

# 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?

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

# “nuts-and-bolts” view

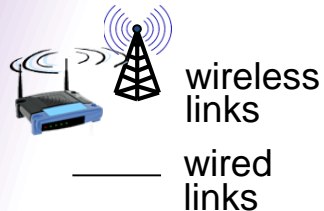


## ❖ *devices*

- hosts = end systems
- running network apps

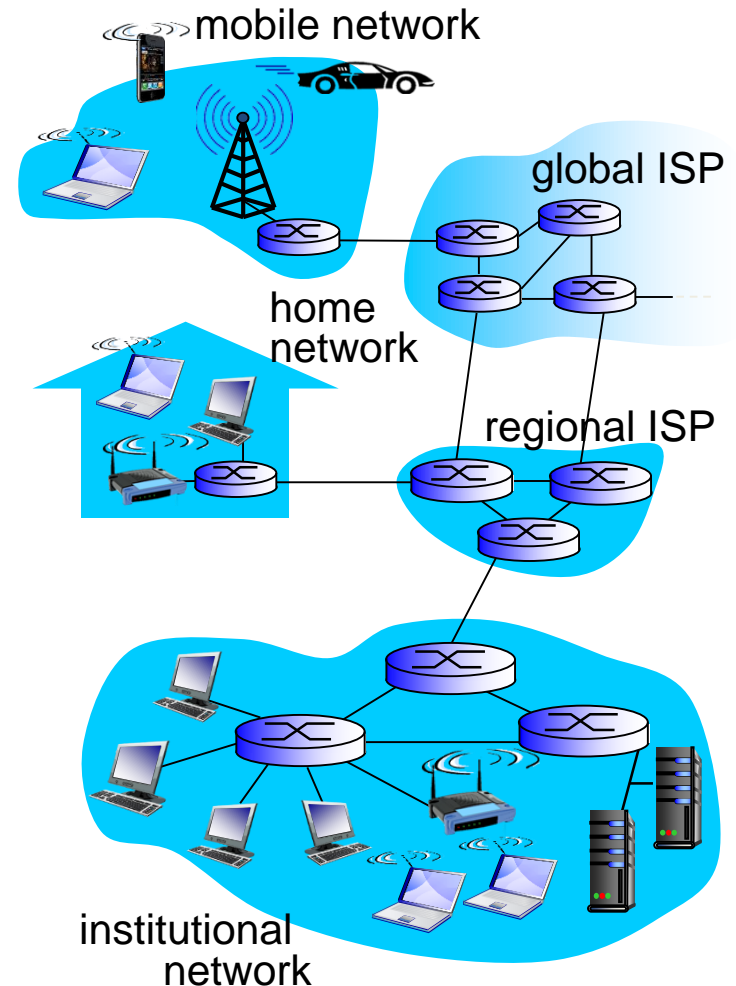
## ❖ *communication links*

- optical fiber, copper wire, radio, satellite
- transmission rate: bandwidth



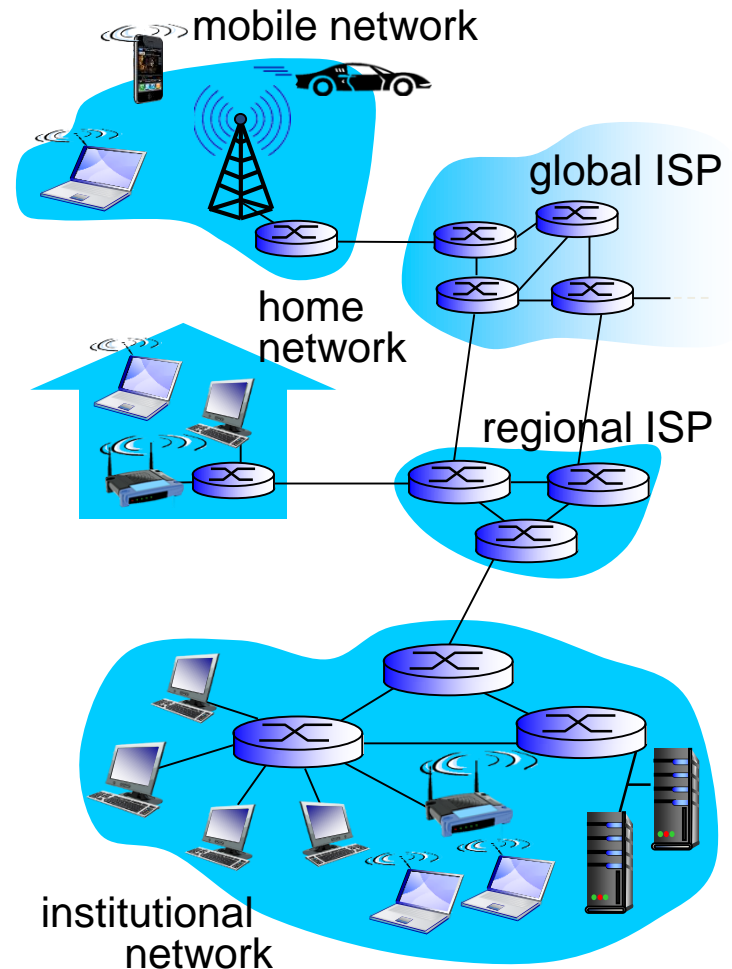
## ❖ *packet switches*

- forward packets (chunks of data)
- routers and switches



# service view

- *infrastructure that provides services to applications*
  - Web, 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

# What is a protocol?

## *human protocols:*

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

... specific messages sent

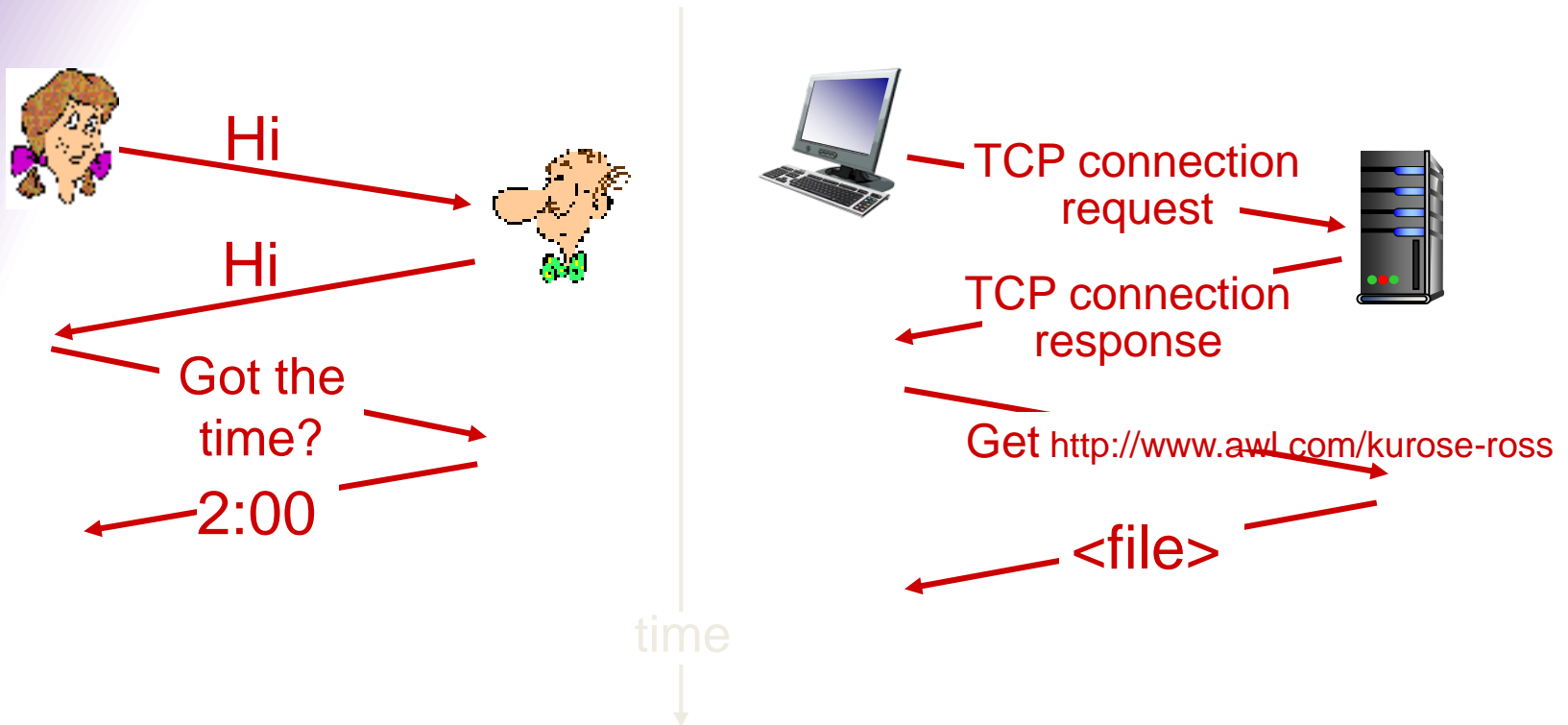
... specific actions taken  
when messages  
received, or other  
events

## *network protocols:*

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

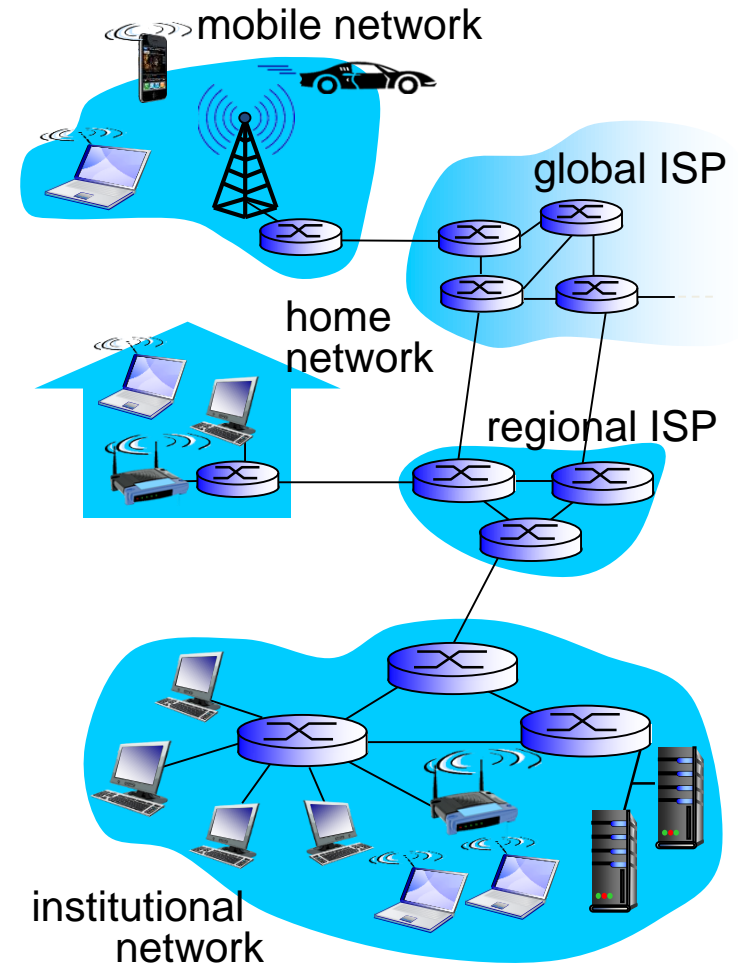
*protocols define format, order of messages sent and received among network entities, and actions taken on transmission and/or receipt of message/event*

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:*

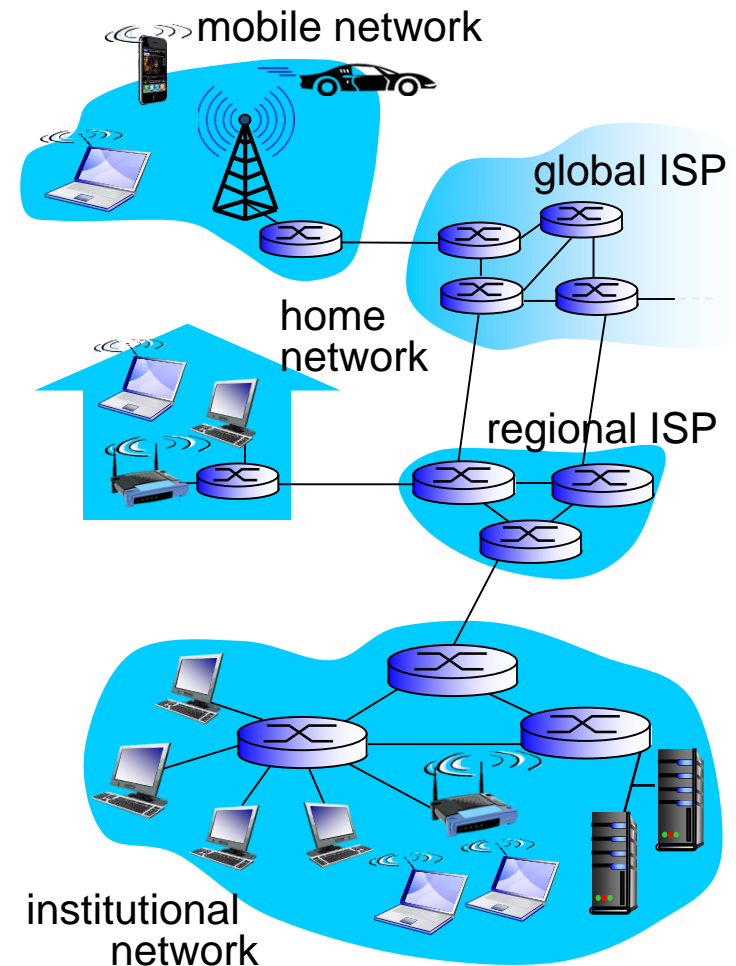
hosts: clients and servers  
servers often in data centers

