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Computer Networking and Security

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Syllabus

Web-Page

https://guilhermeir.github.io/teaching/M1Networks.html

Bibliography

- J. Kurose, K. Ross. *Computer Networking: A Top-Down Approach*. 8th Edition. Pearson, 2020.
- A. Tanenbaum, N. Feamster, D. Wetherall. *Computer Networks*. 6th Edition. Pearson, 2021.
- Guy Pujolle. *Les Réseaux*. 9th Edition. Eyrolles, 2018.

Topics

1. Introduction (Internet, OSI model)
2. Network Layer
3. Transport Layer
4. Application Layer
5. Wireless and Mobile Networks
6. Security
7. Cloud Networking

Evaluation

- 5 In-class Quizzes — 1 pt/quiz
- Seminars — 5 pts
- Final Exam — 10 pts

Final Grade = Q + S + F

About the seminars

Deliverables

- S1: Choice of Topic
- S2: Midterm Report
  - Problem understanding and questions
- S3: Presentations
  - Discussion

Topics

1. Internet-based Applications
2. Wireless Access Networks
3. Cellular (Mobile) Networks
4. Security
5. Cloud/Edge/Fog Computing
6. Software-Defined Networks
7. In-Network AI
8. Telecom Data Analytics

Syllabus
Schedule

Class	Date	Time	Topics (Tentative)	Content
1	16/02	17h15 – 20h30	Intro	[K] Ch. 1 [T] Ch. 1
2	09/03	17h15 – 20h30	S1 Network Layer	[K] Ch. 4 and 5 [T] Ch. 5
3	05/04	17h15 – 20h30	Q1 Network Layer	
4	19/04	15h30 – 18h45	Q2 Transport Layer	[K] Chapter 3 [T] Chapter 6
5	09/05	15h30 – 18h45	Q3 Transport Layer	
6	10/05	13h45 – 17h00	S2 Application Layer	[K] Chapter 2 [T] Chapter 7
7	24/05	13h45 – 17h00	Q4 Wireless and Mobile Nets	[K] Chapter 7 [T] Chapter 2
8	05/06	13h45 – 17h00	Q5 Security	[T] Chapter 8 [K] Chapter 8
9	07/06	13h45 – 17h00	Cloud	TBA
10	19/06	13h45 – 17h00	S3	-
	21/06	08h30 – 10h30	Final Exam	-

Computer Networks
Class 1: Introduction

Introduction

Class goal:

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

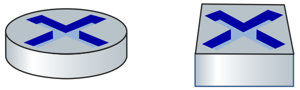
Overview/roadmap:

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

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)

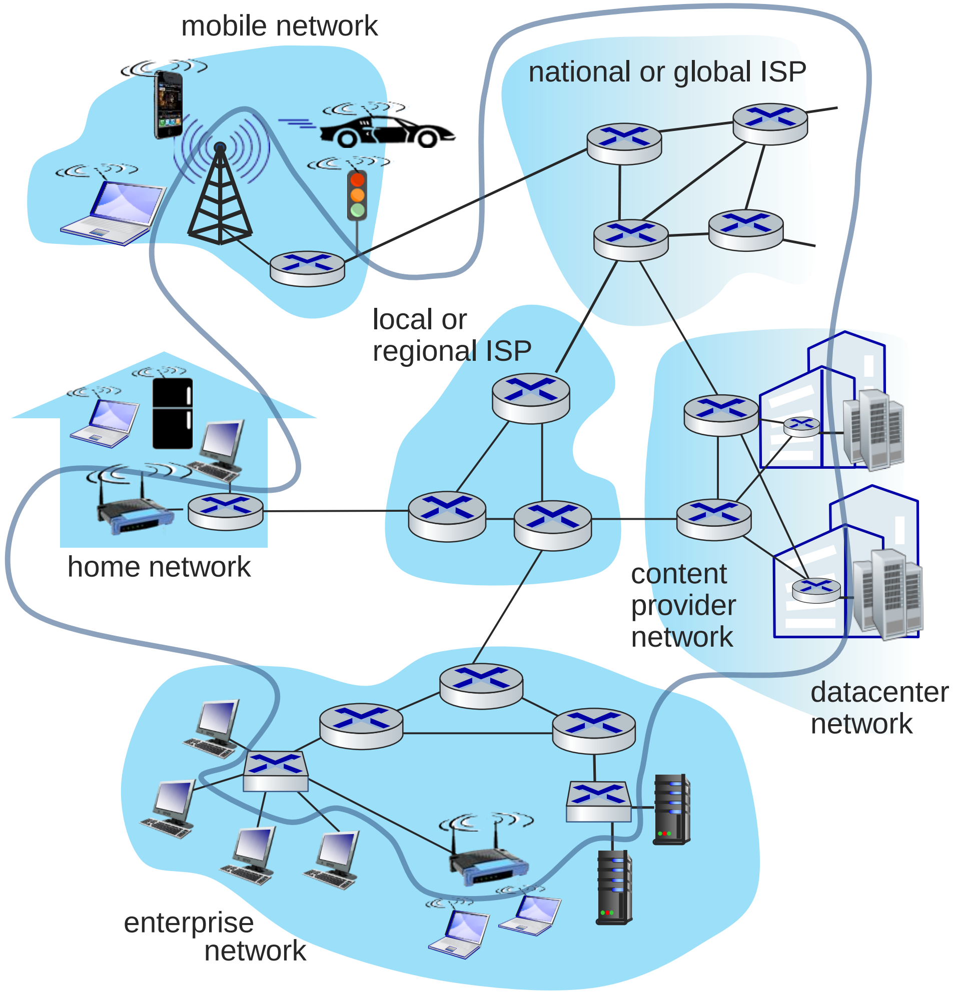
- *routers*, *switches*

Communication links:

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

Networks

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



Internet-connected devices

Amazon Echo

Internet refrigerator

IP picture frame

Pacemaker & Monitor

Tweet-a-watt: monitor energy use

bikes

Security Camera

Slingbox: remote control cable TV

Web-enabled toaster + weather forecaster

AR devices

cars

scooters

Internet phones

Gaming devices

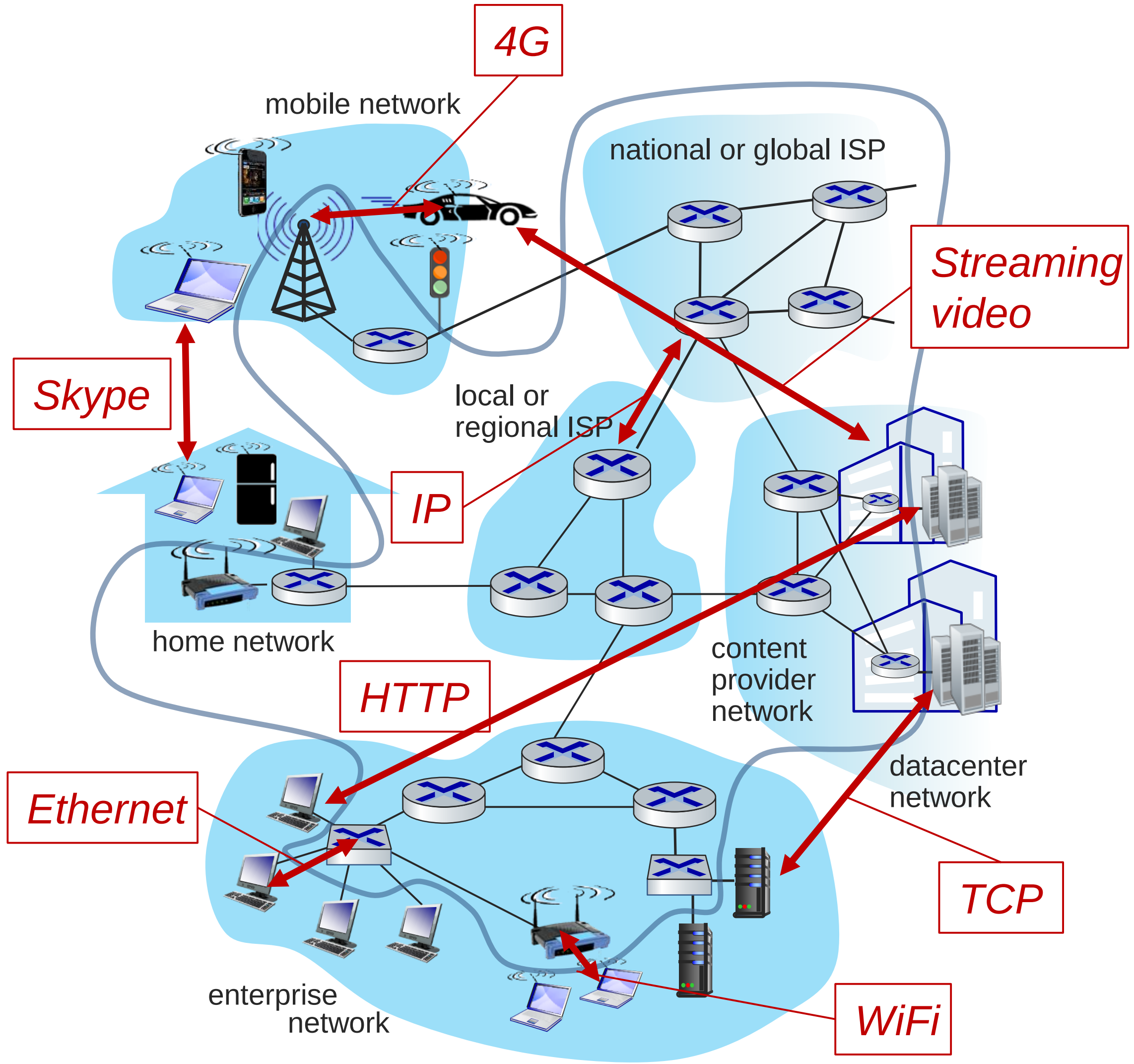
sensorized, bed mattress

Fitbit

Others?

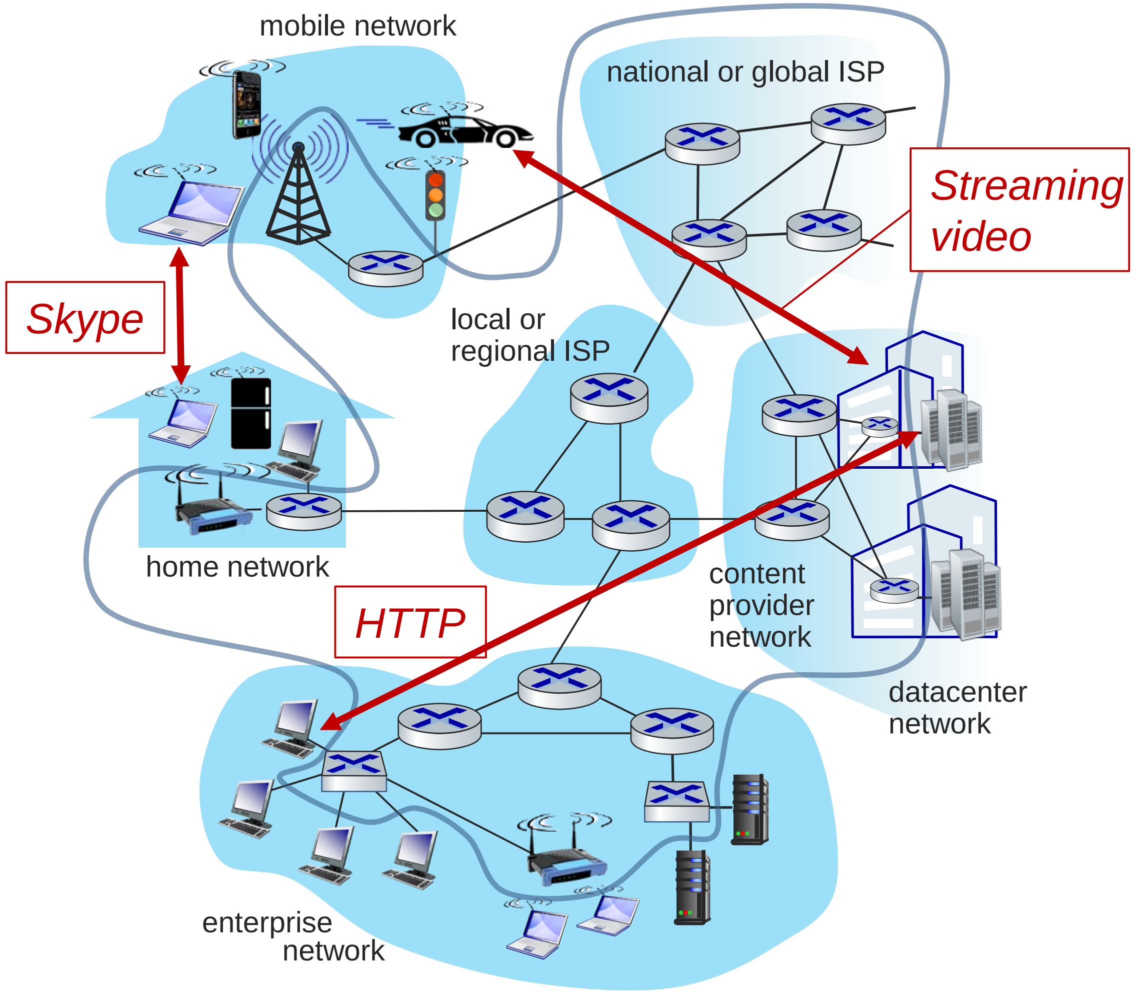
The Internet: a "nuts and bolts" view

- *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 “services” view

- *Infrastructure* that provides services to applications:
  - Web, streaming video, multimedia teleconferencing, email, games, e-commerce, social media, inter-connected appliances, …
- provides *programming interface* to distributed applications:
  - “hooks” allowing sending/receiving apps to “connect” to, use Internet transport service
  - provides service options, analogous to postal service



What’s a protocol?

Human protocols:

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

Network protocols:

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

Rules for:

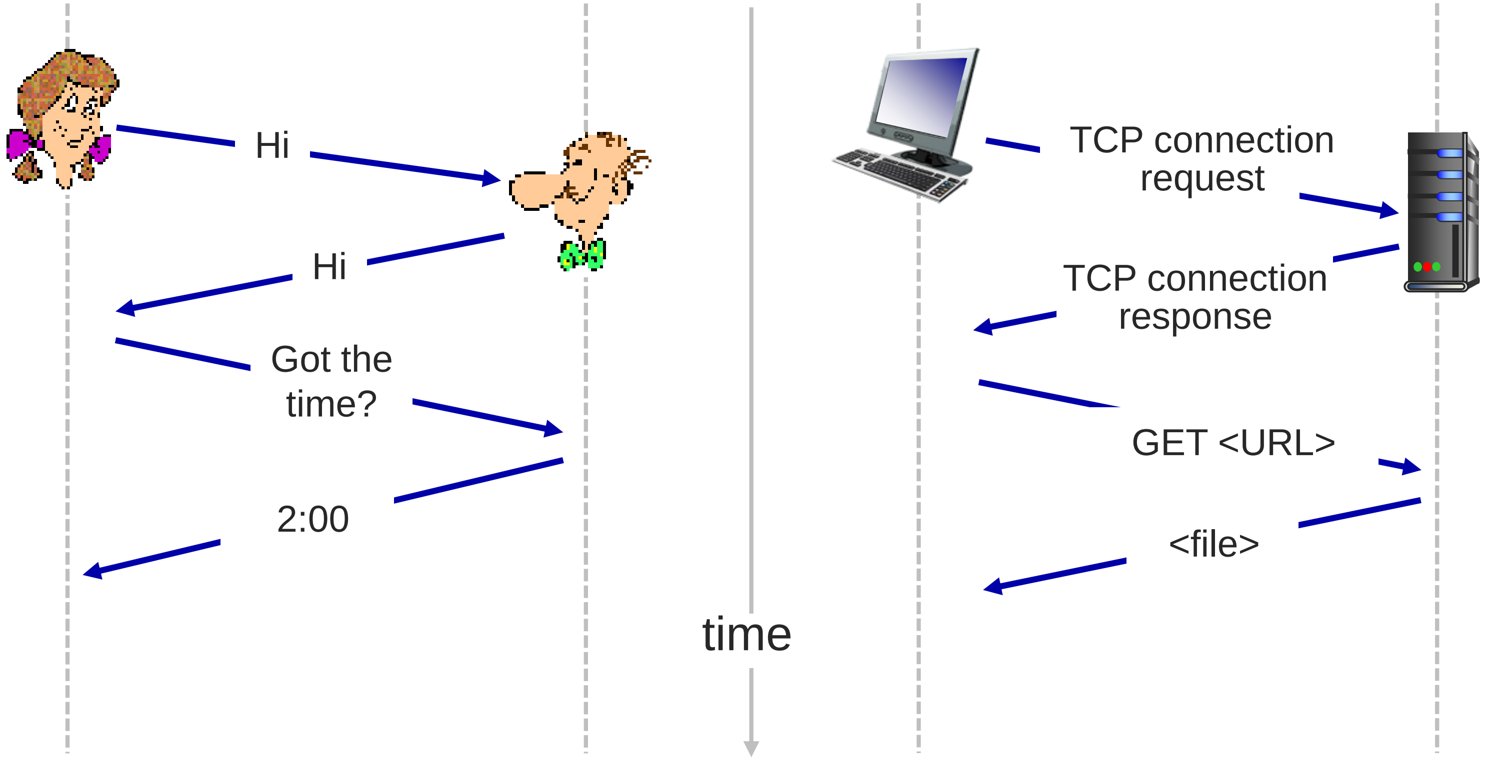
… specific messages sent

… specific actions taken when message received, or other events

Protocols define the format, order of messages sent and received among network entities, and actions taken on message transmission, receipt

What's a protocol?

