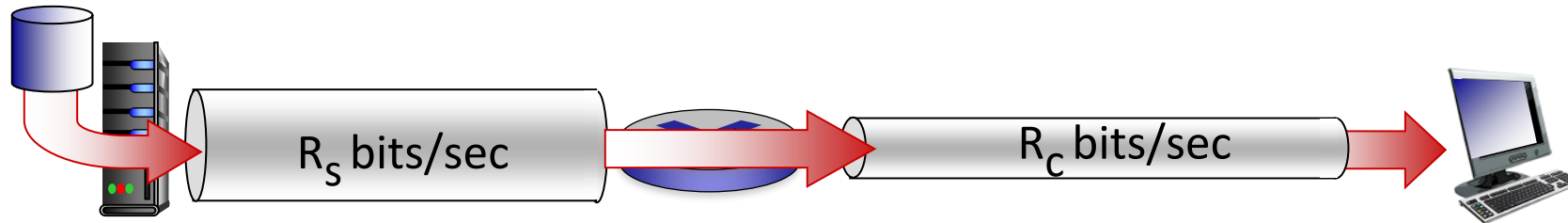


# Throughput

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



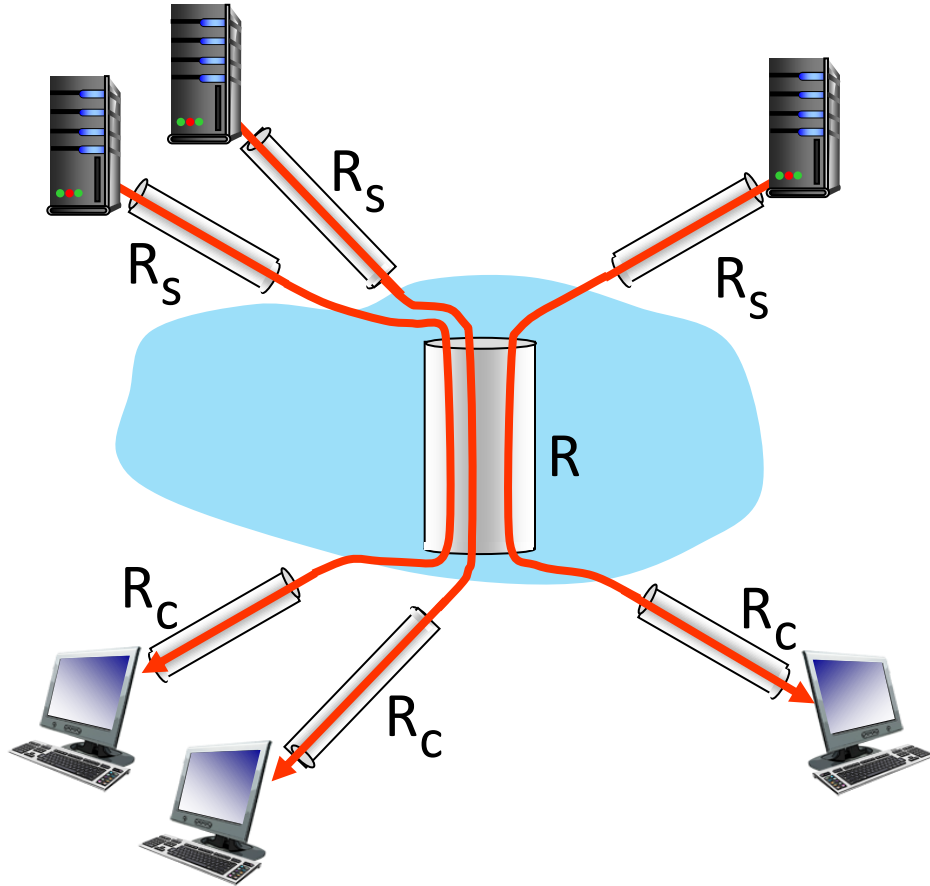
$R_s > R_c$  What is average end-end throughput?