❖ *access networks, physical media:*

wired, wireless communication links

❖ *network core:*

interconnected routers  
network of networks



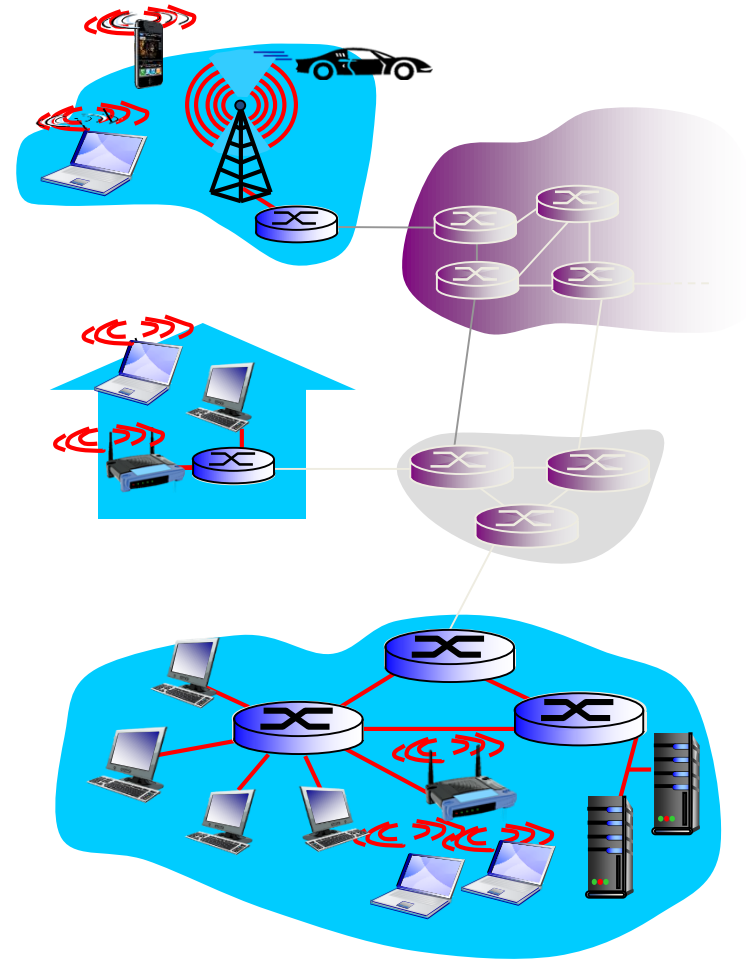
# Access networks and physical media

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

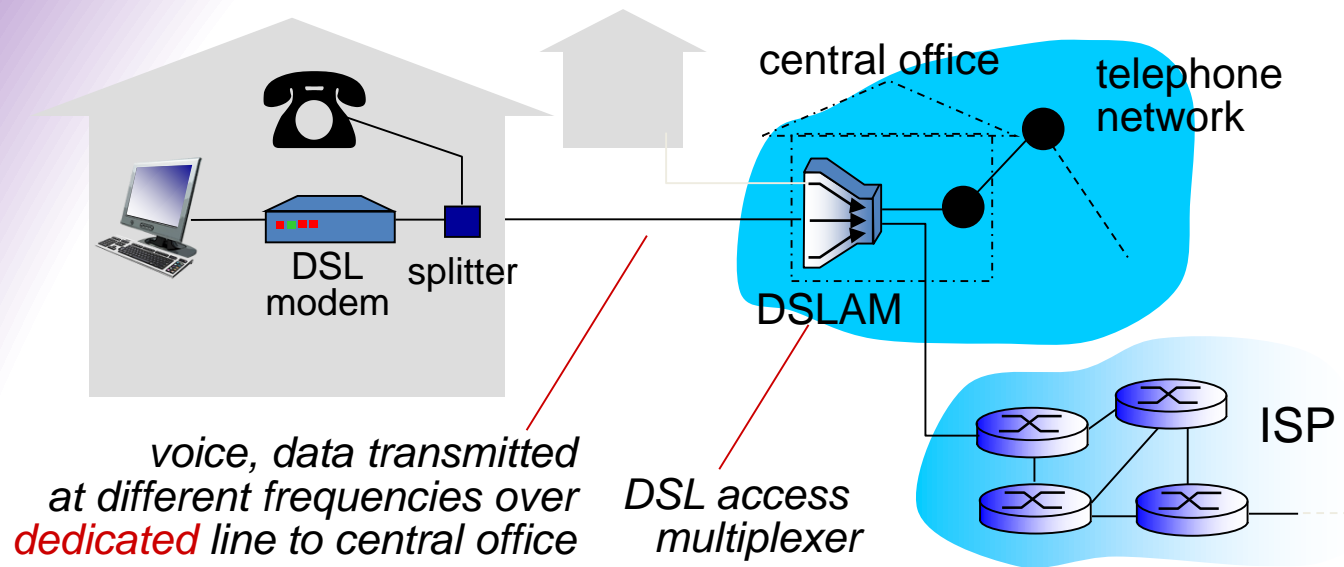
- residential access nets
- institutional access networks (school, company)
- mobile access networks

*keep in mind:*

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

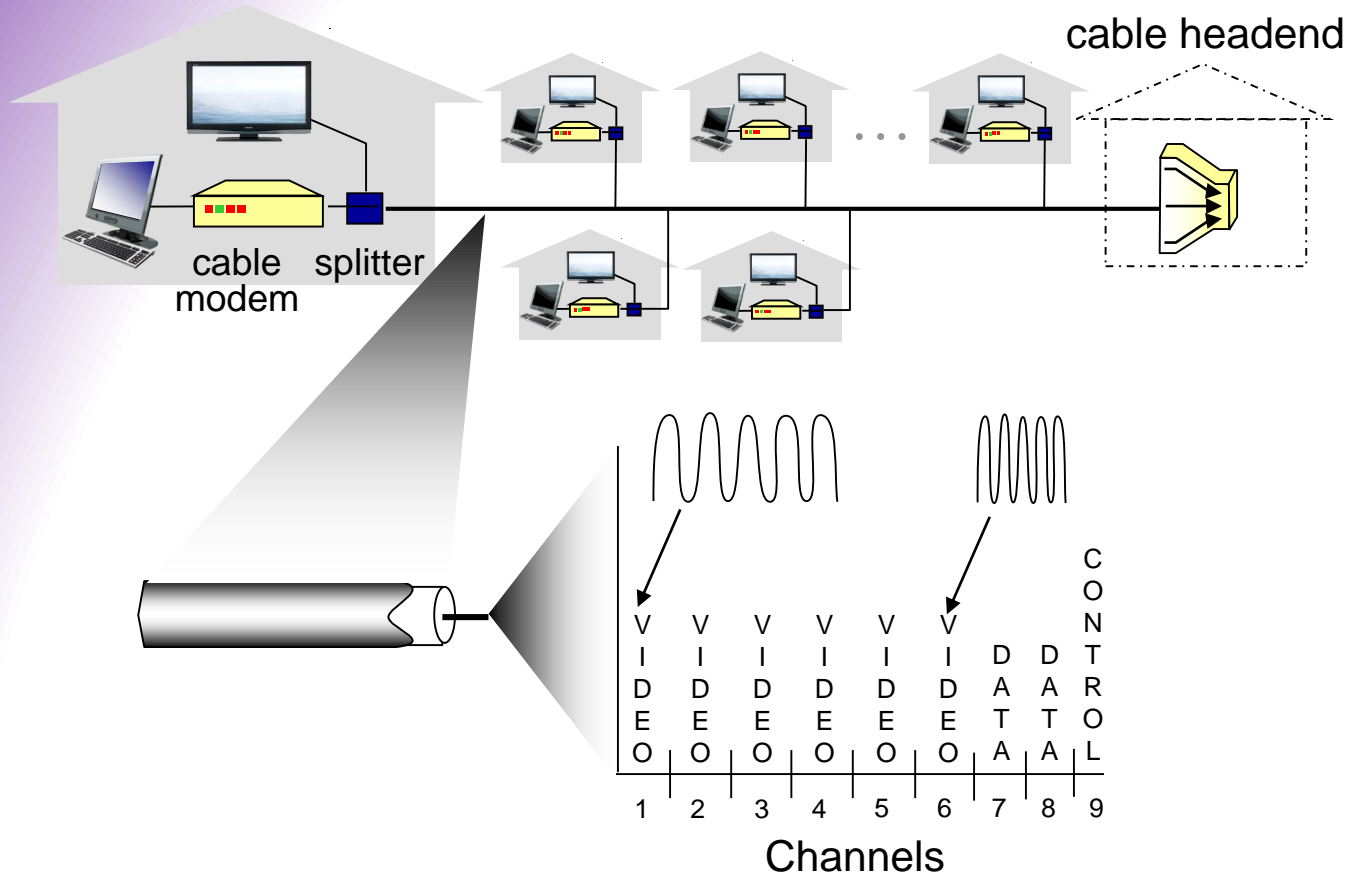


# Access net: digital subscriber line (DSL)



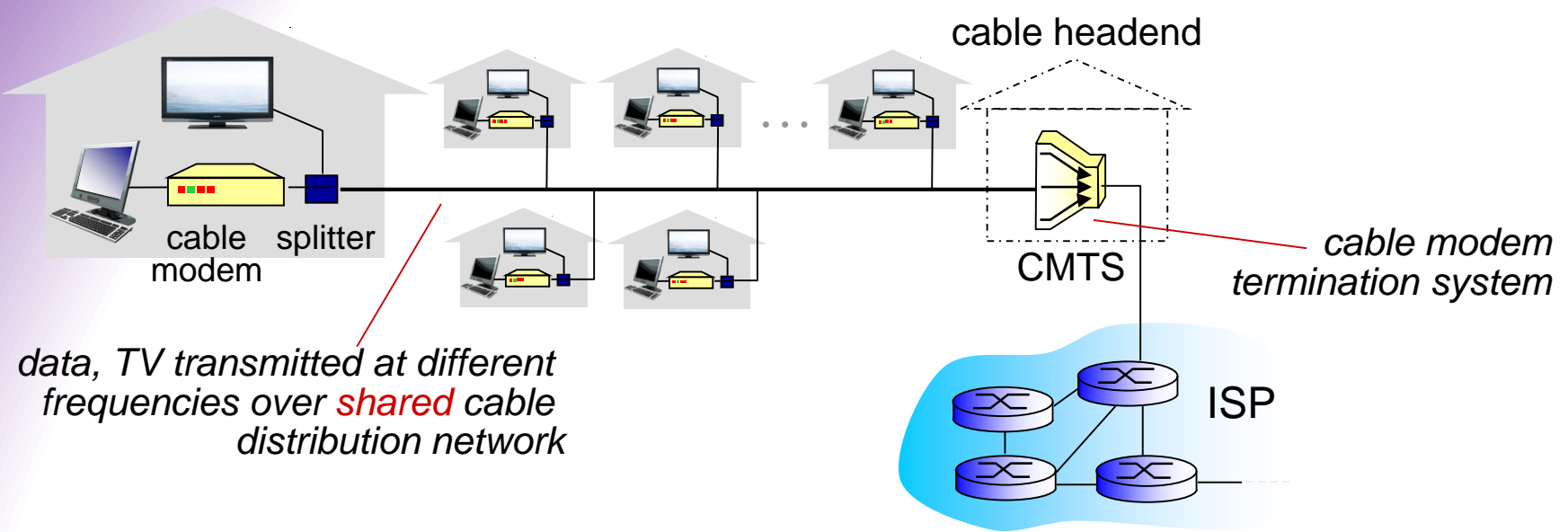
- ❖ use **existing** telephone line to central office DSL access multiplexer (DSLAM)
  - data over DSL phone line goes to Internet
  - voice over DSL phone line goes to telephone net
- ❖ < 2.5 Mbps upstream transmission rate (typically < 1 Mbps)
- ❖ < 24 Mbps downstream transmission rate (typically 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

# Access net: cable network



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

# Access net: cable network



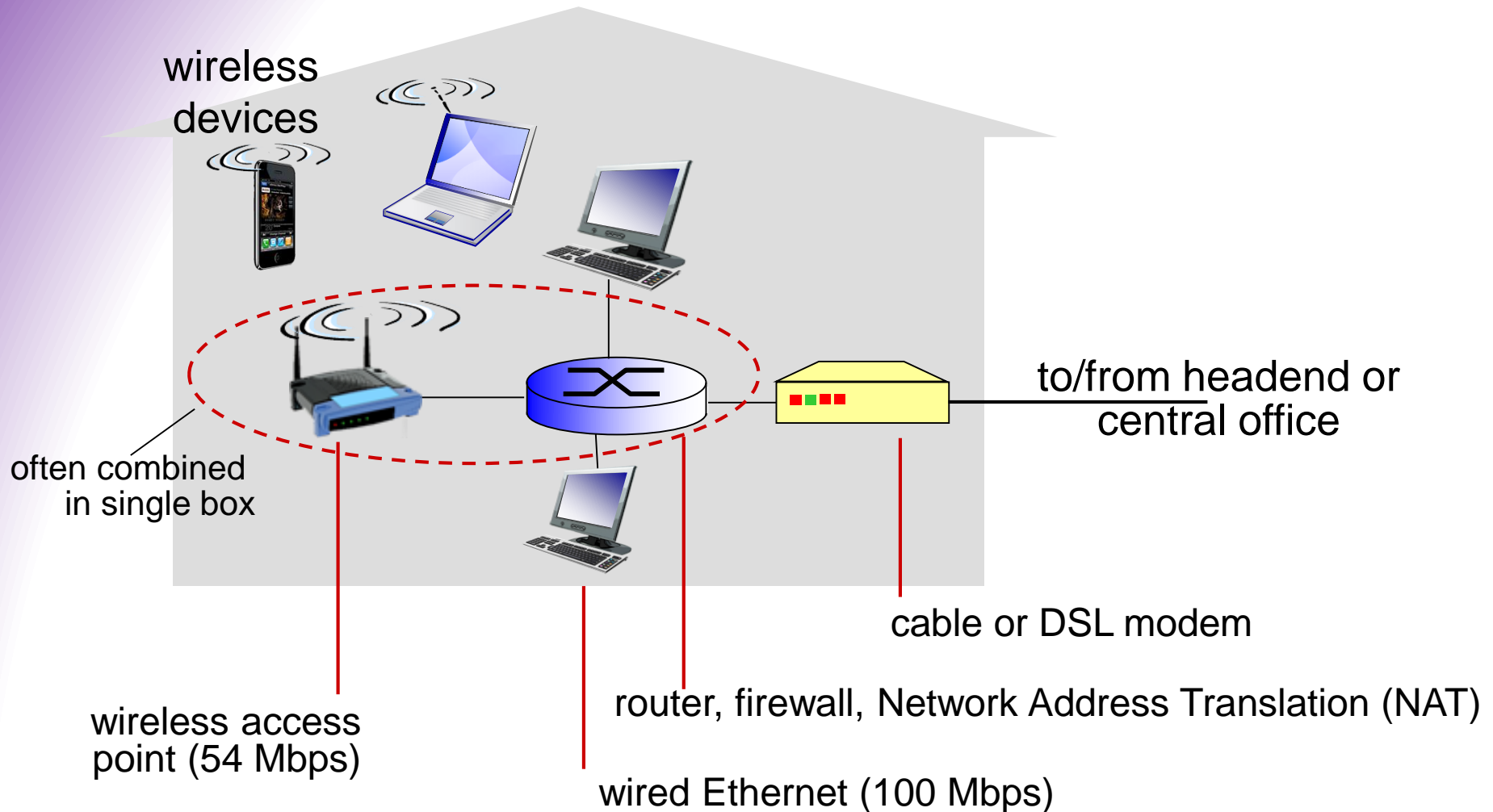
## ❖ hybrid fiber coax (HFC)

- asymmetric: up to 30 Mbps downstream transmission rate, 2 Mbps upstream transmission rate

