

# Lai NGUYEN



## ■ Research & Interests

- **Distributed systems:** Analysis, optimization, and control of systems with limited communication.
- **Communication networks and protocols:**
  - Network architecture, routing algorithms, protocols, applications, and services.
  - Network design, measurement, analysis, optimization, and management.

## ■ Areas of specialty

- Networked dynamic systems, distributed cooperative control, network routing, constrained communication protocols, water systems.

## ■ Contact

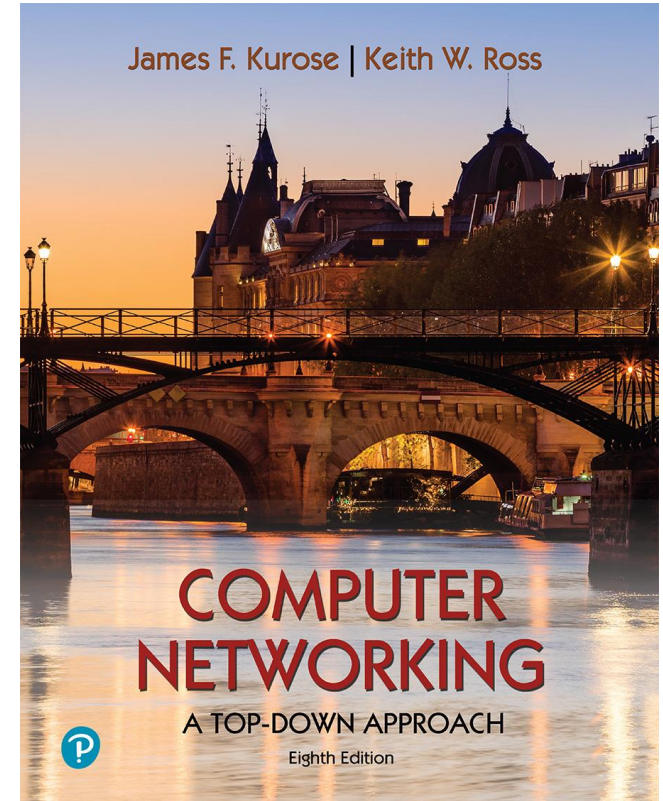
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# Computer Networks

*Lectured by:*

**Nguyen Le Duy Lai**

*lai@hcmut.edu.vn*



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

8<sup>th</sup> edition

Jim Kurose, Keith Ross  
Pearson, 2020

# Course details

<b>Credits</b>	3 (3.2.7)			<b>Code</b>	CO3093
<b>Credits Hours</b>	Total: <b>75</b>	Lecture: <b>30</b>	Quiz: <b>10</b>	Lab: <b>20</b>	Assignments: <b>15</b>
<b>Evaluation</b>	Exercise:	Lab: <b>10%</b>	Midterm:	Assignments: <b>30%</b>	Final exam: <b>60%</b>
<b>Assessment method</b>	<b>Final exam: <i>Multiple choice questions</i>, ~ 90 minutes</b> Laboratory work is compulsory (No lab work = No assignment mark)				
<b>Prerequisites</b>					
<b>Co-requisites</b>					
<b>Undergraduate Programs</b>	Computer Science and Computer Engineering				
<b>Website</b>	<a href="http://e-learning.hcmut.edu.vn/">http://e-learning.hcmut.edu.vn/</a>				

# Course outline (1)

- Fundamental concepts in the *design* and *implementation* of computer networks
  - *Protocols, standards, services and applications*
  - *Introduction to network programming*
  - *Basic network security*
- The goals of the course are to build on basic networking knowledge in providing ...
  - an understanding of the tradeoffs and existing *technologies* used in complex networked systems
  - concrete experience of the *challenges* through a series of lab exercises.

# Course outline (2)

- The topics to be covered include:
  - *Introduction to the Internet structure, network application architecture, performance*
  - *OSI and TCP/IP reference models.*
  - *Common applications and application-layer protocols: Web (HTTP), DNS, E-mail (POP3, IMAP, SMTP), P2P, and CDN.*
  - *Internet transport protocols (UDP and TCP)*
  - *Issues related to routing and internetworking, Internet addressing, routing protocols and Internet Protocol (IP).*
  - *Network technologies, especially LAN technologies (Ethernet, wireless networks and Bluetooth).*
  - *Network-programming interface*
  - *Network security*

# Contents

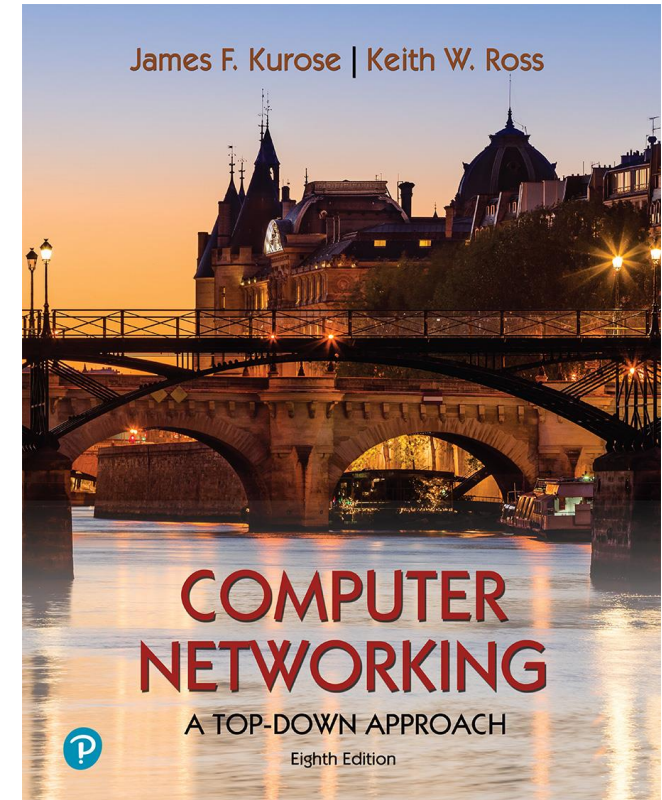
- Computer Networks and the Internet
- Application Layer
- Transport Layer
- The Network Layer: Data Plane
- The Network Layer: Control Plane
- The Link Layer and LANs
- Wireless and Mobile Networks
- Security in Computer Networks
- Multimedia Networking

# References

- *"Computer Networking: A Top-Down Approach"*, Jim Kurose, Keith Ross, 8<sup>th</sup> Global Edition, Pearson, 2021.
- *"Computer Networks"*, Andrew S. Tanenbaum, Nick Feamster, David J. Wetherall, 6th Edition, Pearson, 2021.
- *"The Illustrated Network: How TCP/IP Works in a Modern Network"*, Walter Goralski, Second Edition, Morgan Kaufman, 2017.
- *"Foundations of Modern Networking: SDN, NFV, QoE, IoT, and Cloud"*, William Stallings, Addison-Wesley Professional, 2016.

# Chapter 1

## Introduction



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

8<sup>th</sup> edition

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Pearson, 2020



# 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:*

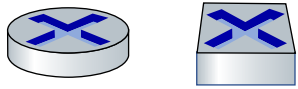
- What is the **Internet**?
- What is a **protocol**?
- **Network edge**: hosts, access network, physical media
- **Network core**: packet/circuit switching, internet structure
- **Performance**: loss, delay, throughput
- **Security**
- Protocol **layers**, service **models**
- History

# 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*

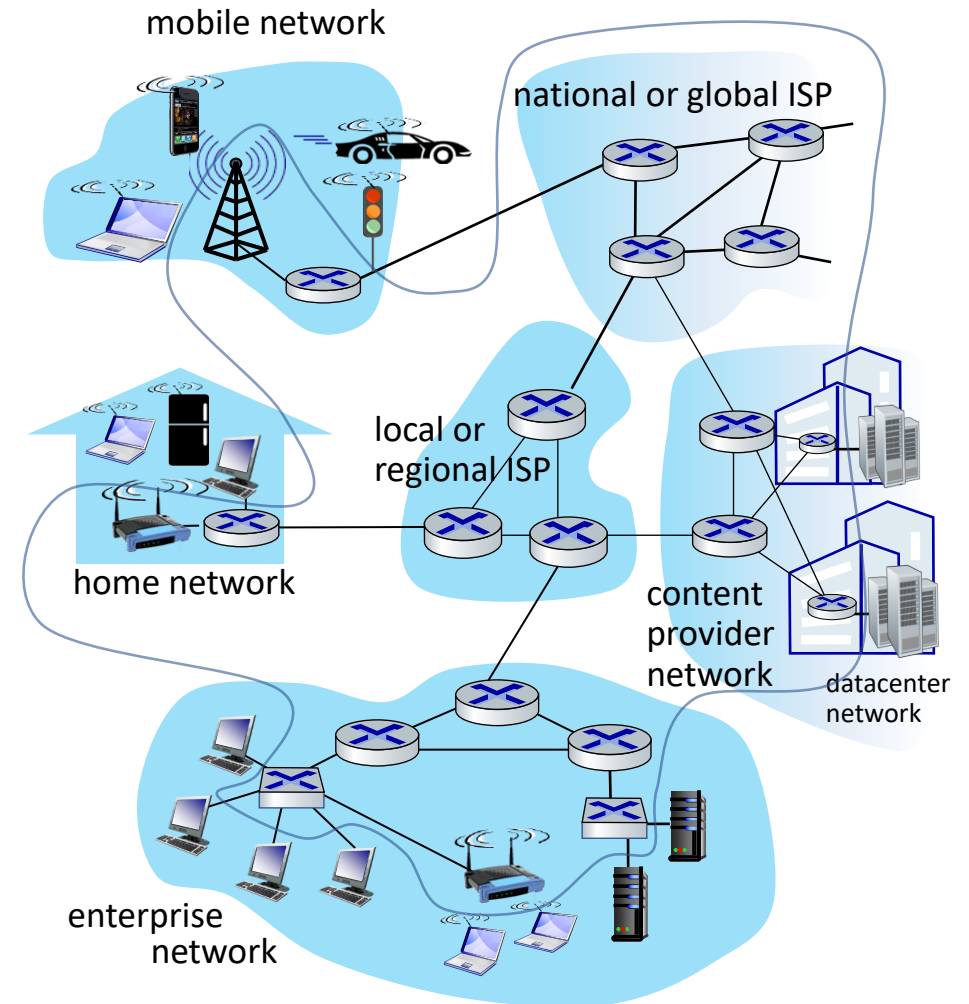


*Communication links*

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

*Networks*

- collection of devices, routers/switches, 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

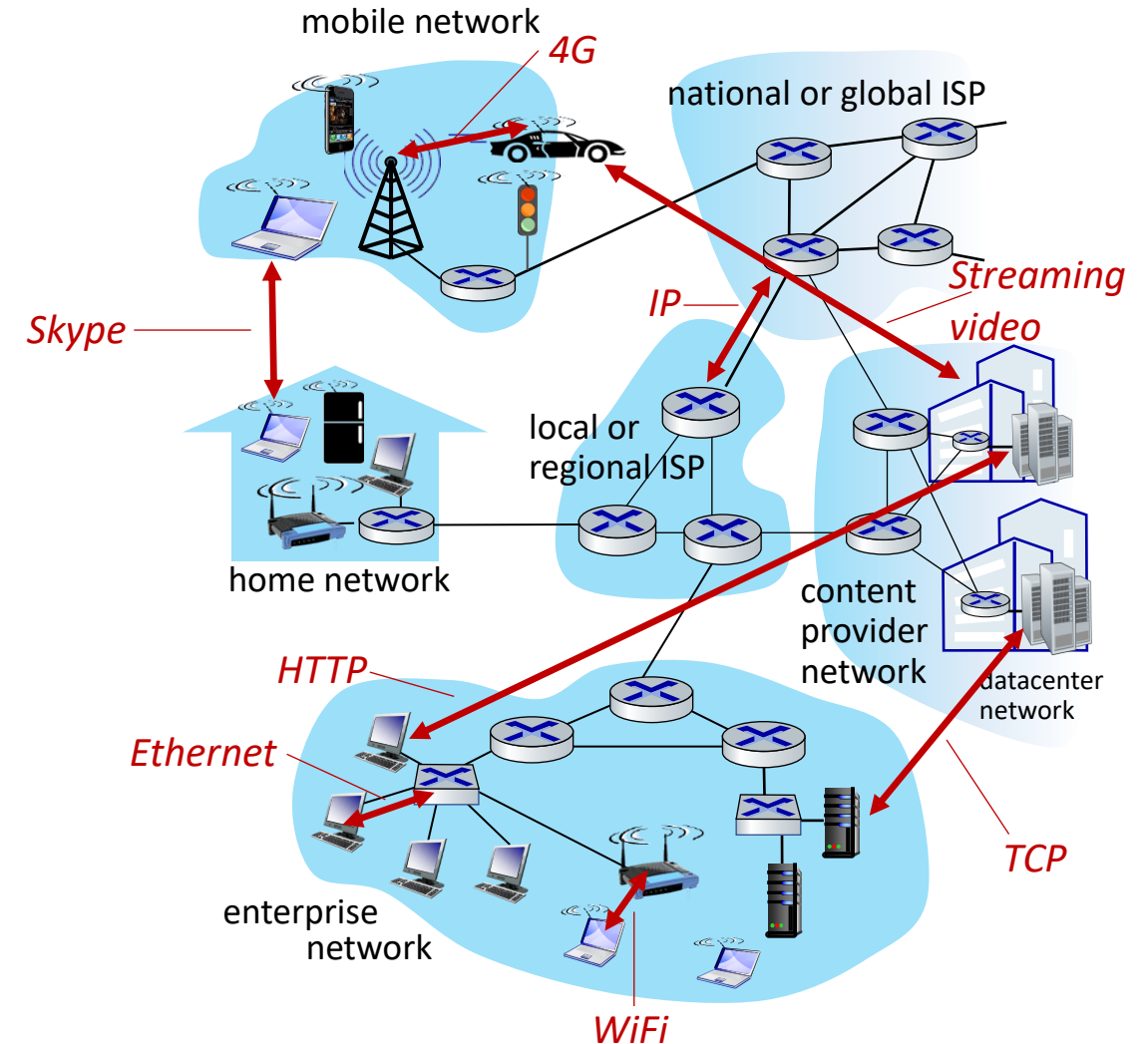


Fitbit

*Others?*

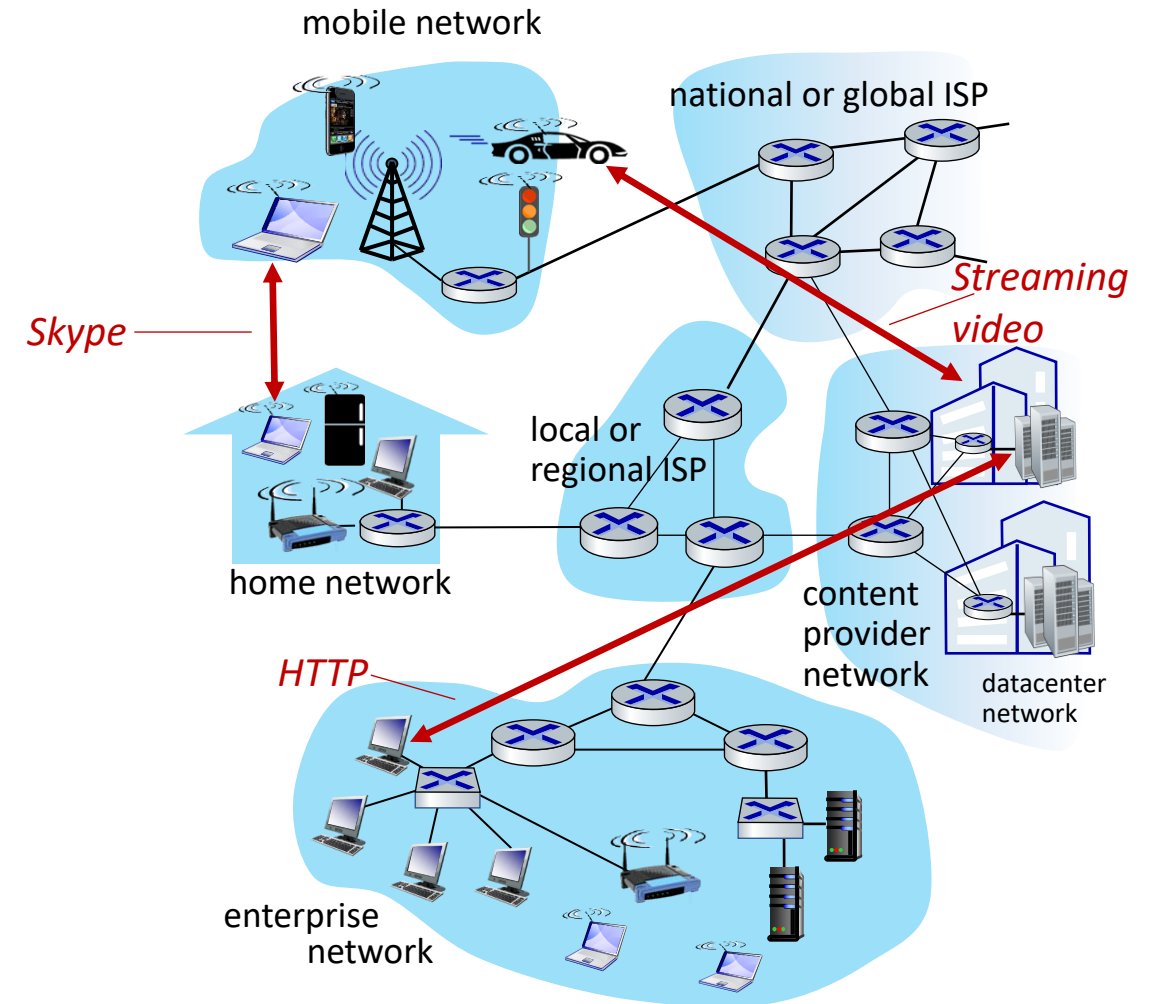
# The Internet: a “nuts and bolts” view

- *Internet: “network of networks”*
  - Interconnected ISPs
- *protocols are everywhere*
  - control sending, receiving of messages
  - e.g., HTTP (Web), RTP (streaming video), Skype, TCP, IP, Wi-Fi, 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:*

