1 Computer networks and Internet

* network components
* Internet architecture
* performance measure
* protocol
* history of computer networking

1.1 Overview of computer networking

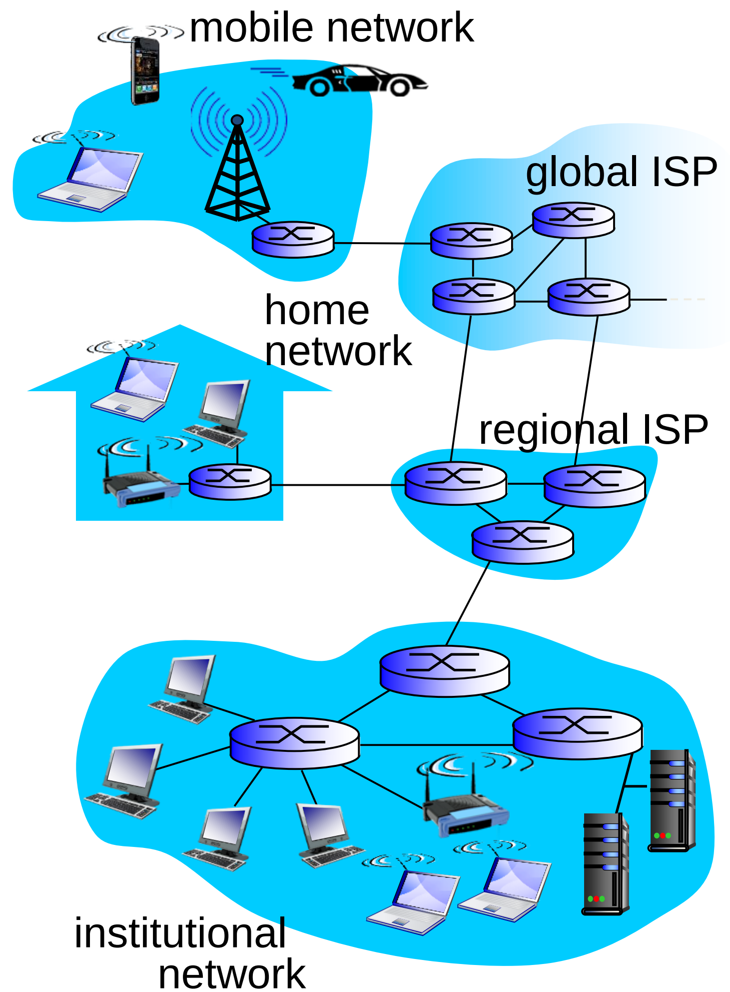
- machines can be connected, information can be exchanged – server, desktop computer, notebook computer, smartphones …
- one specific computer network – **Internet**
- probably the largest network – billions of connected computing devices

What is the Internet?

- nuts-and-bolts view – the basic hardware and software components
- what services are provided
- how machines communicate – protocol

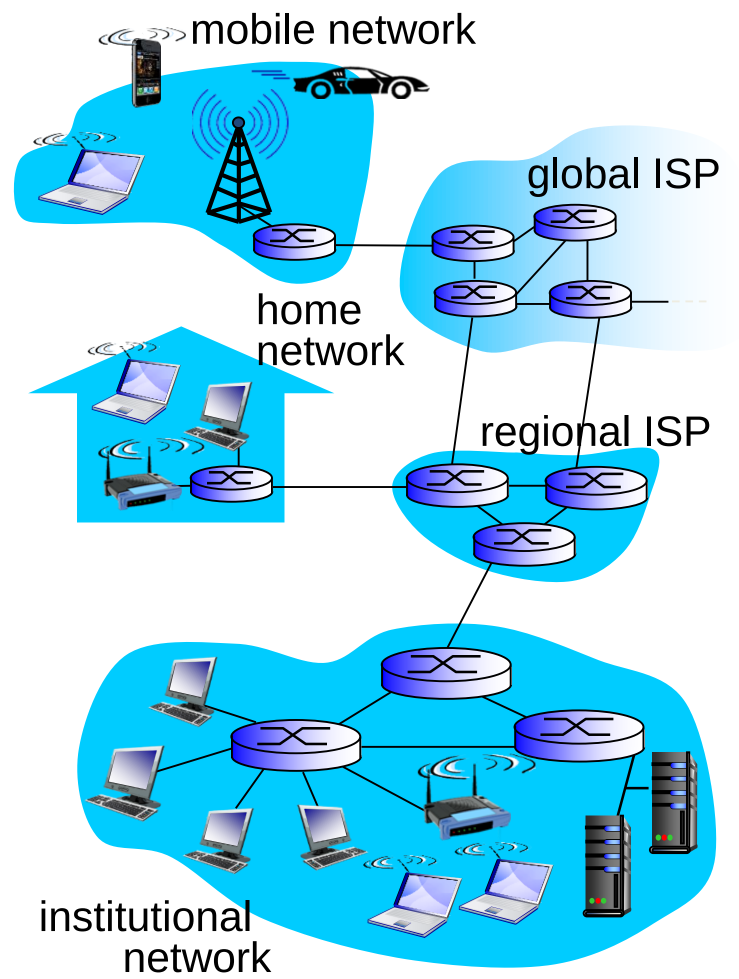
“nuts-and-bolts” view

- *devices*
  - hosts = end systems
  - running network apps
- *communication links*
  - optical fiber, copper wire, radio, satellite
  - transmission rate: bandwidth
- *packet switches*
  - forward packets (chunks of data)
  - routers and switches



service view

- *infrastructure that provides services to applications*
  - Web, Voice over Internet Protocol (VoIP), email, games, e-commerce, social nets, …
- *provides programming interface to apps*
  - hooks that allow sending and receiving app programs to “connect” to Internet
  - provides service options, analogous to postal service



"Fun" internet appliances

IP picture frame
http://www.ceiva.com/

Web-enabled toaster +
weather forecaster

Tweet-a-watt:
monitor energy use

Internet
refrigerator

Slingbox: watch,
control cable TV remotely

Internet phones

Internet of Things (IoT)

What is a protocol?

human protocols:

- "what is the time?"
- "I have a question"
- introductions

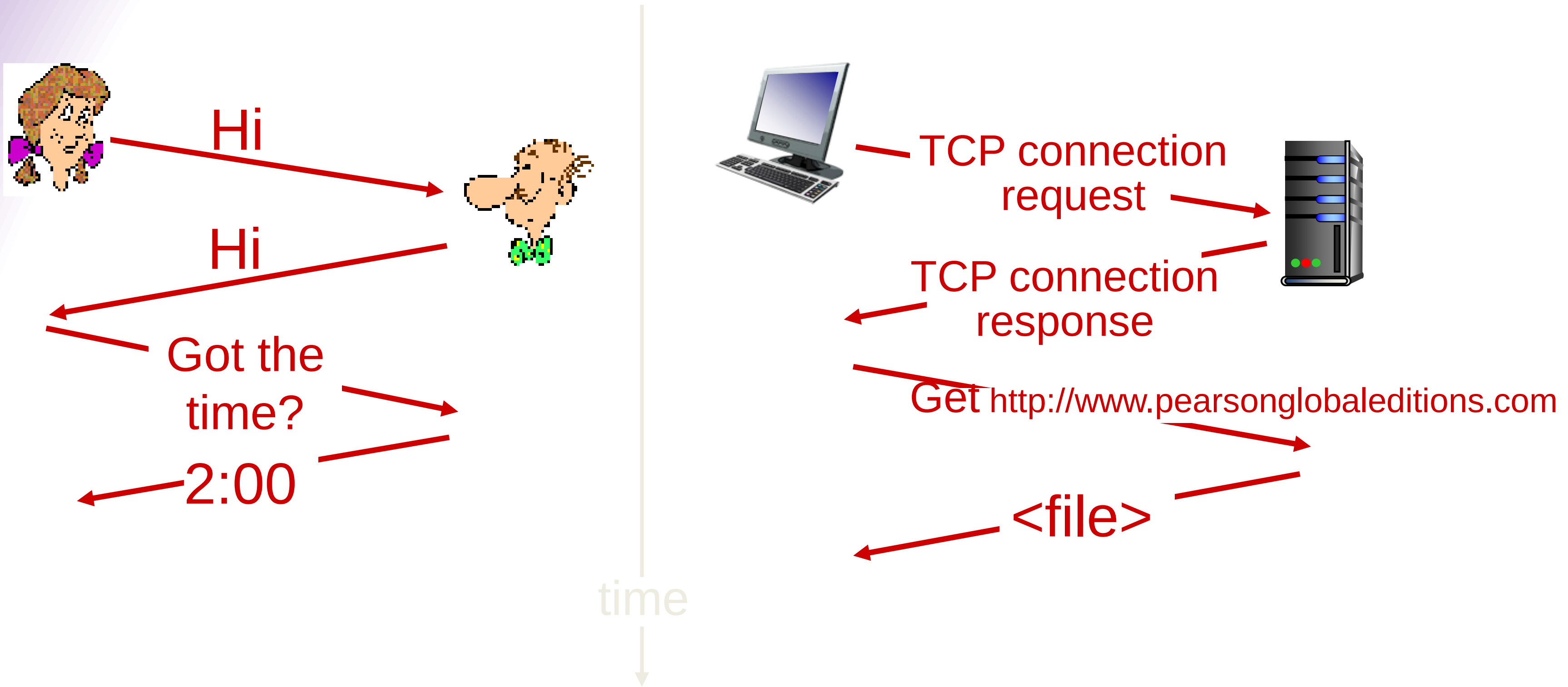
… specific messages sent

… specific actions taken when messages received, or other events

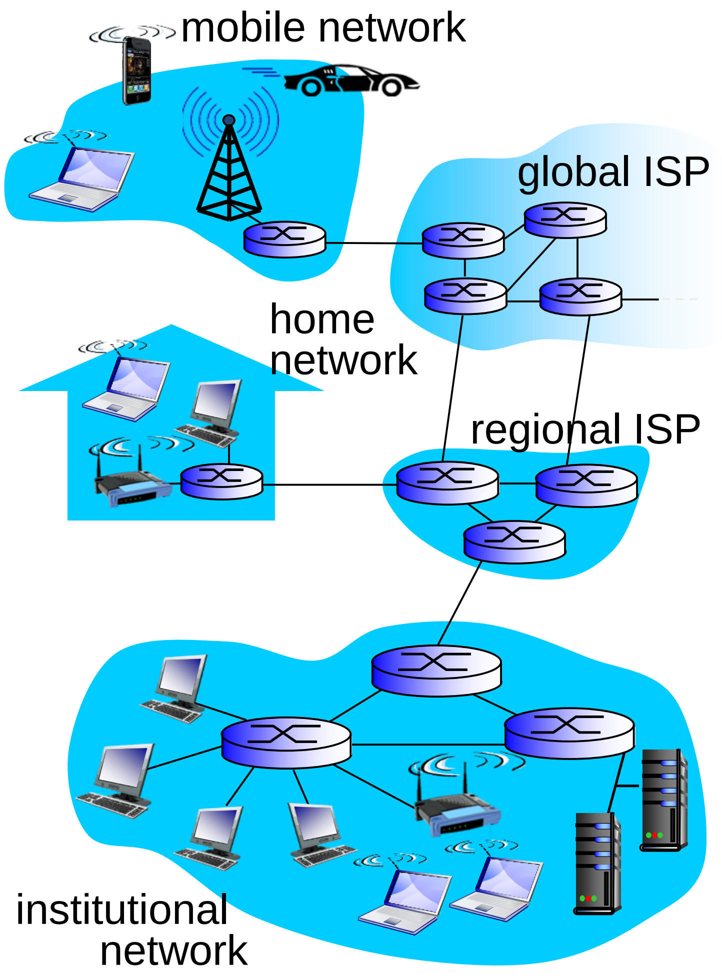
network protocols:

- machines rather than humans
- all communication activity in Internet governed by protocols

protocols define format, order of messages sent and received among network entities, and actions taken on transmission and/or receipt of message/event a human protocol and a computer network protocol:



- *Internet:* "network of networks"
  - Interconnected Internet Service Providers (ISPs)
- *protocols* control sending, receiving of messages
  - e.g., Transmission Control Protocol (TCP), Internet Protocol (IP), HyperText Transfer Protocol (HTTP), Skype, 802.11
- *Internet standards*
  - Request for Comments (RFCs)
  - Internet Engineering Task Force (IETF)



1.2 Network components

- edge of network – computers, smartphones …
- access networks, physical media
- core of network – routers, switches …

- *network edge:*

  hosts: clients and servers

  servers often in data centers

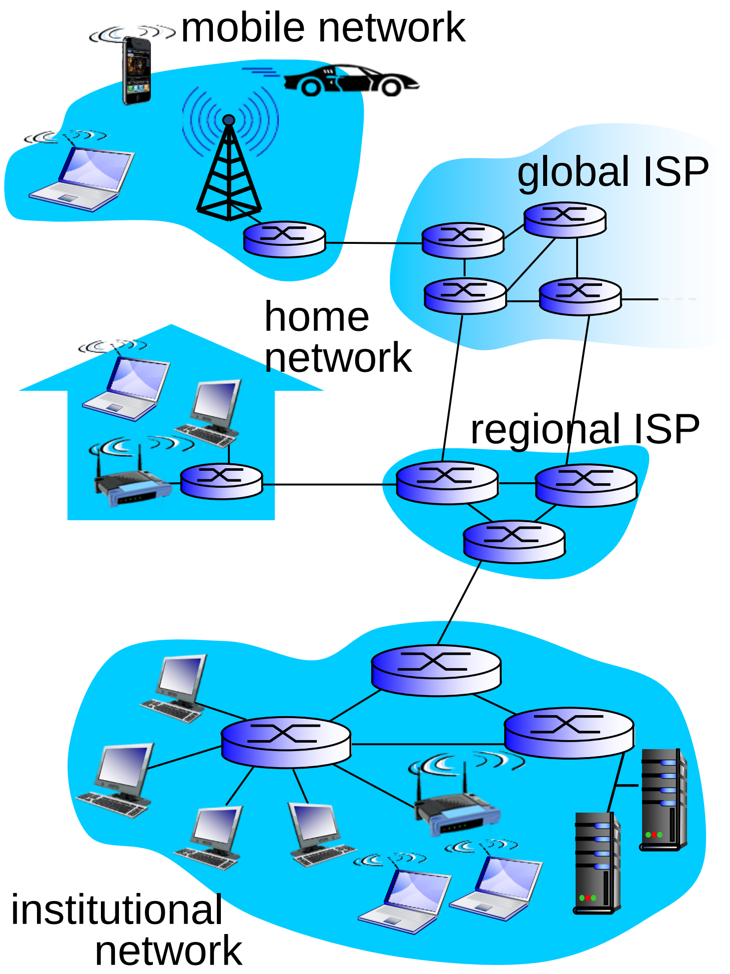
- *access networks, physical media:*

  wired, wireless communication links

- *network core:*

  interconnected routers

  network of networks



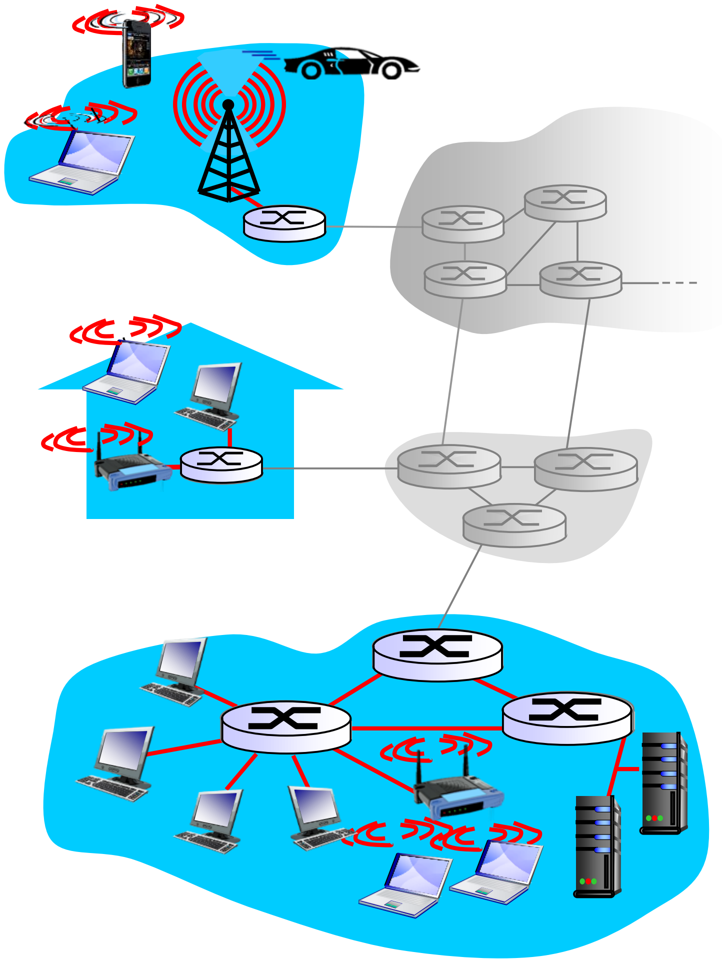
Access networks and physical media

Q: How to connect end systems to edge router?