A human protocol and a computer network protocol:



Q: other human protocols?

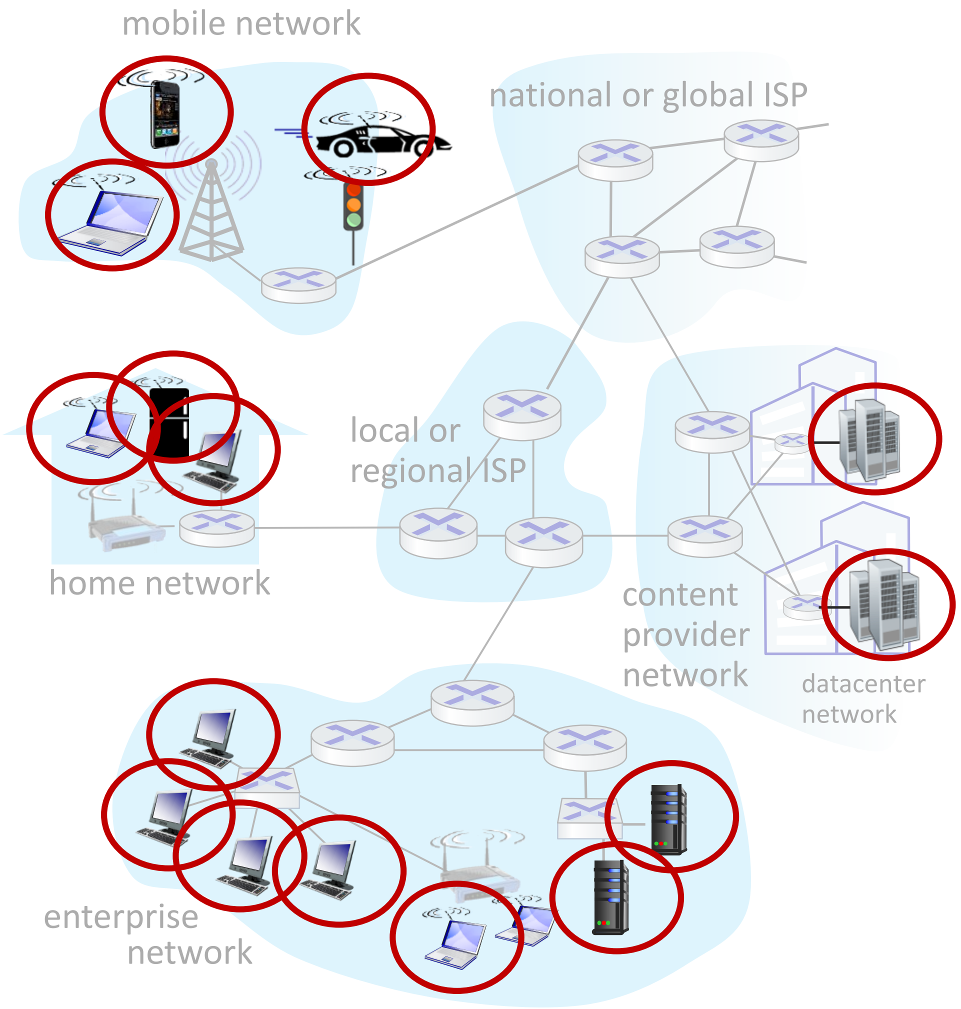
Roadmap

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

A closer look at Internet structure

Network edge:

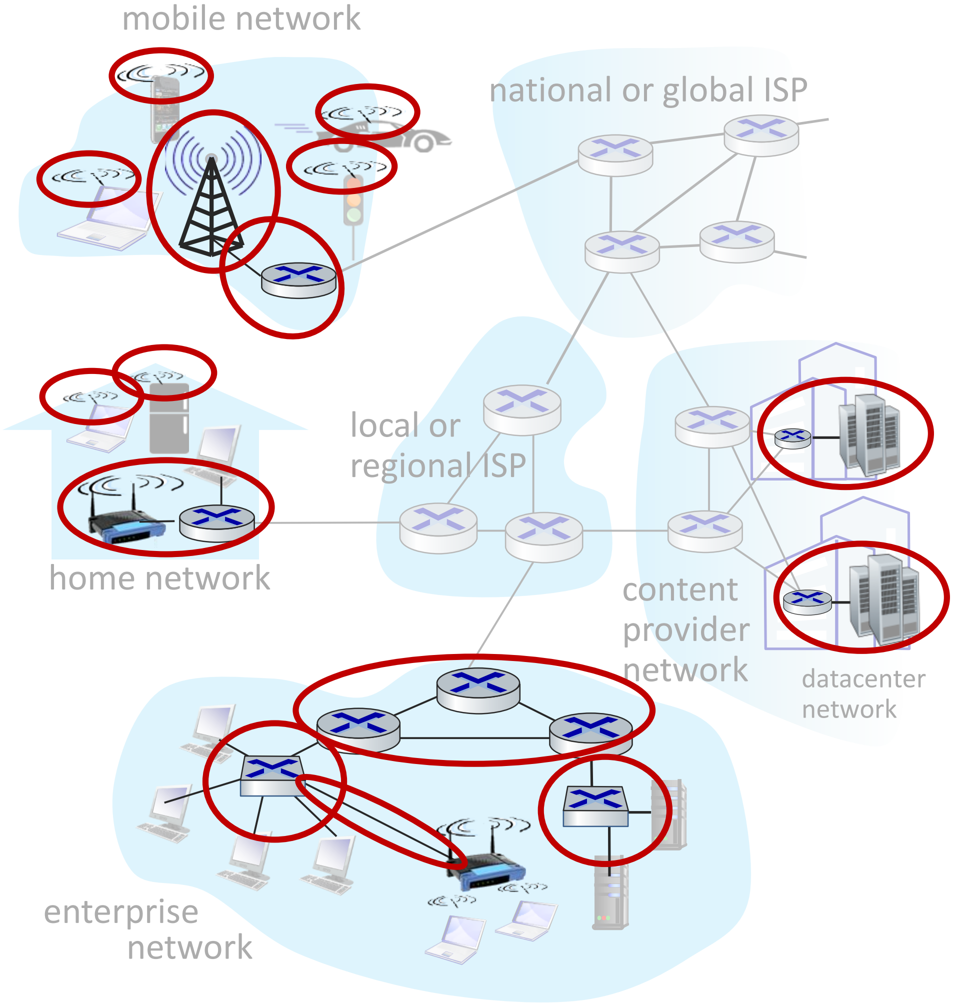
- hosts: clients and servers
- servers often in data centers



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

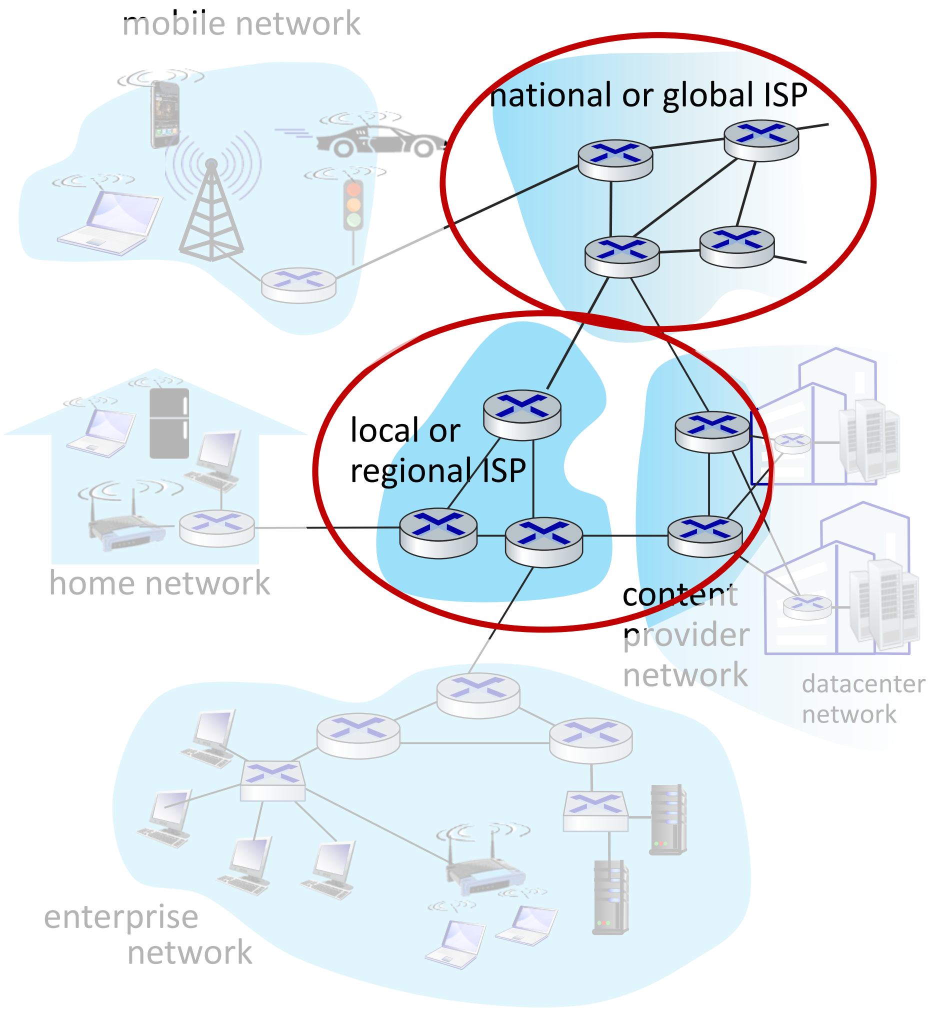


A closer look at Internet structure

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

Access networks, physical media:
- wired, wireless communication links

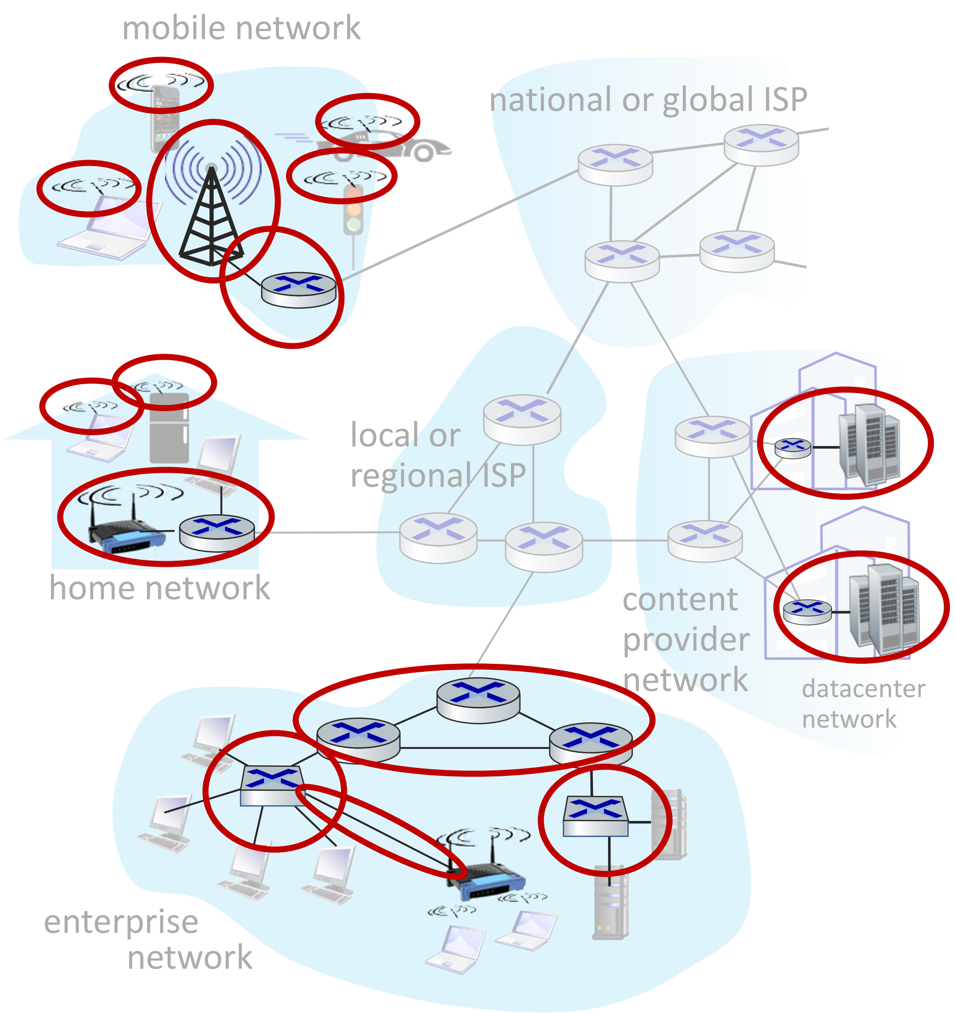
Network core:
- interconnected routers
- network of networks



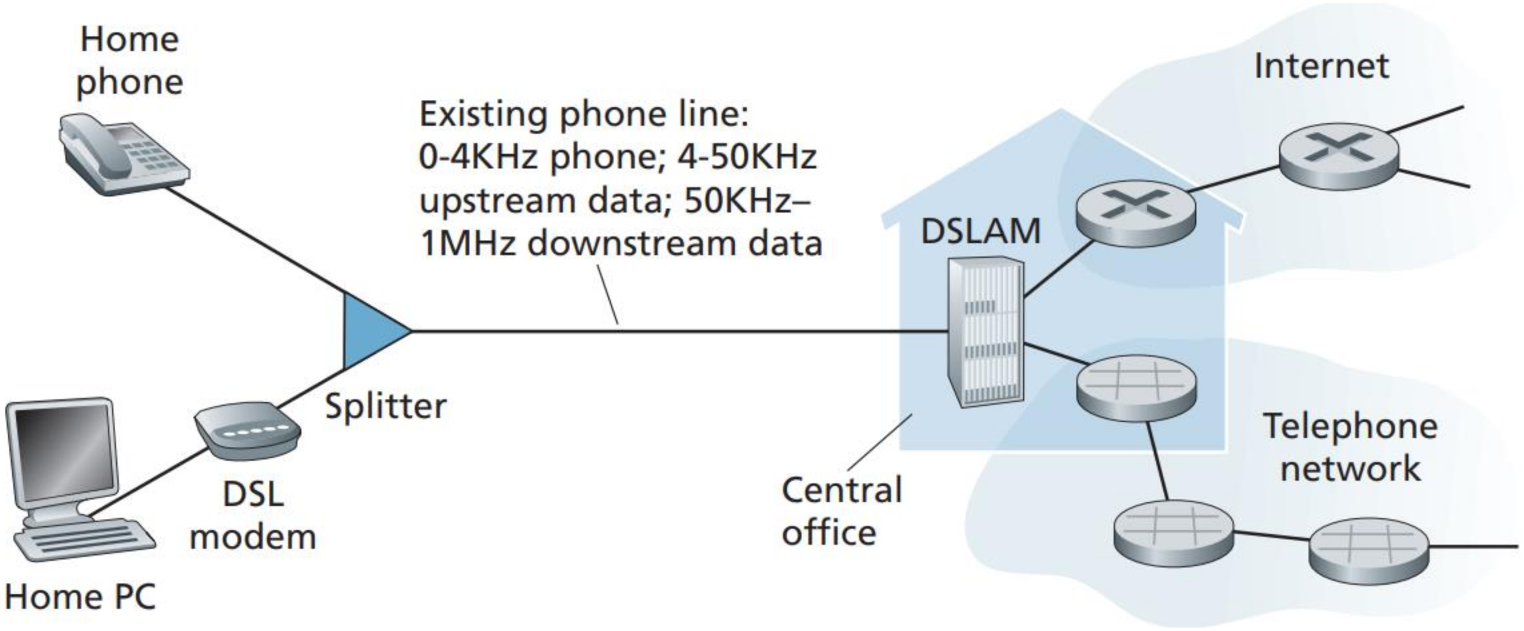
Access Networks and Physical Media

Q: How to connect end systems to edge router?