*bottleneck link*

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

# Throughput: network scenario



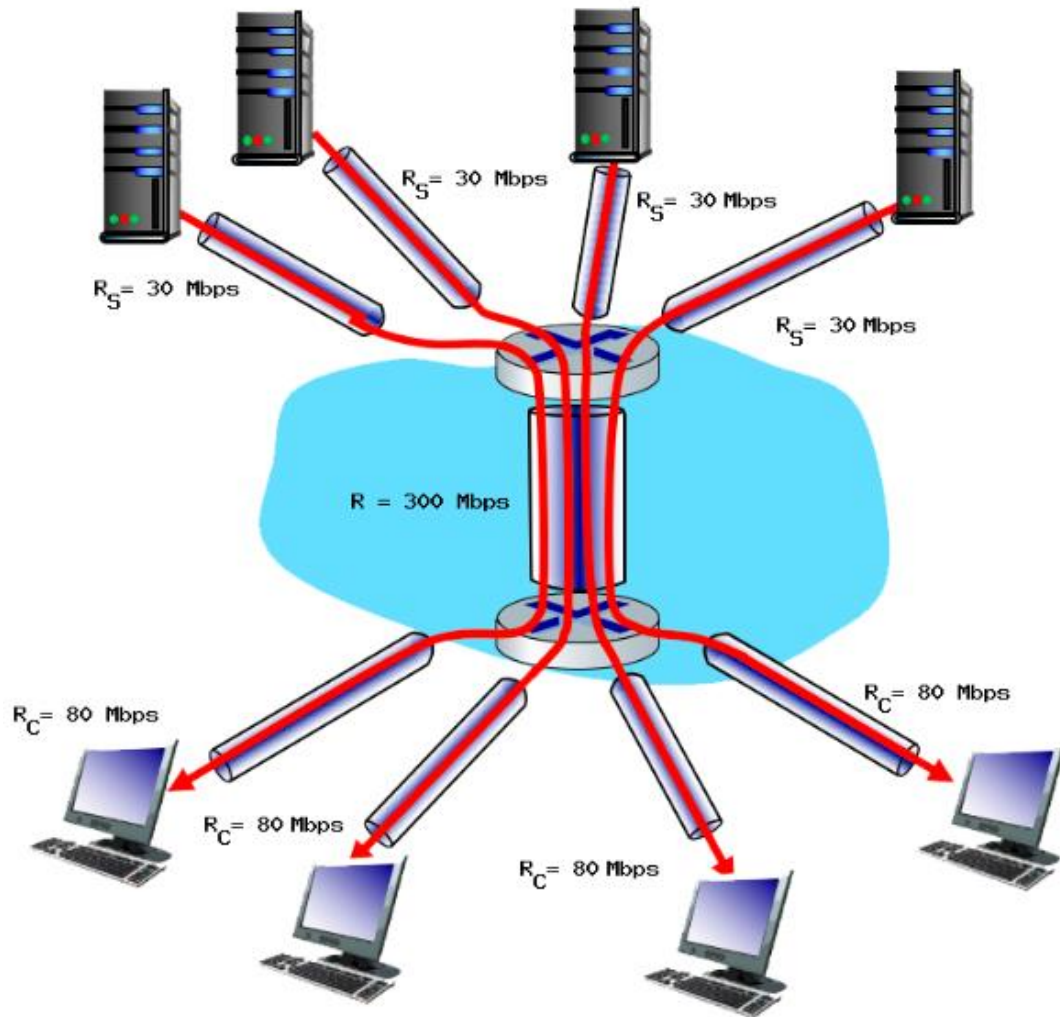
10 connections (fairly) share  
backbone bottleneck link  $R$  bits/sec

- 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/](http://gaia.cs.umass.edu/kurose_ross/)

