

# Data Networks: Introduction

# Course Overview

18 Lectures (15 lectures \* 2 points = 30 points)

18 Practical Lessons (3 labs \* 15 points = 45 points)

3 Midterm Tests (25 points)

Exam (must have 60 points)

# References

- Kurose, James F. **Computer networking : a top-down approach** / James F. Kurose, Keith W. Ross – 7<sup>th</sup> edition. – USA: Pearson Education, 2017
- **Computer Networking Problems and Solutions** Russ White and Ethan Banks. – USA: Pearson Education, 2018
- Douglas E. Comer **The Internet Book** Everything You Need to Know about Computer Networking and How the Internet Works 5th edition. - Taylor & Francis Group, 2019
- Douglas E. Comer **Computer Networks and Internets** 6th edition. - Pearson Education, Inc., 2015
- Andrew S. Tanenbaum, David J. Wetherall **Computer Networks** 5th edition. - Prentice Hall, Indian International Ed., 2010

# Study Tools

- Lecture PPTs, Labs, Additional materials:  
<https://jointvlab.ipt.pt/moodle/>
- Wireshark, Packet Tracer

# Topic 1: introduction

## *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*

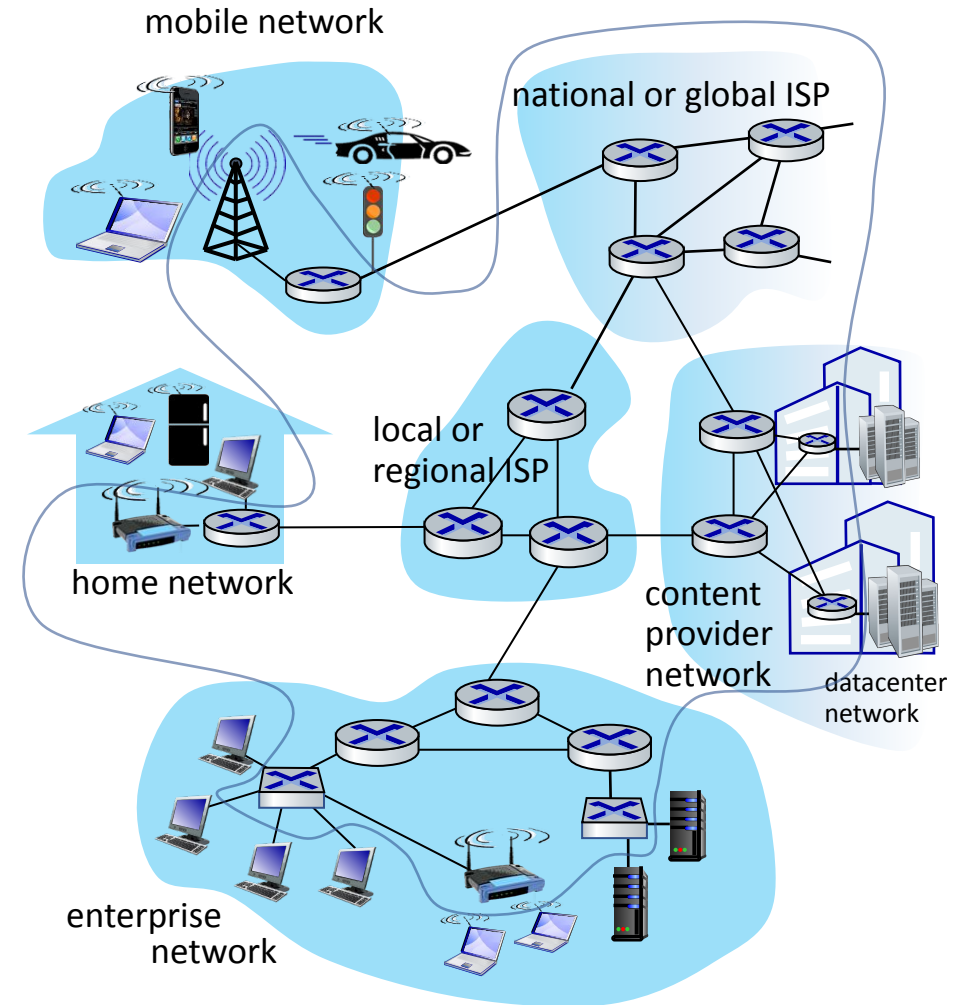


*Communication links*

- 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

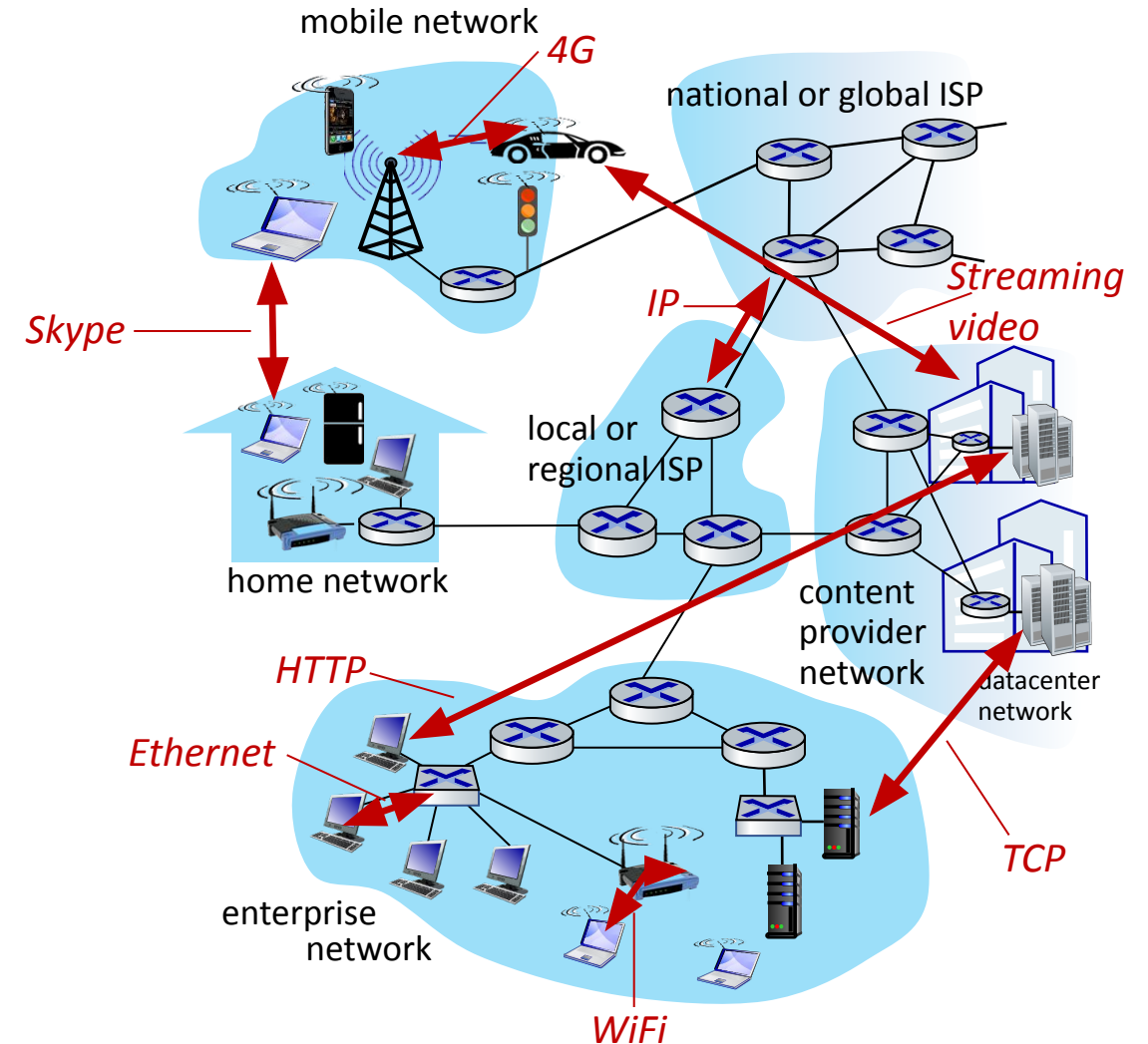


Fitbit

*Others?*

# The Internet: a “nuts and bolts” view

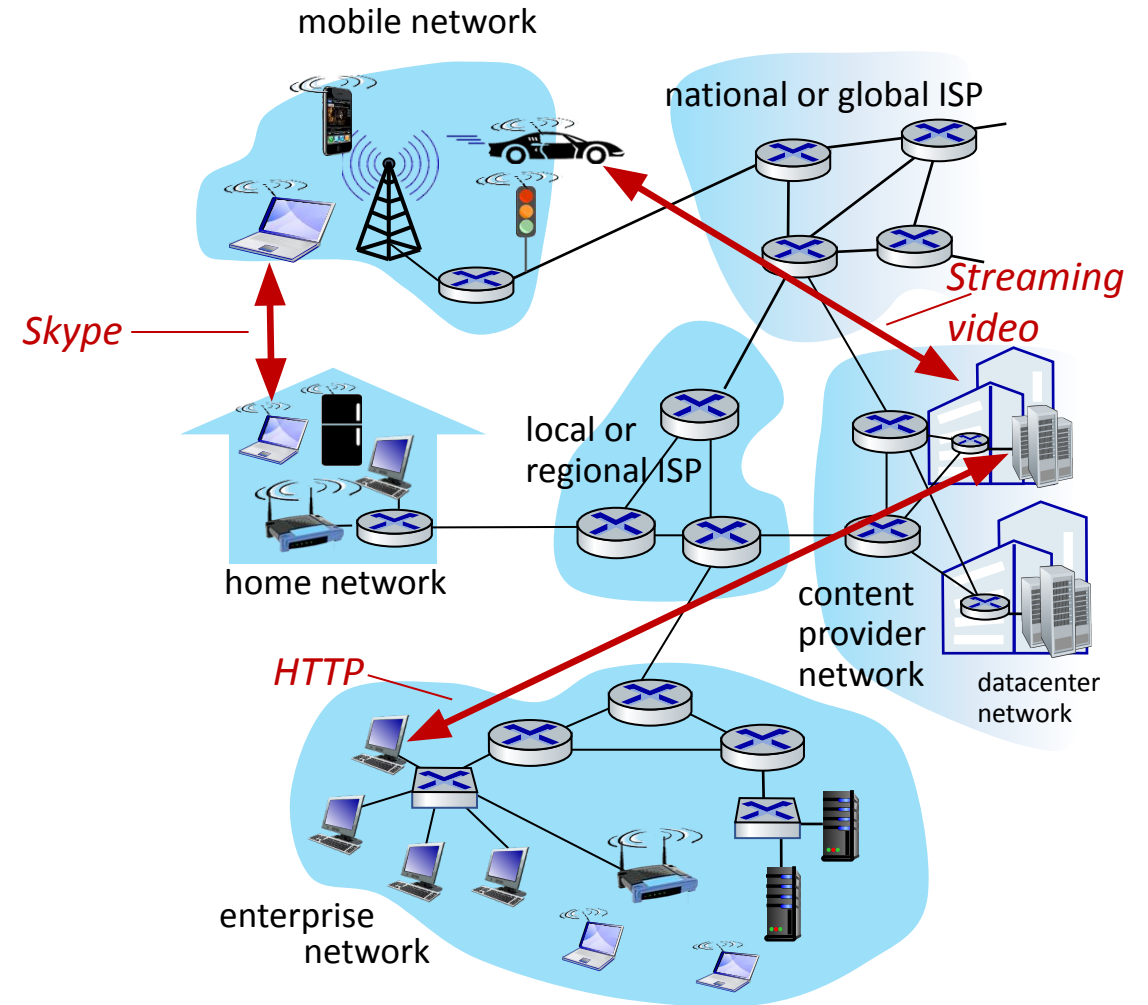
- *Internet: “network of networks”*
  - Interconnected ISPs
- *protocols are everywhere*
  - control sending, receiving of messages
  - e.g., HTTP (Web), streaming video, Skype, TCP, IP, WiFi, 4G, Ethernet
- *Internet standards*
  - RFC: Request for Comments
  - IETF: Internet Engineering Task Force





# 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

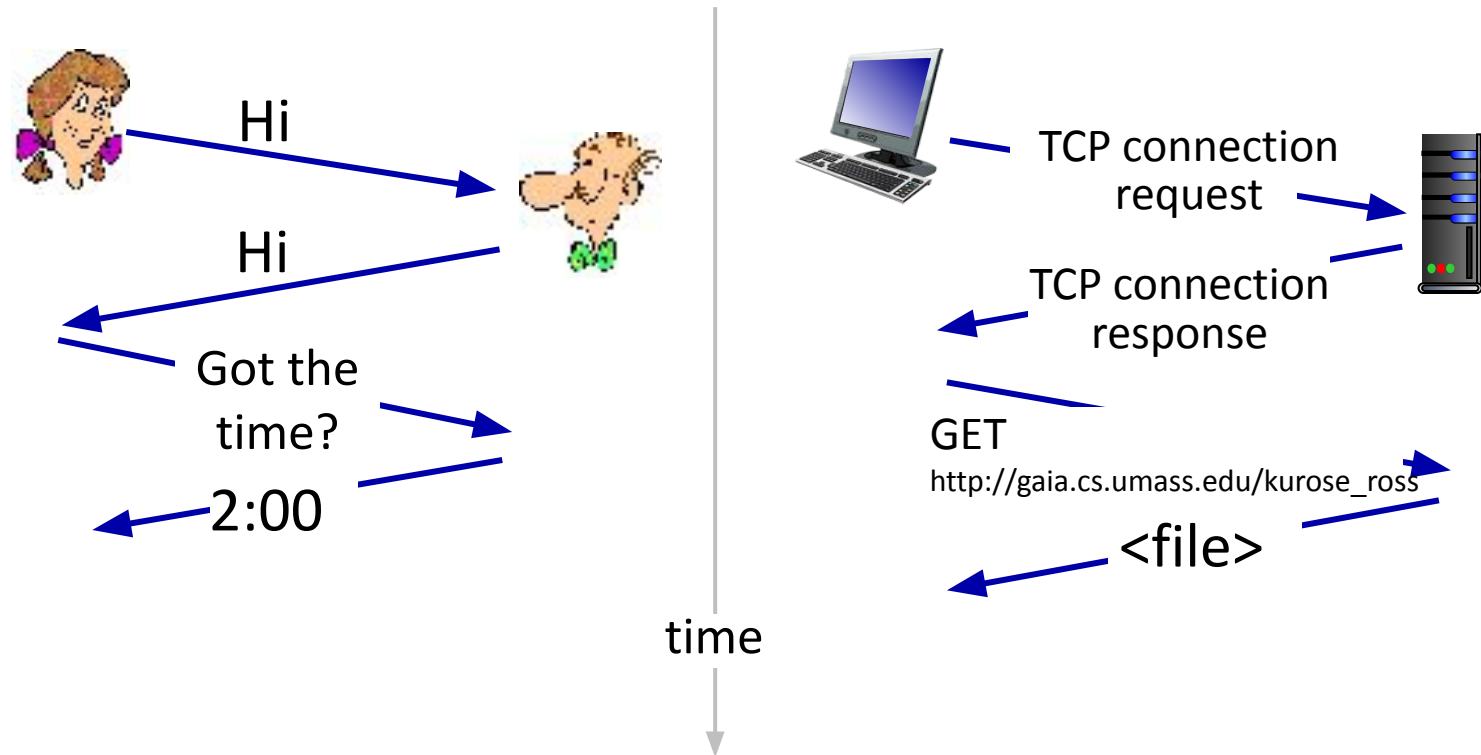
## *Network protocols:*

- 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?

