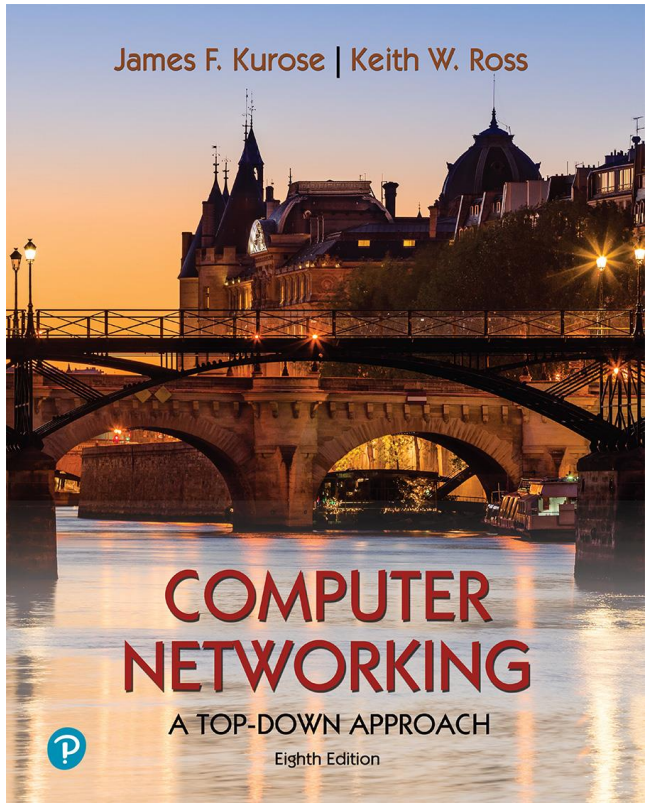
# Chapter 1 Introduction




*Computer Networking: A Top-Down Approach*

8th edition
Jim Kurose, Keith Ross
Pearson, 2020

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- If you use these slides (e.g., in a class) that you mention their source (after all, we'd like people to use our book!)
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For a revision history, see the slide note for this page.

Thanks and enjoy! JFK/KWR

# Part I: The Internet

(with a capital I)

# 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*

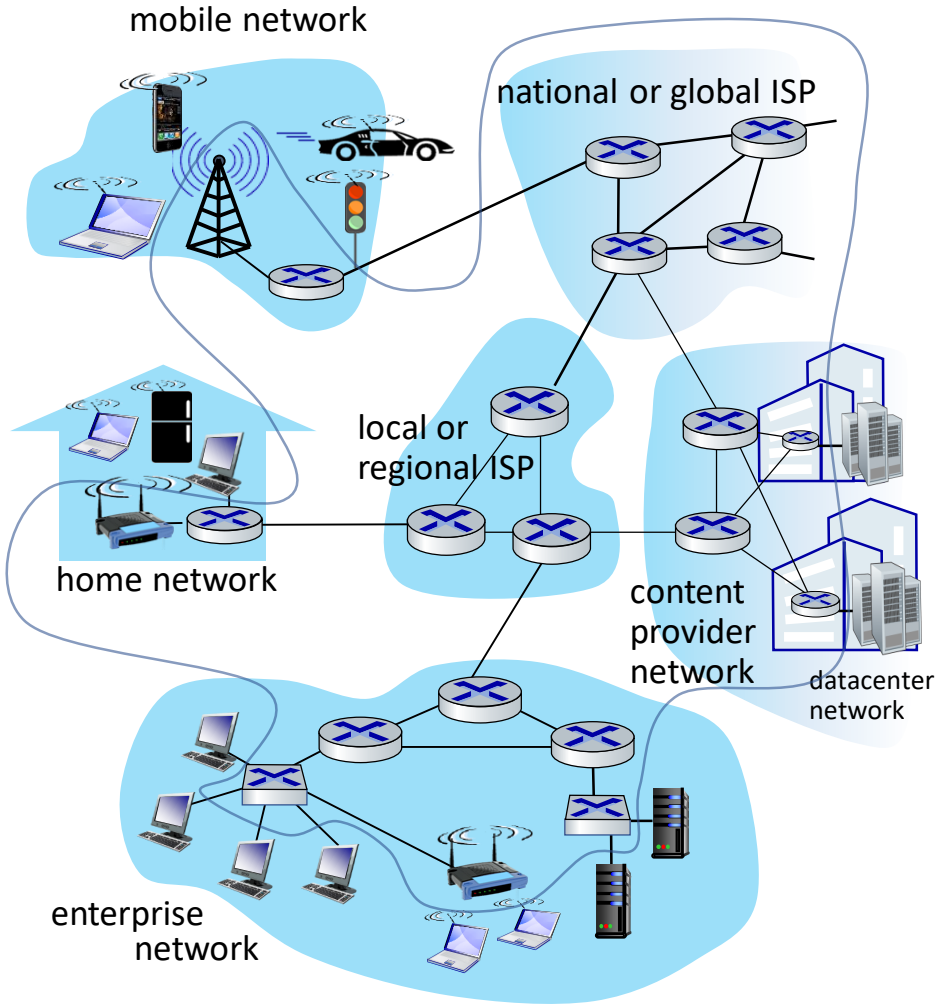
*Communication links*

- 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

Web-enabled toaster + weather forecaster

Slingbox: remote control cable TV

Security Camera

AR devices

Internet phones

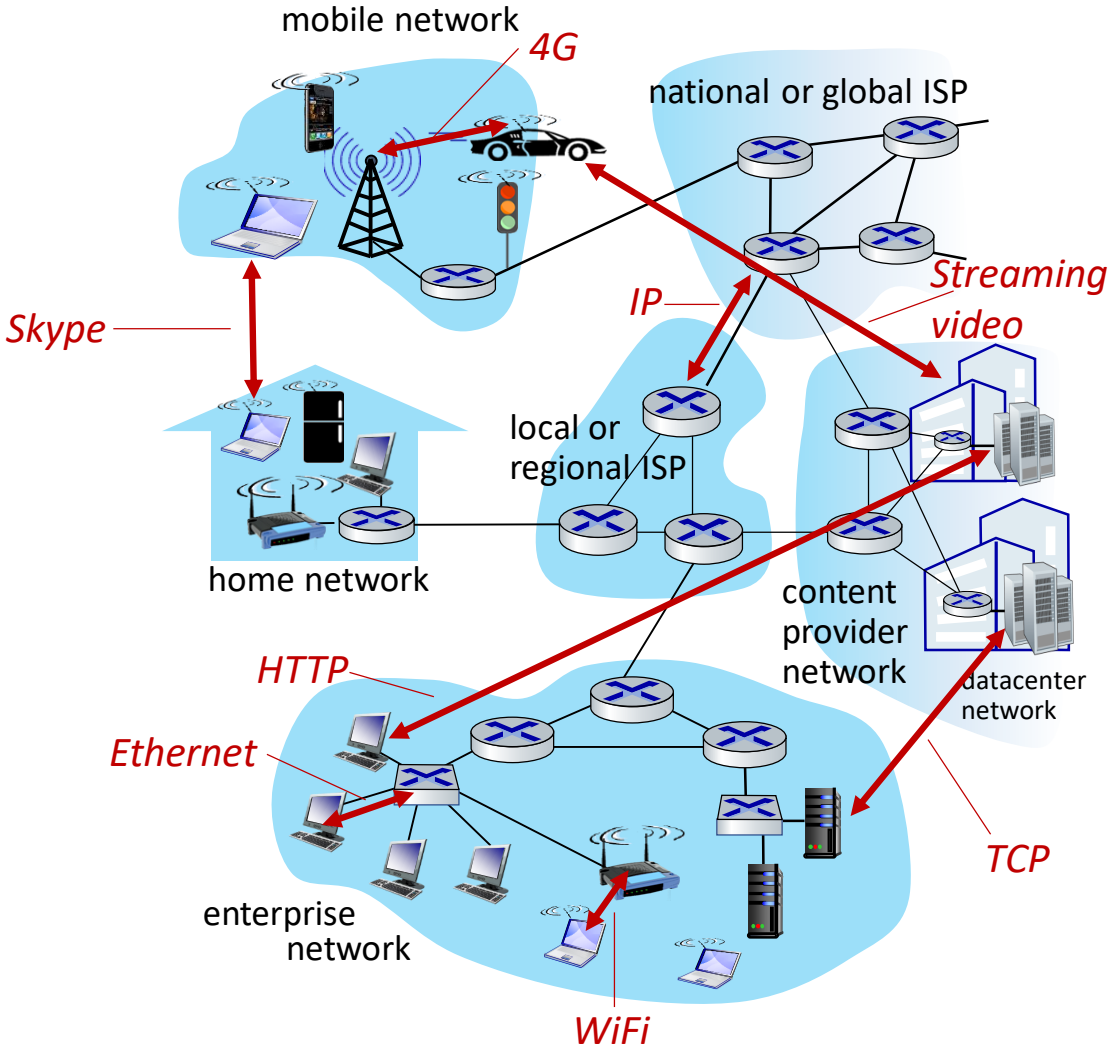
sensorized, bed mattress

Fitbit

*Others?*

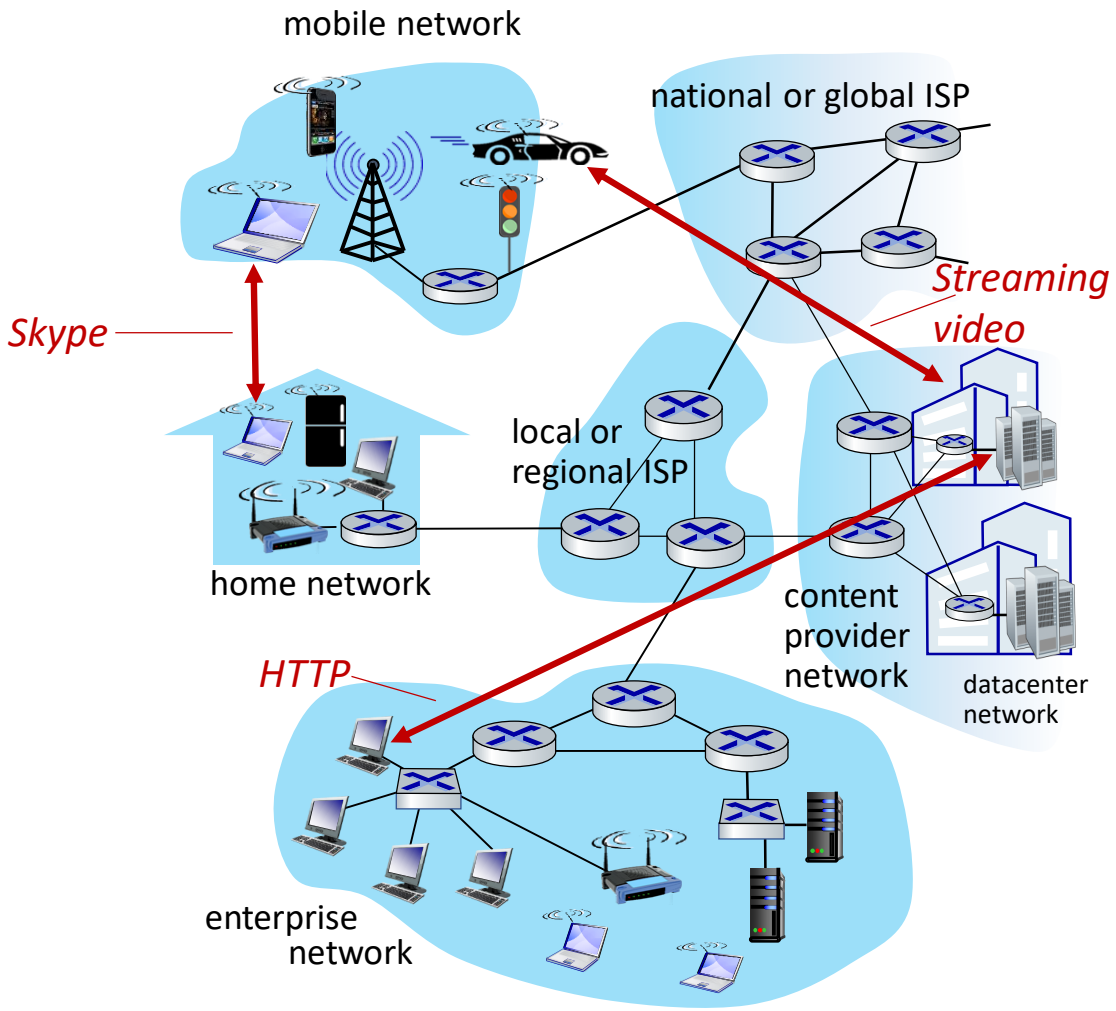
# The Internet: a "nuts and bolts" view

- *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

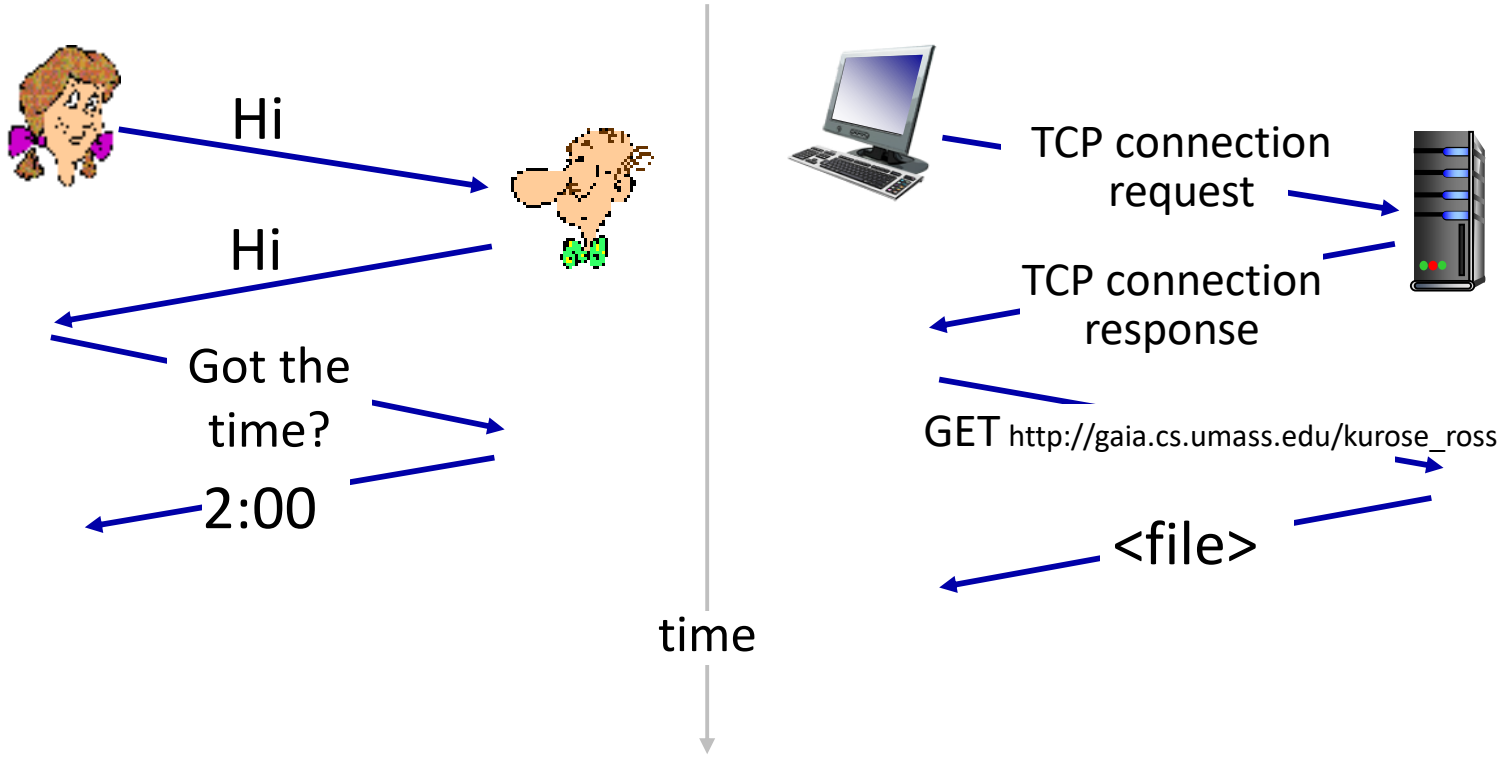
*Network protocols:*

- 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?