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

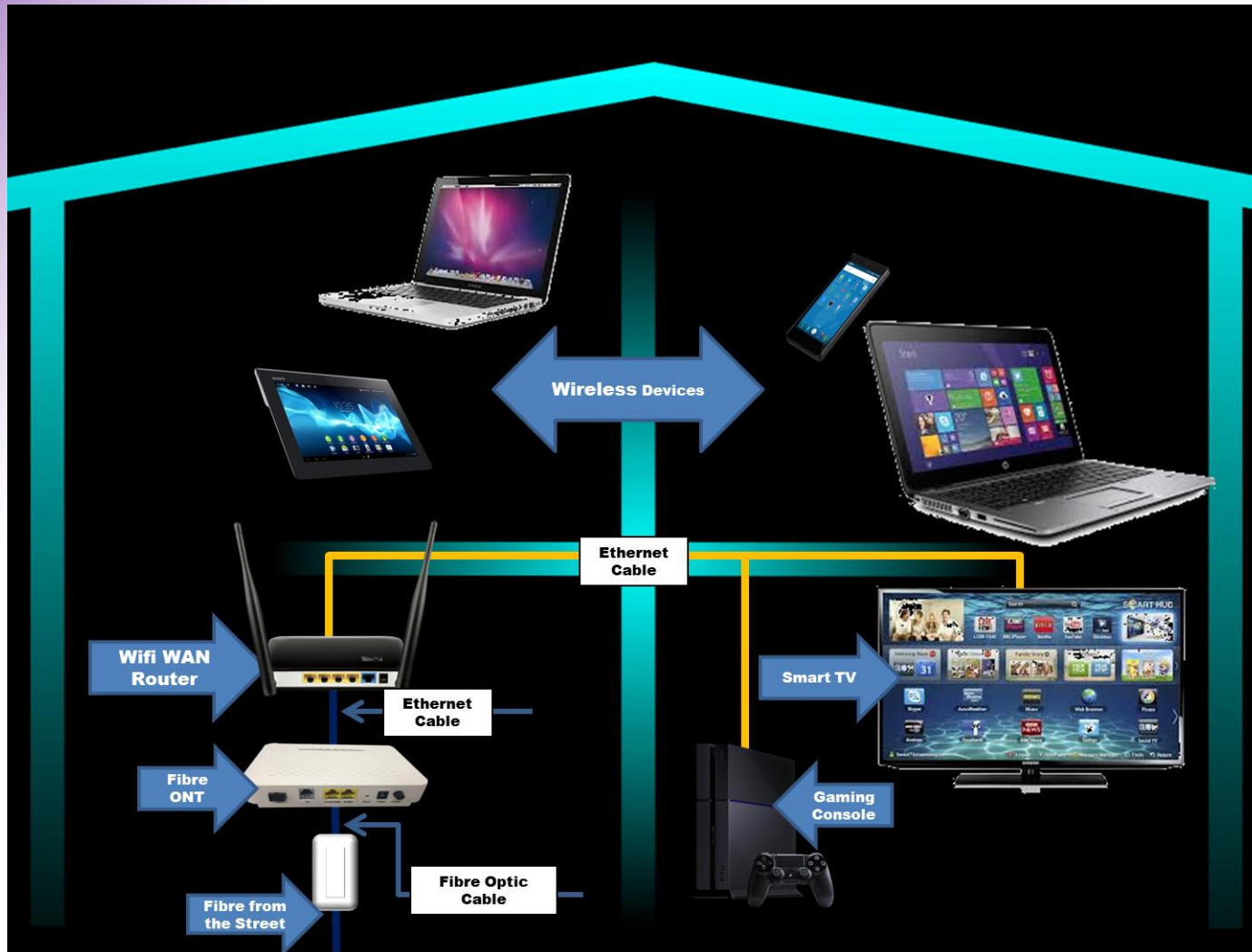
- homes *share access network* to cable headend
- unlike DSL, which has dedicated access to central office

# Access net: home network

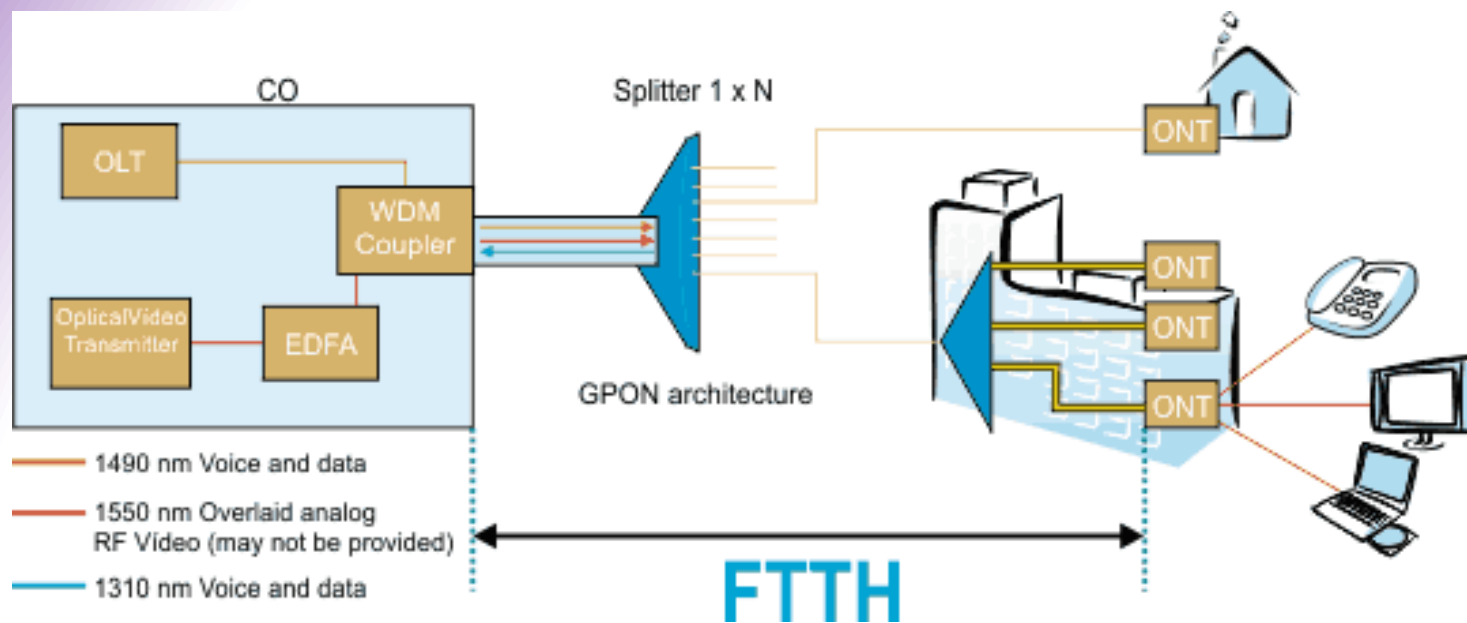




# Access net: fiber to the home (FTTH)



ONT  
Optical  
Network  
Terminal



GPON - Gigabit Passive Optical Networks

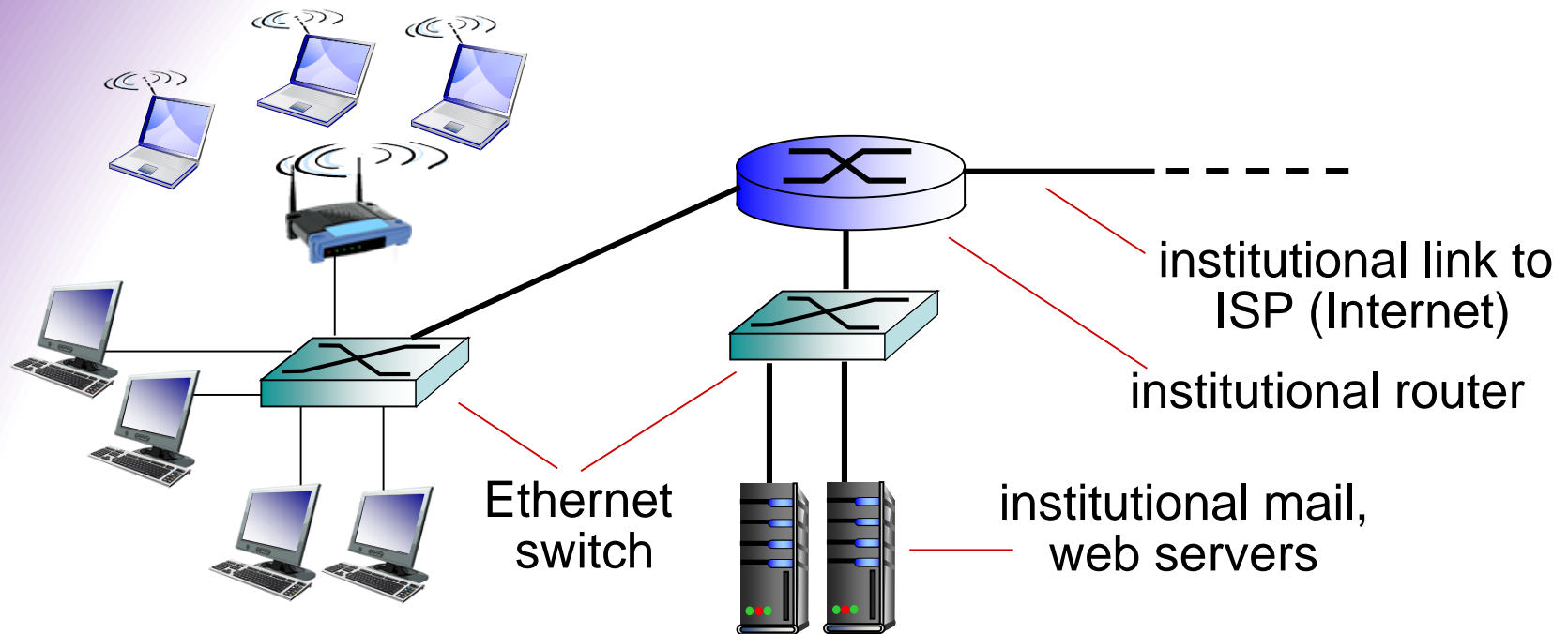
CO - Central Office

OLT – optical line terminator

WDM – wavelength-division multiplexing

EDFA – erbium-doped fiber amplifier

# Enterprise access networks (Ethernet)



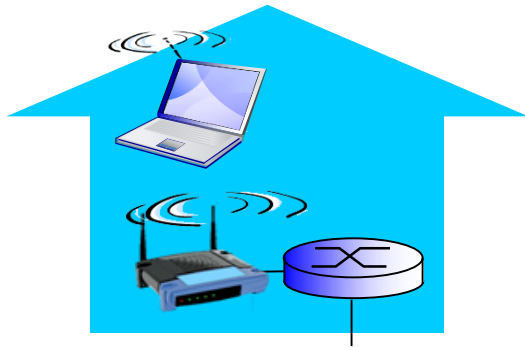
- typically used in companies, universities, etc.
- 10 Mbps, 100 Mbps, 1 Gbps, 10 Gbps transmission rates
- today, end systems typically connect into Ethernet switch

# 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



to Internet

## wide-area wireless access

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

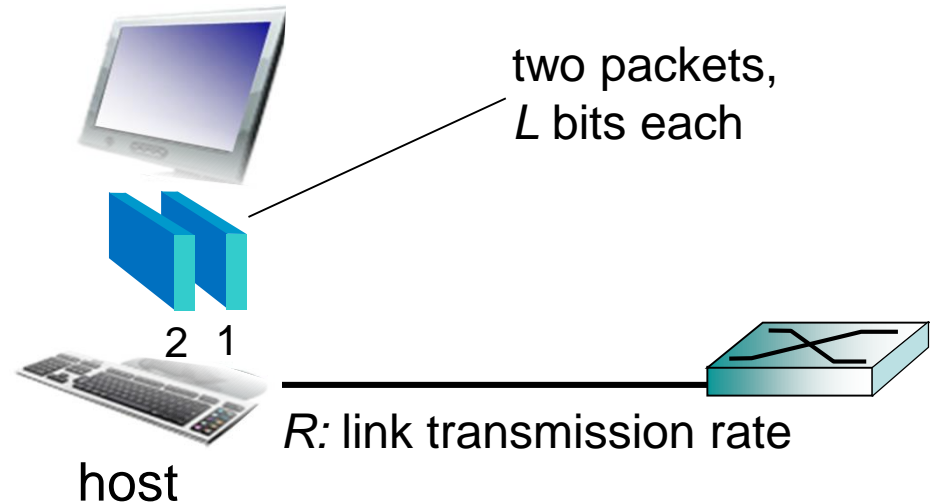


to Internet

# 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)*

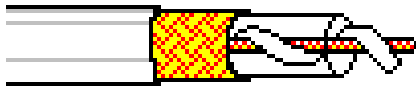
- two insulated copper wires
  - Category 5: 100 Mbps, 1 Gbps Ethernet
  - Category 6: 10 Gbps



# 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

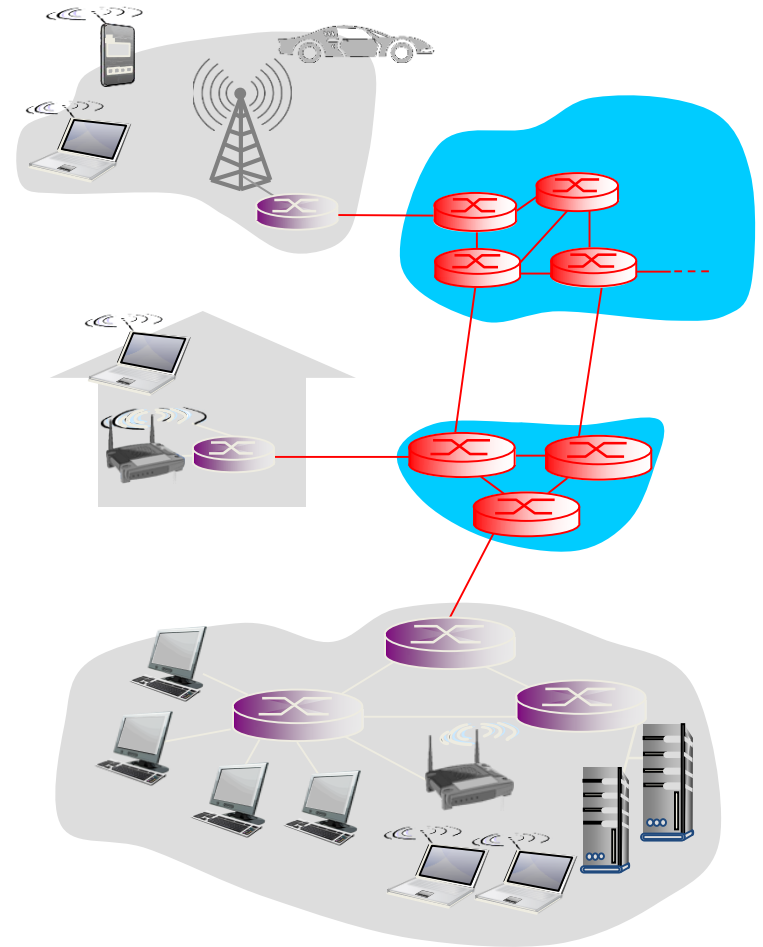
### ❖ **satellite**

- Kbps to 45 Mbps channel (or multiple smaller channels)
- 270 msec end-end delay
- geosynchronous versus low altitude