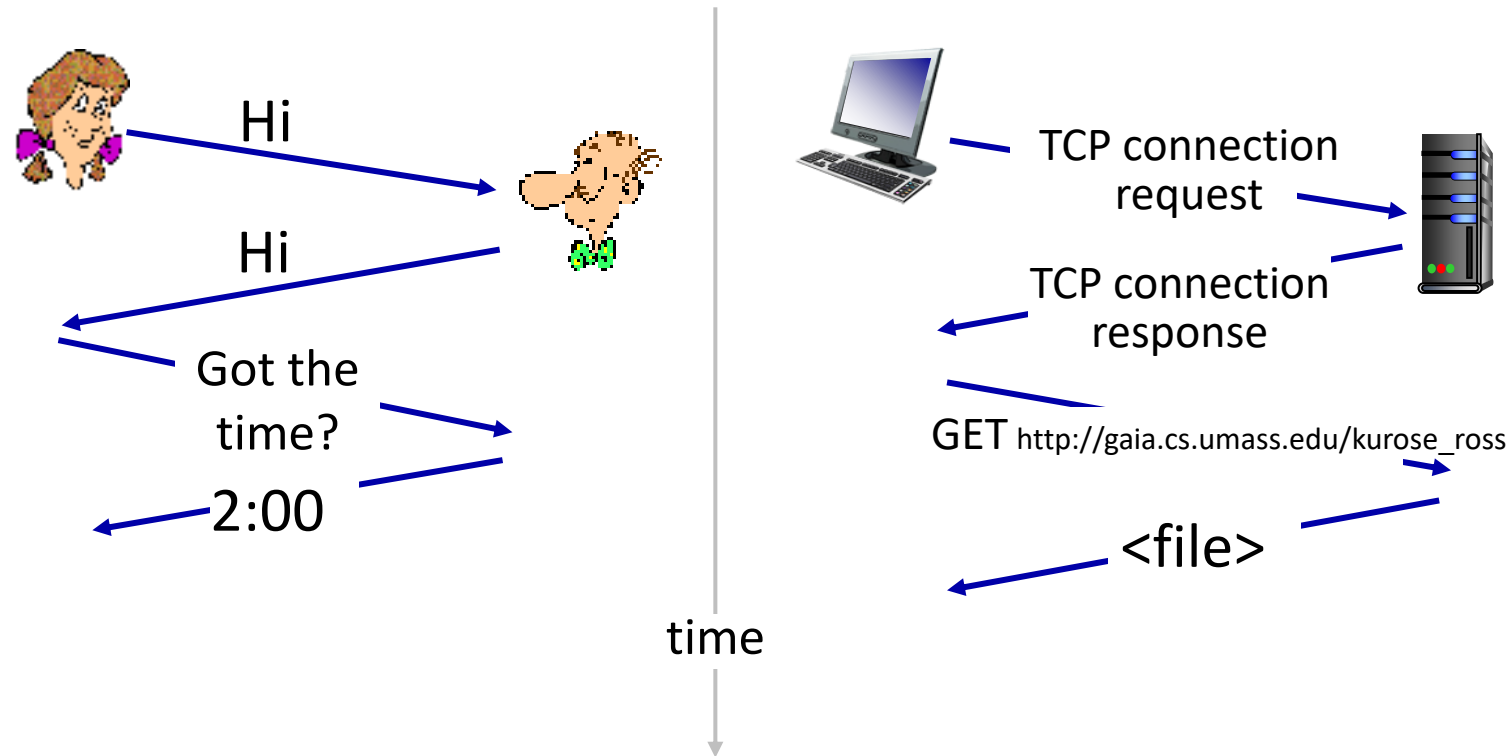
- computers (devices) rather than humans
- all communication activity in Internet governed by *protocols*

*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

- 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

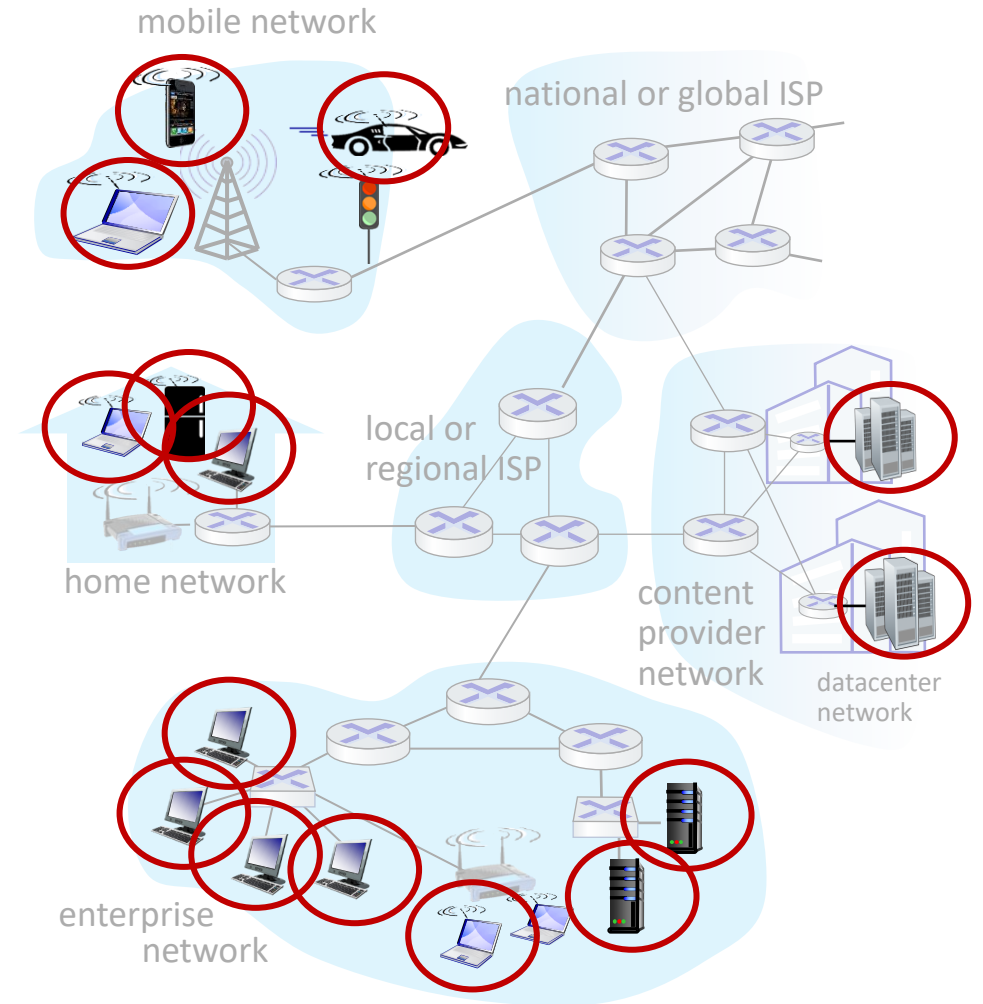




# A closer look at Internet structure

## Network edge:

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



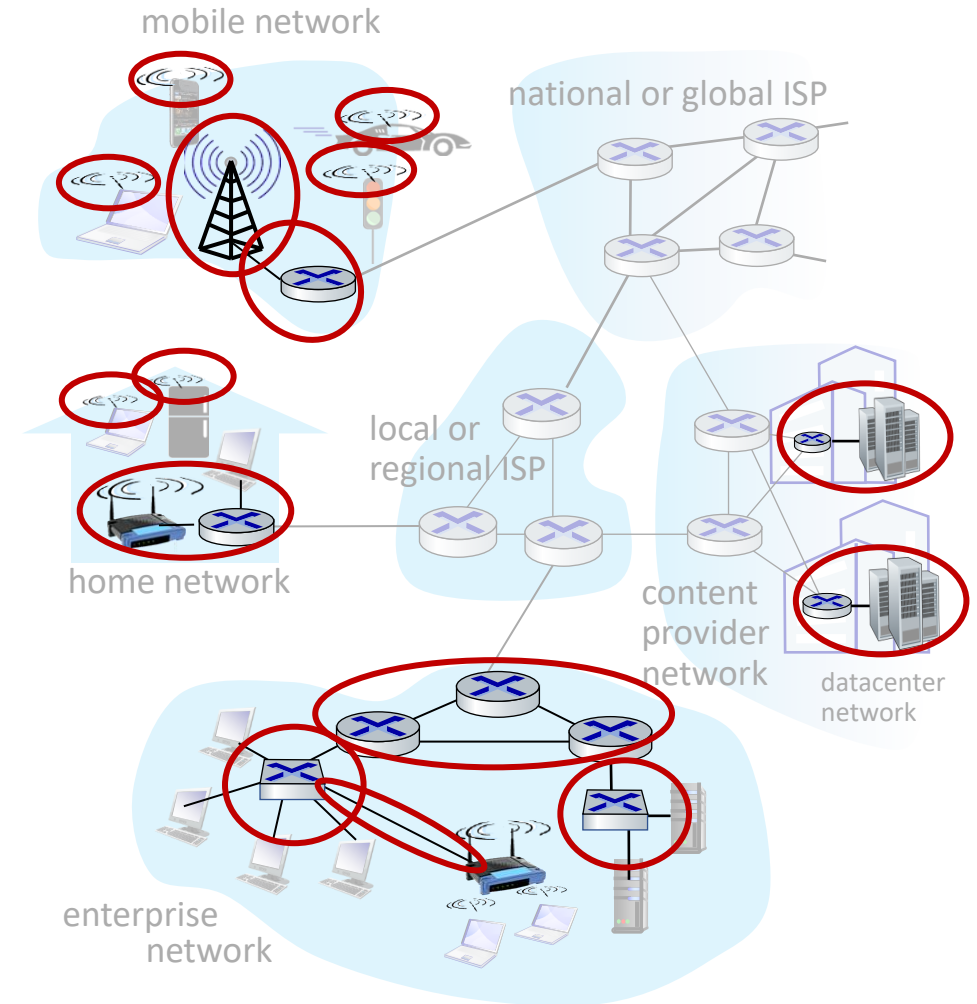
# A closer look at Internet structure

## Network edge:

- hosts: clients and servers
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## Access networks, physical media:

- wired, wireless communication links



# A closer look at Internet structure

## Network edge:

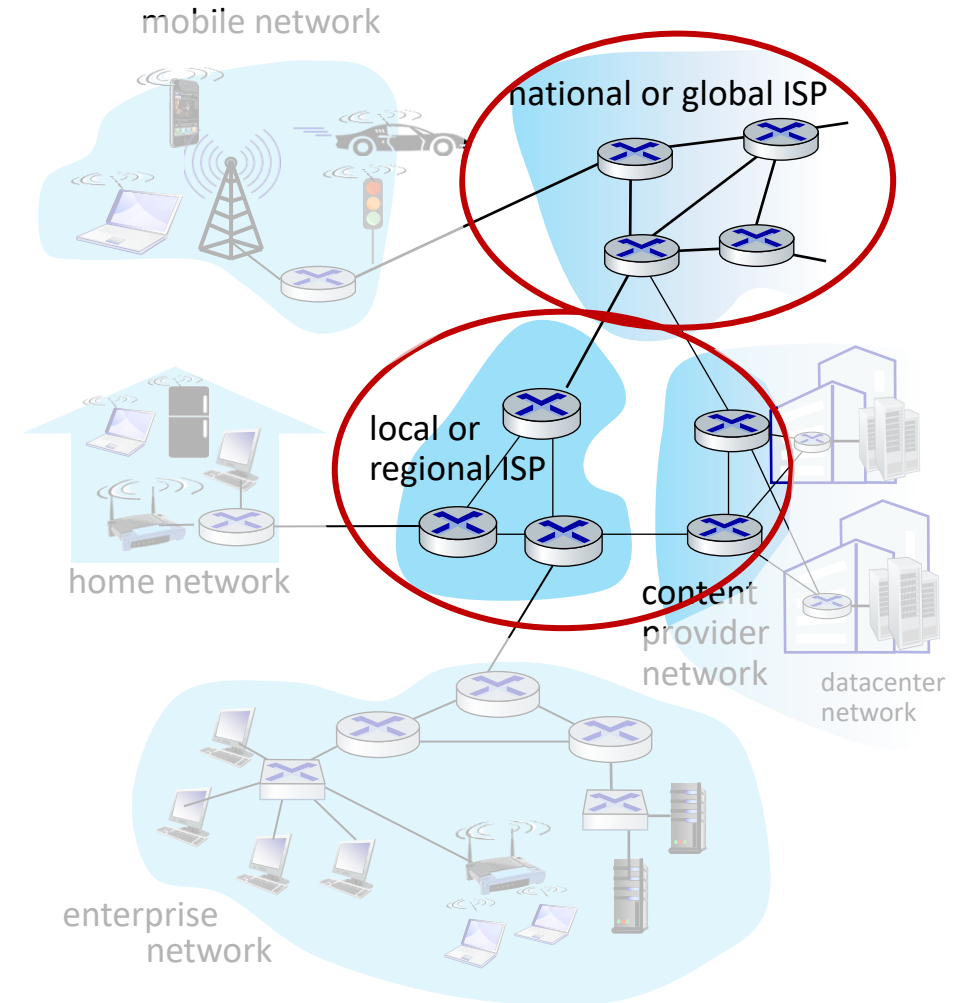
- hosts: clients and servers
- servers often in data centers