# Topic 1: roadmap

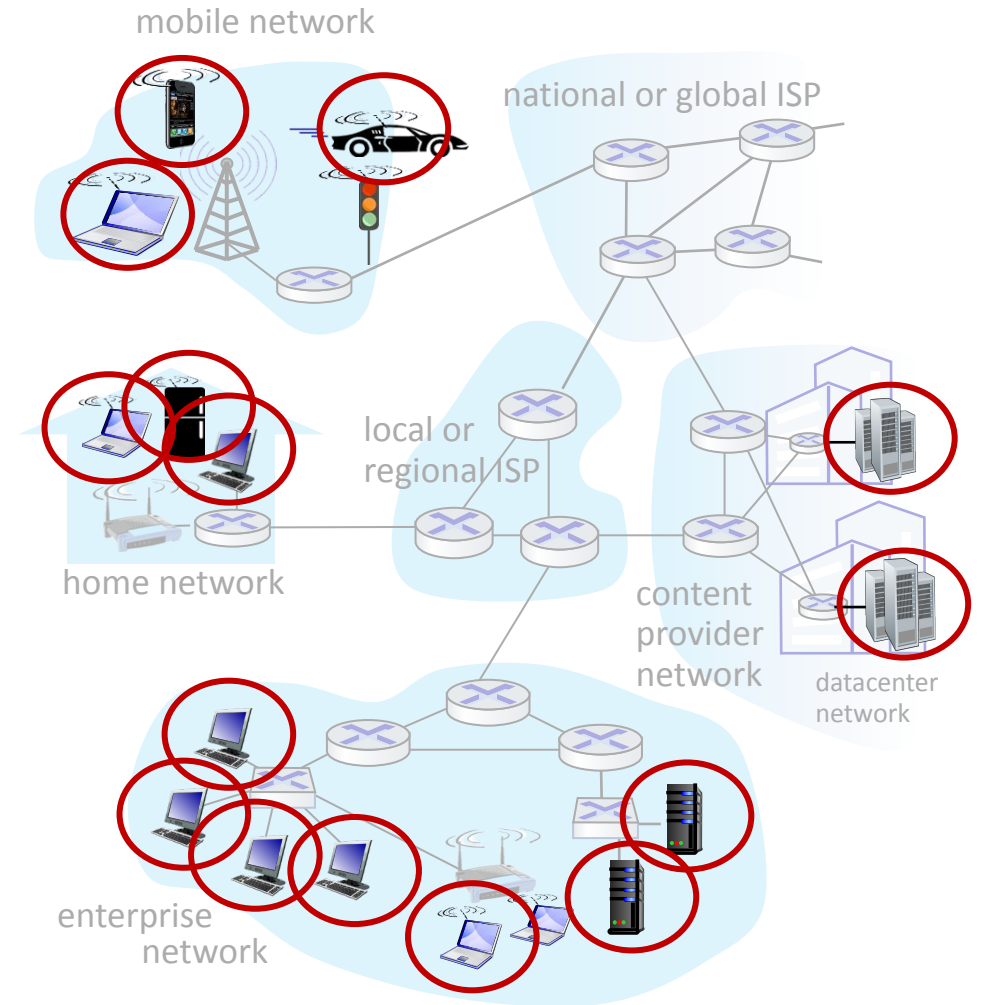
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# A closer look at Internet structure

## Network edge:

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



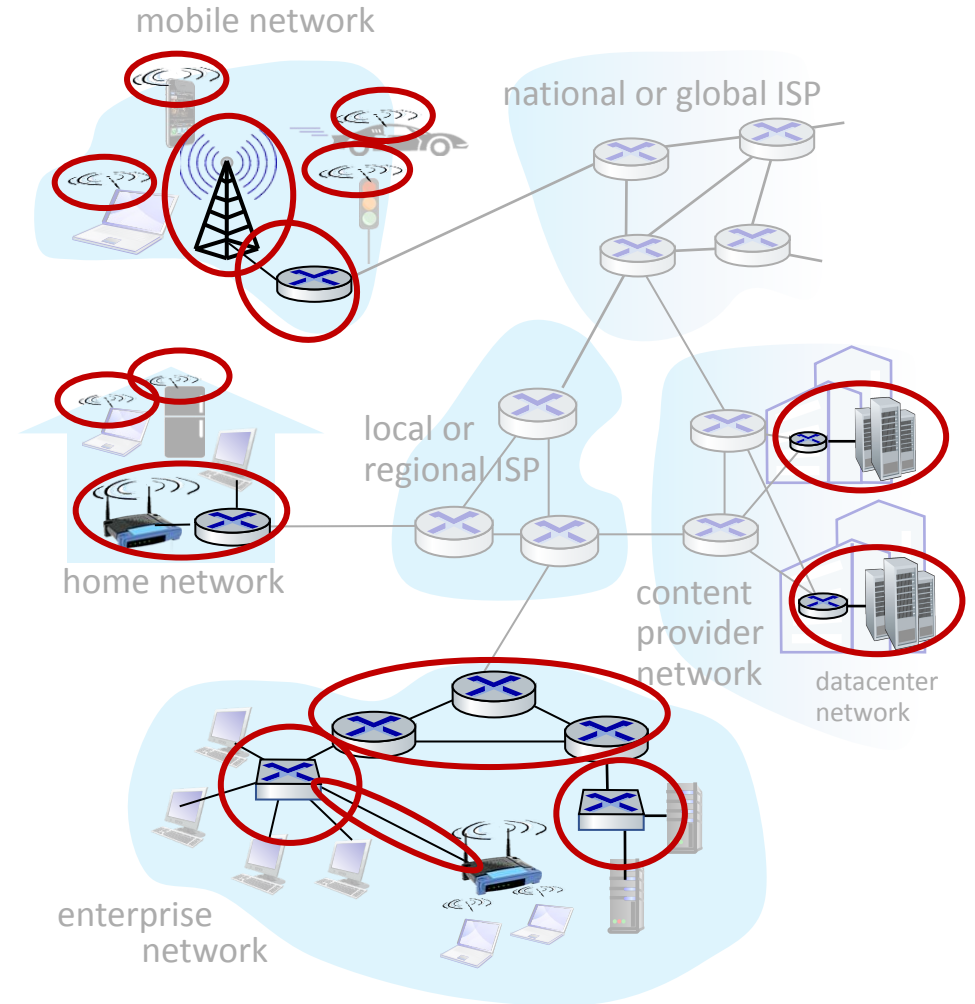
# A closer look at Internet structure

## Network edge:

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## Access networks, physical media:

- wired, wireless communication links



# A closer look at Internet structure

## Network edge:

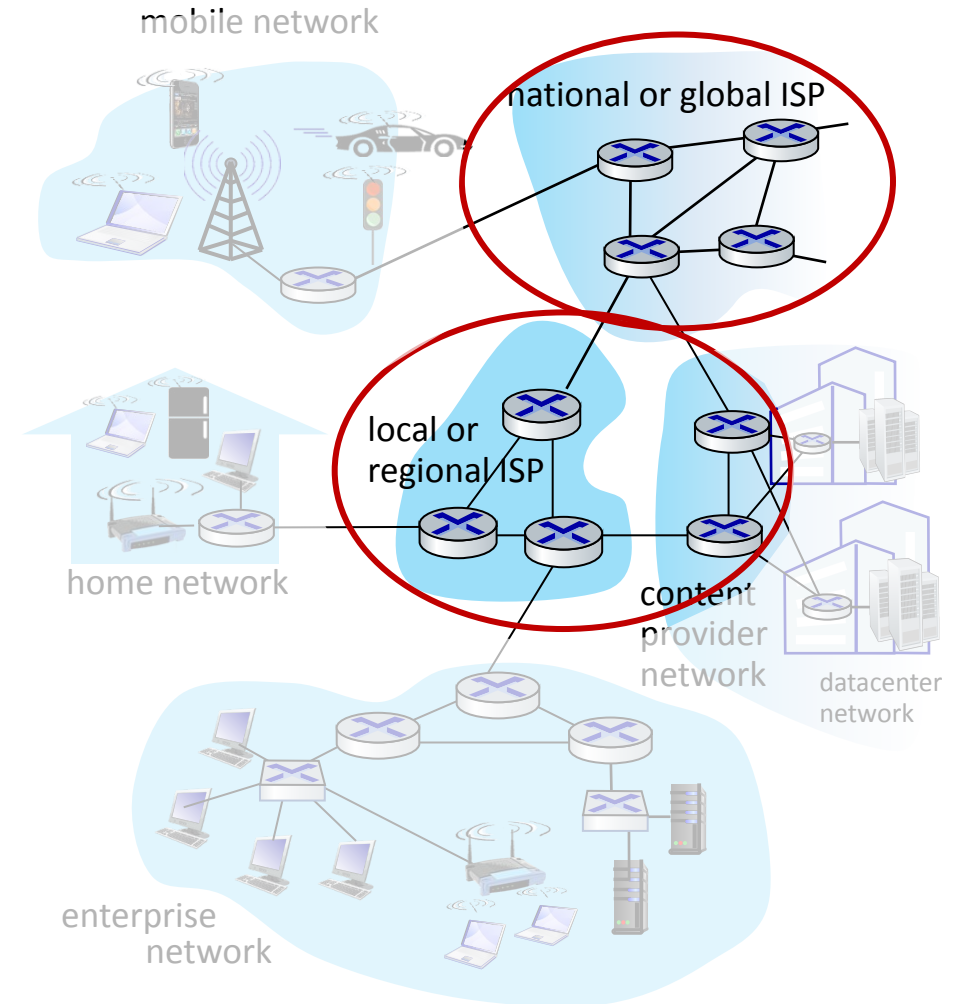
- hosts: clients and servers
- servers often in data centers