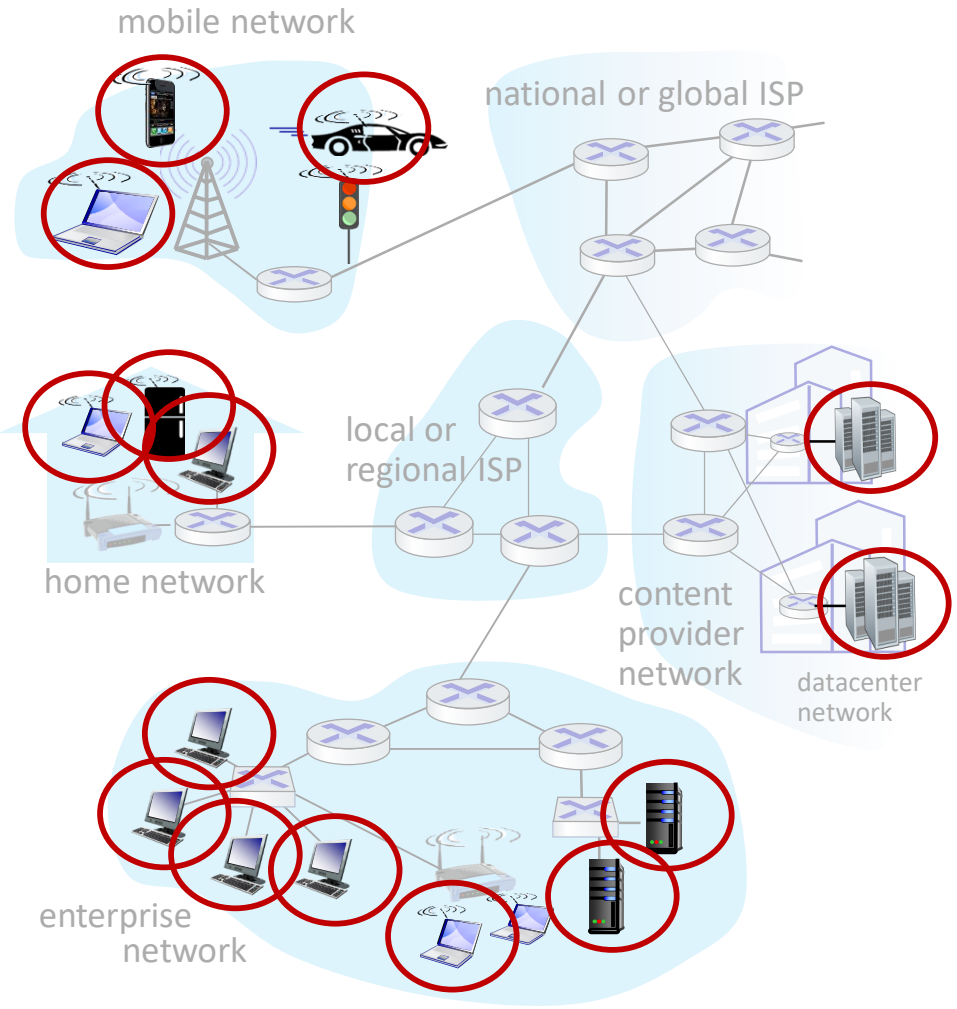
A human protocol and a computer network protocol:



# A closer look at Internet structure

## Network edge:

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



# Client vs Server

- When used in connection-oriented protocols:
  - Client: party that creates connection
  - Server: party that awaits connections
- When used in application-level protocols:
  - Client: party that requests something
  - Server: party that provides something
- When used to categorize end hosts:
  - Client: computer that mostly runs programs that act as application-level clients
  - Server: computer that mostly runs programs that act as application-level servers

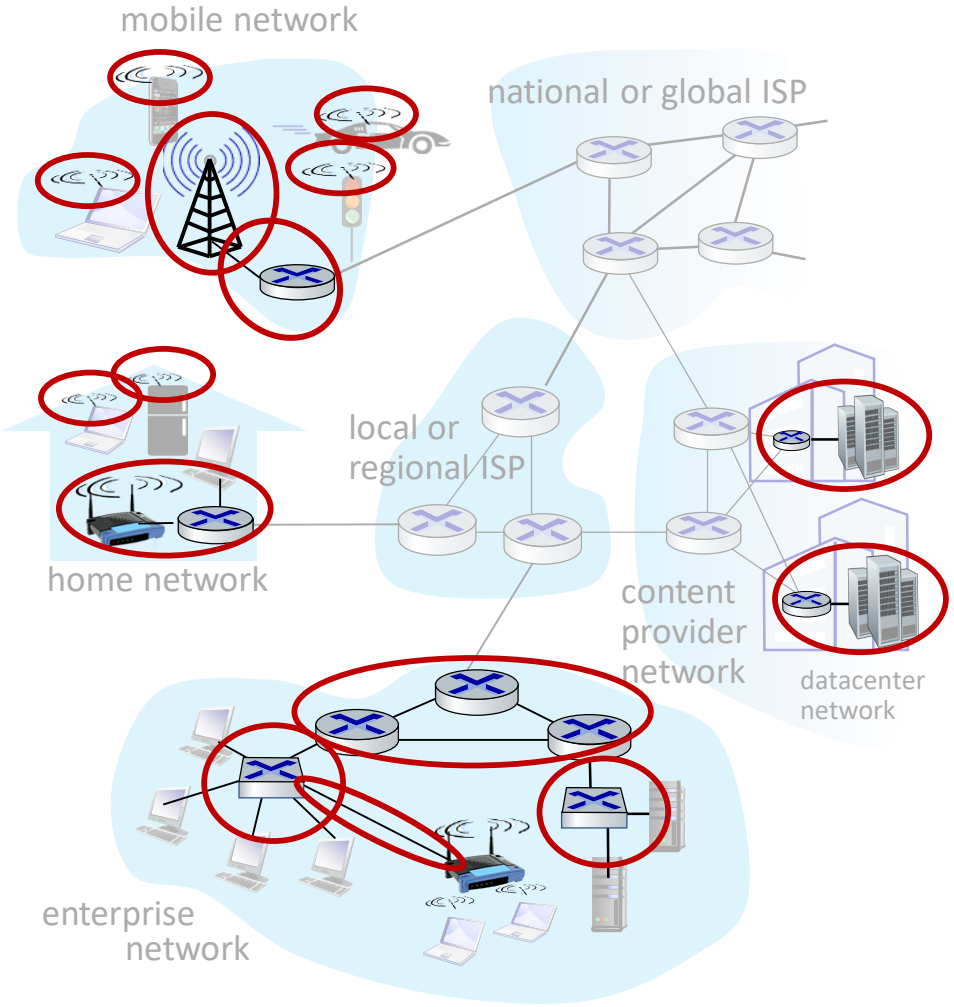
# A closer look at Internet structure

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:

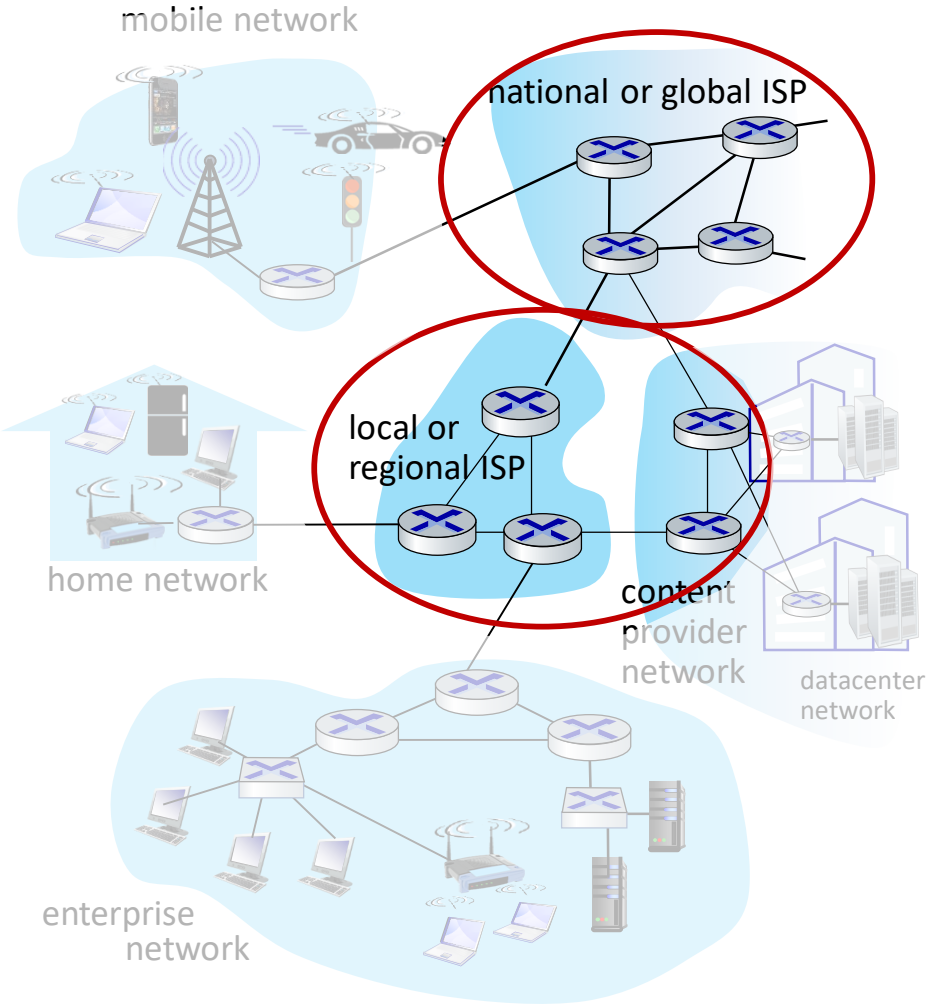
- hosts: clients and servers
- servers often in data centers

## Access networks, physical media:

- wired, wireless communication links

## Network core:

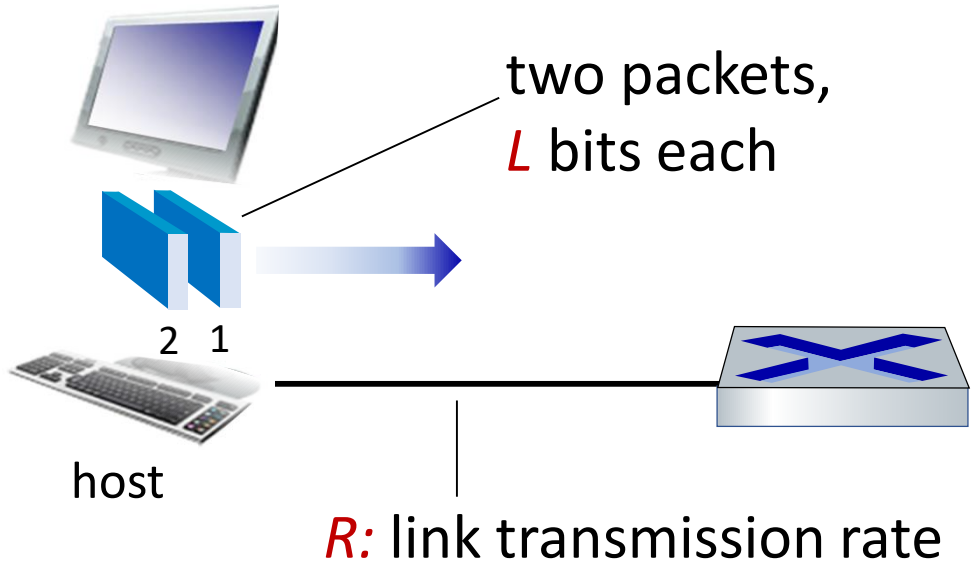
- interconnected routers
- network of networks



# 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*



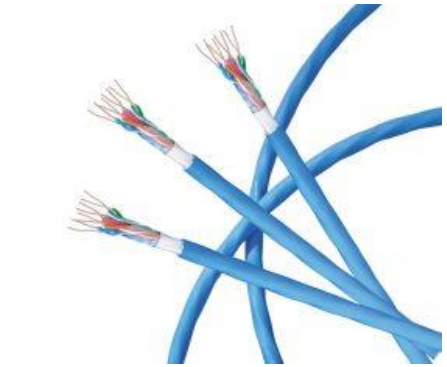

$$\text{packet transmission delay} = \text{time needed to transmit } L\text{-bit packet into link} = \frac{L \text{ (bits)}}{R \text{ (bits/sec)}}$$

# 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



- Other examples:
  Coax, Fiber
  Wireless links; Satellite;