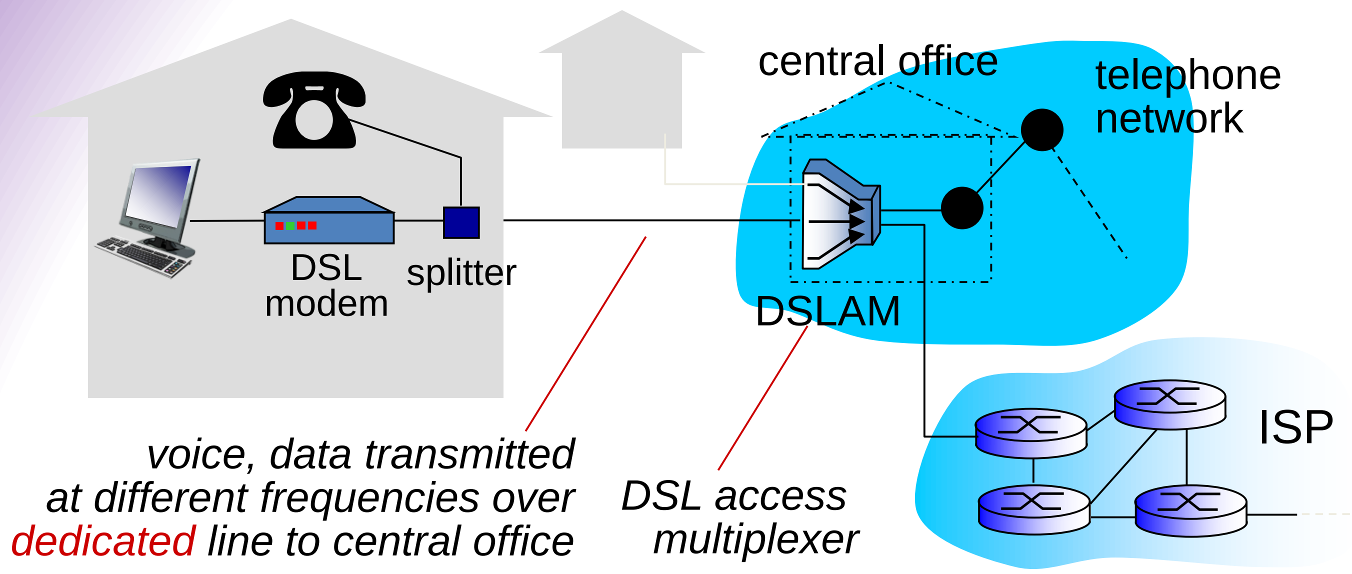
- residential access nets
- institutional access networks (school, company)
- mobile access networks

keep in mind:

- bandwidth (bits per second - bps) of access network?
- shared or dedicated?

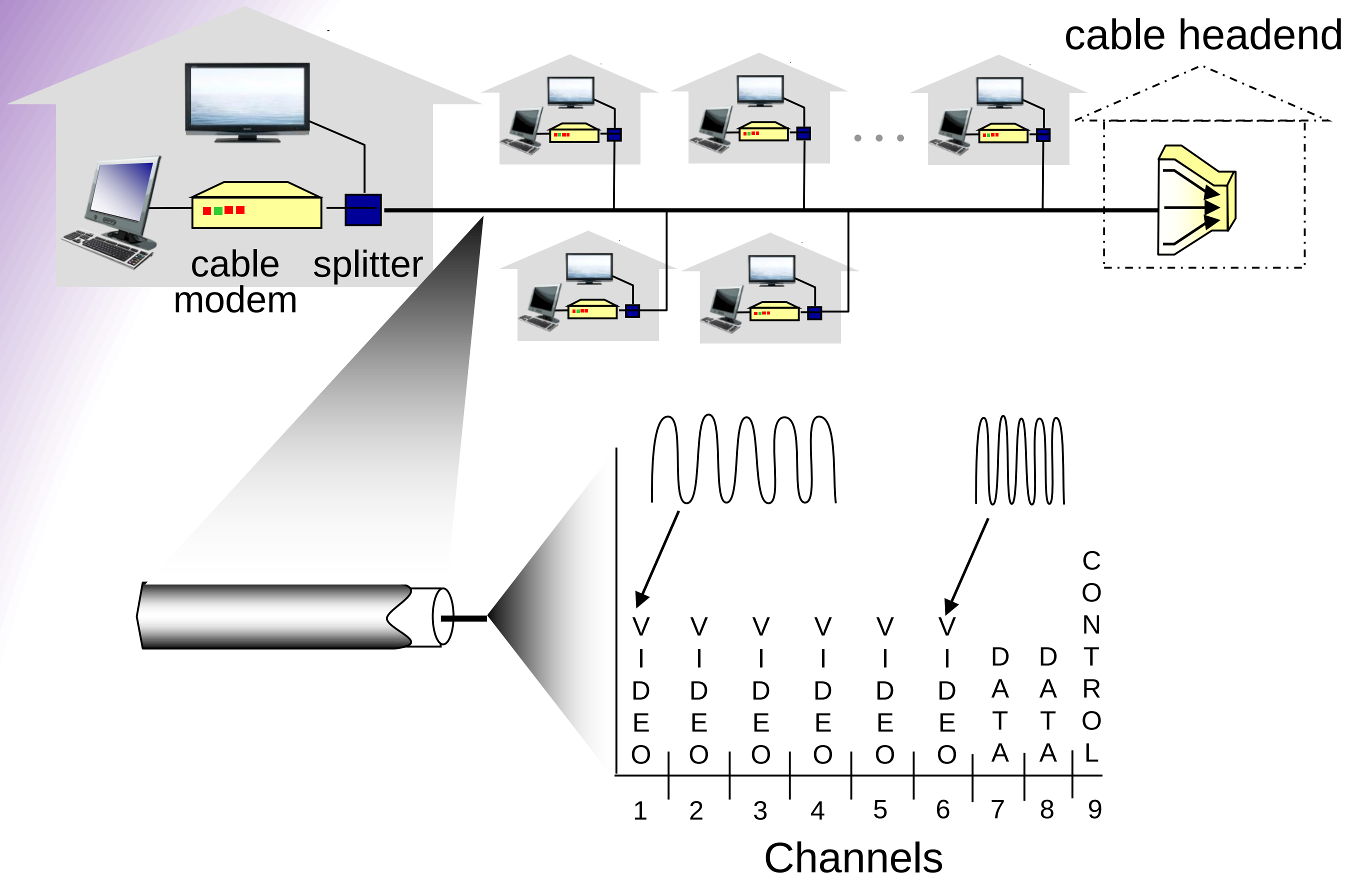


Access net: digital subscriber line (DSL)



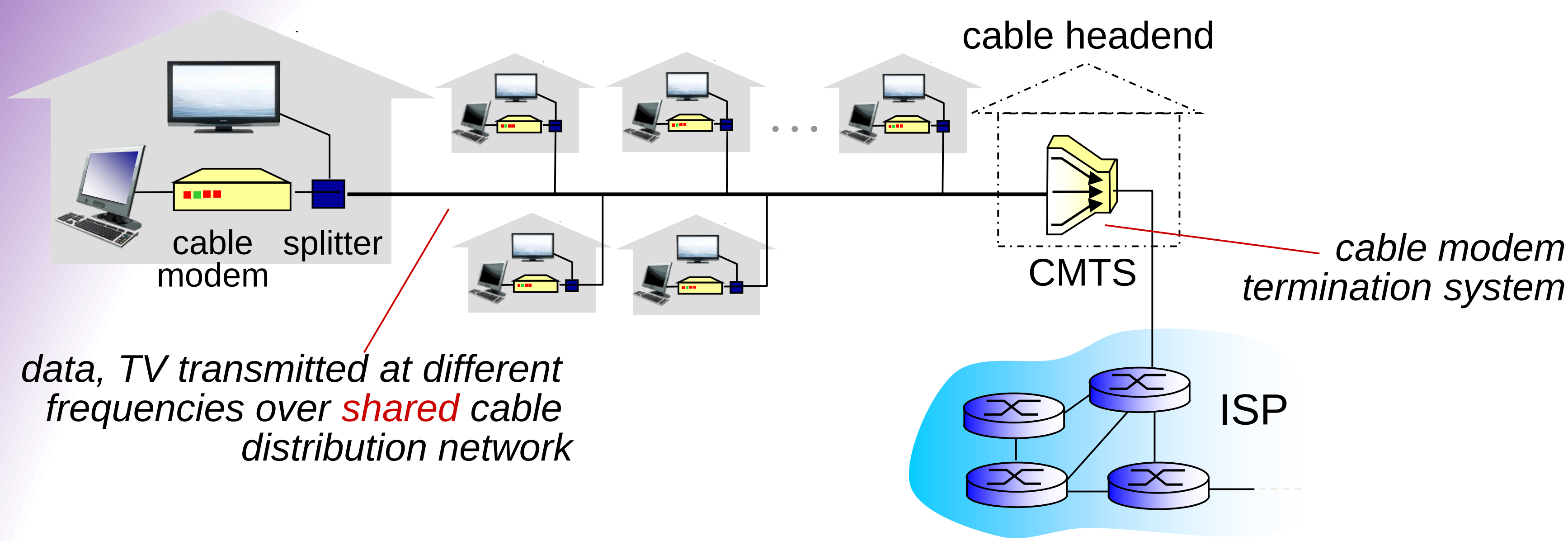
- use *existing* telephone line to central office DSL access multiplexer (DSLAM)
  - data over DSL phone line goes to Internet
  - voice over DSL phone line goes to telephone net
- < 2.5 Mbps upstream transmission rate (typically < 1 Mbps)
- < 24 Mbps downstream transmission rate (typically < 10 Mbps)

Access net: cable network



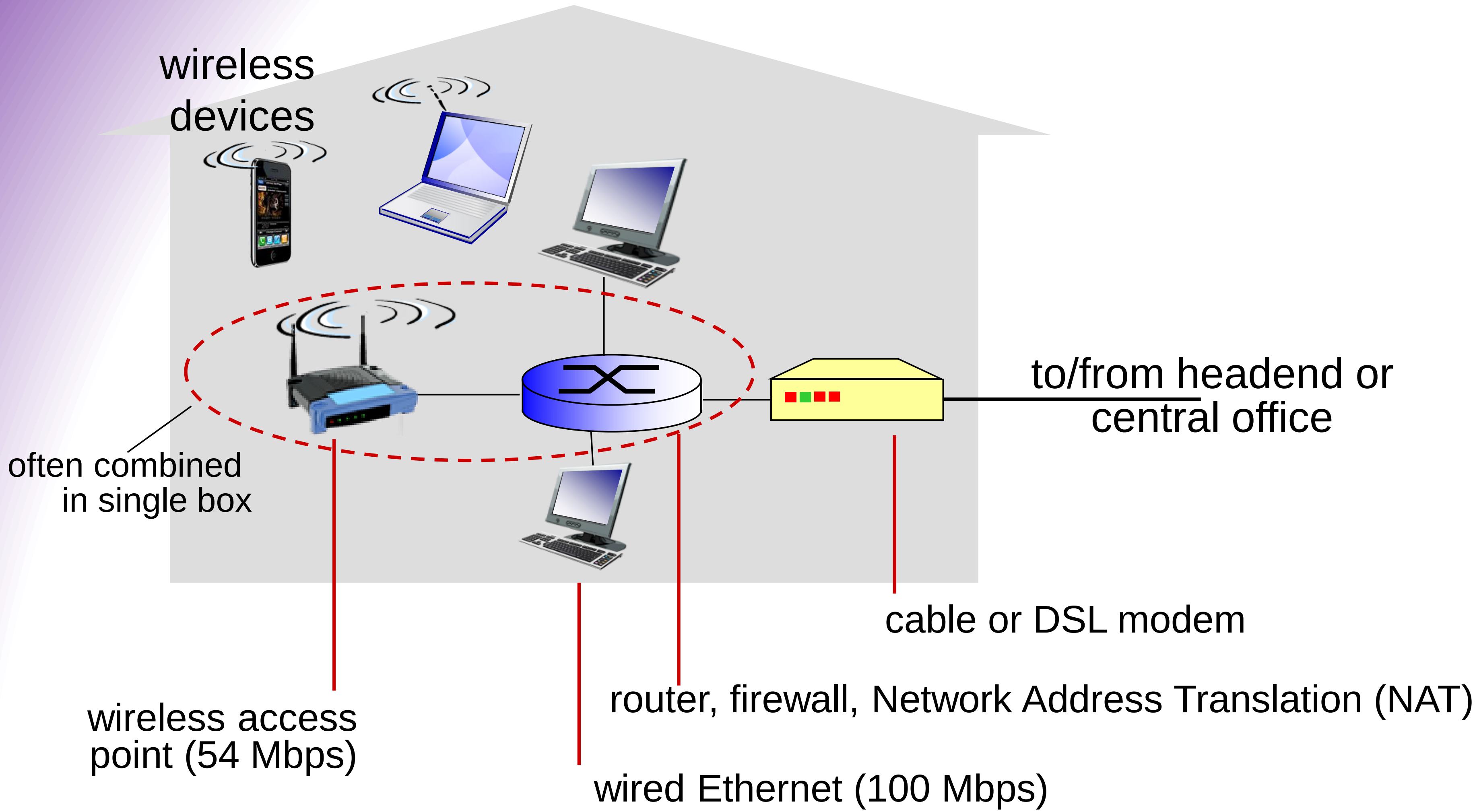
frequency-division multiplexing (FDM): different channels transmitted in different frequency bands

Access net: cable network

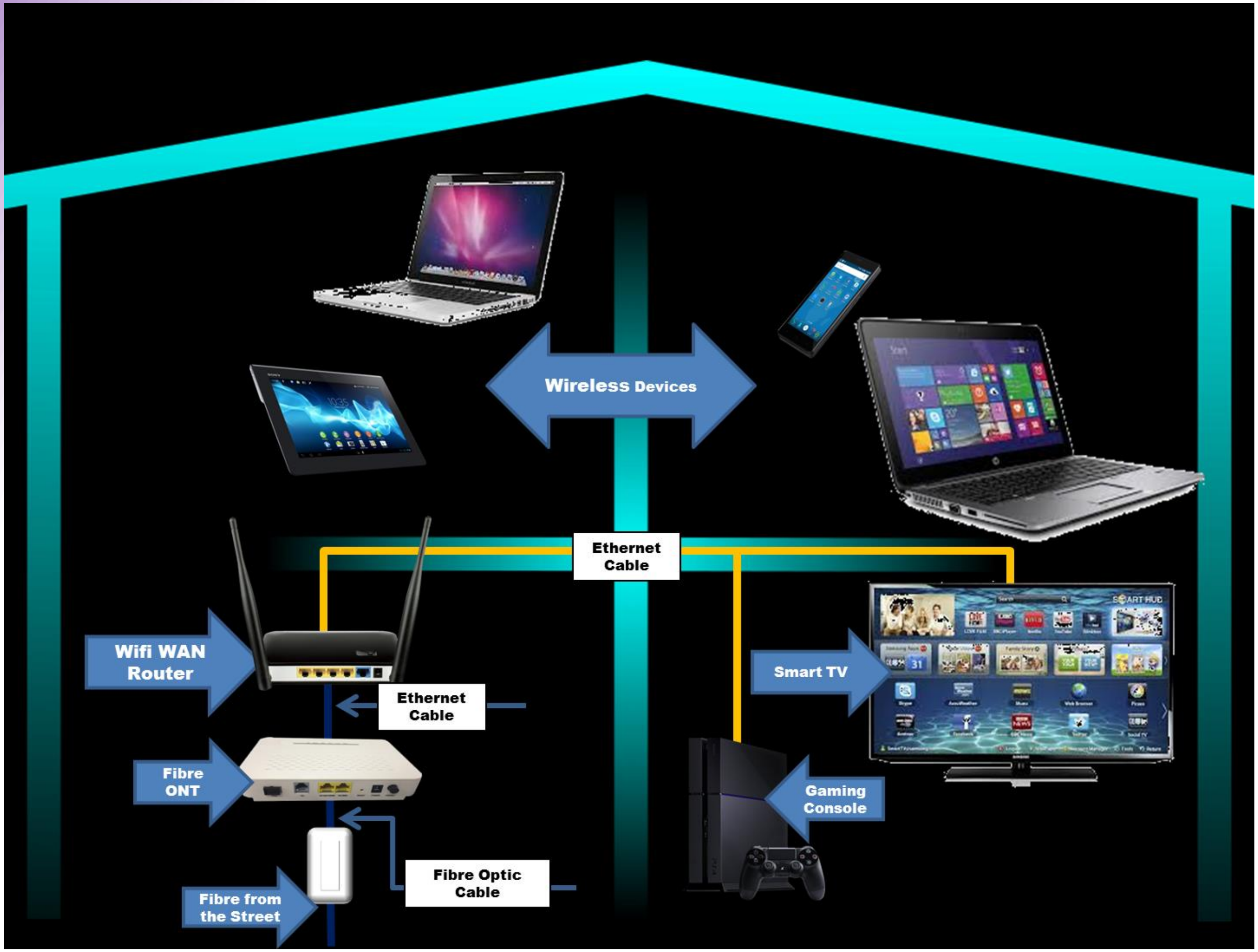


- hybrid fiber coax (HFC)
  - asymmetric: up to 30 Mbps downstream transmission rate, 2 Mbps upstream transmission rate
- network of cable, fiber attaches homes to ISP router
  - homes *share access network* to cable headend
  - unlike DSL, which has dedicated access to central office

