Overview of last class
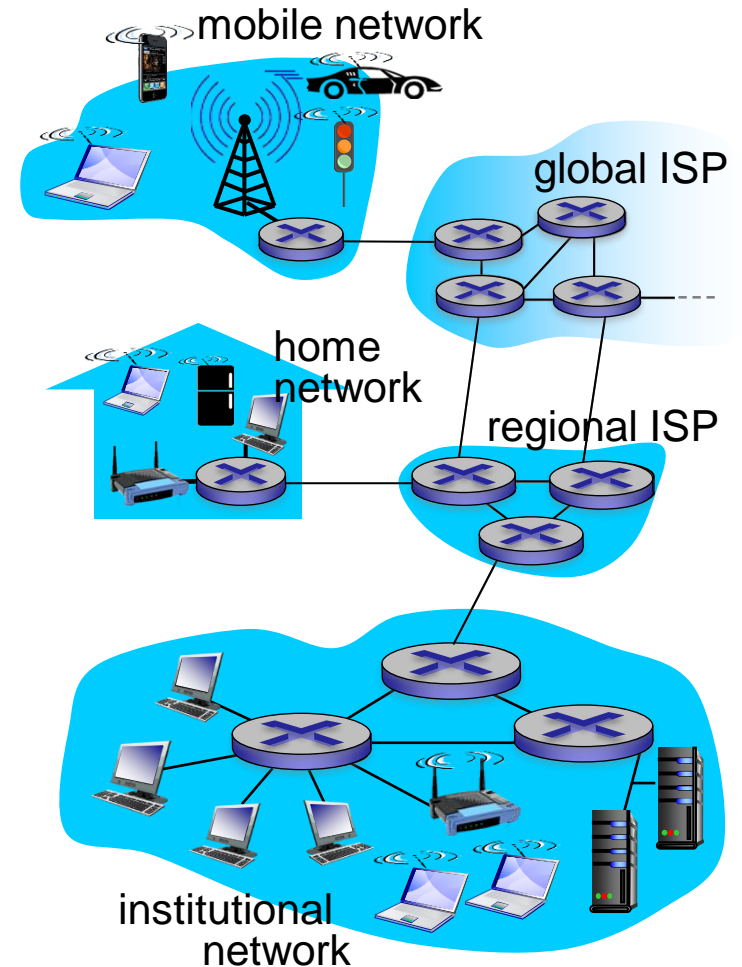
Nuts and bolts view of Internet

- *network edge:*
  - hosts: clients and servers (servers often in data centers)
  - access networks: hosts + wired/wireless communication links

- *network core:*
  - interconnected routers
  - network of networks

mobile network

global ISP

home network

regional ISP

institutional network

What's a protocol?

human protocols:
- "what's the time?"
- "I have a question"
- introductions

… specific messages sent

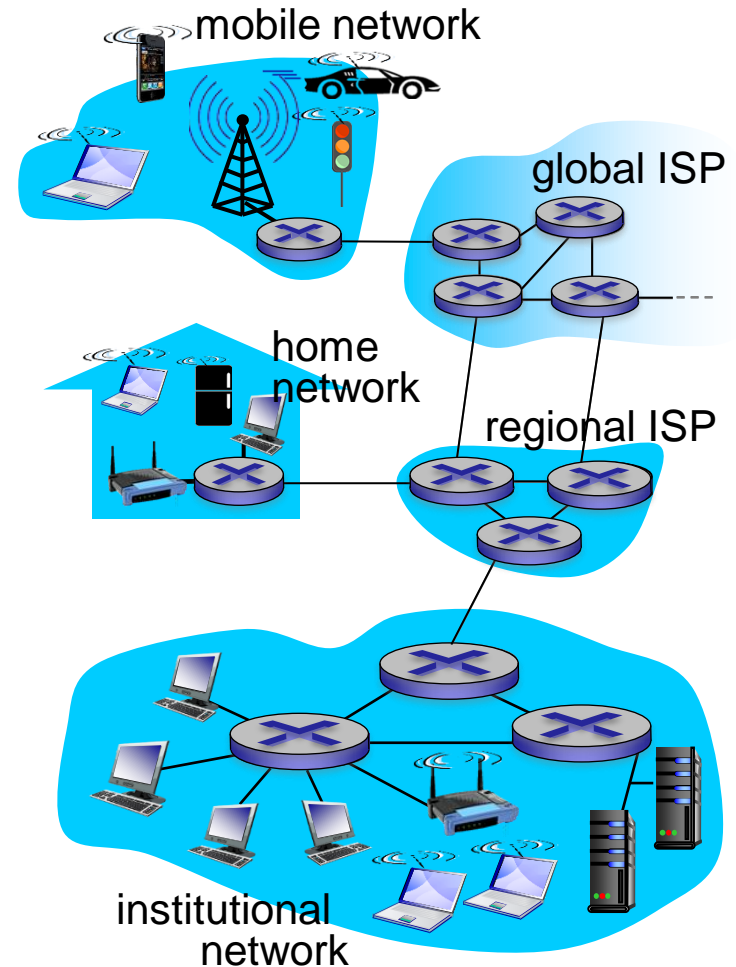… specific actions taken when messages received, or other events

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 message transmission, receipt
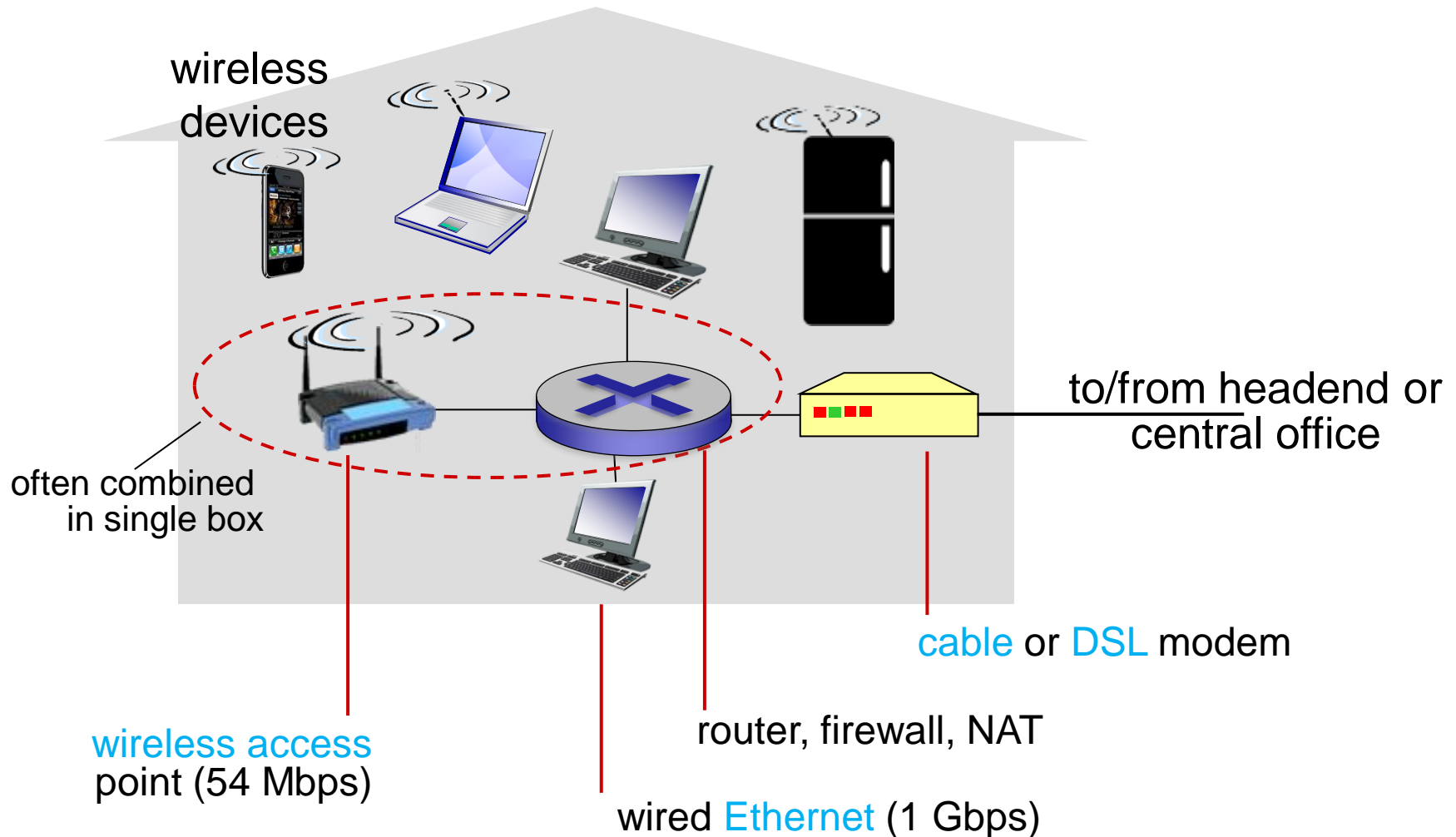
What's the Internet: a service view

- *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
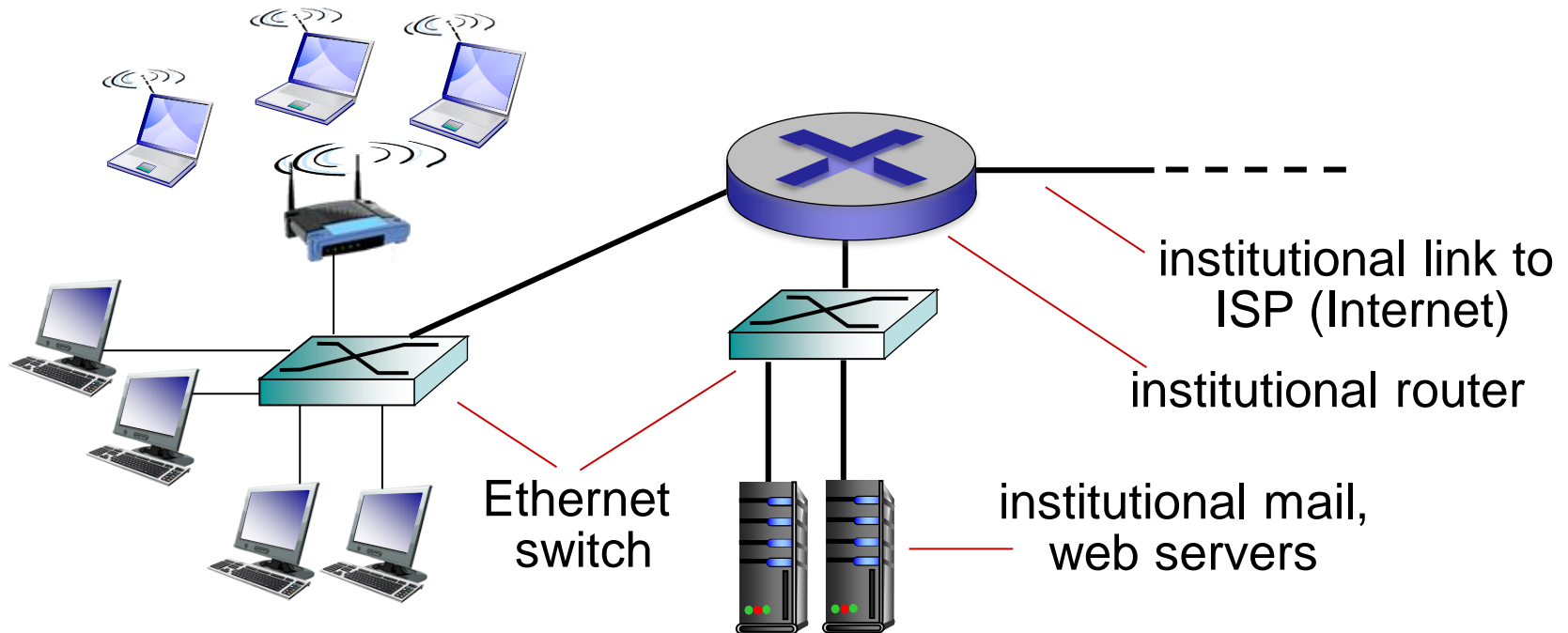 - provides service options, analogous to postal service