## Access networks, physical media:

- wired, wireless communication links

## Network core:

- interconnected routers
- network of networks



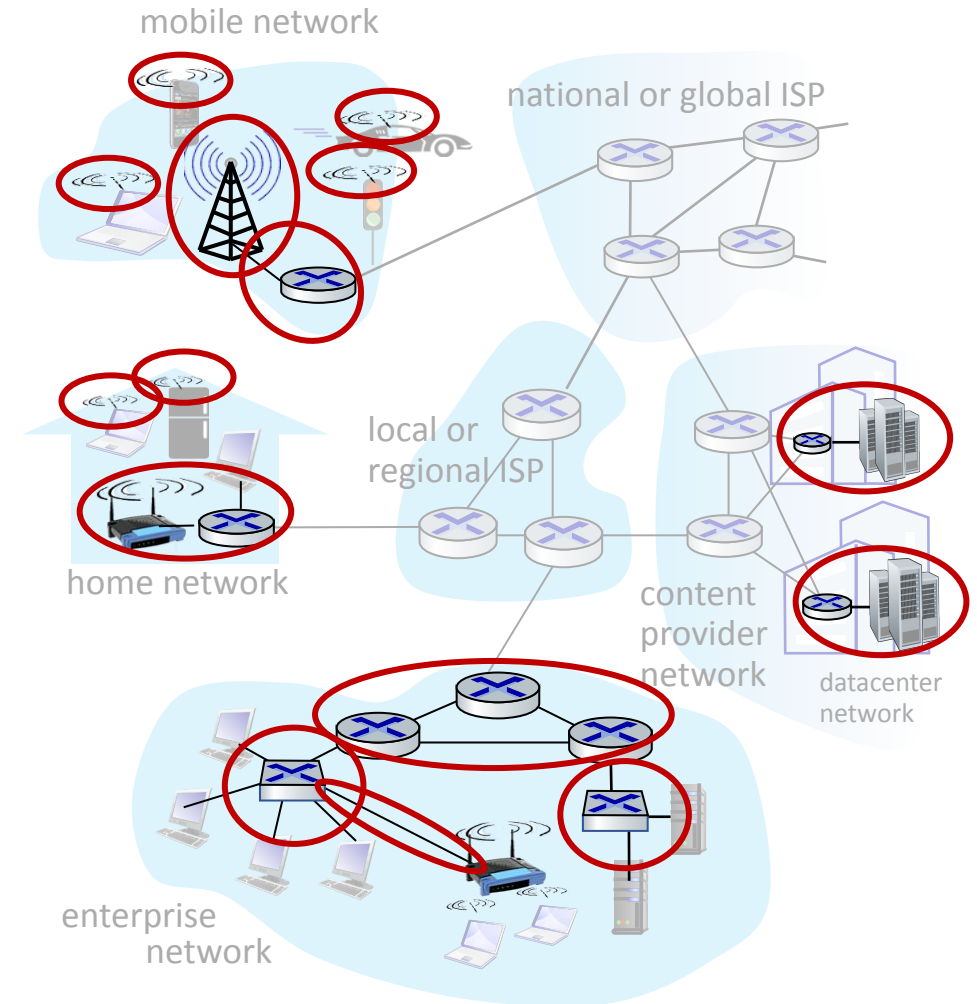
# Access networks and physical media

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

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

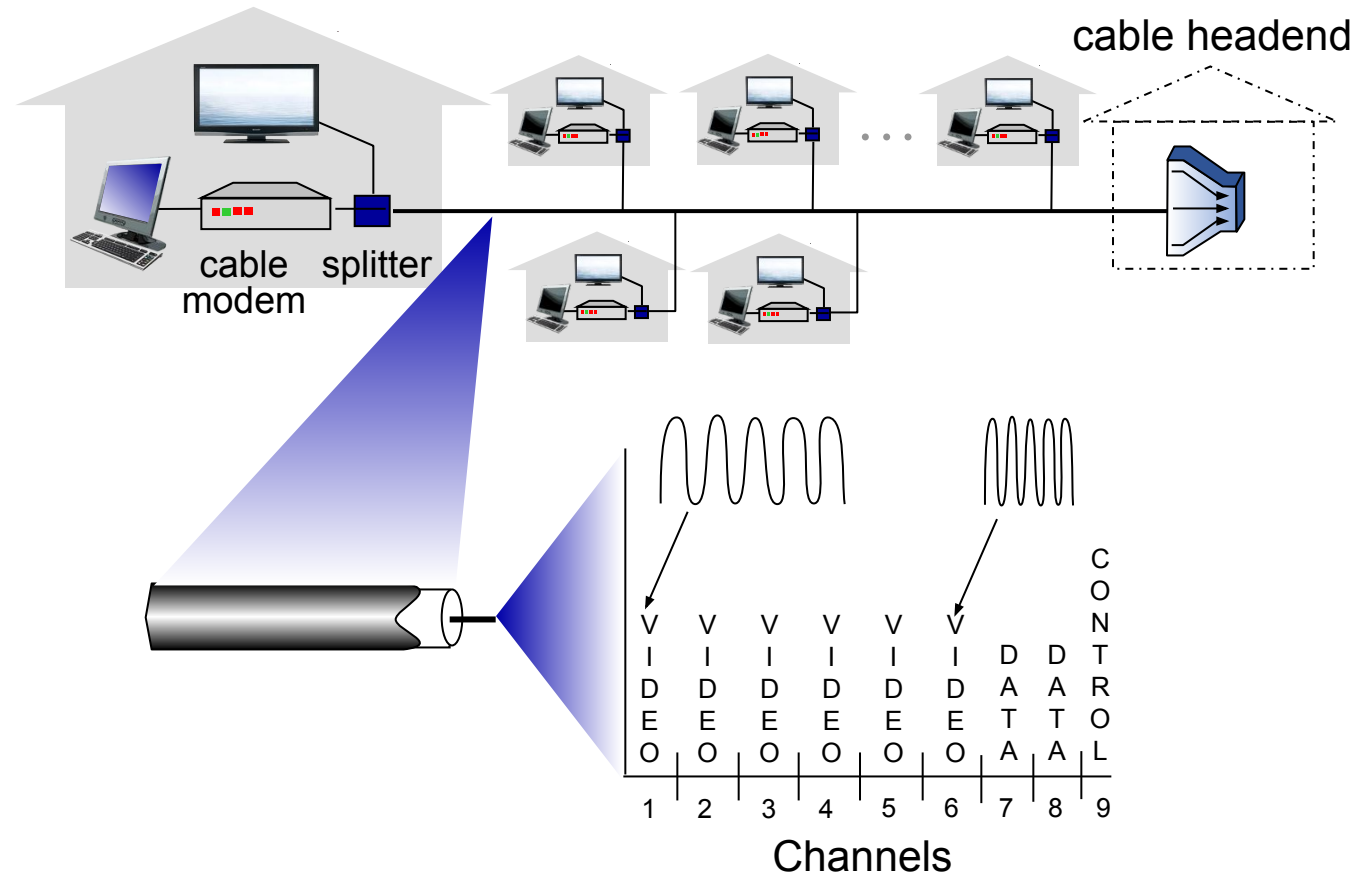
*What to look for:*

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



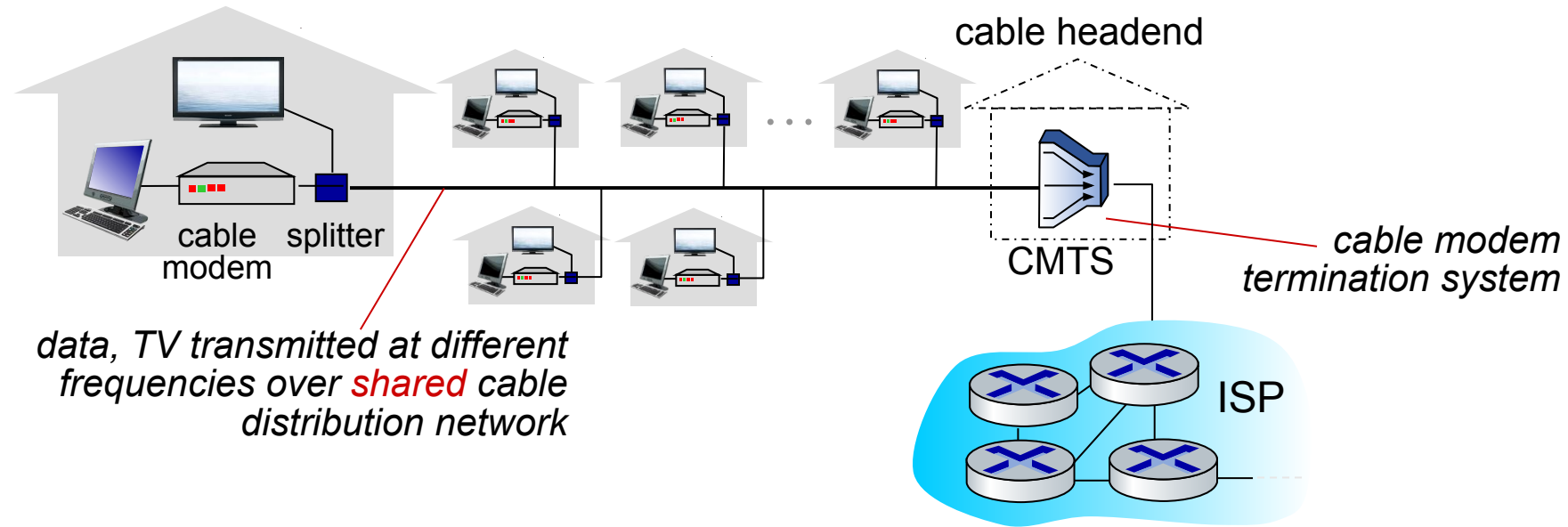


# Access networks: cable-based access



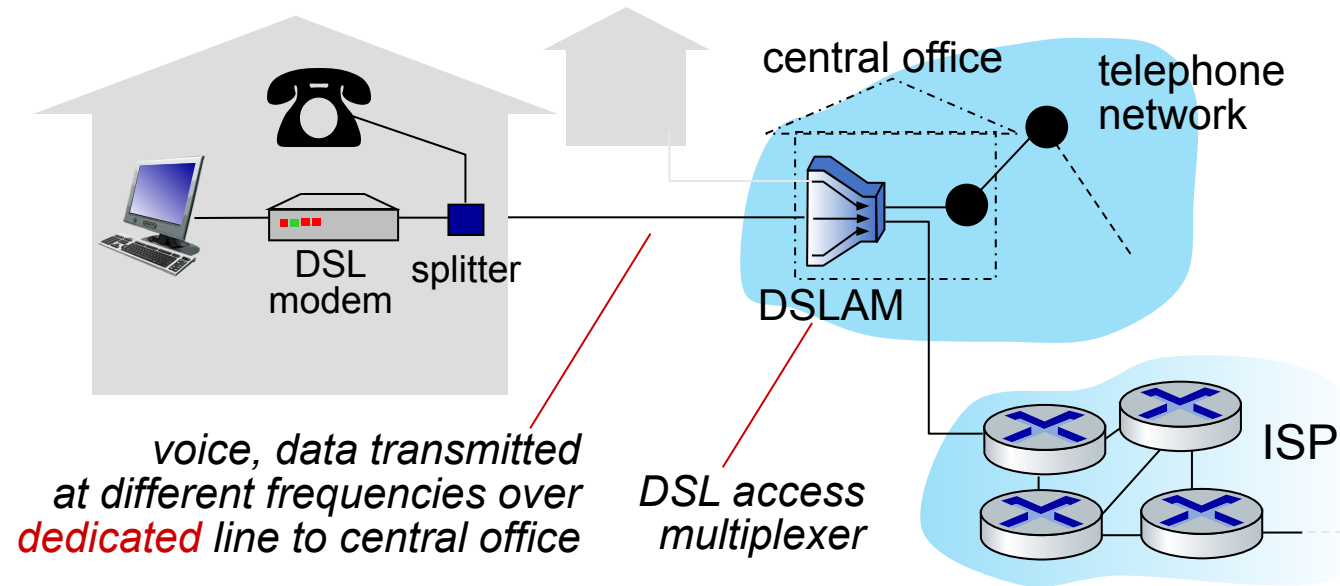
*frequency division multiplexing (FDM)*: different channels transmitted in different frequency bands

# Access networks: cable-based access



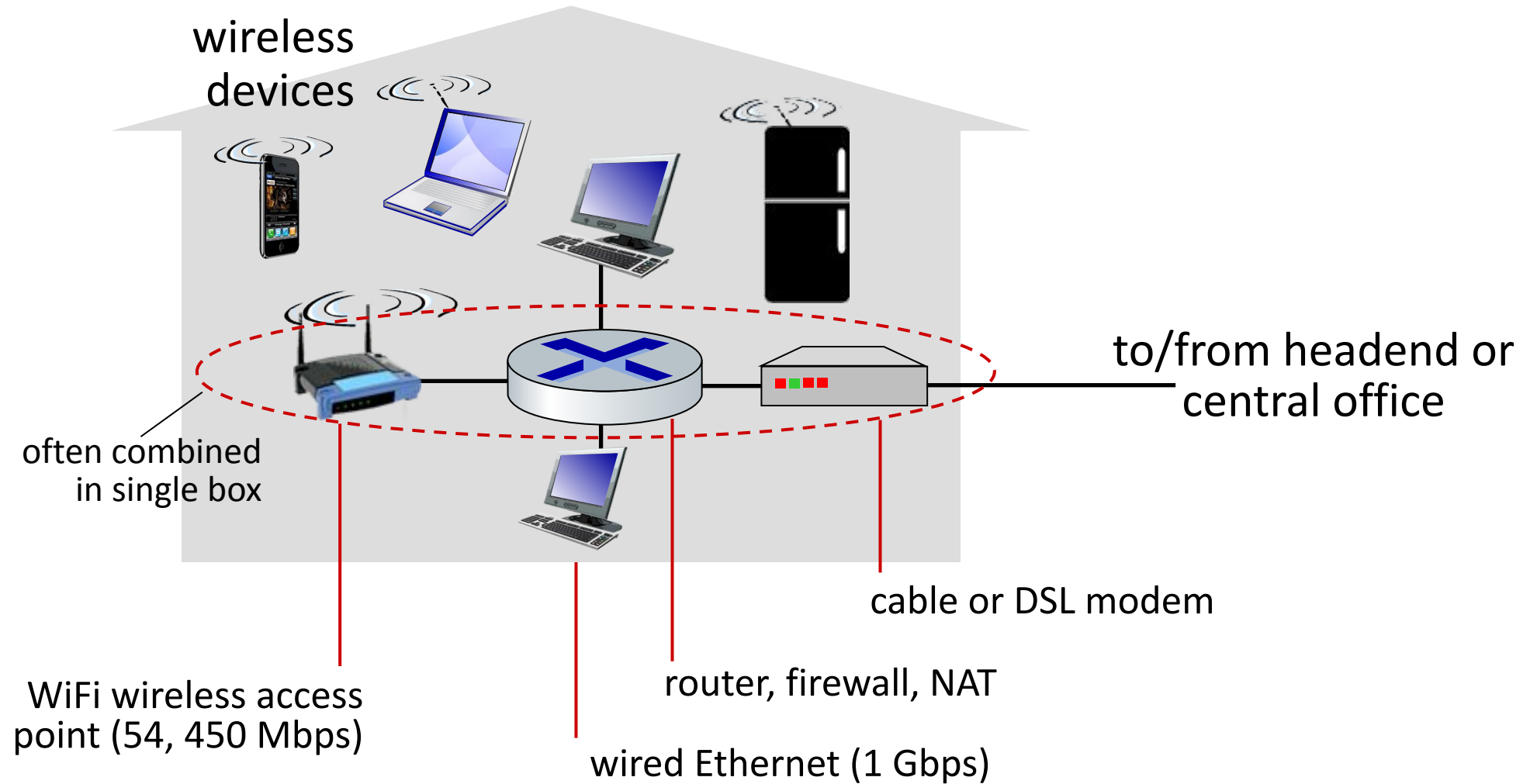
- HFC: hybrid fiber coax
  - asymmetric: up to 40 Mbps – 1.2 Gbs downstream transmission rate, 30-100 Mbps upstream transmission rate
- network of cable, fiber attaches homes to ISP router
  - homes *share access network* to cable headend

# Access networks: digital subscriber line (DSL)



- use *existing* telephone line to central office DSLAM
  - data over DSL phone line goes to Internet
  - voice over DSL phone line goes to telephone net
- 24-52 Mbps dedicated downstream transmission rate
- 3.5-16 Mbps dedicated upstream transmission rate

# Access networks: home networks



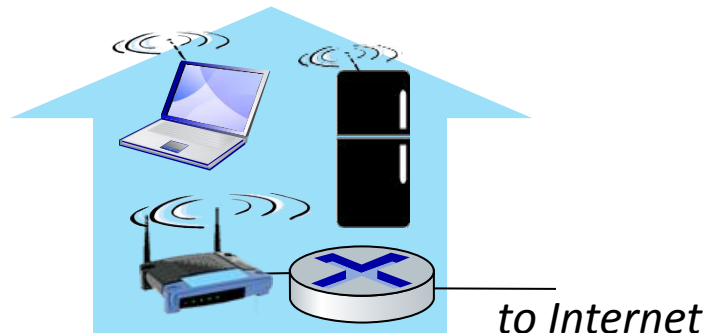
# Wireless access networks

Shared *wireless* access network connects end system to router

- via base station aka “access point”

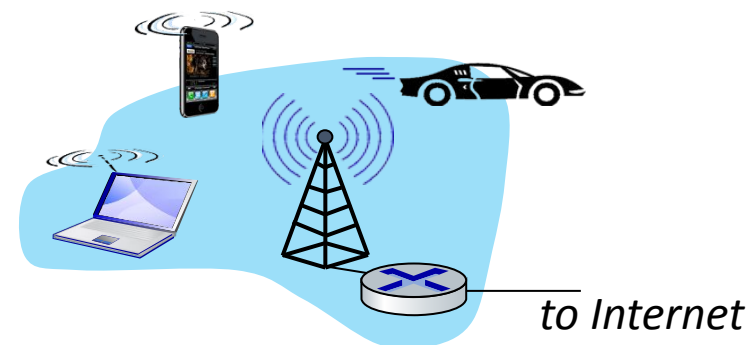
## Wireless local area networks (WLANs)

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

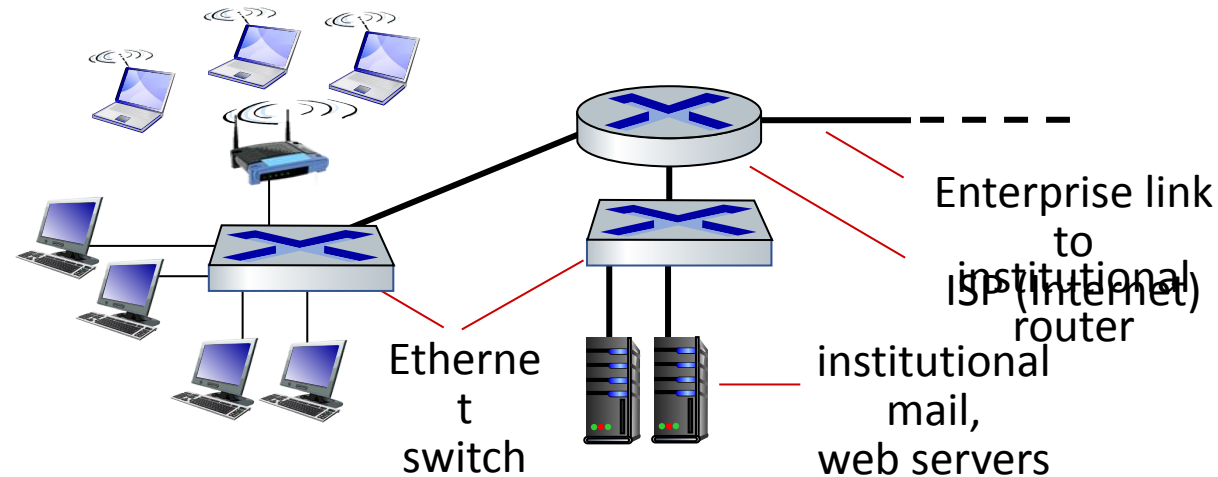


## Wide-area cellular access networks

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



# Access networks: enterprise networks

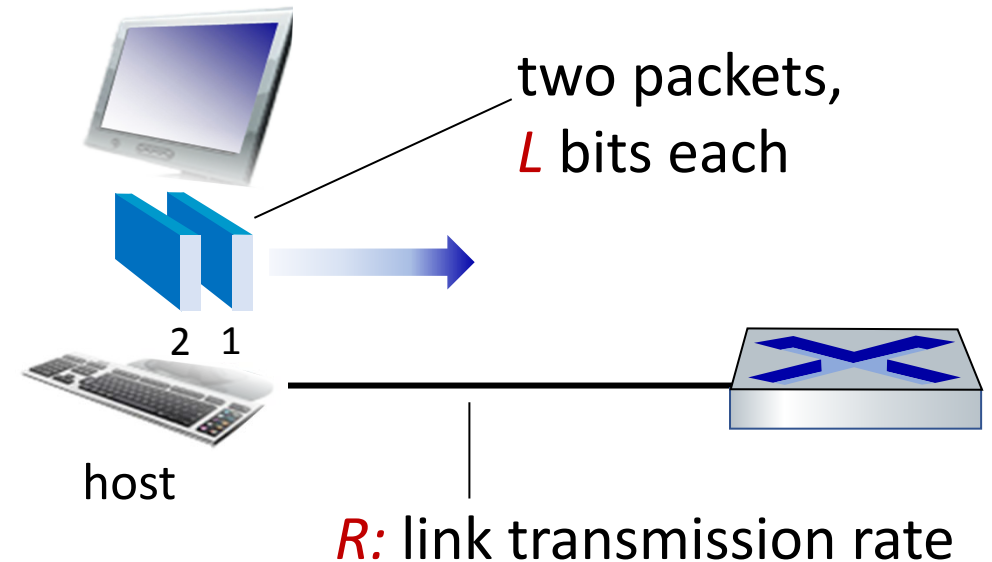


- companies, universities, etc.
- mix of wired, wireless link technologies, connecting a mix of switches and routers (we'll cover differences shortly)
  - Ethernet: wired access at 100Mbps, 1Gbps, 10Gbps
  - WiFi: wireless access points at 11, 54, 450 Mbps

# Host: sends *packets* of data

host sending function:

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



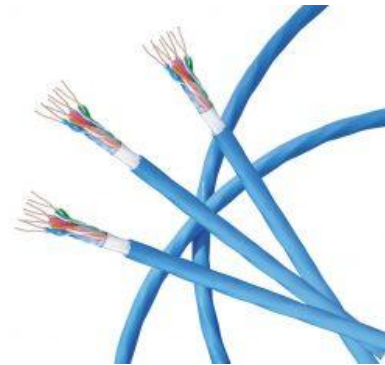
$$\text{packet transmission delay} = \text{time needed to transmit } L\text{-bit packet into link} = \frac{L \text{ (bits)}}{R \text{ (bits/sec)}}$$

# Links: physical media

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

## Twisted pair (TP)

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





# Links: physical media

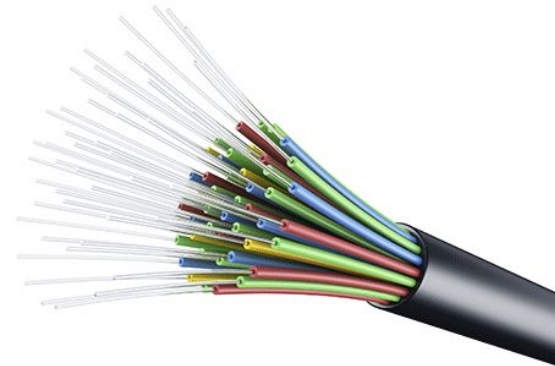
## Coaxial cable:

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



## Fiber optic cable:

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



# Links: physical media

## Wireless radio

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

## Radio link types:

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

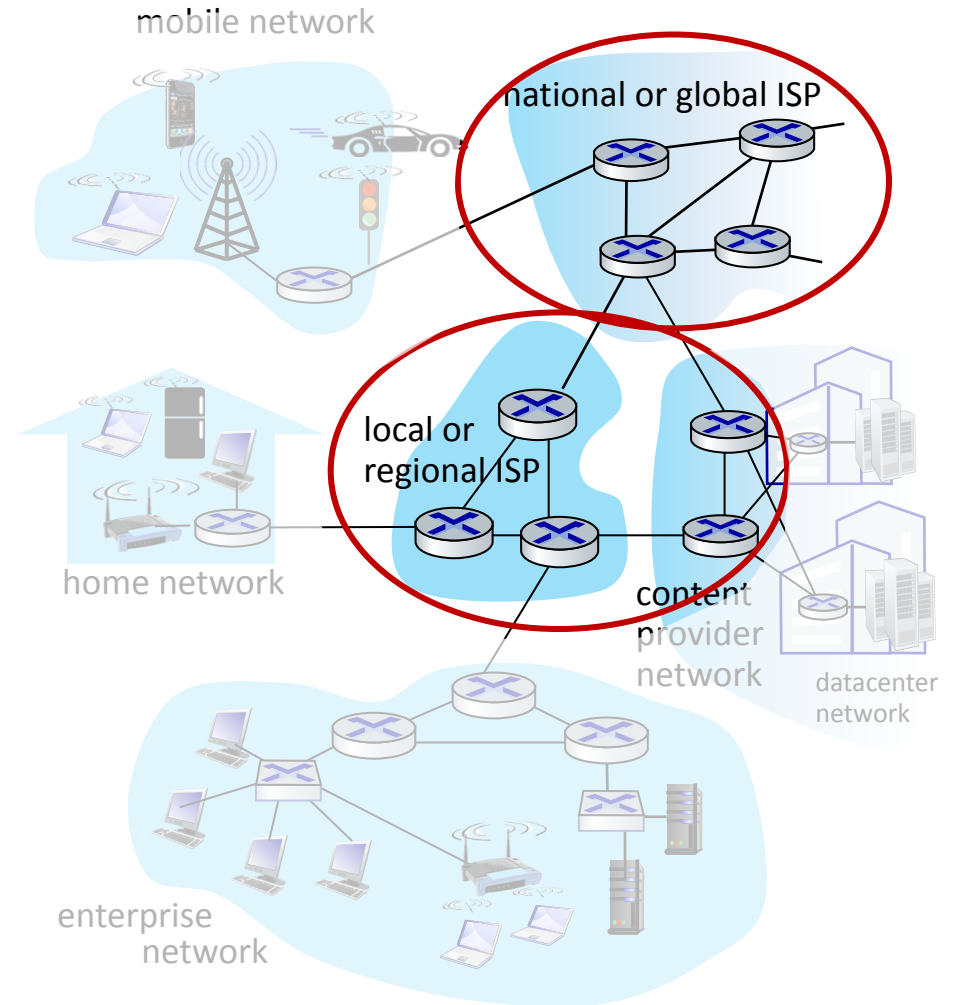
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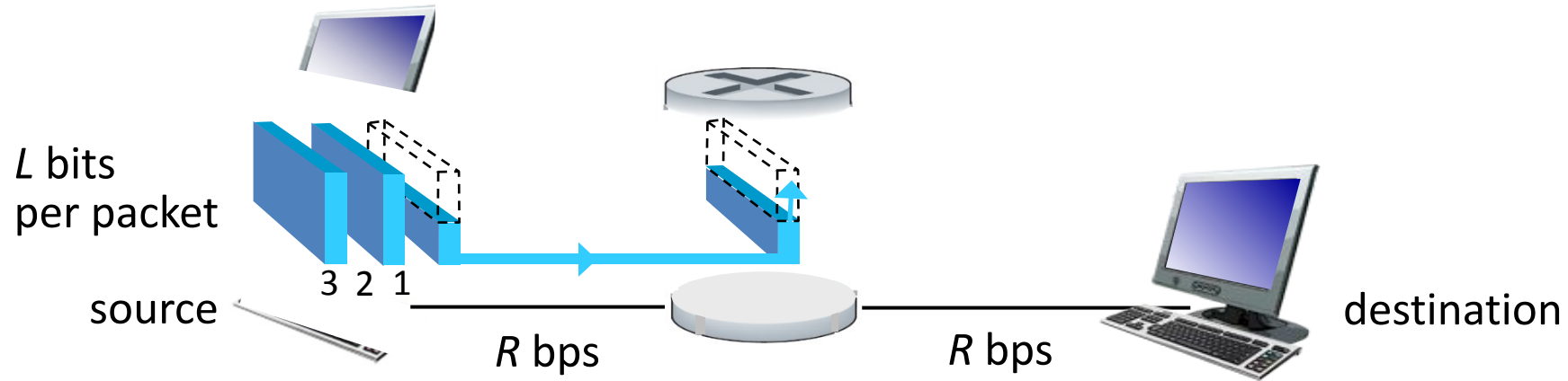