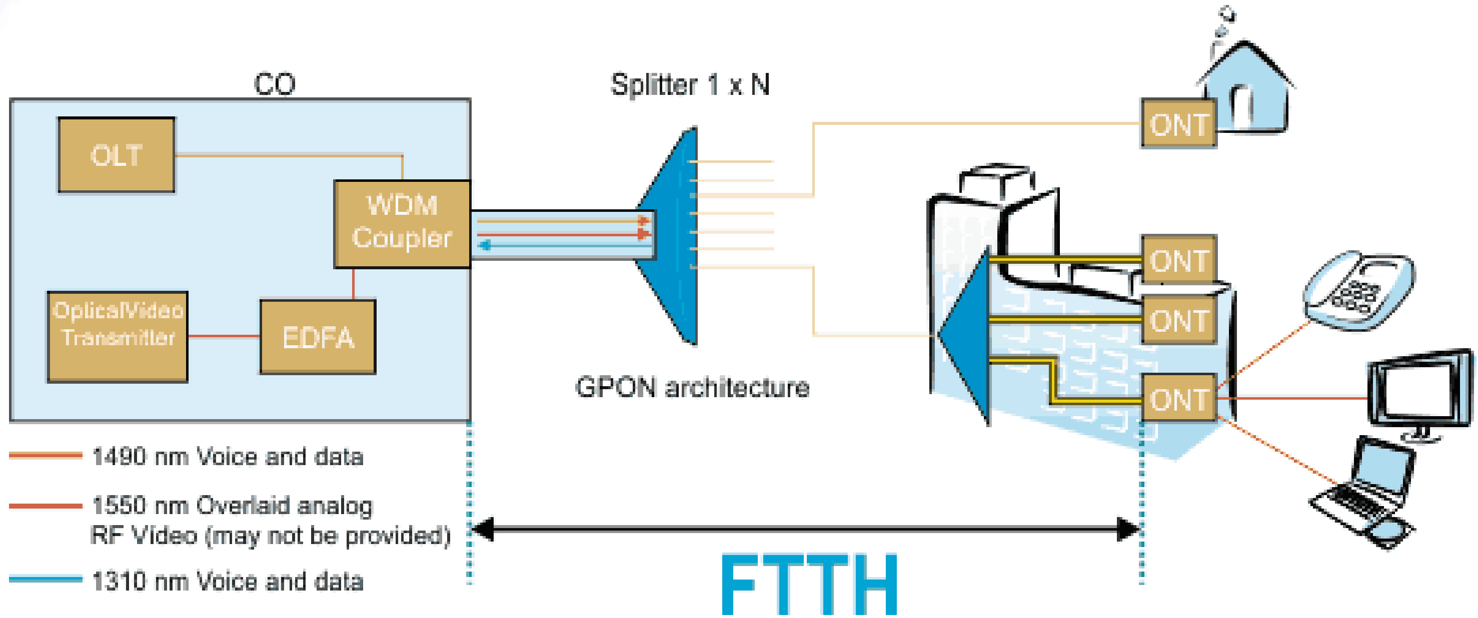
Access net: home network



Access net: fiber to the home (FTTH)

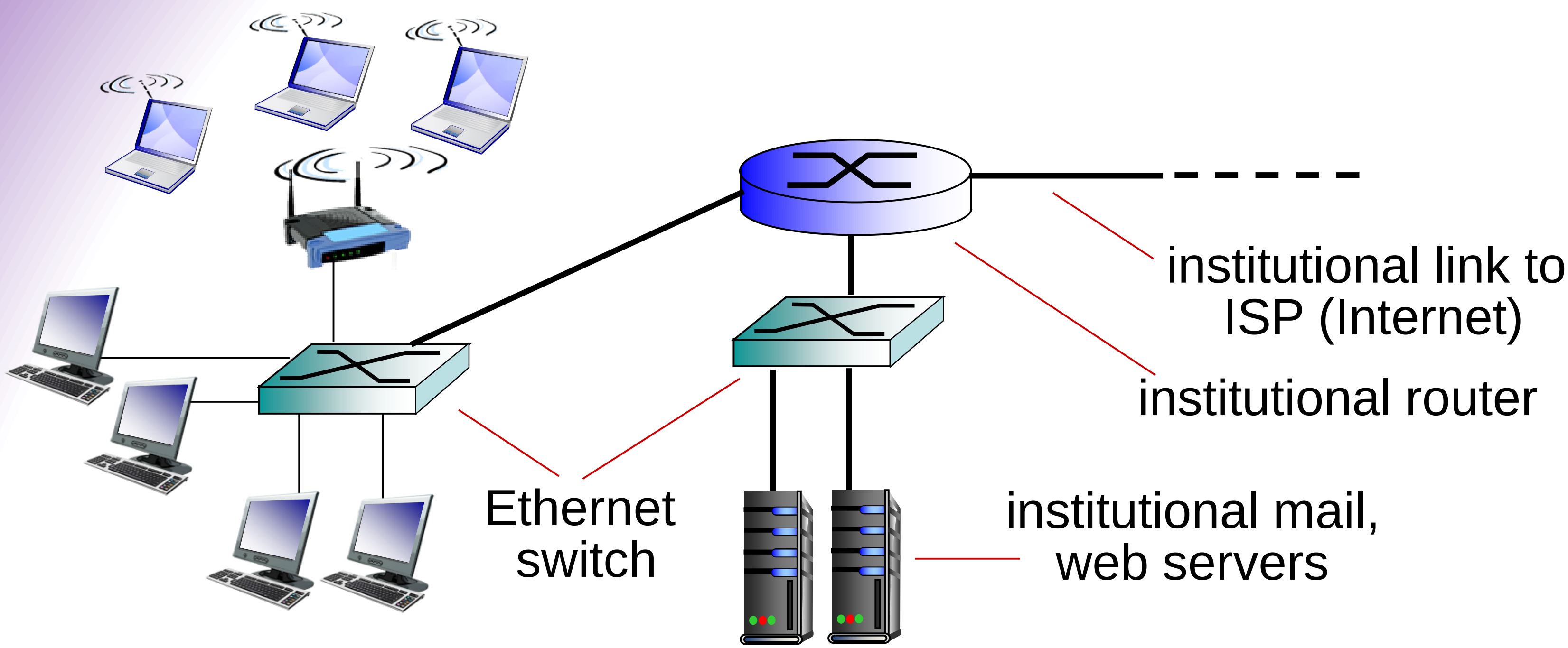


ONT
Optical
Network
Terminal



GPON - Gigabit Passive Optical Networks
CO - Central Office
OLT – optical line terminator
WDM – wavelength-division multiplexing
EDFA – erbium-doped fiber amplifier

Enterprise access networks (Ethernet)



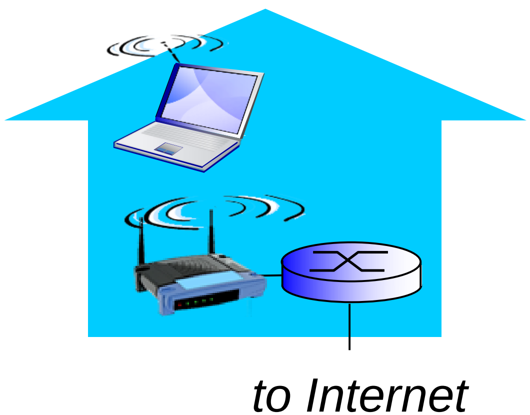
- typically used in companies, universities, etc.
- 10 Mbps, 100 Mbps, 1 Gbps, 10 Gbps transmission rates
- today, end systems typically connect into Ethernet switch

Wireless access networks

- shared *wireless* access network connects end system to router
  - via base station aka "access point"

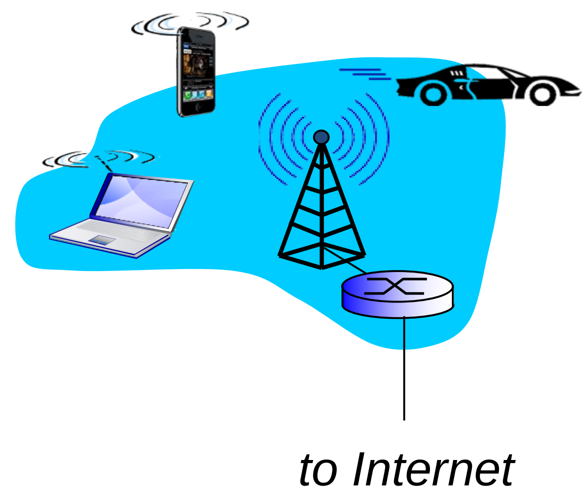
wireless LANs:

- within building (100 ft)
- 802.11b/g (WiFi): 11 Mbps, 54 Mbps transmission rates



wide-area wireless access

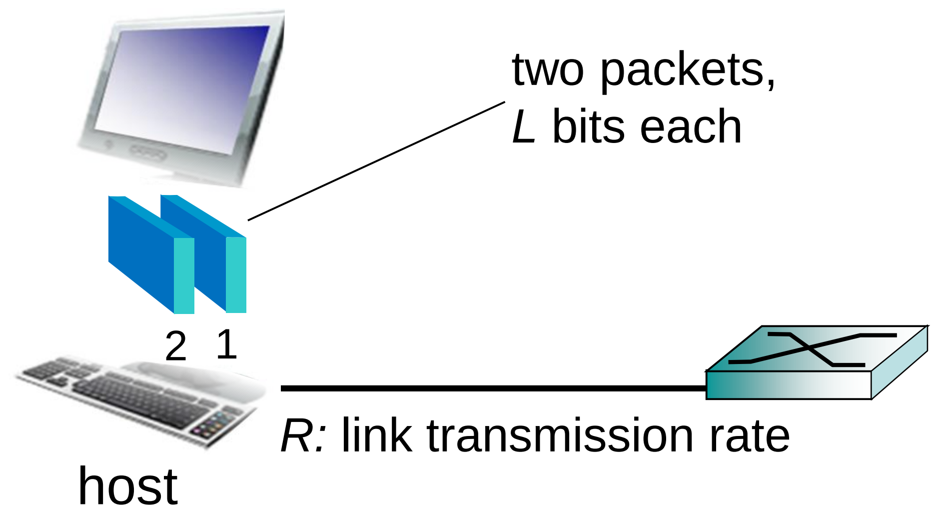
- provided by telco (cellular) operator, 10's km
- between 1 and 10 Mbps
- 3G, 4G: Long-Term Evolution (LTE)



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 (*link capacity, link bandwidth)*



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

Physical media

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

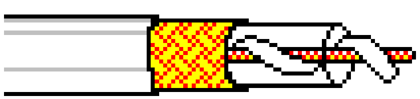
twisted pair (TP)

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

Physical media: coax, fiber

coaxial cable:

- two concentric copper conductors
- bidirectional
- broadband:
  - multiple channels on cable
  - HFC



fiber optic cable:

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

Physical media: radio

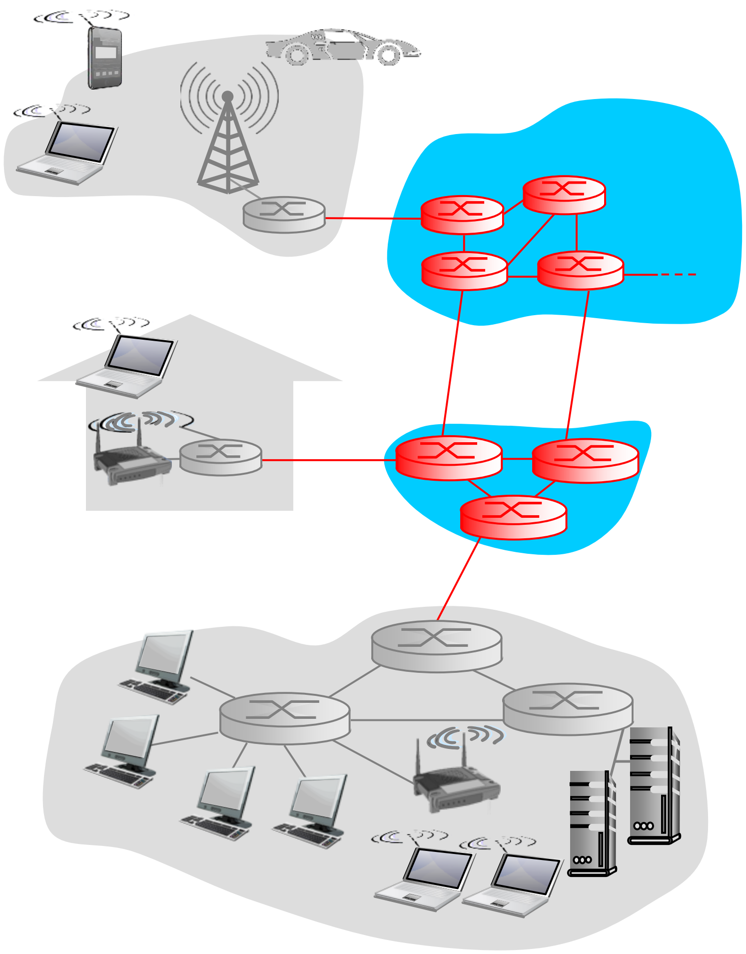
- signal carried in electromagnetic spectrum
- no physical "wire"
- bidirectional
- propagation environment effects:
  - reflection
  - obstruction by objects
  - interference

radio link types:

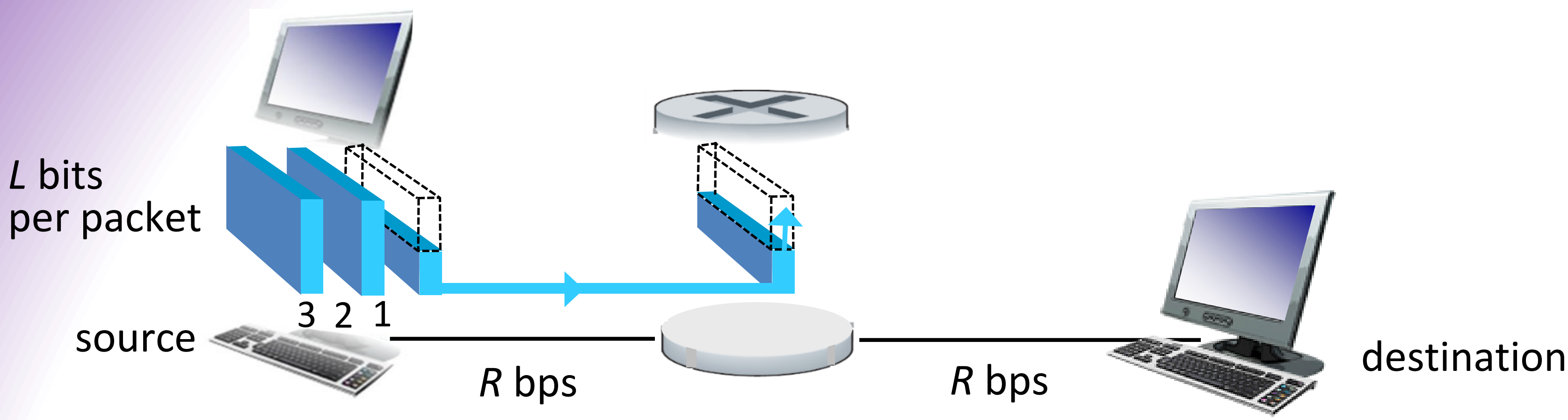
- terrestrial microwave
  - e.g. up to 45 Mbps channels
- LAN (e.g., WiFi)
  - 11 Mbps, 54 Mbps
- wide-area (e.g., cellular)
  - 3G, 4G, 5G cellular: few Mbps and above
- satellite
  - Kbps to 45 Mbps channel (or multiple smaller channels)
  - 270 msec end-end delay
  - geosynchronous (36,000 km above Earth's surface) versus low-earth orbiting (LEO)