User vs Service Provider

mobile network

global ISP

home network

regional ISP

institutional network

Access network: home network

wireless devices

often combined
in single box

to/from headend or
central office

cable or DSL modem

router, firewall, NAT

wireless access
point (54 Mbps)

wired Ethernet (1 Gbps)

Enterprise access networks (Ethernet)

institutional link to ISP (Internet)

institutional router

Ethernet switch

institutional mail, web servers

- typically used in companies, universities, etc.
- 10 Mbps, 100Mbps, 1Gbps, 10Gbps 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.)
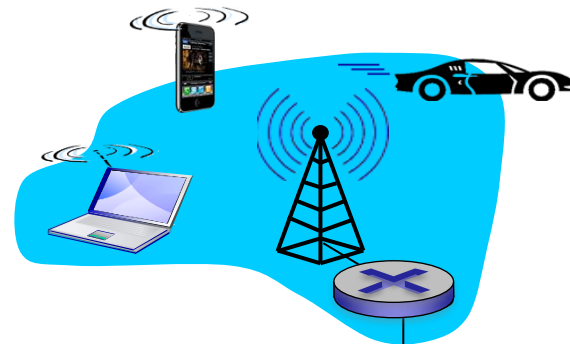- 802.11b/g/n (WiFi): 11, 54, 450 Mbps transmission rate
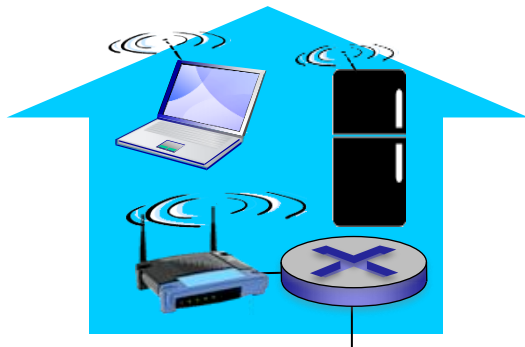
to Internet

Distributed

wide-area wireless access

- provided by telco (cellular) operator, 10's km
- between 1 and 10 Mbps
- 3G, 4G/LTE, 5G

Centralized *to Internet*

Physical media

twisted pair (TP)
Coaxial cable
Fibler

- **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

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)
  - 54 Mbps
- wide-area (e.g., cellular)
  - 4G cellular: ~ 10 Mbps
- satellite
  - Kbps to 45Mbps channel (or multiple smaller channels)
  - 270 msec end-end delay
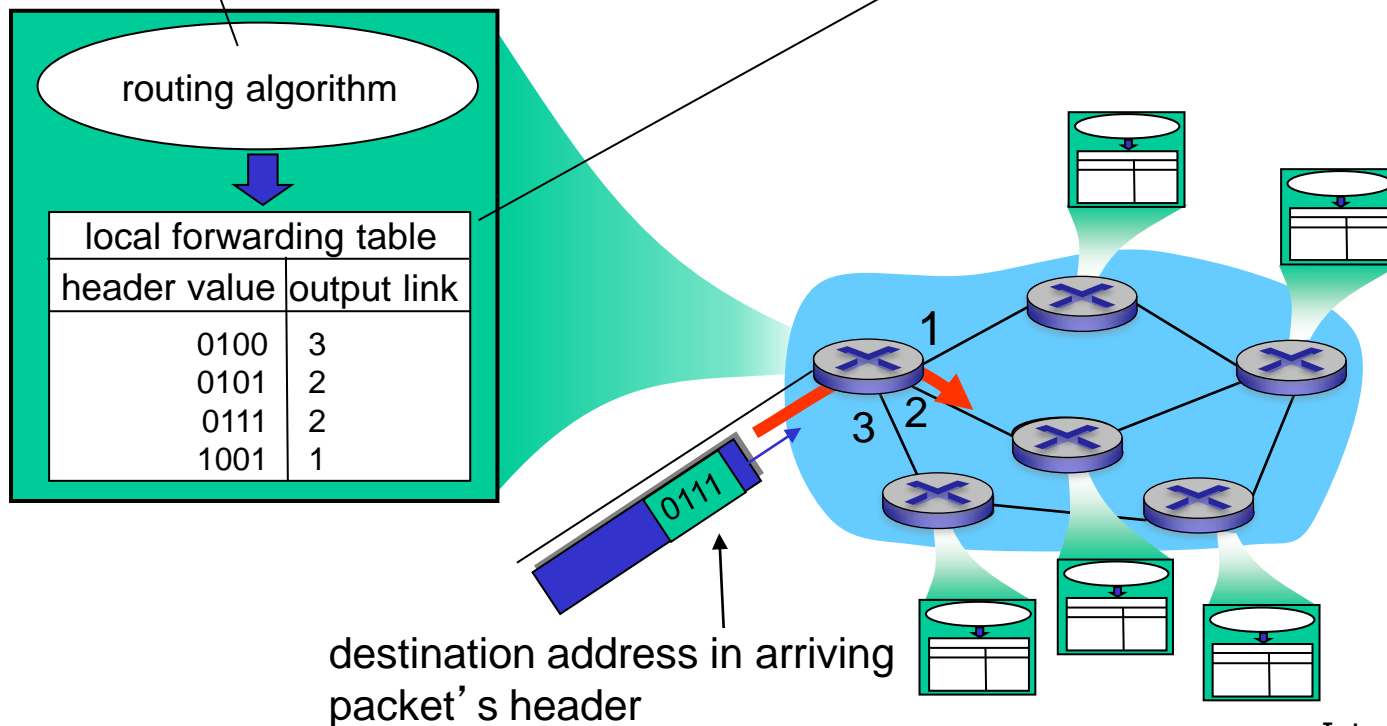 - geosynchronous versus low altitude

Class Today

Chapter 1: roadmap

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

routing algorithm

local forwarding table

header value	output link
0100	3
0101	2
0111	2
1001	1

0111

destination address in arriving packet's header

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
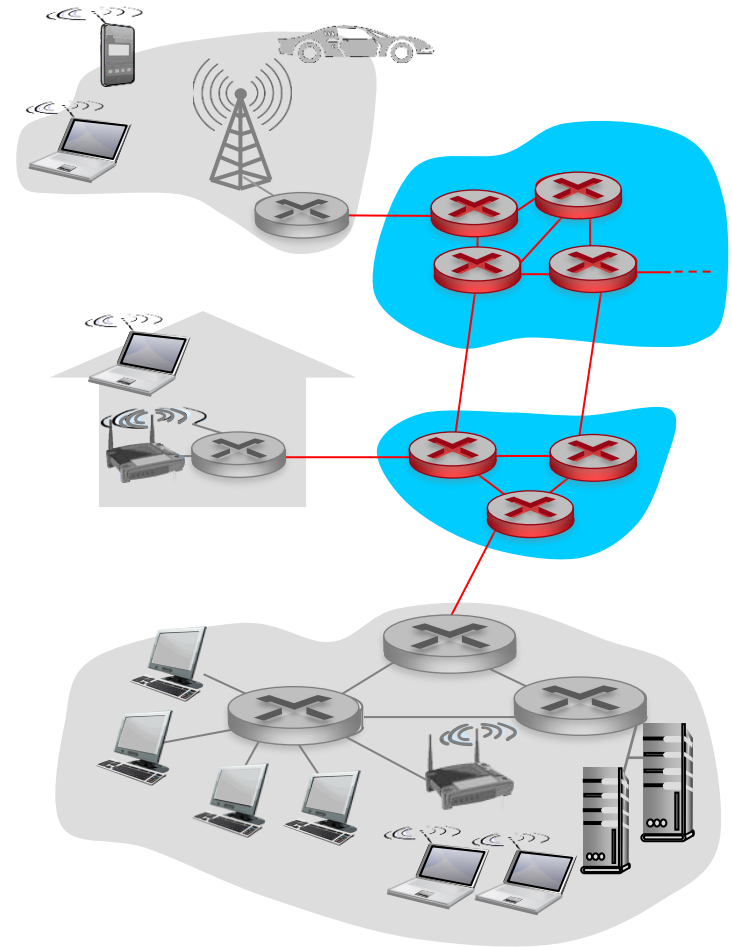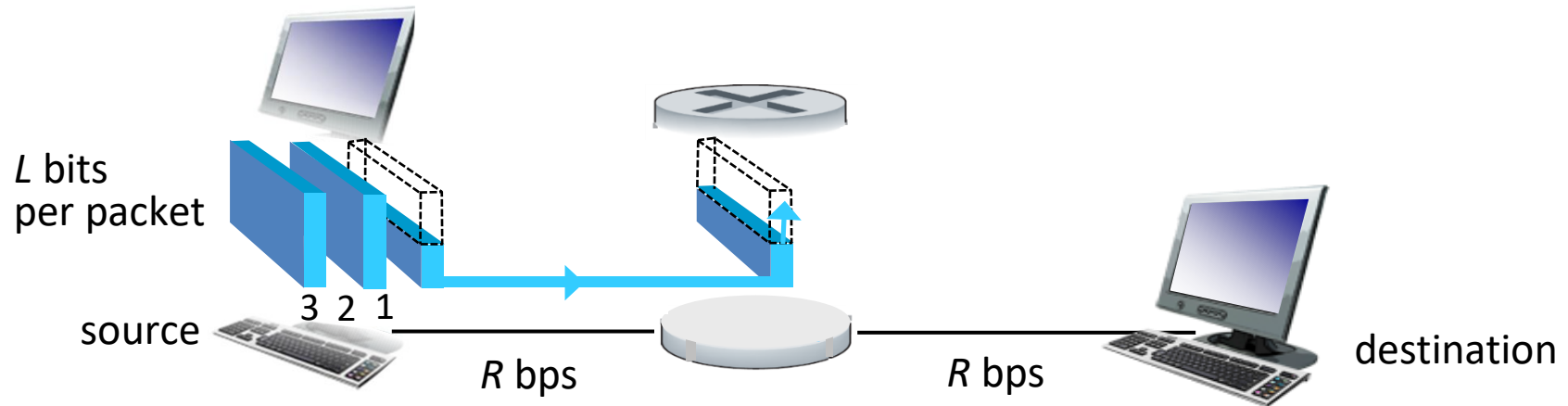
Transmission Delay