# The network core

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



# Packet-switching: store-and-forward

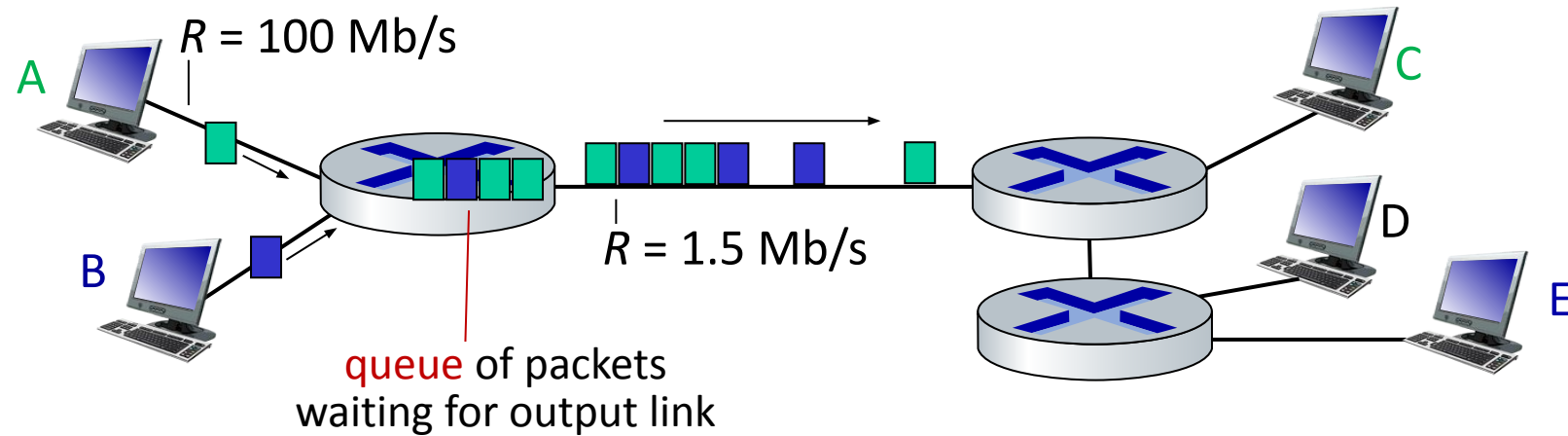


- **Transmission delay:** takes  $L/R$  seconds to transmit (push out)  $L$ -bit packet into link at  $R$  bps
- **Store and forward:** entire packet must arrive at router before it can be transmitted on next link
- **End-end delay:**  $2L/R$  (above), assuming zero propagation delay (more on delay shortly)

## *One-hop numerical example:*

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

# Packet-switching: queueing delay, loss



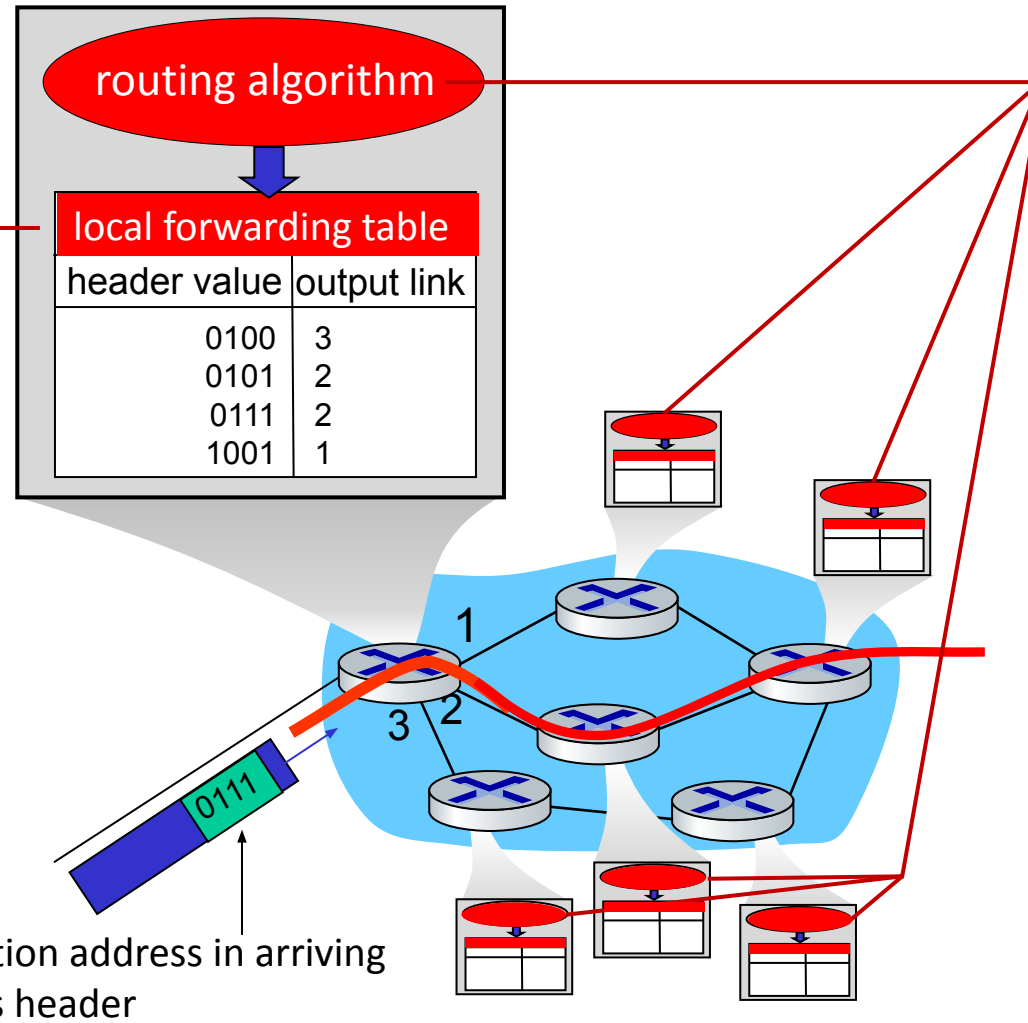
***Packet queuing and loss:*** if arrival rate (in bps) to link exceeds transmission rate (bps) of link for a period of time:

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

# Two key network-core functions

## Forwarding:

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



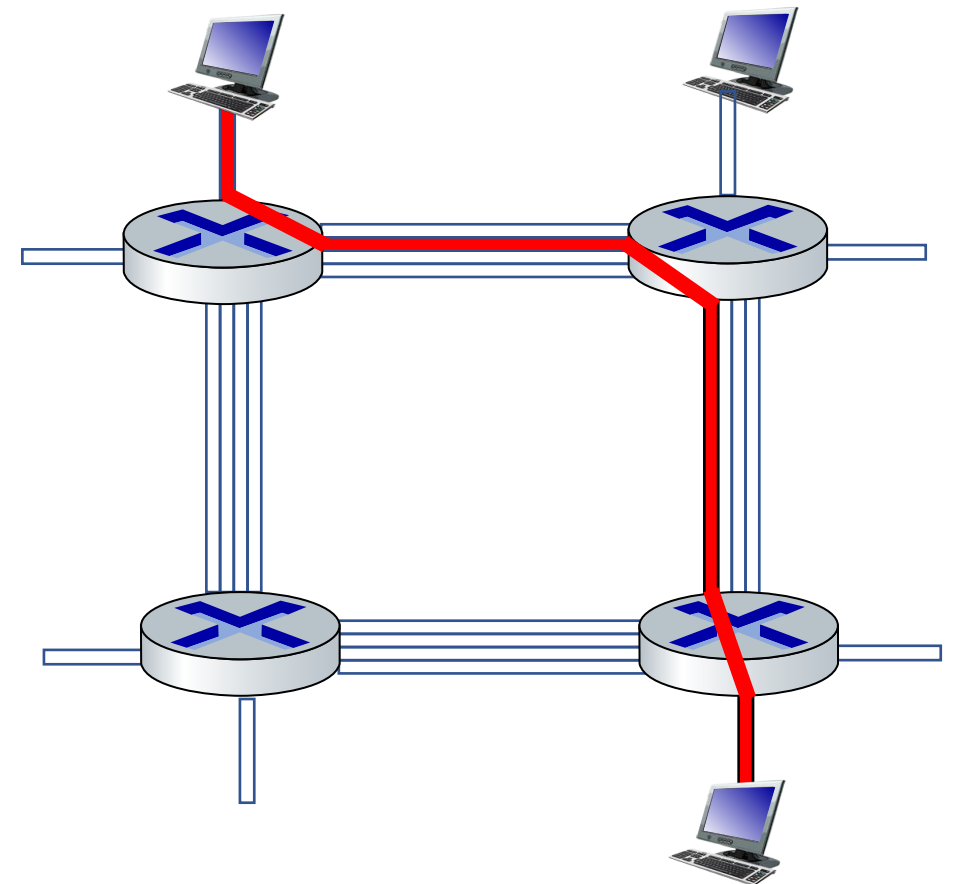
## Routing:

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

# Alternative to packet switching: circuit switching

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

- in diagram, each link has four circuits.
  - call gets 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

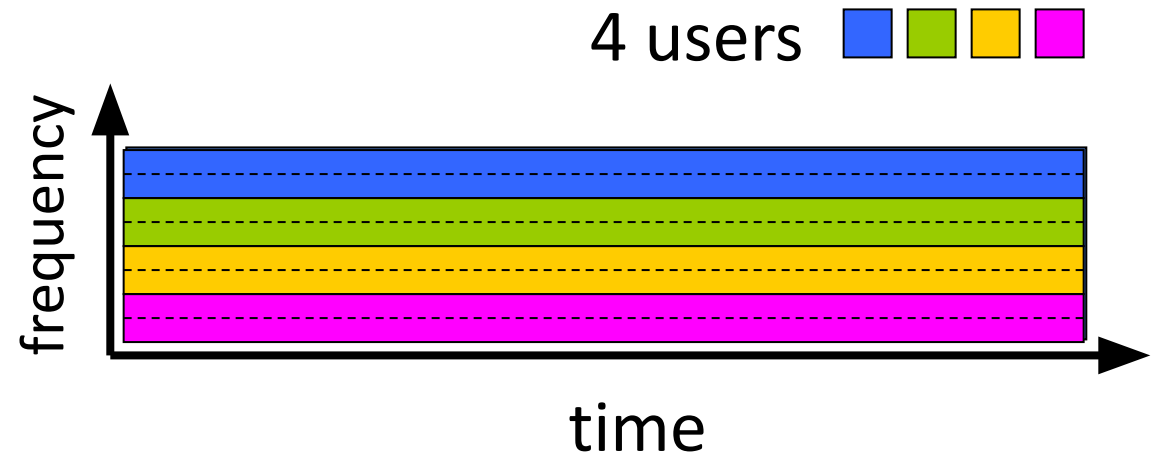




# Circuit switching: FDM and TDM

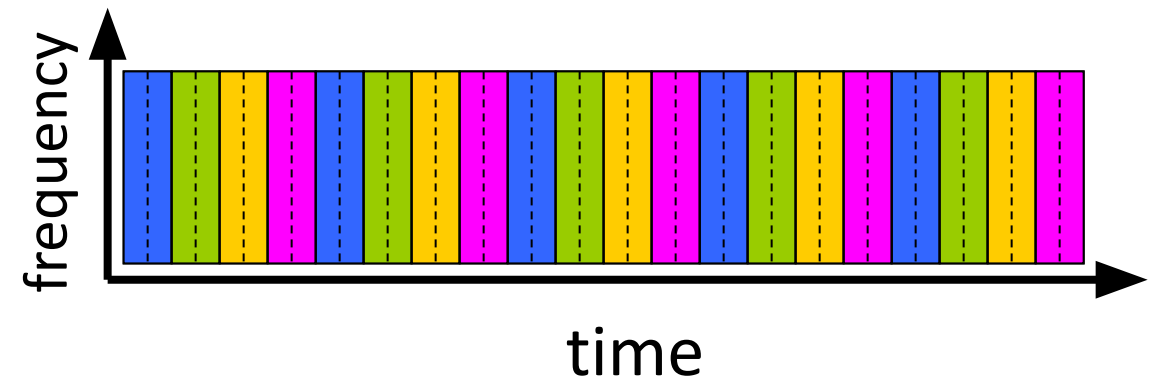
## Frequency Division Multiplexing (FDM)

- 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)

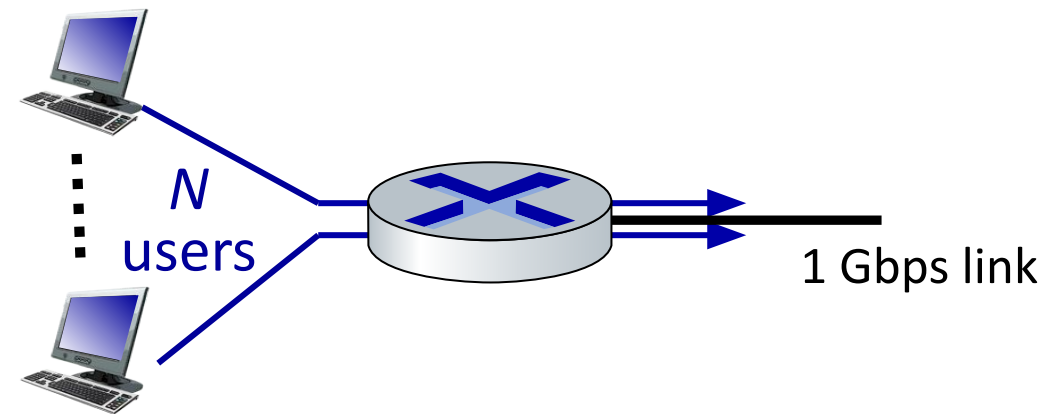


# Packet switching versus circuit switching

*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 ?

# Packet switching versus circuit switching

Is packet switching a “slam dunk winner”?