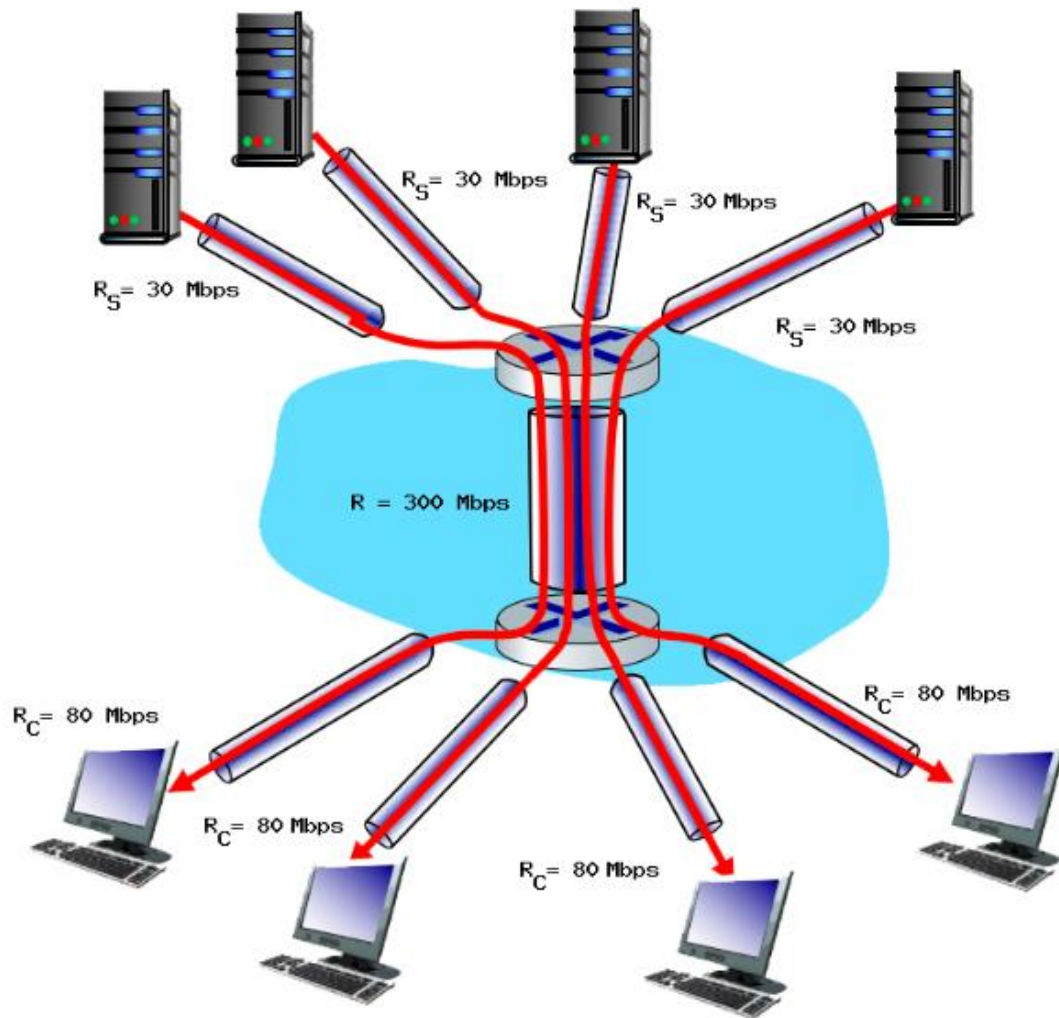


# Example:



- Consider this scenario, with four different servers connected to four different clients over four three-hop paths.
- The four pairs share a common middle hop with a transmission capacity of  $R = 300 \text{ Mbps}$ .
- The four links from the servers to the shared link have a transmission capacity of  $R_S = 30 \text{ Mbps}$ .
- Each of the four links from the shared middle link to a client has a transmission capacity of  $R_C = 80 \text{ Mbps}$ .

# Example:



- What is the maximum achievable end-end throughput (in Mbps) for each of four client-to-server pairs, assuming that the middle link is fairly shared (divides its transmission rate equally)? **30Mbps**
- Which link is the bottleneck link ( $R_c$ ,  $R_s$ , or  $R$ )?  **$R_s$**
- Assuming that the servers are sending at the maximum rate possible, what are the link utilizations for the server links ( $R_s$ )? **1**
- Assuming that the servers are sending at the maximum rate possible, what are the link utilizations for the client links ( $R_C$ )? **0.38**
- Assuming that the servers are sending at the maximum rate possible, what is the link utilizations for the shared link ( $R$ )? **0.4**

# 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



# Network security

- **field of network security:**
  - how bad guys can attack computer networks
  - how we can defend networks against attacks
  - how to design architectures that are immune to attacks
- **Internet not originally designed with (much) security in mind**
  - *original vision:* “a group of mutually trusting users attached to a transparent network” 😊
  - Internet protocol designers playing “catch-up”
  - security considerations in all layers!