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*

two packets, *L* bits each

2 1

R: link transmission rate

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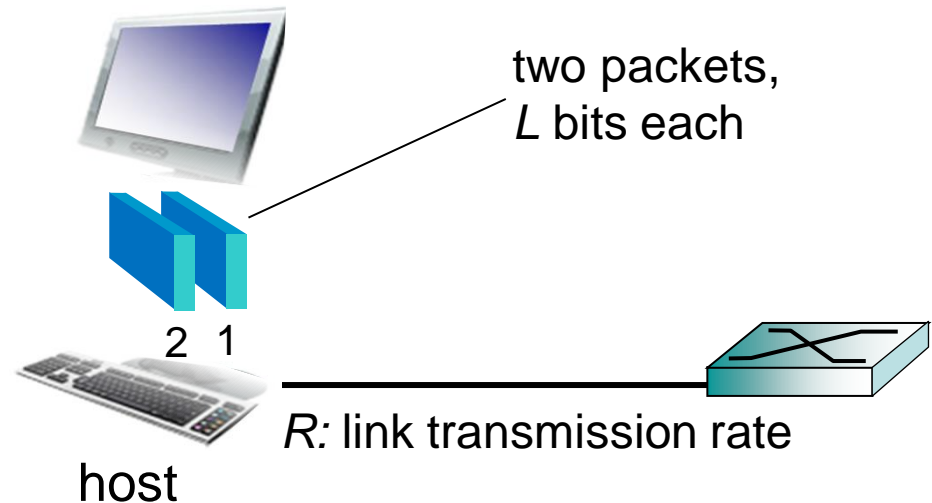
$$\begin{array}{ccccc} \text{packet} \\ \text{transmission} \\ \text{delay} \end{array} = \begin{array}{c} \text{time needed to} \\ \text{transmit } L\text{-bit} \\ \text{packet into link} \end{array} = \frac{L \text{ (bits)}}{R \text{ (bits/sec)}}$$

Packet-switching: store-and-forward

L bits per packet

source — *R* bps — *R* bps — destination

3 2 1

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

one-hop numerical example:

- *L* = 7.5 Mbits
- *R* = 1.5 Mbps
- one-hop transmission delay = 5 sec

more on delay shortly …

Packet Switching: queueing delay, loss

A *R* = 100 Mb/s

R = 1.5 Mb/s

B

queue of packets
waiting for output link

C

D

E
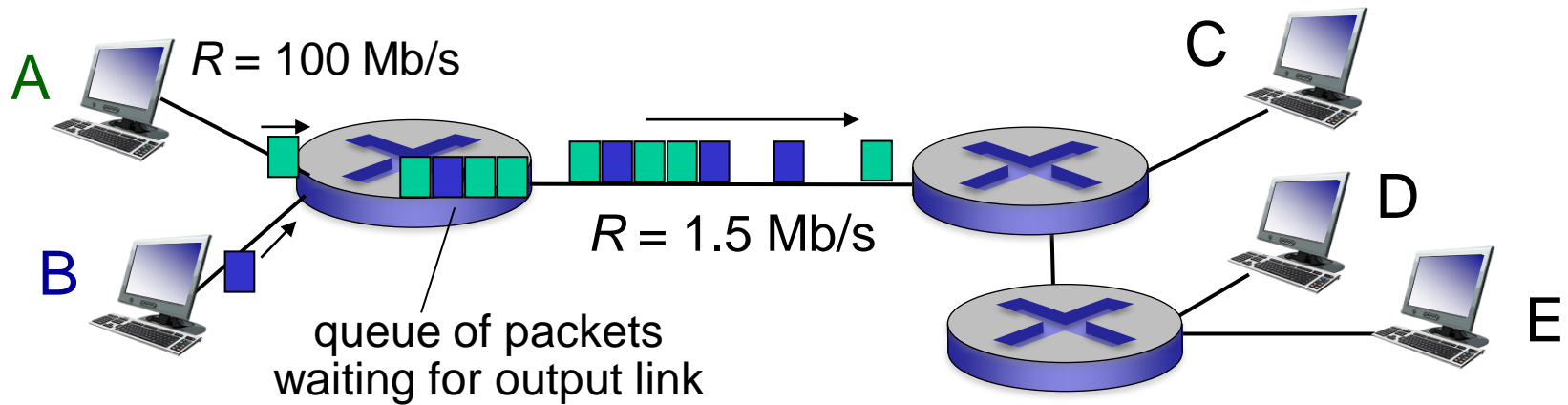
queuing and loss (stochastic multiplexing): best effort

- 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

Alternative core: circuit switching

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

- 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)*
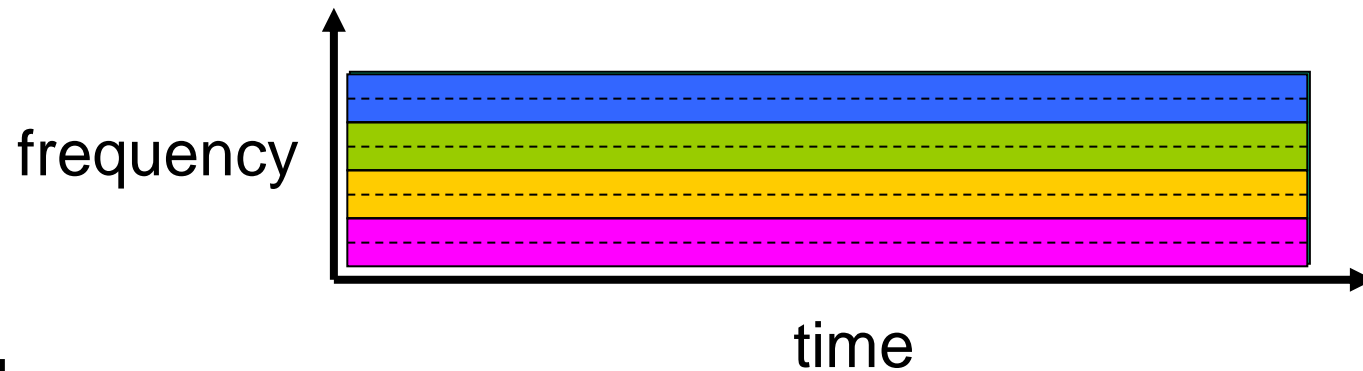- commonly used in traditional telephone networks
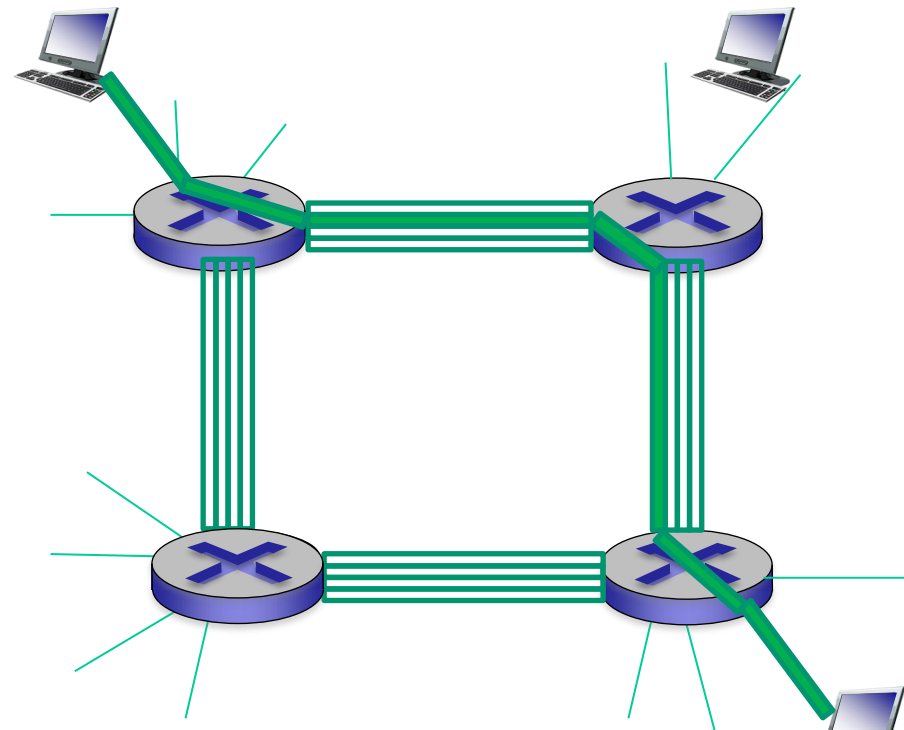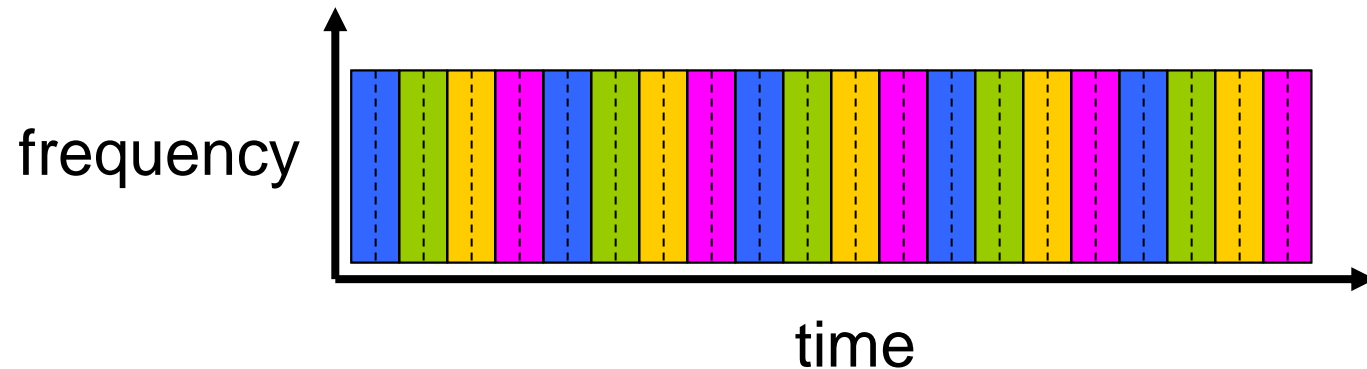
Circuit switching in mobile: FDM versus TDM