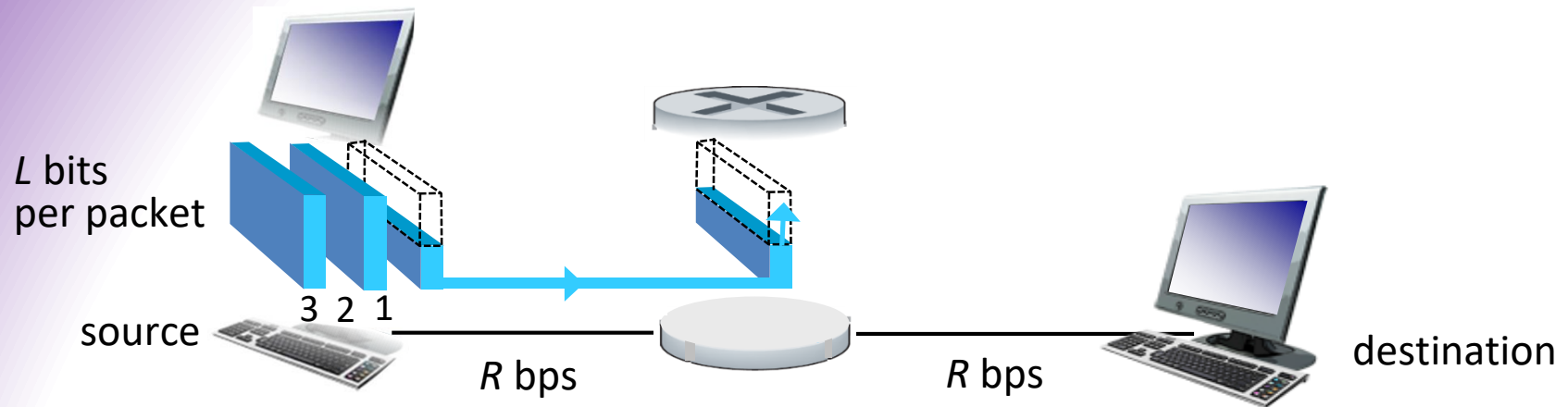


# The network core

- 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

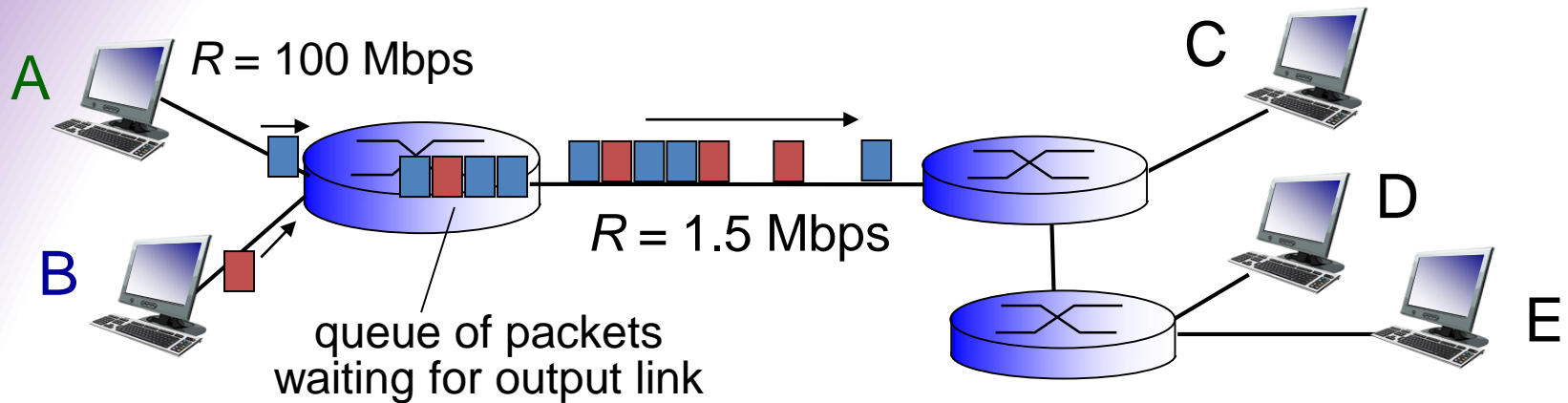


# Packet-switching: store-and-forward



- 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
  - ❖ end-end delay =  $2L/R$  (assuming zero propagation delay)
- one-hop numerical example:*
- $L = 7.5$  Mbits
  - $R = 1.5$  Mbps
  - one-hop transmission delay = ?
- } more on delay shortly ...

# Packet Switching: queuing delay, loss



## queuing and loss:

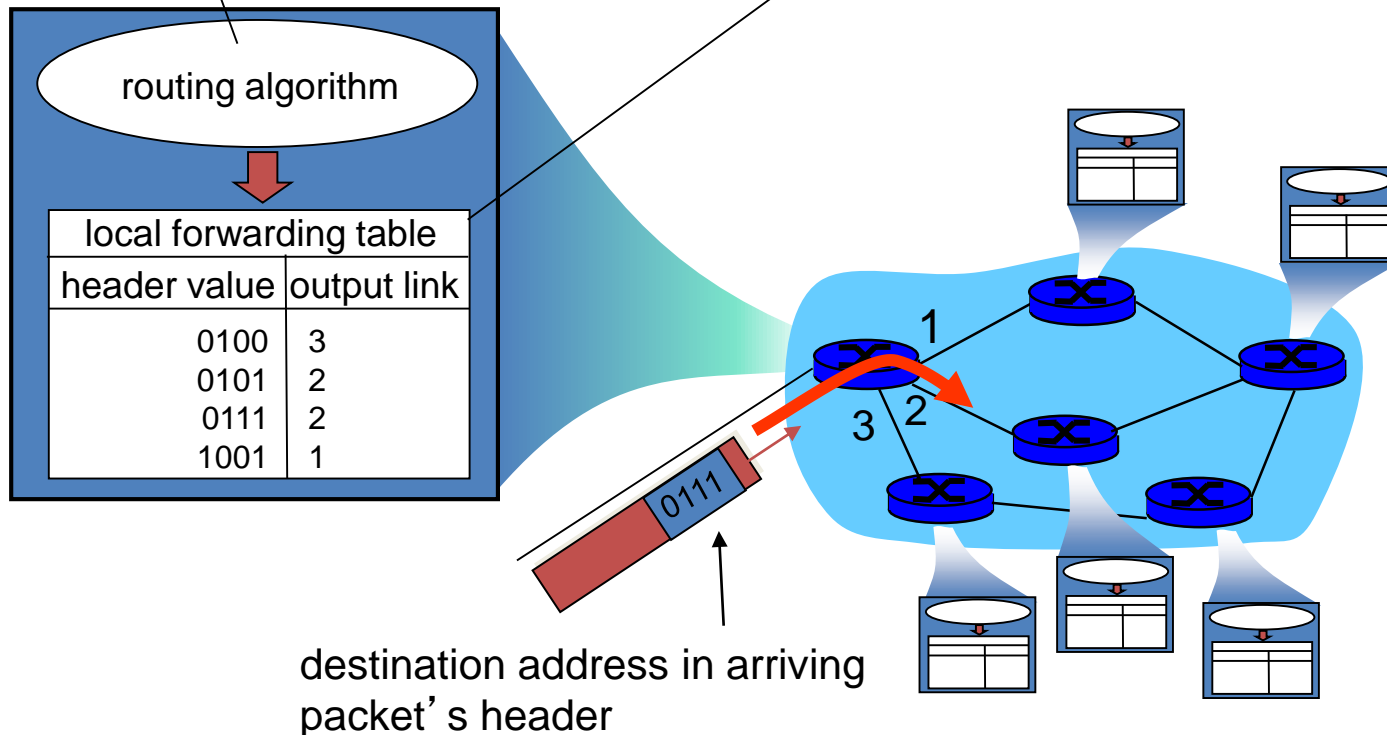
- ❖ If arrival rate (in bits) to link exceeds transmission rate of link for a period of time:
  - packets will queue, wait to be transmitted on link
  - packets can be dropped (lost) if memory (buffer) fills up

# Two key network-core functions

**routing:** determines source-destination route taken by packets

- *routing algorithms*

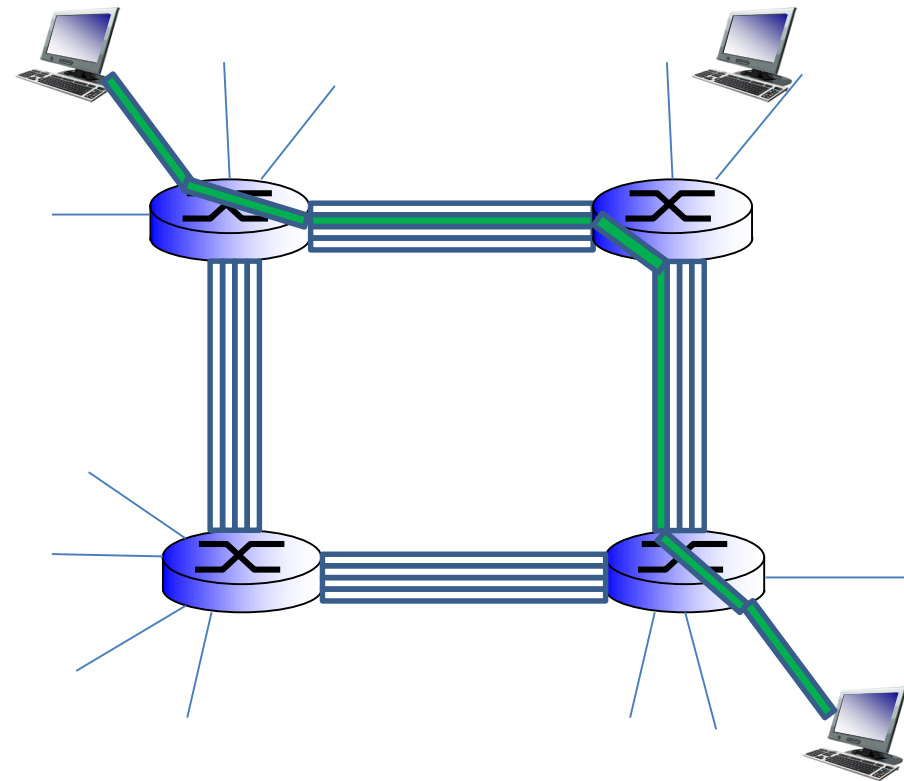
**forwarding:** move packets from router's input to appropriate router output



# Alternative core: circuit switching

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

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



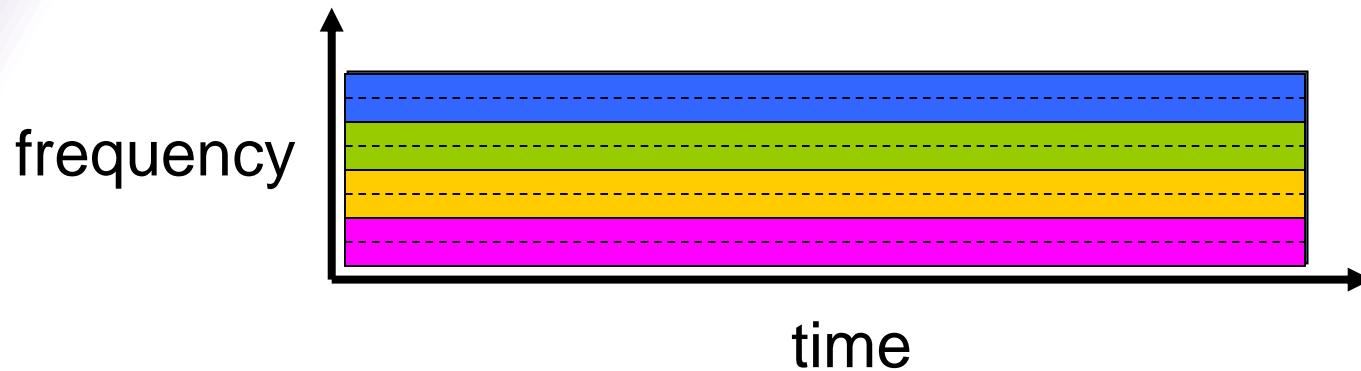
*Circuit-switching networks have a much longer history than Internet!*

# Circuit switching: FDM versus TDM

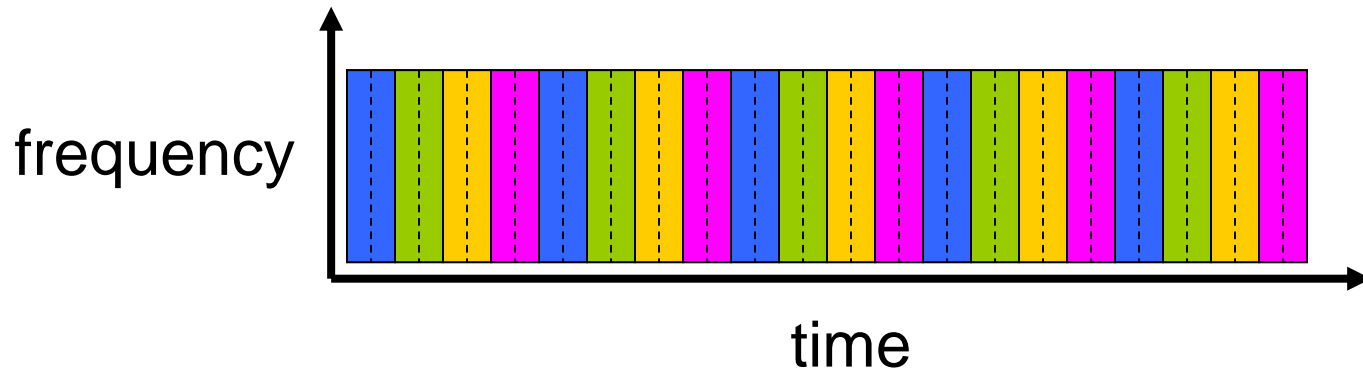
FDM

Example:

4 users



time-division multiplexing (TDM)

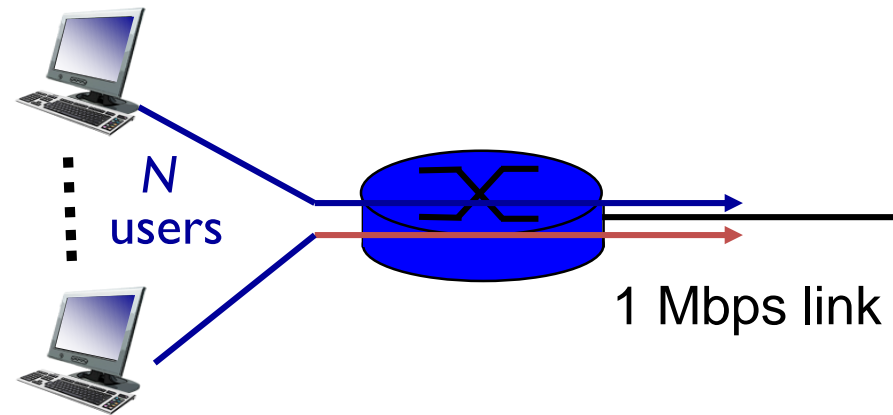


# Packet switching versus circuit switching

*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 ?