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

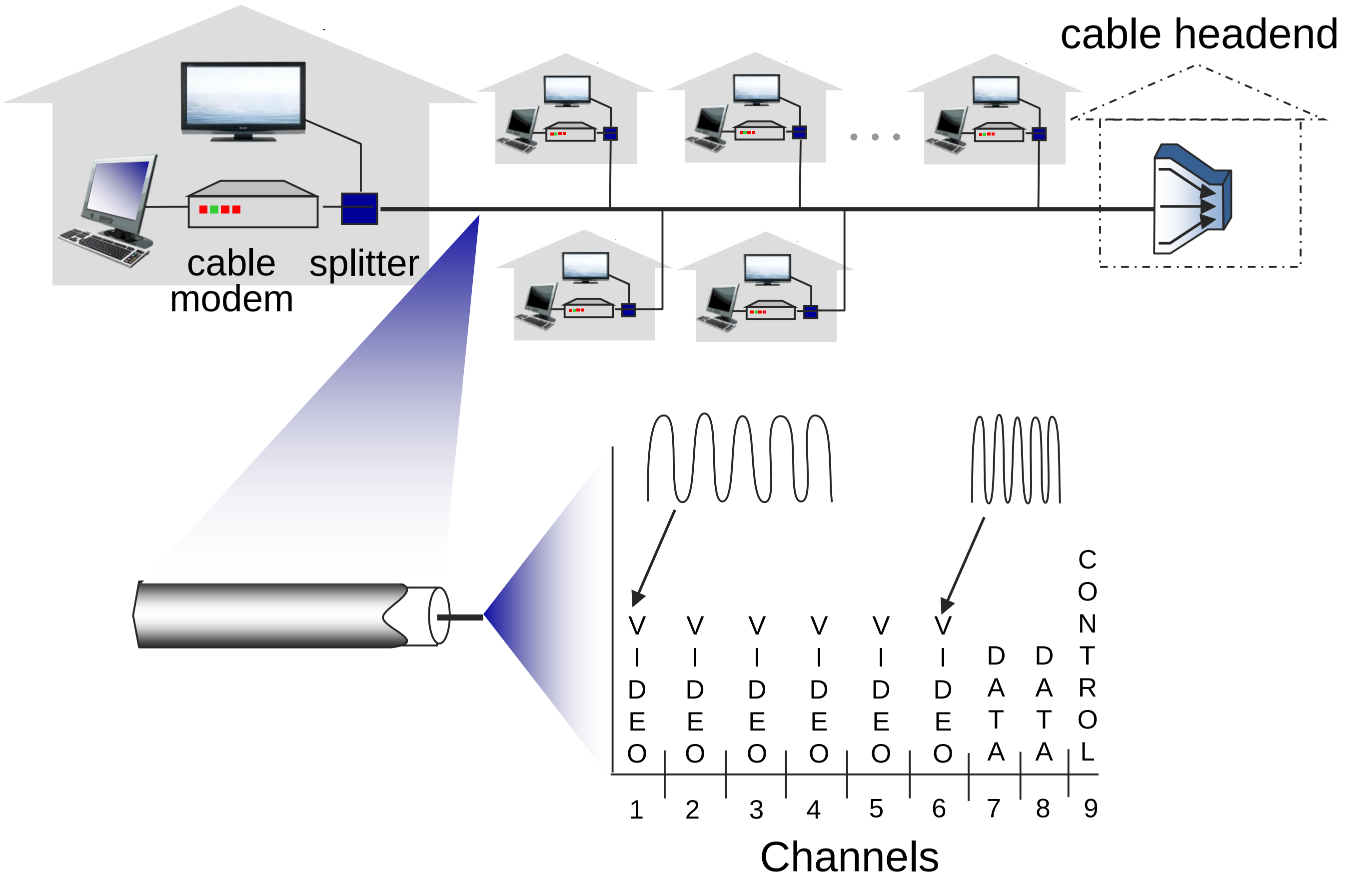


Access Networks: Digital Subscriber Line (DSL)



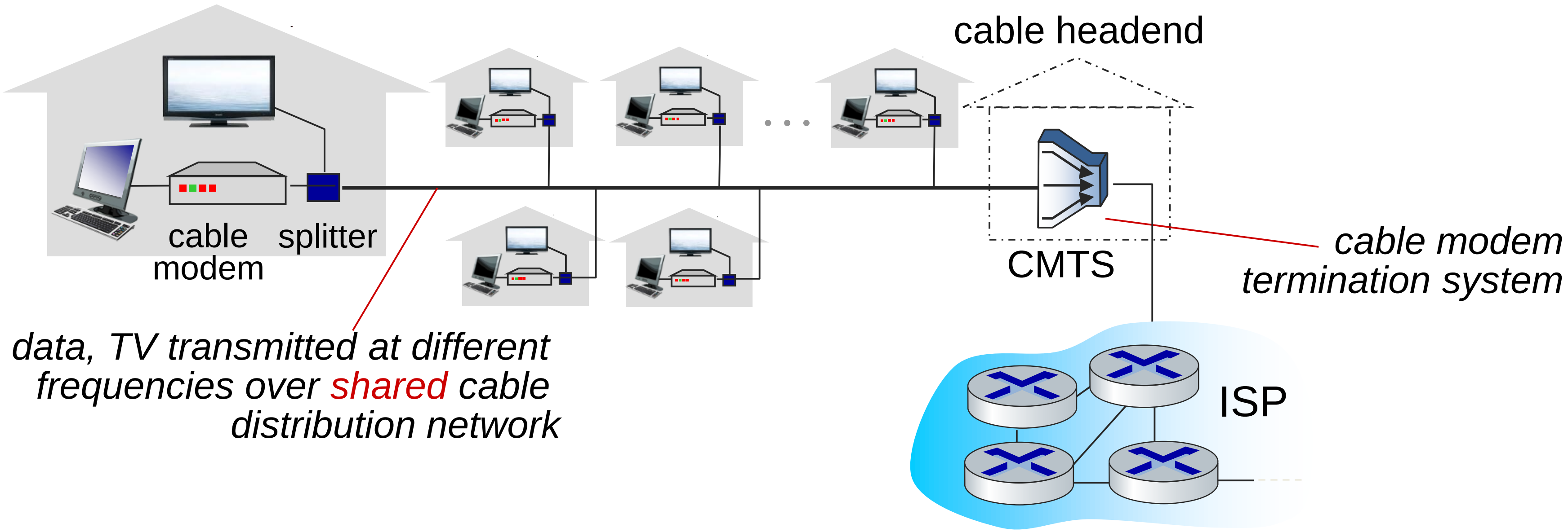
- use *existing* telephone line to central office DSLAM
  - data over DSL phone line goes to Internet
  - voice over DSL phone line goes to telephone net
- 24-52 Mbps dedicated downstream transmission rate
- 3.5-16 Mbps dedicated upstream transmission rate

Access Networks: Cable-based Access



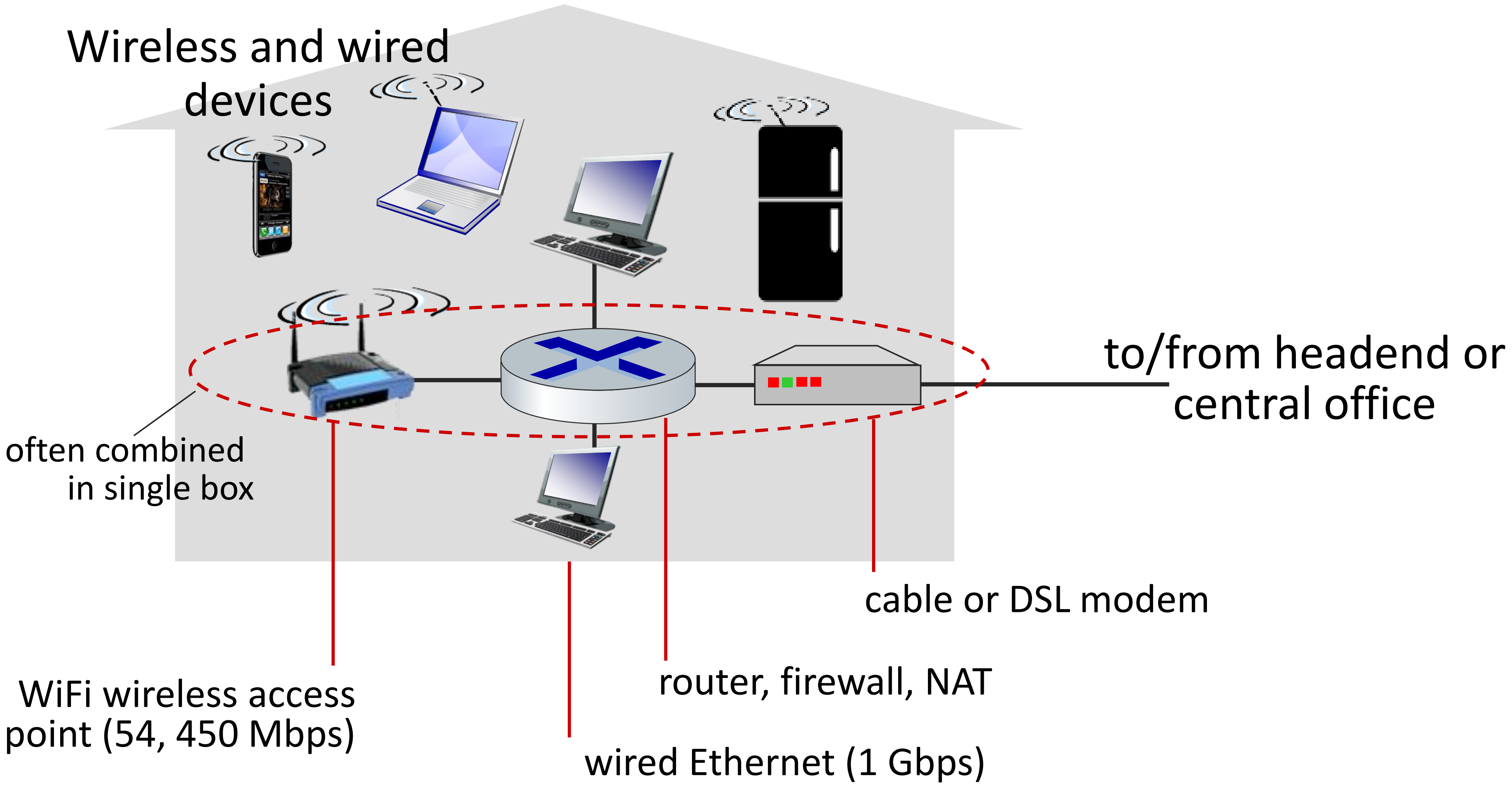
Frequency Division Multiplexing (FDM): Different channels transmitted in different frequency bands

Access Networks: Cable-based Access

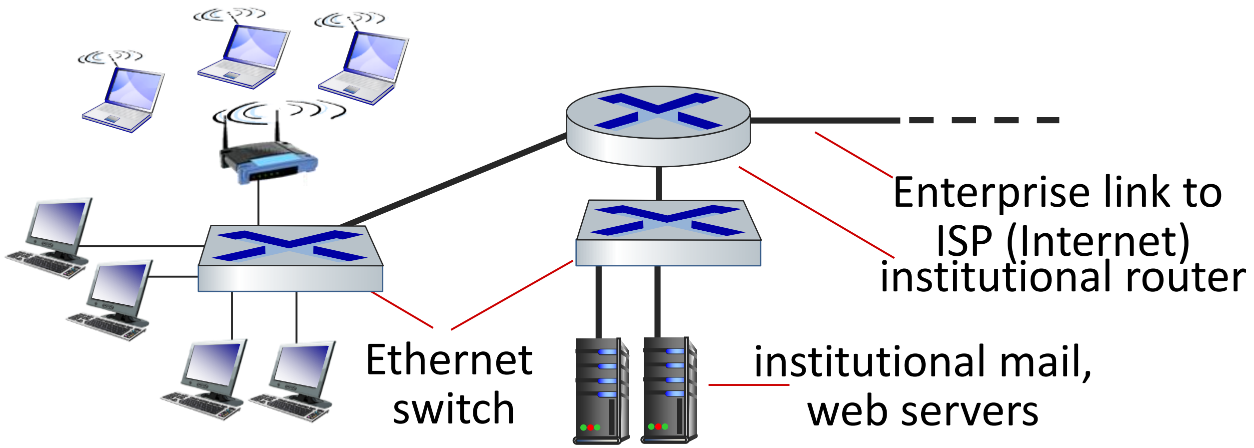


- HFC: hybrid fiber coax
  - asymmetric: up to 40 Mbps – 1.2 Gbps downstream transmission rate, 30-100 Mbps upstream transmission rate
- network of cable, fiber attaches homes to ISP router
  - homes *share access network* to cable headend

Access Networks: Home Networks



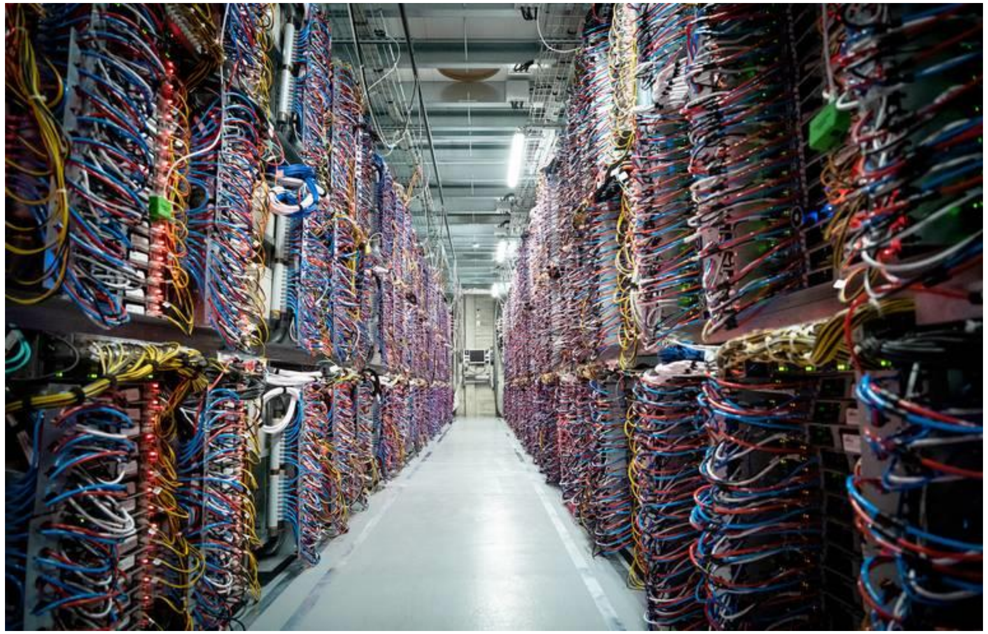
Access Networks: Enterprise Networks



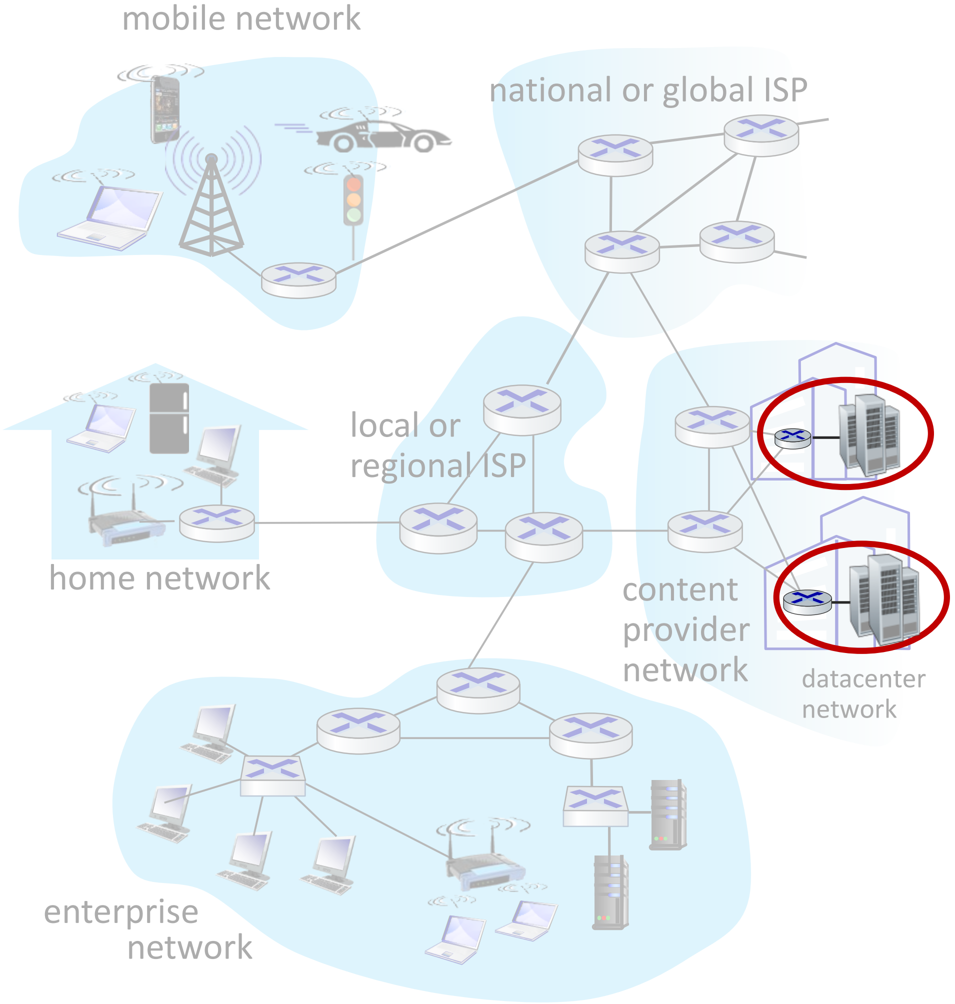
- companies, universities, etc.
- mix of wired, wireless link technologies, connecting a mix of switches and routers (we'll cover differences shortly)
    - Ethernet: wired access at 100Mbps, 1Gbps, 10Gbps
    - WiFi: wireless access points at 11, 54, 450 Mbps

Access Networks: Datacenter Networks

- high-bandwidth links (10s to 100s Gbps) connect hundreds to thousands of servers together, and to Internet



Source: https://www.20minutes.fr/economie/3157959-20211028-marseille-apportent-data-centers-ville



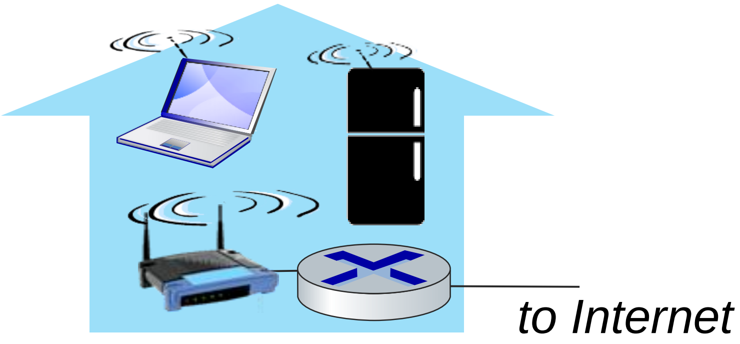
Wireless Access Networks

Shared *wireless* access network connects end system to router

- via base station aka “access point”