- great for “bursty” data – sometimes has data to send, but at other times not
  - resource sharing
  - simpler, no call setup
- **excessive congestion possible:** packet delay and loss due to buffer overflow
  - protocols needed for reliable data transfer, congestion control
- **Q: How to provide circuit-like behavior?**
  - bandwidth guarantees traditionally used for audio/video applications

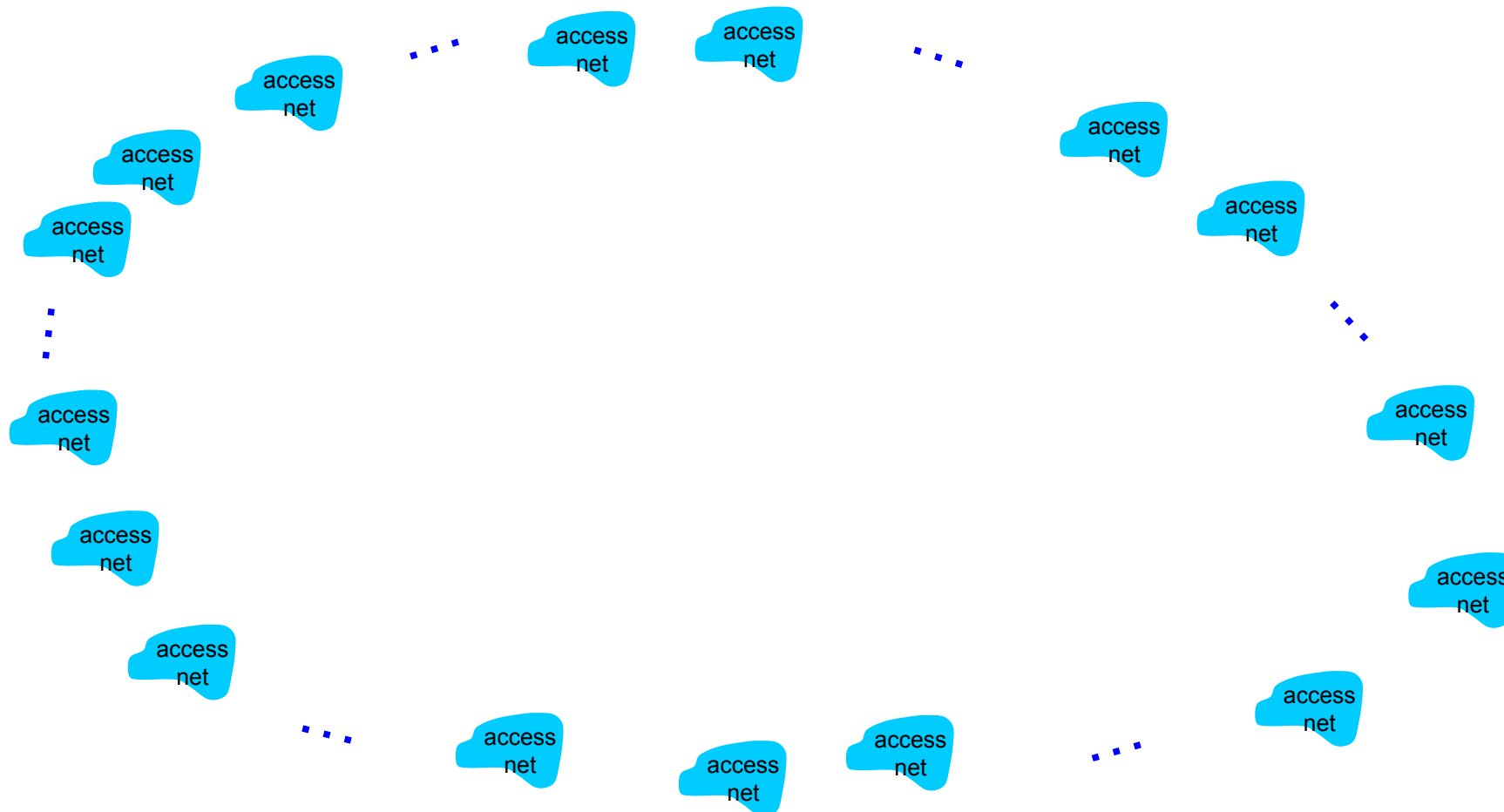
**Q:** human analogies of reserved resources (circuit switching) versus on-demand allocation (packet switching)?

# Internet structure: a “network of networks”

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

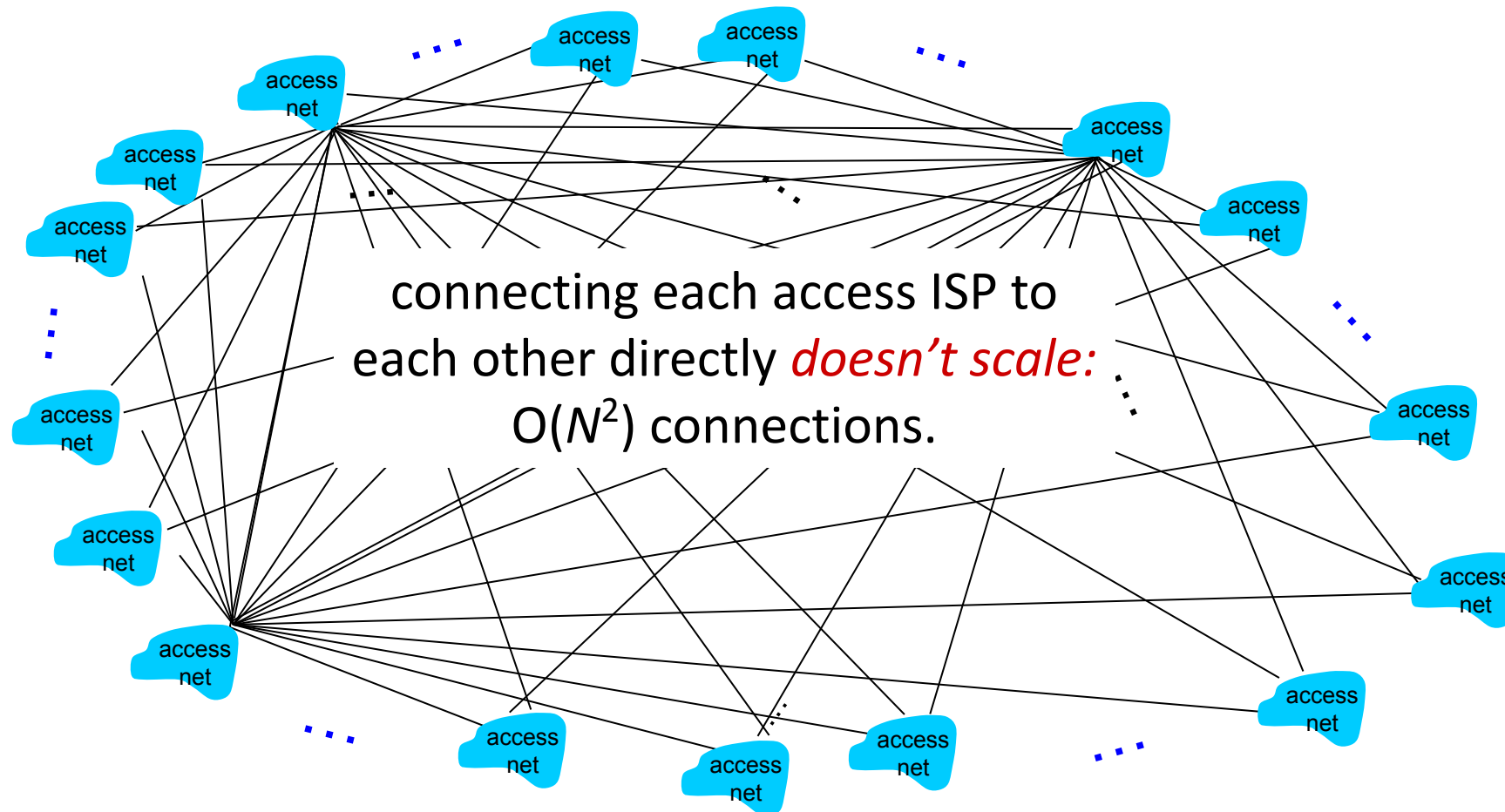
# Internet structure: a “network of networks”

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



# Internet structure: a “network of networks”

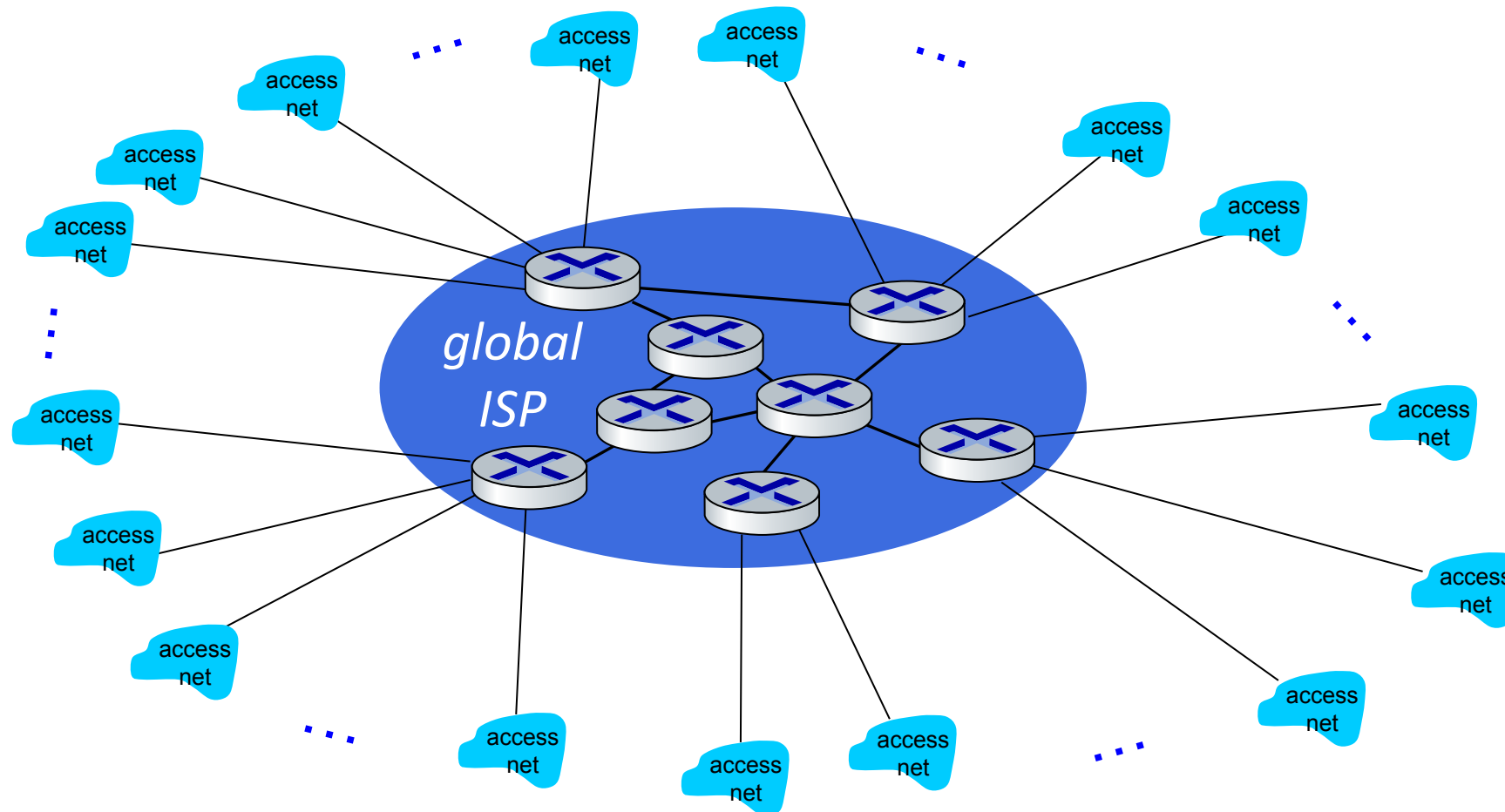
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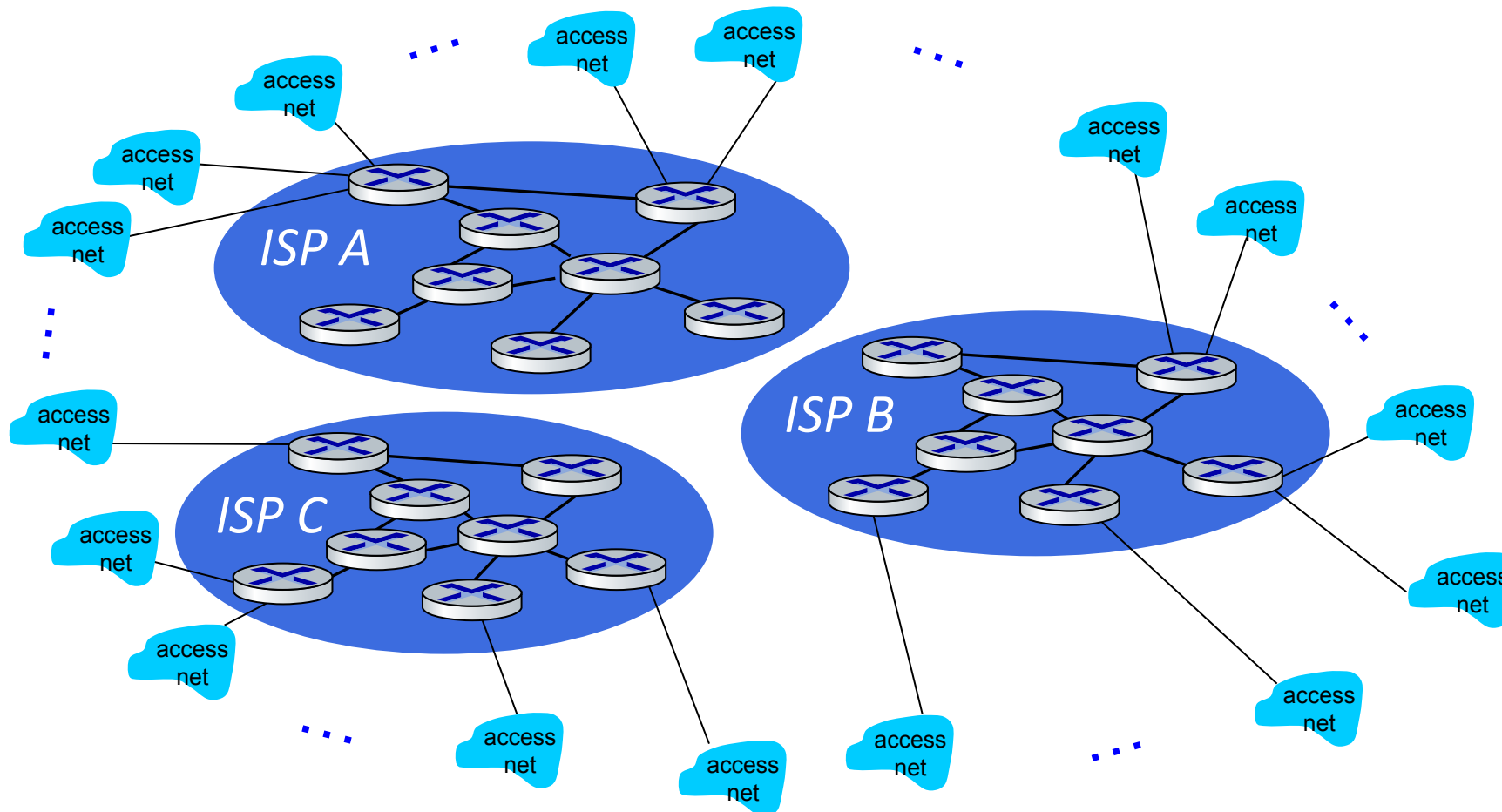
*Option: connect each access ISP to one global transit ISP?*

*Customer and provider ISPs have economic agreement.*



# Internet structure: a “network of networks”

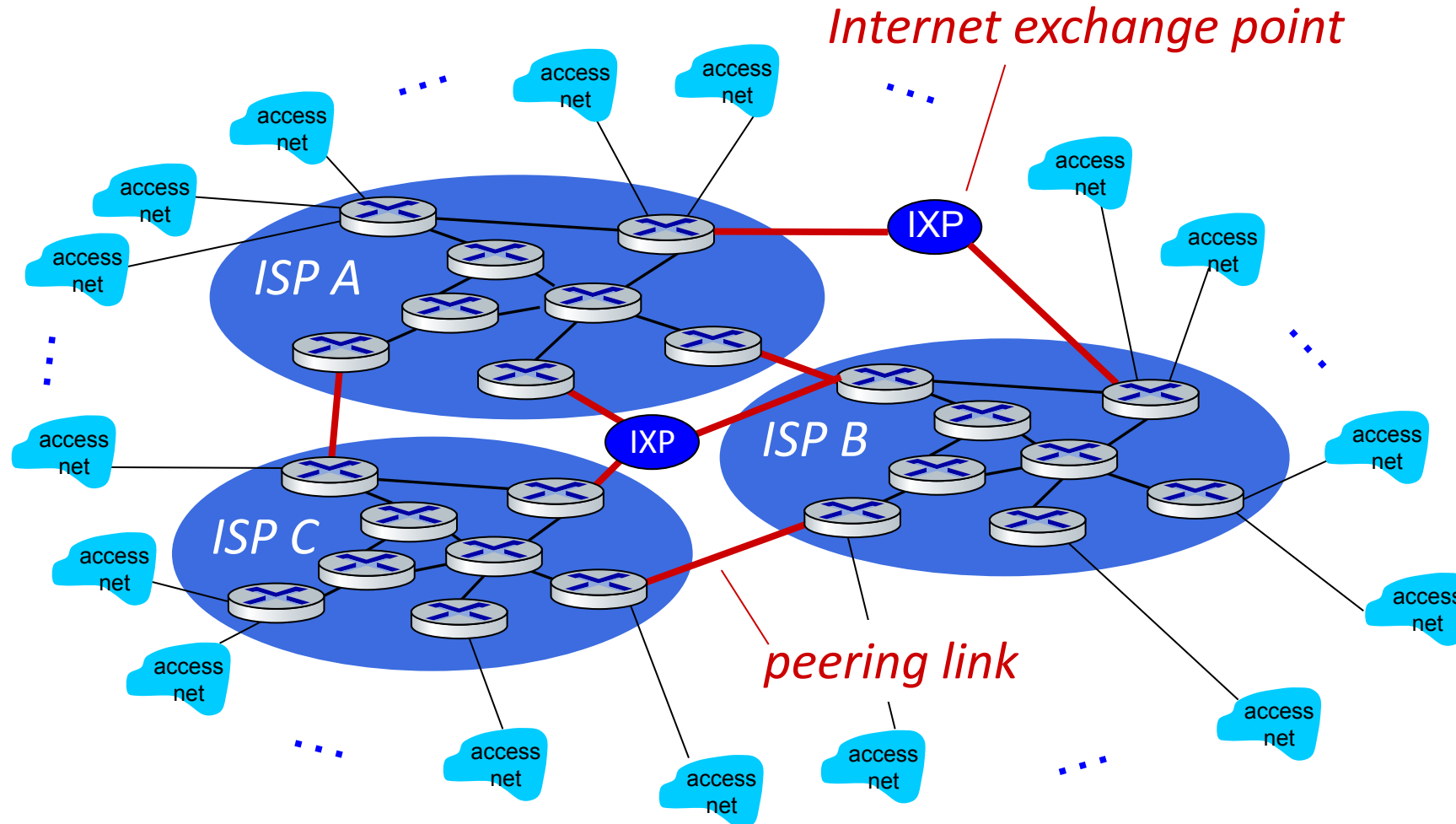
But if one global ISP is viable business, there will be competitors ....