\* Check out the online interactive exercises for more examples: [http://gaia.cs.umass.edu/kurose\\_ross/interactive/](http://gaia.cs.umass.edu/kurose_ross/interactive/)

# Packet switching versus circuit switching

- 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

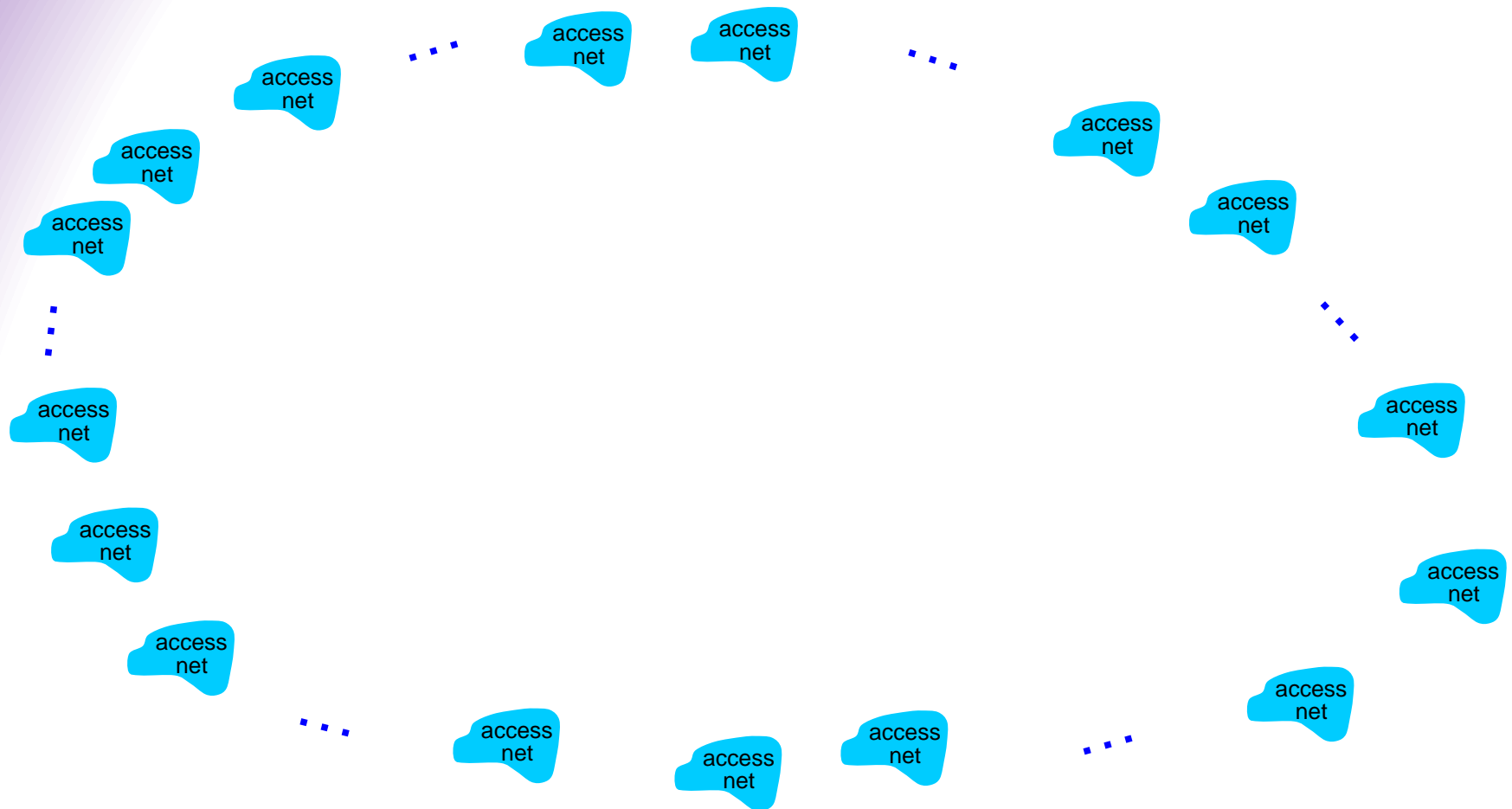
**Q:** human analogies of reserved resources (circuit switching) versus on-demand allocation (packet-switching)?



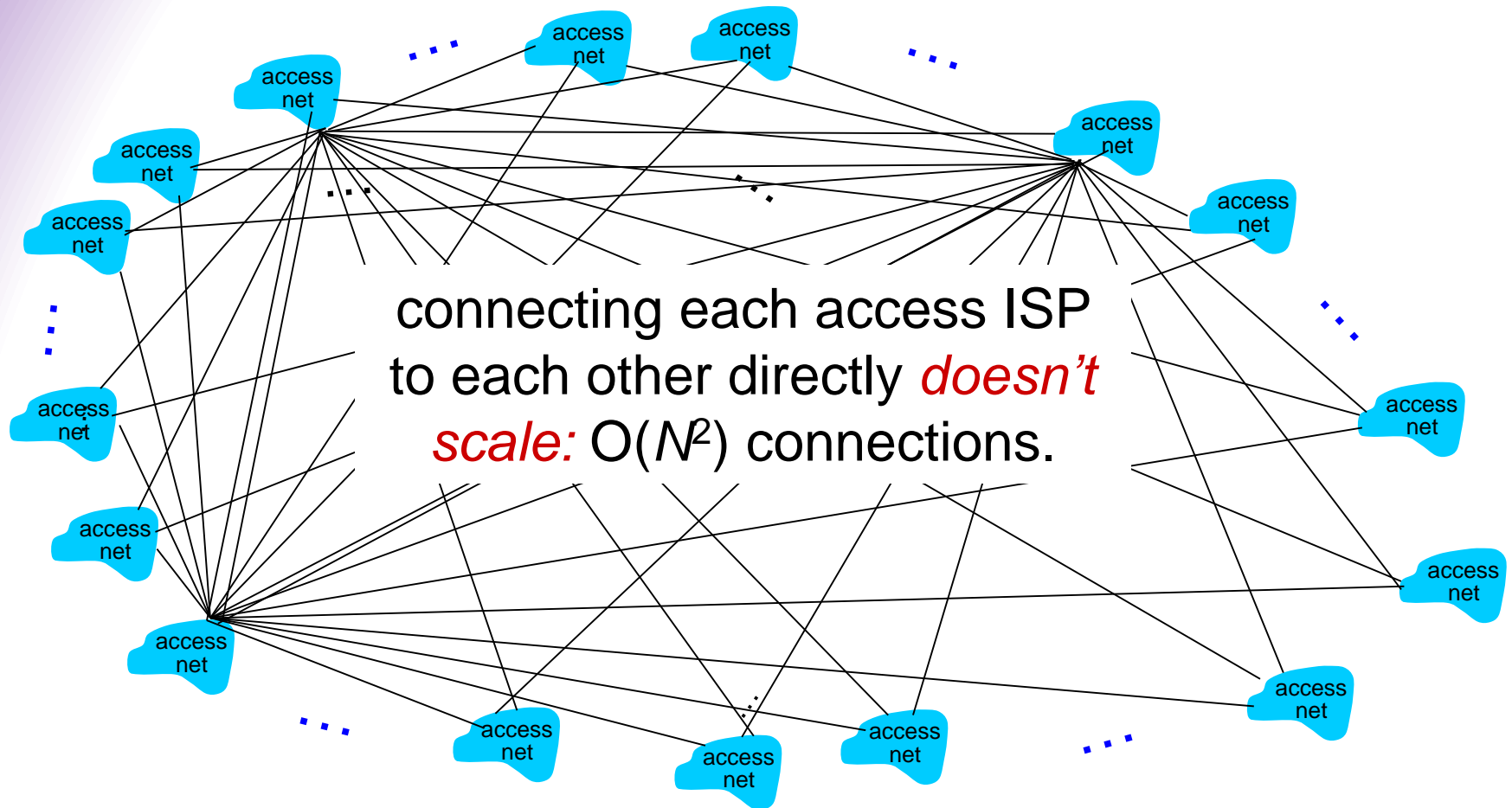
## 1.3 Internet architecture

- ❖ 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

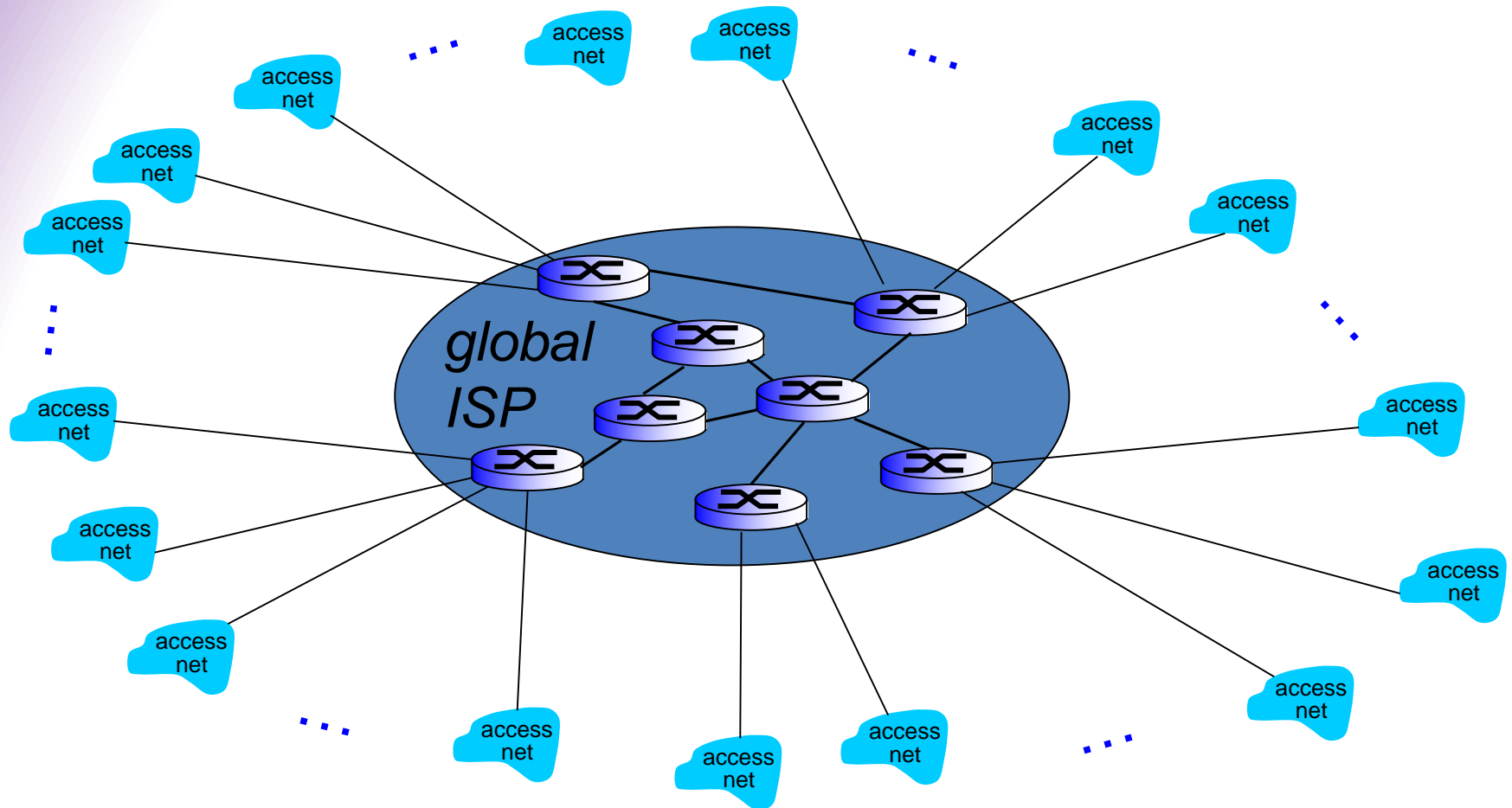
**Question:** given *millions* of access ISPs, how to connect them together?



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

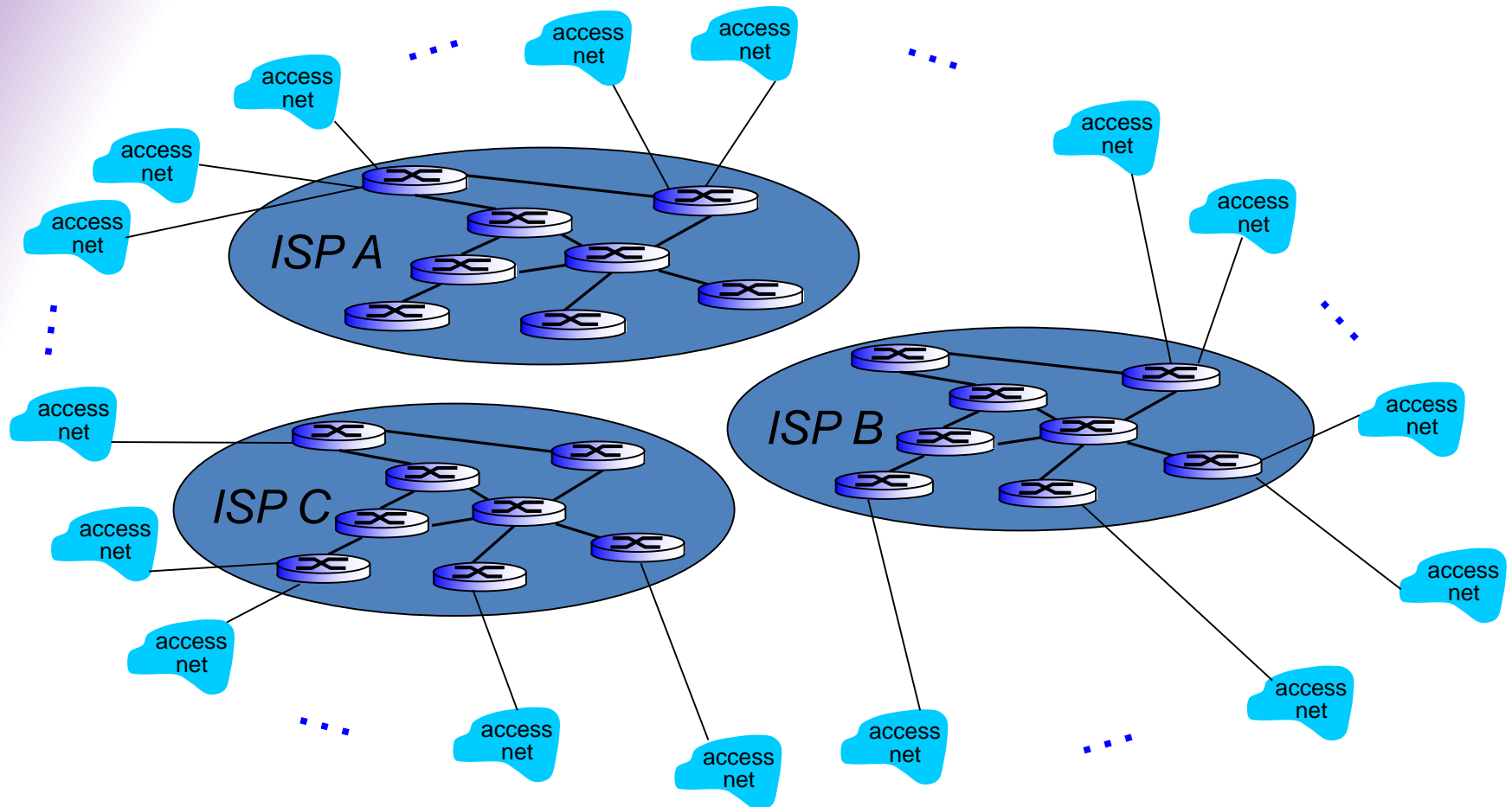


*Option: connect each access ISP to a global transit ISP? **Customer** and **provider** ISPs have economic agreement.*