## Access networks, physical media:

- wired, wireless communication links

## Network core:

- interconnected routers
- network of networks



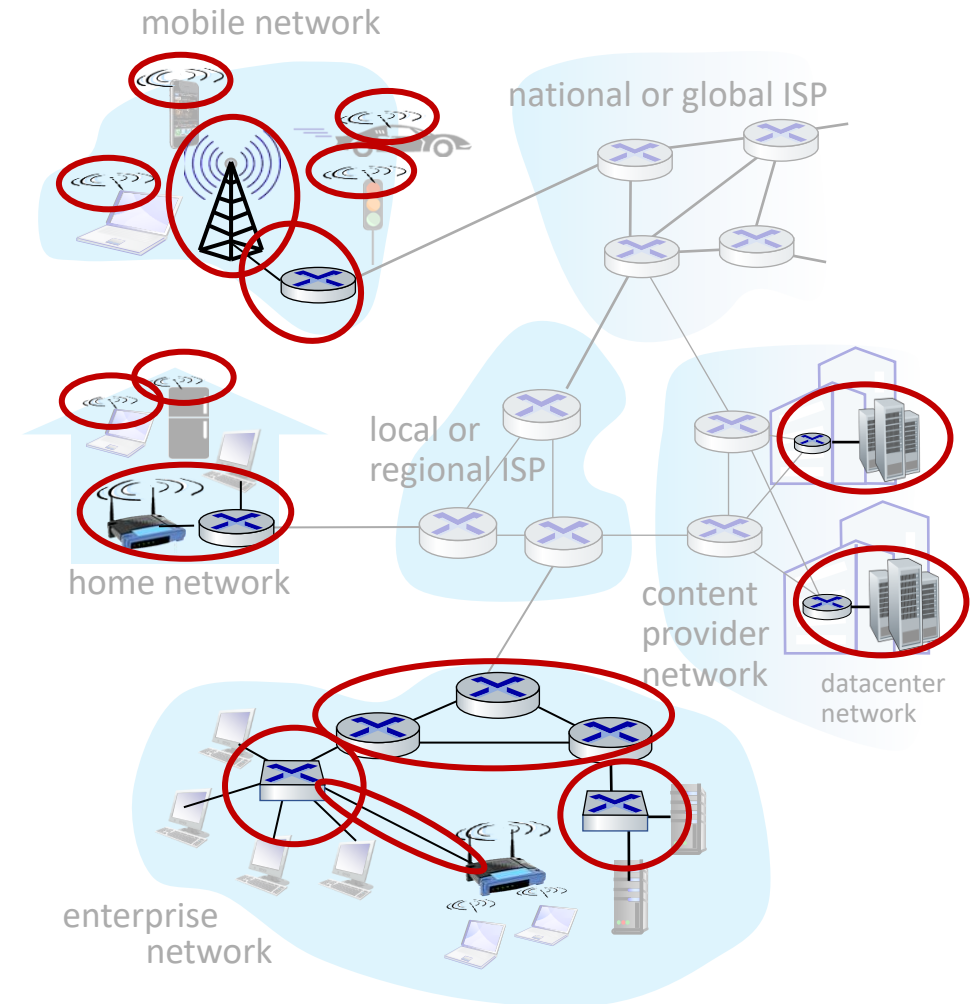
# Access networks and physical media

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

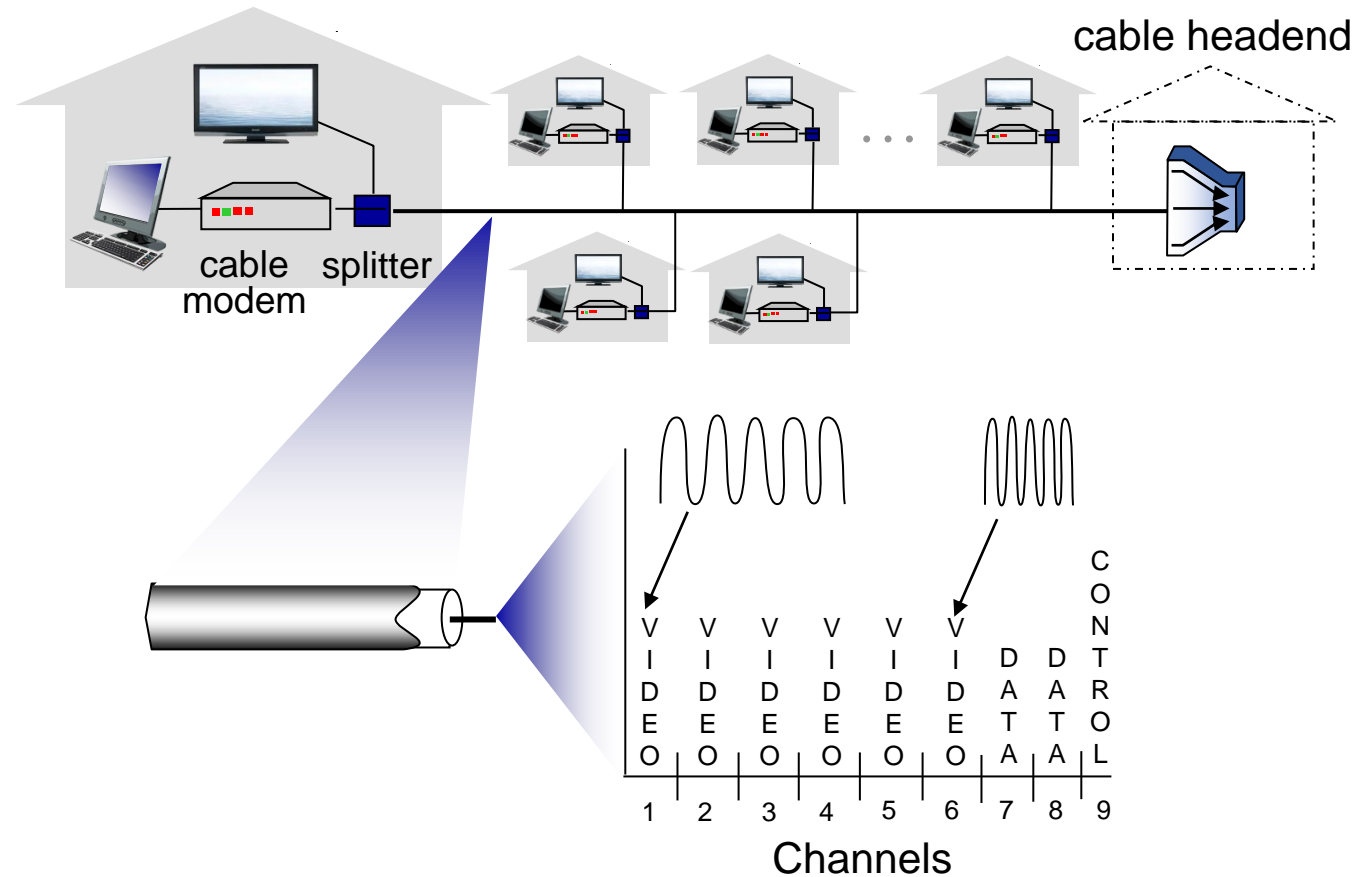
- residential access nets
- institutional access networks (school, company)
- mobile access networks (WiFi, 4G/5G)

*What to look for:*

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

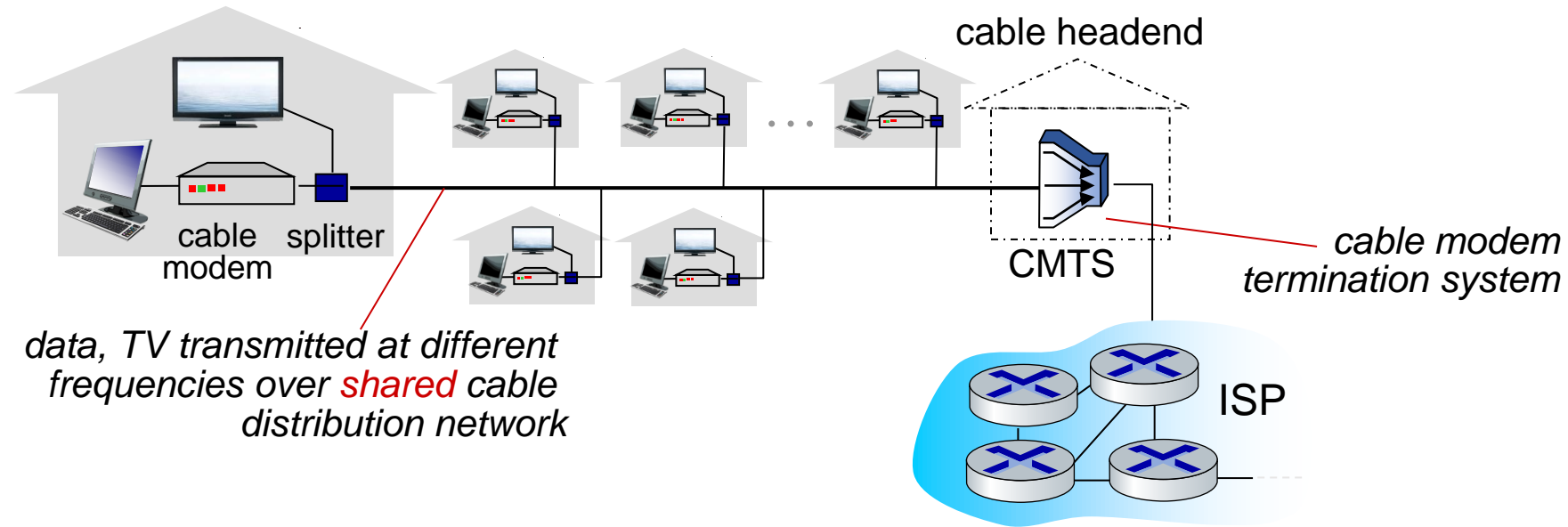


# Access networks: cable-based access



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

# Access networks: cable-based access



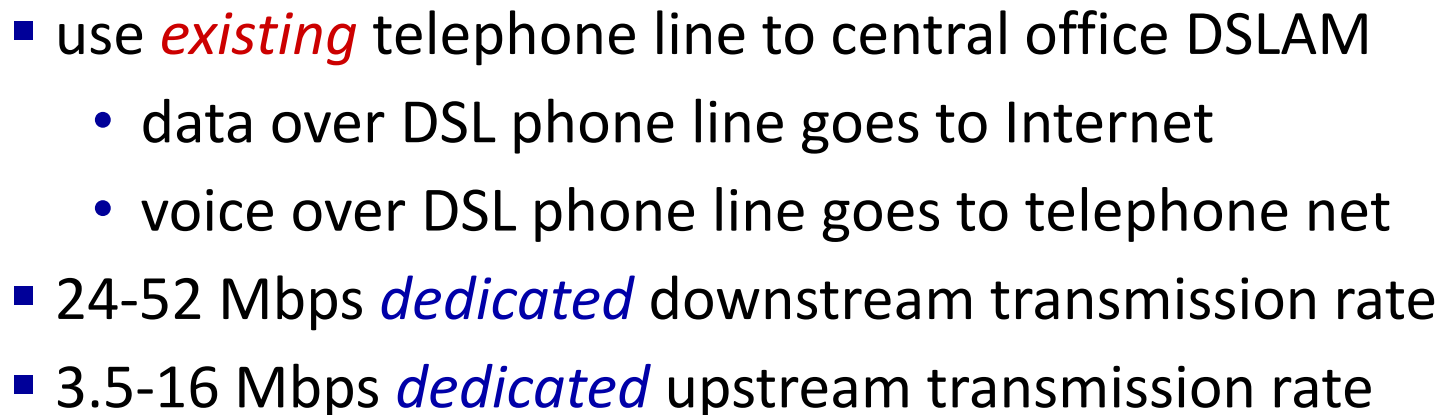
## ■ HFC: hybrid fiber coax

- asymmetric: up to 40 Mbps – 1.2 Gbs downstream transmission rate, 30-100 Mbps upstream transmission rate 

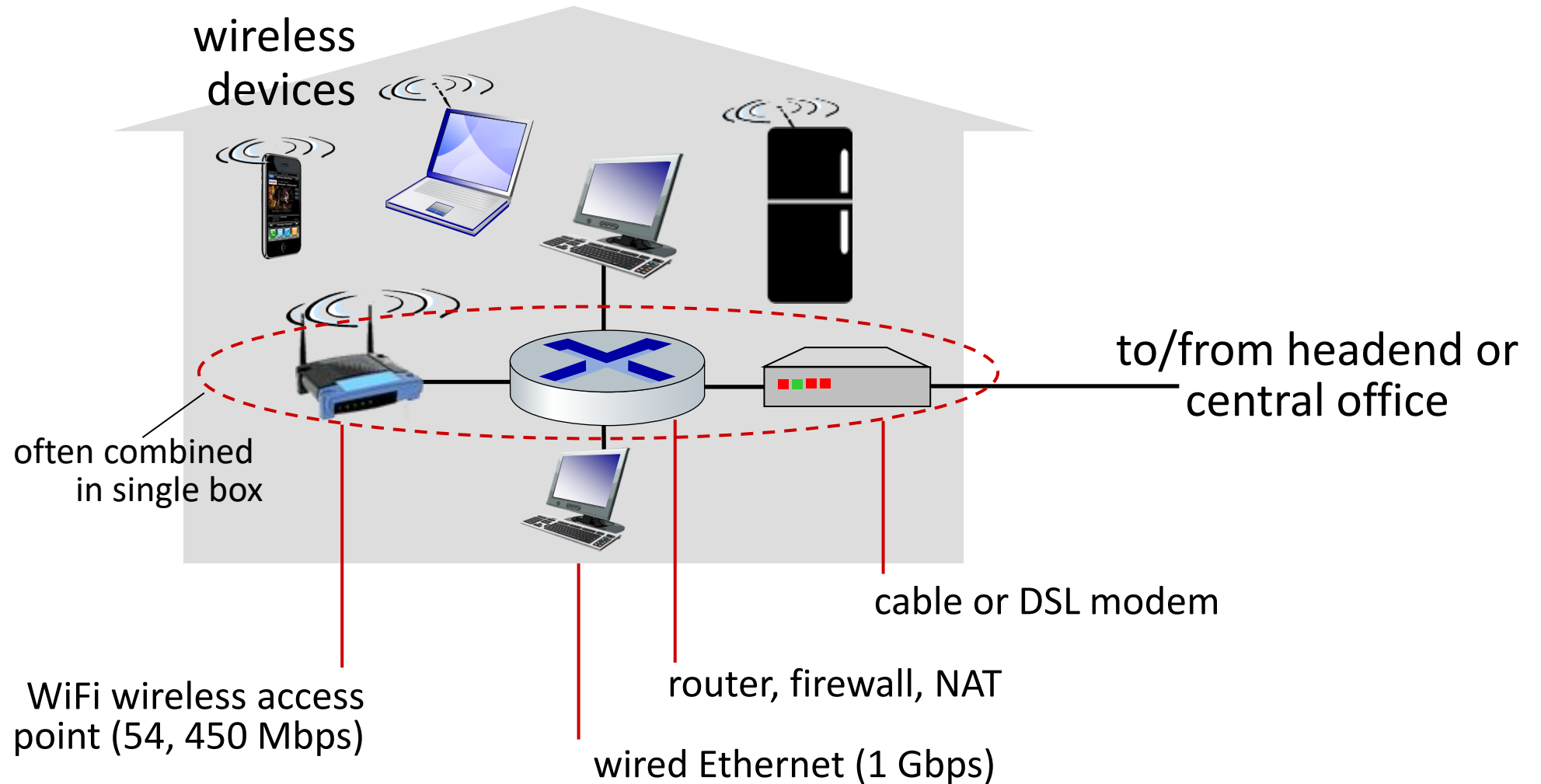
## ■ network of cable, fiber attaches homes to ISP router

- homes *share access network* to cable headend

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# Access networks: home networks





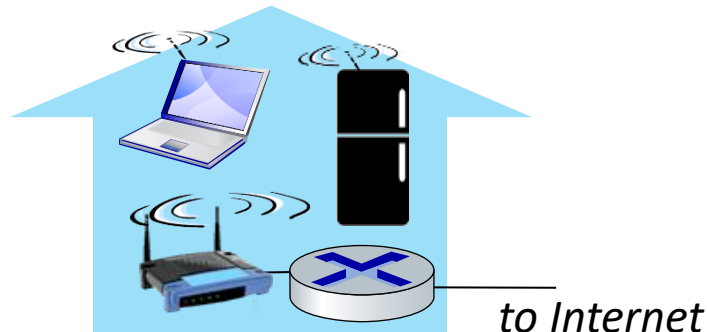
# Wireless access networks

Shared *wireless* access network connects end system to router

- via base station aka “access point”

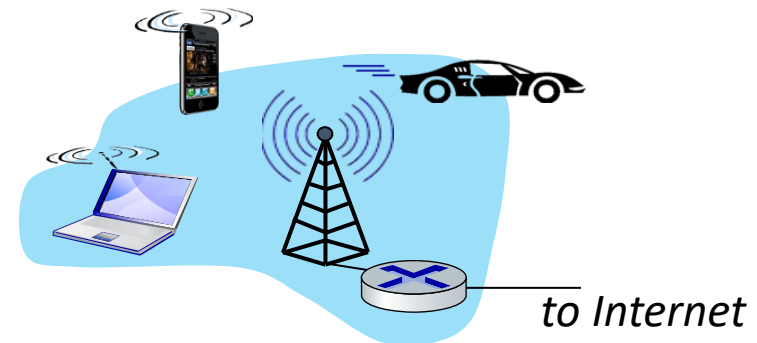
## Wireless local area networks (WLANs)

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

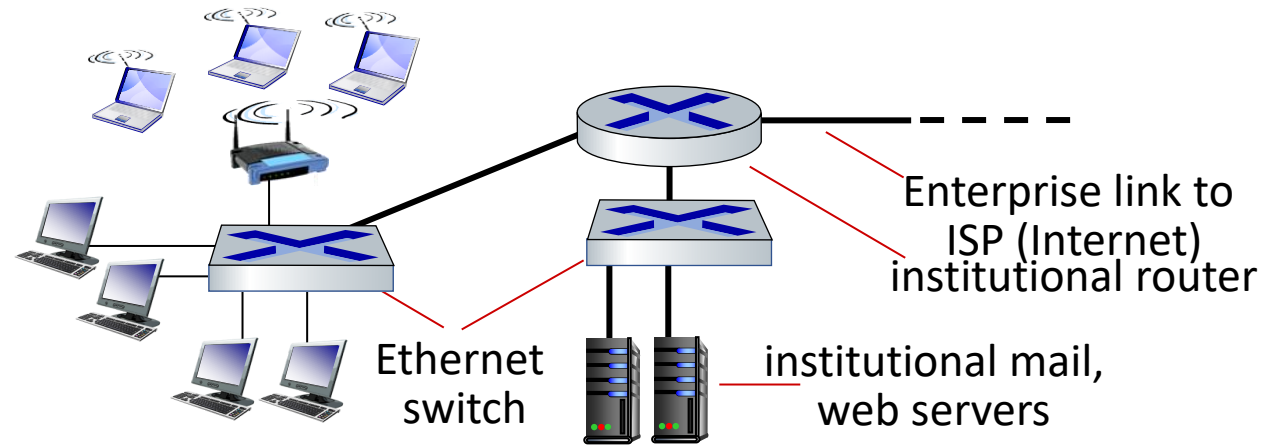


## Wide-area cellular access networks

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



# Access networks: enterprise networks

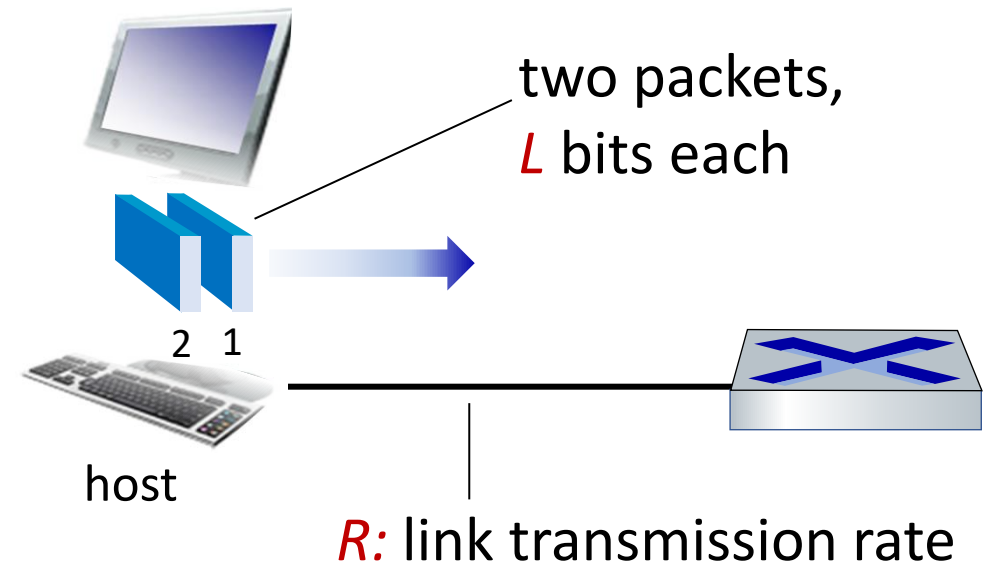


- companies, universities, etc.
- mix of wired, wireless link technologies, connecting a mix of switches and routers (we'll cover differences shortly)
  - Ethernet: wired access at 100Mbps, 1Gbps, 10Gbps
  - WiFi: wireless access points at 11, 54, 450 Mbps