Example:

4 users

FDM

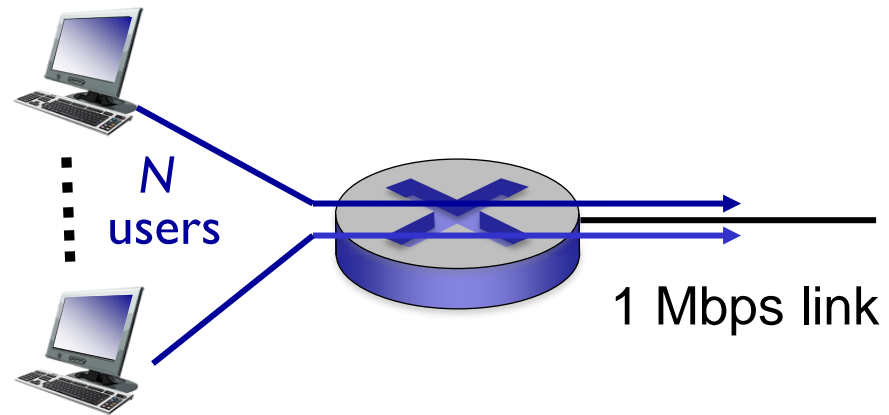frequency

time

TDM

frequency

time

Packet switching versus circuit switching

packet switching allows more users to use network!

example:

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

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

N users

1 Mbps link

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/

On

Off

user data 100 kbps

Circuit switch

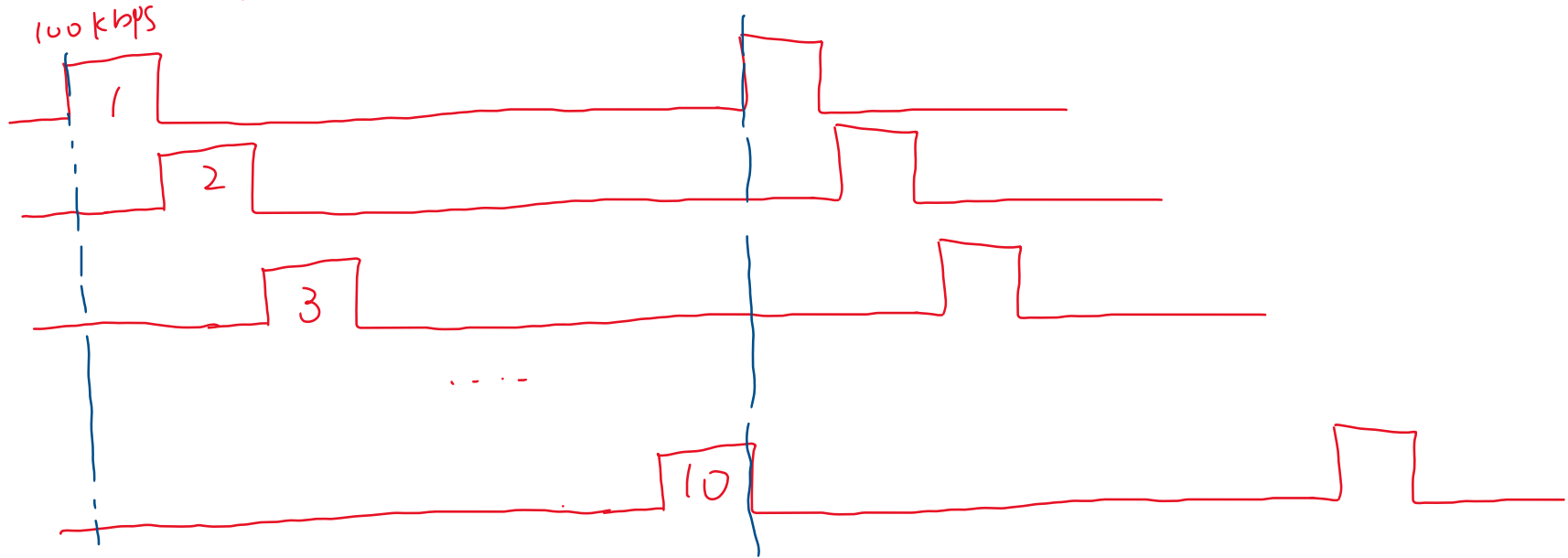each user buy 100kbps bandwith

Total: 1Mbps

The number of users to be supported $\dfrac{1Mbps}{100\,kbps} = 10$

Considering off periods, average rate of each user is

$$100 \times 10\% = 10\,kbps$$

Roughly, the bandwidth can hold $\dfrac{1Mbps}{10\,kbps} = 100$ users

However, if more than 10 users are on simultaneously.

Overload the link !

Ideal alignment to support 100 users

100 kbps

In practice, each user is "on" with prob. p, "off" with Prob. $1-p$

($p = 10\%$ in the above example)

Given N on/off users, the prob. that n of them are "on" simultaneously is

$$\binom{N}{n} p^n (1-p)^{N-n}, \text{ Binomial Distribution}$$

Packet switching versus circuit switching

is packet switching a "slam dunk winner?"

- 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 (chapter 7)

Q: human analogies of reserved resources (circuit switching) versus on-demand allocation (packet-switching)?
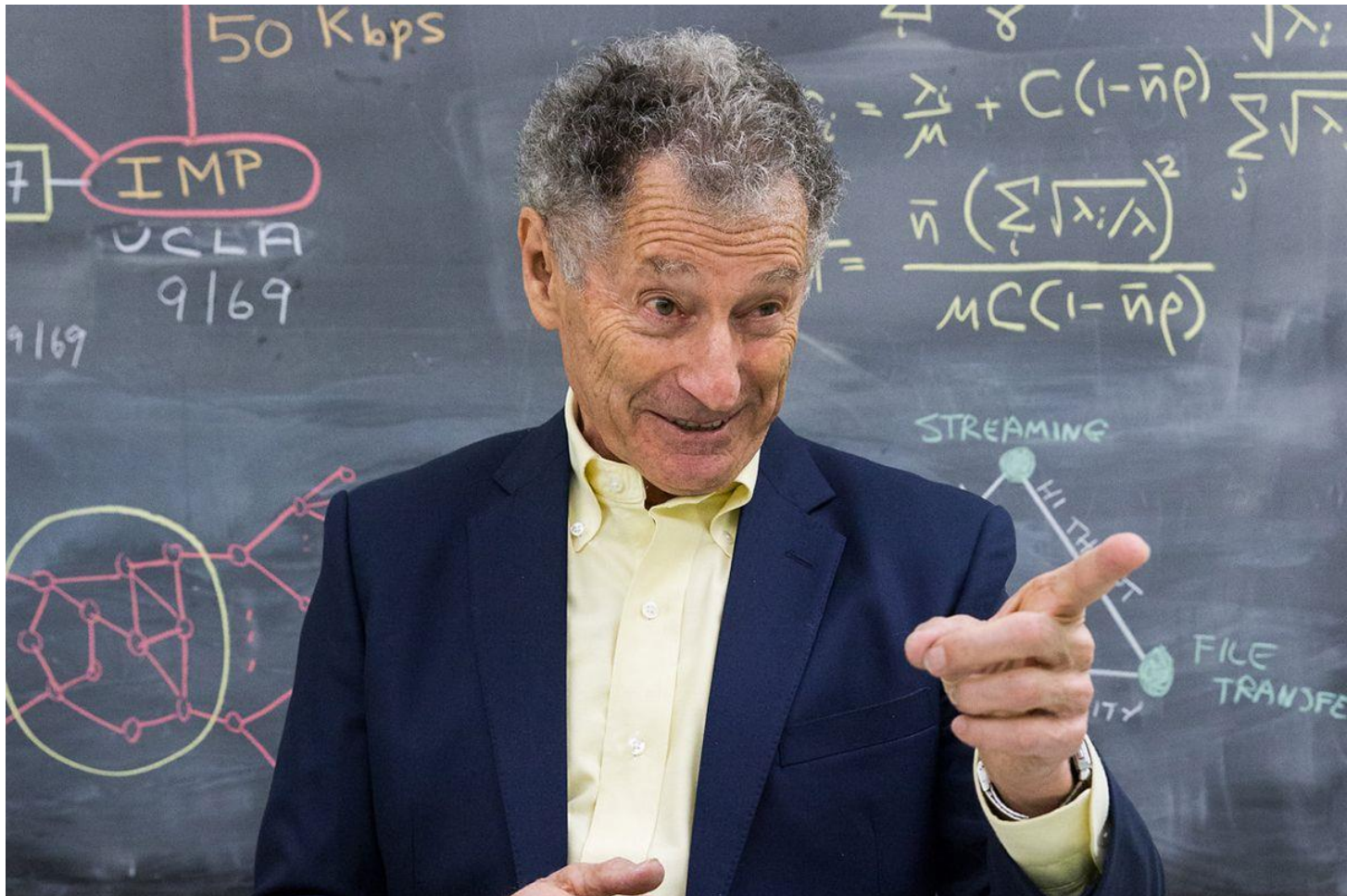
Prof. Leonard Kleinrock (UCLA): In the early 1970s, he applied queueing theory to model the performance of packet switching networks.