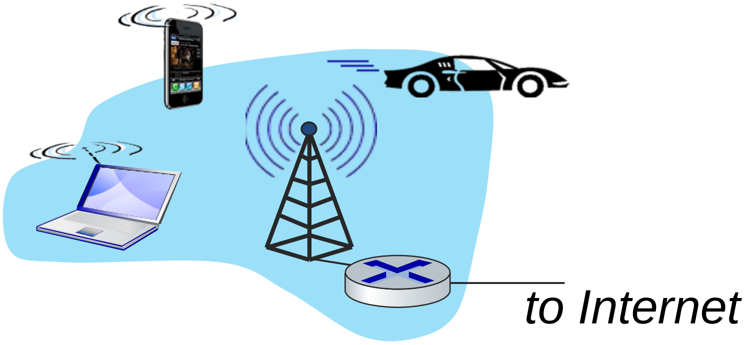
Wireless local area networks (WLANs)

- typically within or around building (~30m)
- 802.11b/g/n (WiFi): 11, 54, 450 Mbps transmission rate



Wide-area cellular access networks

- provided by mobile, cellular net. operator (10’s km)
- 10’s Mbps
- 4G/5G cellular networks



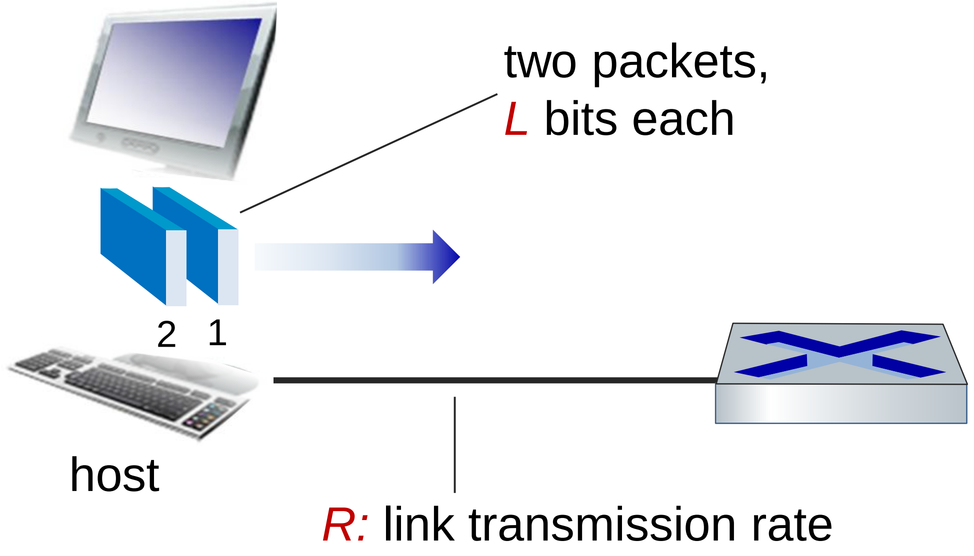
Host: Sends *packets* of data

Shared *wireless* access network connects end system to router

- via base station aka "access point"

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*



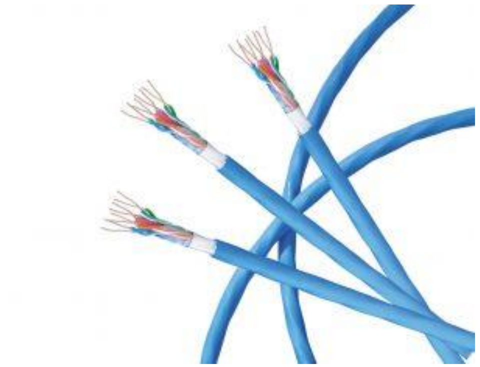
$$\text{packet transmission delay} = \text{time needed to transmit } L\text{-bit packet into link} = \frac{L \text{ (bits)}}{R \text{ (bits/sec)}}$$

Link: 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



Link: 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

Link: Physical Media

Wireless radio

- signal carried in various “bands” in electromagnetic spectrum
- no physical “wire”
- broadcast, “half-duplex” (sender to receiver)
- propagation environment effects:
  - reflection
  - obstruction by objects
  - Interference/noise

Radio link types:

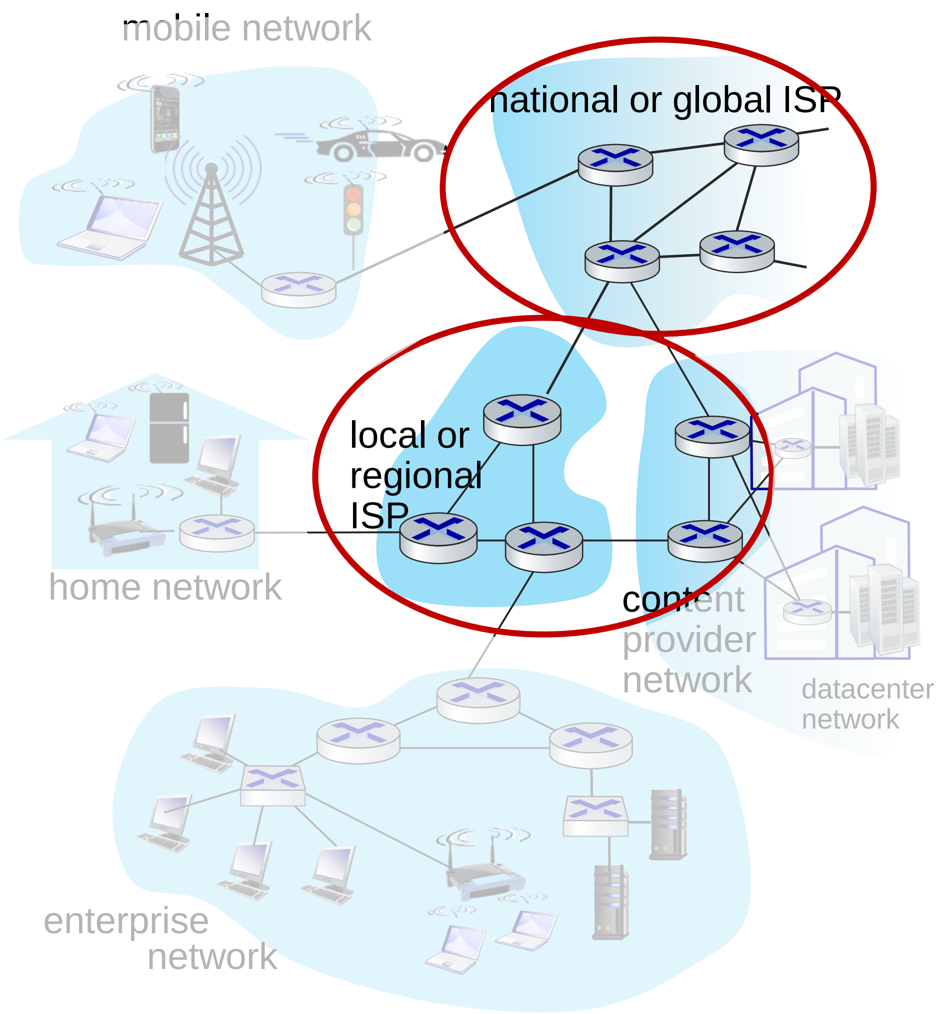
- Wireless LAN (WiFi)
  - 10-100’s Mbps; 10’s of meters
- wide-area (e.g., 4G cellular)
  - 10’s Mbps over ~10 Km
- Bluetooth: cable replacement
  - short distances, limited rates
- terrestrial microwave
  - point-to-point; 45 Mbps channels
- satellite
  - up to 45 Mbps per channel
  - 270 msec end-end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

Roadmap

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

The Network Core

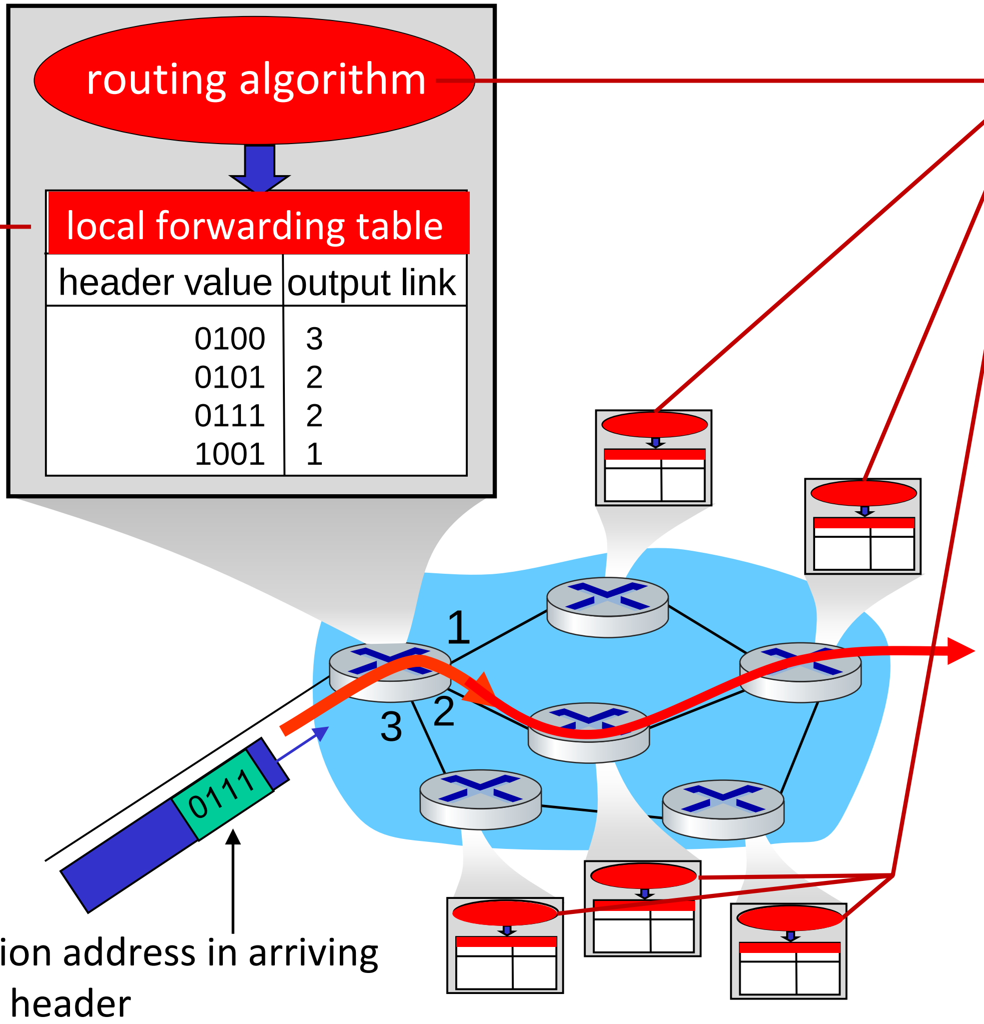
- mesh of interconnected routers
- packet-switching: hosts break application-layer messages into *packets*
  - network forwards packets from one router to the next, across links on path from source to destination



Internet's Network-Core Functions

Forwarding:

- aka "switching"
- *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


45 h
3,053 miles
48 h
3,309 miles
routing
United States
San Jose
Northampton
Victoria
Seattle
WASHINGTON
MONTANA
NORTH DAKOTA
MINNESOTA
Minneapolis
WISCONSIN
MICHIGAN
Toronto
Quebec City
Montreal
Ottawa
MAINE
VERMONT
NEW HAMPSHIRE
Portland
OREGON
IDAHO
WYOMING
SOUTH DAKOTA
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TENNESSEE
NORTH CAROLINA
Charlotte
OKLAHOMA
ARKANSAS
Los Angeles
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NEW MEXICO
Atlanta
SOUTH CAROLINA
MISSISSIPPI
ALABAMA
GEORGIA
San Diego
Phoenix
Dallas
Tucson
El Paso
TEXAS
BAJA CALIFORNIA
SONORA
CHIHUAHUA
COAHUILA
Austin
Houston
San Antonio
LOUISIANA
New Orleans
Jacksonville
Orlando
Tampa
FLORIDA


forwarding
forwarding
45 h
3,053 miles
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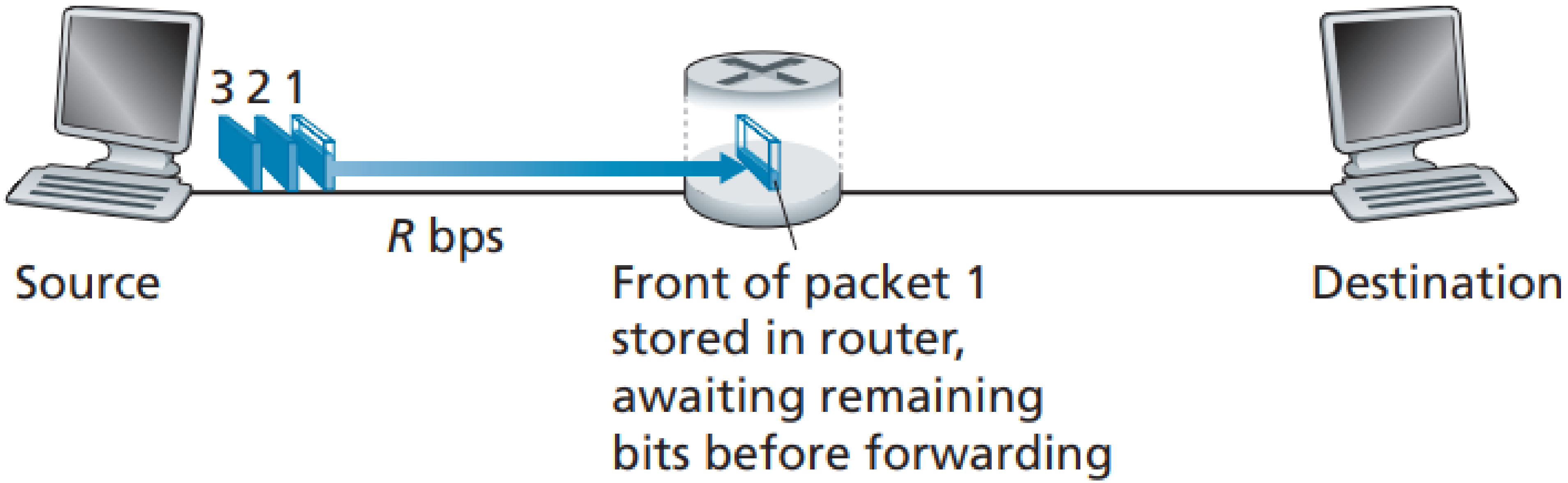
San Jose
Northampton
Cleveland
Sacramento