# 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*



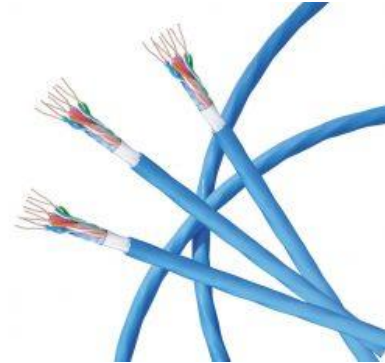
$$\begin{array}{l} \text{packet} \\ \text{transmission} \\ \text{delay} \end{array} = \begin{array}{l} \text{time needed to} \\ \text{transmit } L\text{-bit} \\ \text{packet into link} \end{array} = \frac{L \text{ (bits)}}{R \text{ (bits/sec)}}$$

# 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

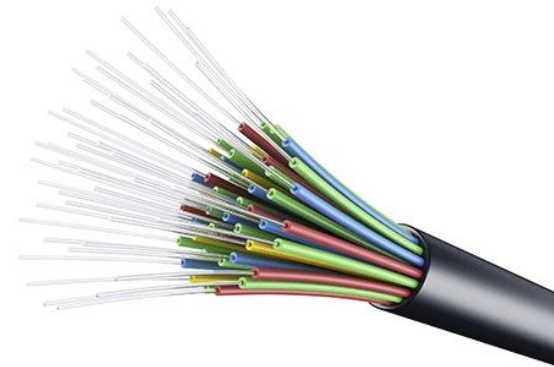
## Coaxial cable:

- 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

## 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

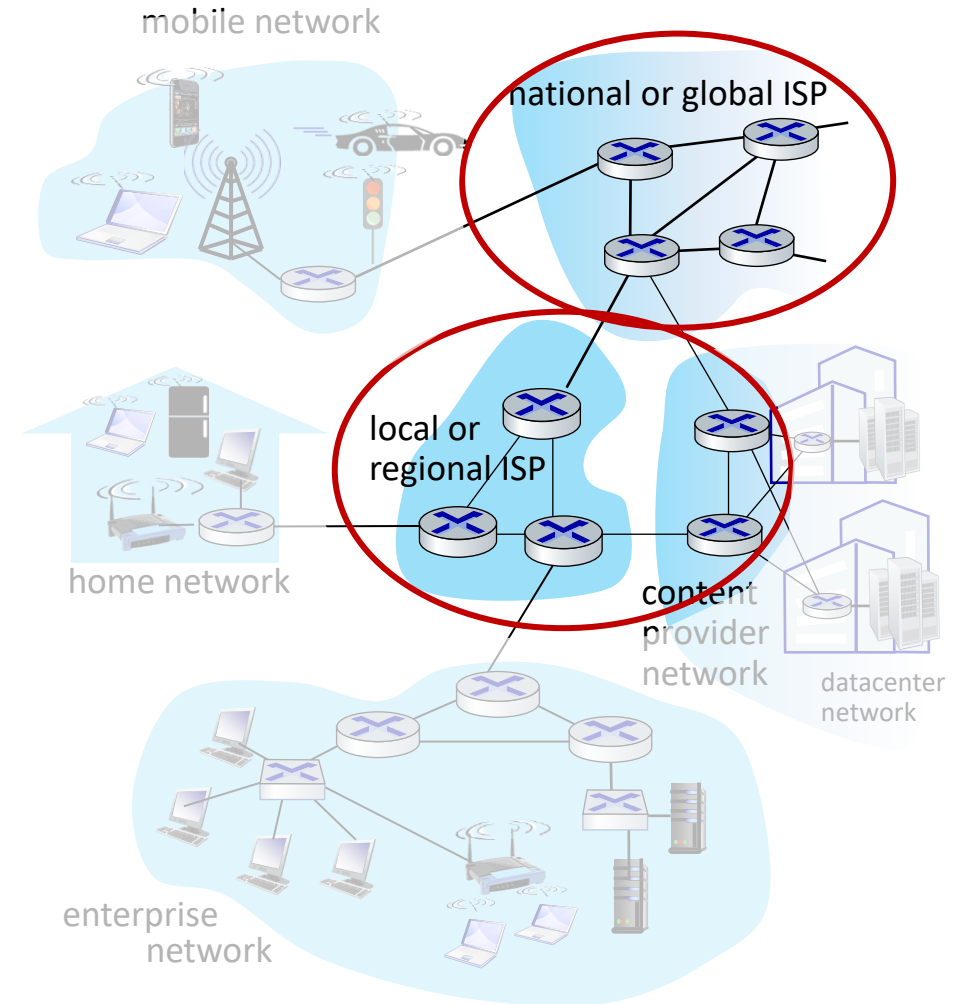
# Chapter 1: roadmap

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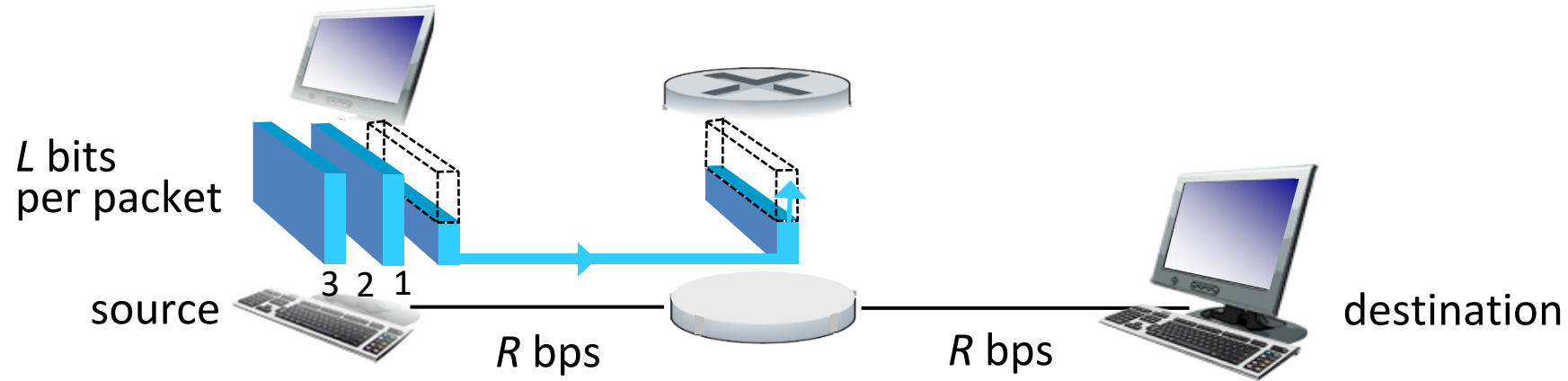
# The network core

- 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

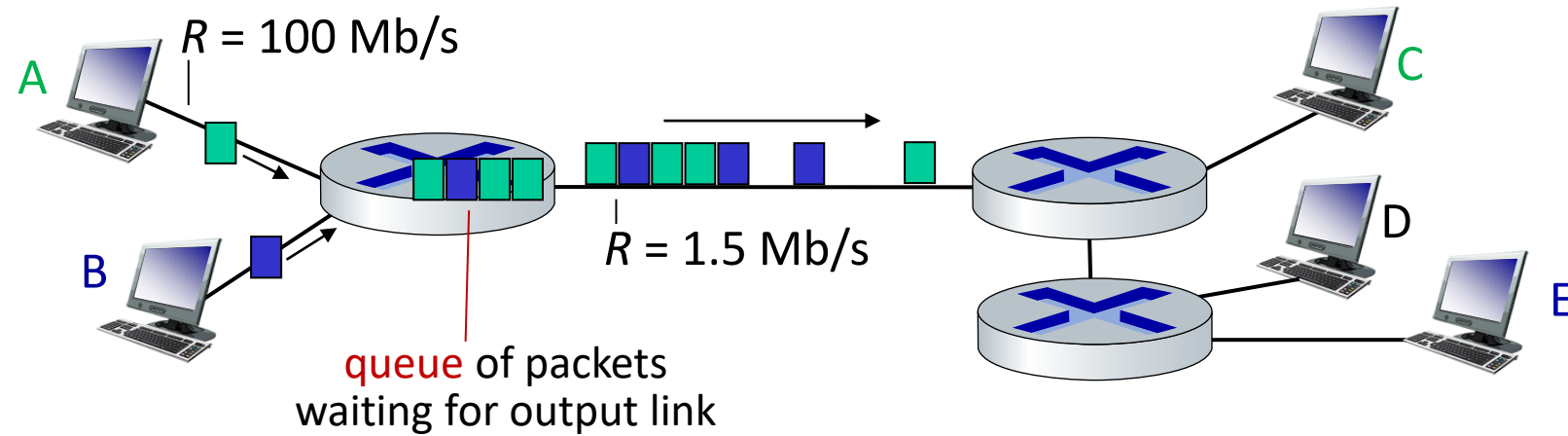


- **Transmission delay:** takes  $L/R$  seconds to transmit (push out)  $L$ -bit packet into link at  $R$  bps
- **Store and forward:** entire packet must arrive at router before it can be transmitted on next link
- **End-end delay:**  $2L/R$  (above), assuming zero propagation delay (more on delay shortly)

## *One-hop numerical example:*

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

# Packet-switching: queueing delay, loss



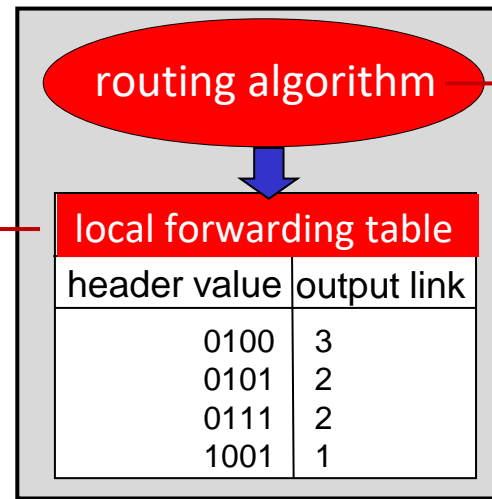
***Packet queuing and loss:*** if arrival rate (in bps) to link exceeds transmission rate (bps) of link for a period of time:

- 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:

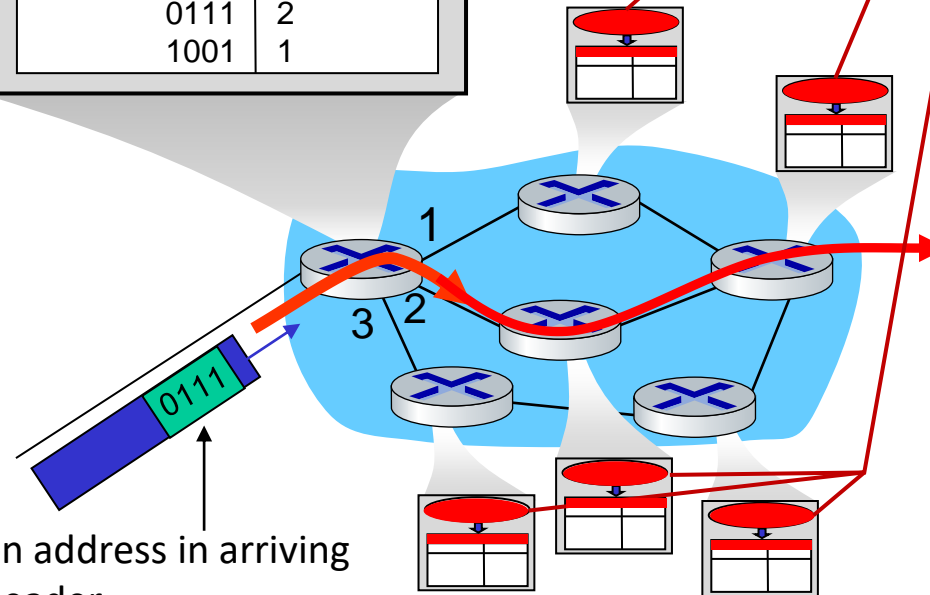
- *local* action: move arriving packets from router's input link to appropriate router output link



destination address in arriving packet's header

## Routing:

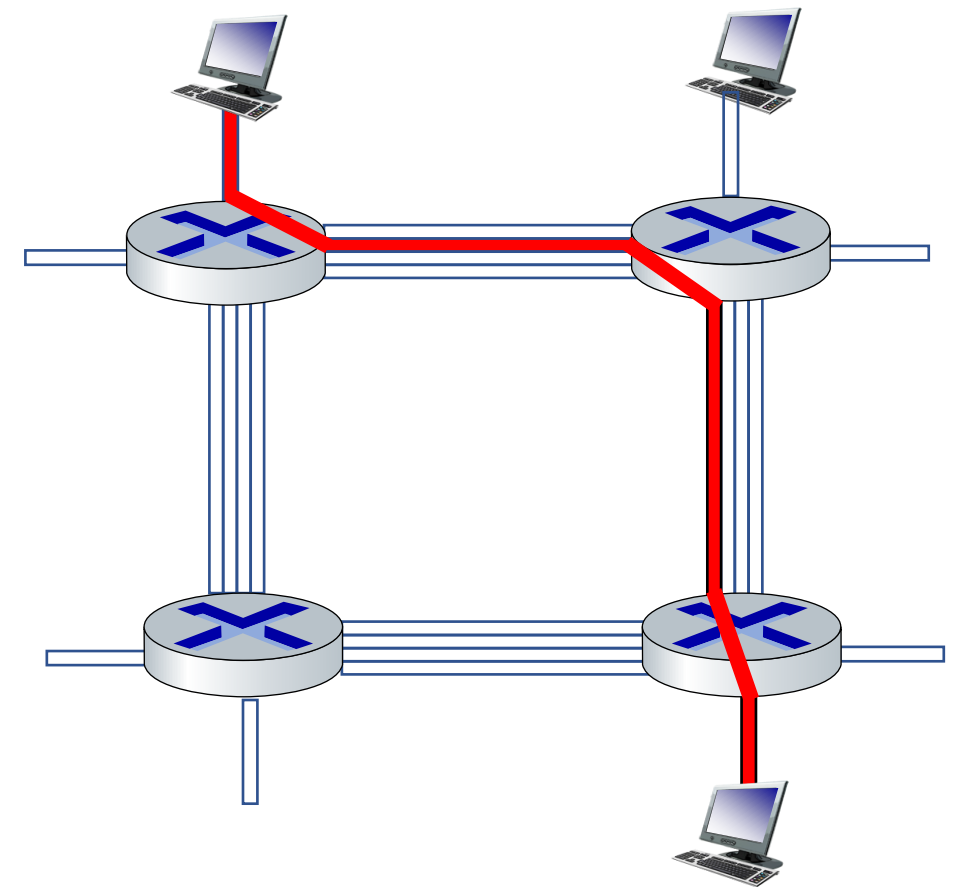
- *global* action: determine source-destination paths taken by packets
- routing algorithms



# Alternative to packet switching: circuit switching

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

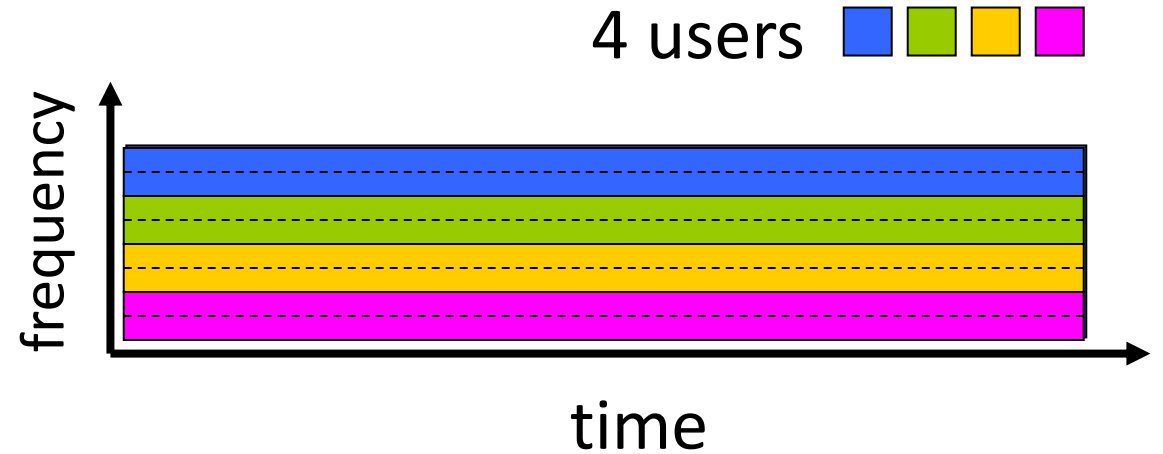
- in diagram, each link has four circuits.
  - call gets 2<sup>nd</sup> circuit in top link and 1<sup>st</sup> circuit in right link.
- dedicated resources: no sharing
  - circuit-like (guaranteed) performance
- circuit segment idle if not used by call (no sharing)
- commonly used in traditional telephone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



# Circuit switching: FDM and TDM

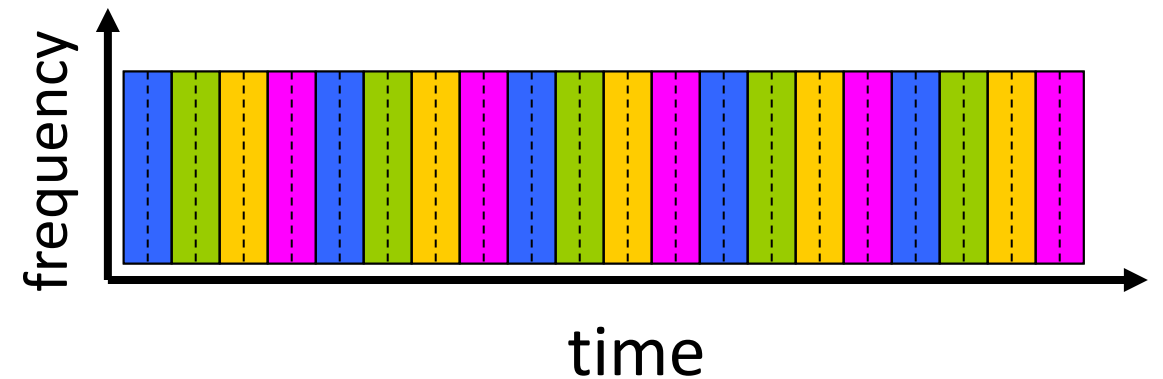
## Frequency Division Multiplexing (FDM)

- 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)

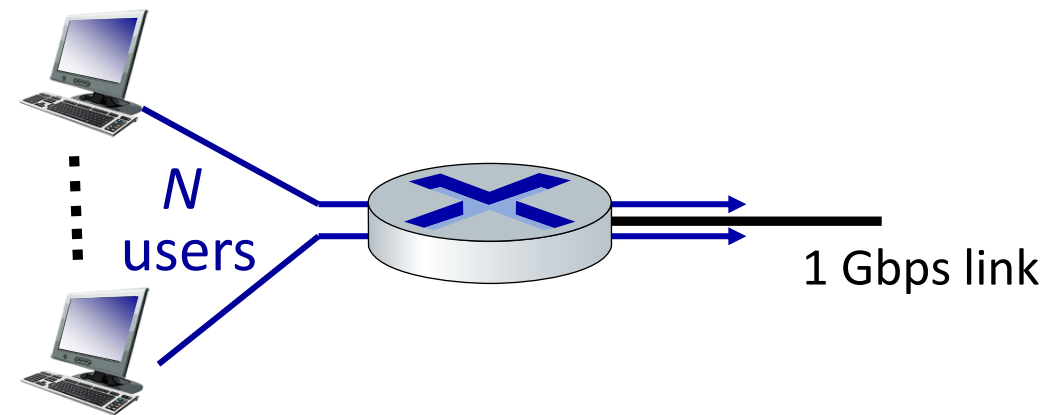


# Packet switching versus circuit switching

*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](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)?