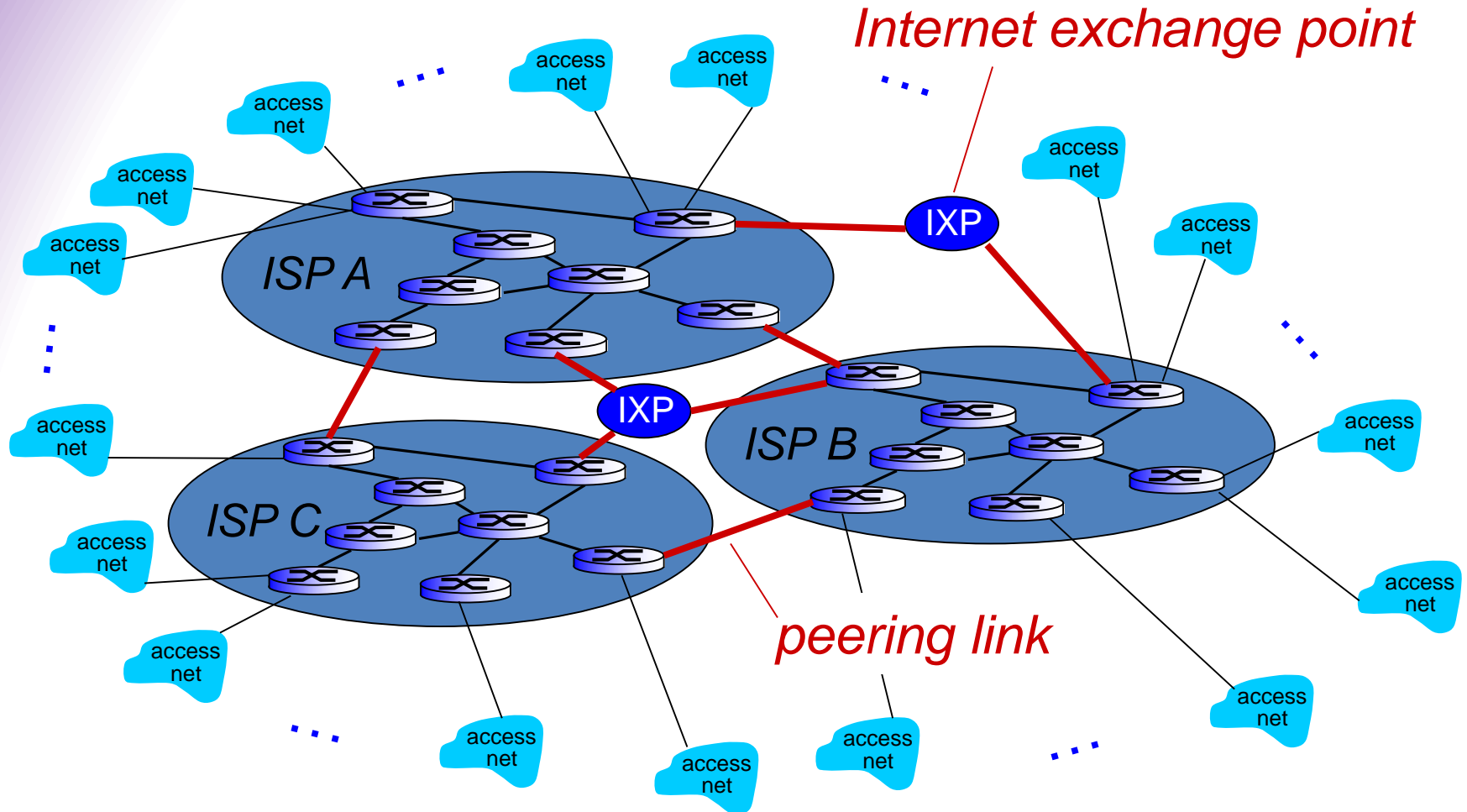


But if one global ISP is viable business, there will be competitors

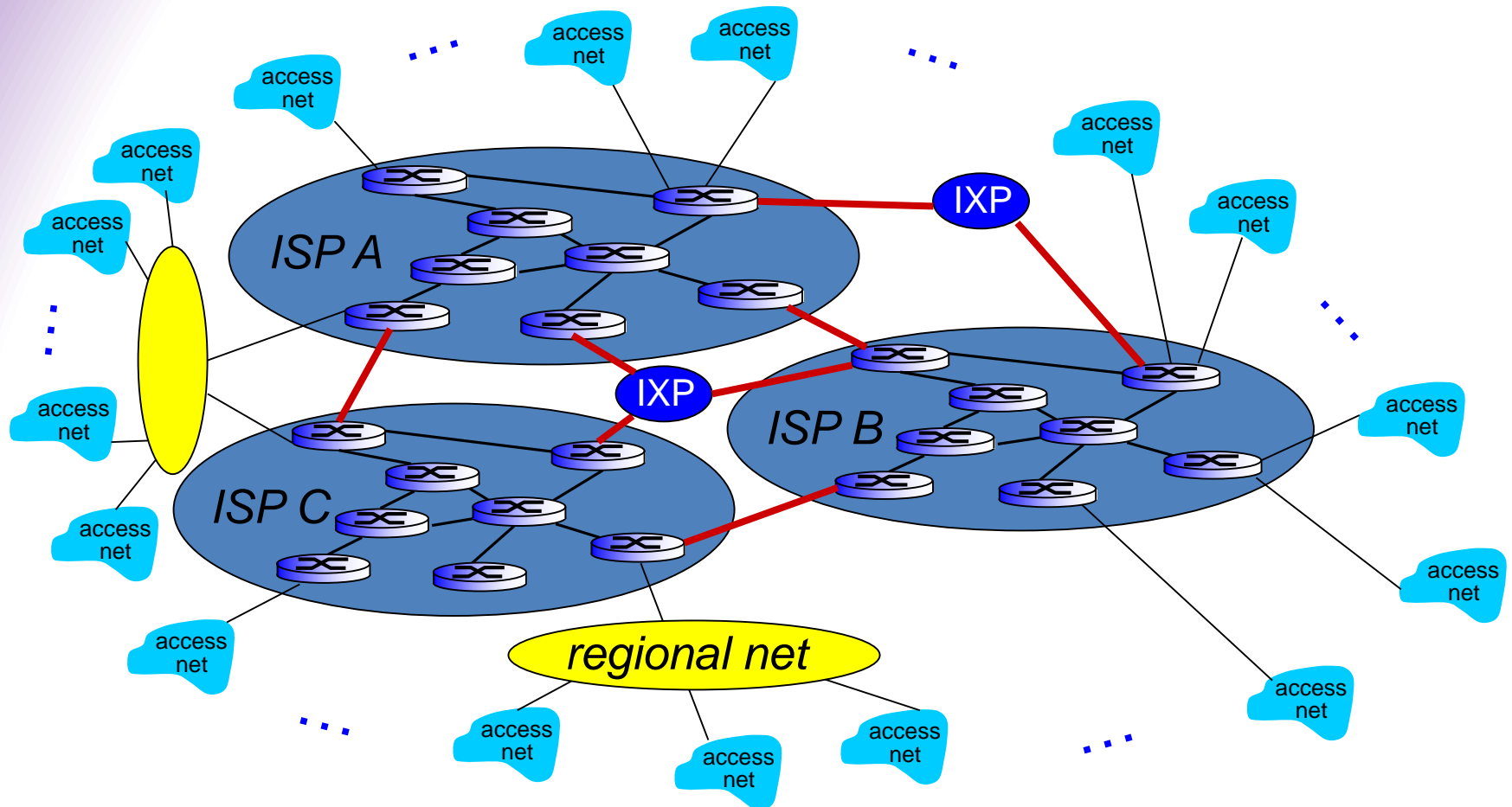
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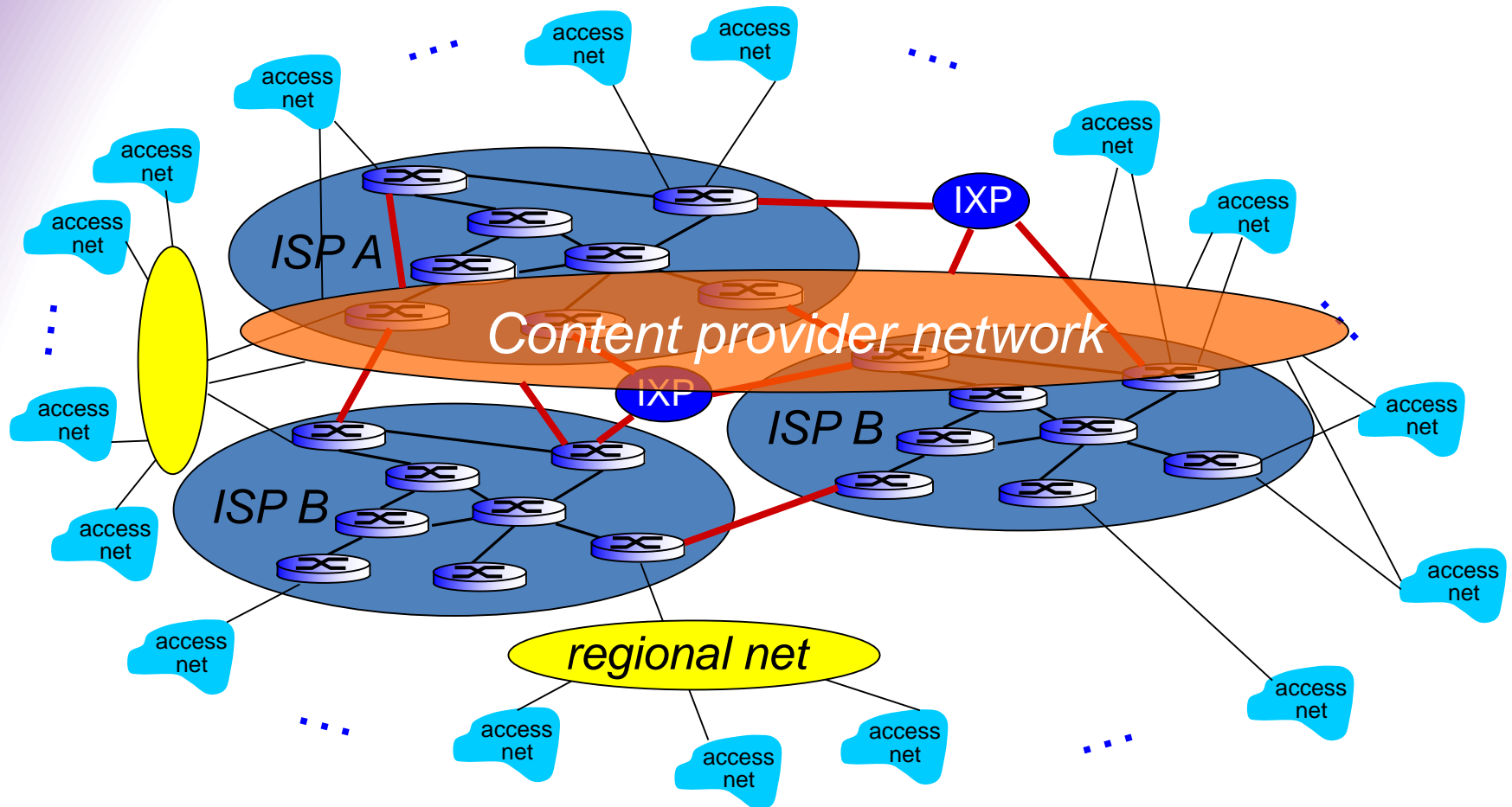
But if one global ISP is viable business, there will be competitors  
.... which must be interconnected



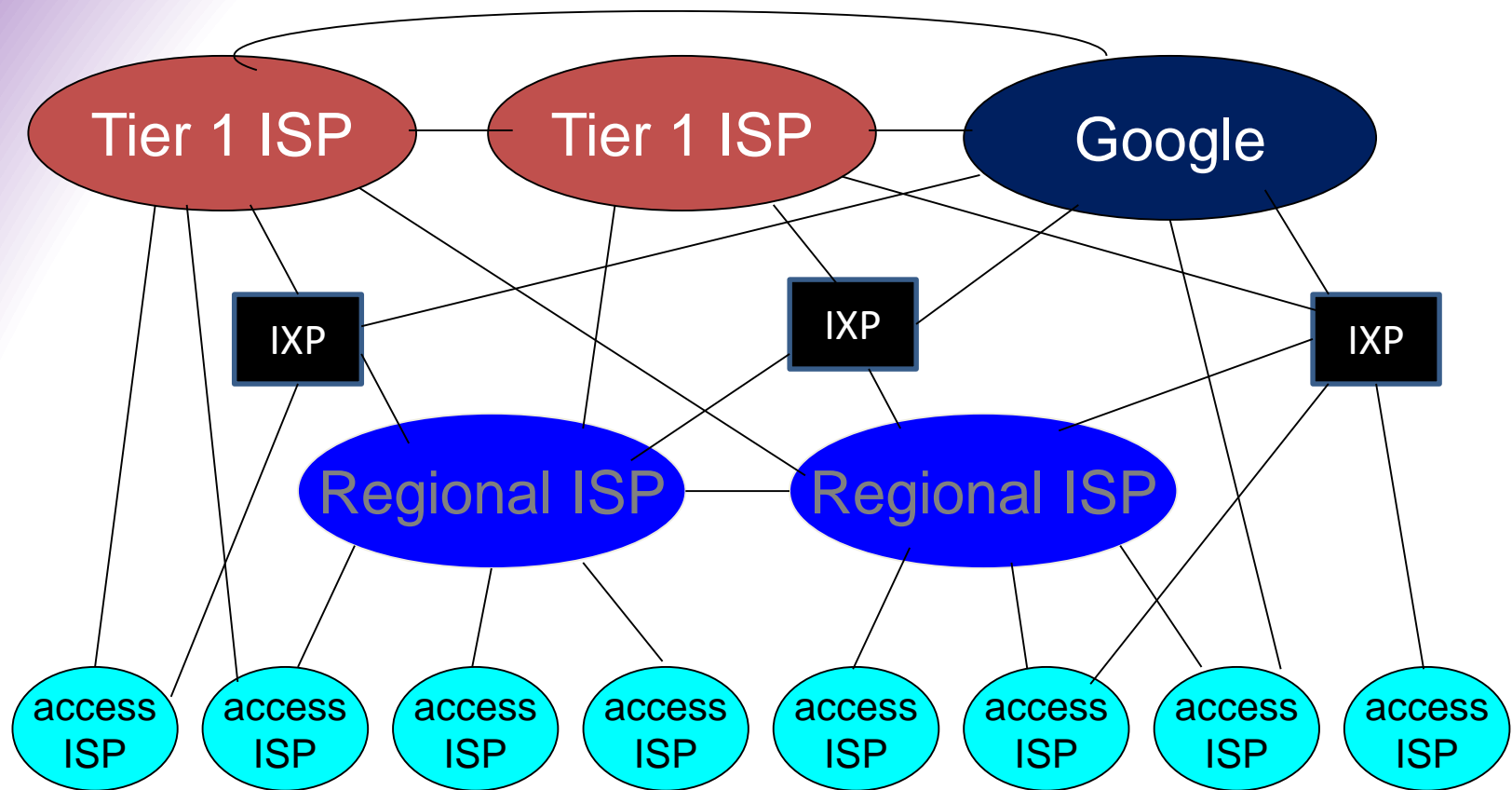
... and regional networks may arise to connect access nets to ISPs