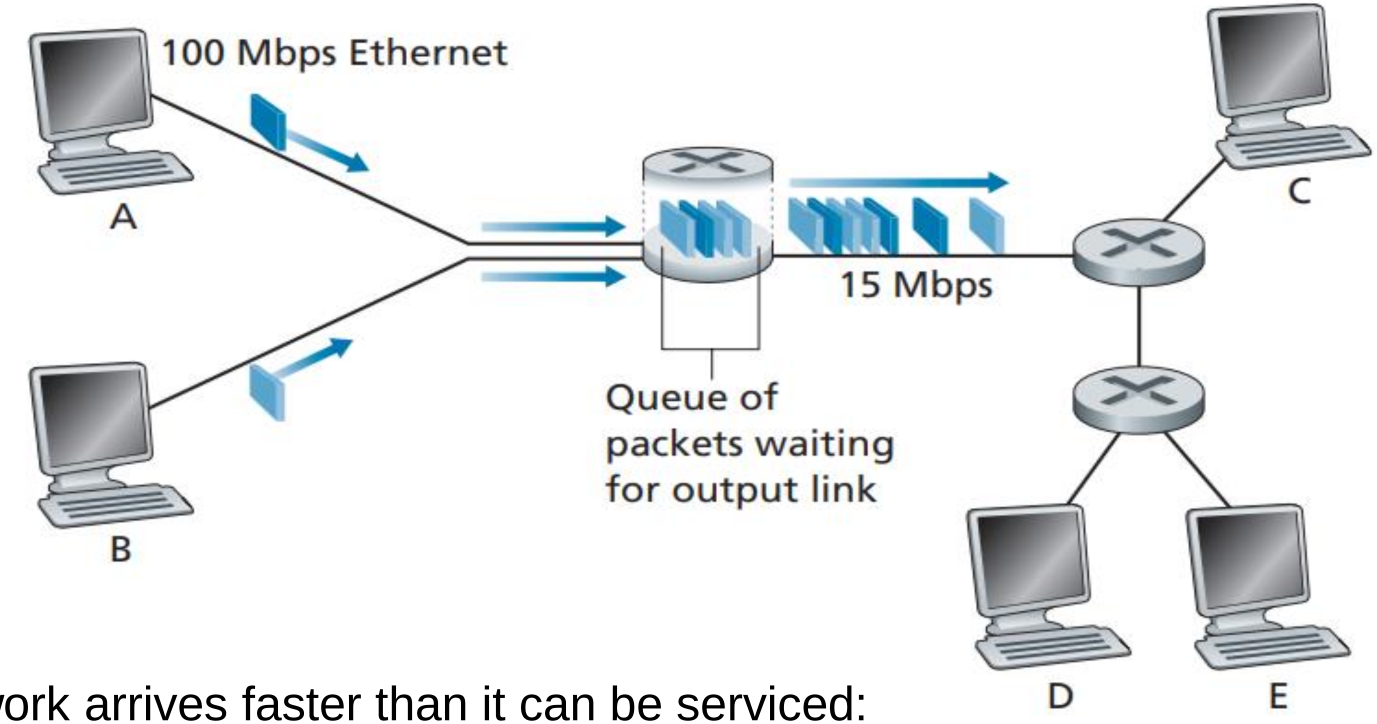
Packet Switching: Store-and-Forward



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

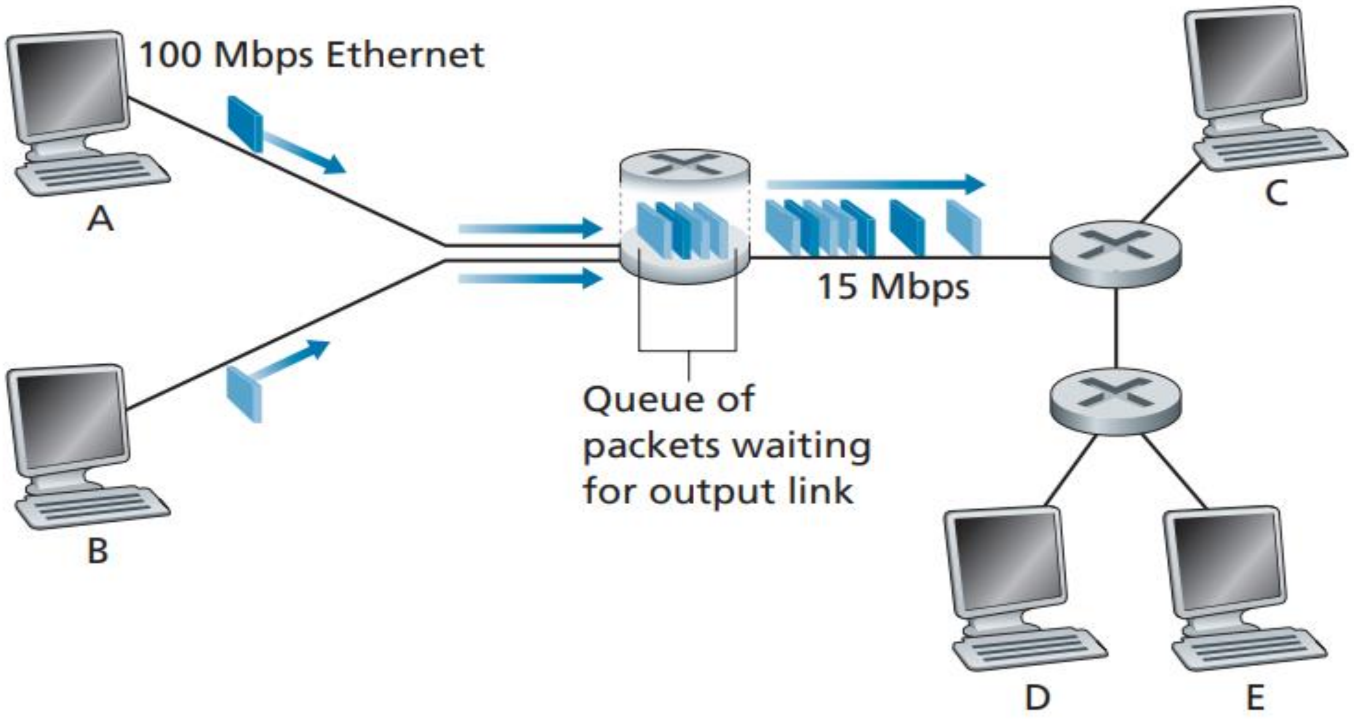
One-hop numerical example:
- *L* = 10 Kbits
- *R* = 100 Mbps
- one-hop transmission delay = 0.1 ms

Packet Switching: Queueing



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

Packet Switching: Queueing



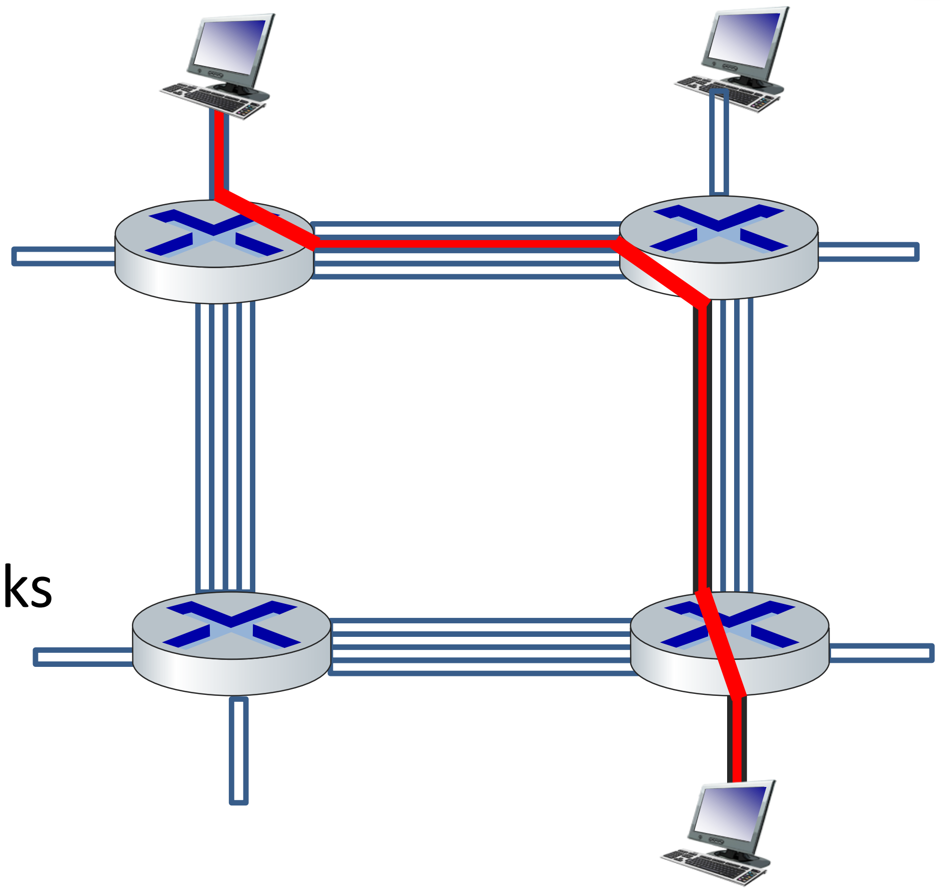
Packet queuing and loss: if arrival rate (in bps) to link exceeds transmission rate (bps) of link for some period of time:

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

Alternative to Packet Switching: Circuit Switching

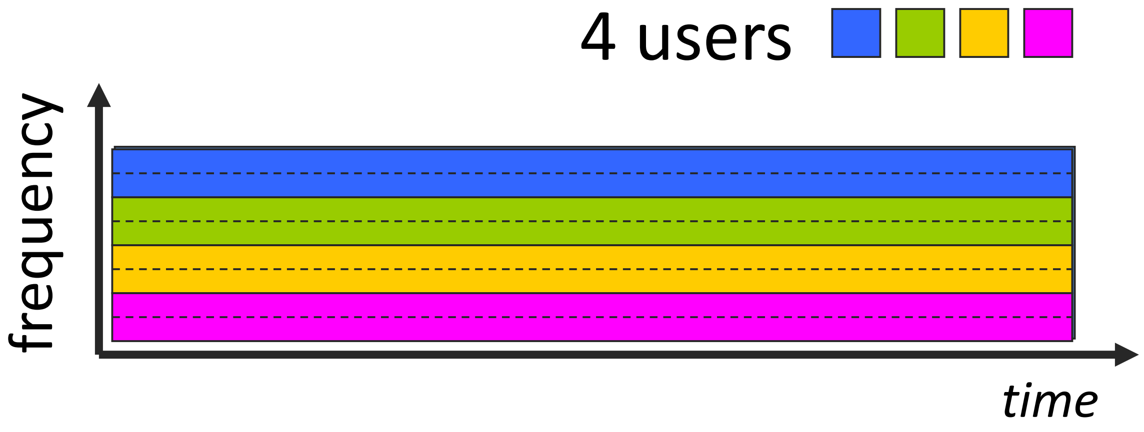
End-end resources allocated to, reserved for “call” between source and destination

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



- commonly used in traditional telephone networks

Circuit Switching: FDM and TDM

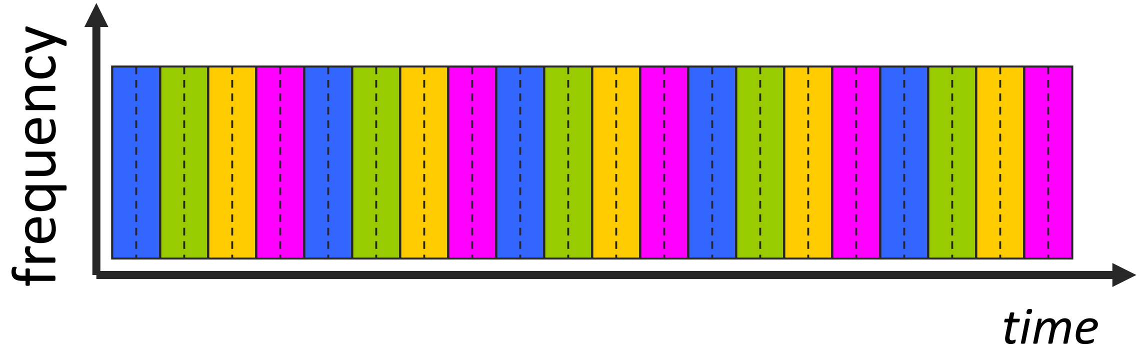


Frequency Division Multiplexing (FDM)

- 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)

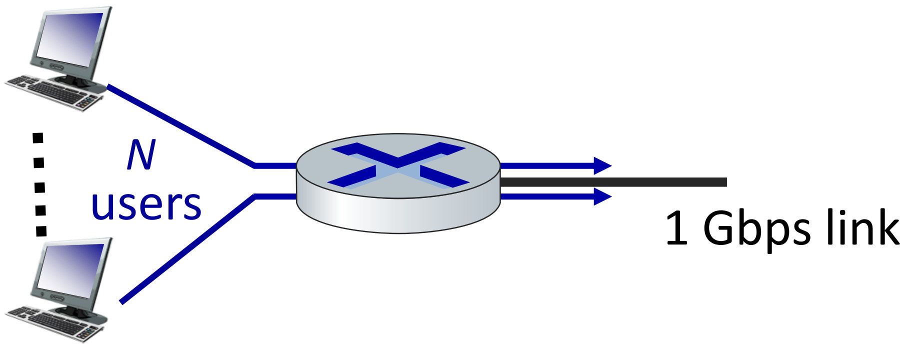
- time divided into slots



Packet Switching versus Circuit Switching

Example:

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



Q: how many users can use this network under circuit-switching and packet-switching?

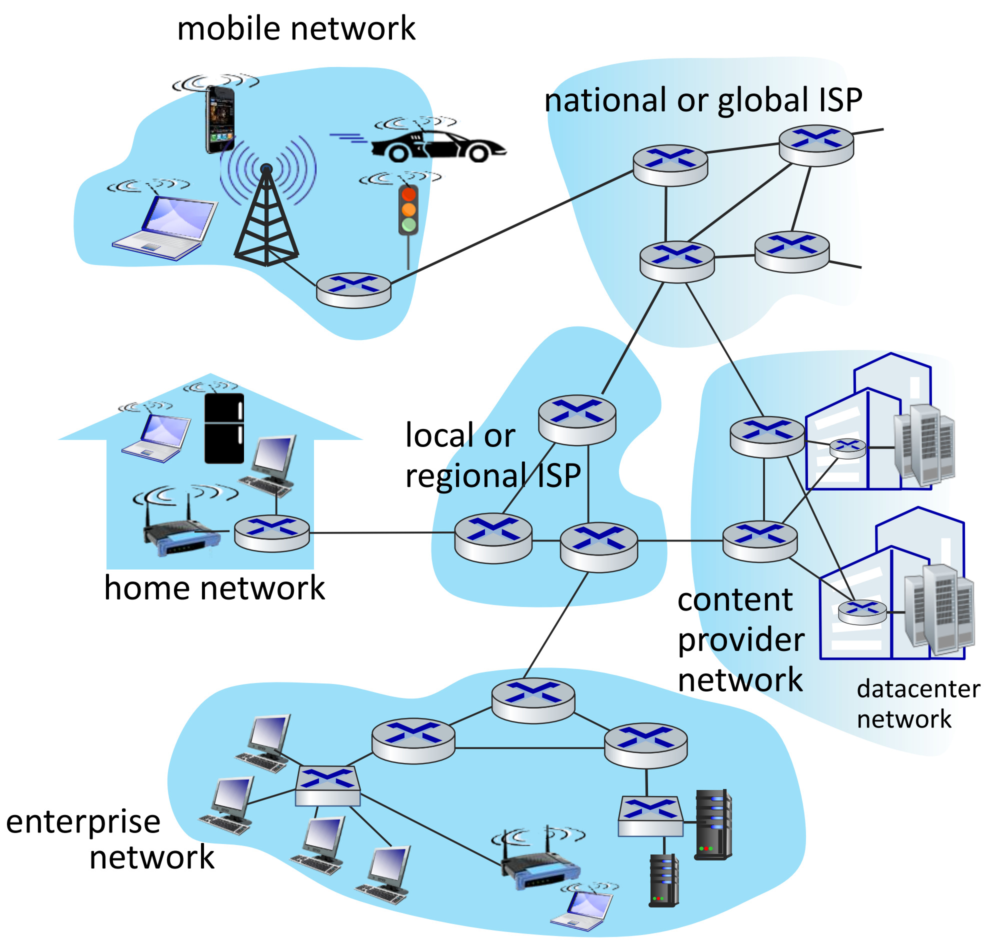
- *circuit switching:* 10 users
- *packet switching:* with 35 users, probability > 10 active at same time is less than .0004

Q: how did we get value 0.0004?

Internet Structure: a “Network of networks”

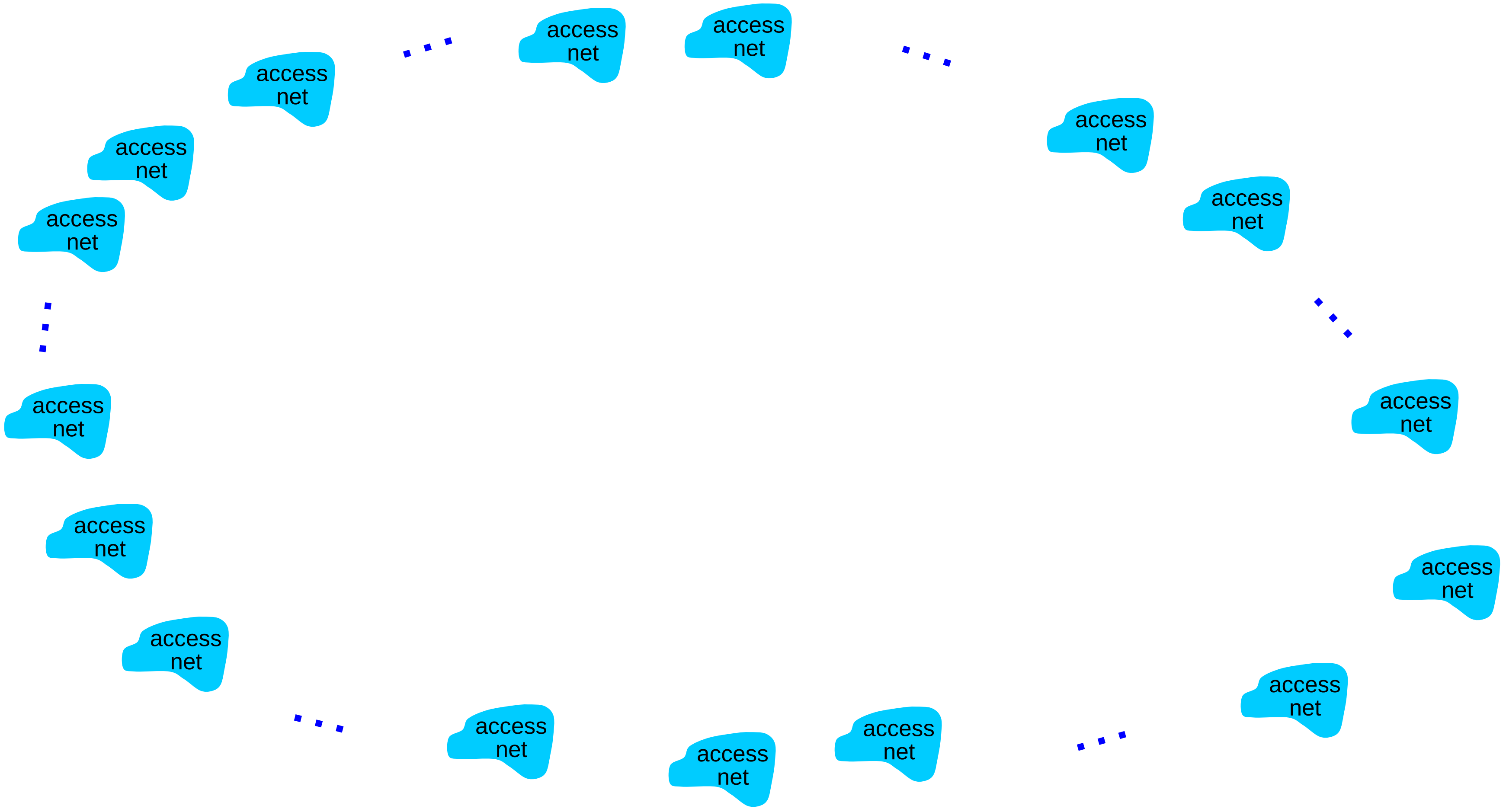
- hosts connect to Internet via access Internet Service Providers (ISPs)
- access ISPs in turn must be interconnected
  - so that *any* two hosts *(anywhere!)* can send packets to each other
- resulting network of networks is very complex
  - evolution driven by economics, national policies