Internet structure: network of networks

- 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
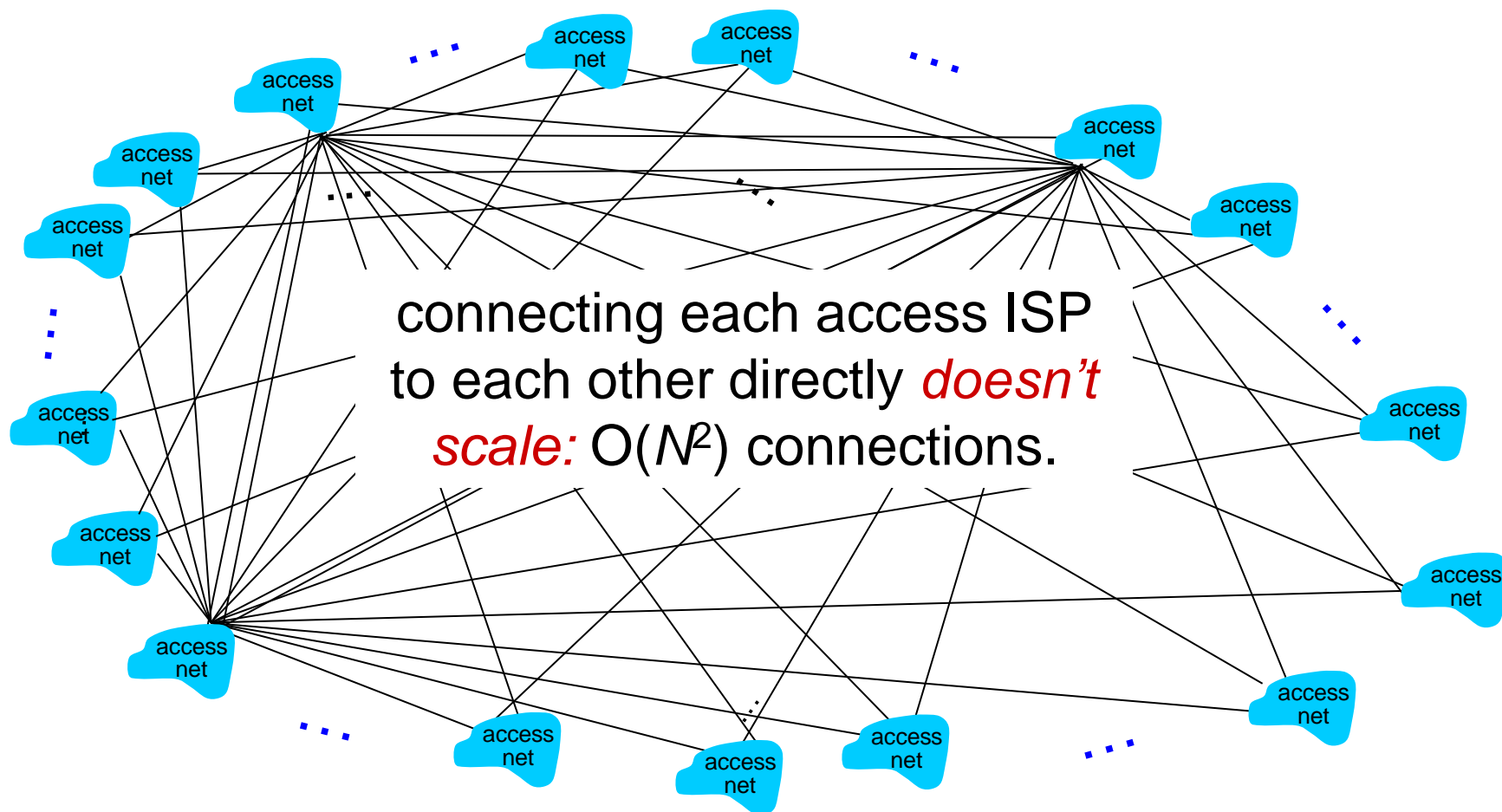- Let's take a stepwise approach to describe current Internet structure

Internet structure: network of networks

Question: given *millions* of access ISPs, how to connect them together?
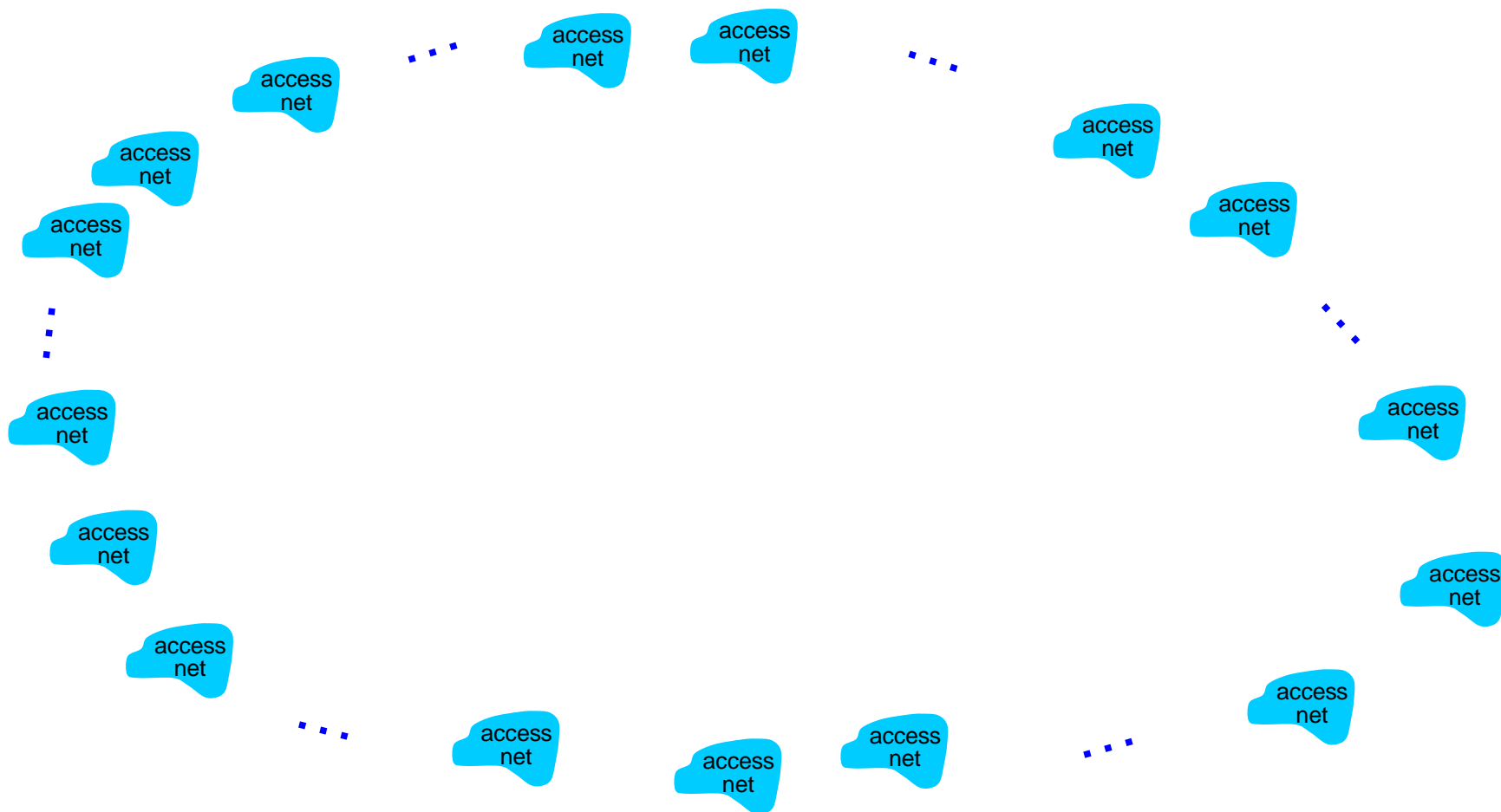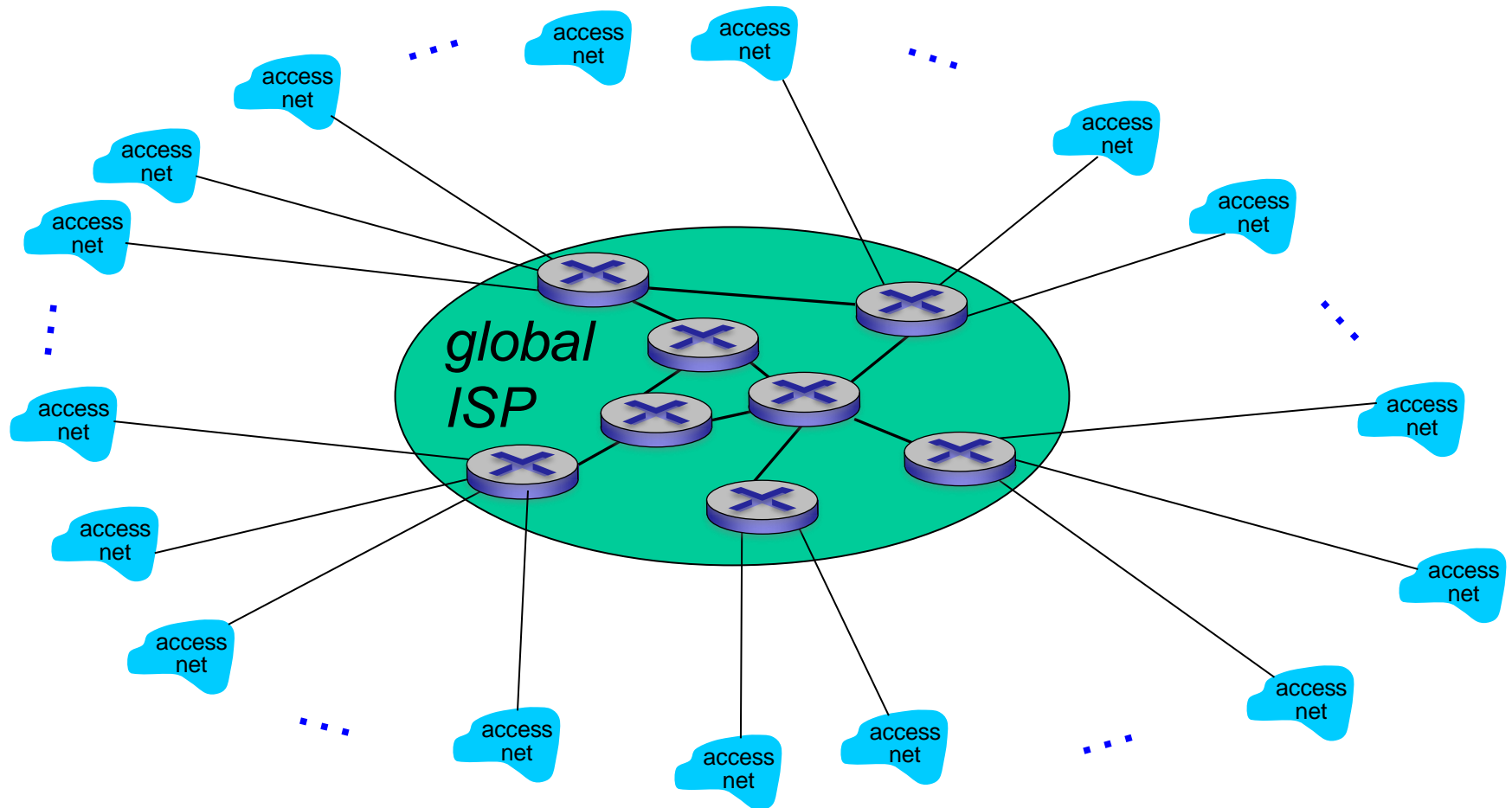
Internet structure: network of networks