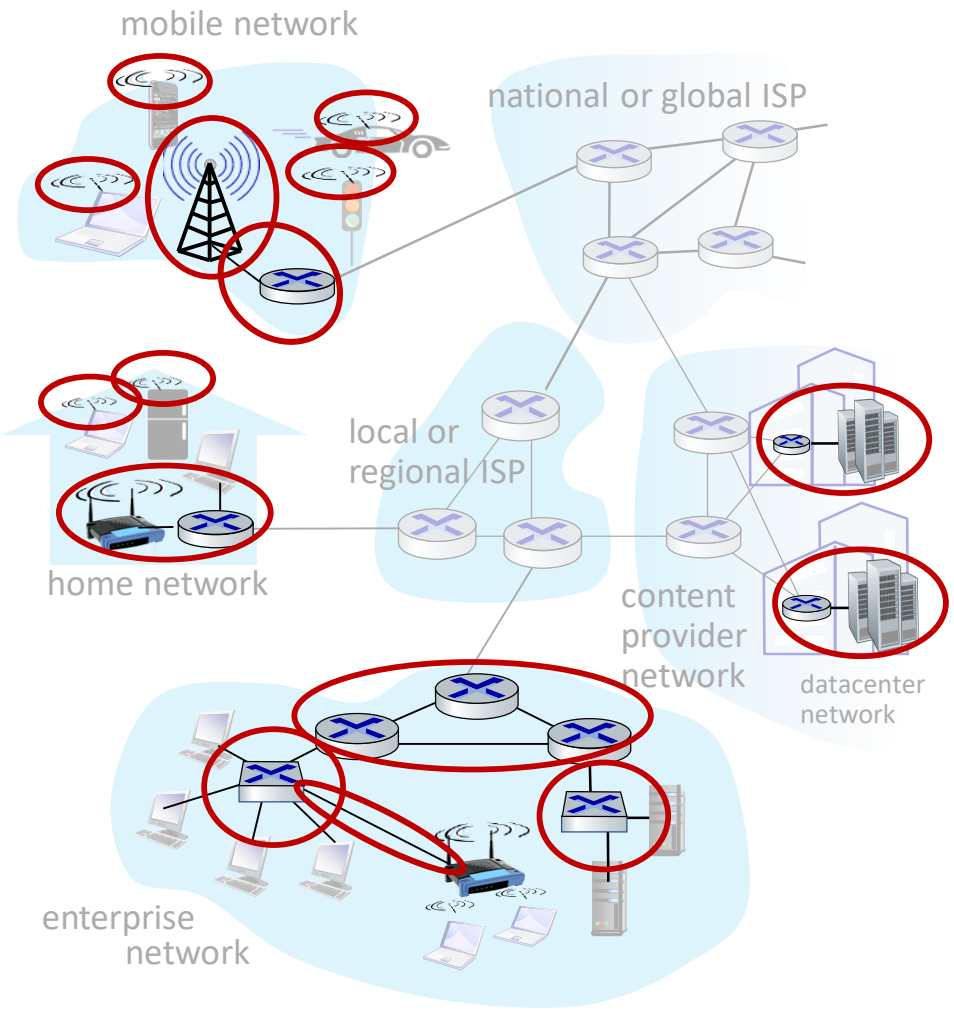
# Access networks and physical media

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

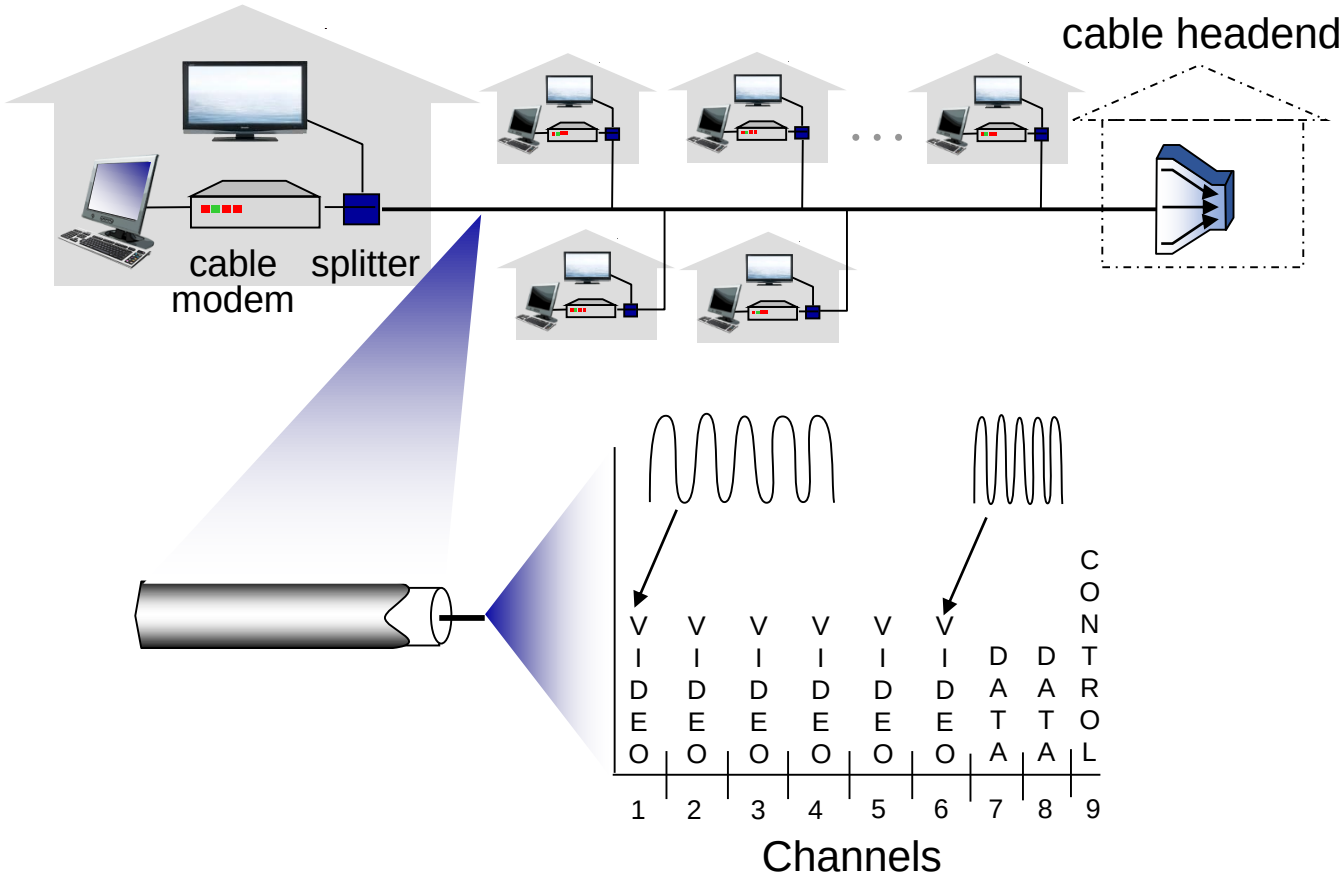
- residential access nets
- institutional access networks (school, company)
- mobile access networks (WiFi, 4G/5G)

*What to look for:*

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

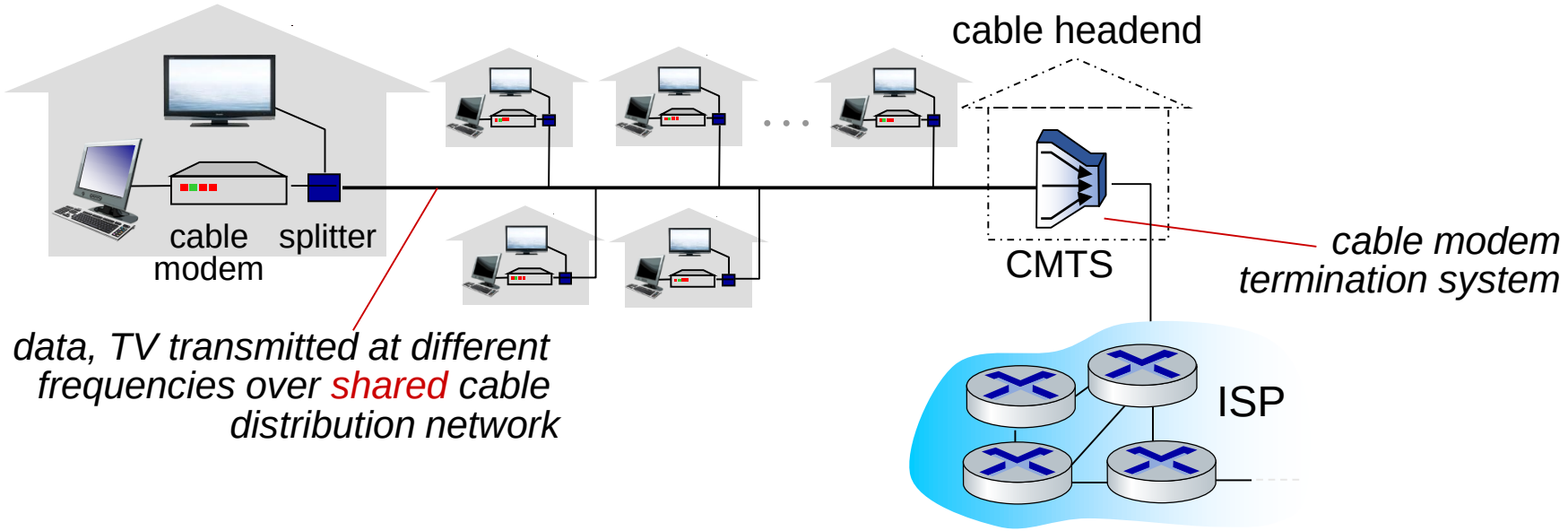


# Access networks: cable-based access




*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

192.168.100.1/cmSignal.htm

Not secure | 192.168.100.1/cmSignal.htm

SURFboard

**Cable Modem**

Status | Signal | Addresses | Configuration | Logs | Open Source | Help

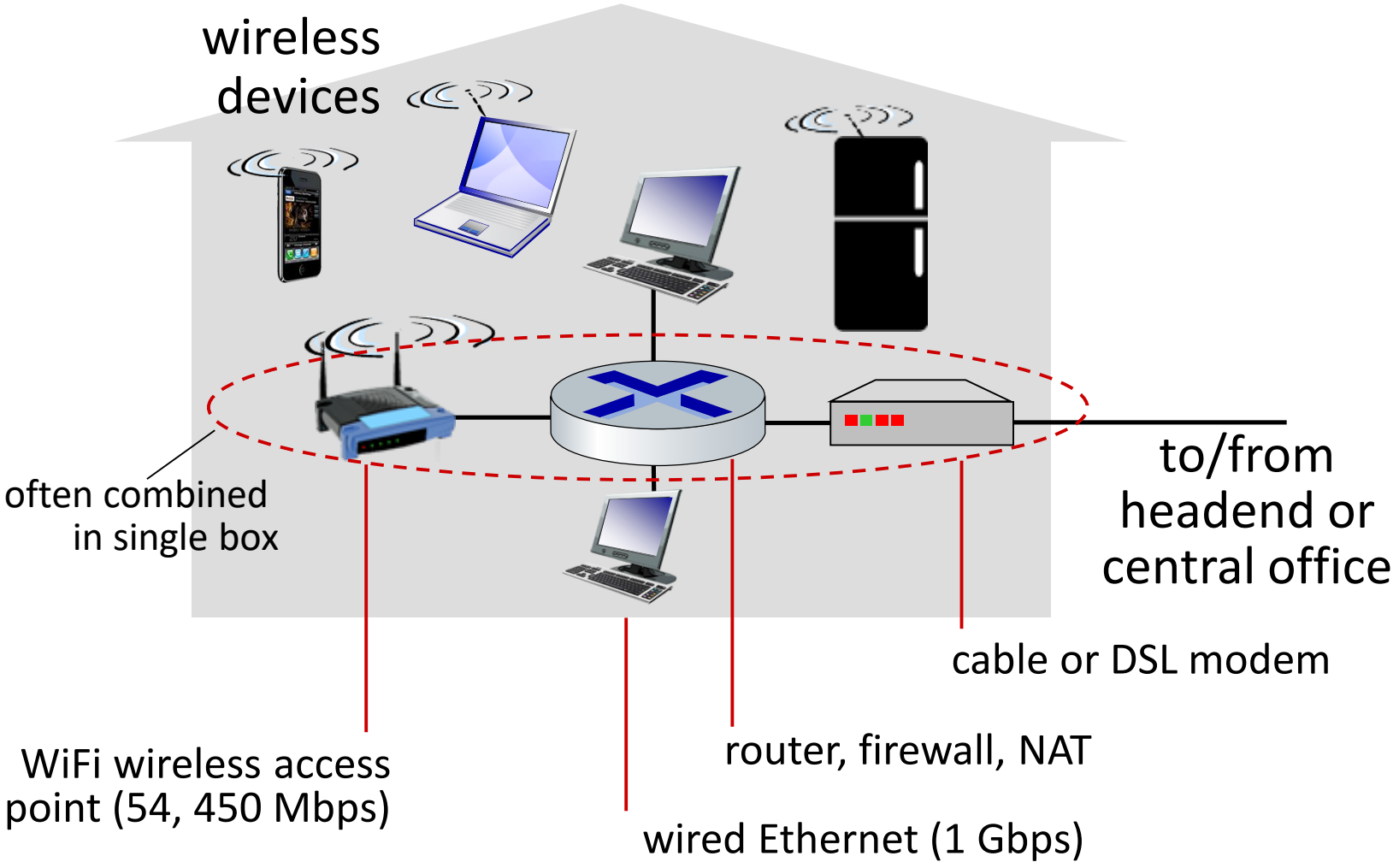
This page provides information about the current upstream and downstream signal status of your Cable Modem.

| Downstream | Bonding Channel Value | | | |
|---|---|---|---|---|
| Channel ID | 34 | 35 | 36 | 37 |
| Frequency | 429000000 Hz | 435000000 Hz | 441000000 Hz | 447000000 Hz |
| Signal to Noise Ratio | 37 dB | 37 dB | 37 dB | 37 dB |
| Downstream Modulation | QAM256 | QAM256 | QAM256 | QAM256 |
| Power Level<br>The Downstream Power Level reading is a snapshot taken at the time this page was requested. Please Reload/Refresh this Page for a new reading | 3 dBmV | 3 dBmV | 3 dBmV | 3 dBmV |

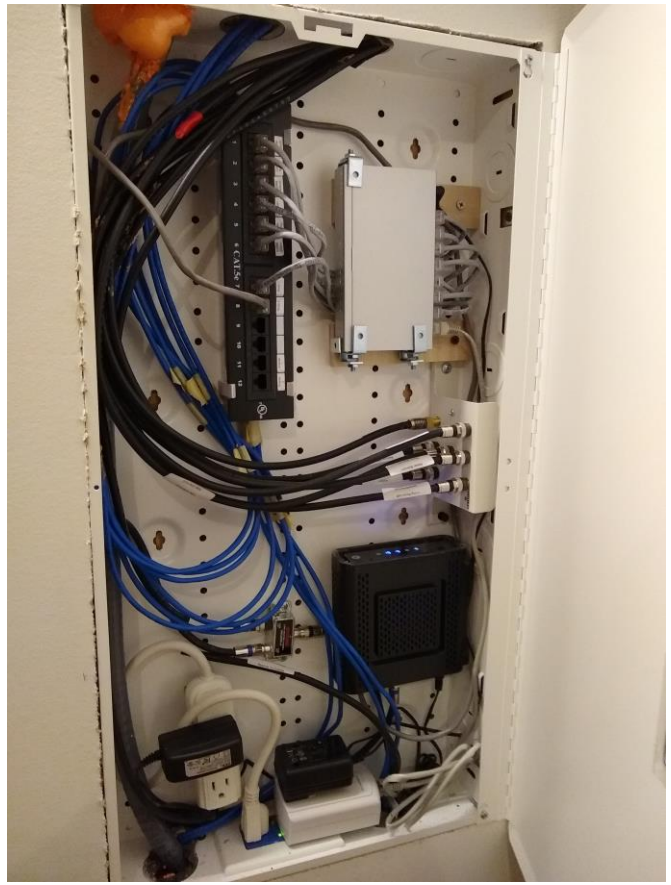
Example:
Dr. Back's Cable Modem Signal Status page.
4 downstream channels (bonded) 34-37 and
4 upstream channels (25-28)

| Upstream | Bonding Channel Value | | | |
|---|---|---|---|---|
| Channel ID | 26 | 28 | 27 | 25 |
| Frequency | 23700000 Hz | 36500000 Hz | 30100000 Hz | 17300000 Hz |
| Ranging Service ID | 13185 | 13185 | 13185 | 13185 |
| Symbol Rate | 5.120 Msym/sec | 5.120 Msym/sec | 5.120 Msym/sec | 5.120 Msym/sec |
| Power Level | 38 dBmV | 39 dBmV | 38 dBmV | 39 dBmV |
| Upstream Modulation | [2] QPSK<br>[1] 32QAM<br>[3] 64QAM | [2] QPSK<br>[1] 32QAM<br>[3] 64QAM | [2] QPSK<br>[1] 32QAM<br>[3] 64QAM | [2] QPSK<br>[1] 32QAM<br>[3] 64QAM |
| Ranging Status | Success | Success | Success | Success |

# Access networks: home networks




Dr. Back's somewhat improvised structured wiring cabinet with cable modem and Gigabit switch



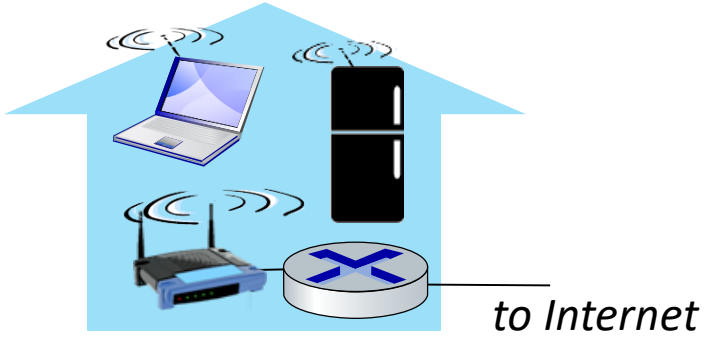
# Wireless access networks

Shared *wireless* access network connects end system to router

- via base station aka “access point”

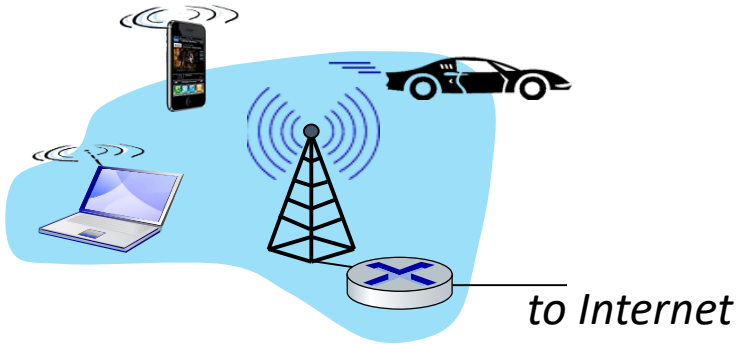
## Wireless local area networks (WLANs)