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



- 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

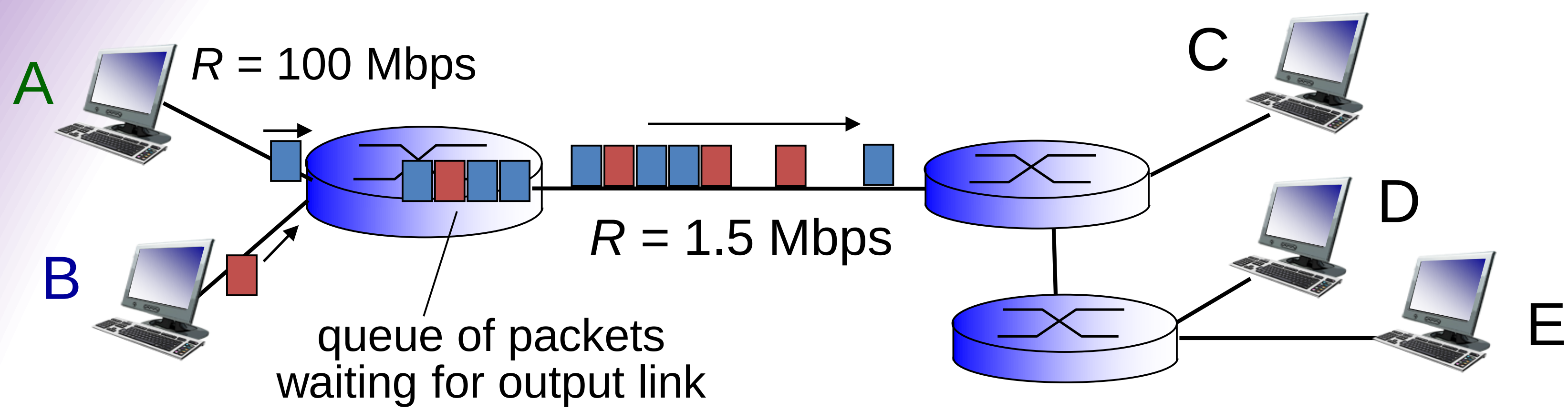
one-hop numerical example:

- *L* = 7.5 Mbits
- *R* = 1.5 Mbps
- one-hop transmission delay = **?**

❖ end-end delay = 2*L*/*R* (assuming zero propagation delay)

more on delay shortly …

Packet Switching: queuing delay, loss



queuing and loss:

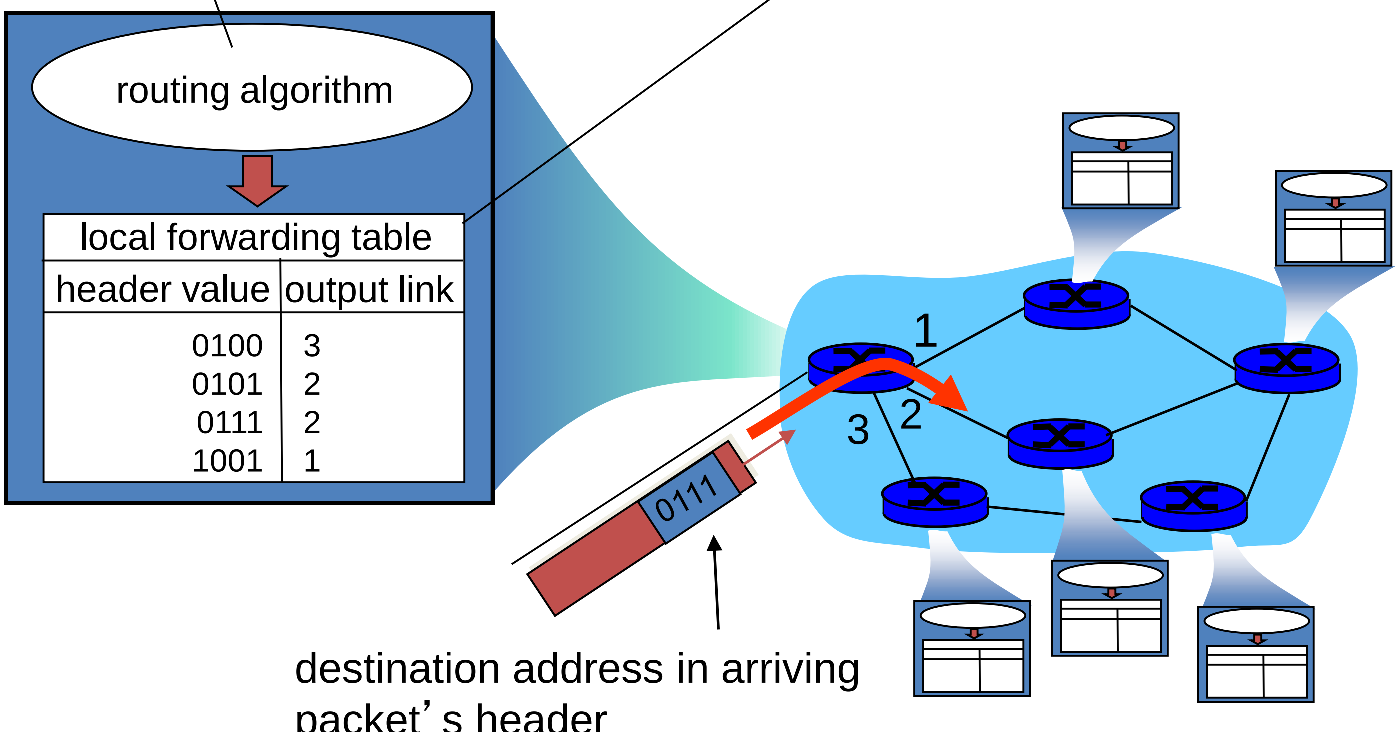
- If arrival rate (in bits) to link exceeds transmission rate of link for a period of time:
  - packets will queue, wait to be transmitted on link
  - packets can be dropped (lost) if memory (buffer) fills up

Two key network-core functions

routing: determines source-destination route taken by packets

- *routing algorithms*

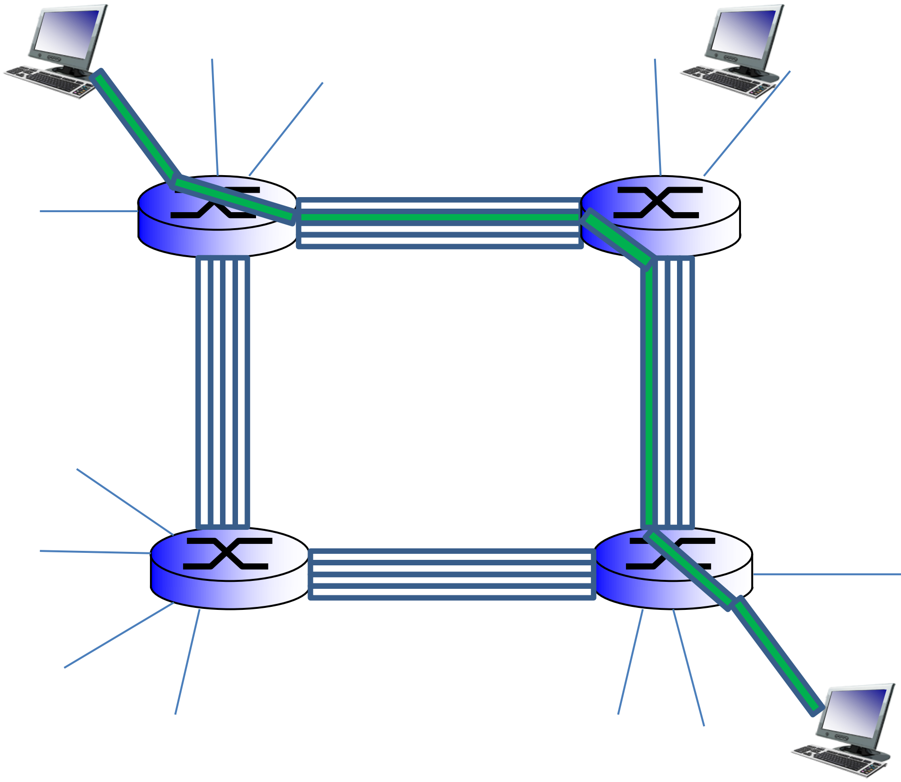
forwarding: move packets from router's input to appropriate router output



Alternative core: circuit switching

end-end resources allocated to, reserved for "call" between source & destination:

- In diagram, each link has four circuits.
  - call gets 2nd circuit in top link and 4th 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



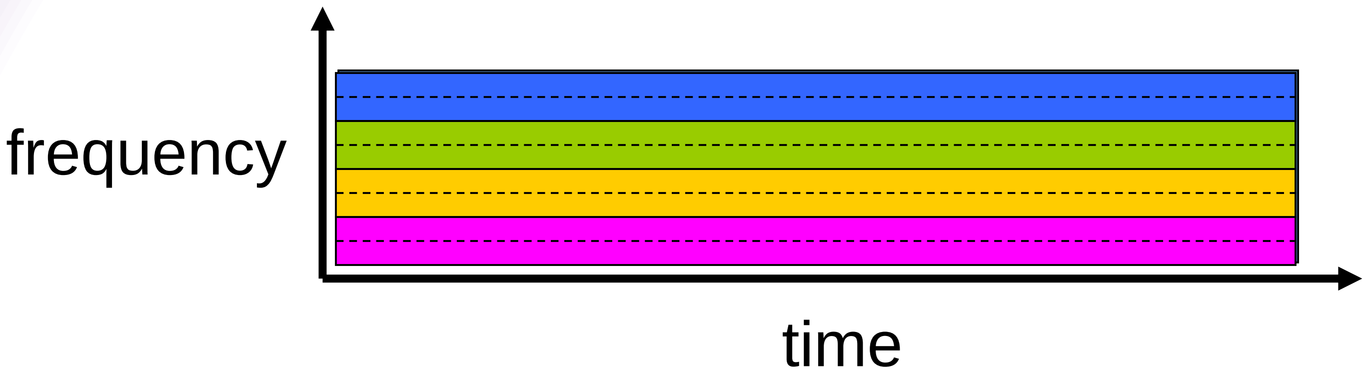
Circuit-switching networks have a much longer history than Internet!

Circuit switching: FDM versus TDM

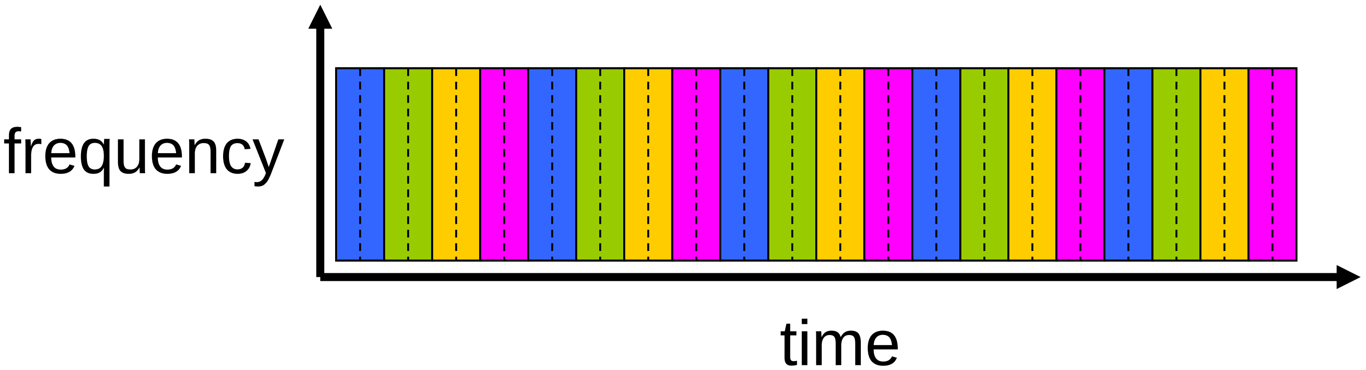
Example:

4 users

FDM



time-division multiplexing (TDM)

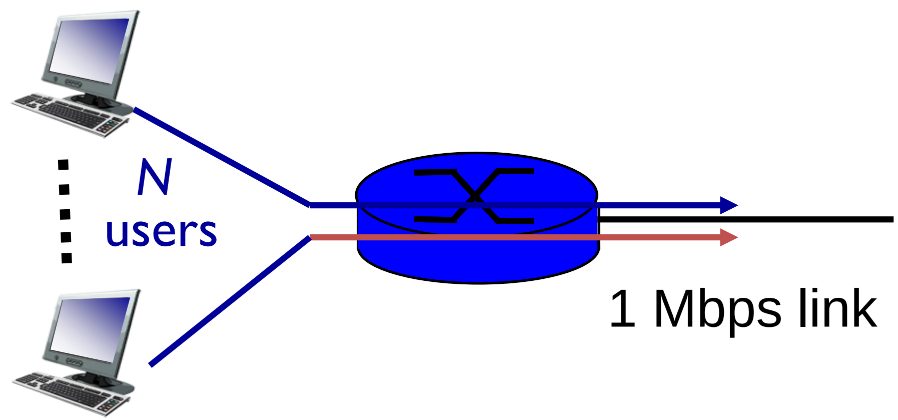


Packet switching versus circuit switching

packet switching allows more users to use network!

example:

- 1 Mbps link
- each user:
  - 100 Kbps 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 ?