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

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

Internet structure: network of networks

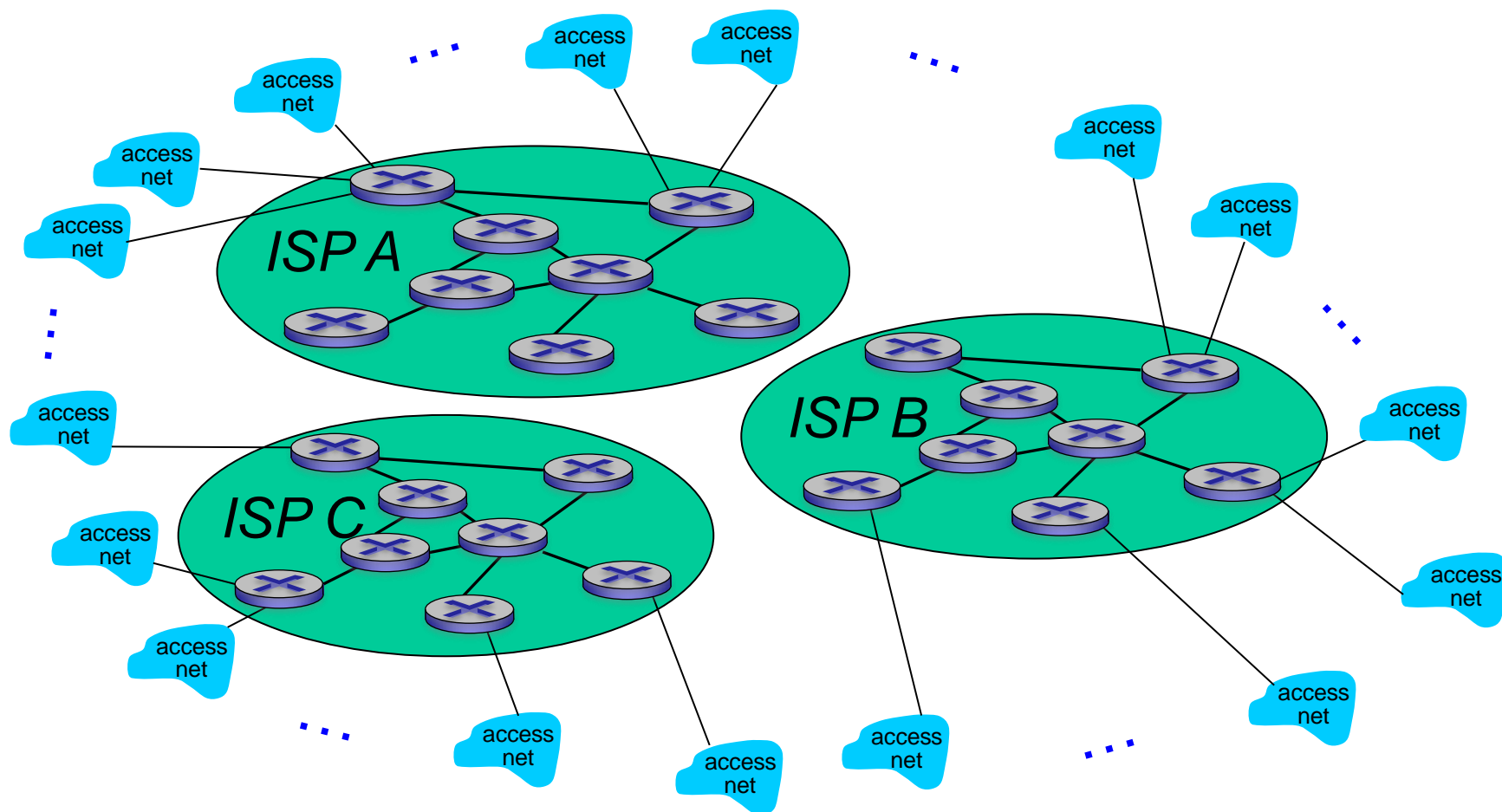*Option:* connect each access ISP to one global transit ISP?
Customer and *provider* ISPs have economic agreement.
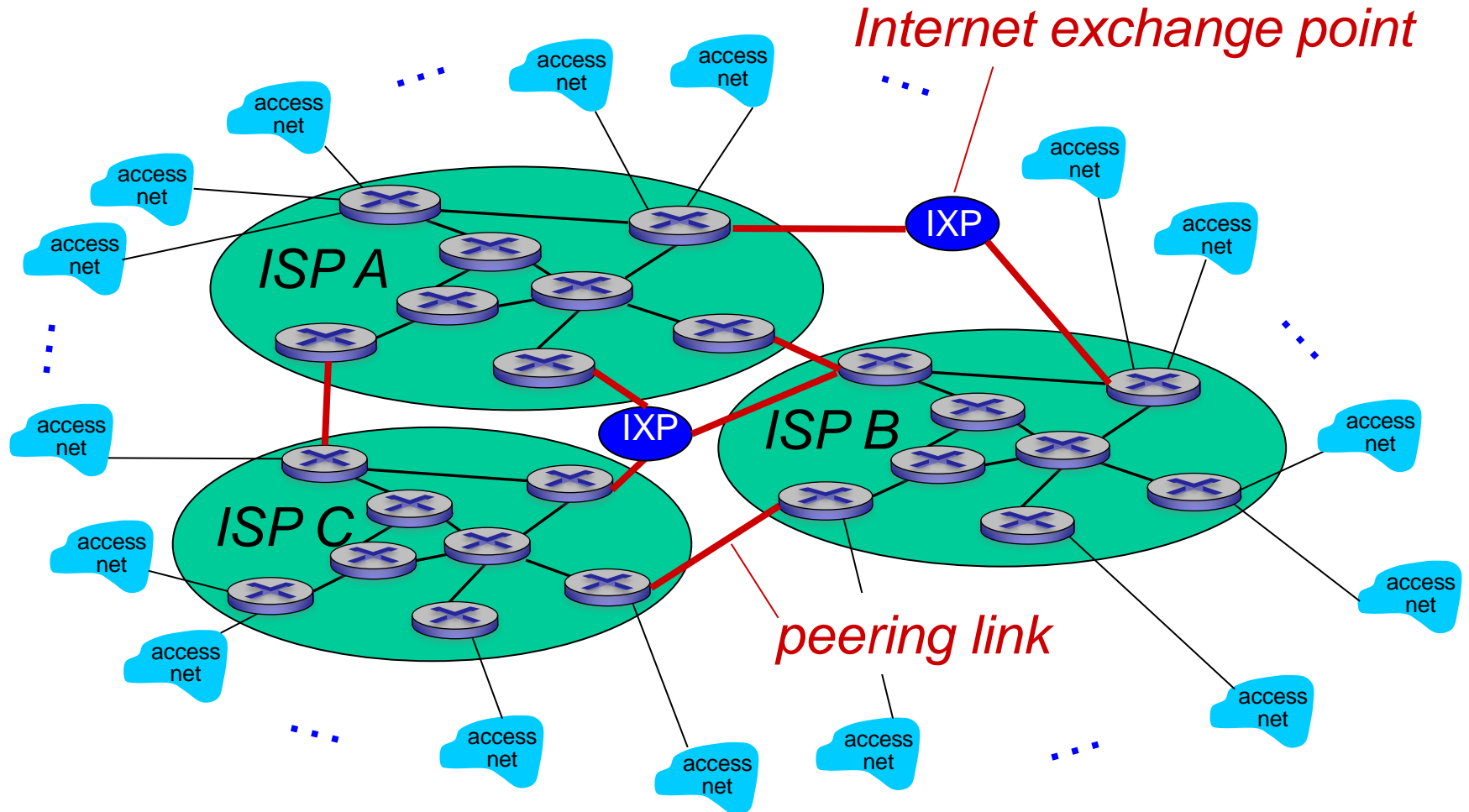
Internet structure: network of networks

But if one global ISP is viable business, there will be competitors ....
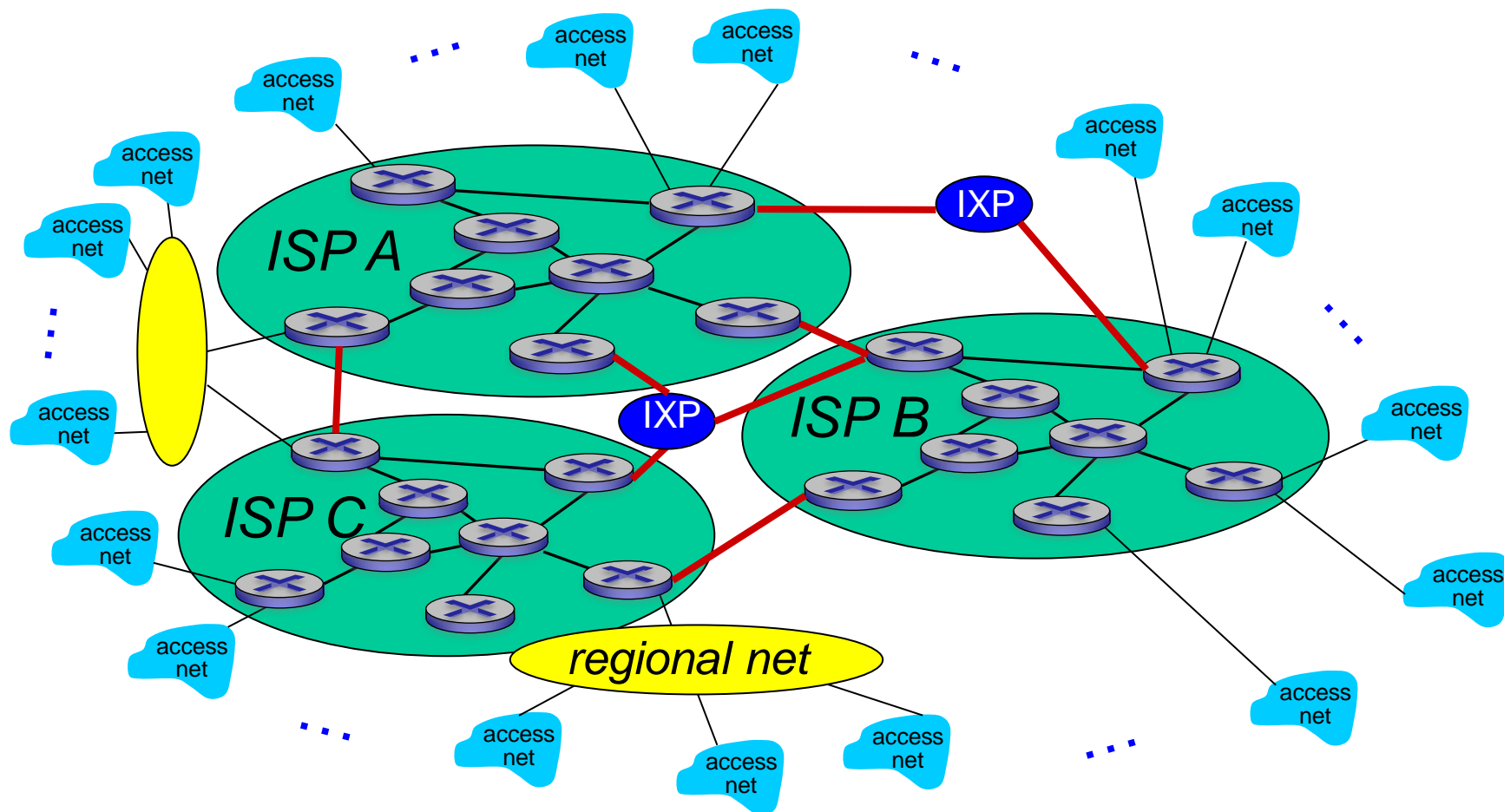
Internet structure: network of networks