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



Internet Structure: a “Network of networks”

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



Internet Structure: a “Network of networks”

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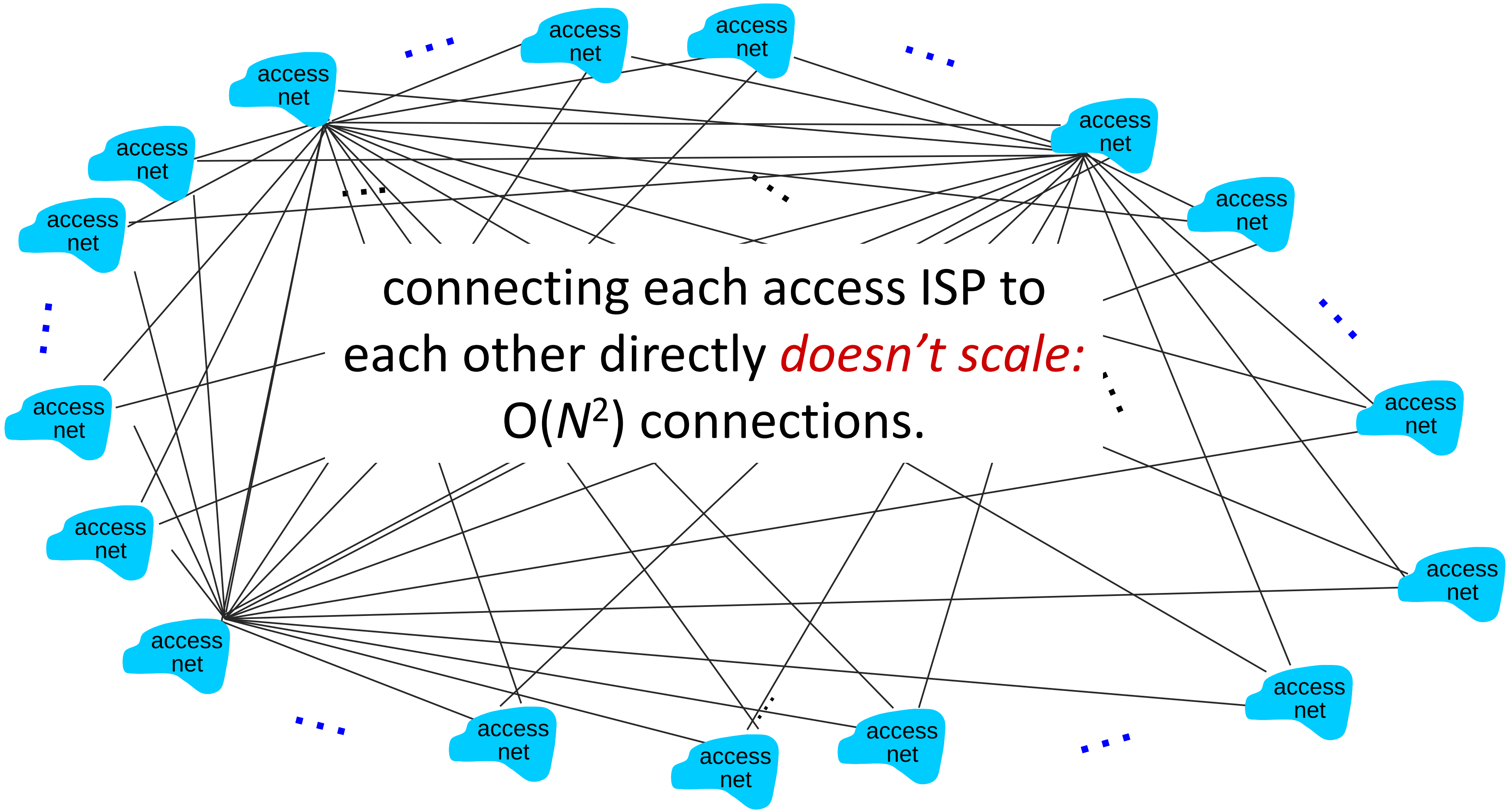
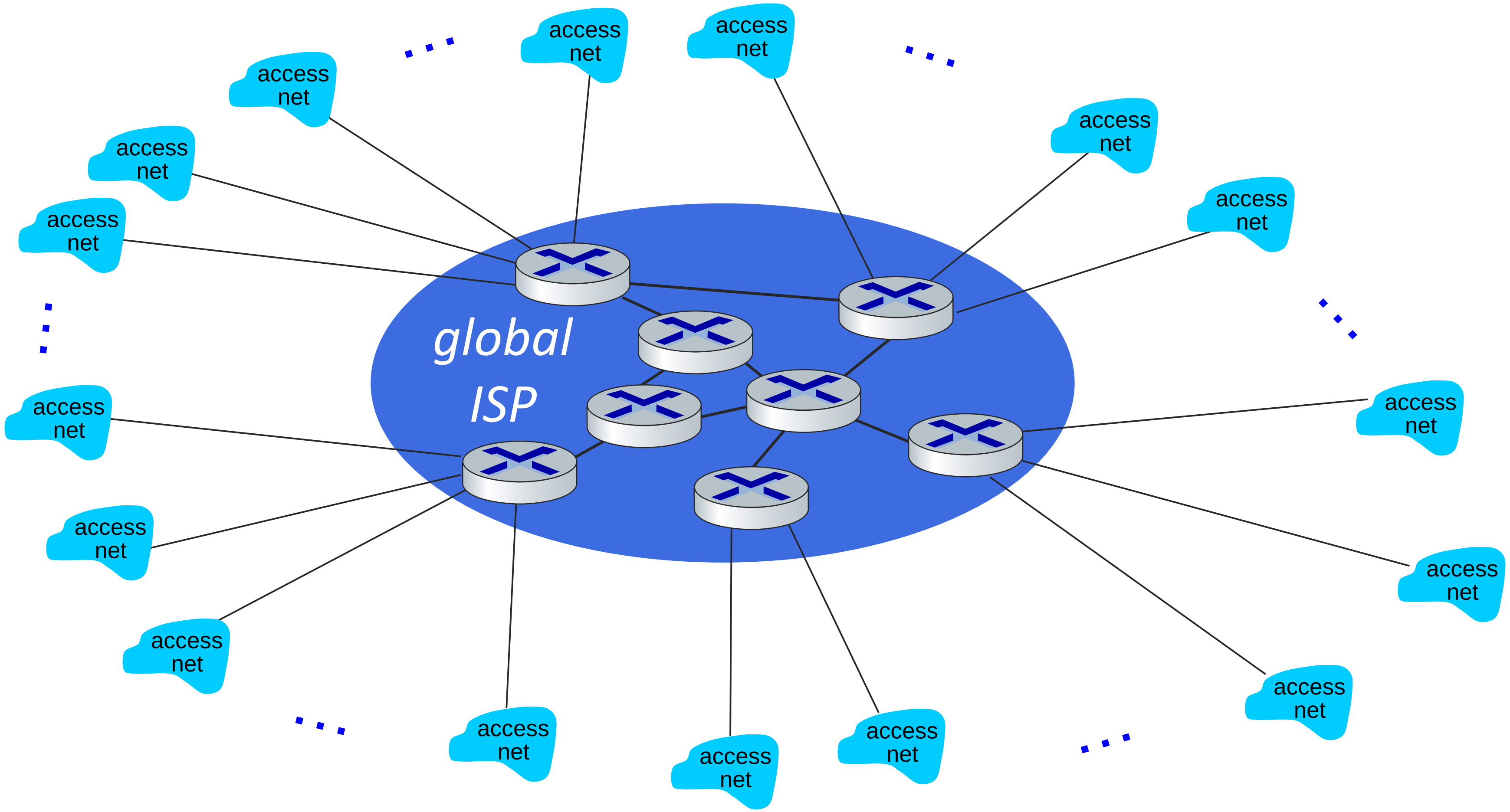


connecting each access ISP to each other directly *doesn’t scale:* $O(N^2)$ connections.

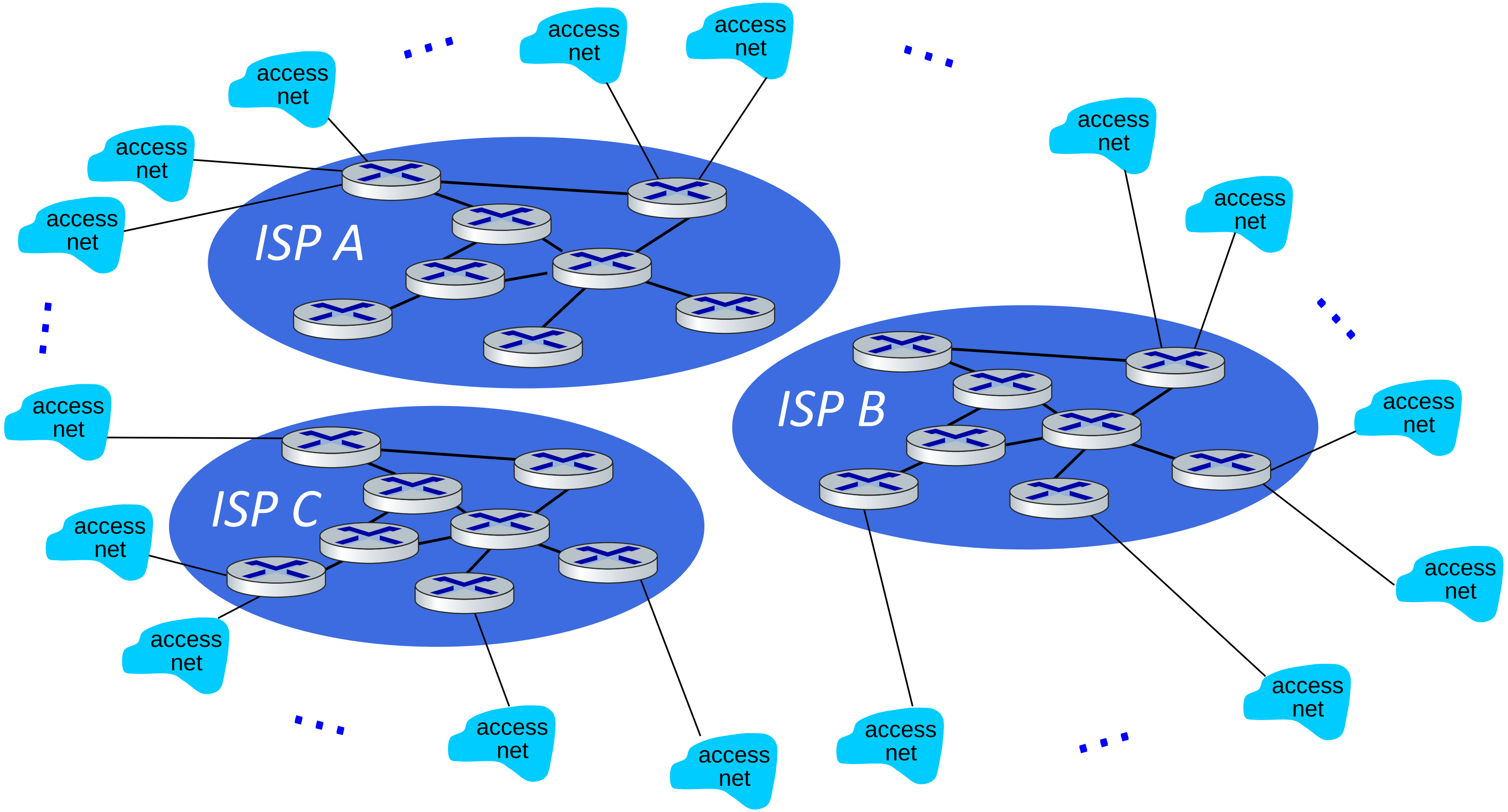
Internet Structure: a "Network of networks"

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



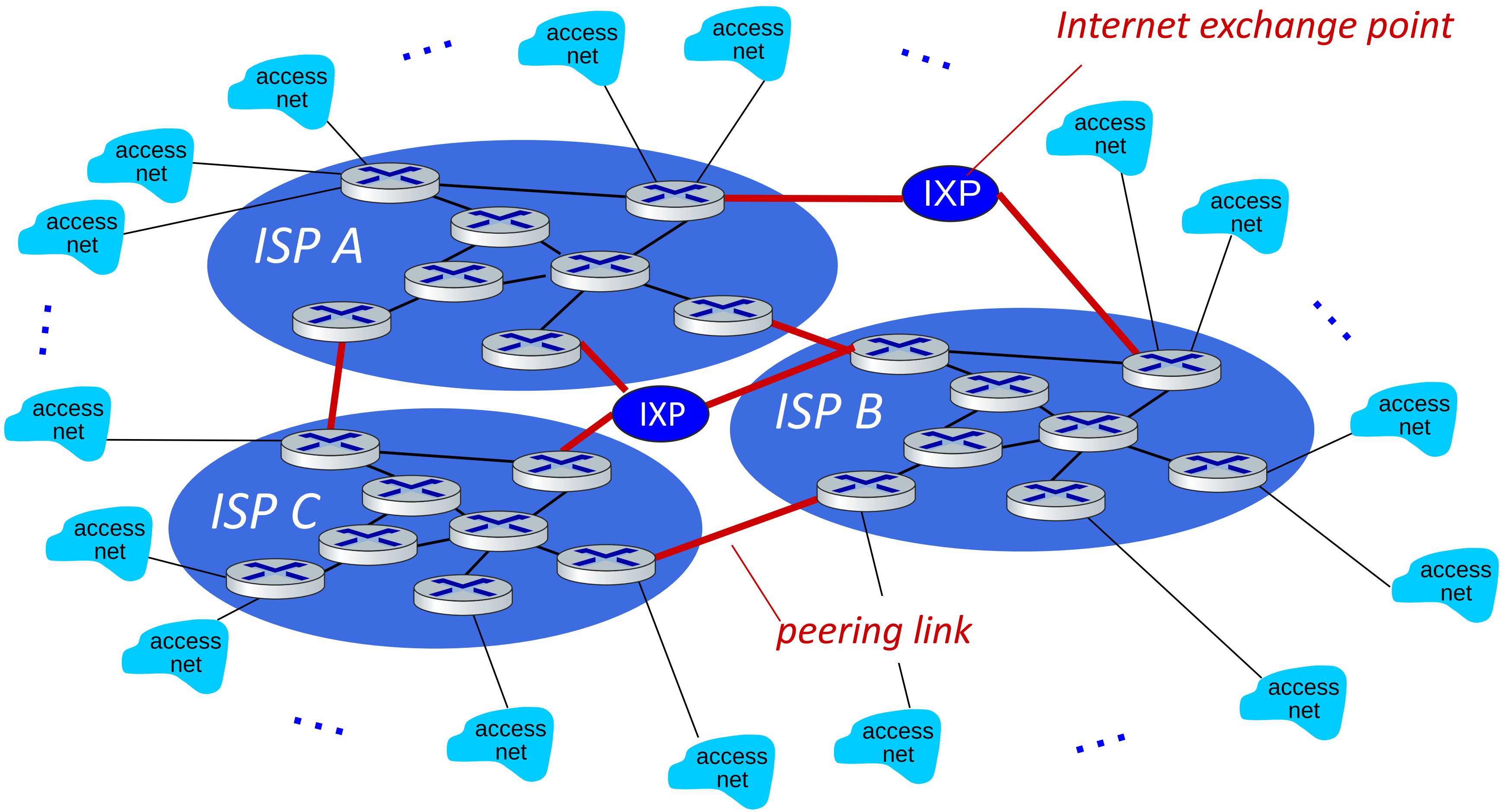
Internet Structure: a "Network of networks"

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



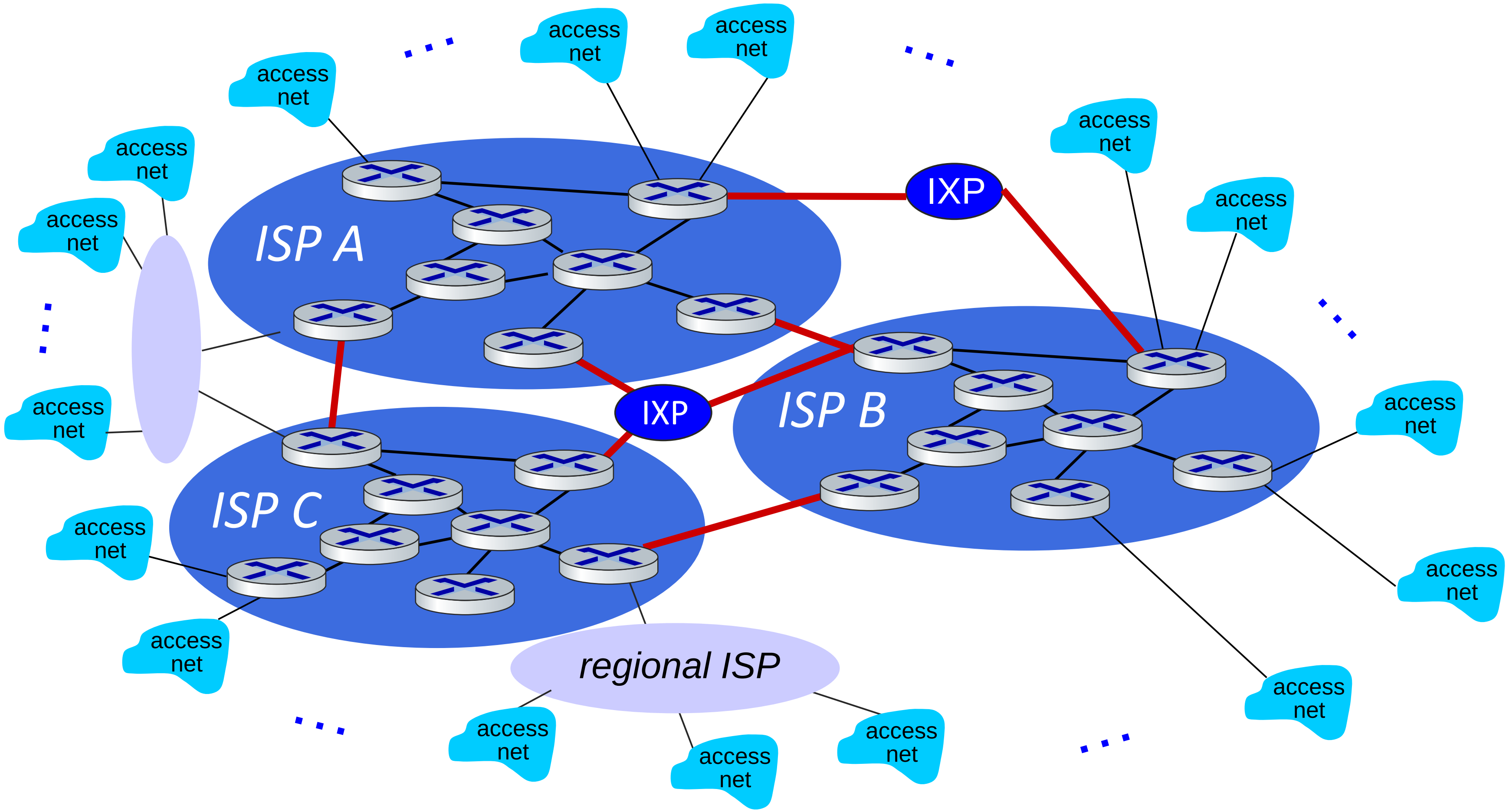
Internet Structure: a “Network of networks”