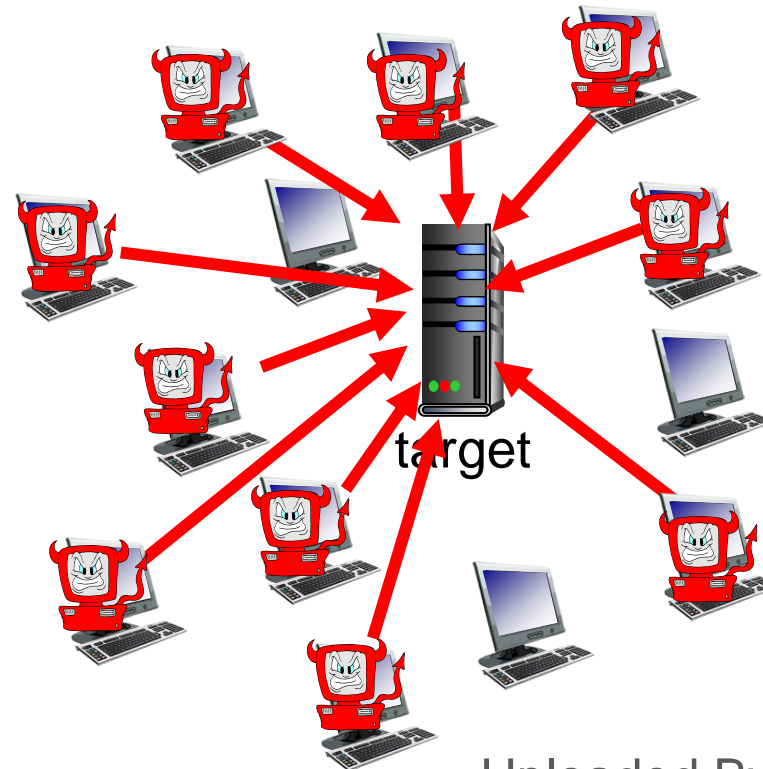
# Bad guys: malware

- malware can get in host from:
  - *virus*: self-replicating infection by receiving/executing object (e.g., e-mail attachment)
  - *worm*: self-replicating infection by passively receiving object that gets itself executed
- **spyware malware** can record keystrokes, web sites visited, upload info to collection site
- infected host can be enrolled in **botnet**, used for spam or distributed denial of service (DDoS) attacks

# Bad guys: denial of service

*Denial of Service (DoS):* attackers make resources (server, bandwidth) unavailable to legitimate traffic by overwhelming resource with bogus traffic

1. select target
2. break into hosts around the network (see botnet)
3. send packets to target from compromised hosts