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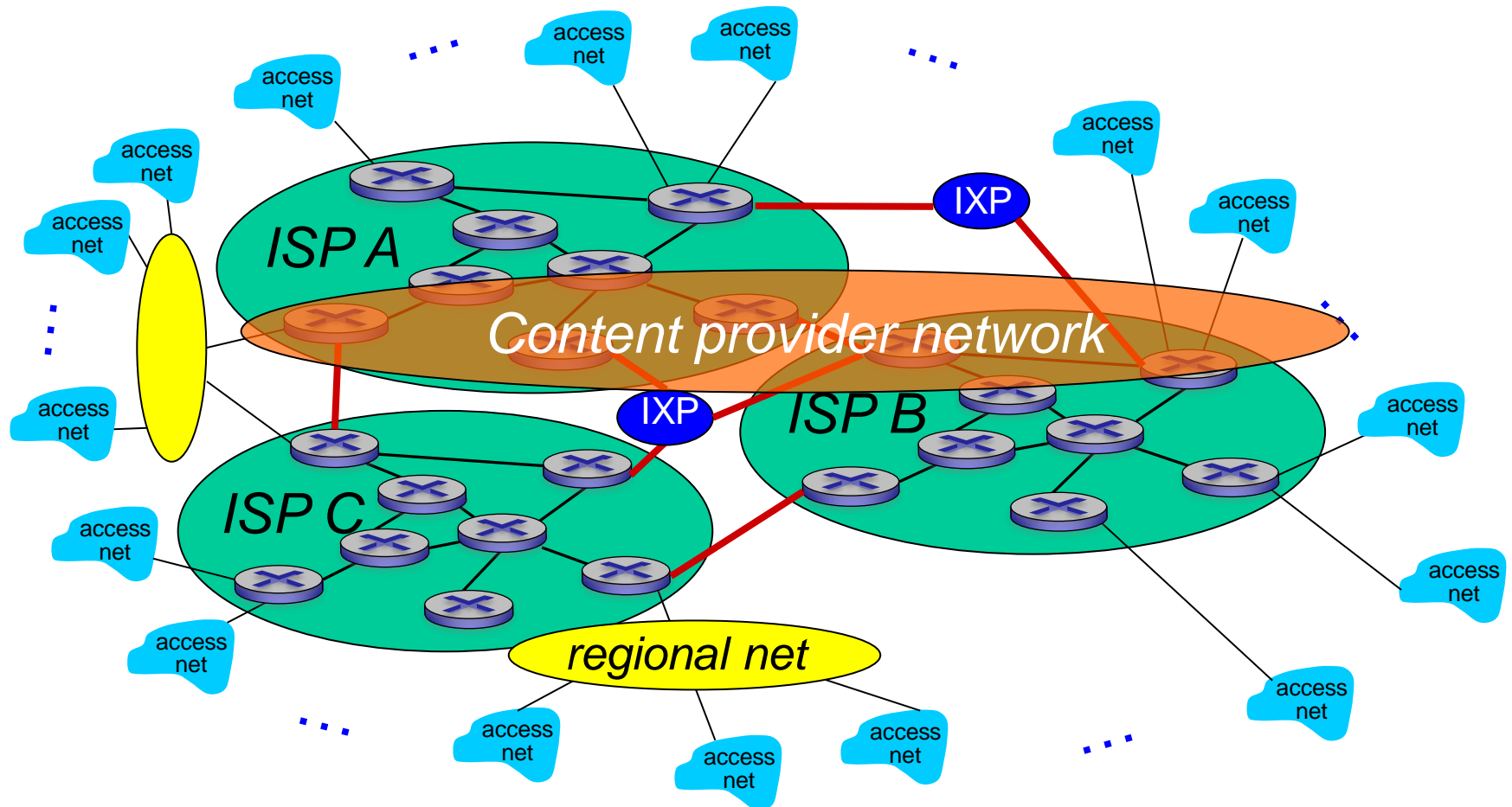

Internet exchange point

IXP

ISP A

ISP B

ISP C

peering link

Internet structure: network of networks

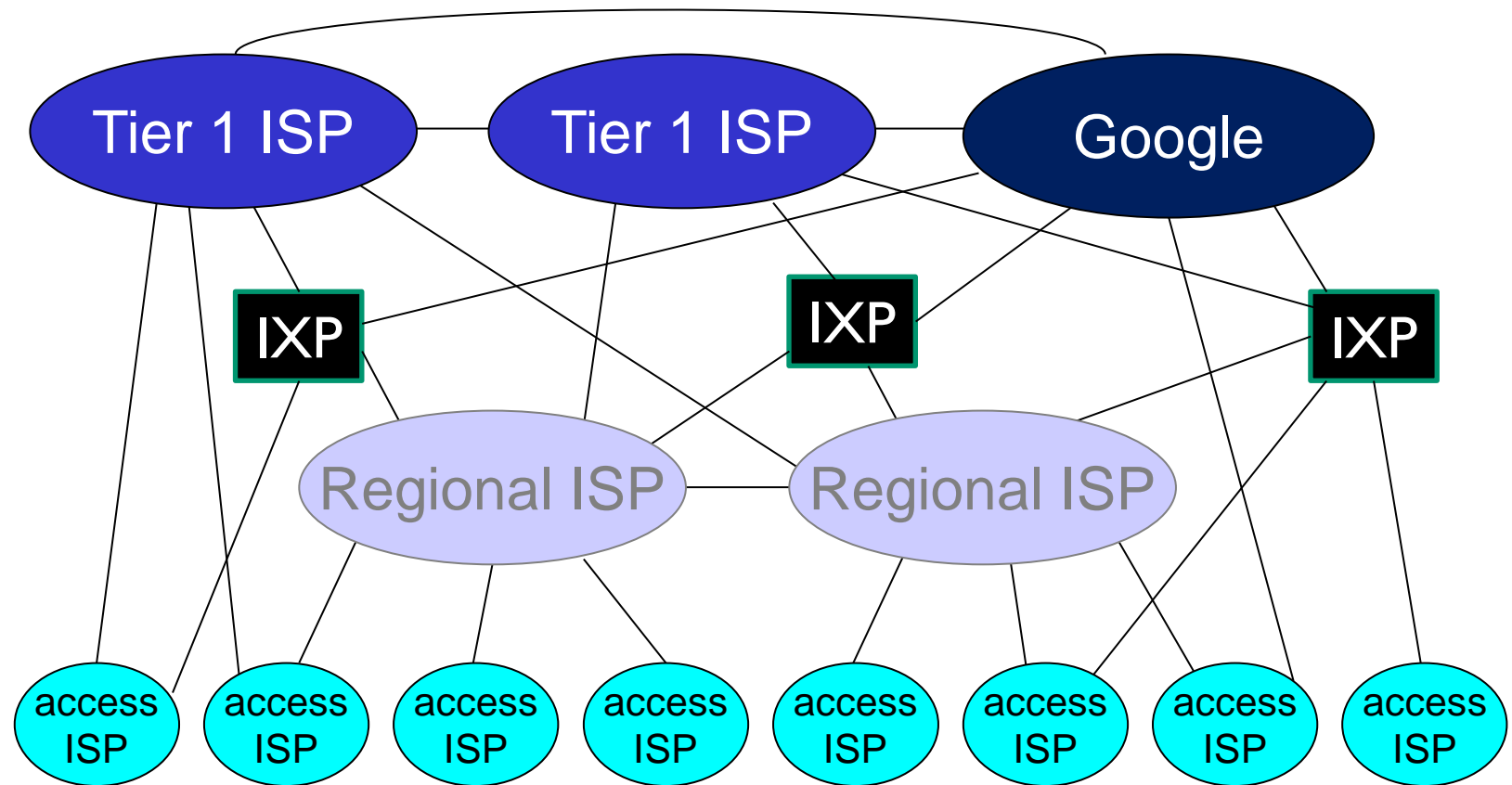… and regional networks may arise to connect access nets to ISPs

Internet structure: 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: 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 network (e.g., Google): private network that connects it data centers to Internet, often bypassing tier-1, regional ISPs

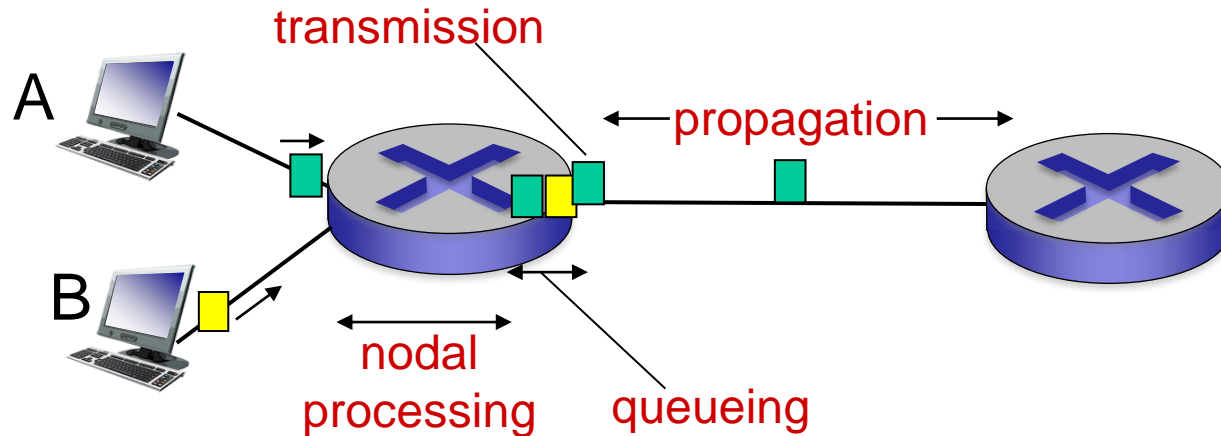# Chapter 1: roadmap

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

packet being transmitted (delay)