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

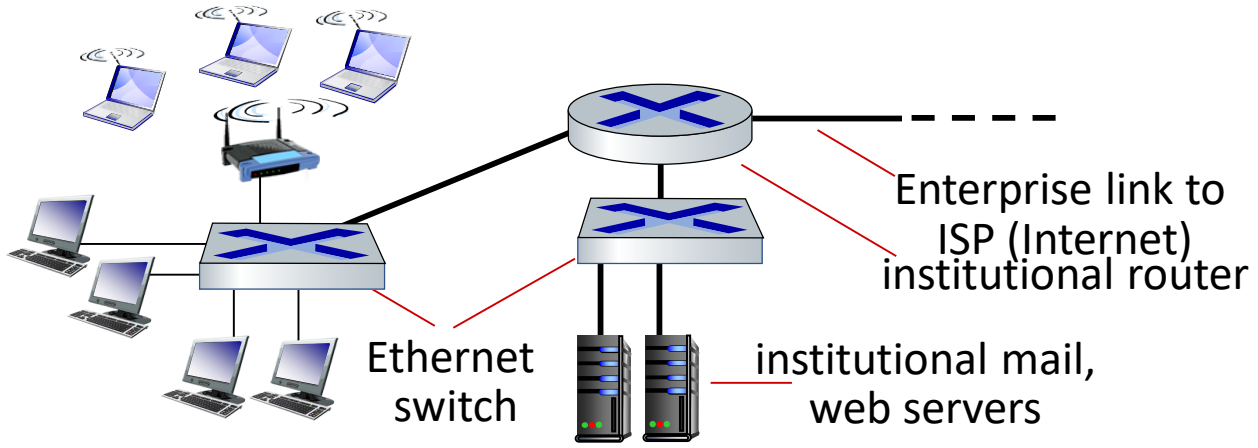



## Wide-area cellular access networks

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



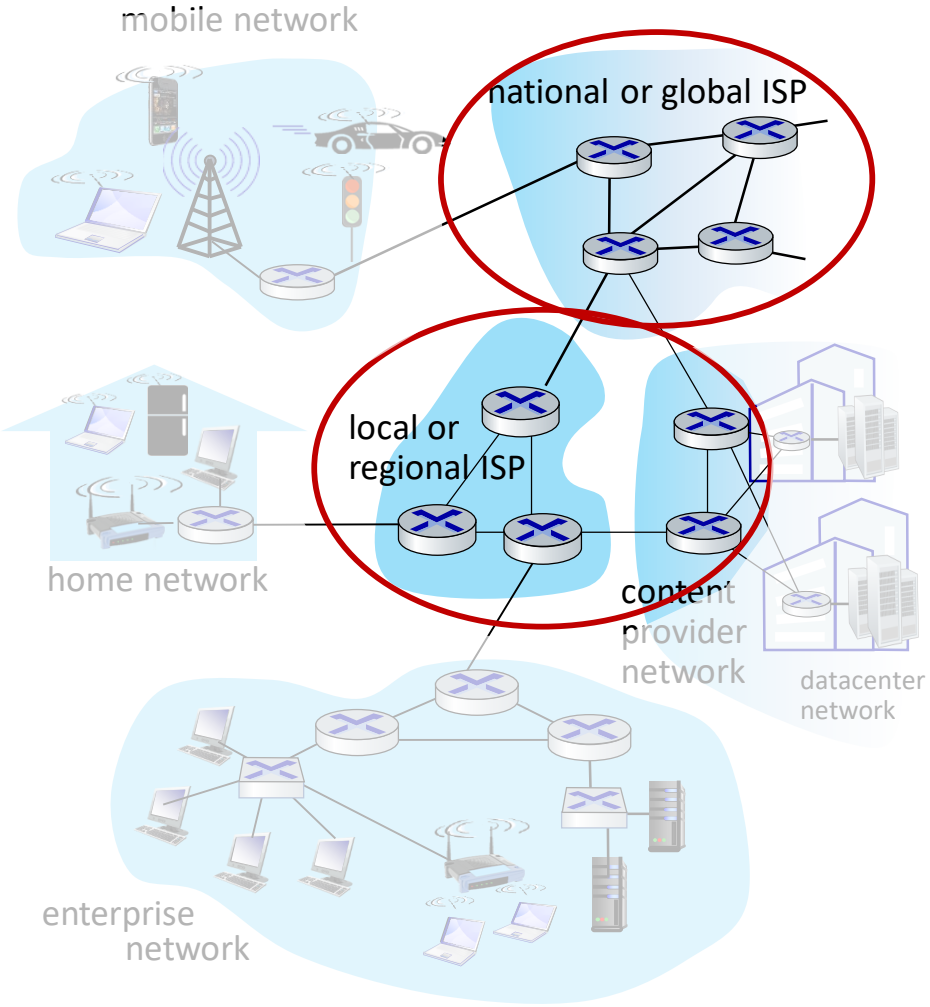
# Access networks: enterprise networks




- 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

# The network core

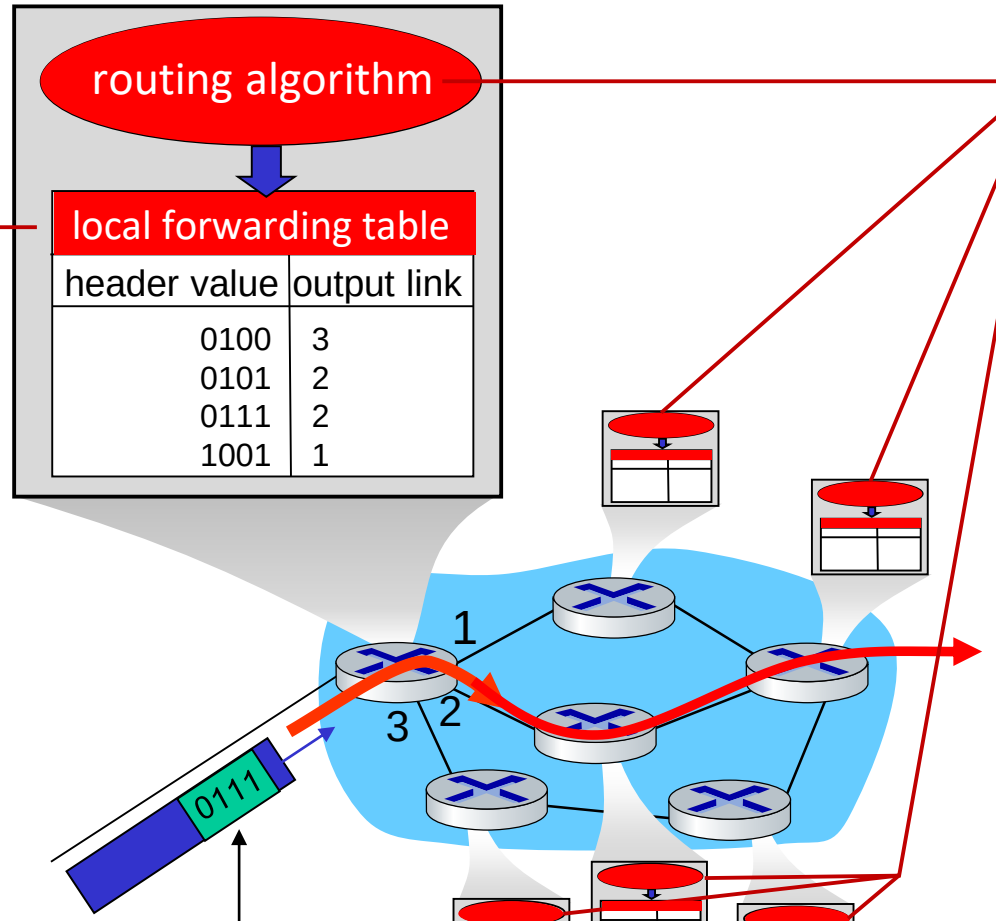
- mesh of interconnected routers
- packet-switching: hosts break application-layer messages into *packets*
  - forward packets from one router to the next, across links on path from source to destination
  - each packet transmitted at full link capacity



# Two key network-core functions

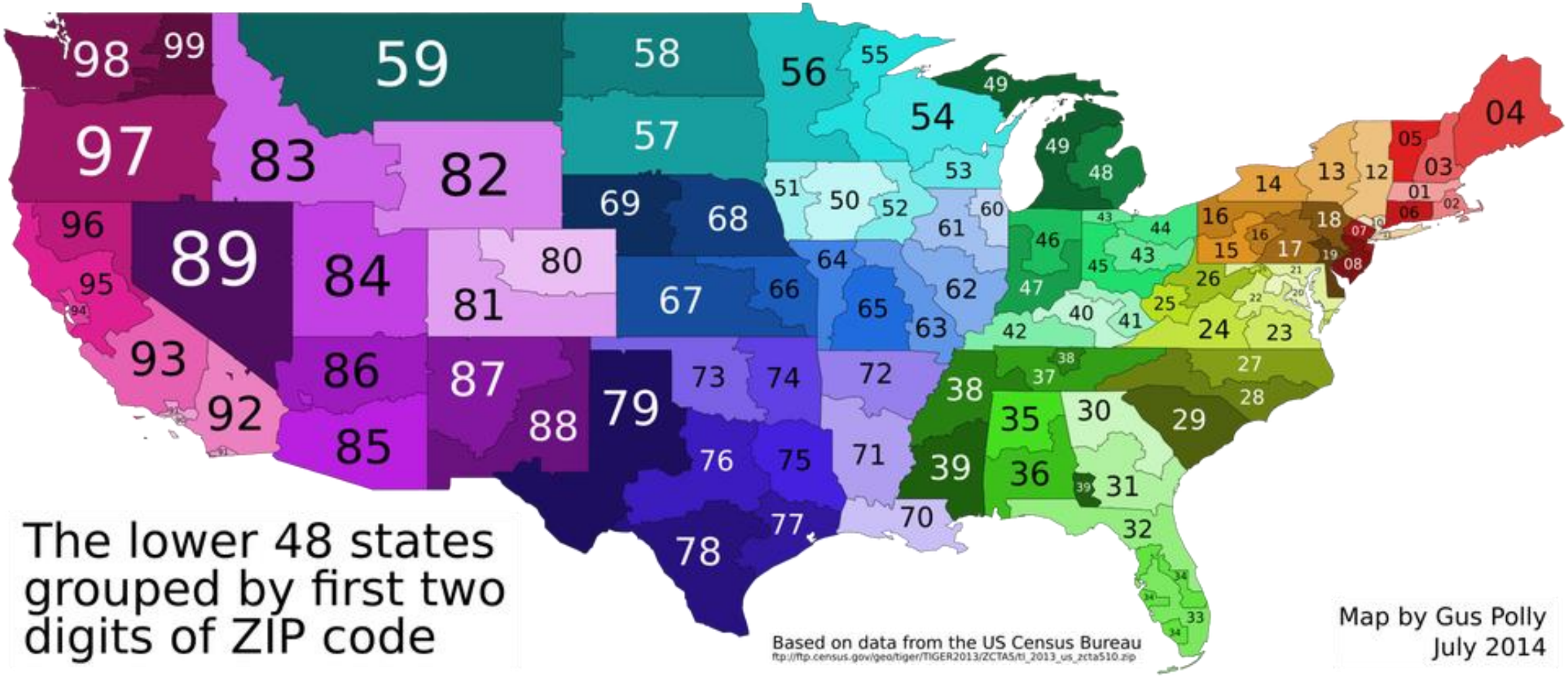
*Forwarding:*

- *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



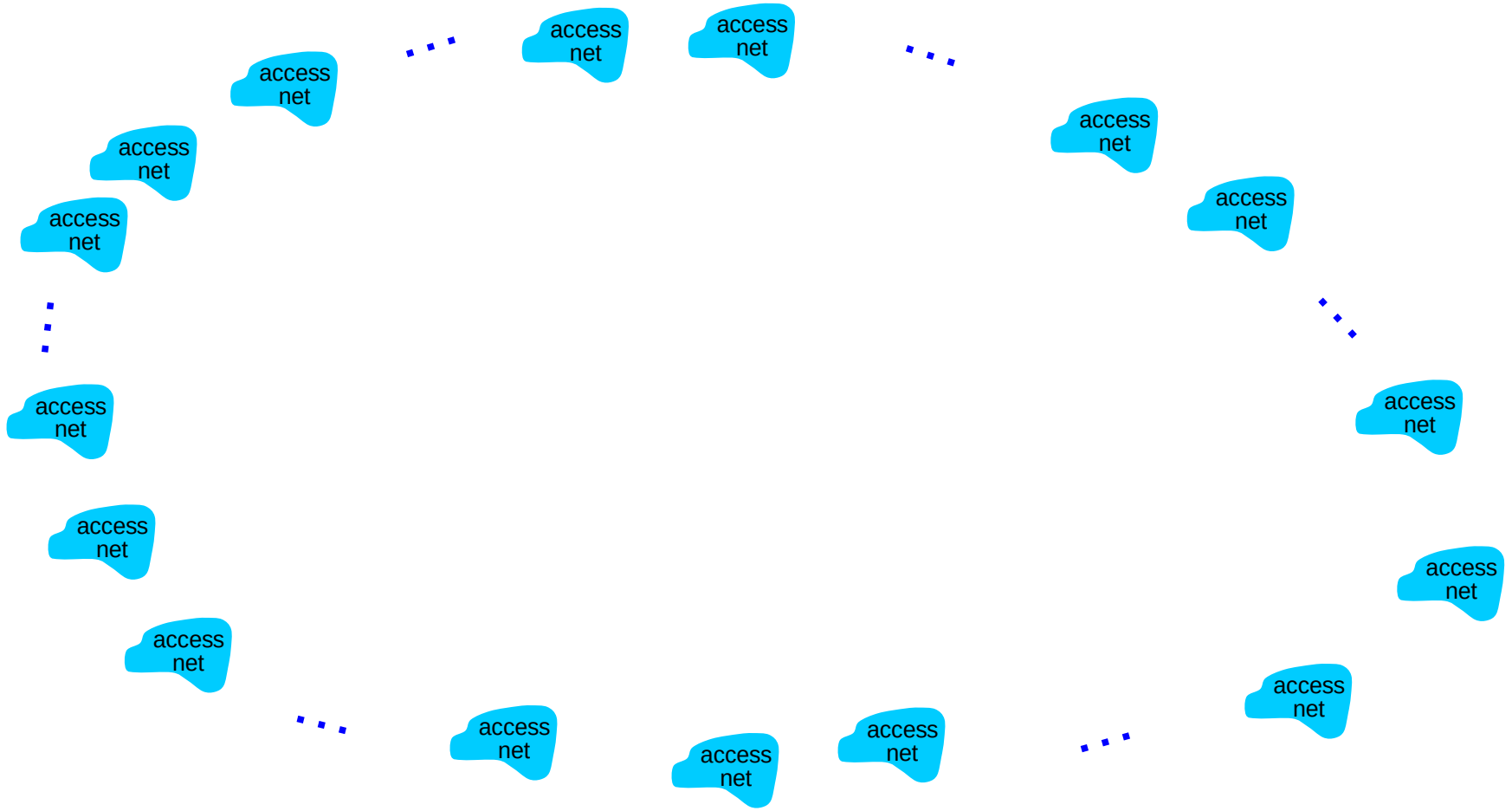

http://i.imgur.com/NJGcg6v.png

# Internet structure: a "network of networks"

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

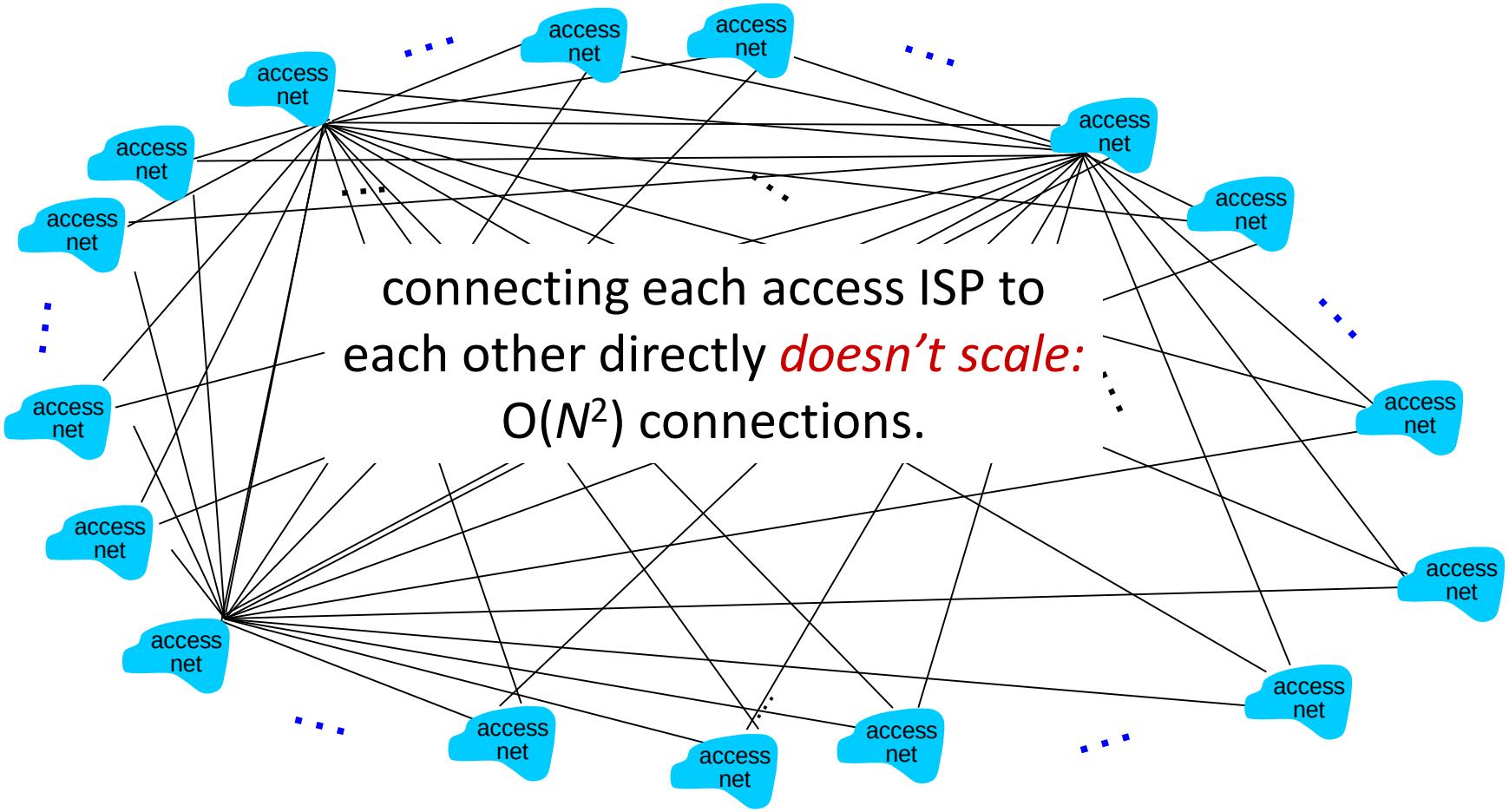
# Internet structure: a “network of networks”