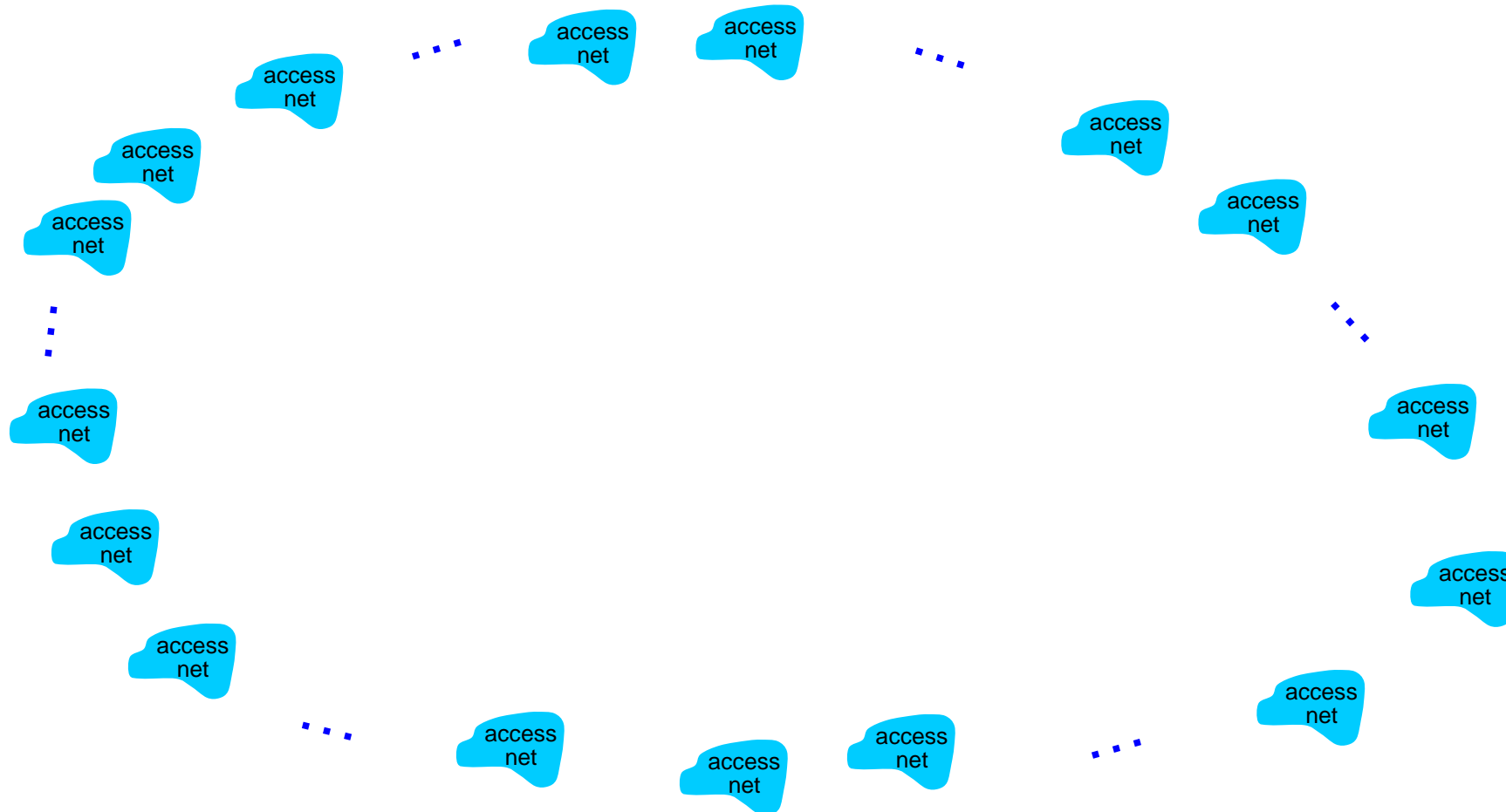
# Internet structure: a “network of networks”

- 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



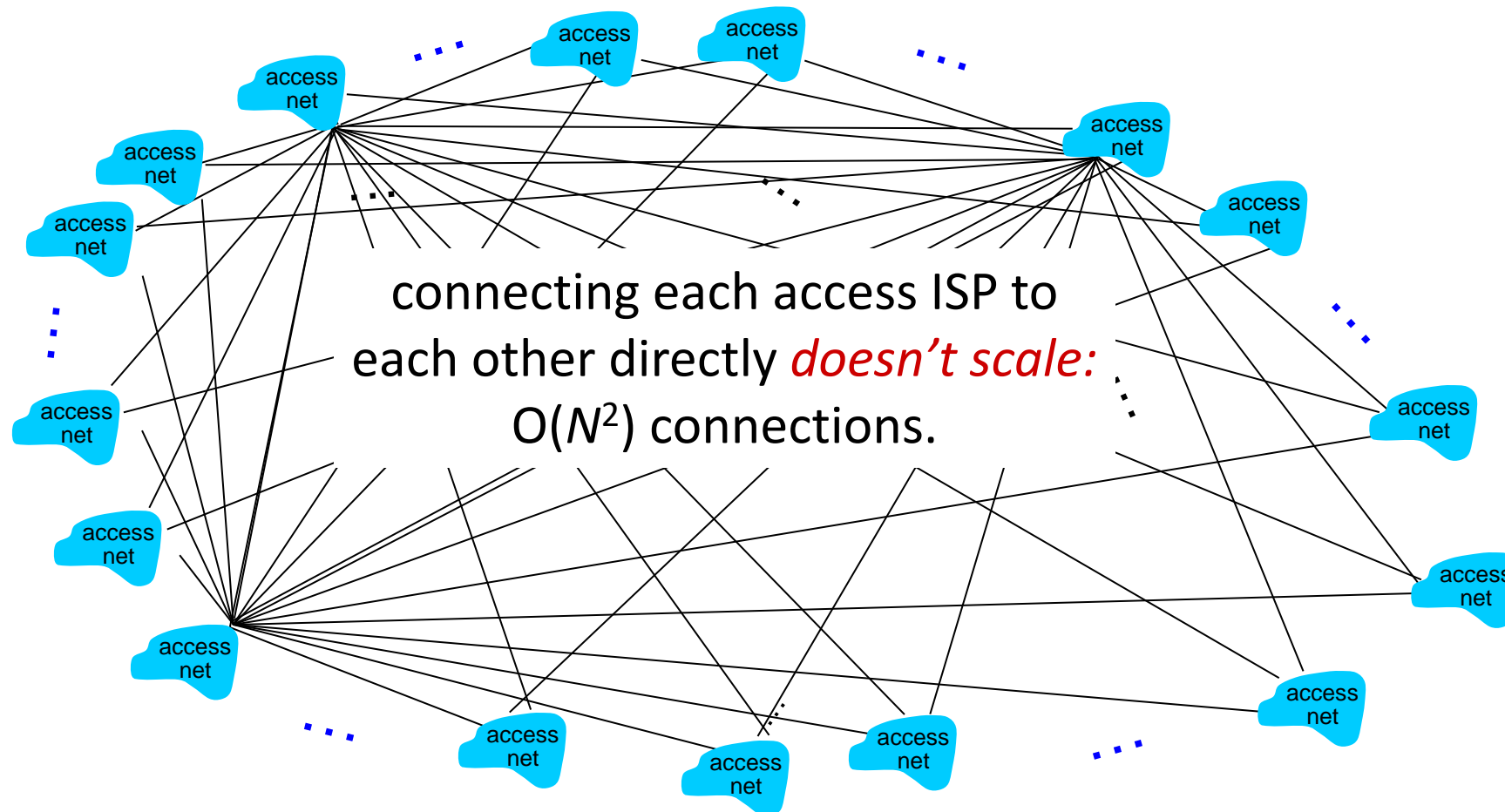
# Internet structure: a “network of networks”

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



# Internet structure: a “network of networks”

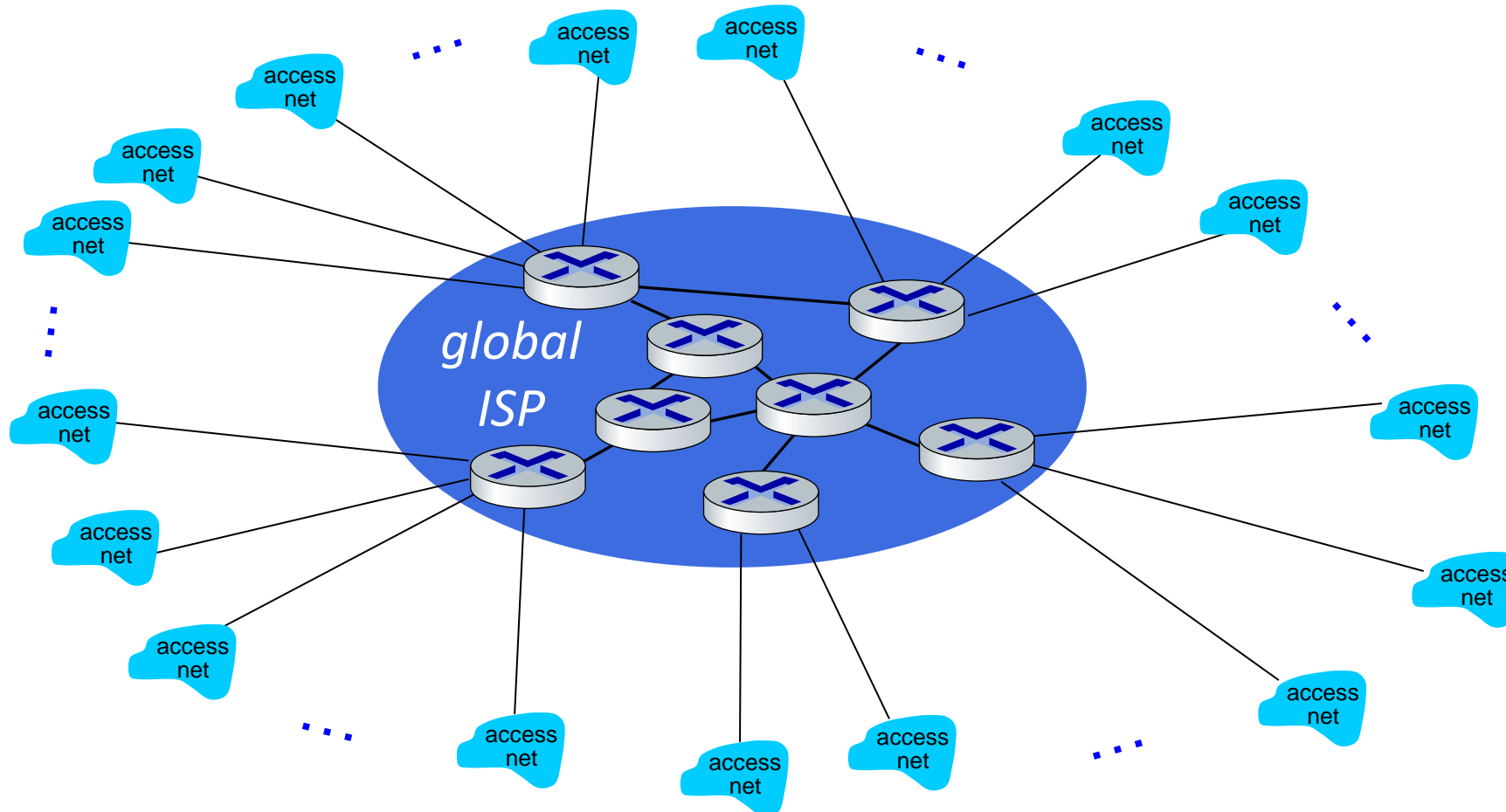
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# Internet structure: a “network of networks”

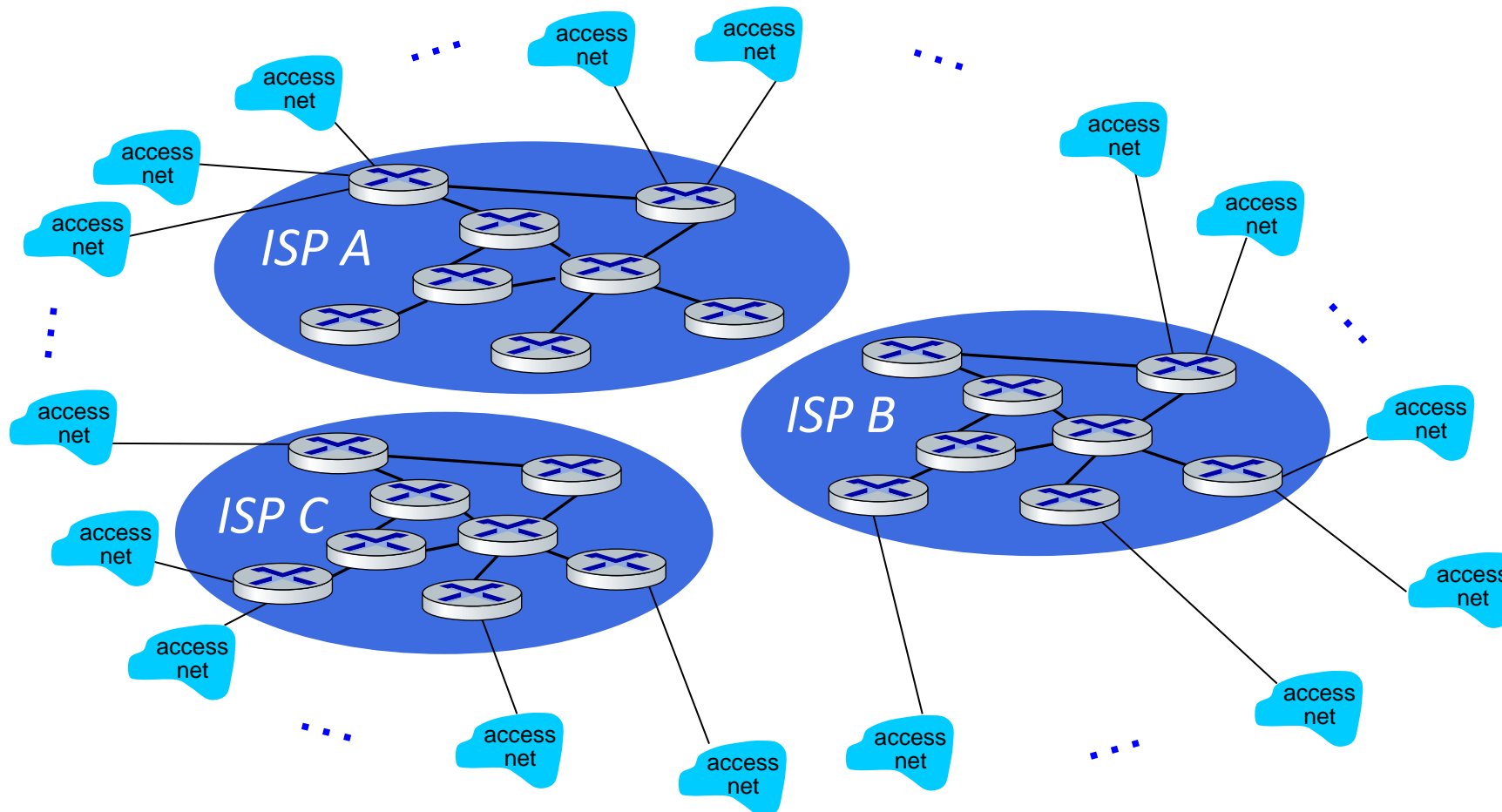
*Option: connect each access ISP to one global transit ISP?*