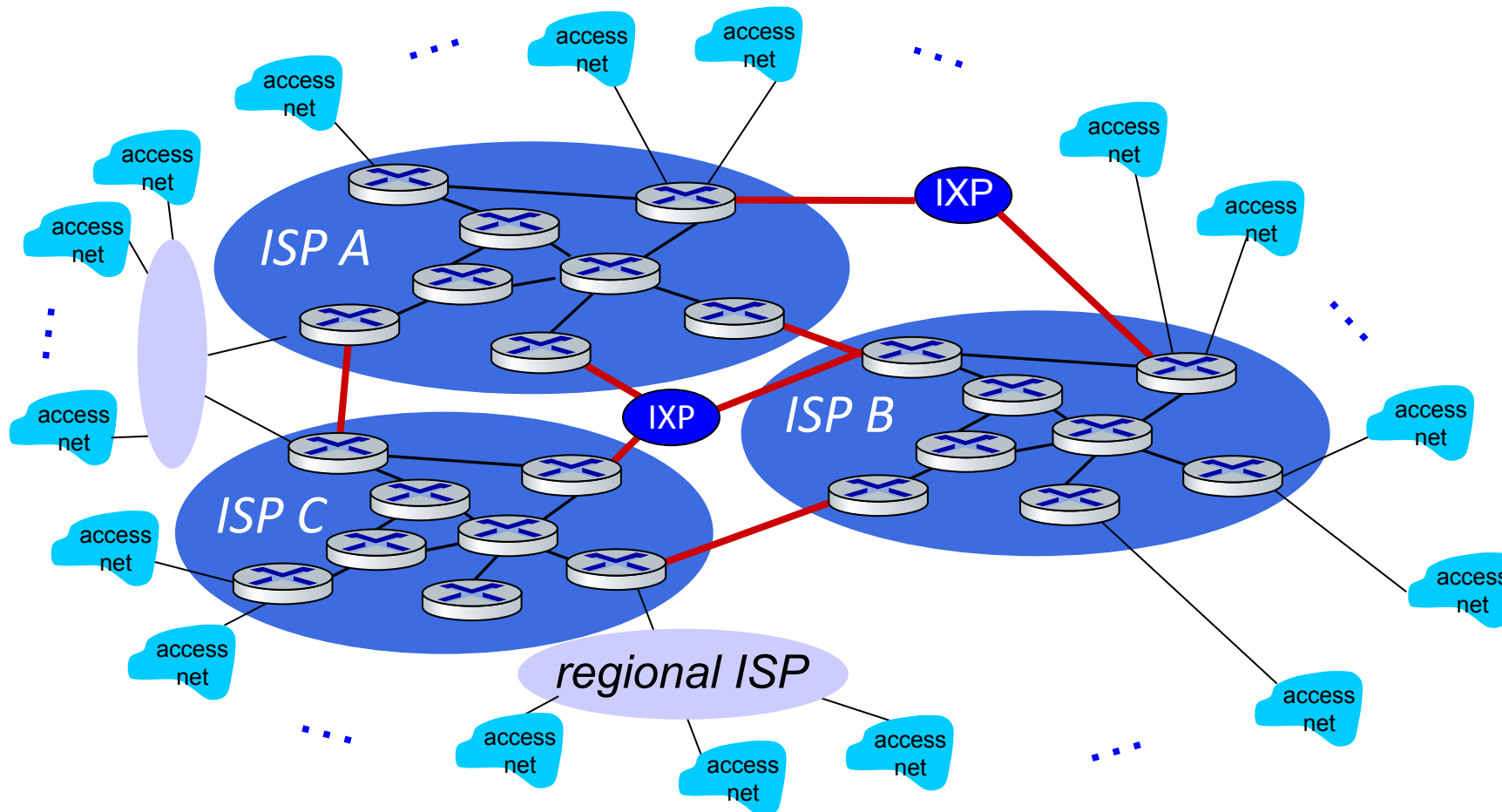
# Internet structure: a “network of networks”

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



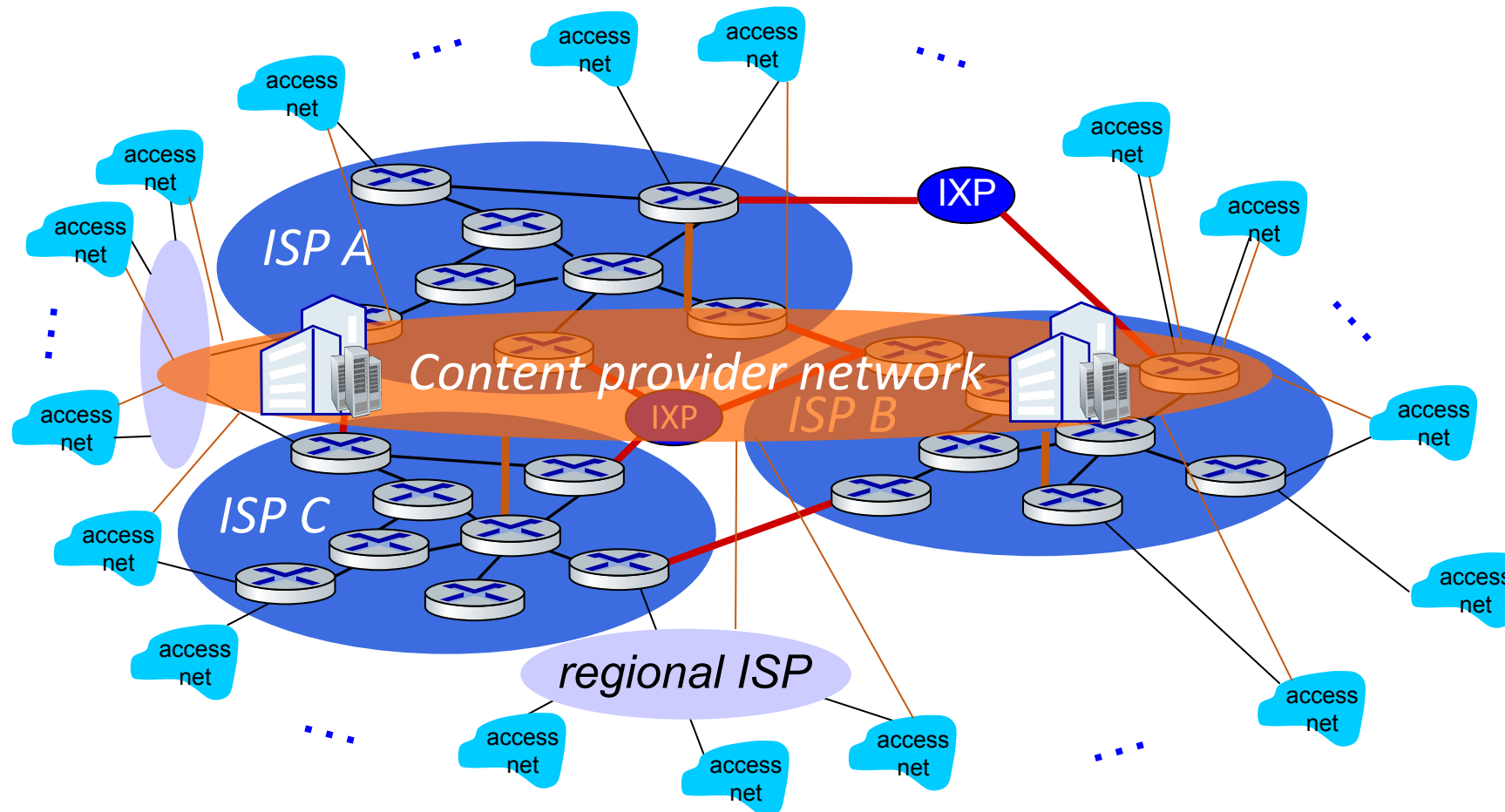
# Internet structure: a “network of networks”

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

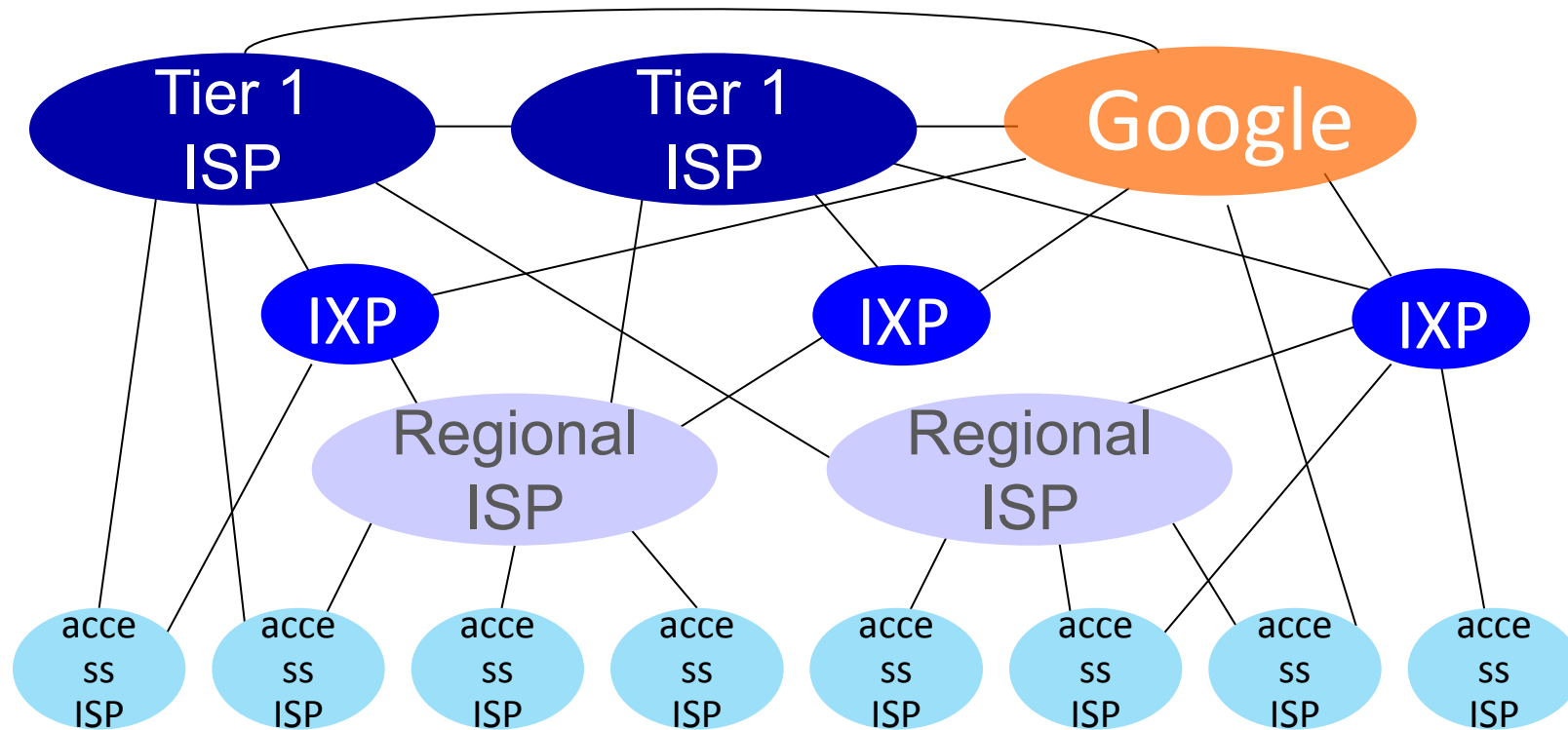


# Internet structure: a “network of networks”

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



# Internet structure: a “network of networks”



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

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

# Topic 1: roadmap

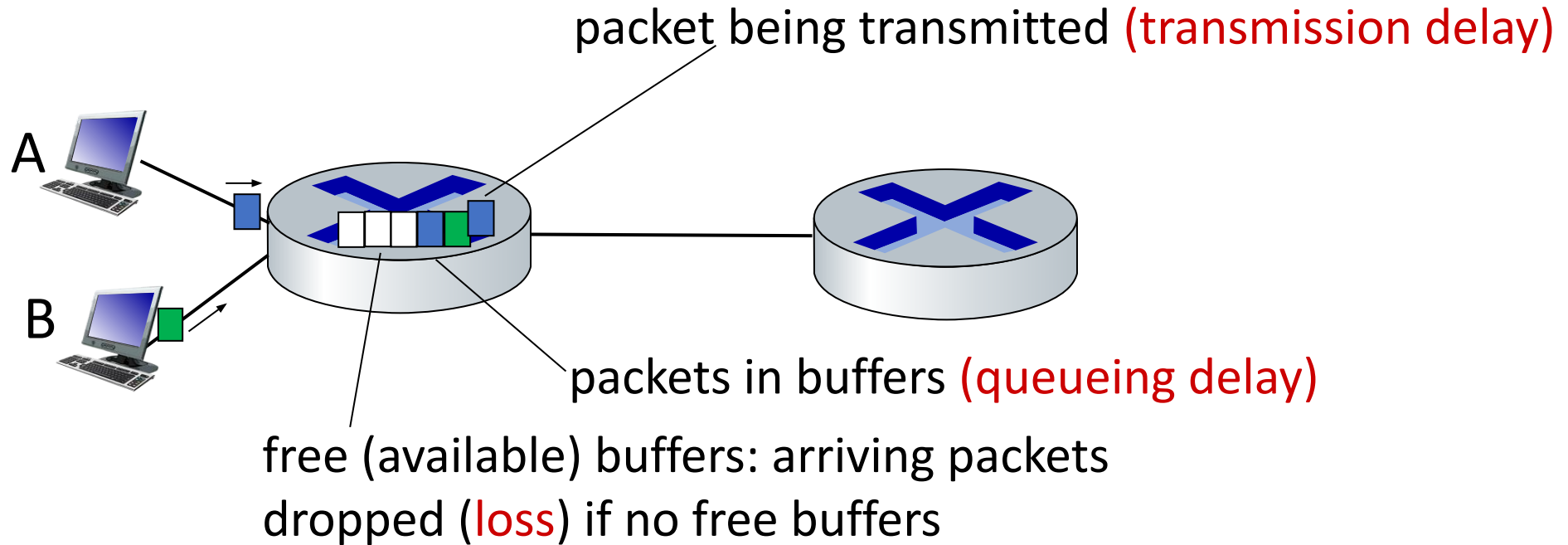
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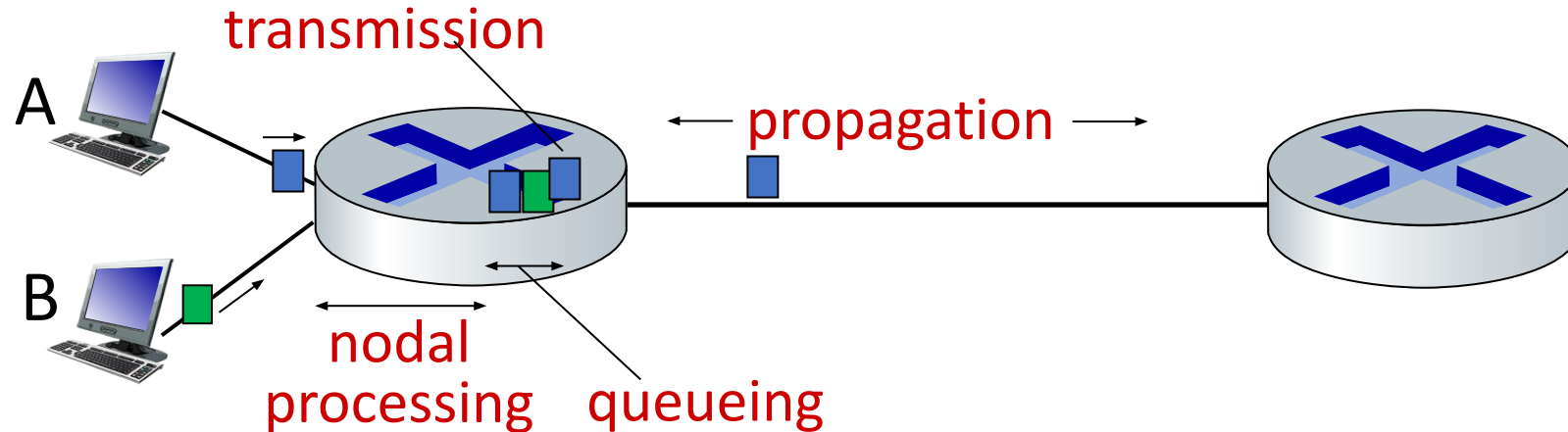
# How do packet loss and delay occur?