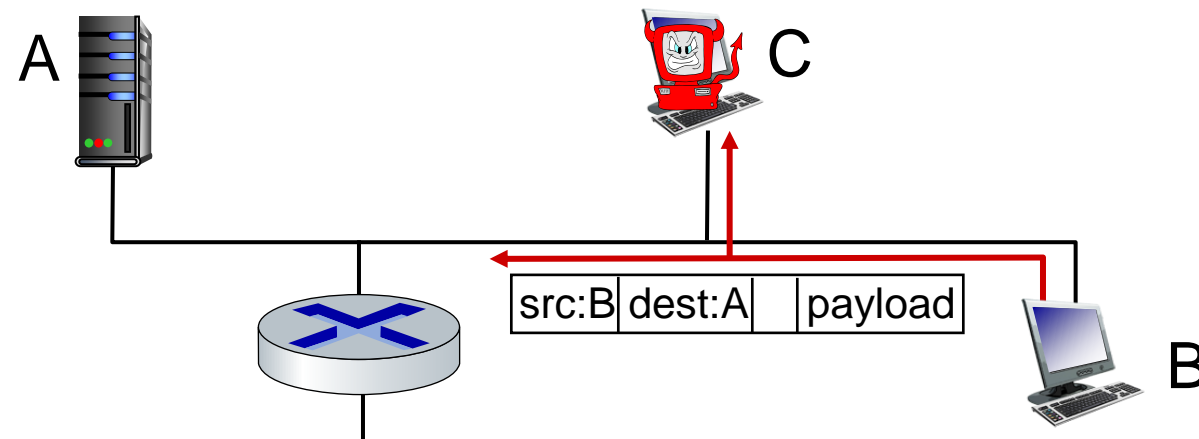




# Bad guys: packet interception

## *packet “sniffing”:*

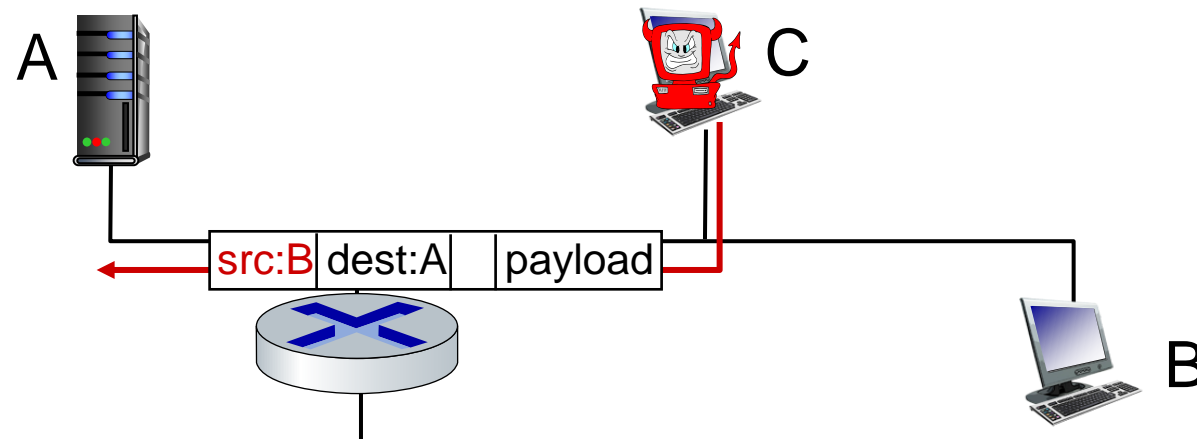
- broadcast media (shared Ethernet, wireless)
- promiscuous network interface reads/records all packets (e.g., including passwords!) passing by



Wireshark software used for our end-of-chapter labs is a (free) packet-sniffer

# Bad guys: fake identity

*IP spoofing*: send packet with false source address



*... lots more on security (throughout, Chapter 8)*



# Chapter 1: roadmap

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



# Protocol “layers” and reference models

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

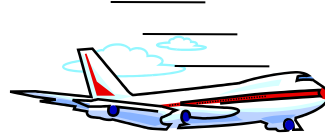
- hosts
- routers
- links of various media
- applications
- protocols
- hardware, software

*Question:*

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

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

# Example: organization of air travel



ticket (purchase)

baggage (check)

gates (load)

runway takeoff

airplane routing

ticket (complain)

baggage (claim)

gates (unload)

runway landing

airplane routing

airplane routing

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

**Q:** describe in words  
the service provided  
in each layer above

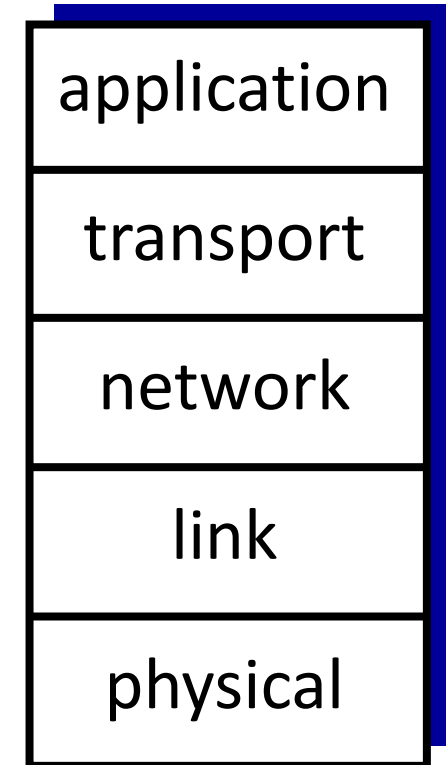
# Why layering?

dealing with complex systems:

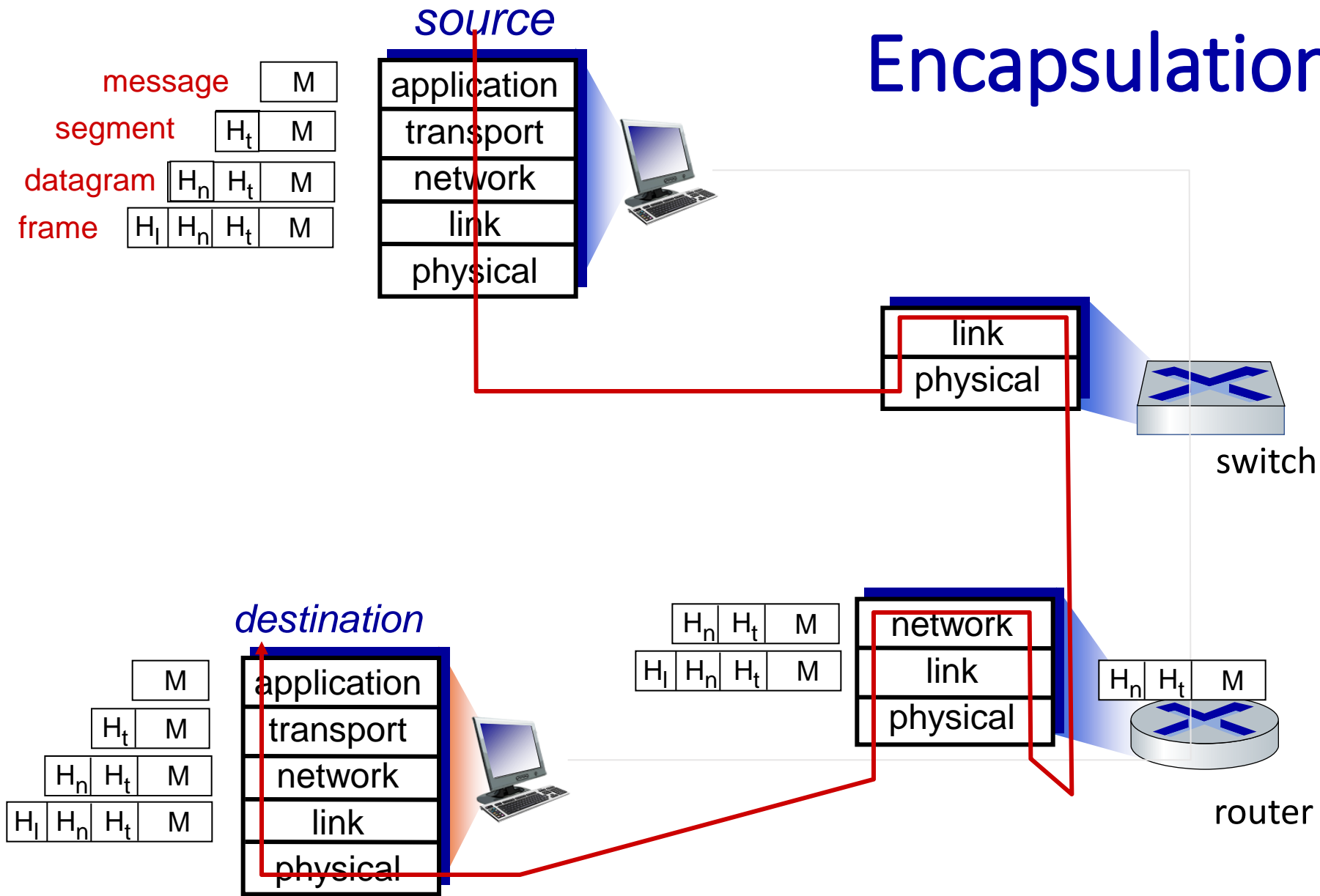
- explicit structure allows identification, relationship of complex system's pieces
  - layered *reference model* for discussion
- modularization eases maintenance, updating of system
  - change in layer's service *implementation*: transparent to rest of system
  - e.g., change in gate procedure doesn't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