*Customer and provider ISPs have economic agreement.*



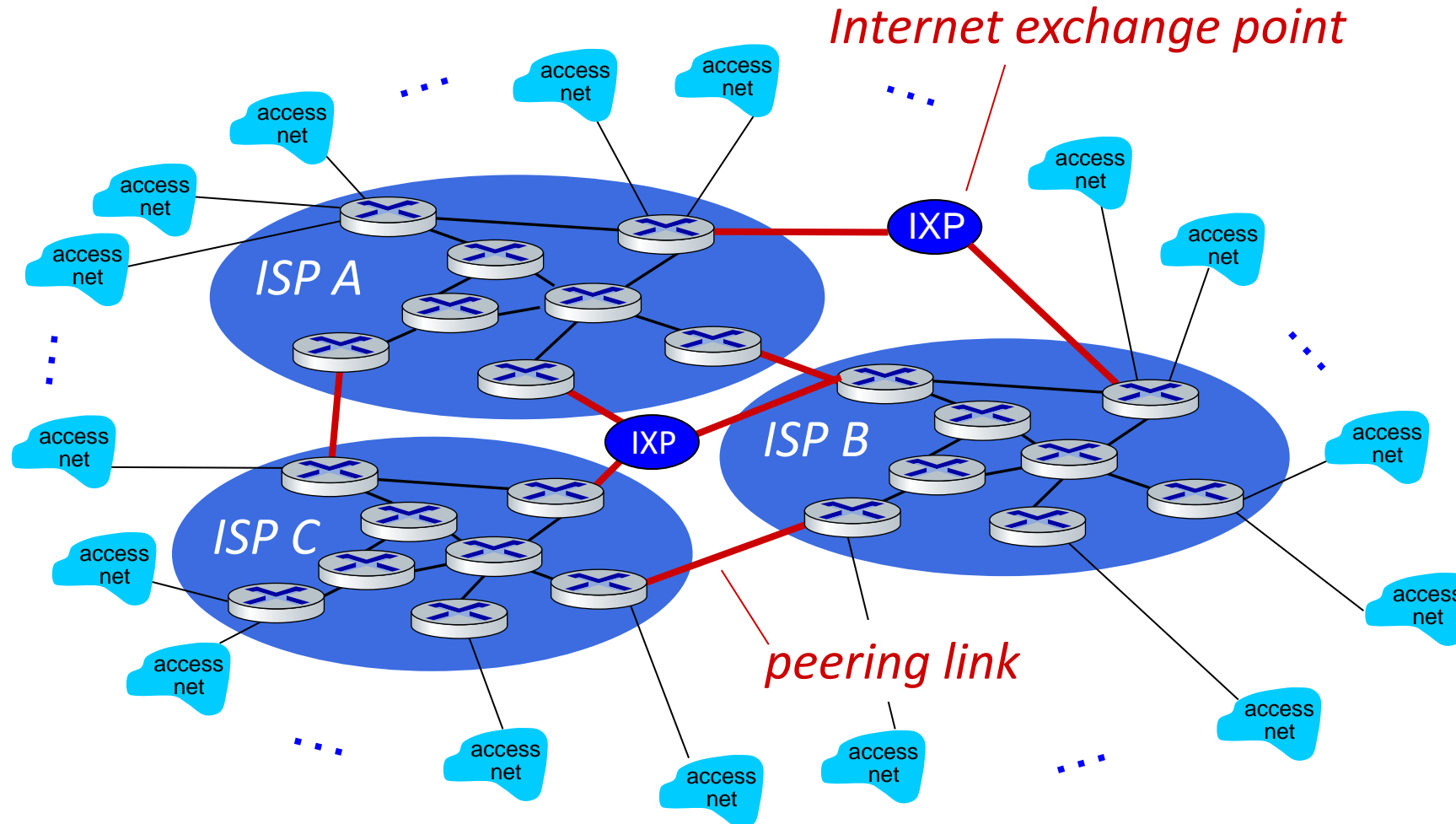
# Internet structure: a “network of networks”

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



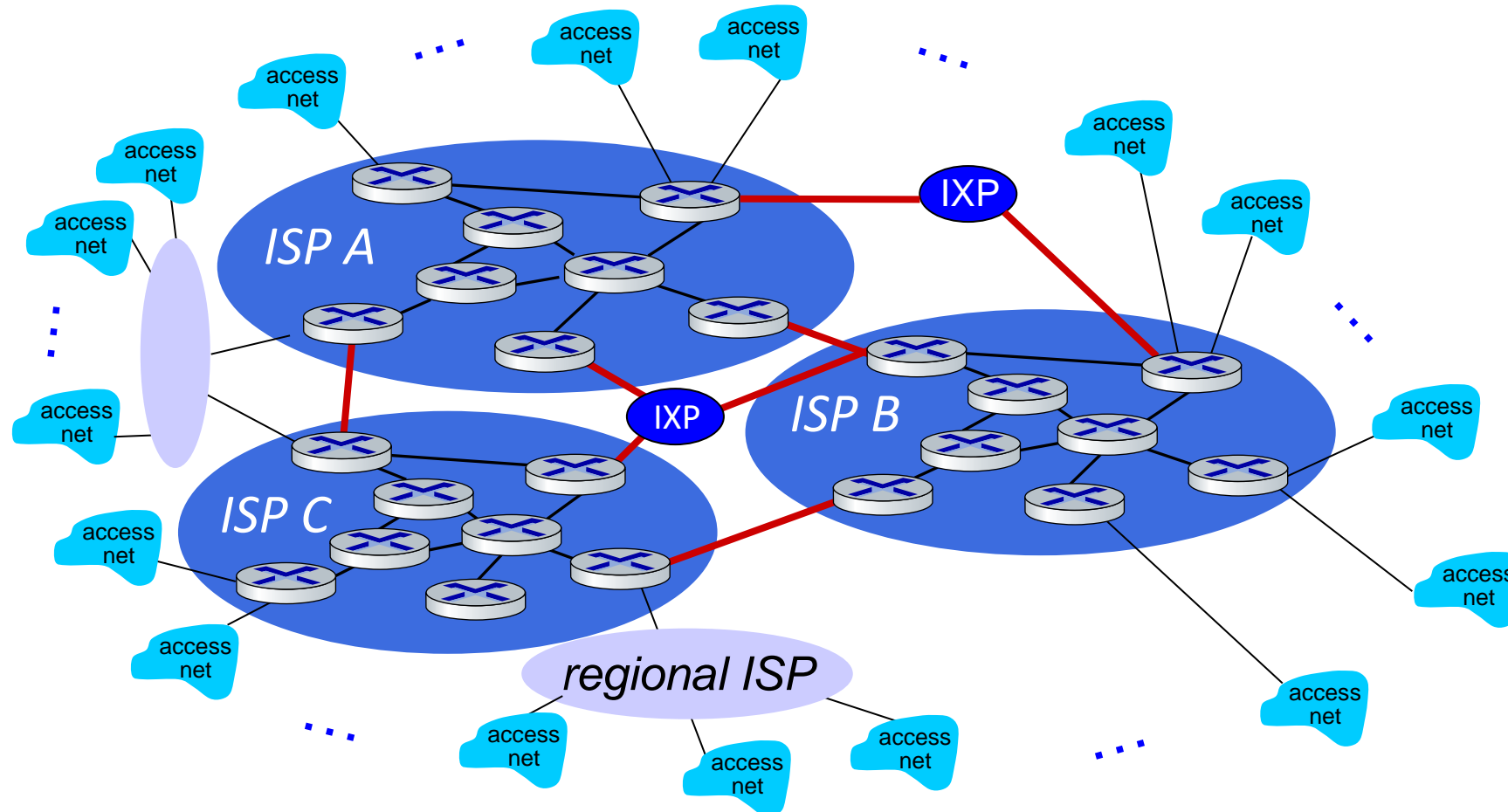
# Internet structure: a “network of networks”

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



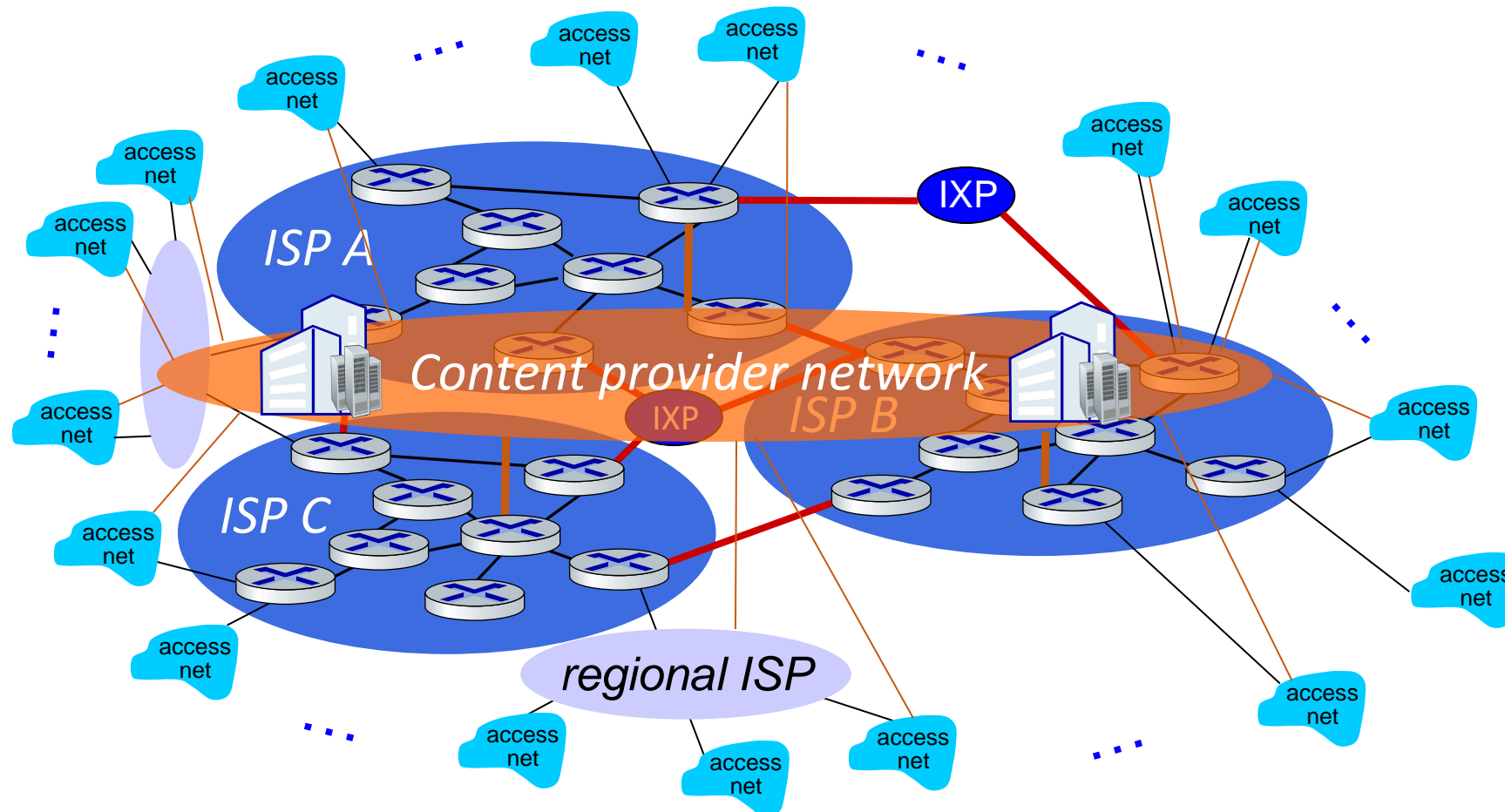
# Internet structure: a “network of networks”

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

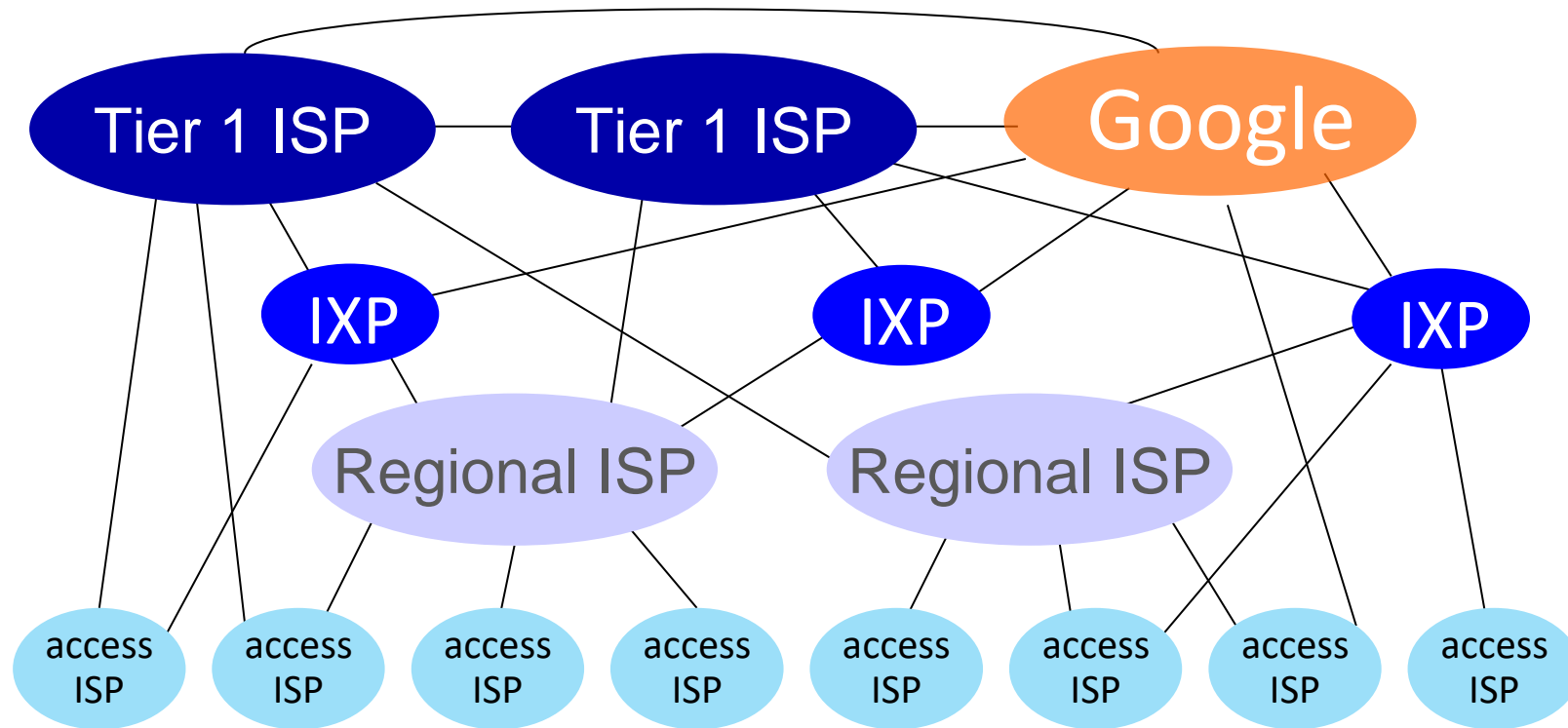


# Internet structure: a “network of networks”

... 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)



# Chapter 1: roadmap

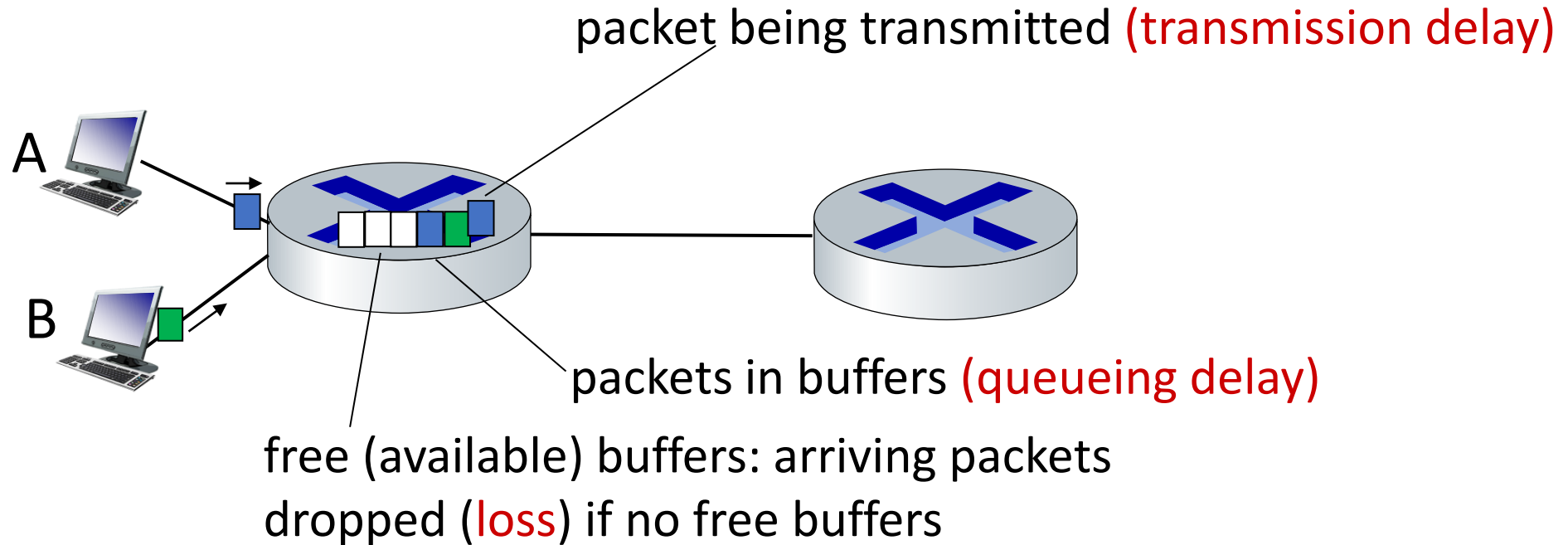
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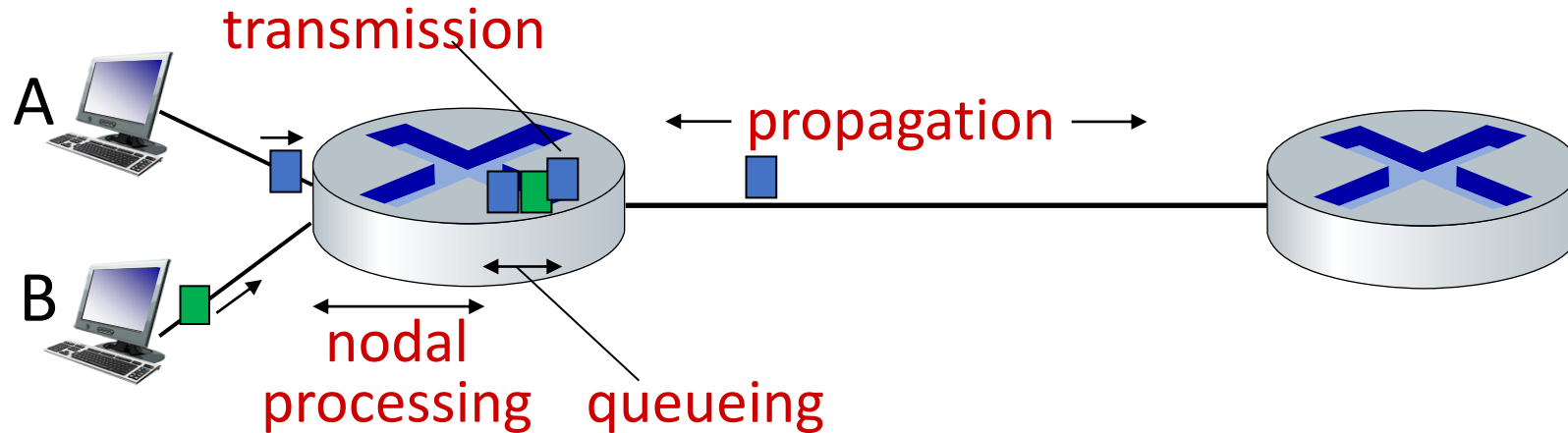
# How do packet loss and delay occur?