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



# Internet structure: a "network of networks"

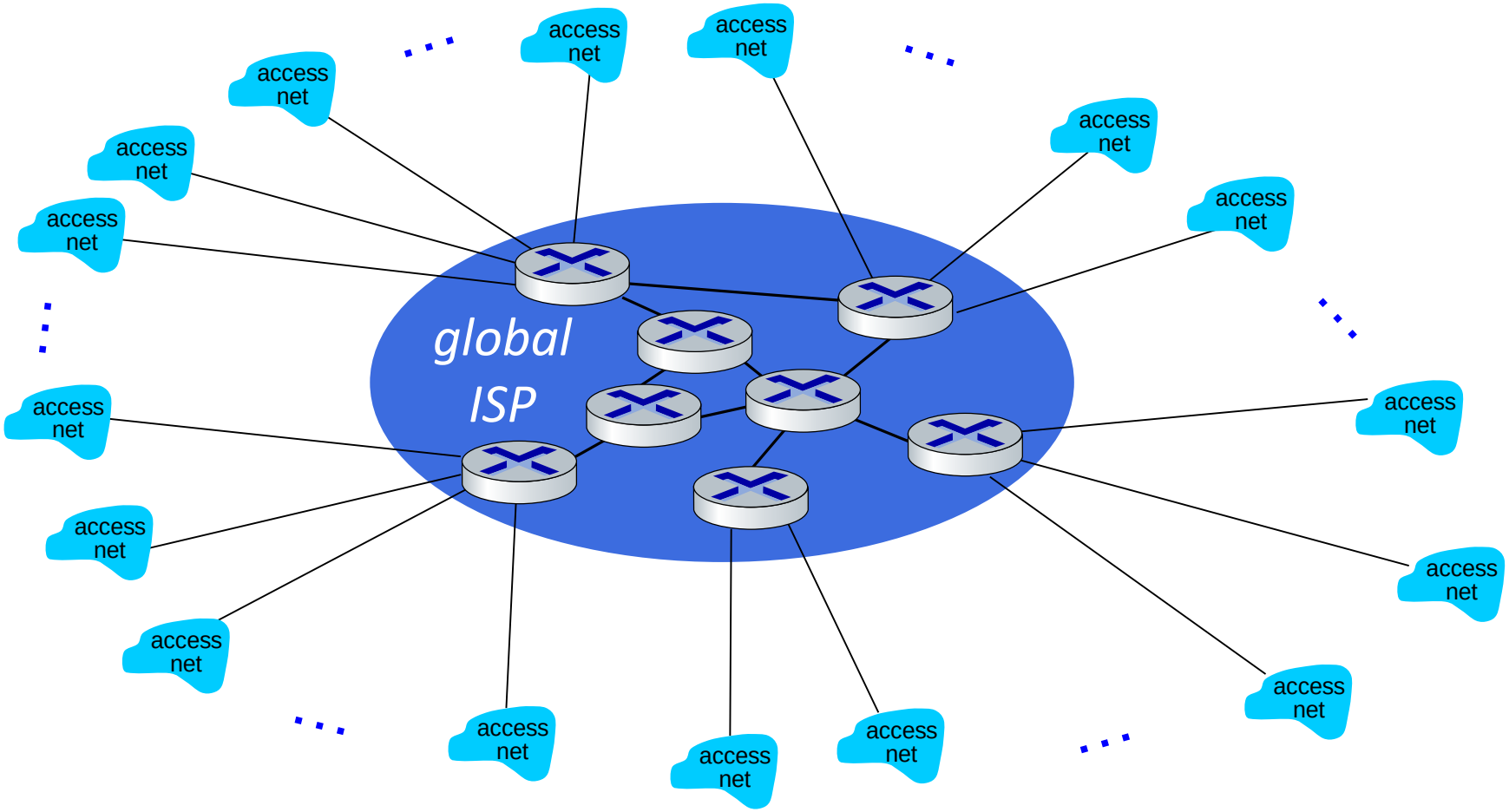
*Question:* given *millions* of access ISPs, how to connect them together?



# Internet structure: a “network of networks”

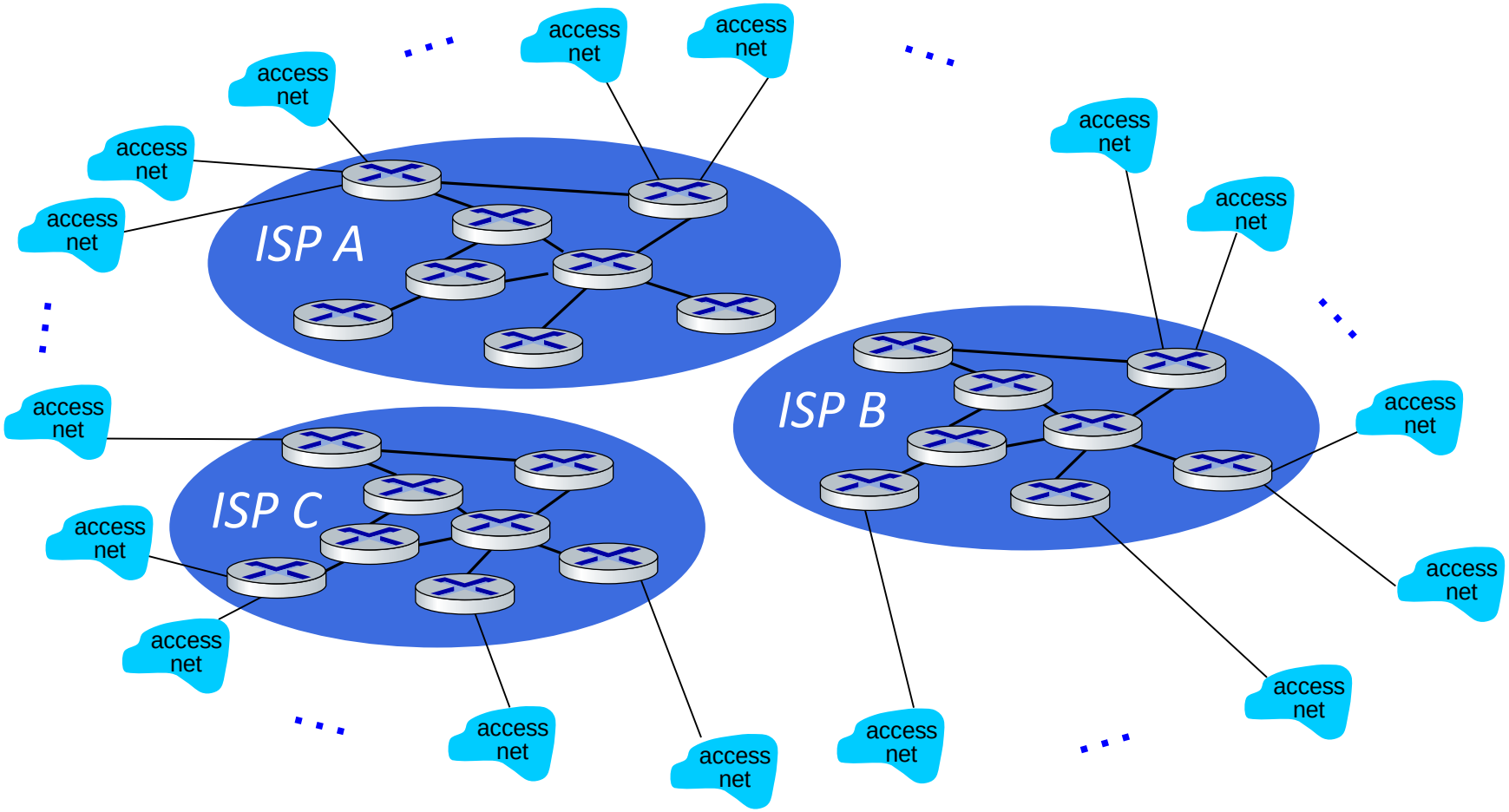
*Option: connect each access ISP to one global transit ISP?*

*Customer and provider ISPs have economic agreement.*



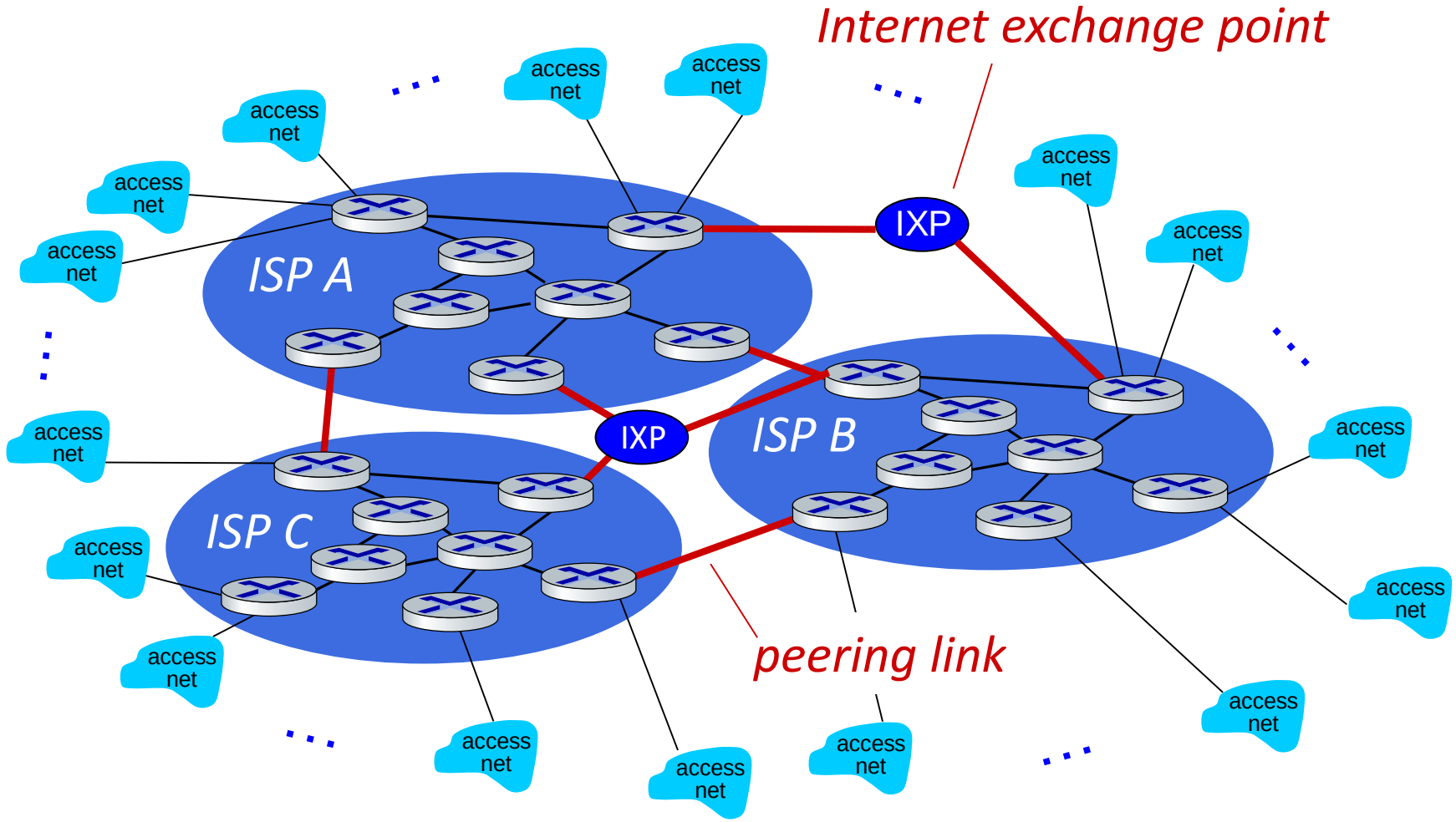
# Internet structure: a “network of networks”

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



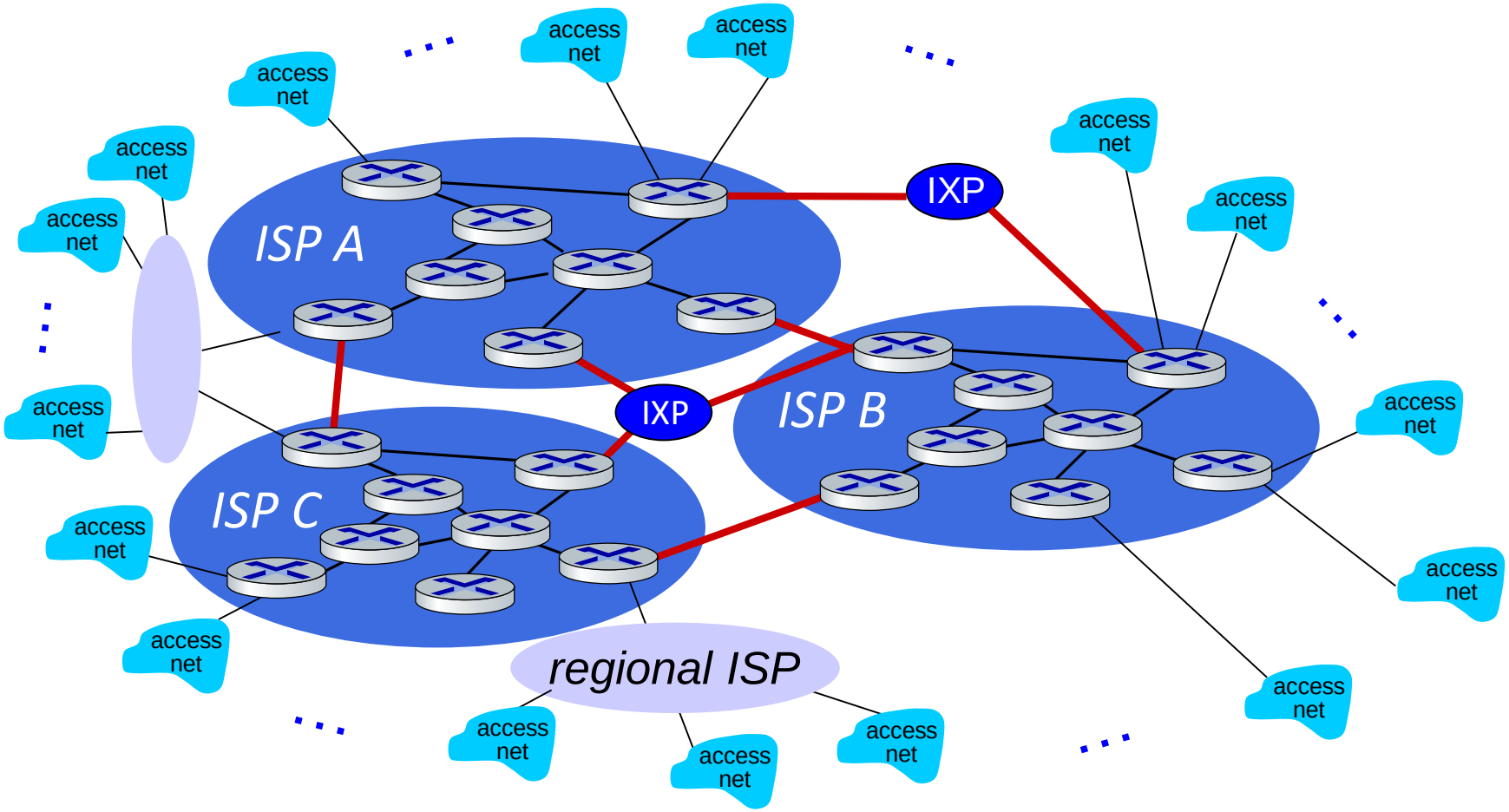
# Internet structure: a “network of networks”