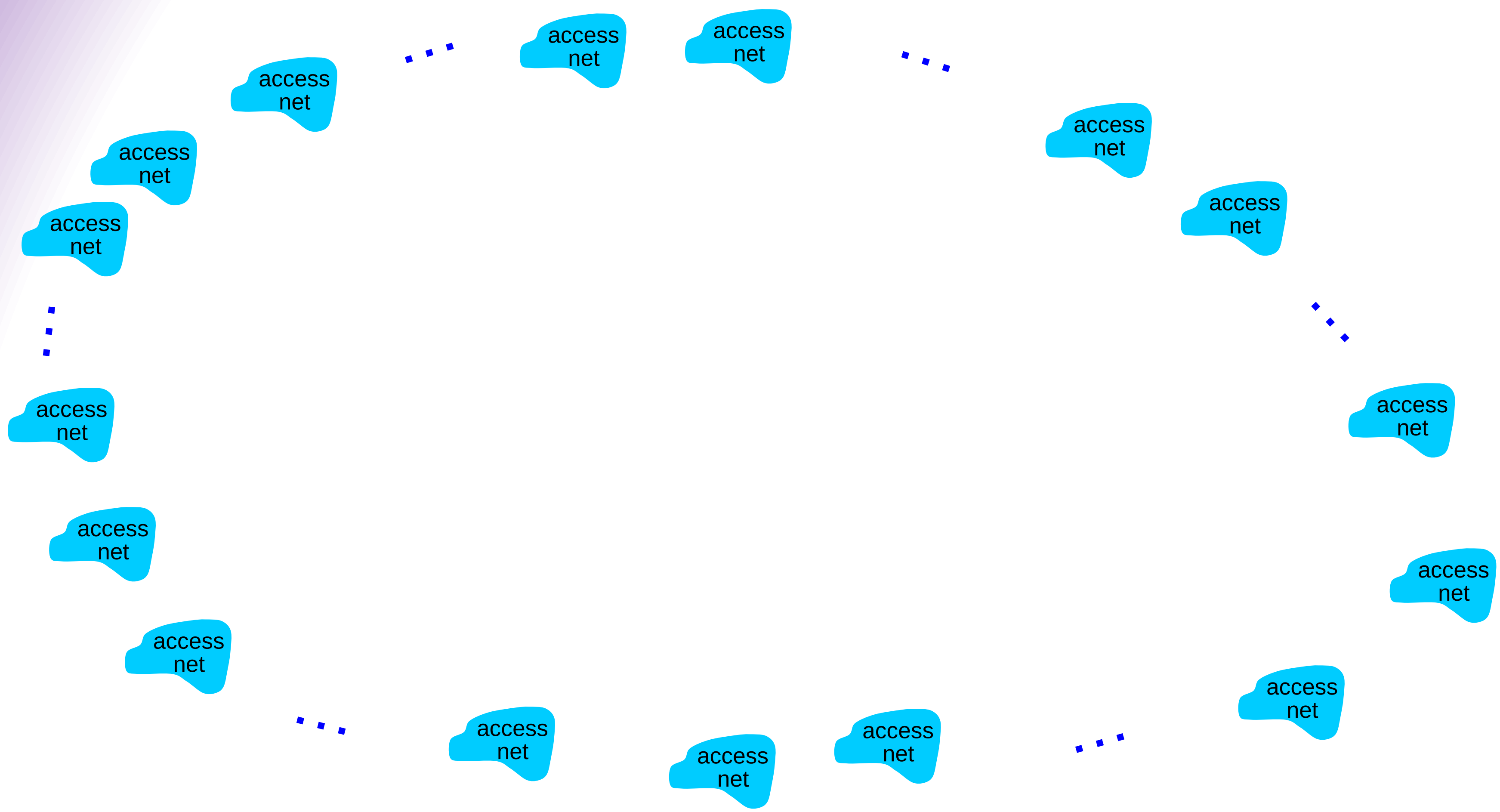
- great for bursty data
  - resource sharing
  - simpler, no call setup
- excessive congestion possible: packet delay and loss
  - protocols needed for reliable data transfer, congestion control
- *Q:* How to provide circuit-like behavior?
  - bandwidth guarantees needed for audio/video apps
  - still an unsolved problem

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

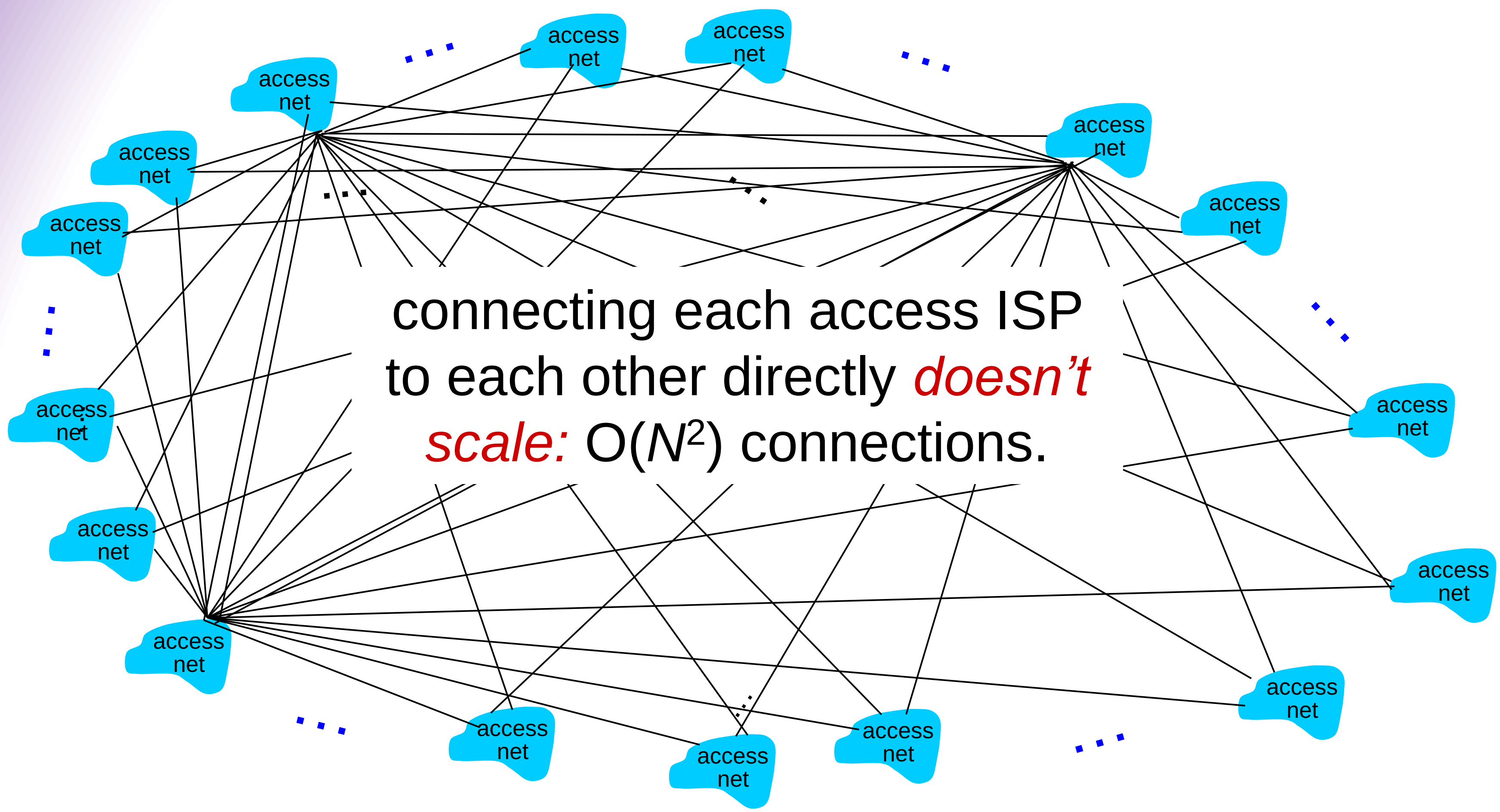
1.3 Internet architecture

- End systems connect to Internet via access ISPs (Internet Service Providers)
  - Residential, company and university 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

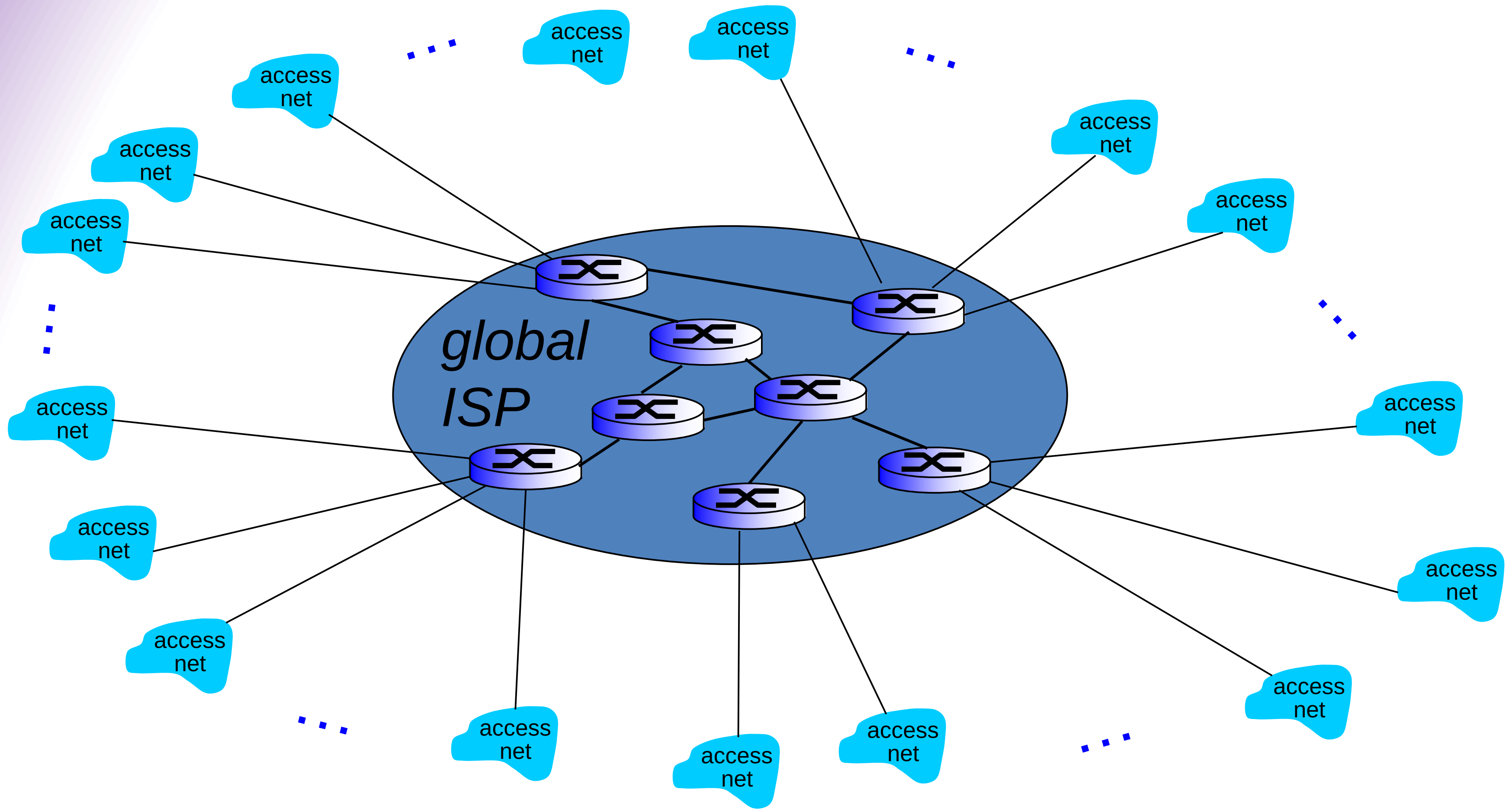
Question: given *millions* of access ISPs, how to connect them together?



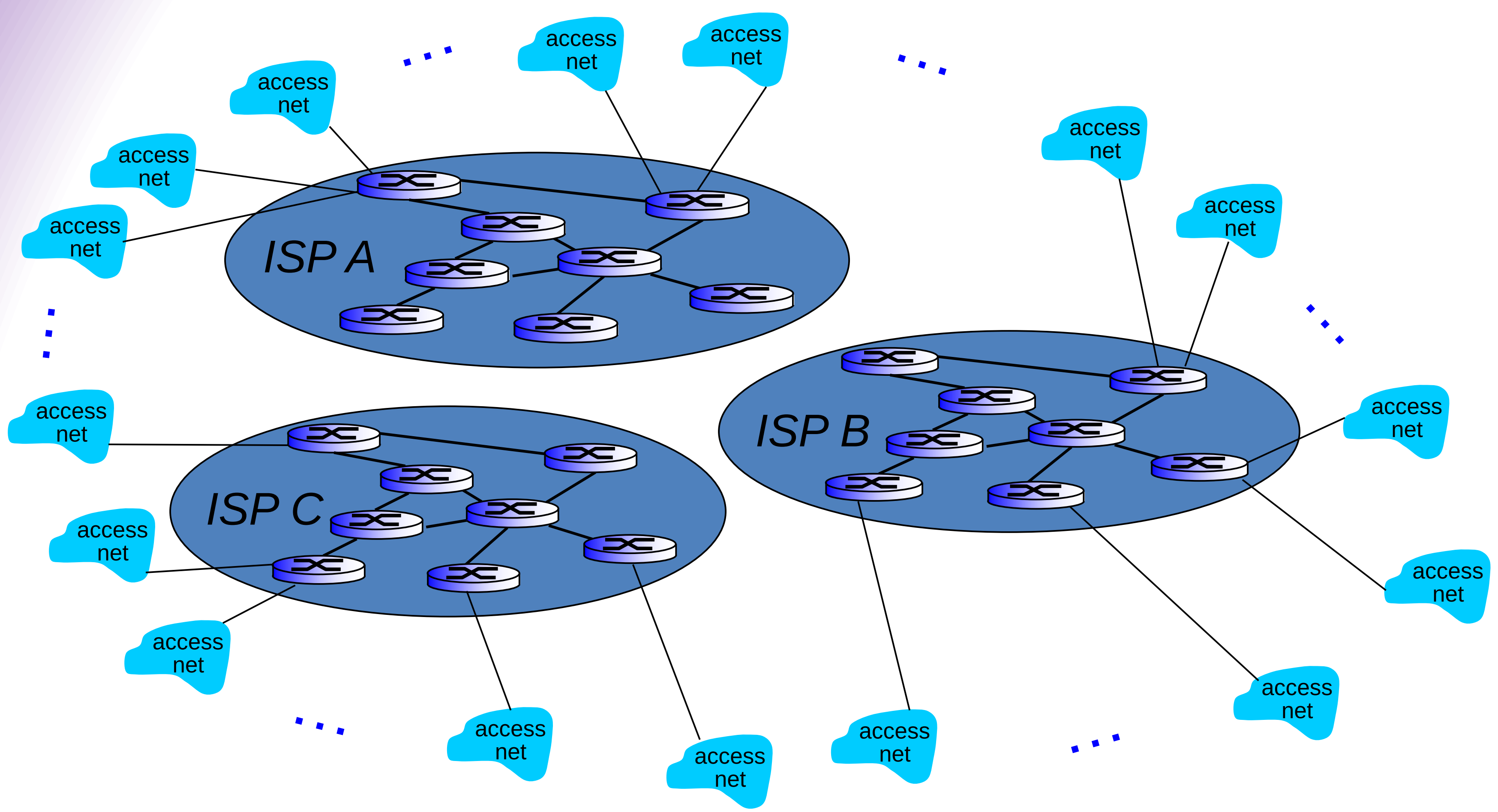
Option: connect each access ISP to every other access ISP?



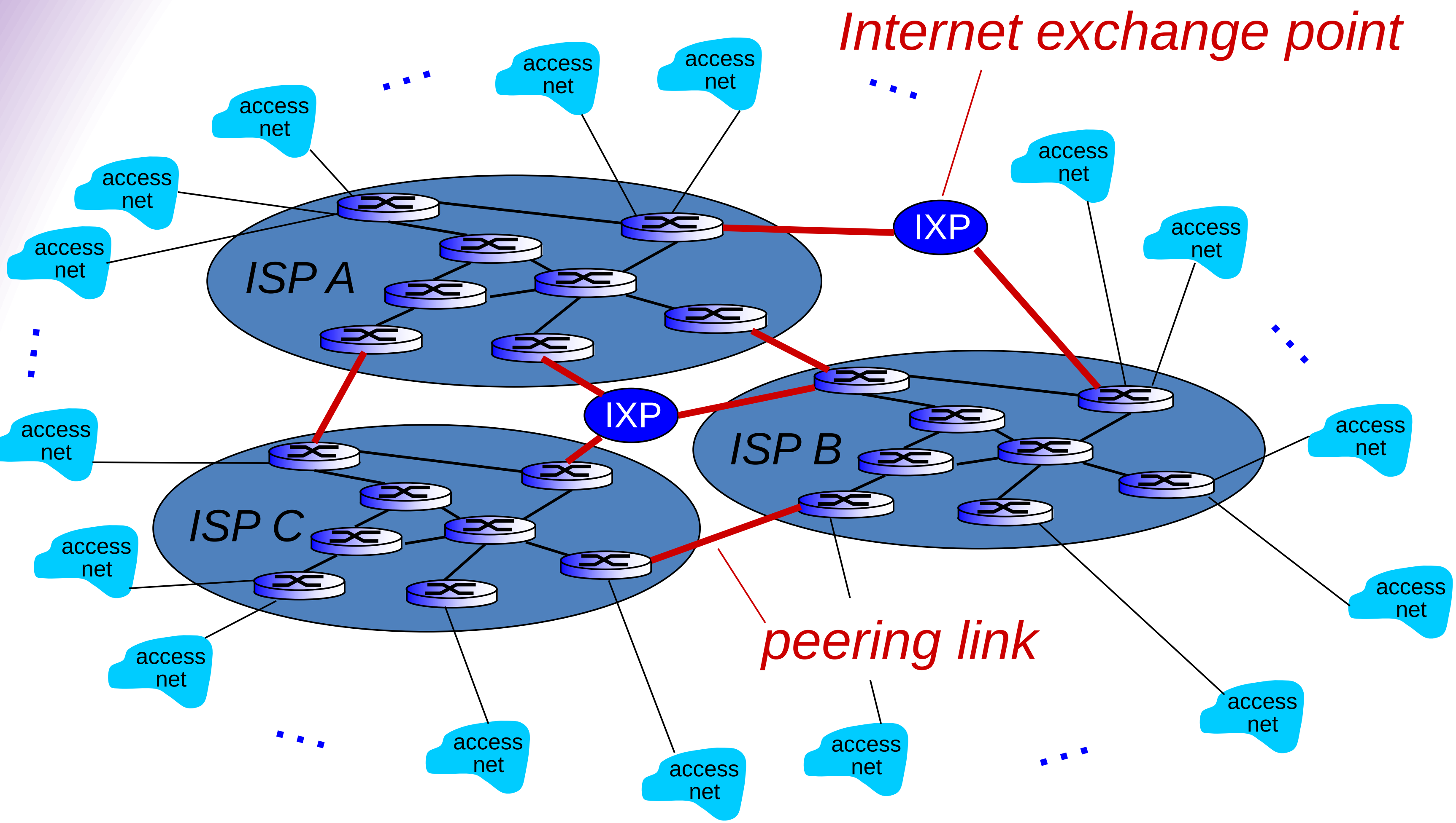
Option: connect each access ISP to a global transit ISP? *Customer* and *provider* ISPs have economic agreement.