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



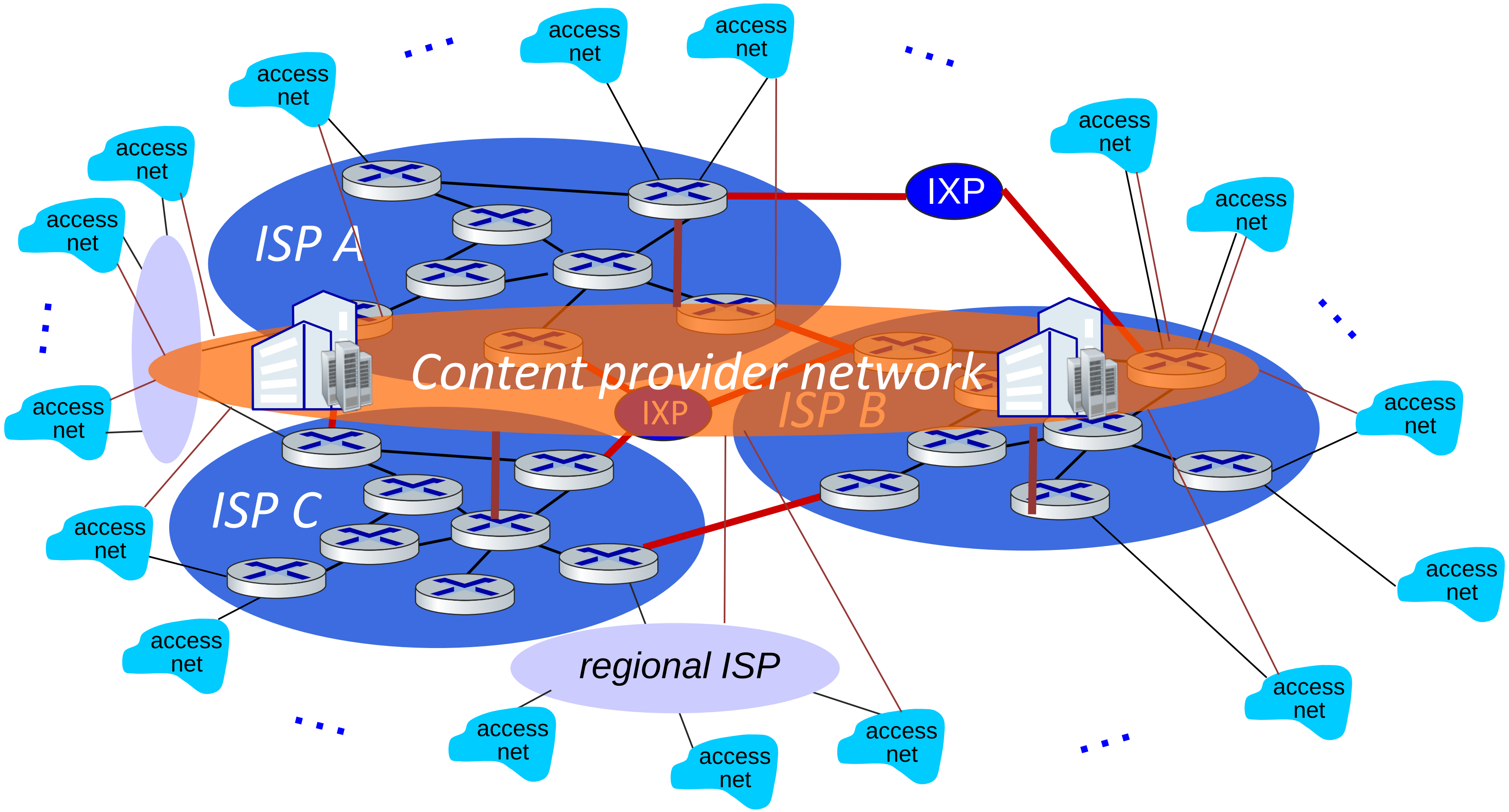
Internet Structure: a “Network of networks”

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

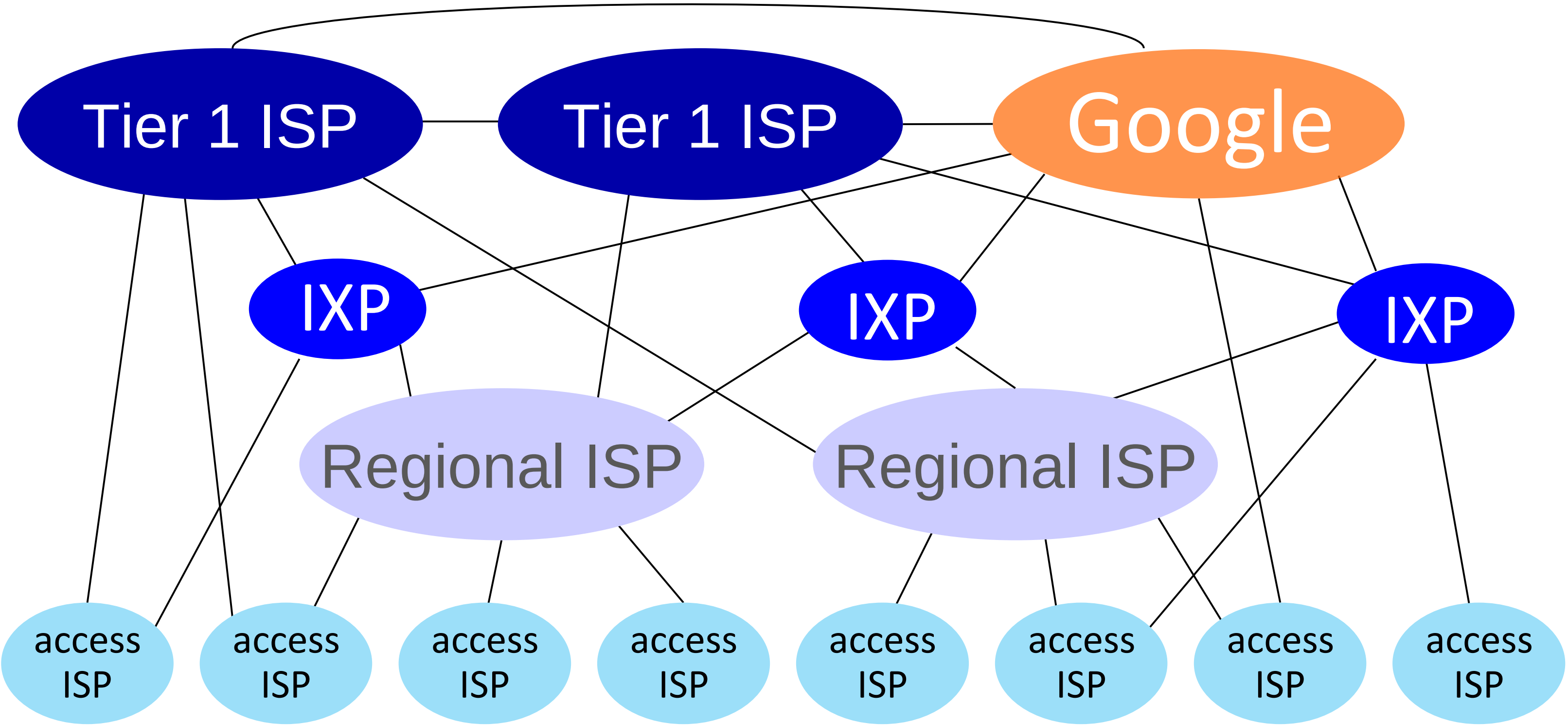


Internet Structure: a “Network of networks”

… 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

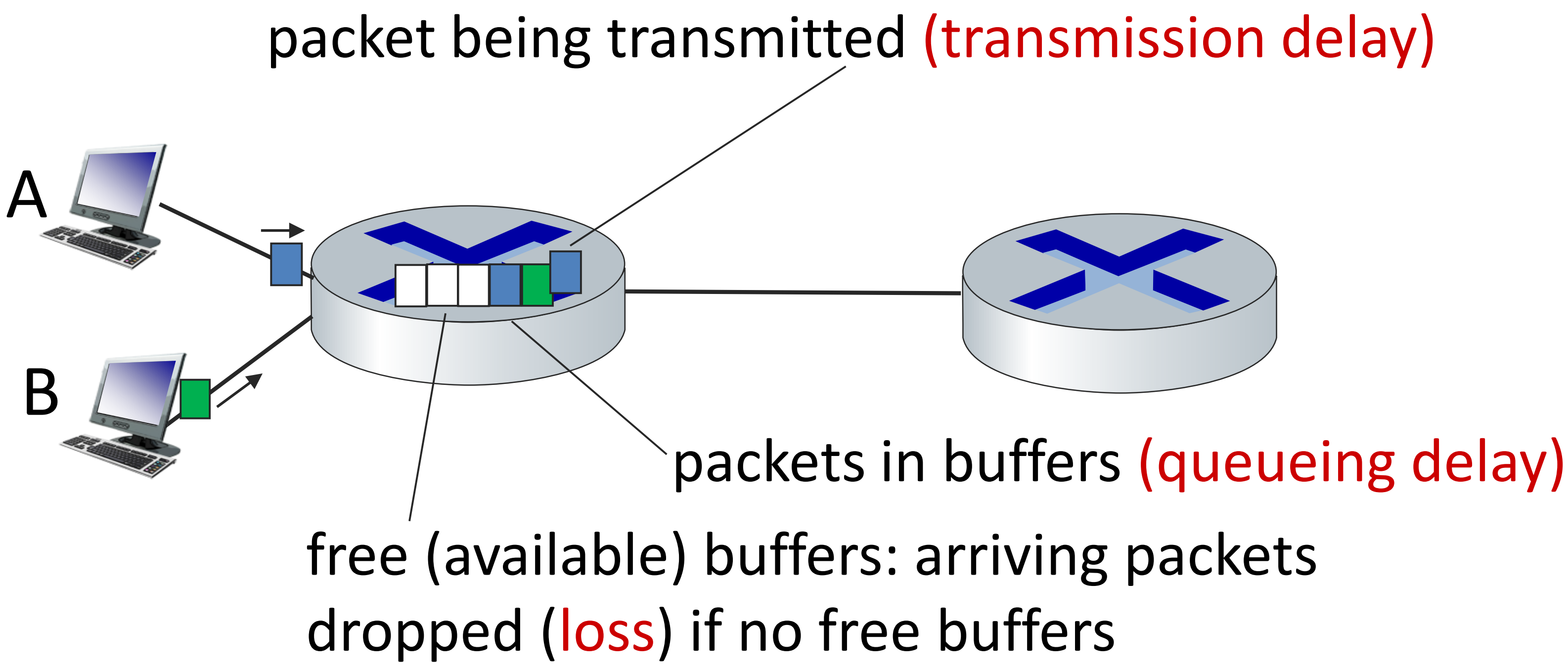
- “tier-1” commercial ISPs (e.g., Level 3, Sprint, AT&T, NTT), national & international coverage
- content provider networks (e.g., Google, Facebook): private network that connects its data centers to Internet, often bypassing tier-1, regional ISPs

Roadmap

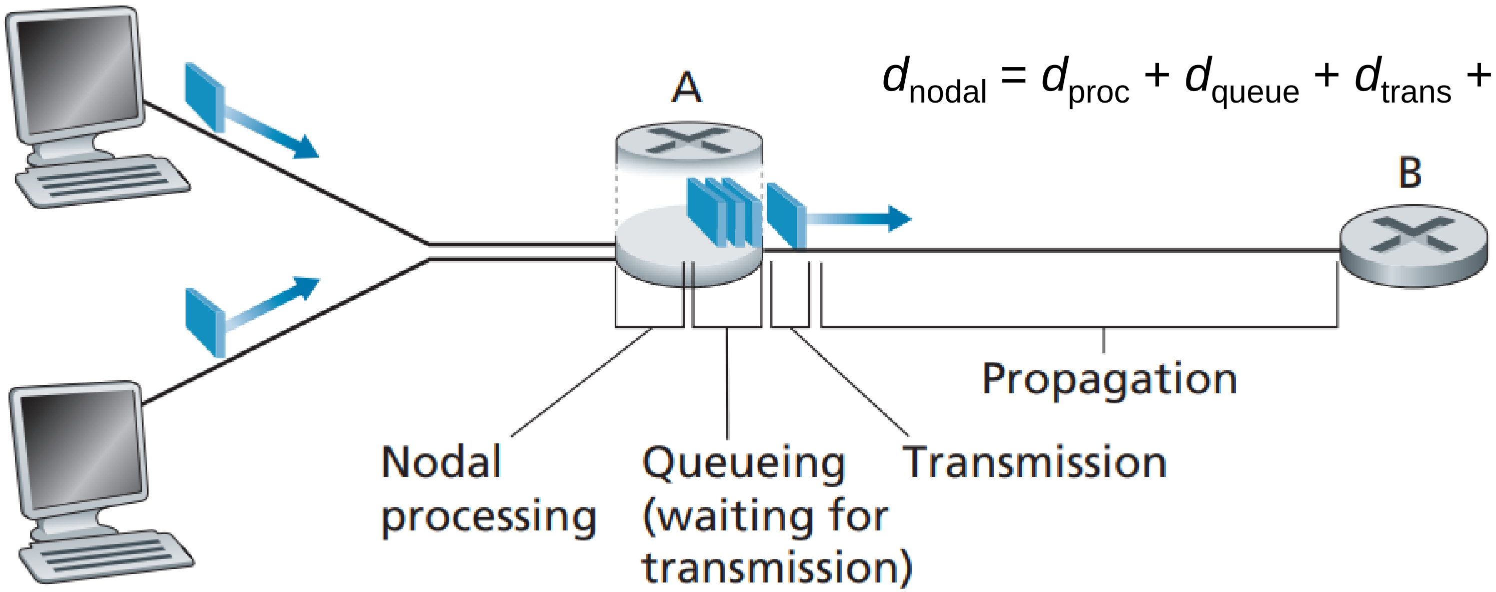
- What *is* the *Internet*? What *is* a *protocol*?
- Network edge: hosts, access network
- Network core: packet/circuit switching
- **Performance: loss, delay, throughput**
- Protocol layers, service models

Reminder: How do packet delay and loss occur?