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



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

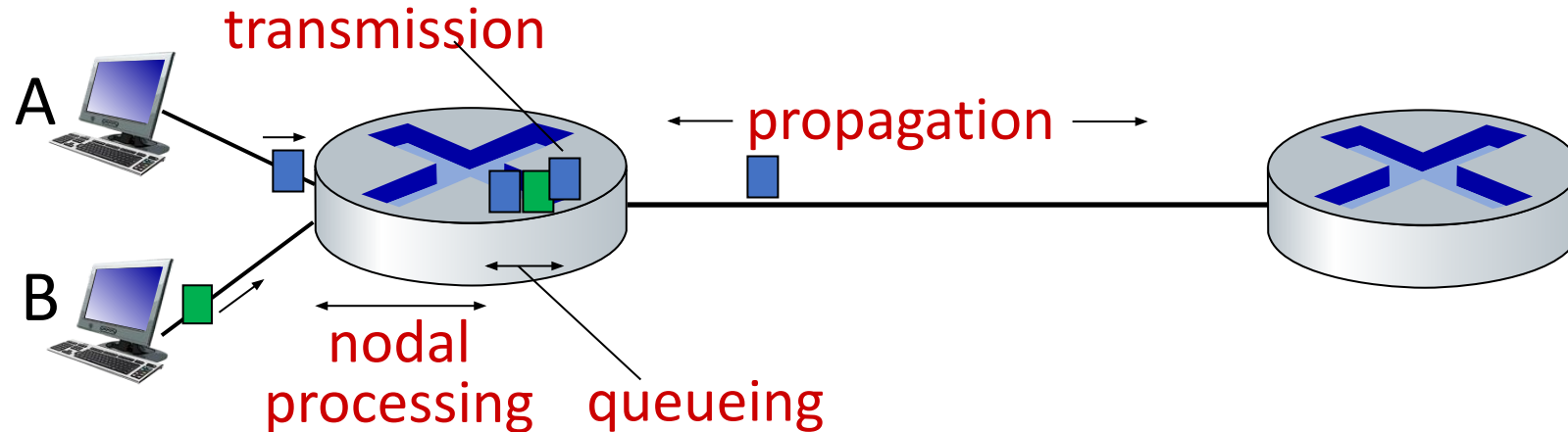
$d_{\text{proc}}$ : nodal processing

- 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:

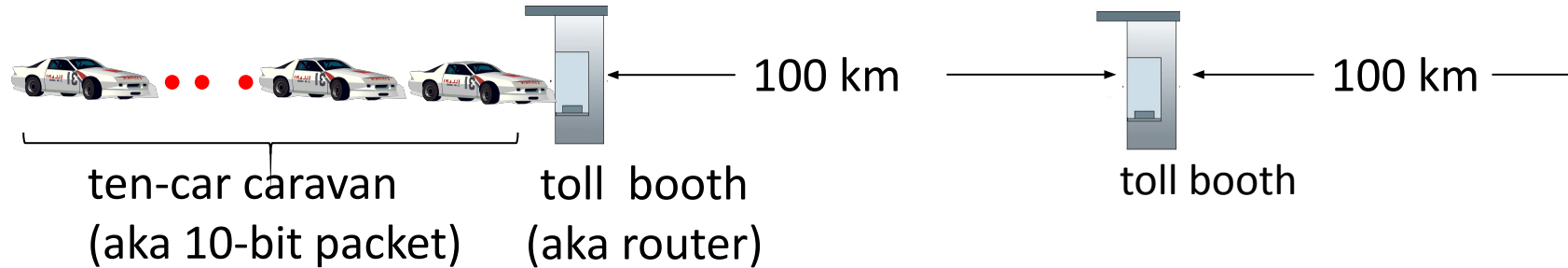
- $d$ : length of physical link
- $s$ : propagation speed ( $\sim 2 \times 10^8$  m/sec)

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

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

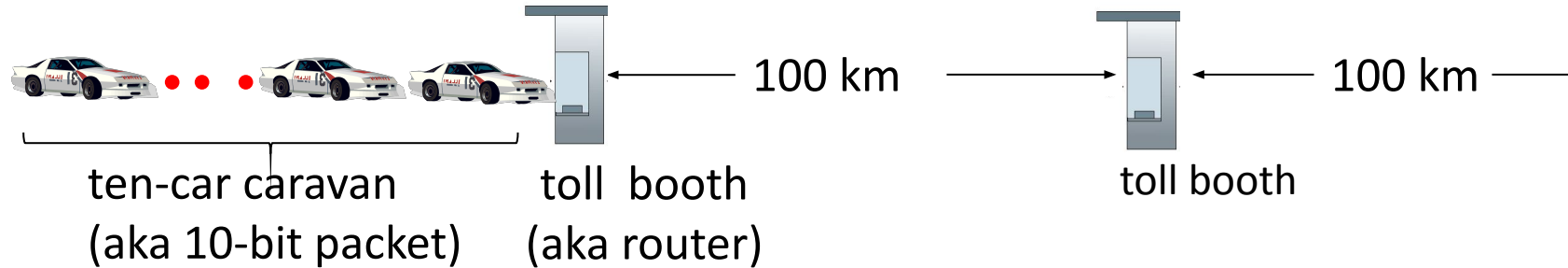


# Caravan analogy



- cars “propagate” at 100 km/hr
  - toll booth takes 12 sec to service car (bit transmission time)
  - car ~ bit; caravan ~ packet
  - **Q: How long until caravan is lined up before 2nd toll booth?**
- time to “push” entire caravan through toll booth onto highway =  $12 * 10 = 120$  sec
  - time for last car to propagate from 1st to 2nd toll both:  $100\text{km}/(100\text{km/hr}) = 1$  hr
  - **A: 62 minutes**

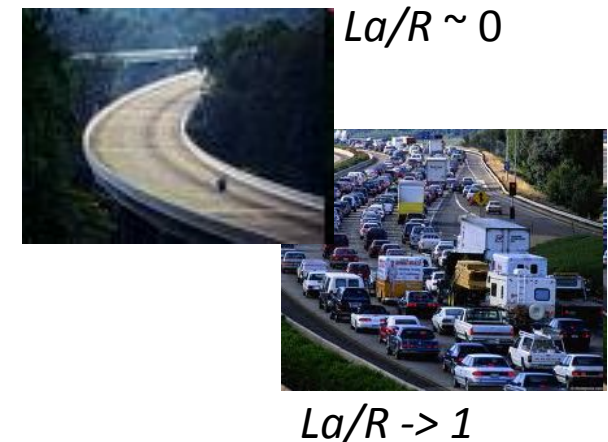
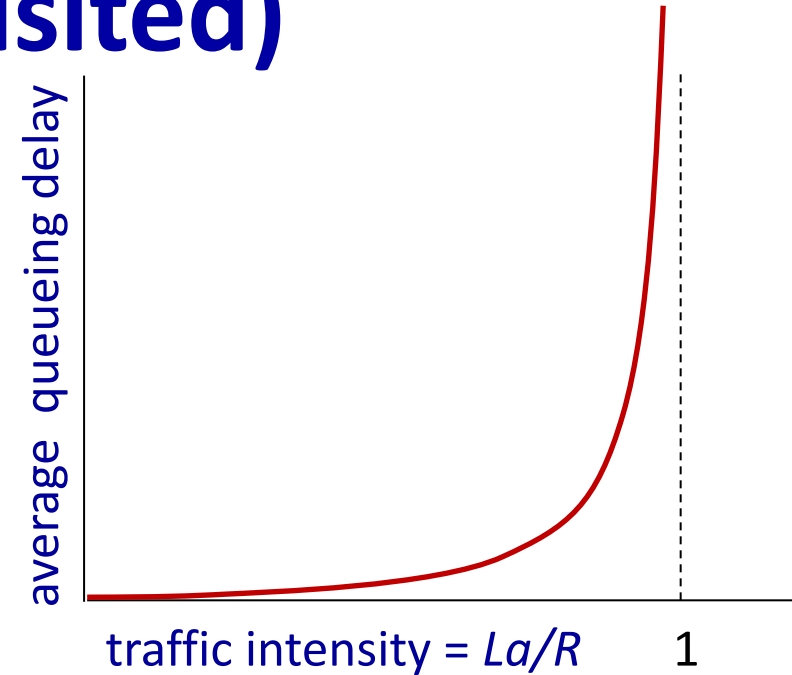
# Caravan analogy



- suppose cars now “propagate” at 1000 km/hr
- and suppose toll booth now takes one min to service a car
- **Q: Will cars arrive to 2nd booth before all cars serviced at first booth?**  
**A: Yes!** after 7 min, first car arrives at second booth; three cars still at first booth

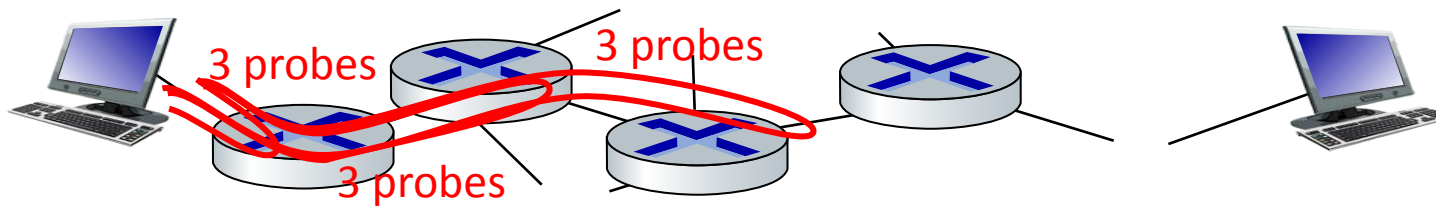
# Packet queueing delay (revisited)

- $R$ : 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

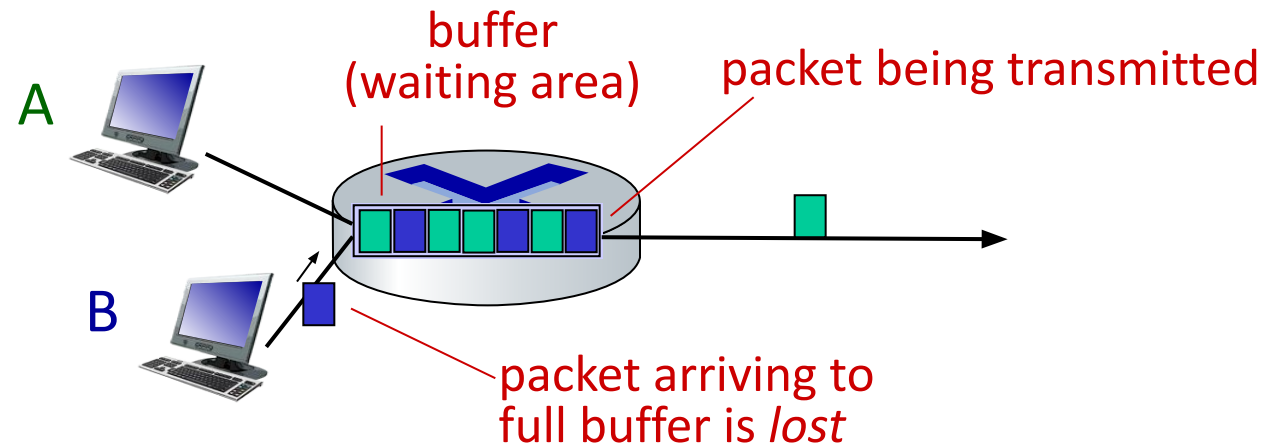
3 delay measurements from  
gaia.cs.umass.edu to cs-gw.cs.umass.edu

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 delay measurements  
3 cht-vbns.gw.umass.edu (128.119.3.130) 6 ms 5 ms 5 ms to border1-rt-fa5-1-0.gw.umass.edu  
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 } trans-oceanic link  
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 reater-gw.fr1.fr.geant.net (62.40.103.54) 112 ms 114 ms 112 ms ← looks like delays  
12 nio-n2.cssi.reater.fr (193.51.206.13) 111 ms 114 ms 116 ms decrease! Why?  
13 nice.cssi.reater.fr (195.220.98.102) 123 ms 125 ms 124 ms  
14 r3t2-nice.cssi.reater.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 \* \* \* ← \* means no response (probe lost, router not replying)  
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)