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



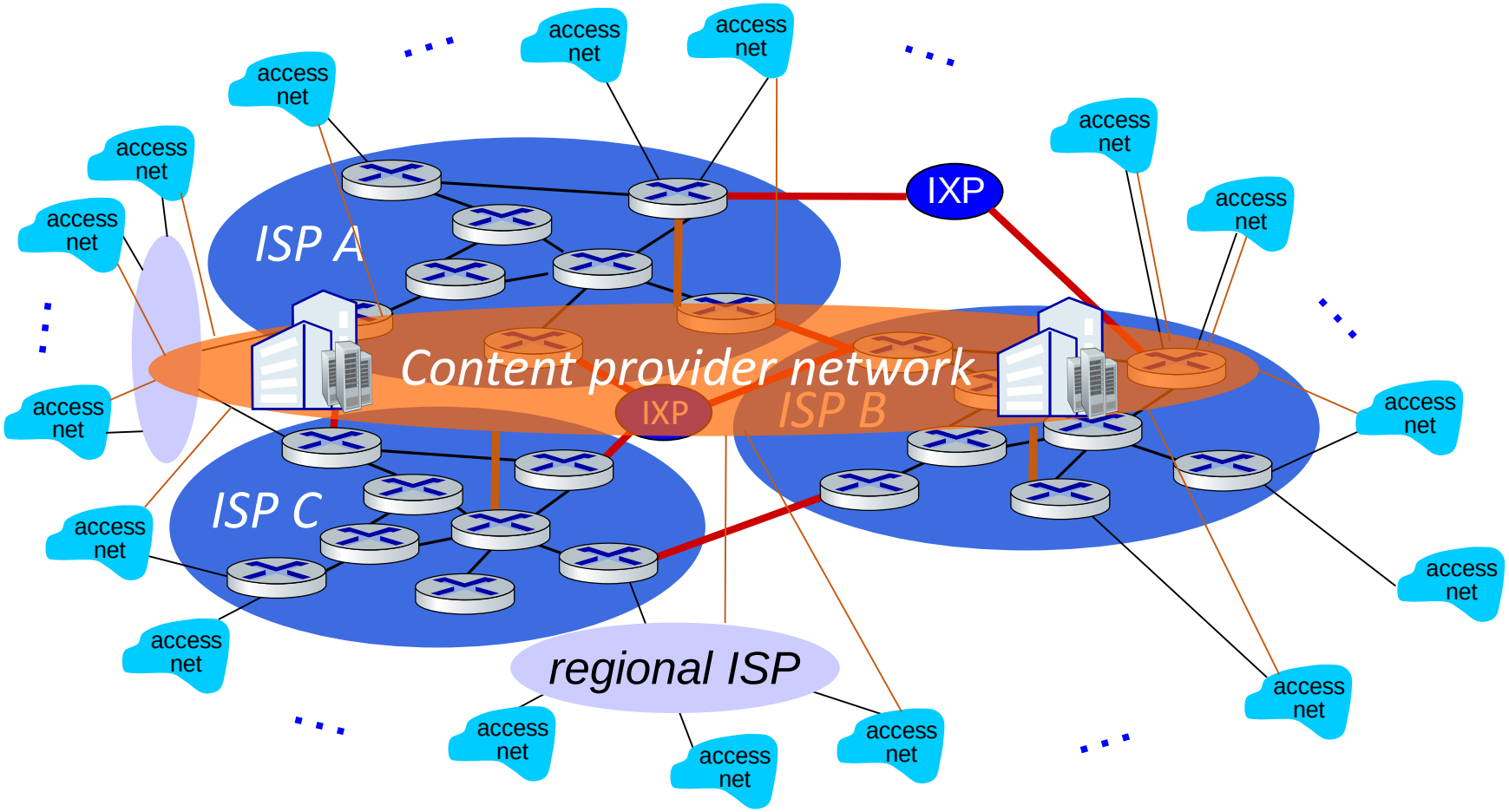
# Internet structure: a “network of networks”

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

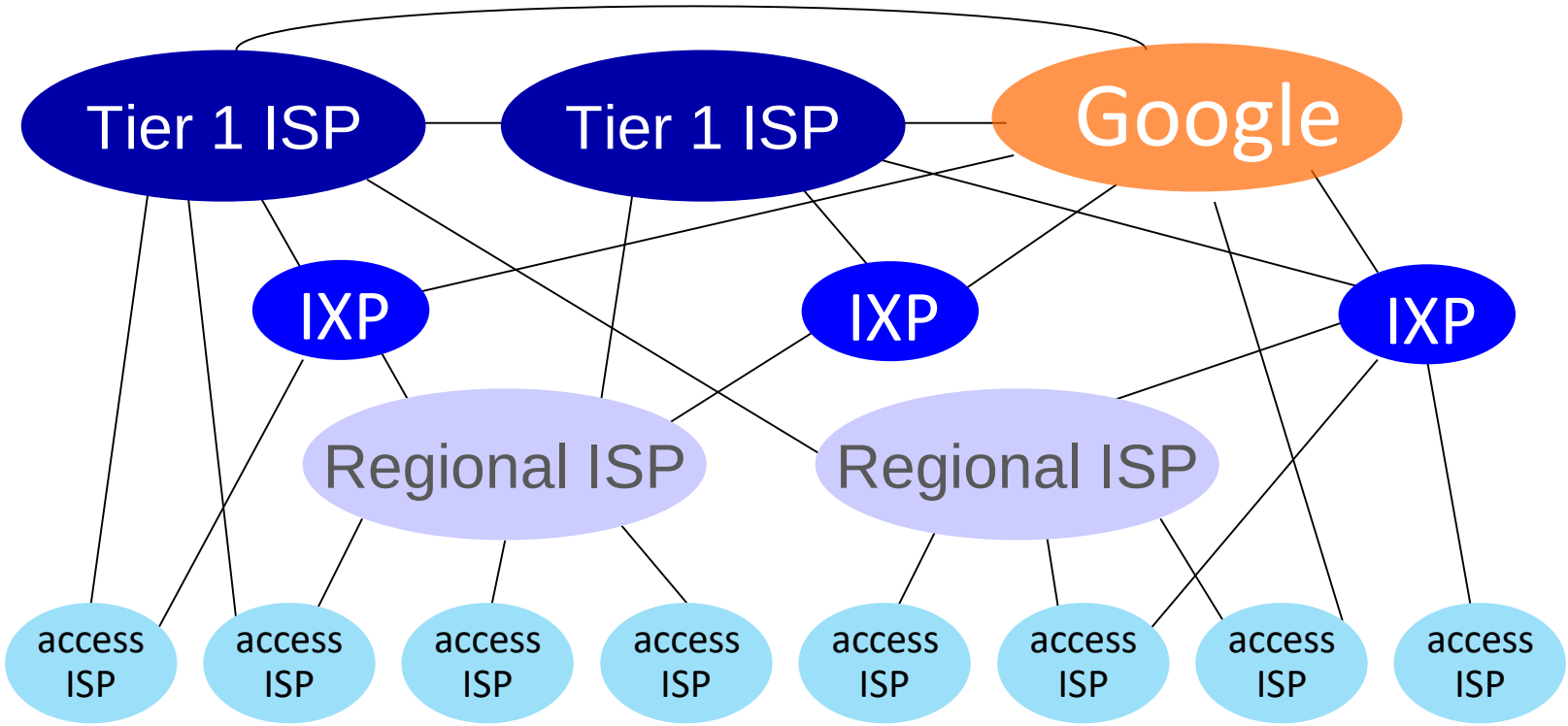


# Internet structure: a “network of networks”

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



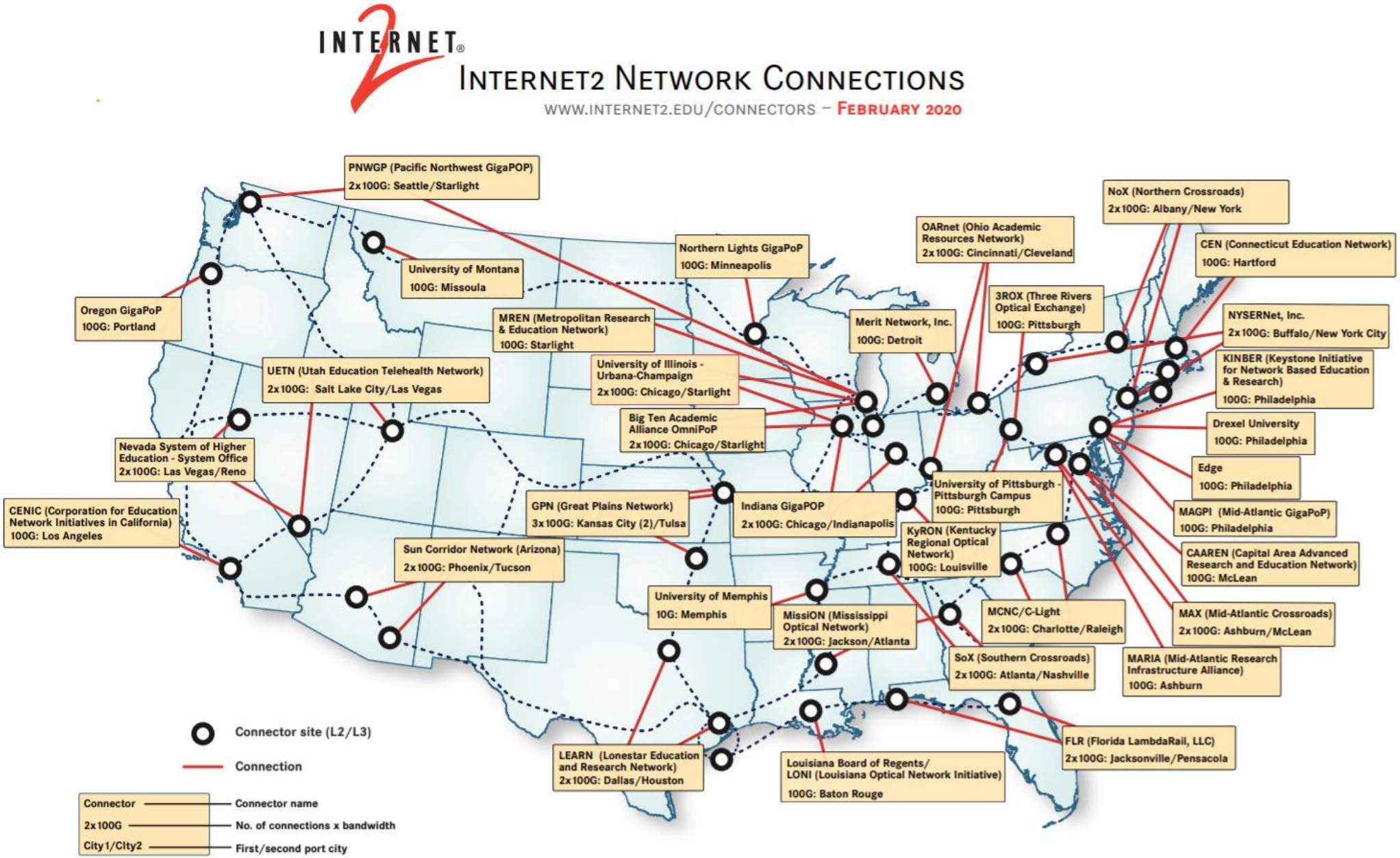
# Internet structure: a "network of networks"




At "center": small # of well-connected large networks

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

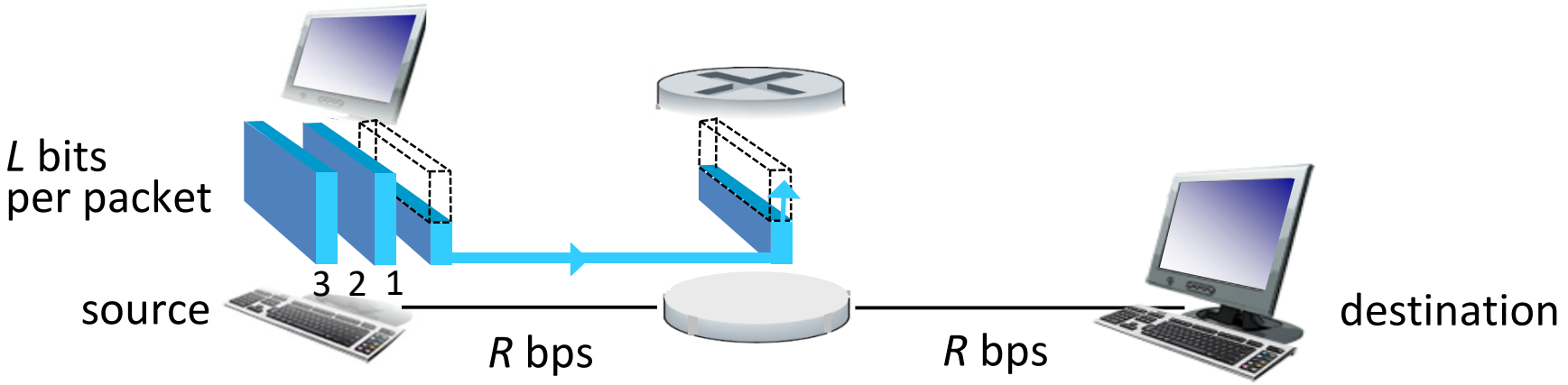
# Tier-1 ISP Network map: Sprint (2019)




https://www.internet2.edu/media/medialibrary/2020/02/19/ConnectorsMap_202002_XaFyViw.pdf

# Part II: On Delay & Throughput

# Packet-switching: store-and-forward

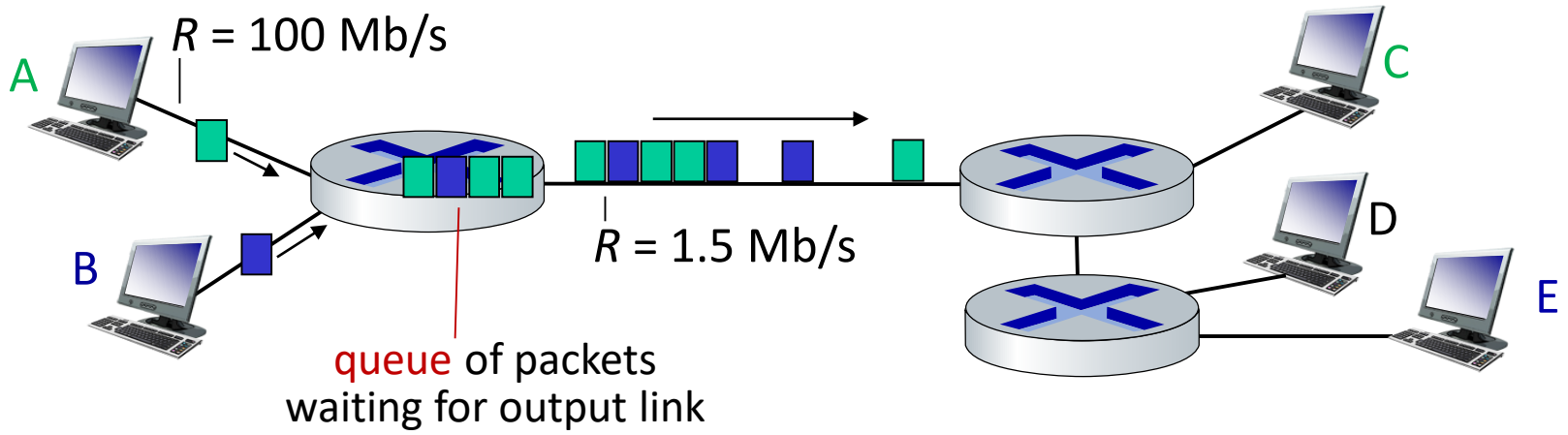



- Transmission delay: takes $L/R$ seconds to transmit (push out) $L$-bit packet into link at $R$ bps
- *Store and forward:* *entire* packet must arrive at router before it can be transmitted on next link
- *End-end delay:* $2L/R$ (above), assuming zero propagation delay (more on delay shortly)