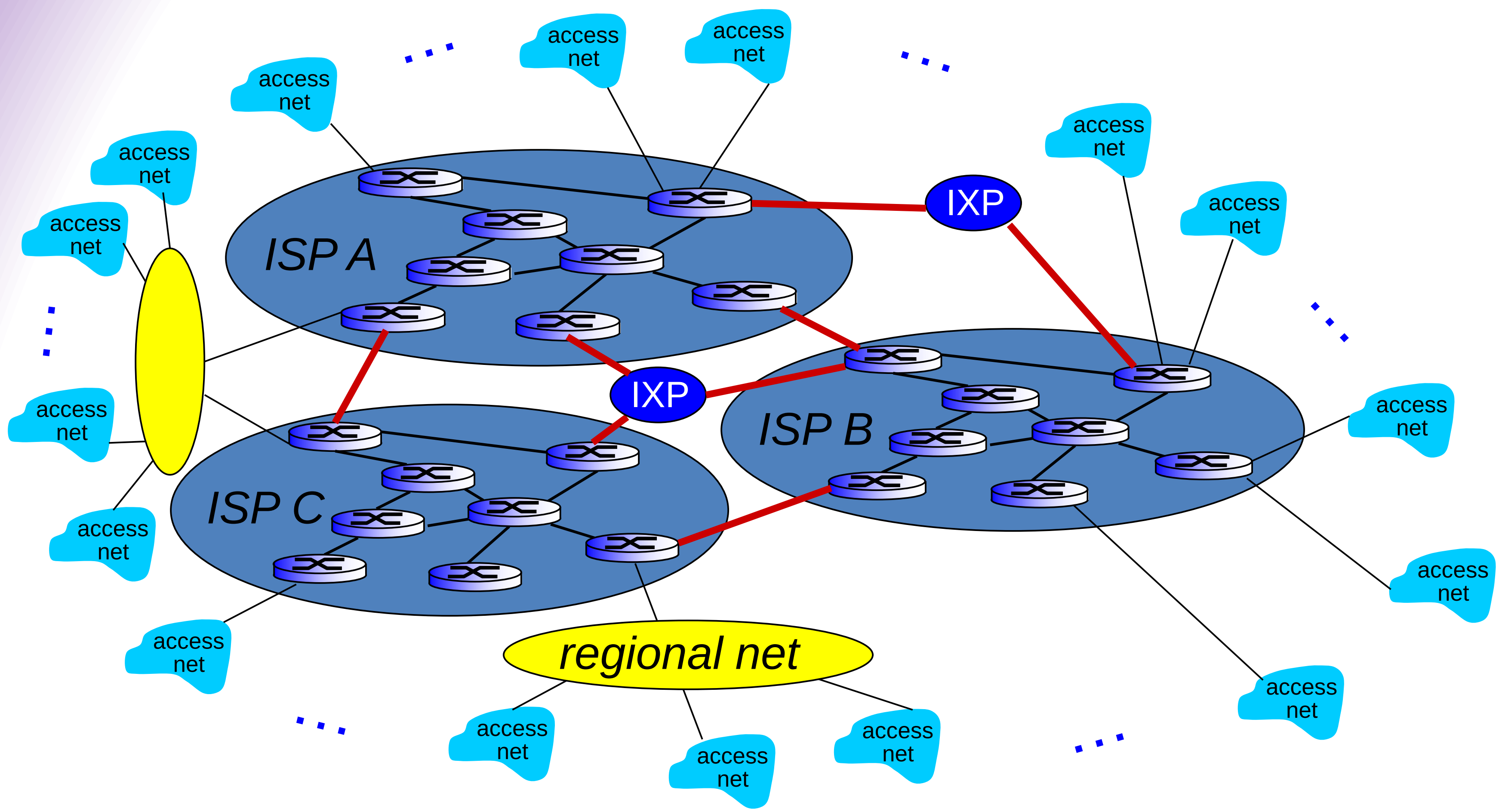
But if one global ISP is viable business, there will be competitors ….



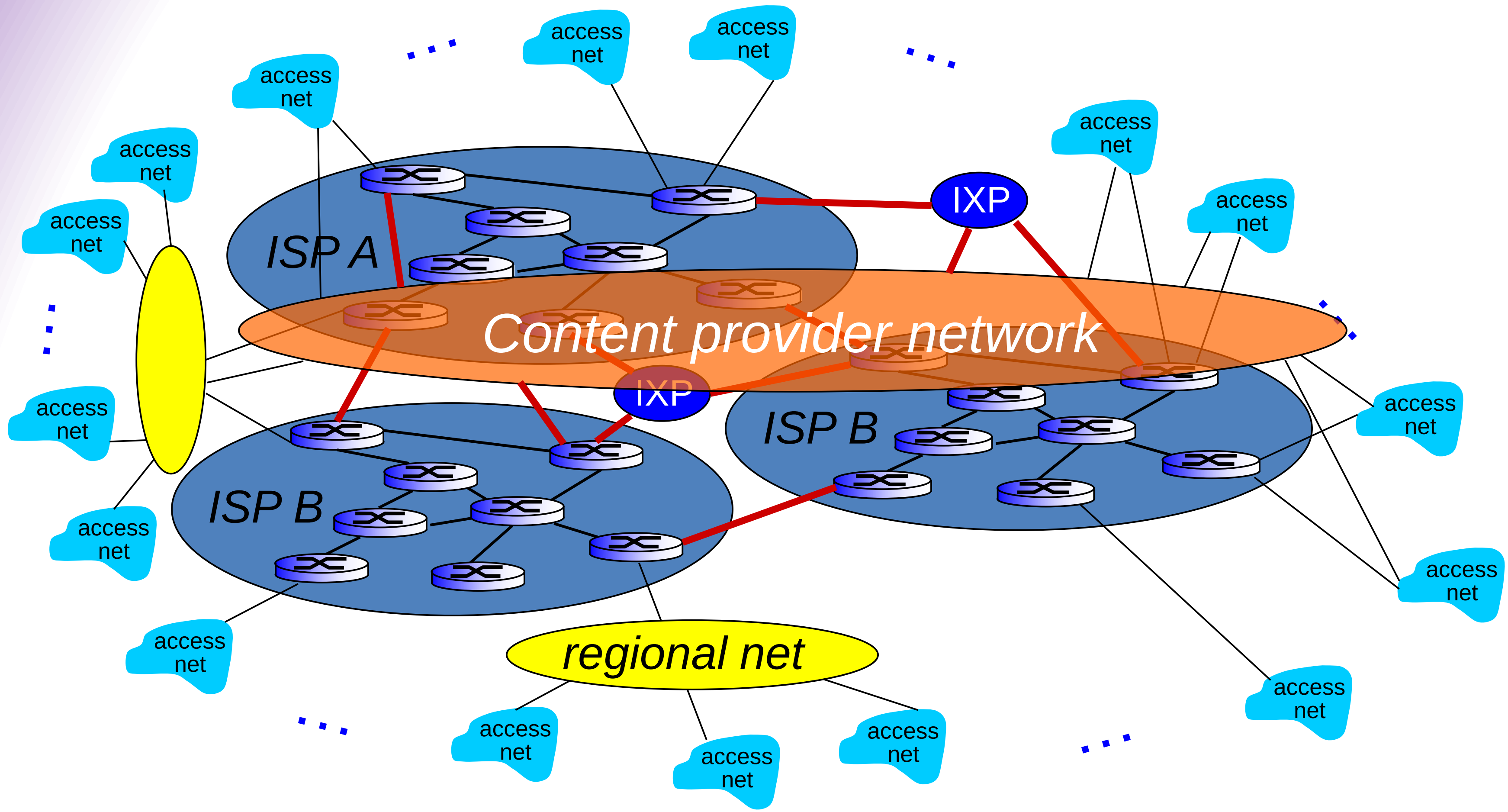
But if one global ISP is viable business, there will be competitors …. which must be interconnected

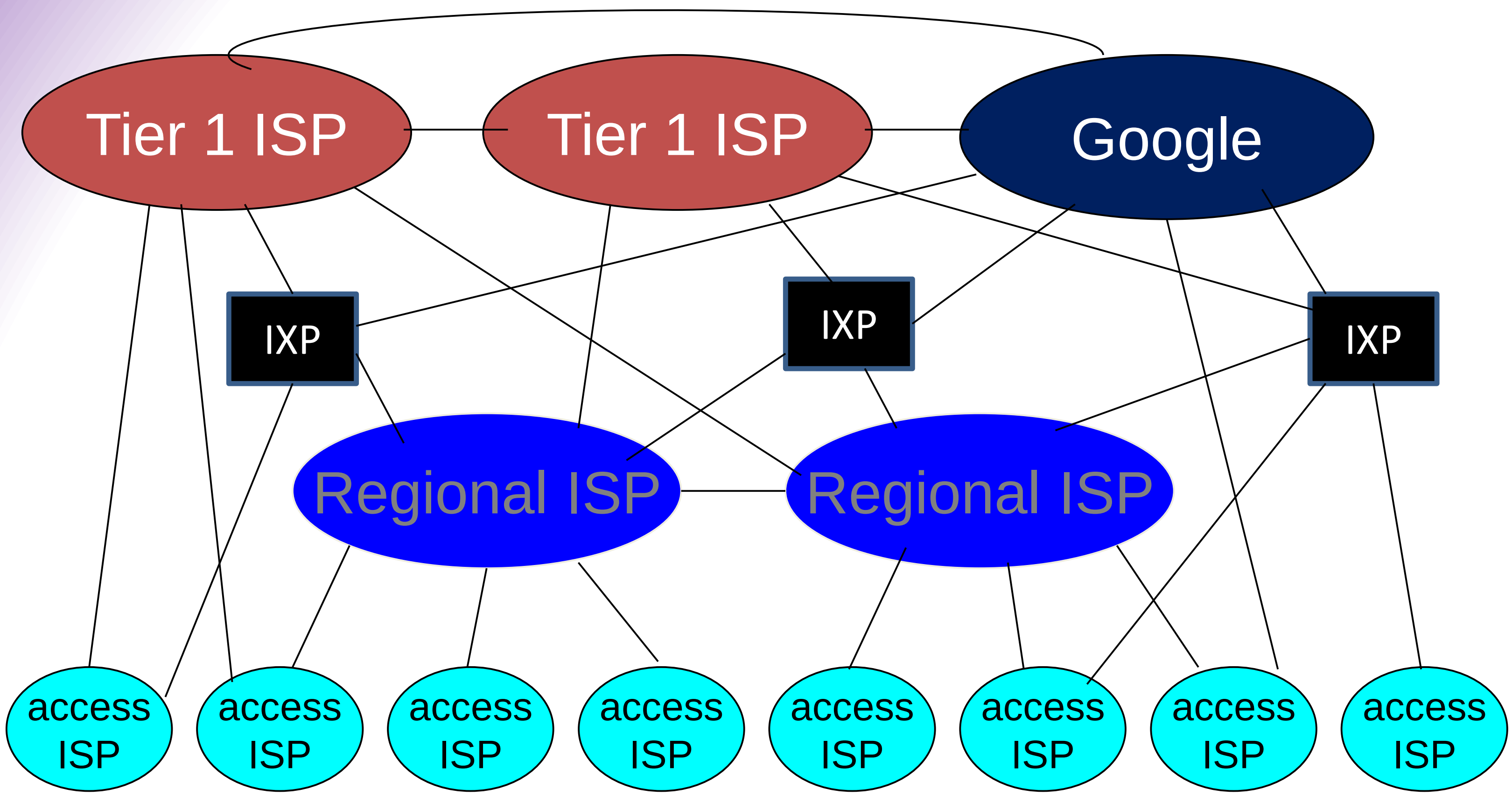


… and regional networks may arise to connect access nets to ISPs



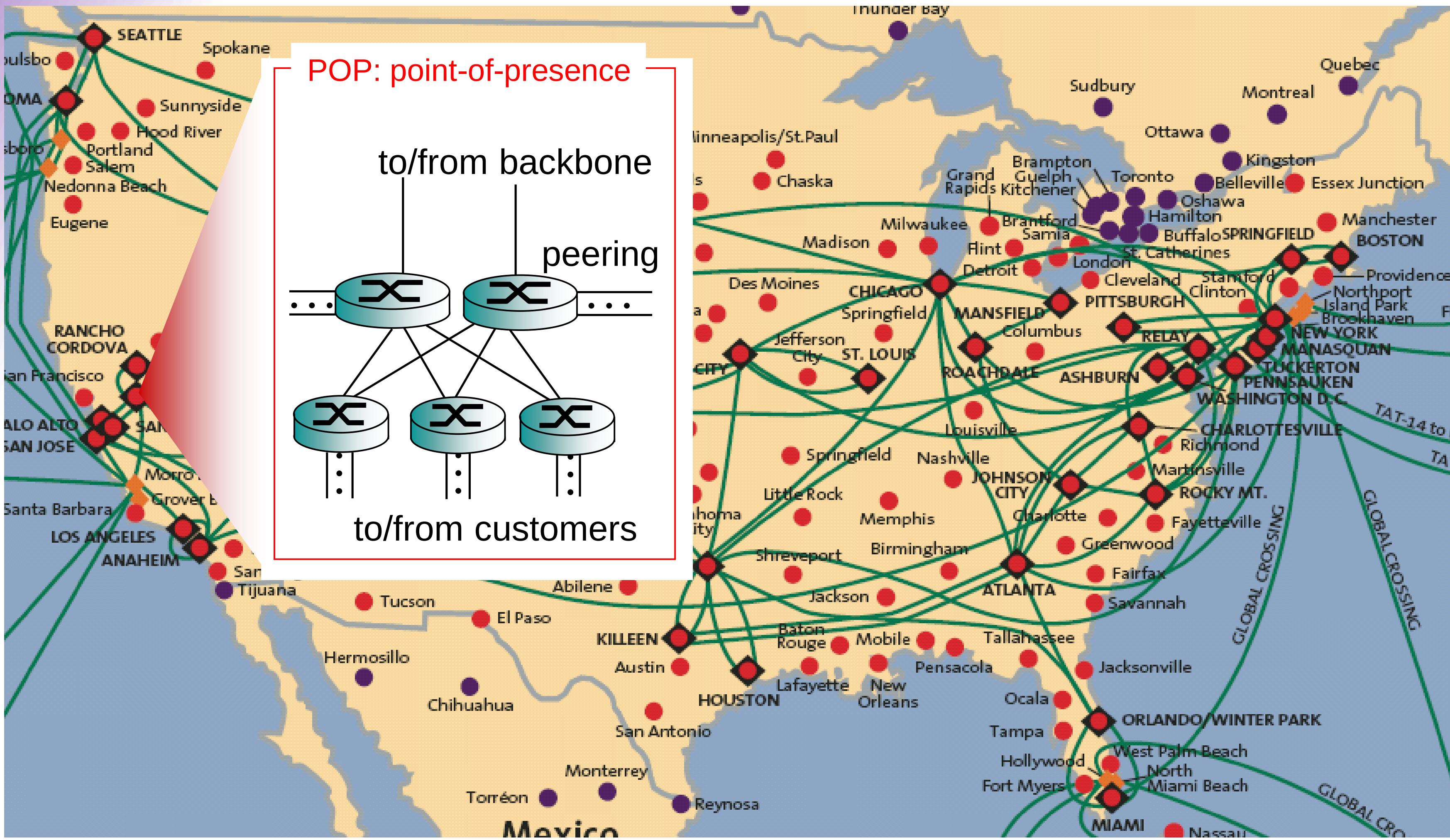
… and content provider networks (e.g., Google, Microsoft, Akamai) may run their own network, to bring services, content close to end users