# 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: roadmap

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

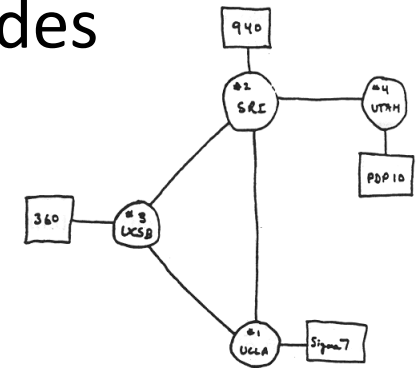




# Internet history

## *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



THE ARPA NETWORK

# Internet history

## *1972-1980: Internetworking, new and proprietary nets*

- **1970:** ALOHAnet satellite network in Hawaii
- **1974:** Cerf and Kahn - architecture for interconnecting networks
- **1976:** Ethernet at Xerox PARC
- **late 70's:** proprietary architectures: DECnet, SNA, XNA
- **late 70's:** switching fixed length packets (ATM precursor)
- **1979:** ARPAnet has 200 nodes

### Cerf and Kahn's internetworking principles:

- minimalism, autonomy - no internal changes required to interconnect networks
- best-effort service model
- stateless routing
- decentralized control

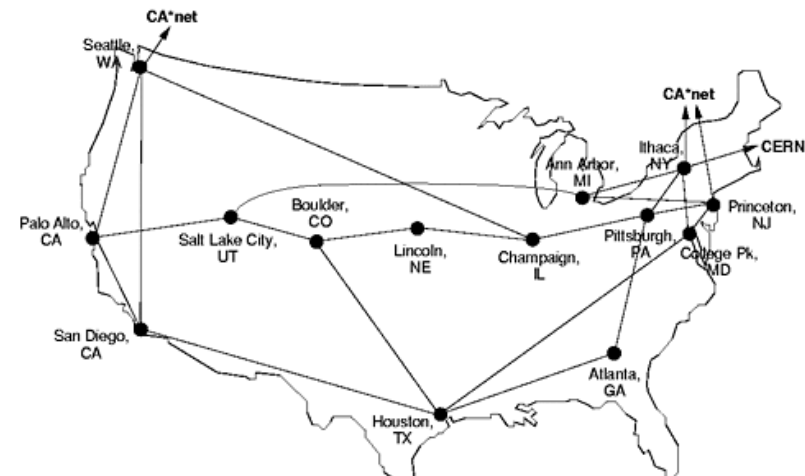
define today's Internet architecture

# 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

NSFNET T1 Network 1991



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# 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: more new applications, Internet is “everywhere”*

- ~18B devices attached to Internet (2017)
  - rise of smartphones (iPhone: 2007)
- aggressive deployment of broadband access
- increasing ubiquity of high-speed wireless access: 4G/5G, WiFi
- emergence of online social networks:
  - Facebook: ~ 2.5 billion users
- service providers (Google, FB, Microsoft) create their own networks
  - bypass commercial Internet to connect “close” to end user, providing “instantaneous” access to search, video content, ...
- enterprises run their services in “cloud” (e.g., Amazon Web Services, Microsoft Azure)

# 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:*

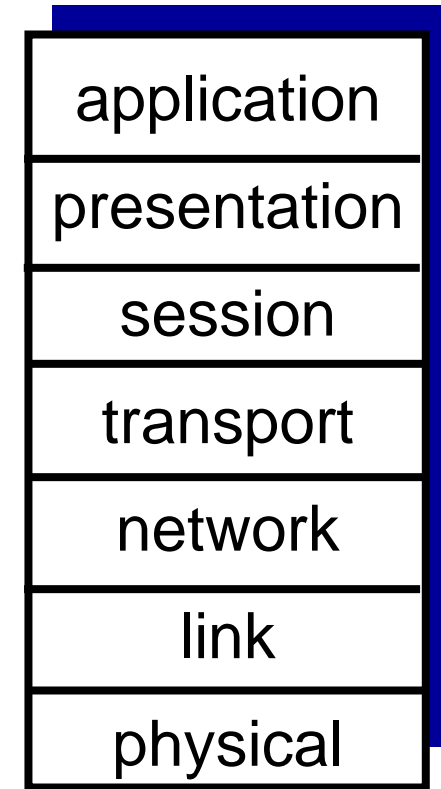
- context, overview, vocabulary, “feel” of networking
- more depth, detail, *and fun* to follow!

# 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