*One-hop numerical example:*

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

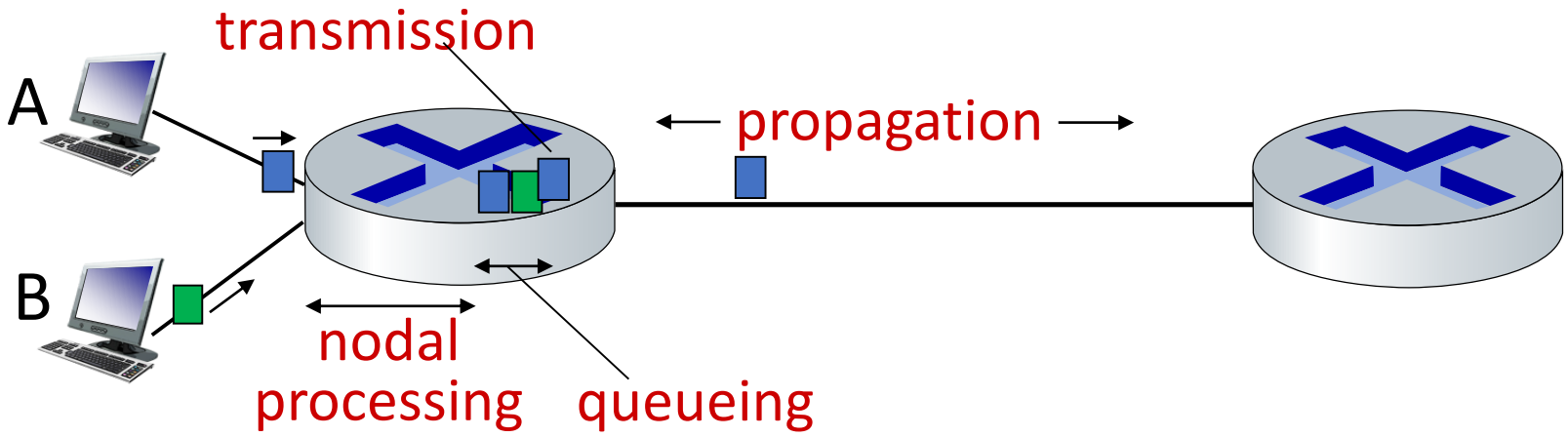
# Packet-switching: queueing delay, loss




*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

# Packet delay: four sources




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

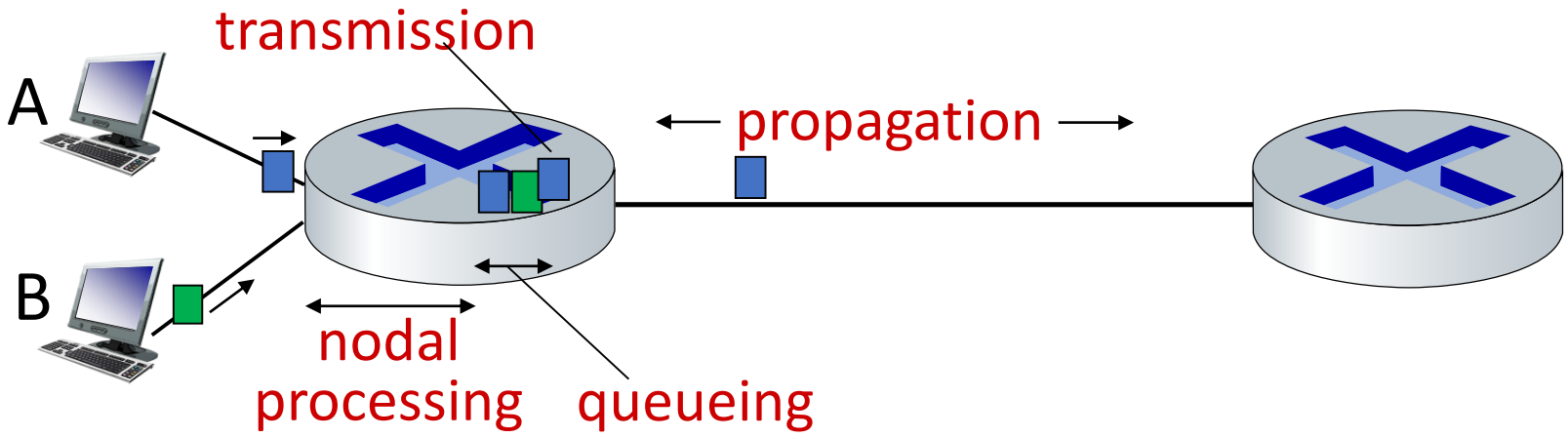
$d_{proc}$: nodal processing

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

$d_{queue}$: queueing delay

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

# Packet delay: four sources




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

$d_{trans}$: transmission delay:

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

$d_{prop}$: propagation delay:

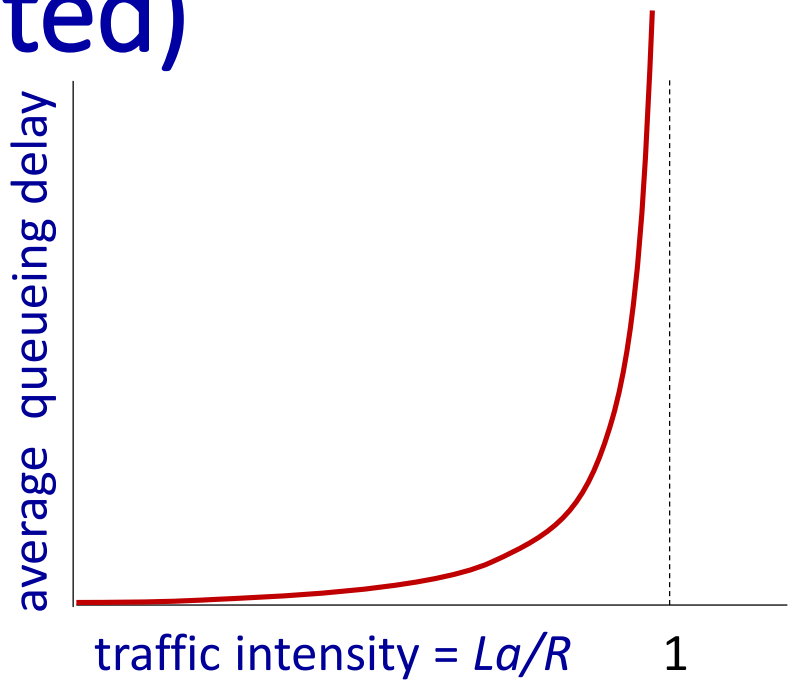
- $d$: length of physical link
- $s$: propagation speed (~$2 \times 10^8$ m/sec)
- $d_{prop} = d/s$

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

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

# Packet queueing delay (revisited)

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



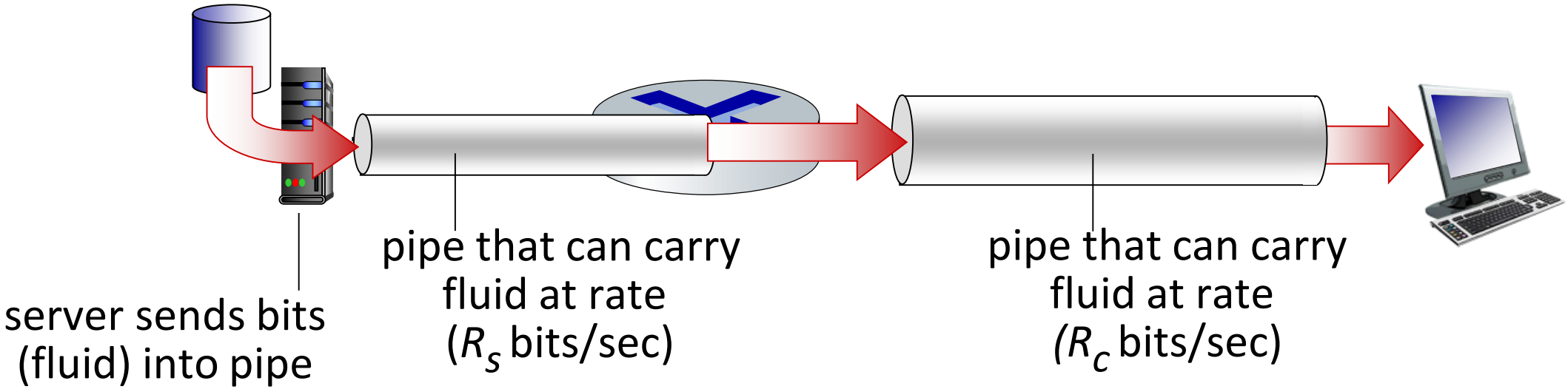

- *La/R* ~ 0: avg. queueing delay small
- *La/R* -> 1: avg. queueing delay large
- *La/R* > 1: more "work" arriving is more than can be serviced - average delay infinite!

*La/R* ~ 0

*La/R -> 1*

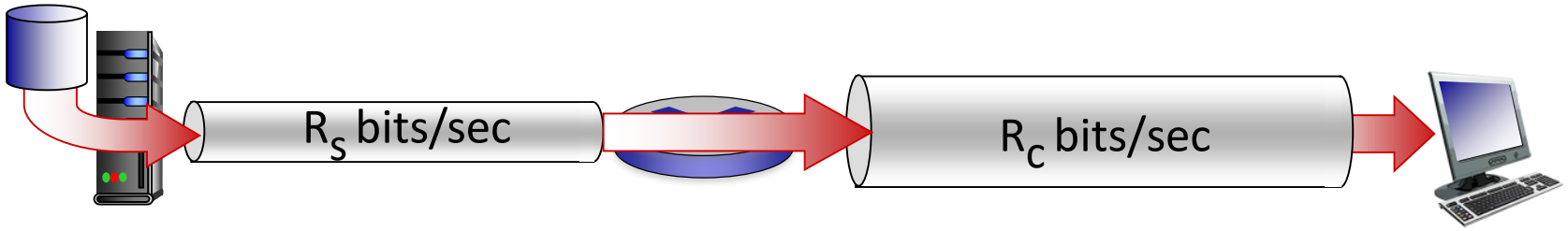
# Throughput

- *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

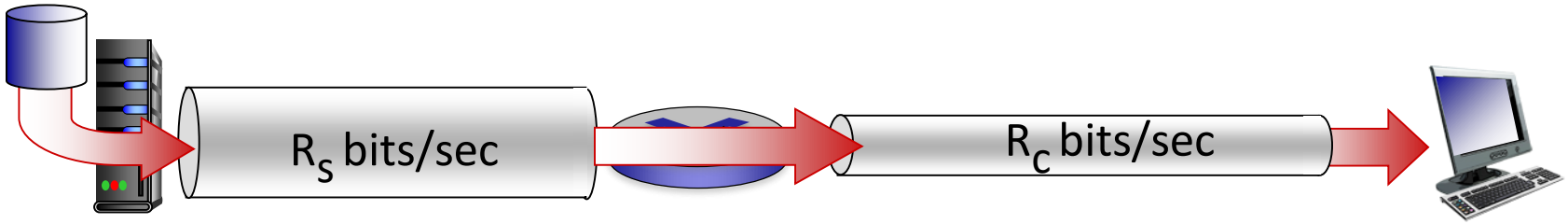


# Throughput

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



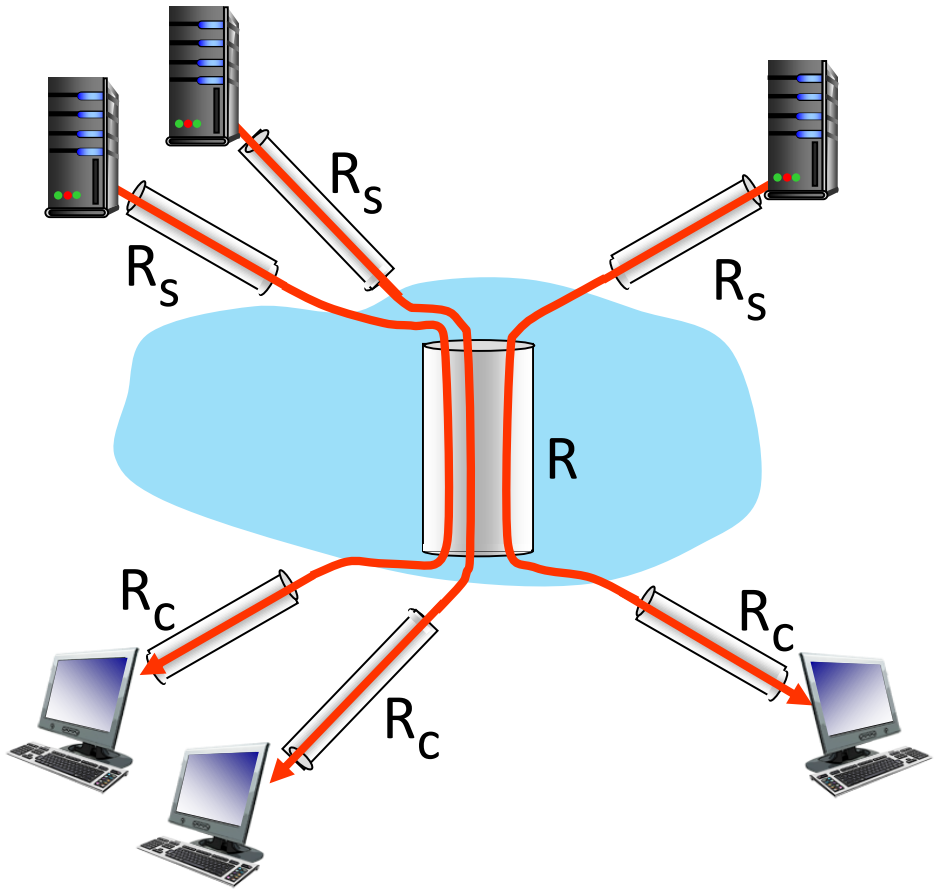

$R_s > R_c$ What is average end-end throughput?




*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/

# Part III: On Layering

# 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?

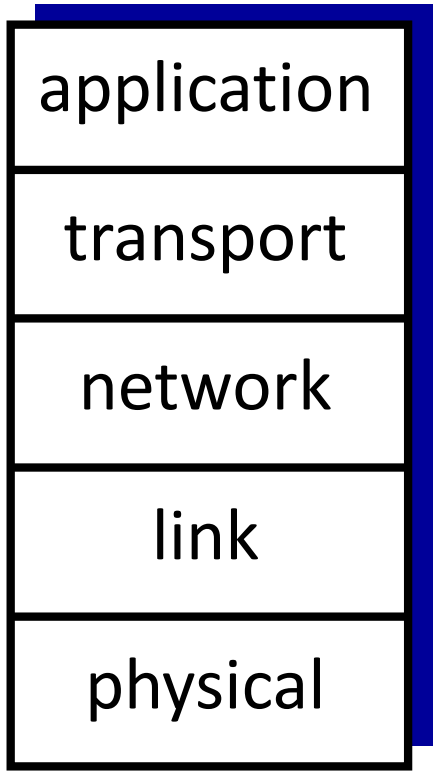
# Why layering?

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
- layering considered harmful?
- layering in other complex systems?