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

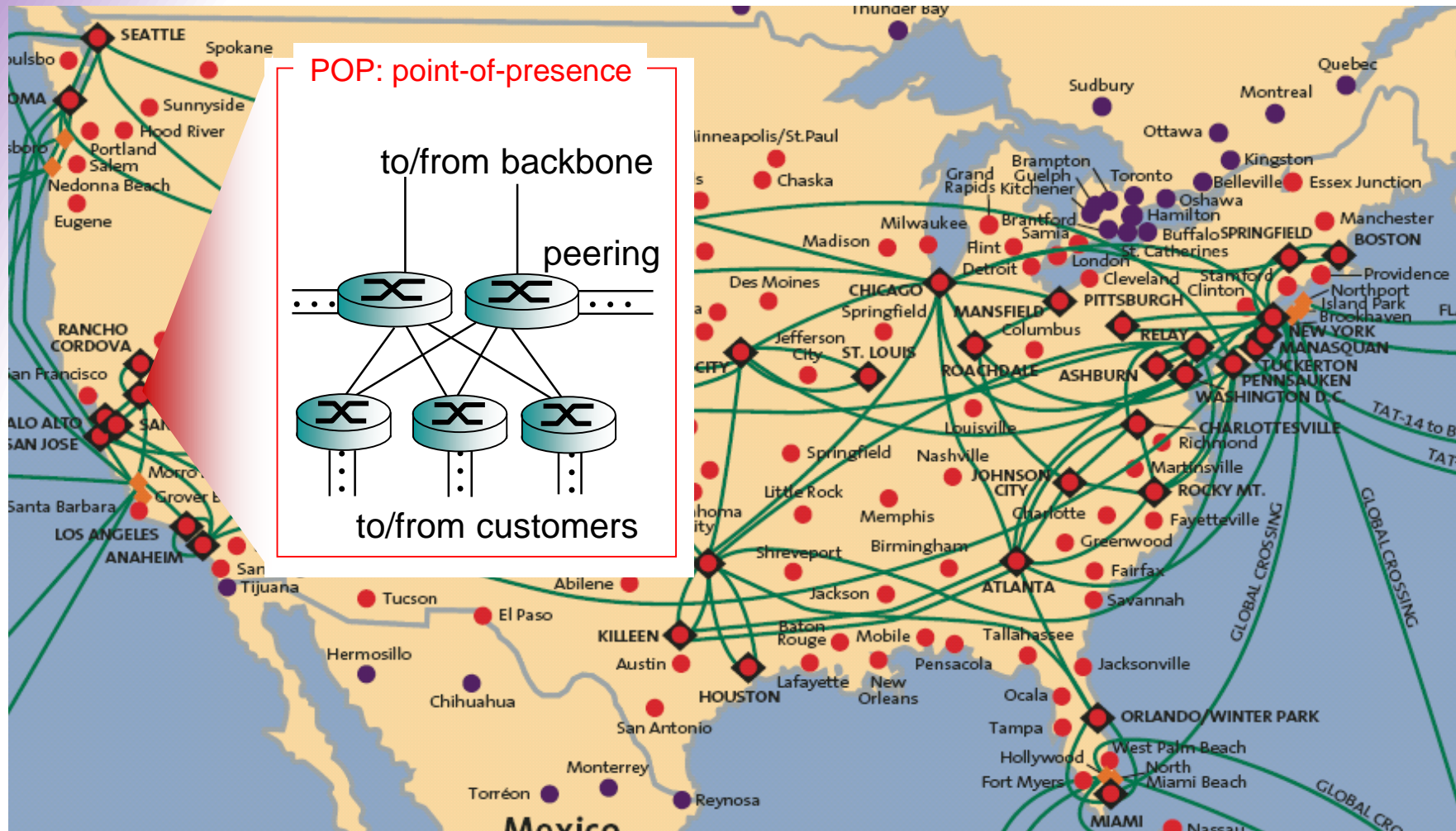






- at center: small number of well-connected large networks
  - “**tier-1**” **commercial ISPs** (e.g., Level 3, Sprint, AT&T, NTT), national & international coverage
  - **content provider network** (e.g, Google): private network that connects its data centers to Internet, often bypassing tier-1, regional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

# Tier-1 ISP: e.g., Sprint



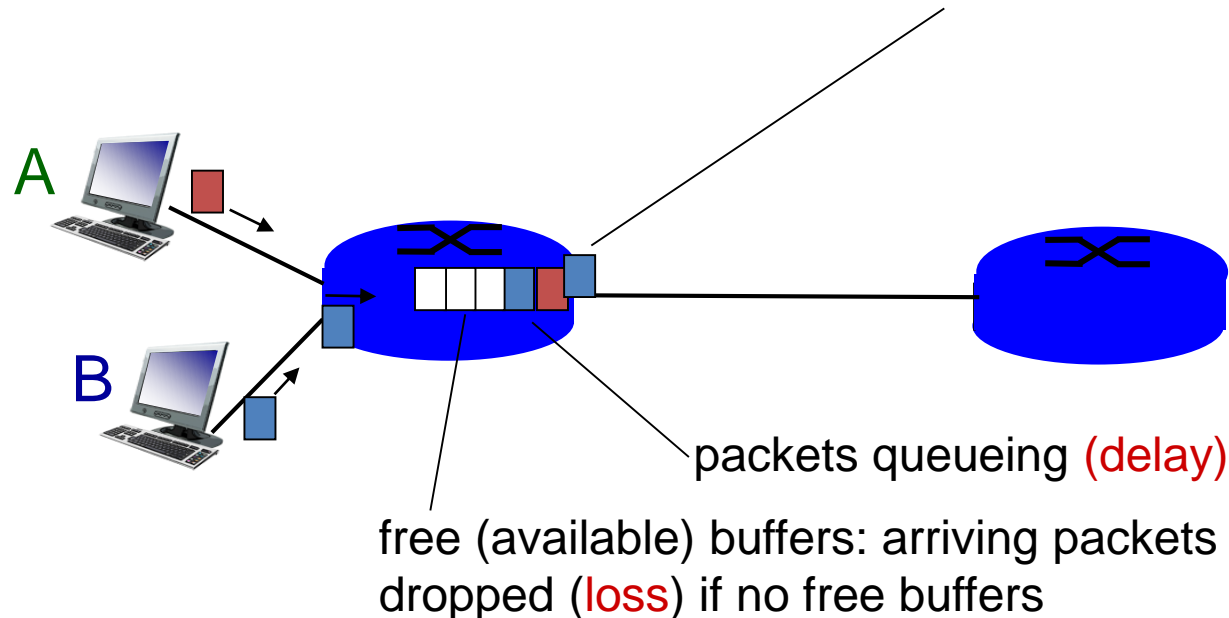
## 1.4 Performance measure

- delay
- packet loss
- throughput

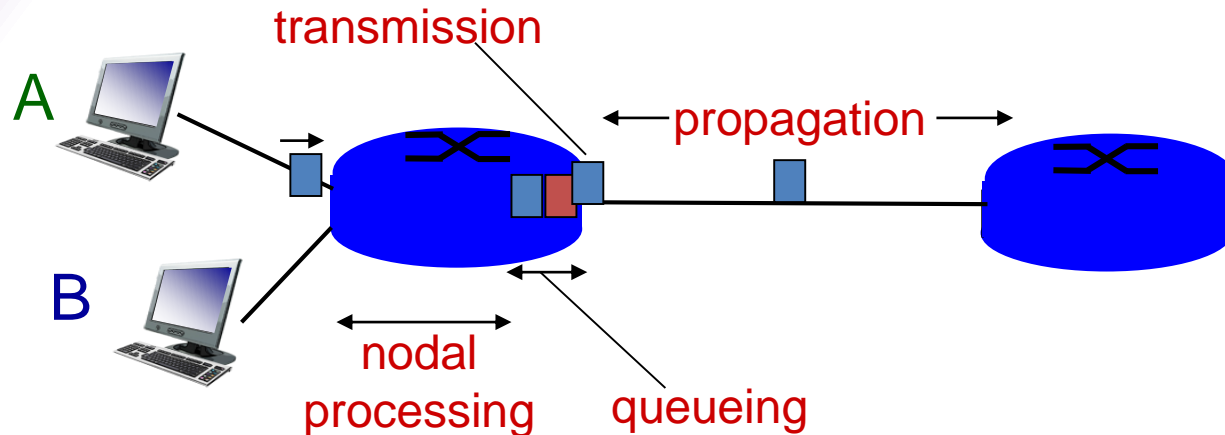
# How do loss and delay occur?

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



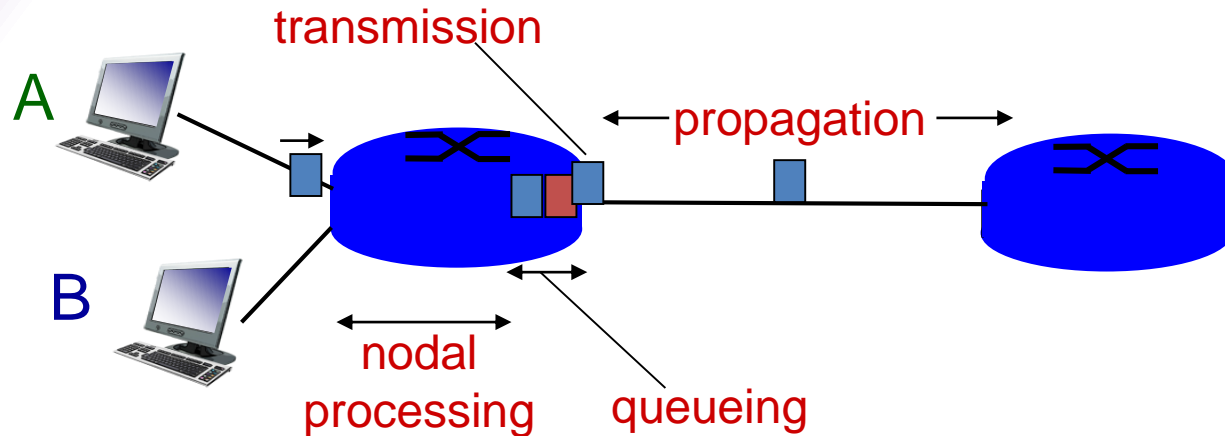
$$d_{\text{nodal}} = d_{\text{proc}} + d_{\text{queue}} + d_{\text{trans}} + d_{\text{prop}}$$

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

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

**$d_{\text{queue}}$ : queuing delay**

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



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

**$d_{\text{trans}}$ : transmission delay:**

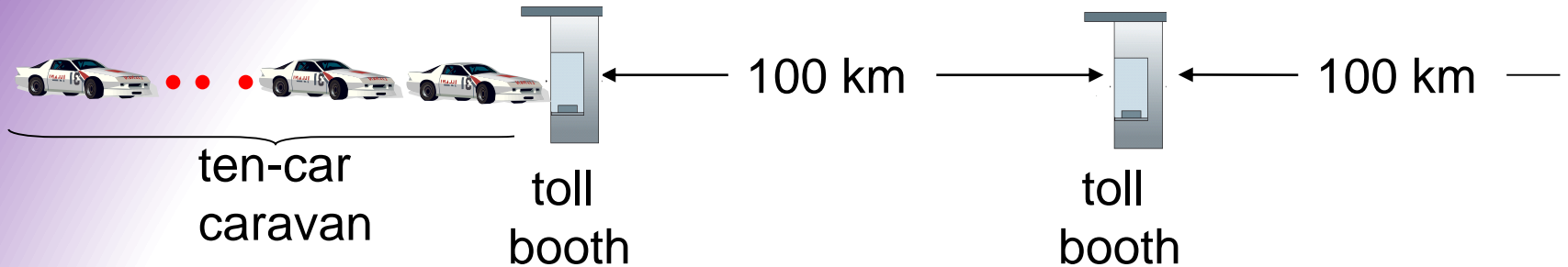
- $L$ : packet length (bits)
- $R$ : link bandwidth (bps)
- $d_{\text{trans}} = L/R$

**$d_{\text{prop}}$ : propagation delay:**

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

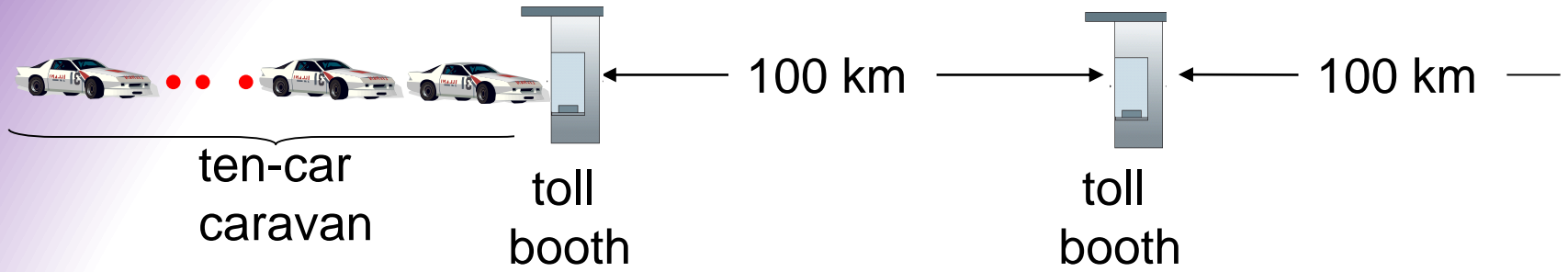
$d_{\text{trans}}$  and  $d_{\text{prop}}$   
very different

# Caravan analogy



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

# Caravan analogy (more)

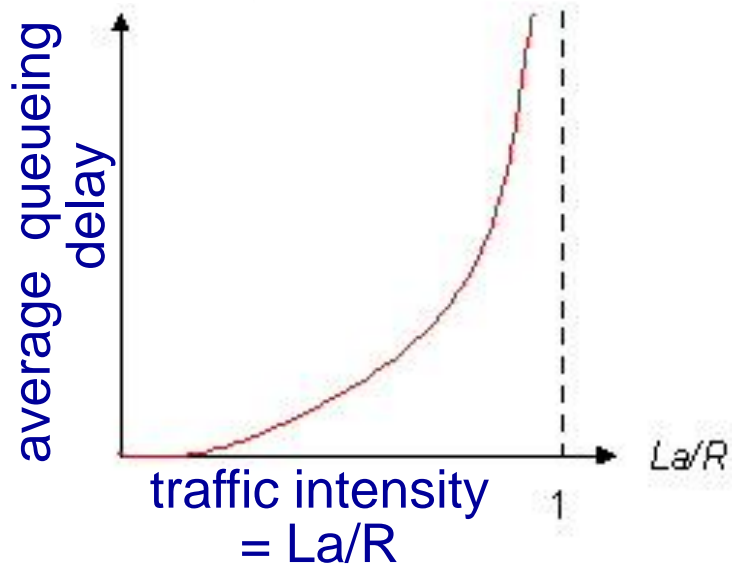


- suppose cars now “propagate” at 1000 km/hr
- and suppose toll booth now takes one min to service a car
- Q: Will cars arrive to 2<sup>nd</sup> booth before all cars serviced at first booth?



# Queuing delay (revisited)

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



- ❖  $La/R \sim 0$ : average queuing delay small
- ❖  $La/R \sim 1$ : average queuing delay large
- ❖  $La/R > 1$ : more “work” arriving than can be serviced, average delay infinite!