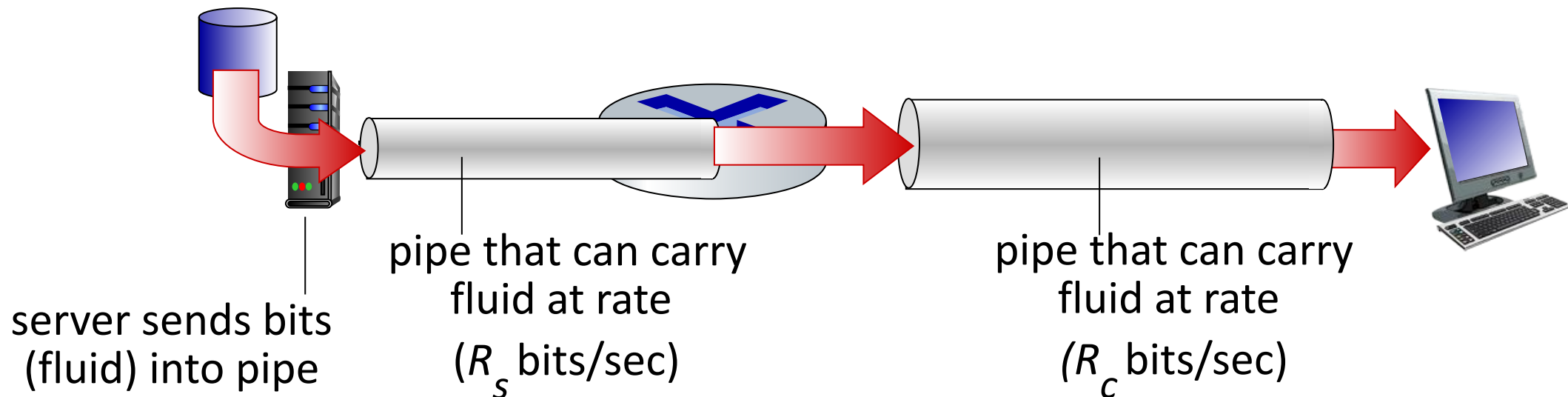
# Packet loss

- 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



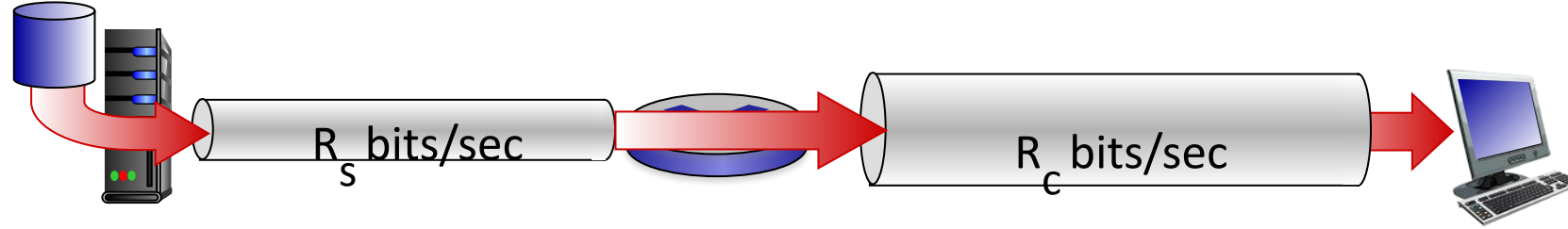
# Throughput

- *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

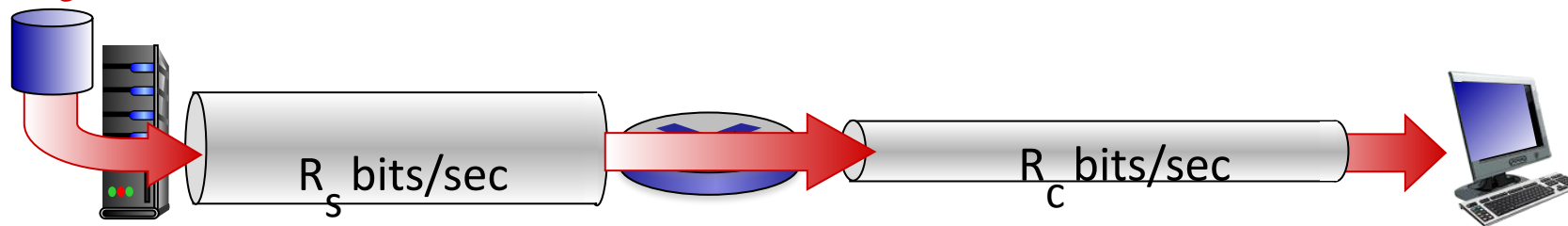


# Throughput

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



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

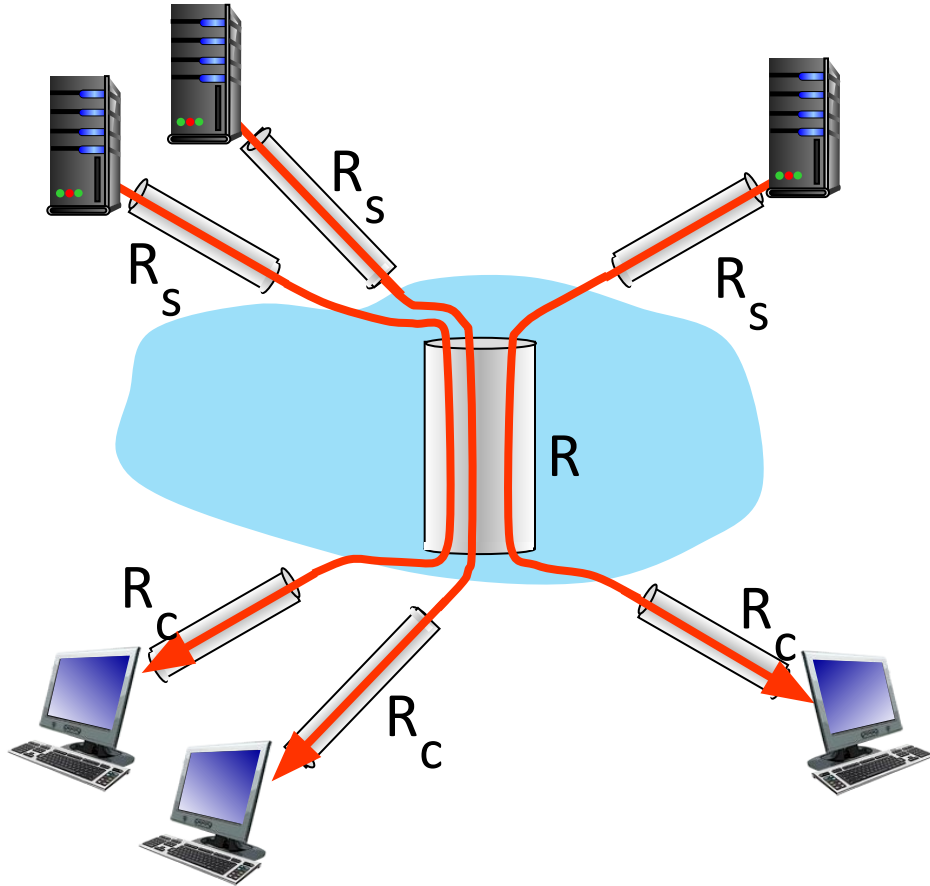


*bottleneck link*

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

# Topic 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!

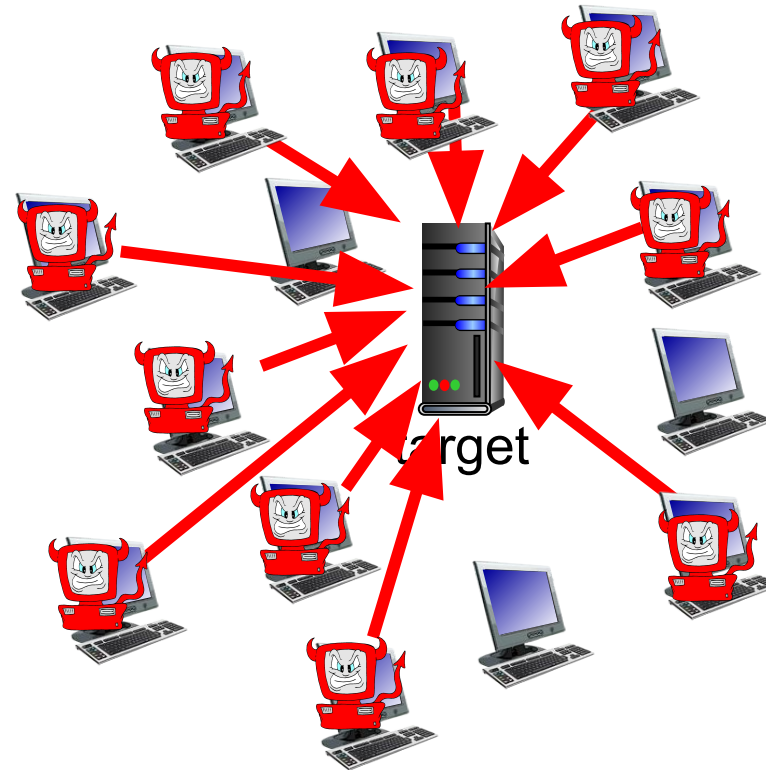
# Bad guys: malware

- 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

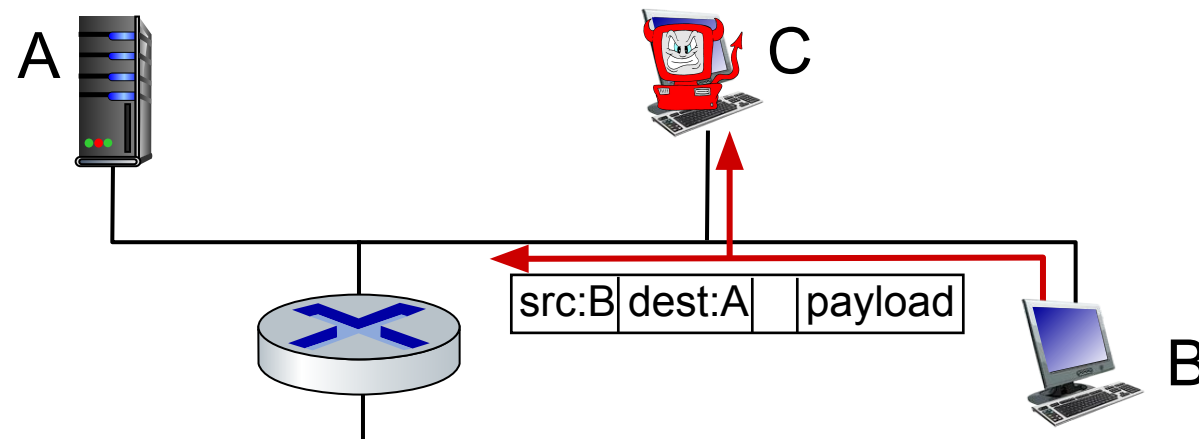
1. select target
2. break into hosts around the network (see botnet)
3. send packets to target from compromised hosts



# Bad guys: packet interception

## *packet “sniffing”:*

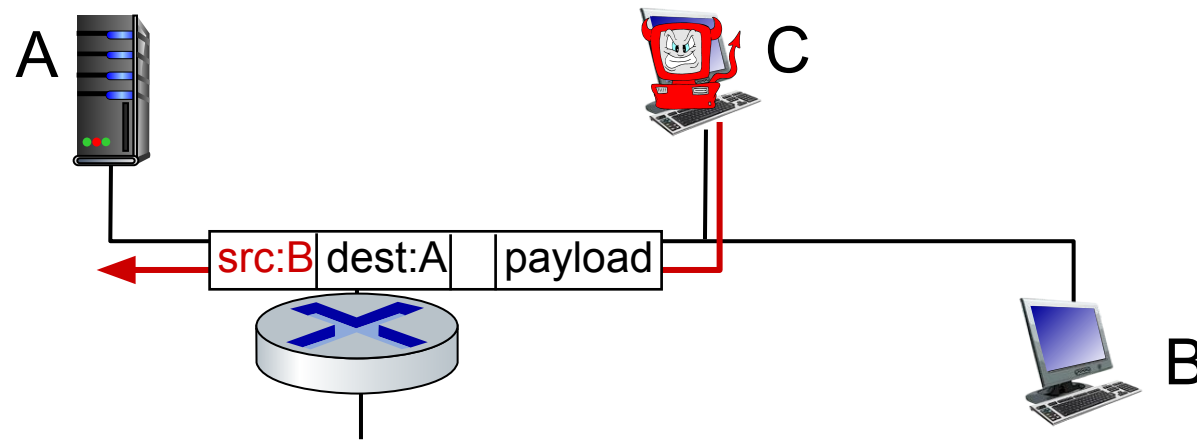
- broadcast media (shared Ethernet, wireless)
- promiscuous network interface reads/records all packets (e.g., including passwords!) passing by



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



# Topic 1: roadmap

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# Protocol “layers” and reference models

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

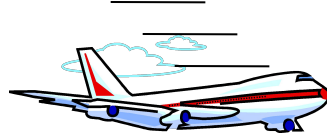
- hosts
- routers
- links of various media
- applications
- protocols
- hardware, software

*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

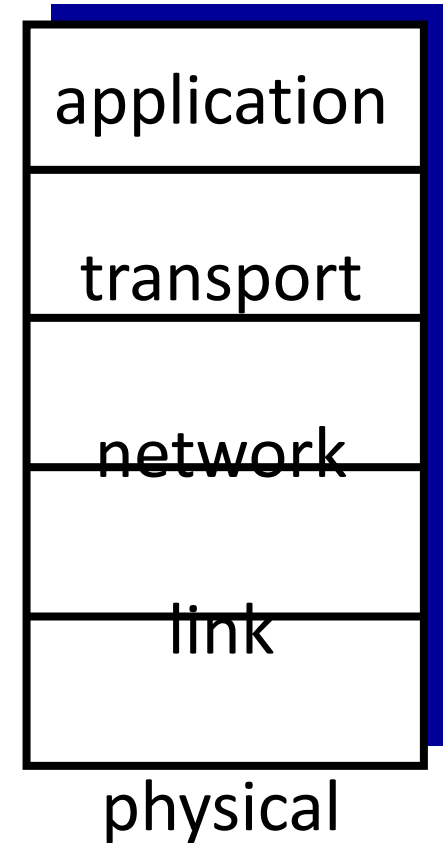
# Why layering?

dealing with complex systems:

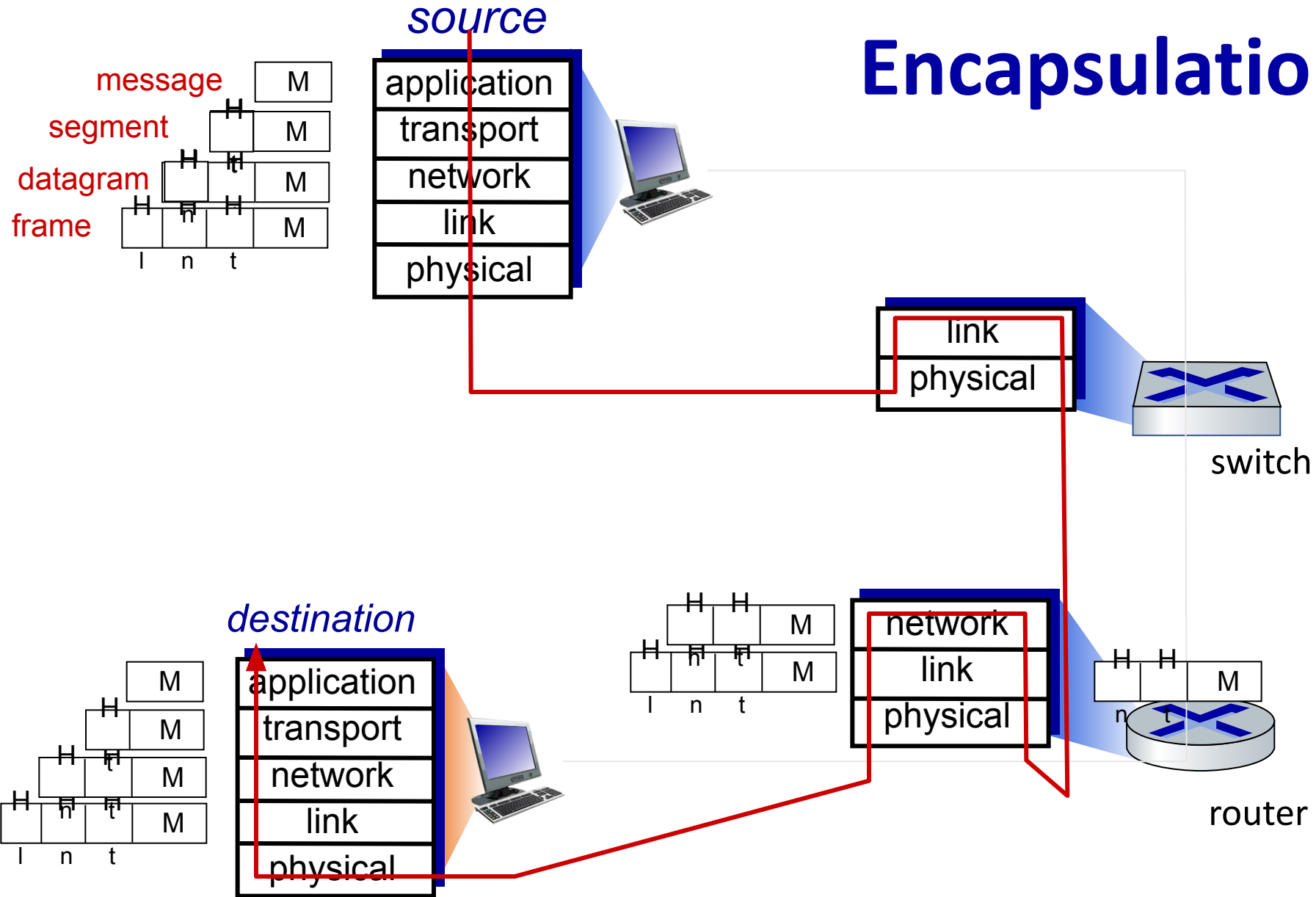
- explicit structure allows identification, relationship of complex system's pieces
  - layered *reference model* for discussion
- modularization eases maintenance, updating of system
  - change in layer's service *implementation*: transparent to rest of system
  - e.g., change in gate procedure doesn't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



# Topic 1: roadmap

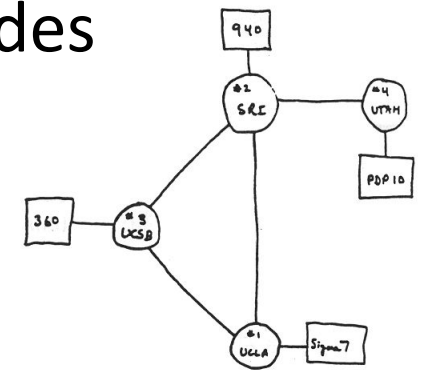
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- Security
- Protocol layers, service models
- **History**



# 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
- **late70'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:

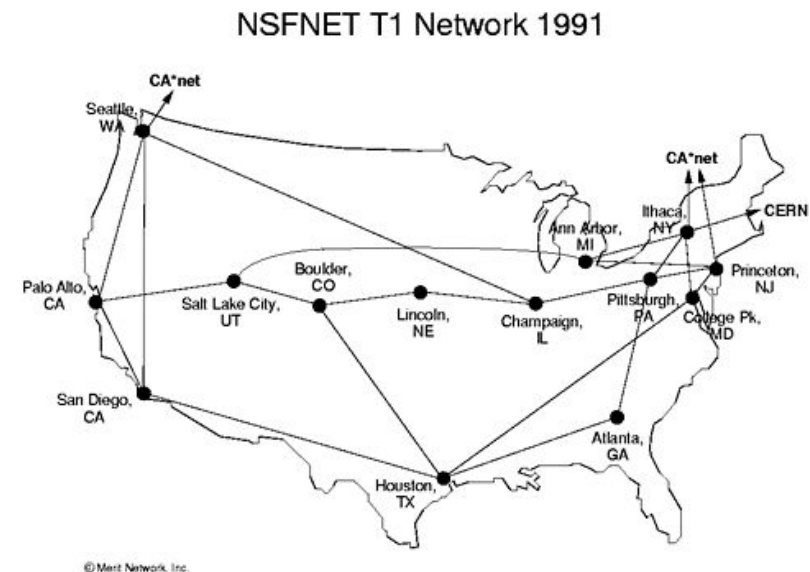
- minimalism, autonomy - no internal changes required to interconnect networks
- best-effort service model
- stateless routing
- decentralized control

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



# 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)

# Topic 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:*

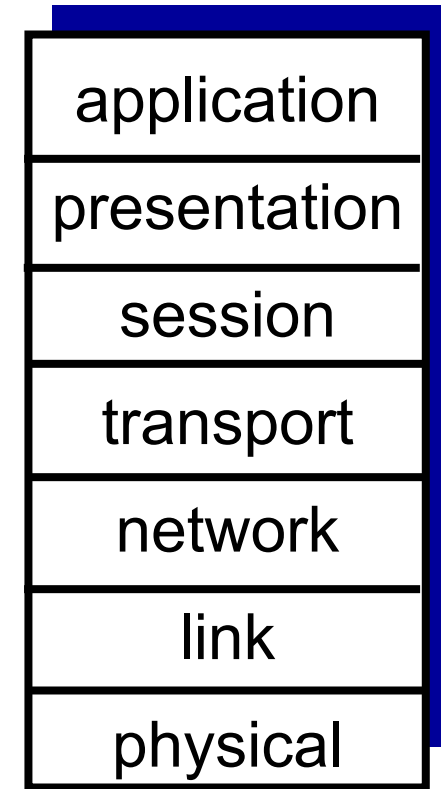
- context, overview, vocabulary, "feel" of networking
- more depth, detail, *and fun* to follow!

# **Additional Topic 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