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

Tier-1 ISP: e.g., Sprint



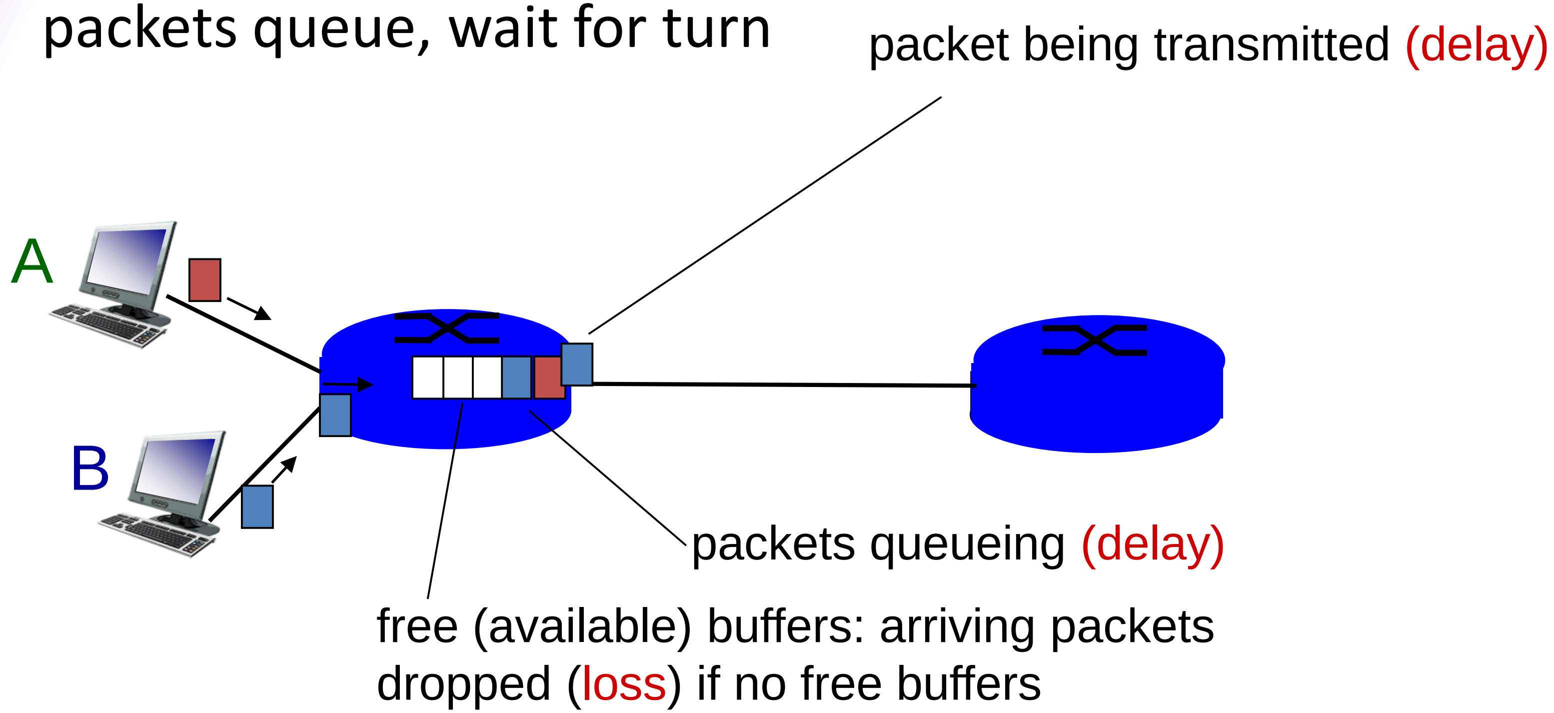
1.4 Performance measure

- delay
- packet loss
- throughput

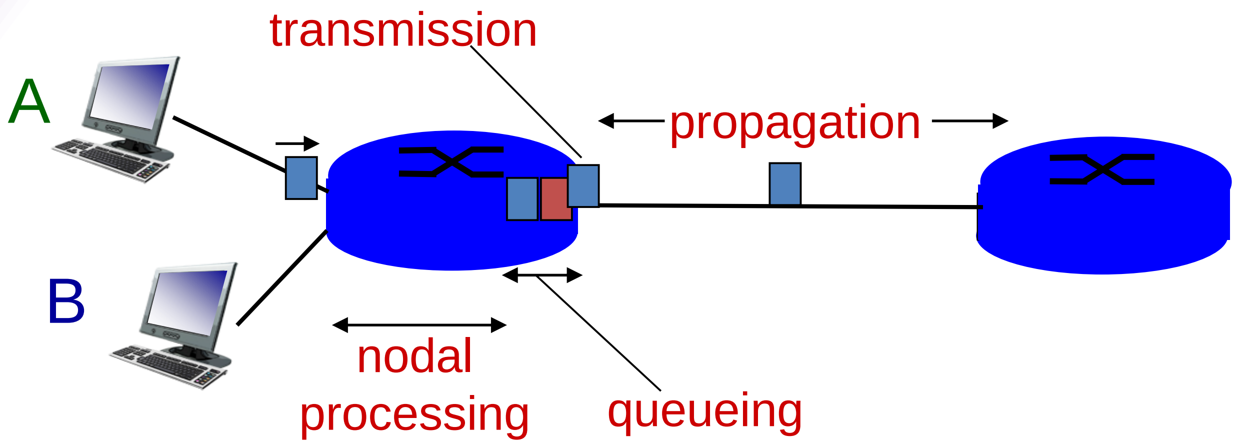
How do loss and delay occur?

packets *queue* in router buffers

- packet arrival rate to link (temporarily) exceeds output link capacity
- packets queue, wait for turn



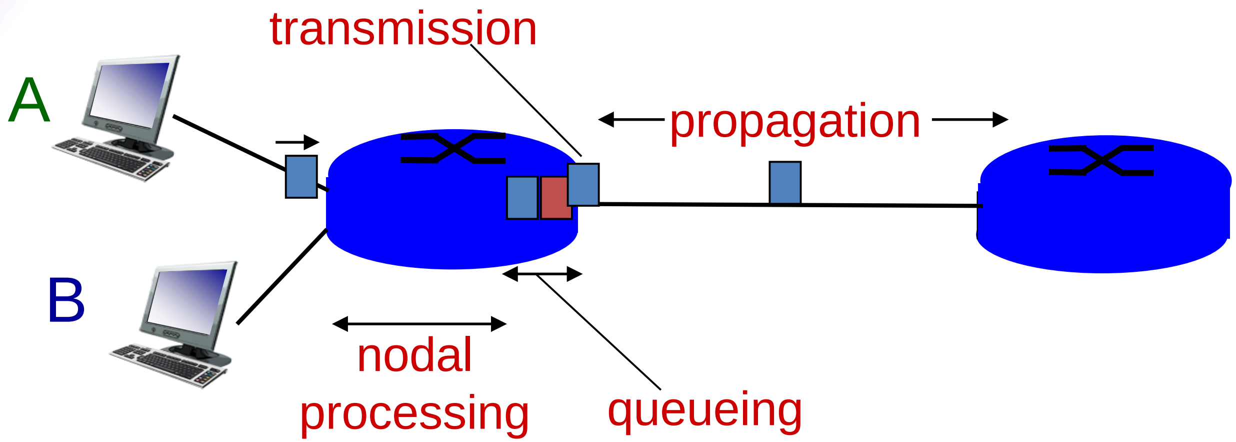
Four sources of packet delay



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

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

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



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

d_{trans}: transmission delay:

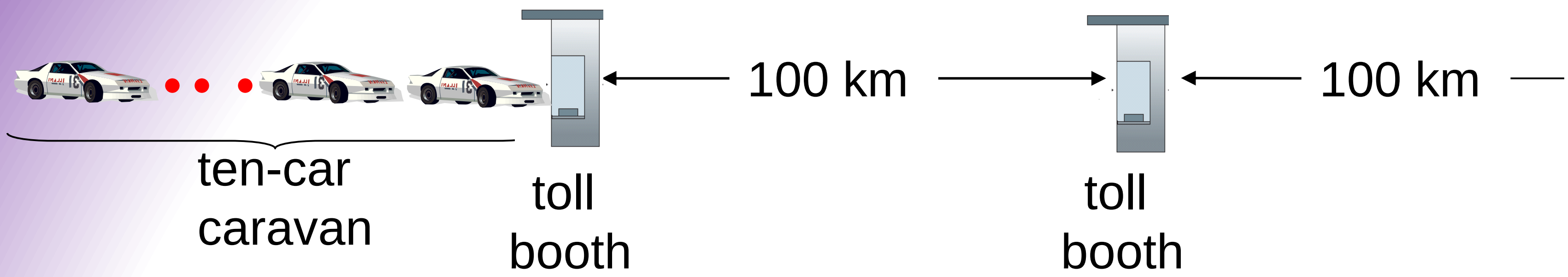
- L: packet length (bits)
- R: link *bandwidth (bps)*
- $d_{trans} = L/R$

d_{trans} and d_{prop}
very different

d_{prop}: propagation delay:

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

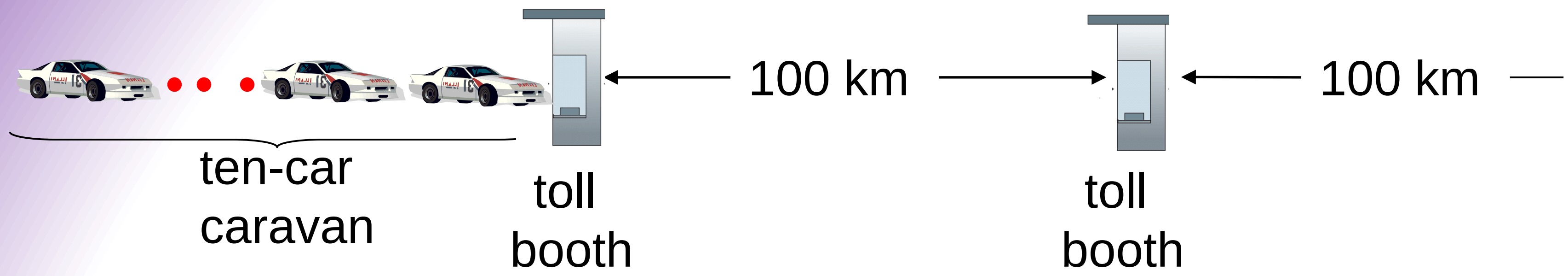
Caravan analogy



- 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 booth: 100km/(100km/hr) = 1 hr
- *A:* 62 minutes

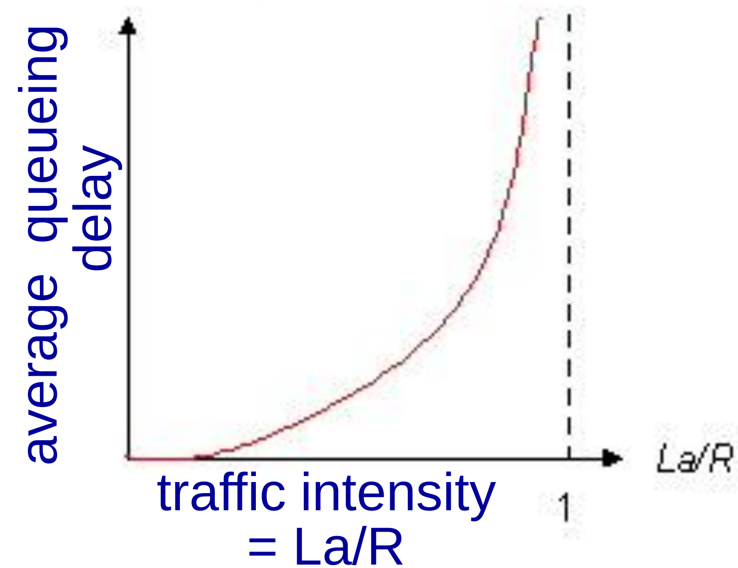
Caravan analogy (more)



- 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 2^{nd} booth before all cars serviced at first booth?
  - *A: Yes!* after 7 min, 1^{st} car arrives at second booth; three cars still at 1^{st} booth.

Queuing delay (revisited)

- *R:* link bandwidth (bps)
- *L:* packet length (bits/packet)
- *a*: average packet arrival rate (packets/sec)
- *La* : average rate (bits/sec)
- *La*/*R*: traffic intensity



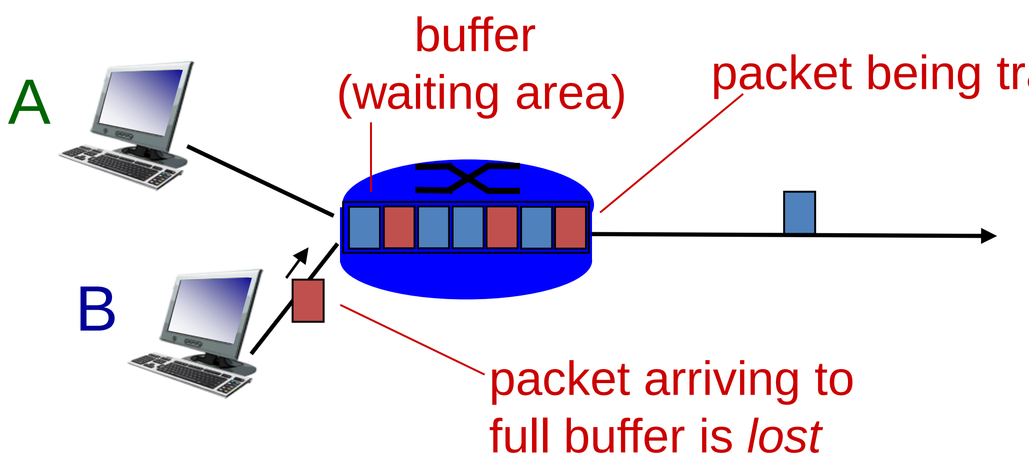
- ❖ *La/R* ~ 0: average queuing delay small
- ❖ *La/R* ~ 1: average queueing delay large
- ❖ *La/R* > 1: more "work" arriving than can be serviced, average delay infinite!

La/R ~ 0

La/R ~ 1

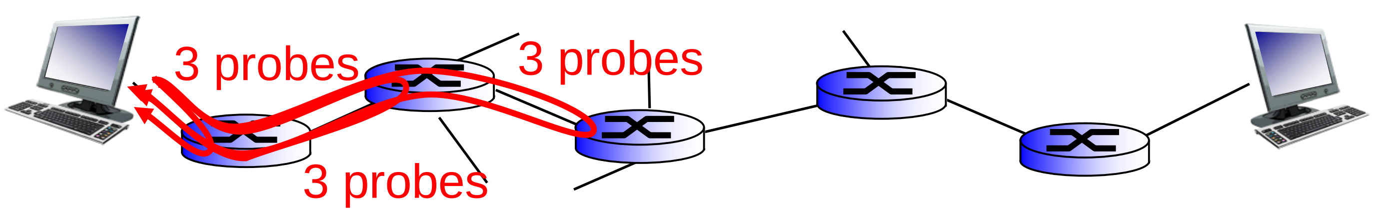
Packet loss

- 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



"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
  - router *i* will return packets to sender
  - sender times interval between transmission and reply.