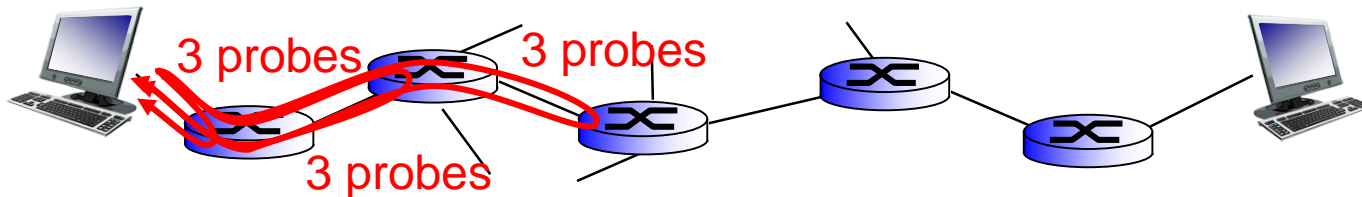
$La/R \sim 0$



$La/R \sim 1$

# “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
  - router  $i$  will return packets to sender
  - sender times interval between transmission and reply.



# “Real” Internet delays, routes

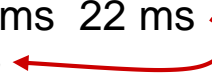
**traceroute:** gaia.cs.umass.edu to www.eurecom.fr

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

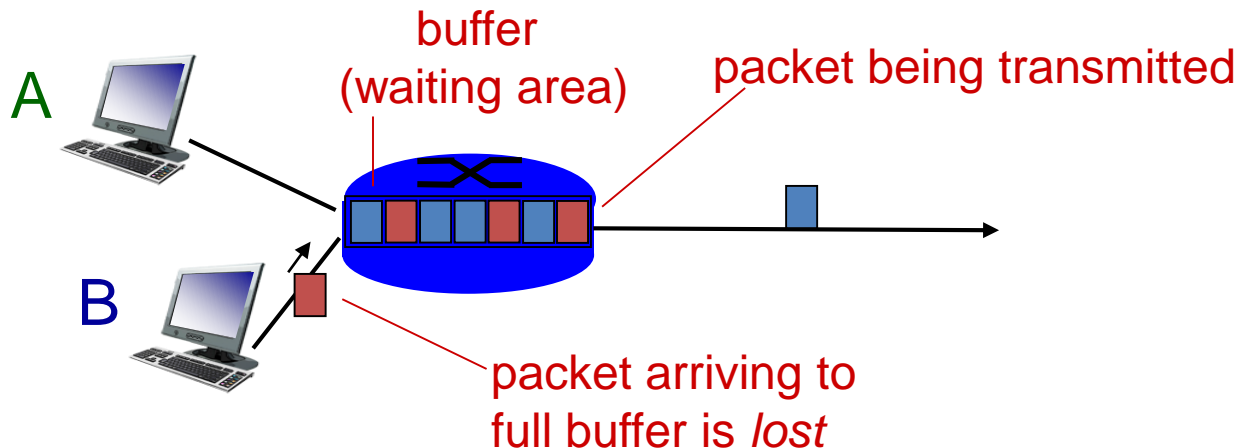


\* means no response (probe lost, router not replying)

\* Do some traceroutes from exotic countries at [www.traceroute.org](http://www.traceroute.org)

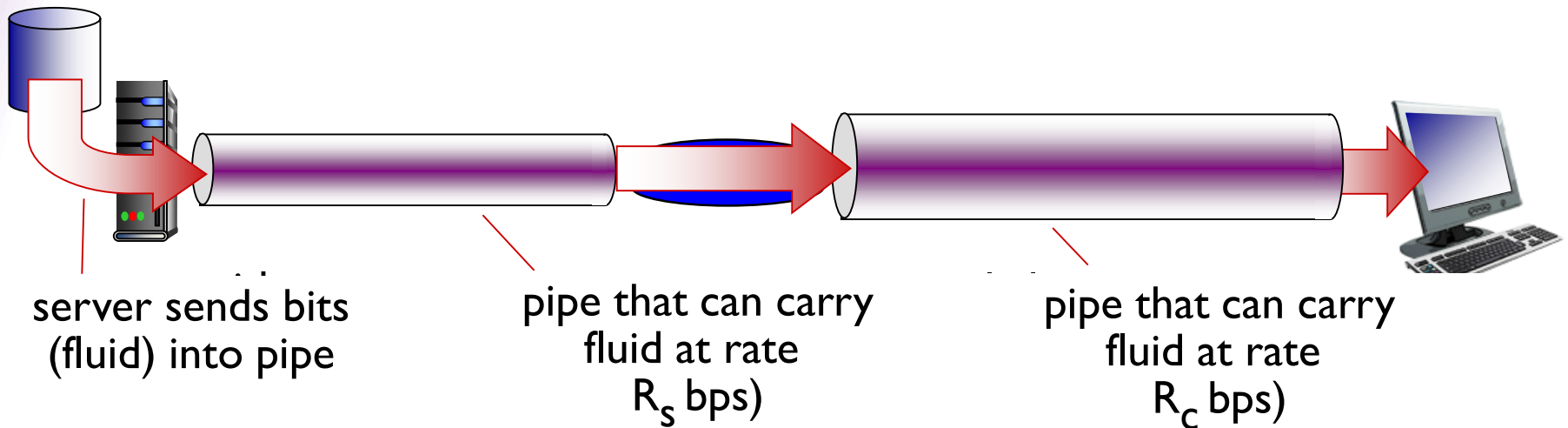
# Packet loss

- 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

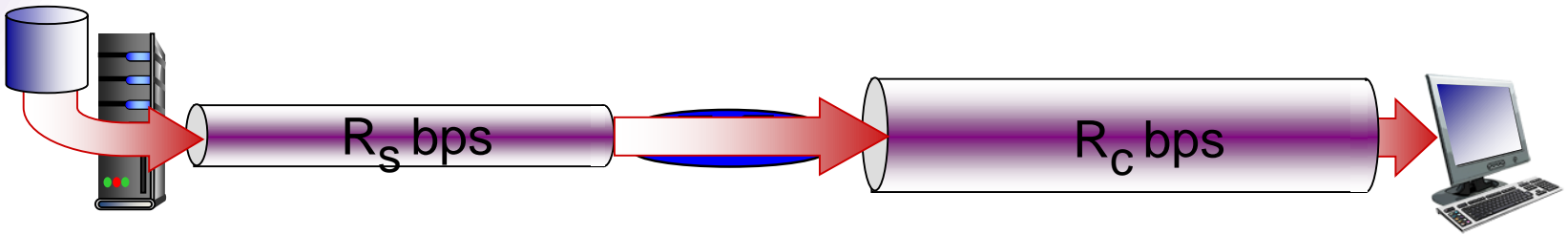


# Throughput

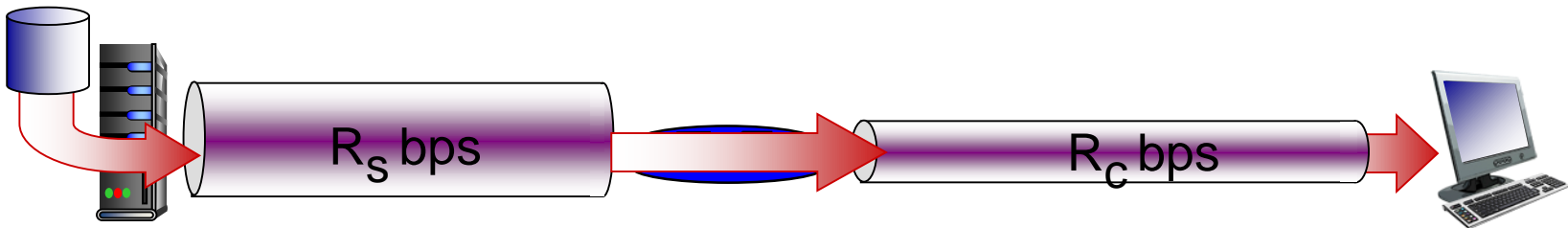
- *throughput*: rate (bits/time unit) at which bits transferred between sender/receiver
  - *instantaneous*: rate at given point in time
  - *average*: rate over longer period of time



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



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

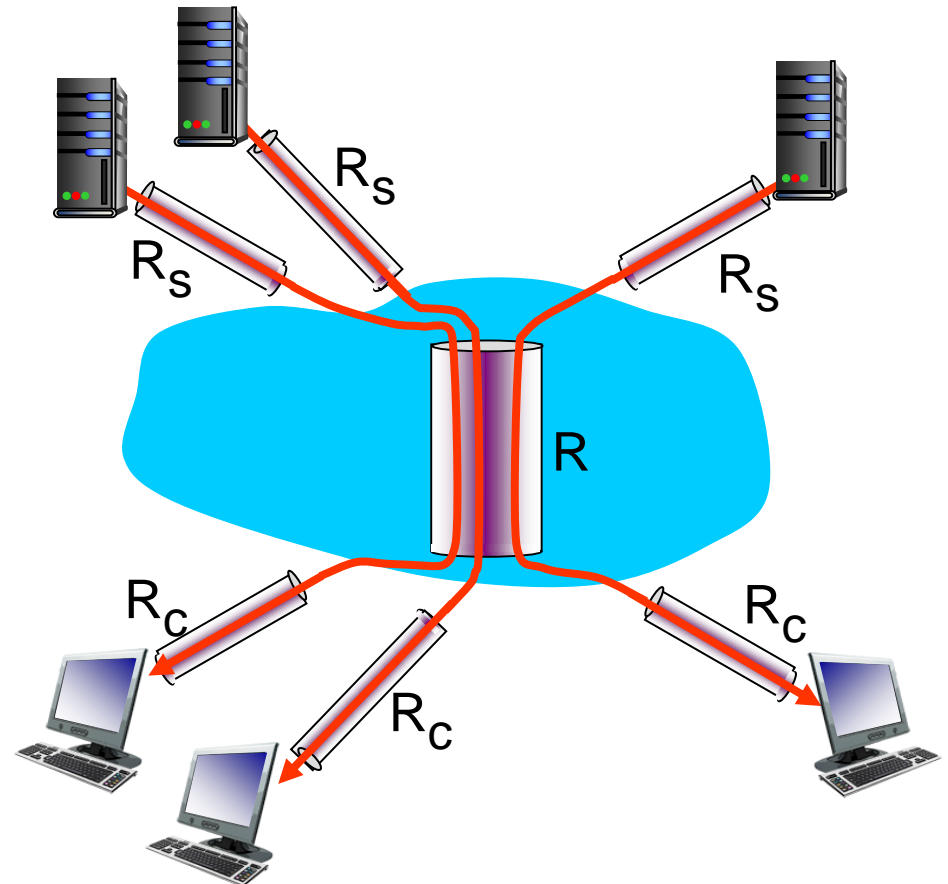


*bottleneck link*

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:*

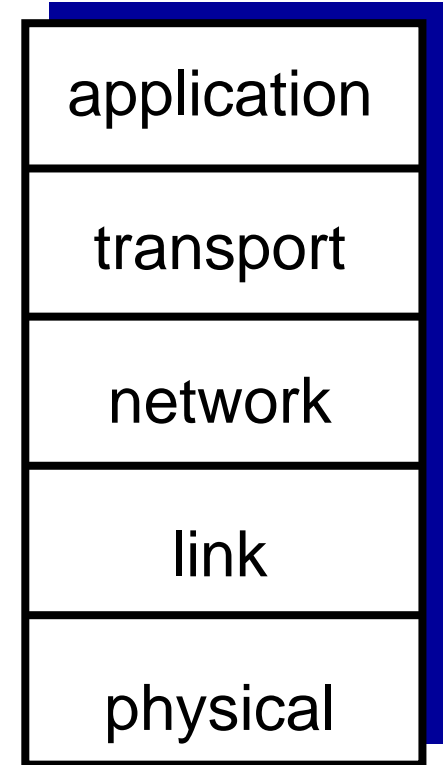
is there any hope of  
*organizing* structure of  
network?

.... or at least our discussion  
of networks?



# Protocol layering

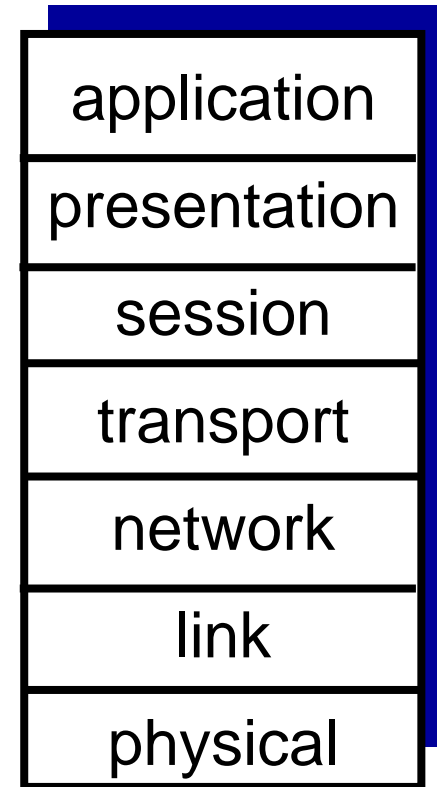
- *application*: supporting network applications
  - FTP, SMTP, HTTP
- *transport*: process-process data transfer
  - TCP, UDP
- *network*: routing of datagrams from source to destination
  - IP, routing protocols
- *link*: data transfer between neighboring network elements
  - Ethernet, 802.111 (WiFi),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

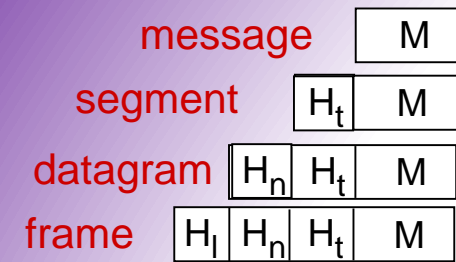


# Why layering?

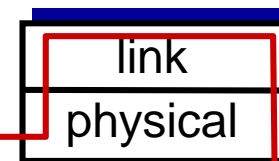
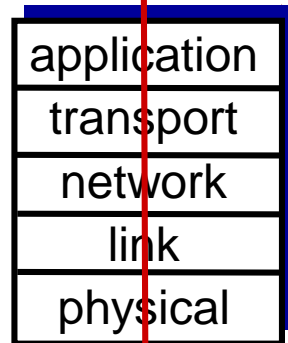
dealing with complex systems:

- 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

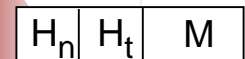
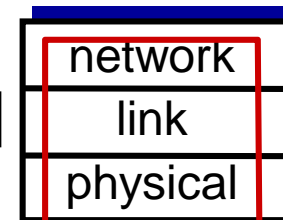
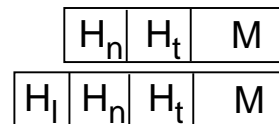
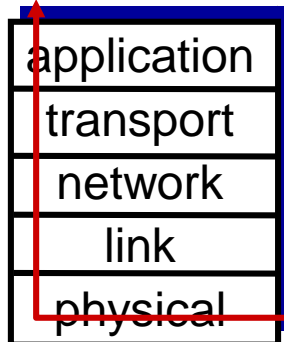


*source*



switch

*destination*



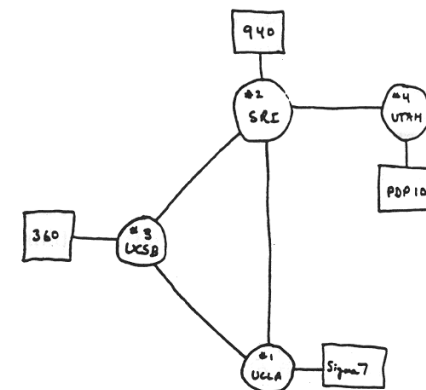
router

## 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



THE ARPA NETWORK

## *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: Cset, 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