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



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

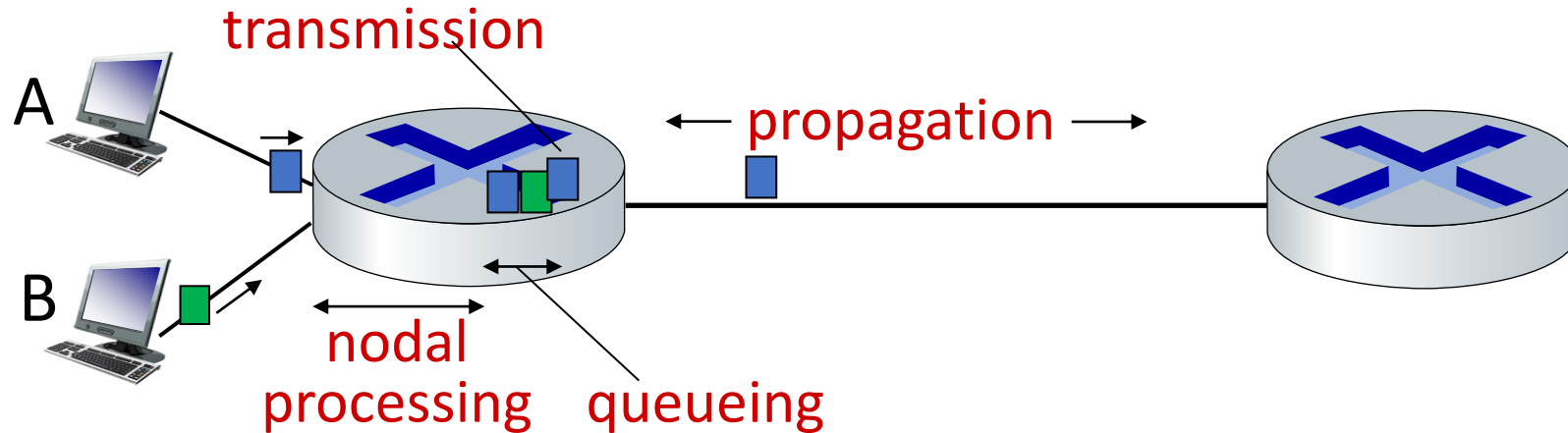
$d_{\text{proc}}$ : nodal processing

- 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:

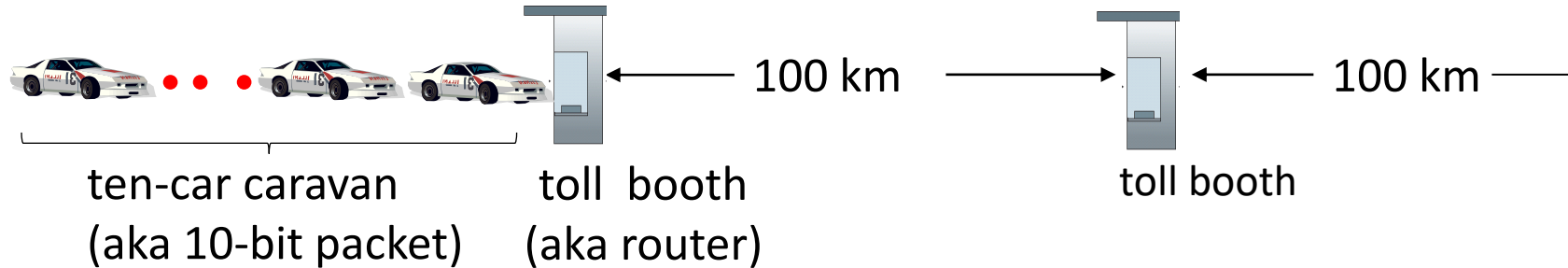
- $d$ : length of physical link
- $s$ : propagation speed ( $\sim 2 \times 10^8$  m/sec)

■  $d_{\text{prop}} = d/s$

$d_{\text{trans}}$  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)

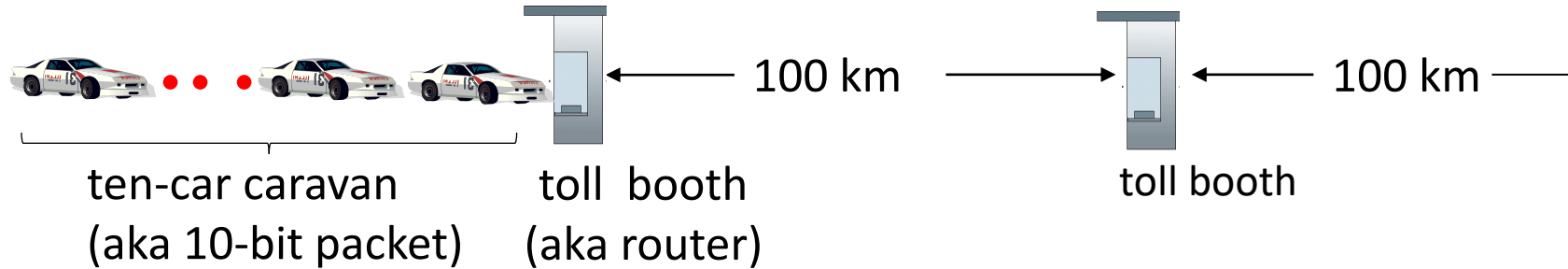
# Caravan analogy



- 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 booth:  $100\text{km} / (100\text{km/hr}) = 1$  hr
- **A: 62 minutes**

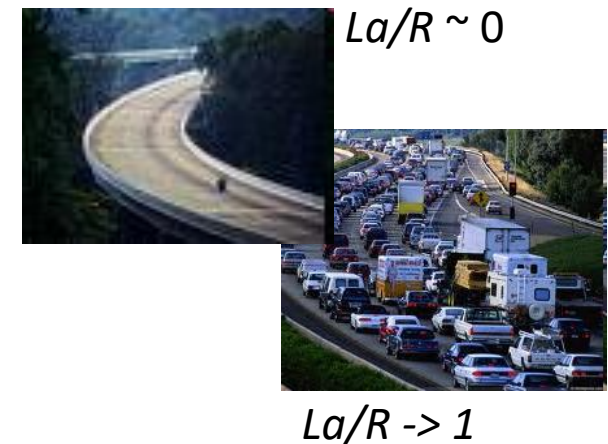
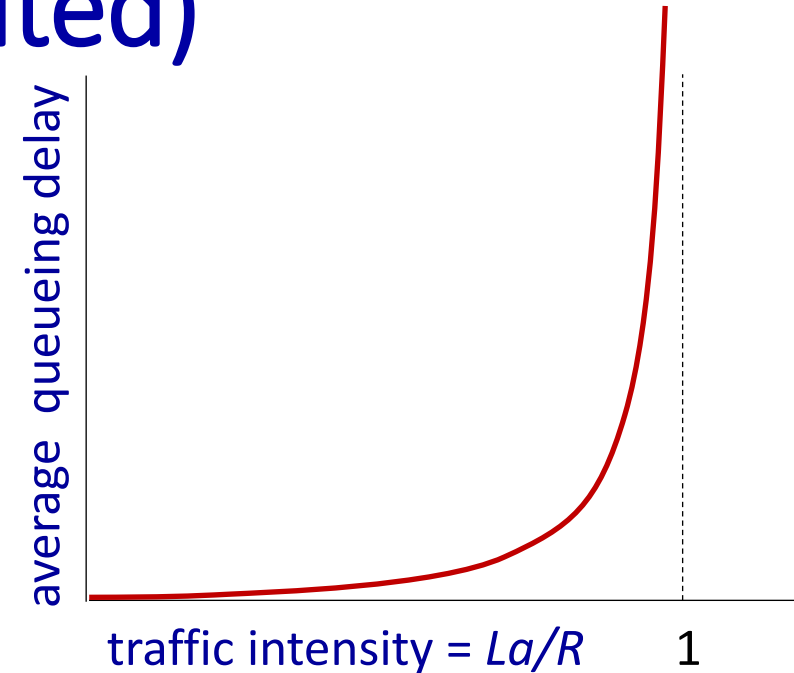
# Caravan analogy



- 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)

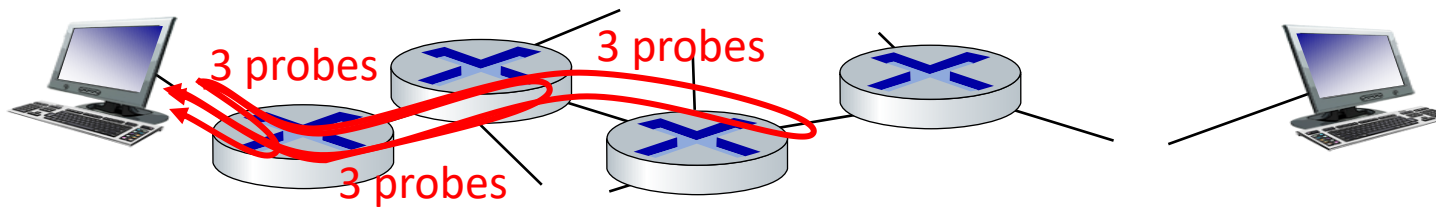
- $R$ : link bandwidth (bps)
- $L$ : packet length (bits)
- $a$ : average packet arrival rate
- $La/R \sim 0$ : avg. queueing delay small
- $La/R \rightarrow 1$ : avg. queueing delay large
- $La/R > 1$ : more “work” arriving is more than can be serviced - average delay infinite!