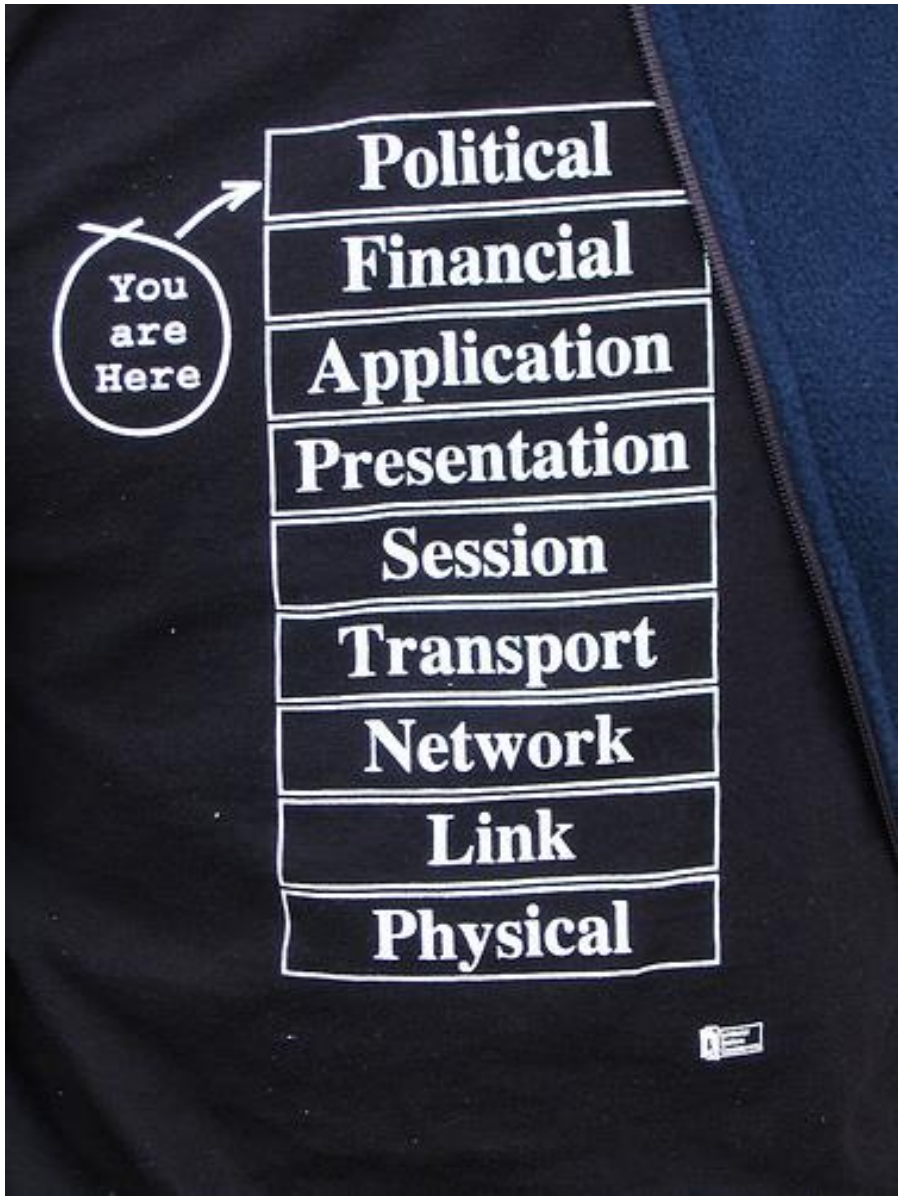
# Internet protocol stack

- *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”

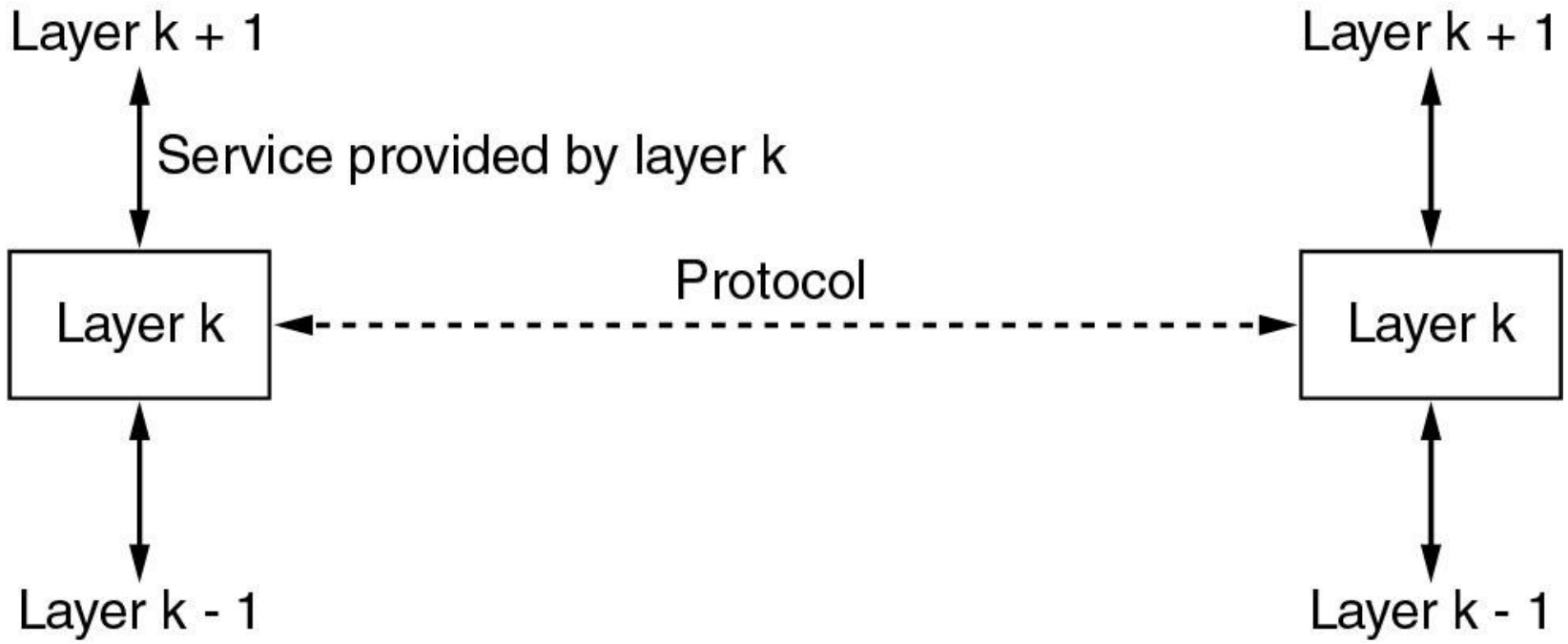


# Historical Sidenote

- Before the Internet protocol stack was established as a de facto standard, there were attempts at designing network protocols by committee, the so-called (Open System Interconnect) OSI/ISO reference model
- Never gained traction, but numbering “Layer 3” etc. survived



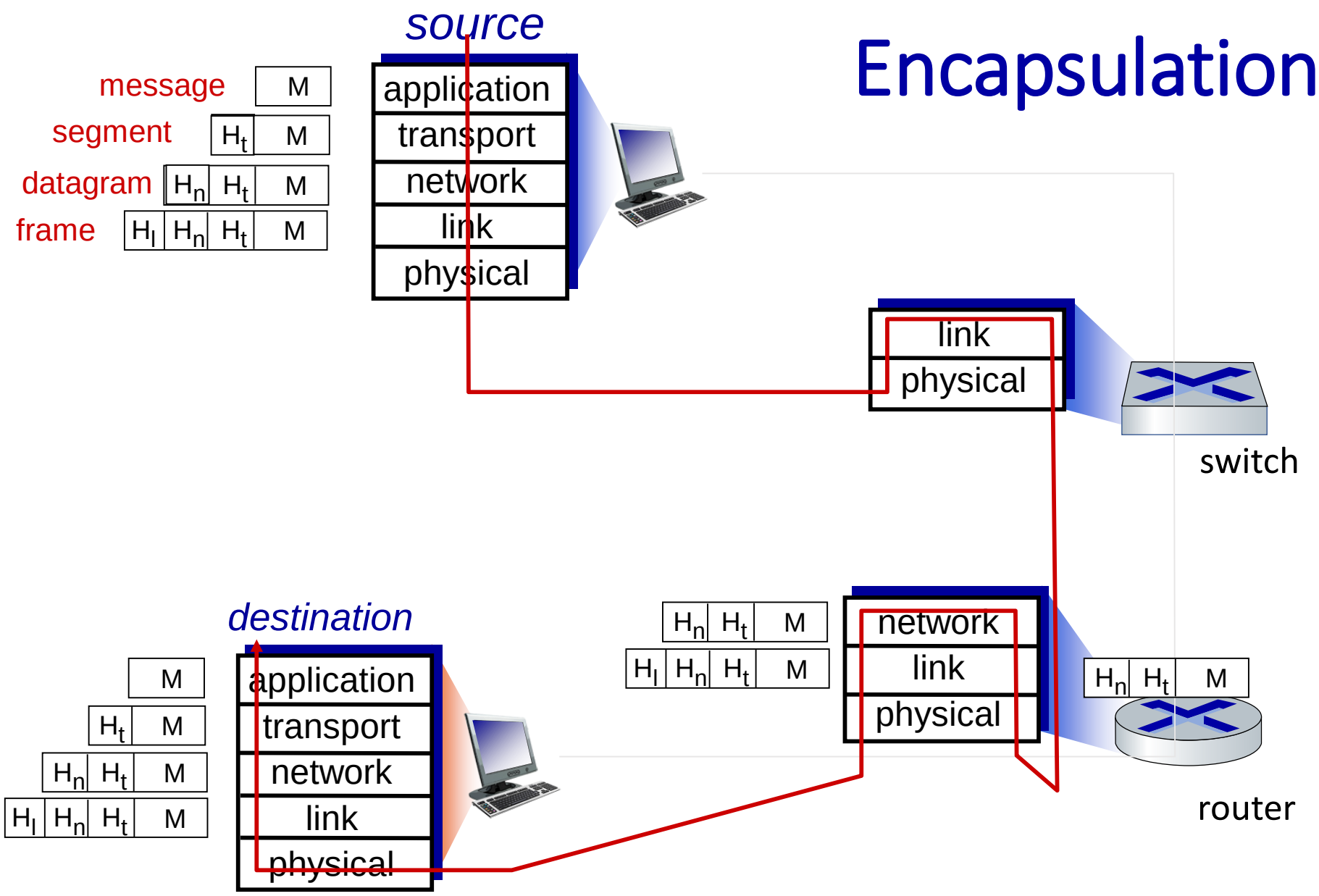
# Services vs Protocols



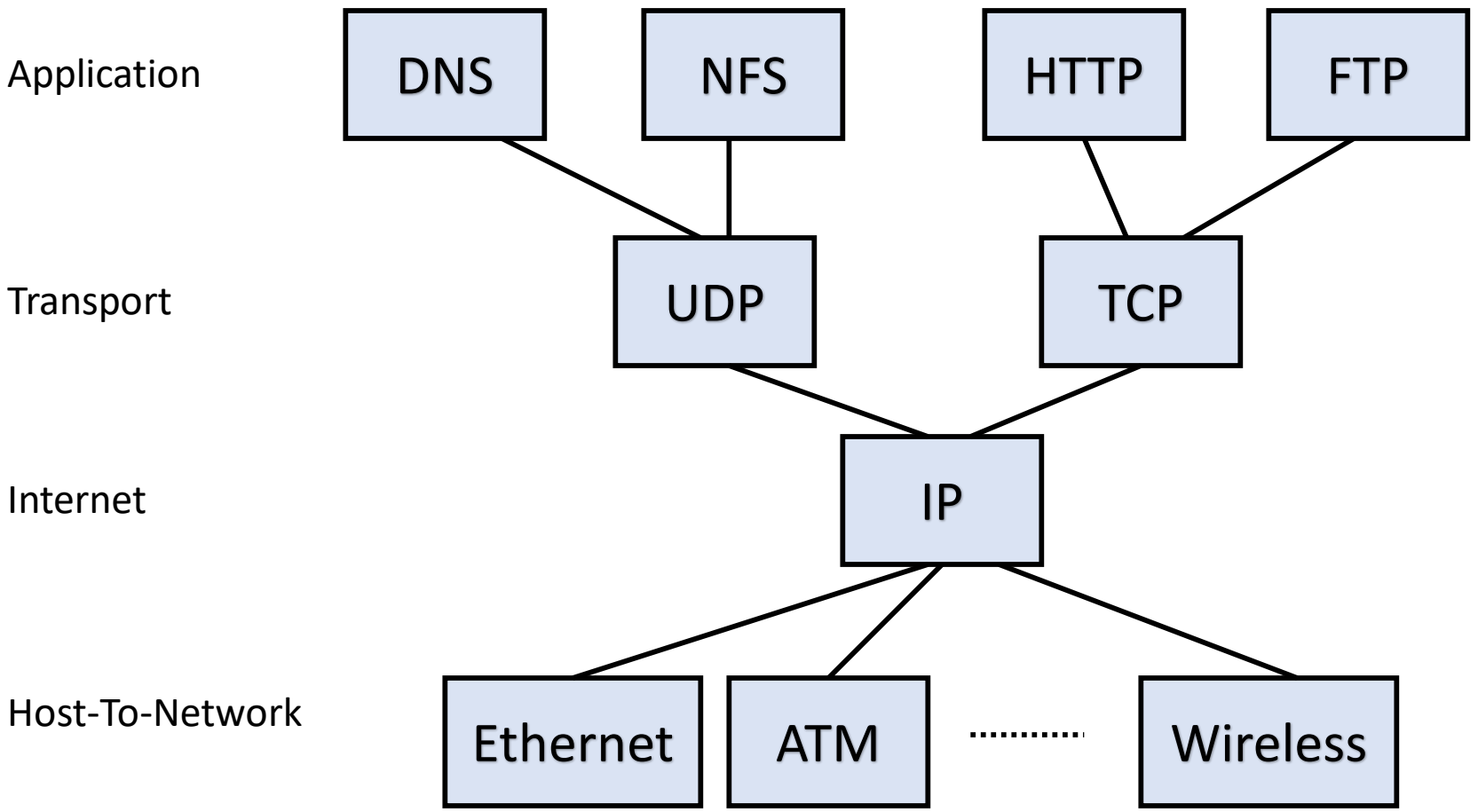

*(horizontal component)*

- Layer *k* may interact with peer layer *k* only via protocols
  Source: Tanenbaum

# Encapsulation

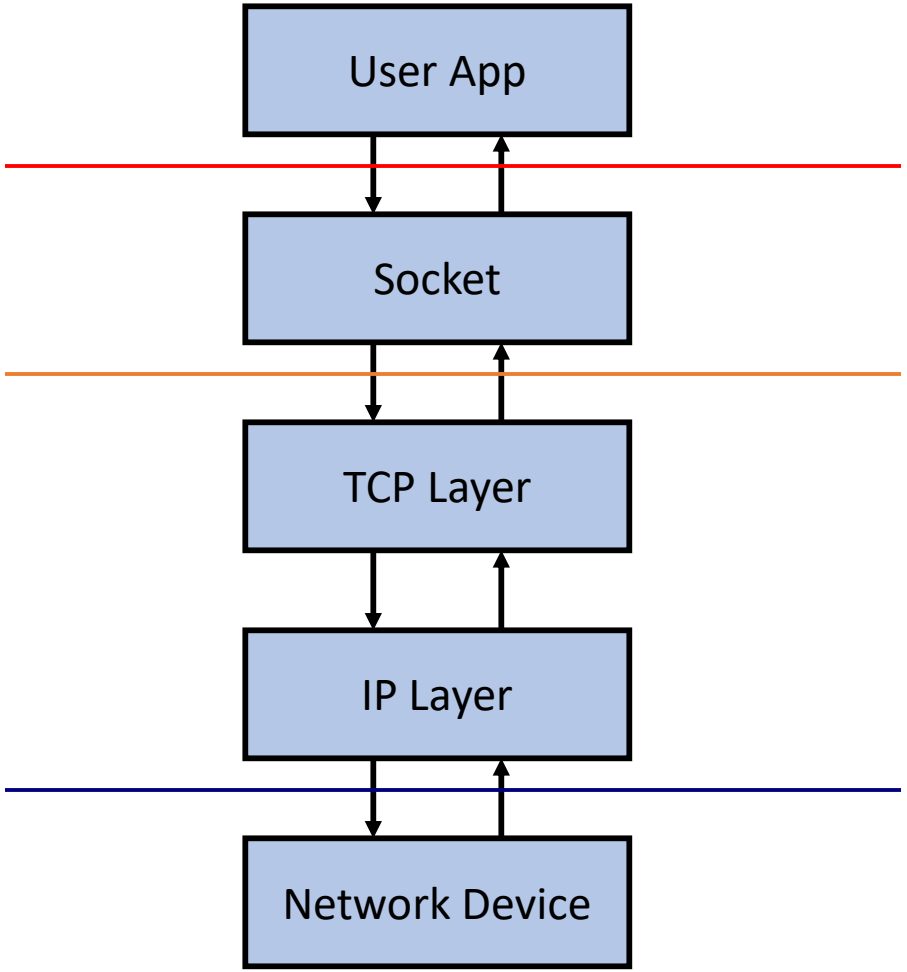


# TCP/IP Hourglass View



# Typical Implementation

may cross multiple boundaries!




user

Kernel:
“top-half”

Kernel:
“sw interrupt”

Kernel:
“hw interrupt”