"Real" Internet delays, routes

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

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

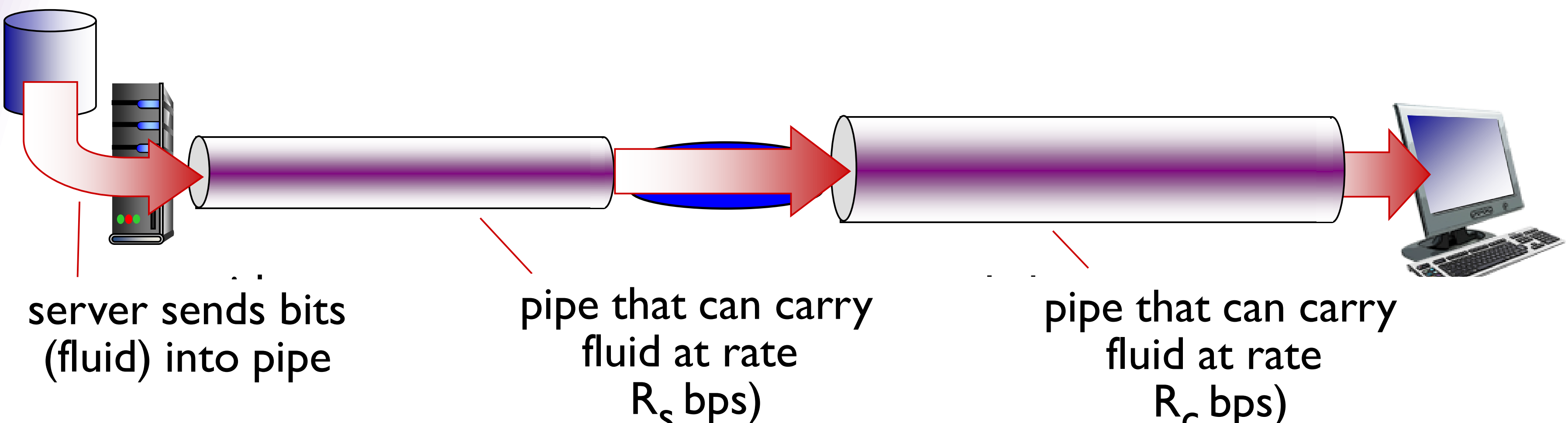
1 cs-gw (128.119.240.254) 1 ms 1 ms 2 ms
2 border1-rt-fa5-1-0.gw.umass.edu (128.119.3.145) 1 ms 1 ms 2 ms
3 cht-vbns.gw.umass.edu (128.119.3.130) 6 ms 5 ms 5 ms
4 jn1-at1-0-0-19.wor.vbns.net (204.147.132.129) 16 ms 11 ms 13 ms
5 jn1-so7-0-0-0.wae.vbns.net (204.147.136.136) 21 ms 18 ms 18 ms
6 abilene-vbns.abilene.ucaid.edu (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

trans-oceanic link

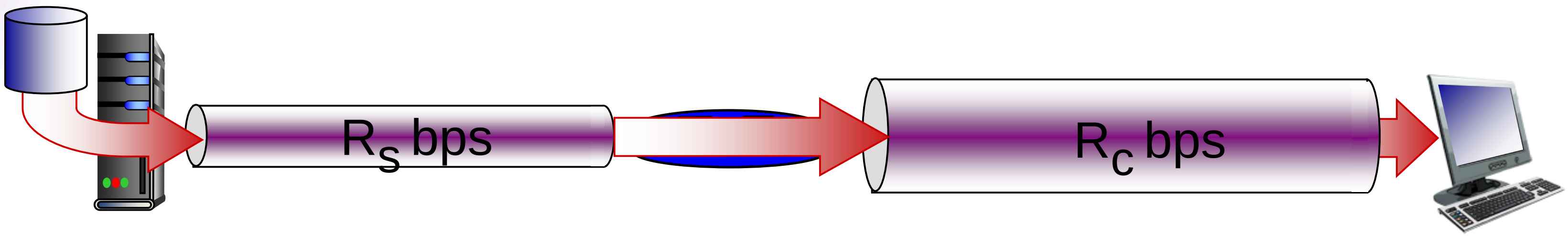
* means no response (probe lost, router not replying)

Throughput

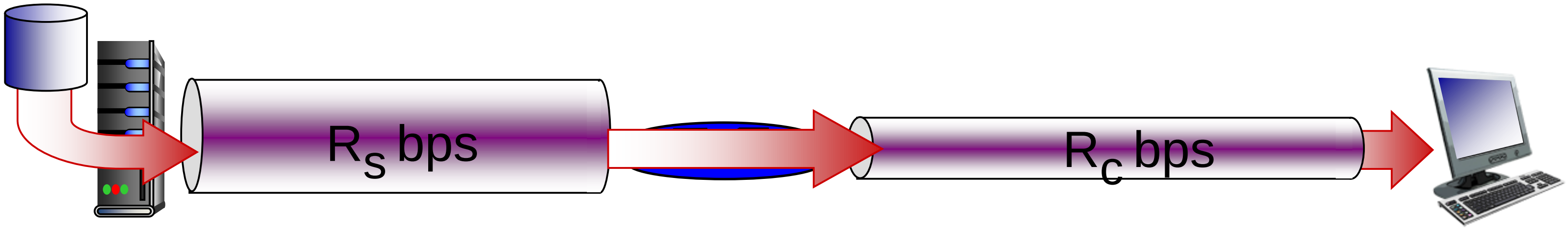
- *throughput:* rate (bits/time unit) at which bits transferred between sender/receiver
  - *instantaneous:* rate at given point in time
  - *average:* rate over longer period of time



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



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

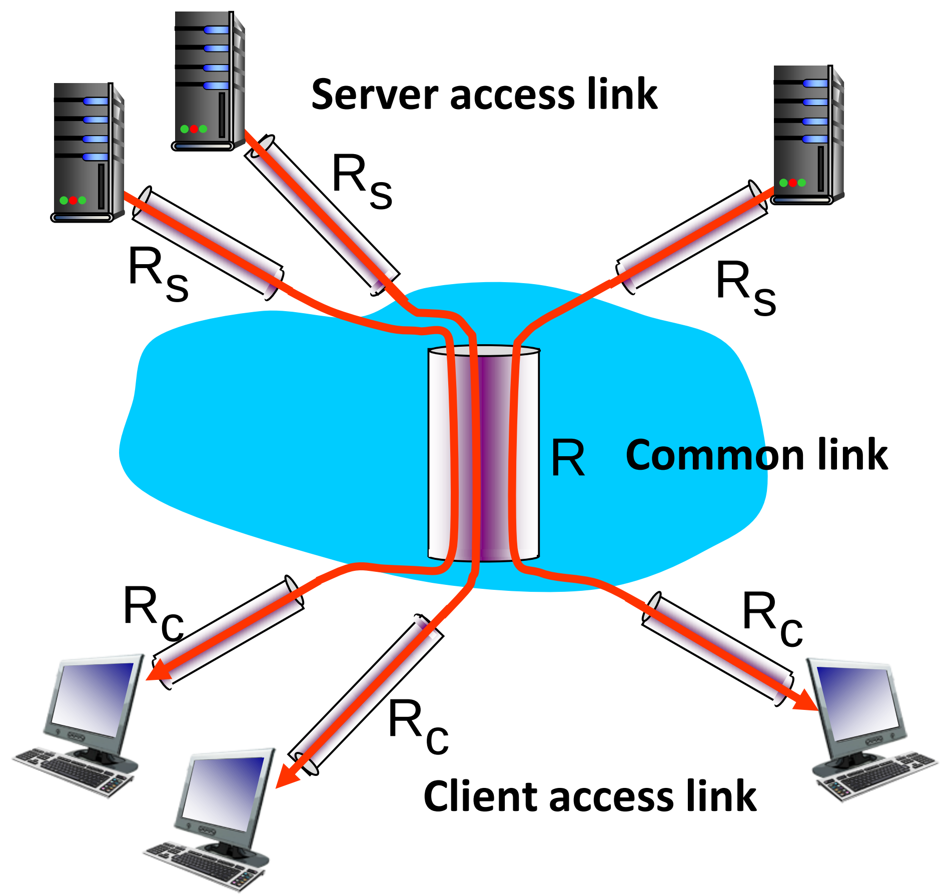


bottleneck link

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

Throughput: Internet scenario

- per-connection end-end throughput: $\min(R_c, R_s, R/10)$
- in practice: R_c or R_s is often bottleneck



10 connections (fairly) share backbone bottleneck link R bps

1.5 Protocol

Networks are complex,
with many "pieces":

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

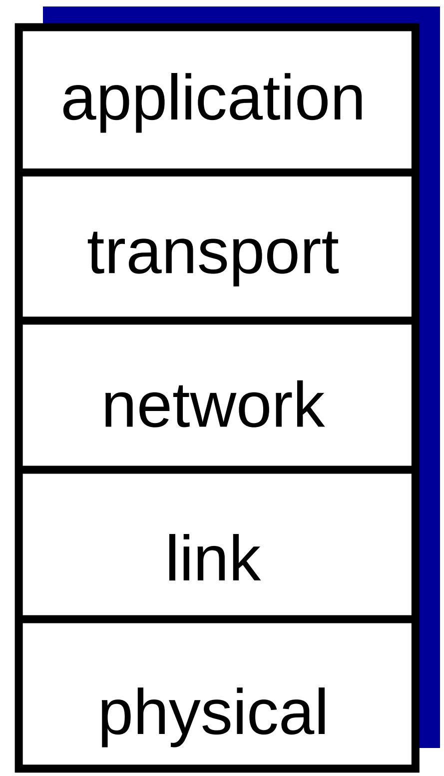
Question:

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

…. or at least our discussion of networks?

Protocol layering

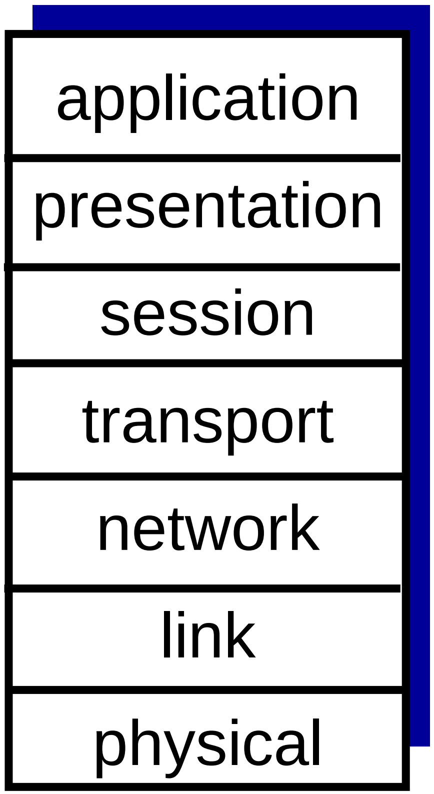
- *application:* supporting network applications
  - FTP, SMTP, HTTP
- *transport:* process-process data transfer
  - TCP, UDP
- *network:* routing of datagrams from source to destination
  - IP, routing protocols
- *link:* data transfer between neighboring network elements
  - Ethernet, 802.111 (WiFi), PPP
- *physical:* bits "on the wire"



5-layer Internet protocol stack

ISO/OSI reference model

- *presentation:* allow applications to interpret meaning of data, e.g., encryption, compression, machine-specific conventions
- *session:* synchronization, checkpointing, recovery of data exchange
- Internet protocol stack "missing" these layers!
  - these services, *if needed,* must be implemented in application
  - needed?



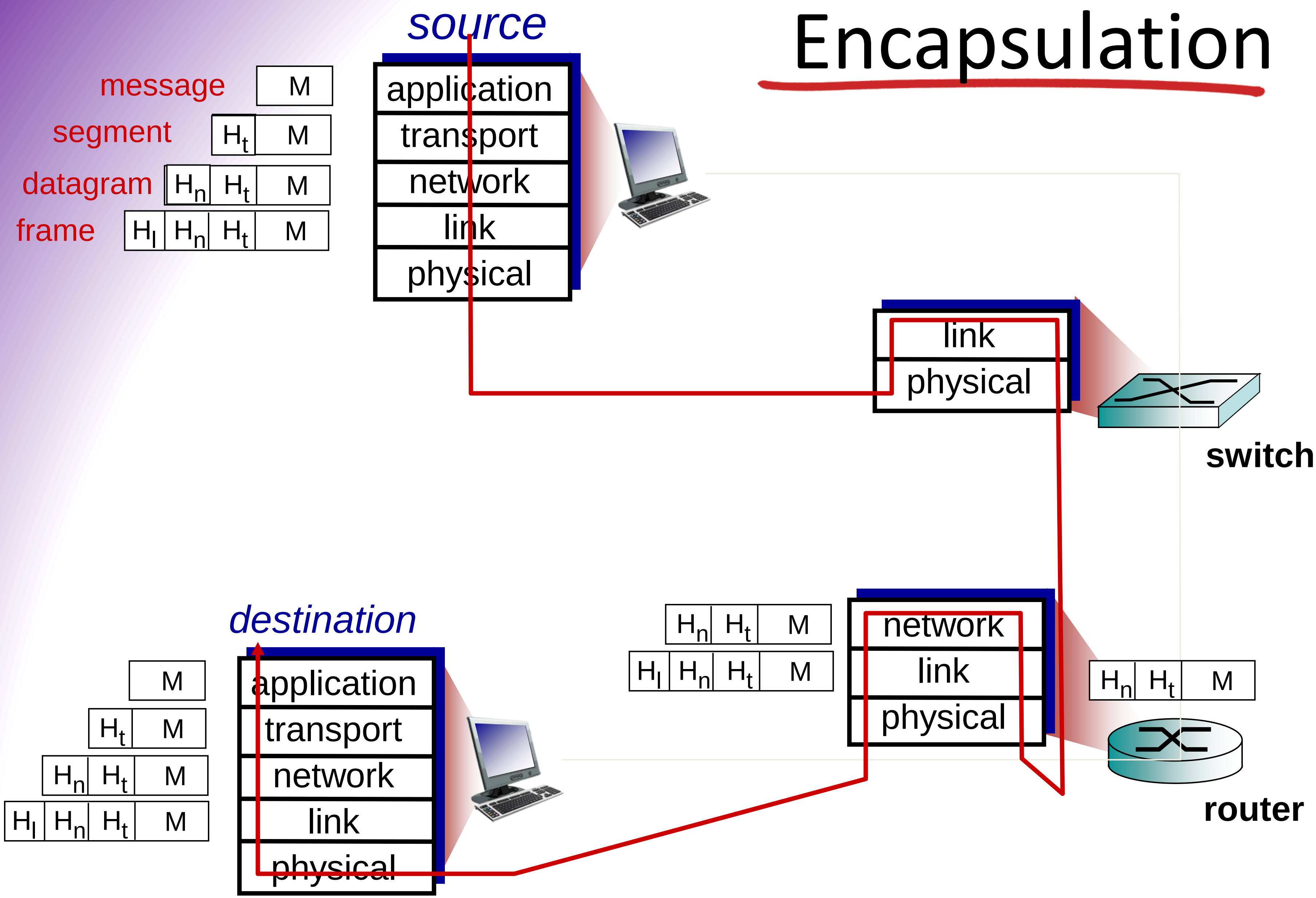
ISO – International Organization for Standards
OSI – Open System Interconnection

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 of implementation of layer's service transparent to rest of system
  - e.g., change in internal function of a layer doesn't affect rest of system

Encapsulation



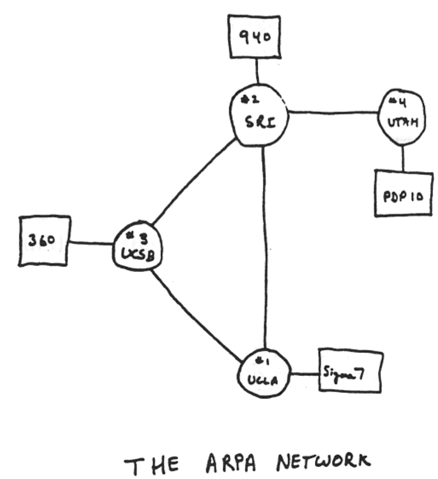
1.6 History of computer networking

- Telegraph Networks
  - First used in about 1844
  - Message switching & digital transmission
- Telephone Networks
  - Bell Telephone Company founded in 1877
  - Circuit Switching
  - Analog transmission → digital transmission
  - Mobile communications
- Internet
  - Packet switching & computer applications

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



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 routers
- decentralized control

define today's Internet architecture

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 in US: Csnet, BITnet, NSFnet, Minitel
- 100,000 hosts connected to confederation of networks

1990, 2000's: commercialization, the Web, new apps

- early 1990's: 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 1990's: commercialization of the Web

late 1990's – 2000's:

- more killer apps: instant messaging, P2P file sharing
- network security to forefront
- est. 50 million host, 100 million+ users
- backbone links running at Gbps

2005-present

- ~750 million hosts
  - Smartphones and tablets
- Aggressive deployment of broadband access
- Increasing ubiquity of high-speed wireless access
- Emergence of online social networks:
  - e.g. Facebook
- Service providers (Google, Microsoft) create their own networks
  - Bypass Internet, providing "instantaneous" access to search, email, etc.
- E-commerce, universities, enterprises running their services in "cloud" (e.g. Amazon EC2)

Chapter Summary

- overview of computer networking, in particular Internet
- network components – edge, core, access network, physical media, protocol
- performance – delay, loss, throughput
- history of Internet

Reference

Chapter 1, Computer Networking: A Top-Down Approach