# “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?

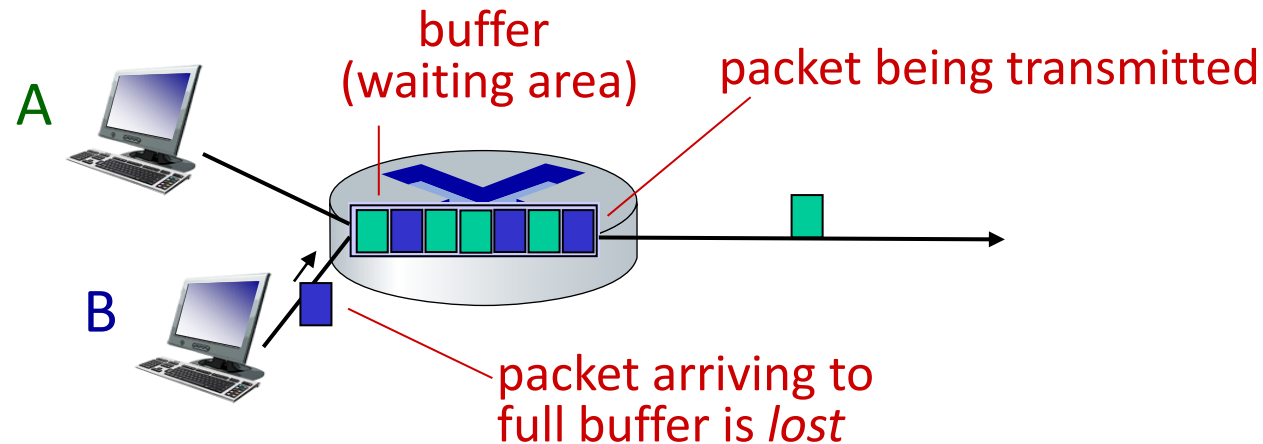
\* means no response (probe lost, router not replying)

```
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)

# Packet loss

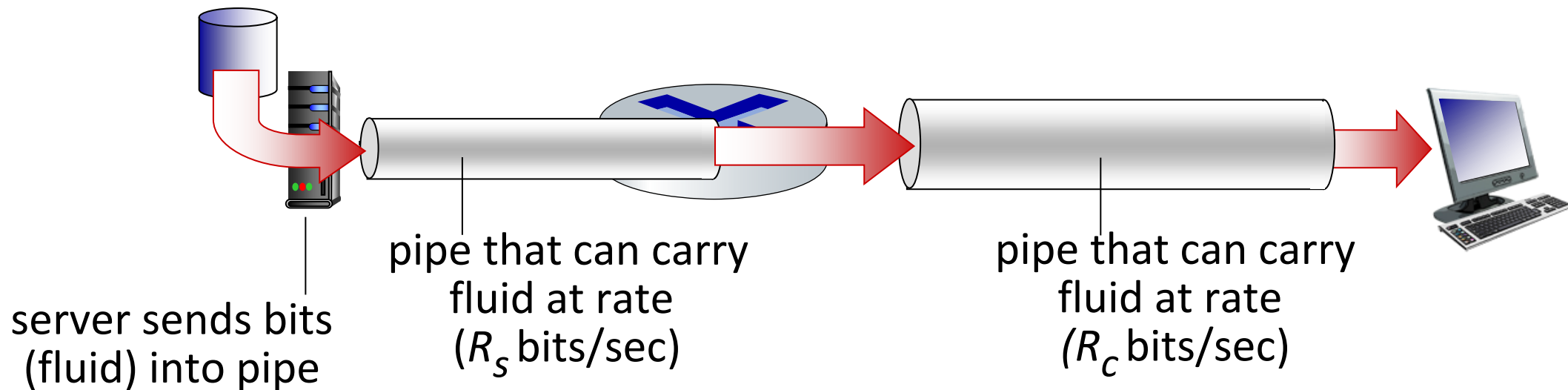
- queue (aka buffer) preceding link in buffer has finite capacity
- packet arriving to full queue dropped (aka lost)
- lost packet may be retransmitted by previous node, by source end system, or not at all



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

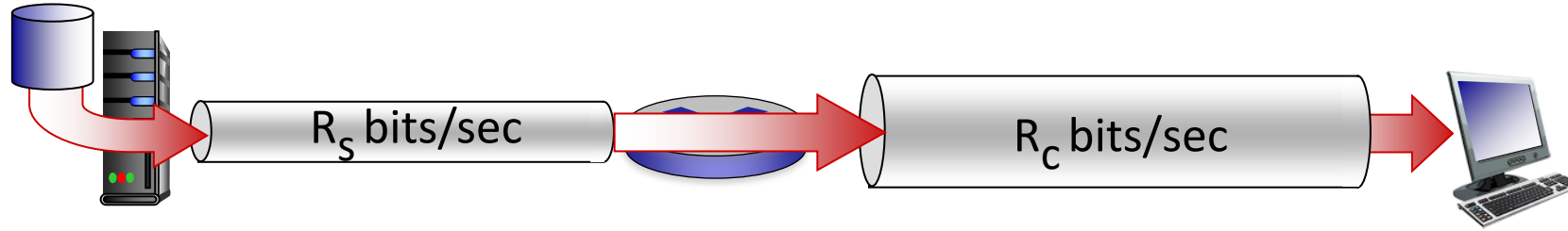
# Throughput

- *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

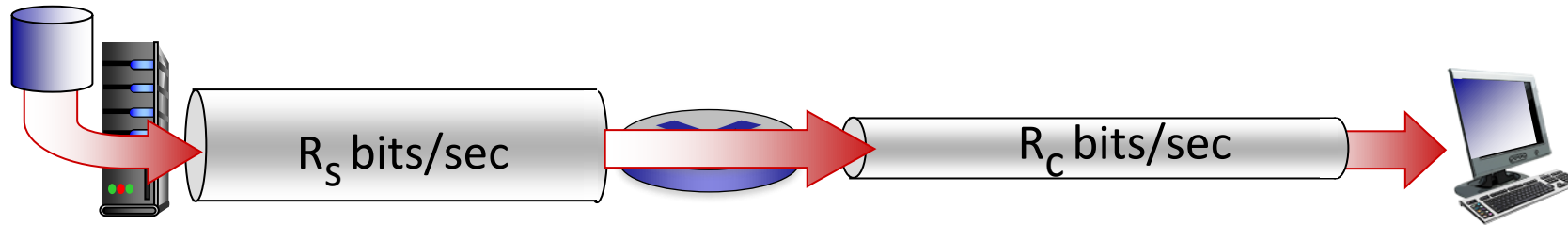


# Throughput

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



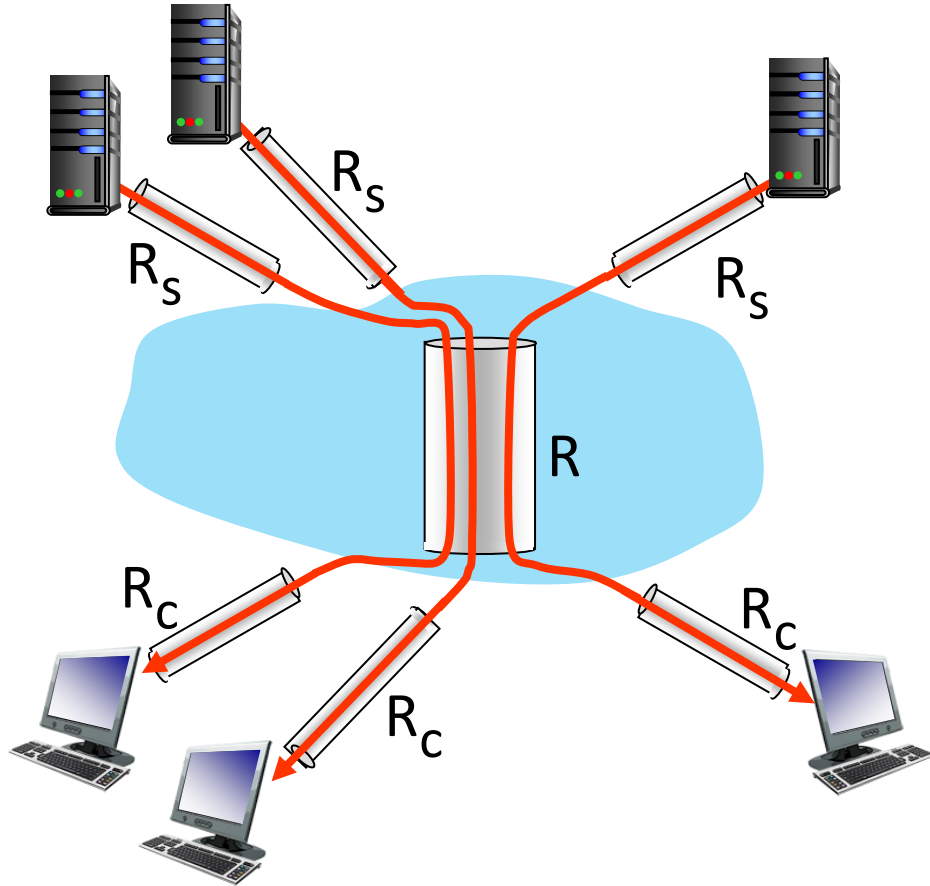
$R_s > R_c$  What is average end-end throughput?



*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/)

# 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!*



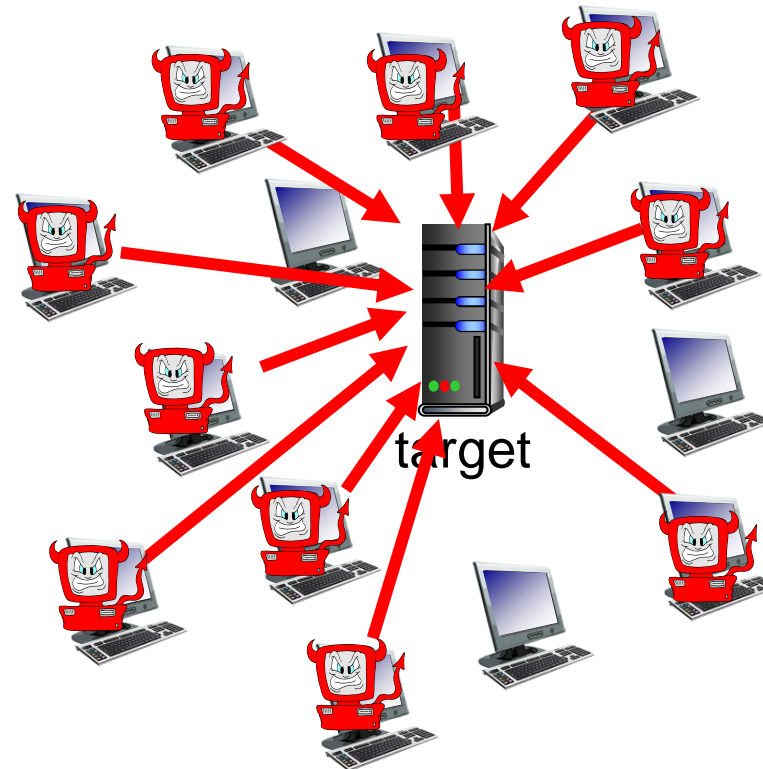
# Bad guys: malware

- 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*

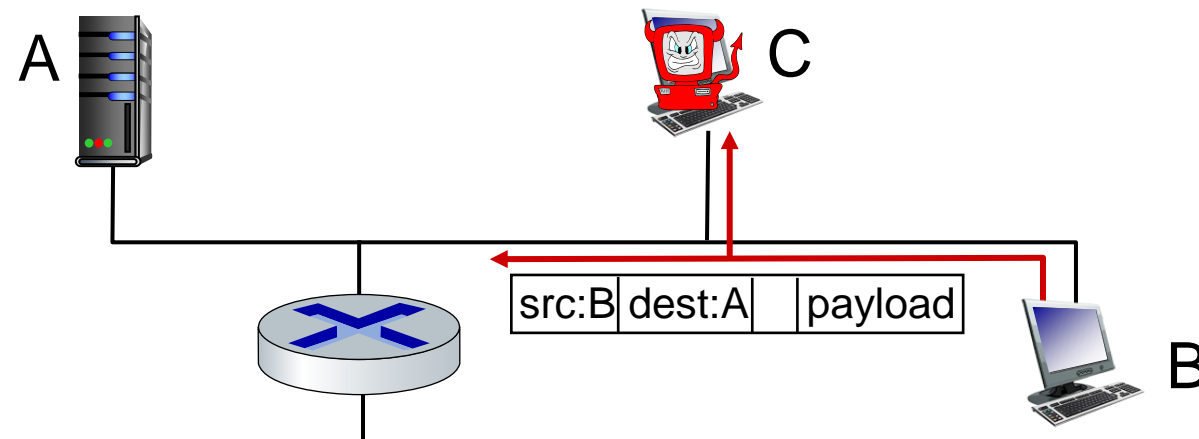
1. select target
2. break into hosts around the network (see botnet)
3. send packets to target from compromised hosts



# Bad guys: packet interception

## *packet “sniffing”:*

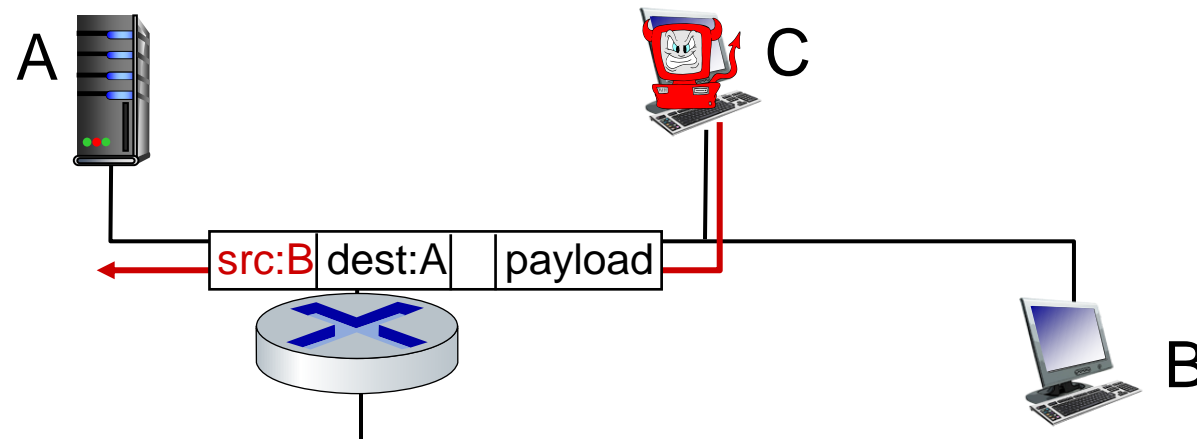
- broadcast media (shared Ethernet, wireless)
- promiscuous network interface *reads/records* all packets (e.g., including passwords!) passing by



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



# Protocol “layers” and reference models

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

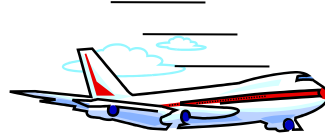
- hosts
- routers
- links of various media
- applications
- protocols
- hardware, software

*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*



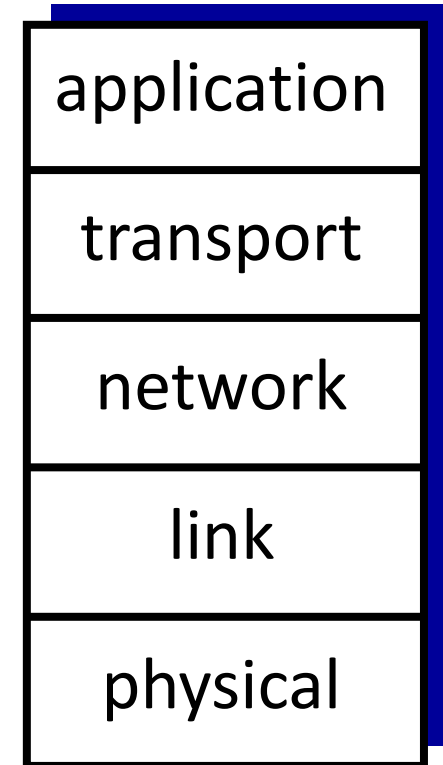
# Why layering?

dealing with *complex systems*:

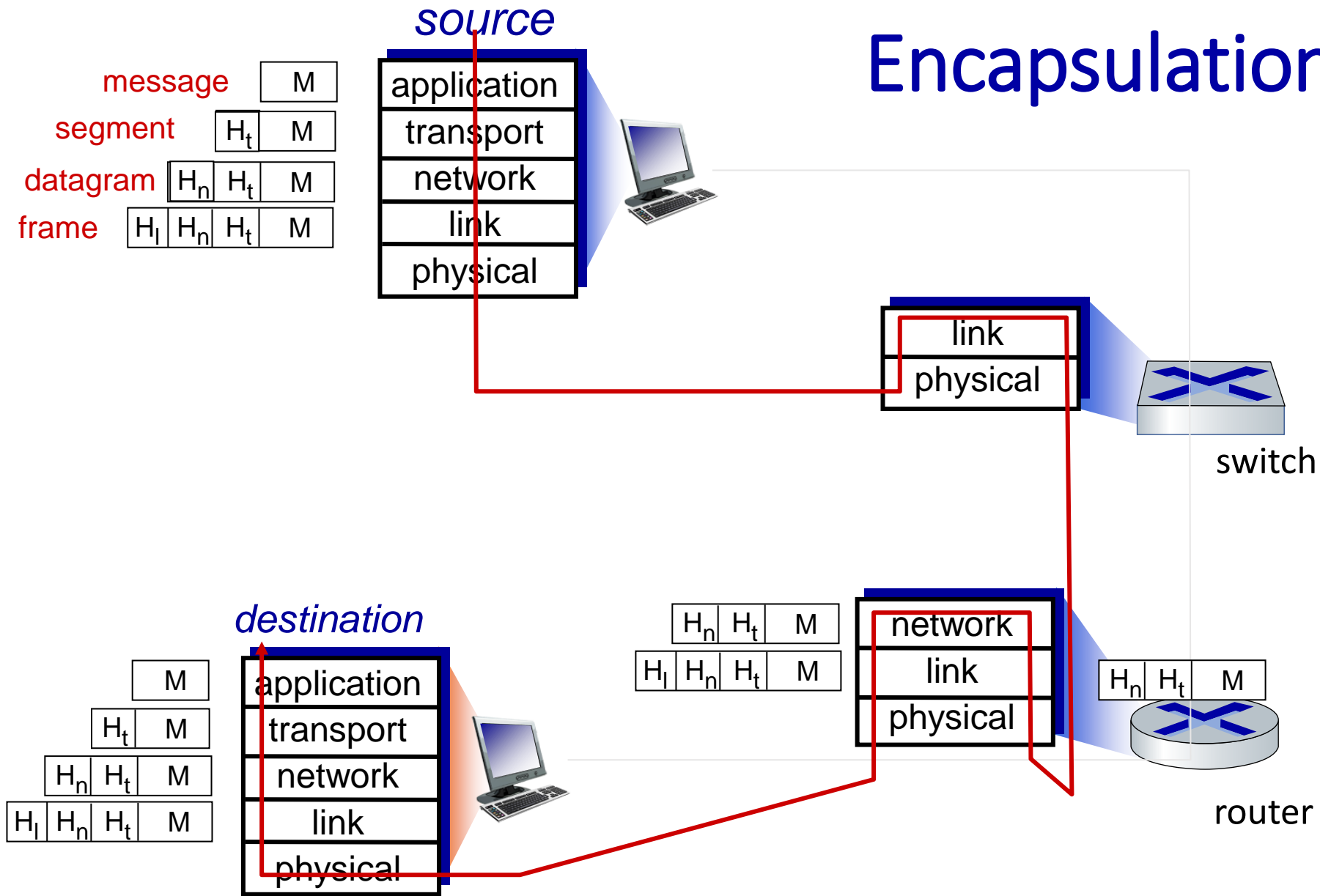
- explicit structure allows *identification, relationship* of complex system's pieces
  - layered *reference model* for discussion
- modularization eases *maintenance, updating* of system
  - change in layer's service *implementation*: transparent to rest of system
  - e.g., change in gate procedure 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 (Wi-Fi), PPP
- *physical*: bits “on the wire”



# Encapsulation



# Chapter 1: roadmap

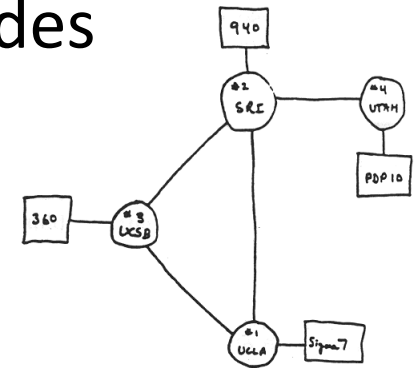
- What *is* the Internet?
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- Protocol layers, service models
- History



# 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

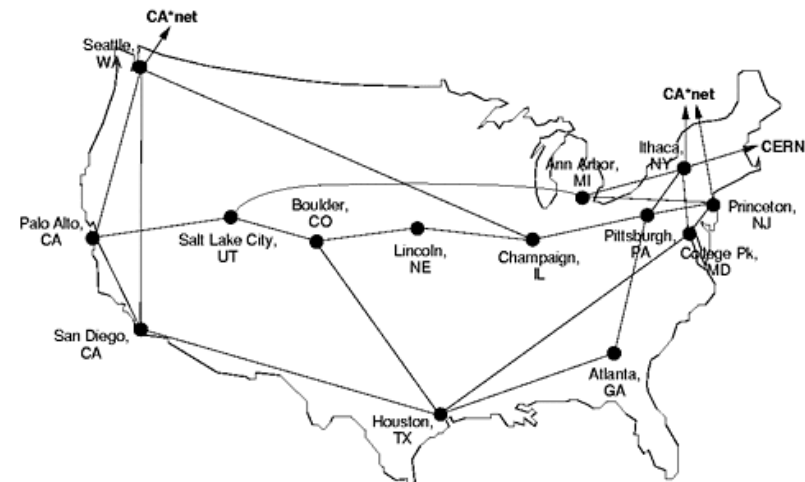
define today's Internet architecture

# 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



© Merit Network, Inc.

# 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:*

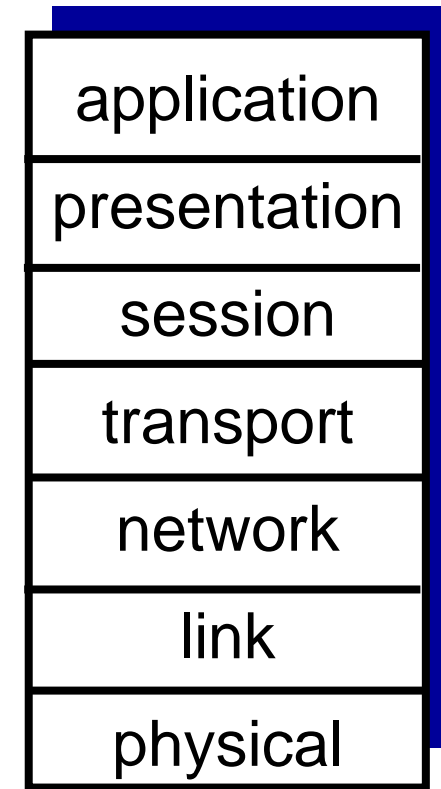
- context, overview, vocabulary, “feel” of networking
- more depth, detail, *and fun* to follow!

# 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