- packets *queue* in router buffers, waiting for turn for transmission
  - queue length grows when arrival rate to link (temporarily) exceeds output link capacity
- packet *loss* occurs when memory to hold queued packets fills up



Packet Delay: 4 Sources

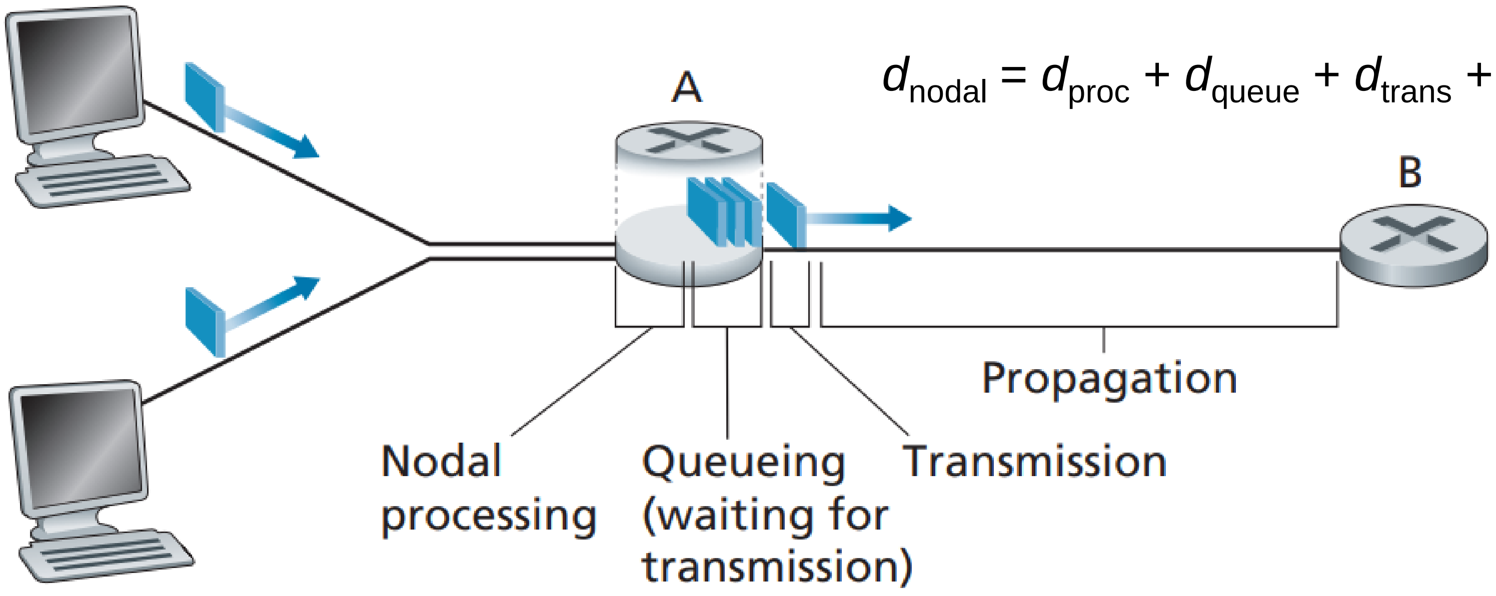


$$d_{nodal} = d_{proc} + d_{queue} + d_{trans} + d_{prop}$$

d_{proc}: nodal processing
- check bit errors
- determine output link
- typically < microsecs

d_{queue}: queueing delay
- time waiting at output link for transmission
- depends on congestion level of router

Packet Delay: 4 Sources



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

d_{trans}: transmission delay:

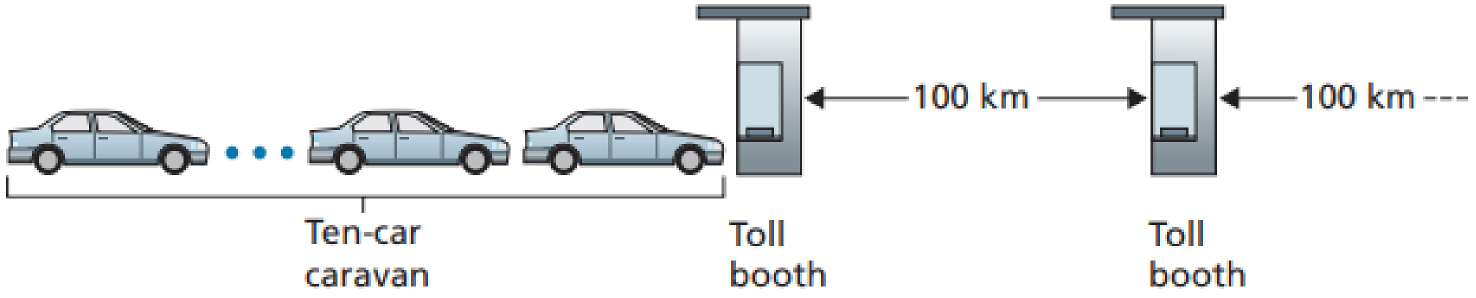
- L: packet length (bits)
- R: link *transmission rate (bps)*
- $d_{trans} = L/R$

d_{prop}: propagation delay:

- d: length of physical link
- s: propagation speed (~2x10^8 m/sec)
- $d_{prop} = d/s$

d_{trans} and d_{prop} *very* different

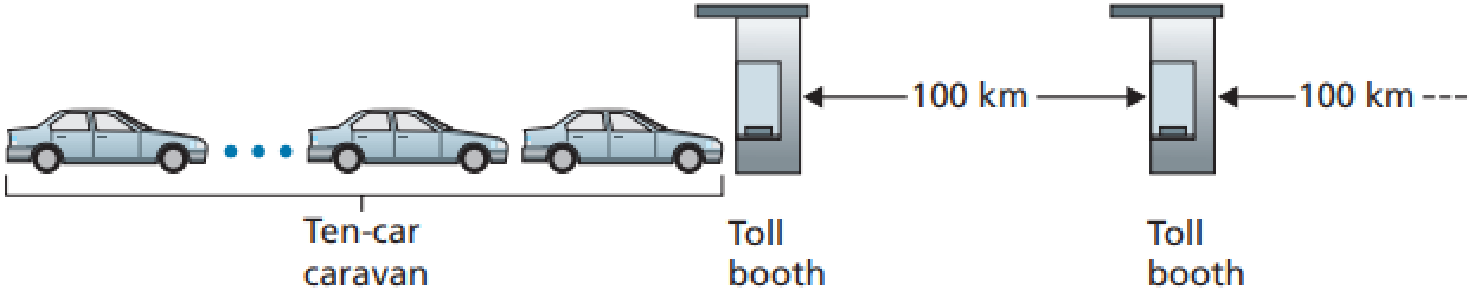
Caravan Analogy



- car ~ bit; caravan ~ packet; toll service ~ link transmission
- toll booth takes 12 sec to service car (bit transmission time)
- "propagate" at 100 km/hr
- *Q:* How long until caravan is lined up before 2nd toll booth?

- time to "push" entire caravan through toll booth onto highway = 12*10 = 120 sec
- time for last car to propagate from 1st to 2nd toll both: 100km/(100km/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?

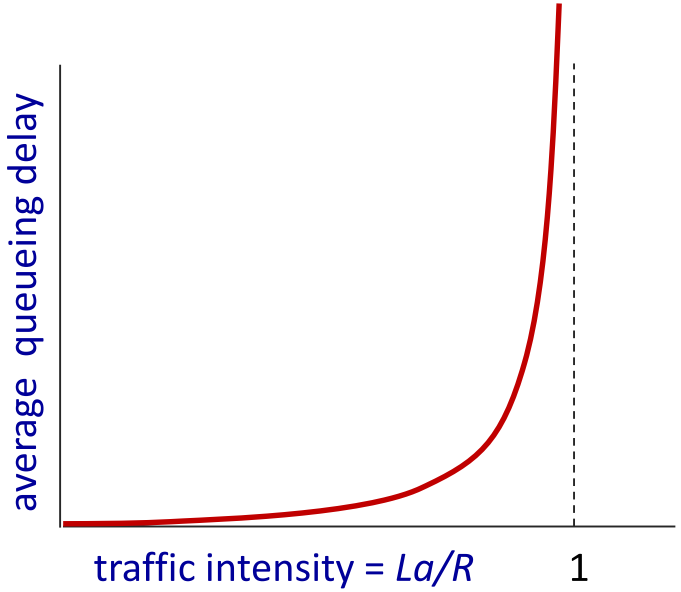
A: Yes! after 7 min, first car arrives at second booth; three cars still at first booth

Packet queueing delay (revisited)

- *a:* average packet arrival rate
- *L:* packet length (bits)
- *R:* link bandwidth (bit transmission rate)

$$\frac{L \cdot a}{R} : \frac{\text{arrival rate of bits}}{\text{service rate of bits}}$$

"traffic intensity"



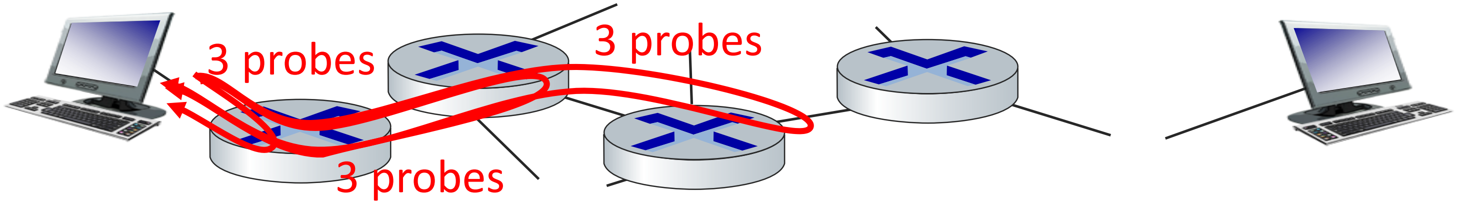
- *La/R* ~ 0: avg. queueing delay small
- *La/R* -> 1: avg. queueing delay large
- *La/R* > 1: more "work" arriving is more than can be serviced - average delay infinite!

La/R ~ 0

La/R -> 1

"Real" Internet delays and routes

- what do "real" Internet delay & loss look like?
- **traceroute*** program: provides delay measurement from source to router along end-end Internet path towards destination. For all *i:*
  - sends three packets that will reach router *i* on path towards destination (with time-to-live field value of *i*)
  - router *i* will return packets to sender
  - sender measures time interval between transmission and reply



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

Traceroute Example

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

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

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

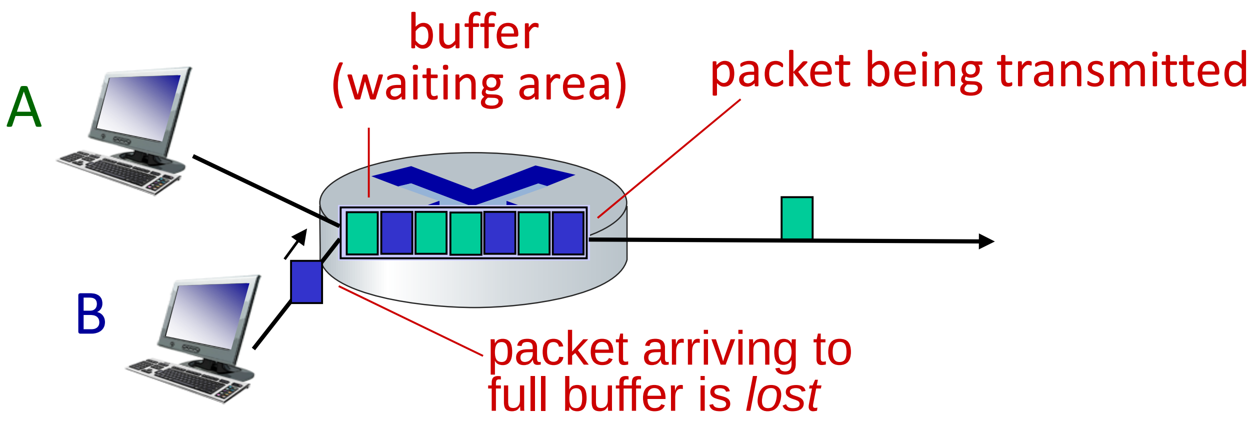
3 delay measurements
to border1-rt-fa5-1-0.gw.umass.edu

trans-oceanic link

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

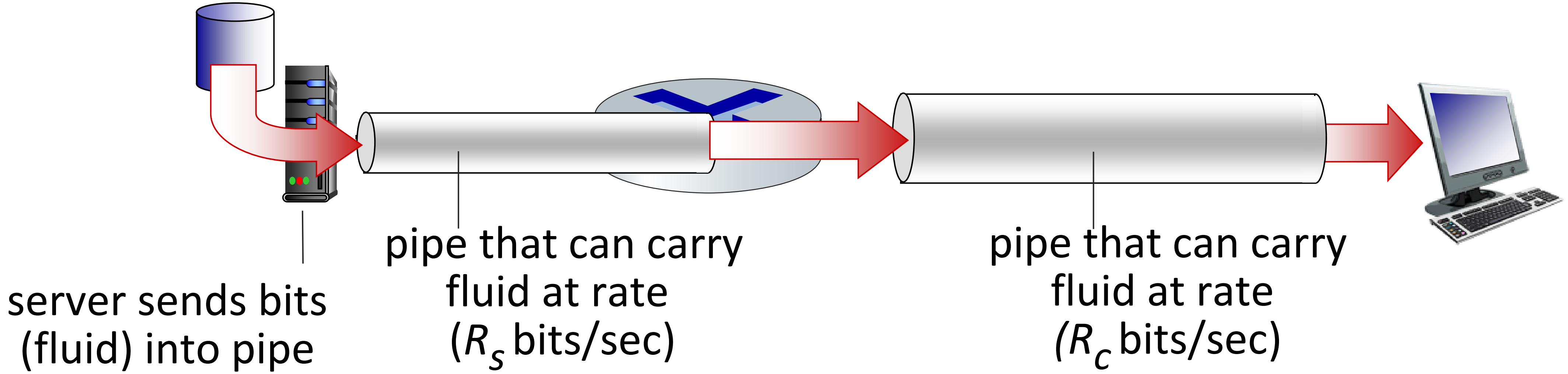
Packet Loss

- 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



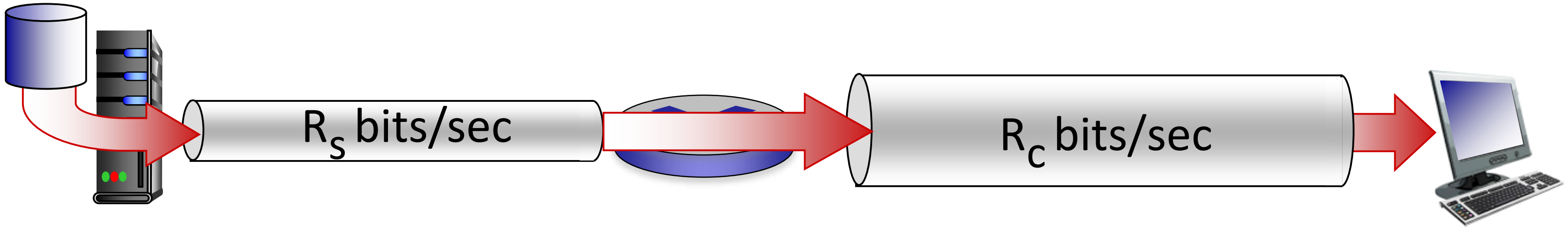
Throughput

- *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

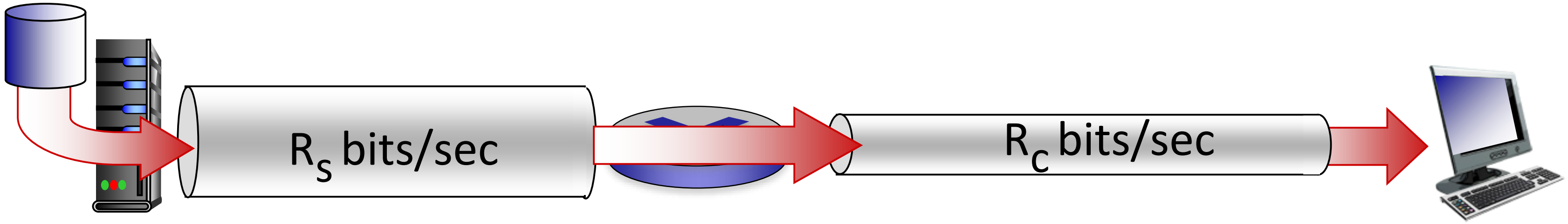


Throughput

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



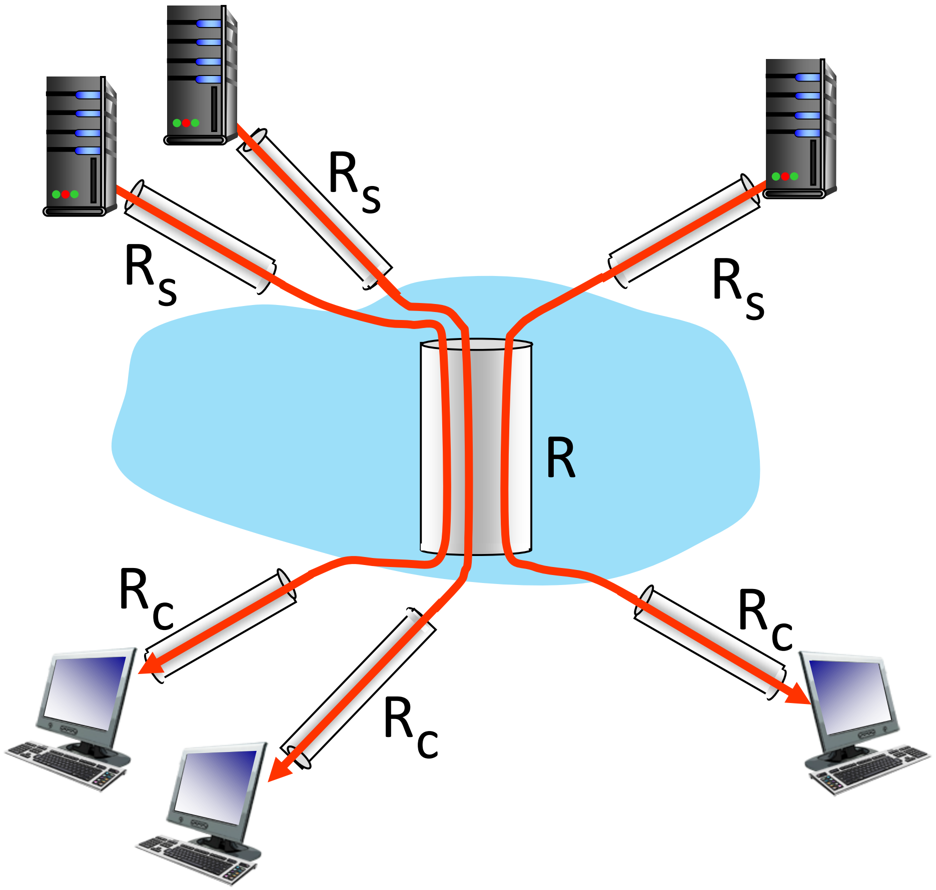
$R_s > R_c$ What is average end-end throughput?



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

Computer Networking and Security
Class 1: Introduction

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