A

B

packets queueing (delay)

free (available) buffers: arriving packets dropped (loss) if no free buffers
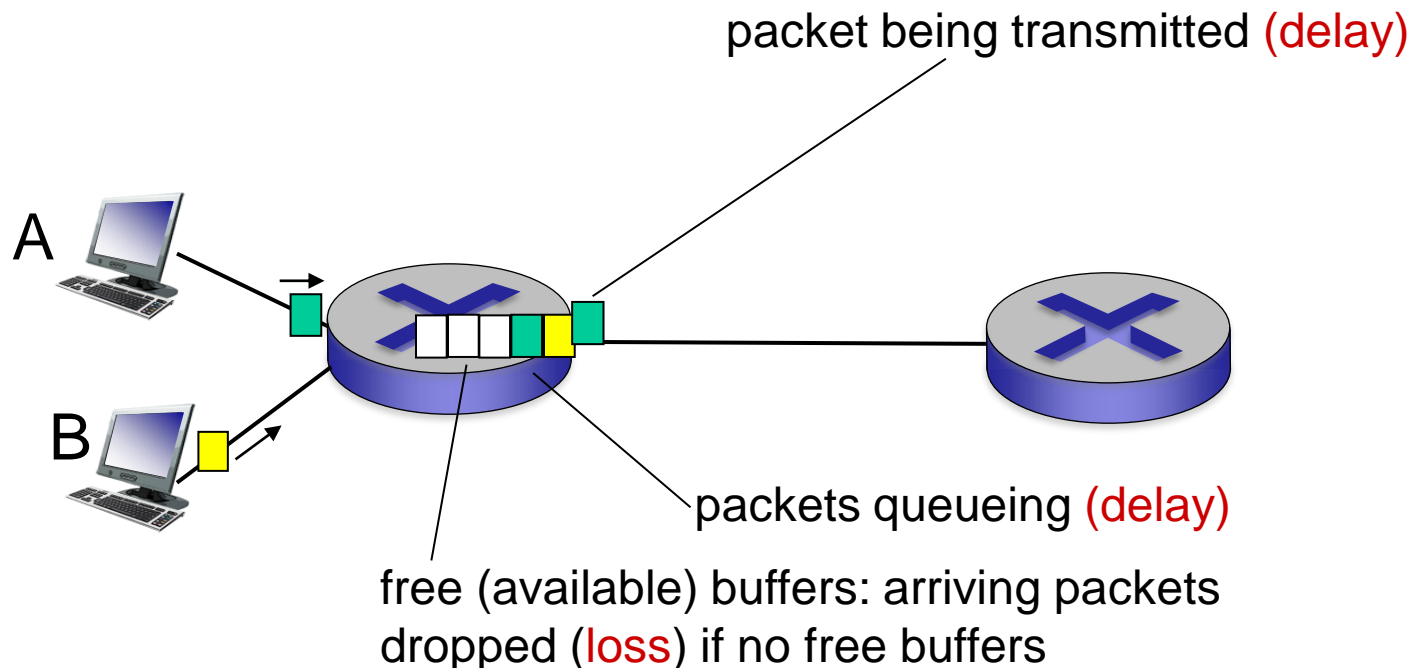
Four sources of packet delay

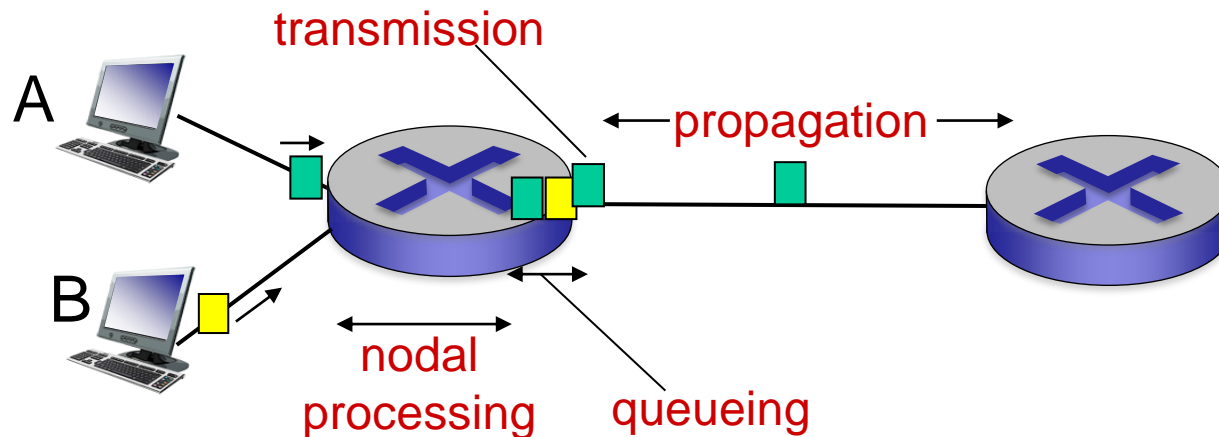$$d_{nodal} = d_{proc} + d_{queue} + d_{trans} + d_{prop}$$

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

Four sources of packet delay

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

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 (~2×10^8 m/sec)
- $d_{\text{prop}} = d/s$

* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/interactive/
* Check out the Java applet for an interactive animation on trans vs. prop delay

Caravan analogy

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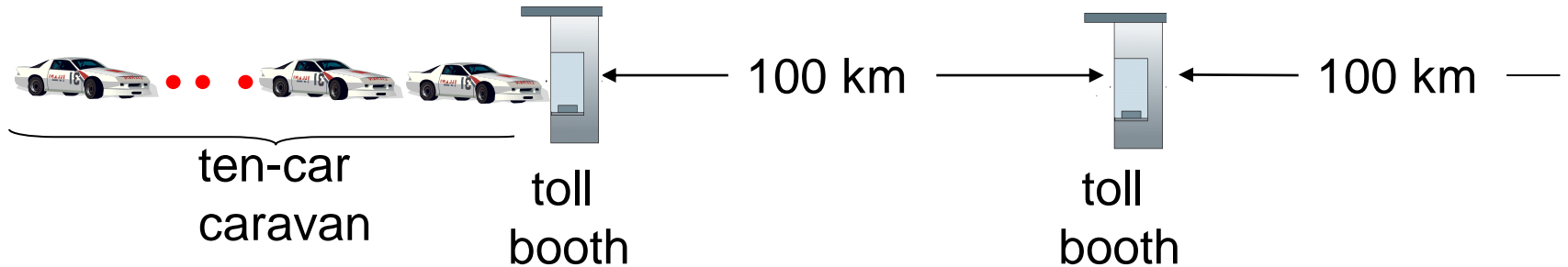
- cars "propagate" at 100 km/hr
- toll booth takes 12 sec to service car (bit transmission time)
- car ~ bit; caravan ~ packet
- *Q: How long until caravan is lined up before 2nd toll booth?*

- time to "push" entire caravan through toll booth onto highway = 12*10 = 120 sec
- time for last car to propagate from 1st to 2nd toll both: 100km/(100km/hr)= 1 hr
- *A: 62 minutes*

Caravan analogy (more)
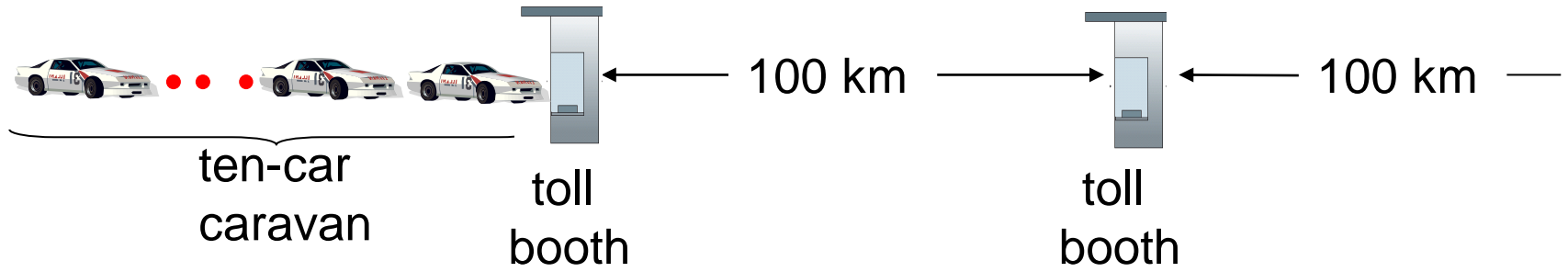
- suppose cars now "propagate" at 1000 km/hr
- and suppose toll booth now takes one min to service a car
- *Q:* Will cars arrive to 2nd booth before all cars serviced at first booth?

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

Queueing delay (revisited)

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

average queueing delay

traffic intensity = *La/R*

1

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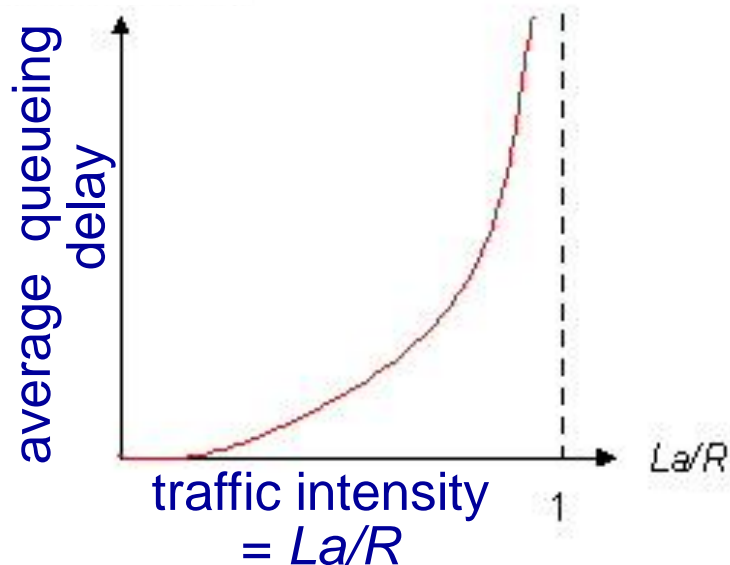
- *La/R* ~ 0: avg. queueing delay small
- *La/R* → 1: avg. queueing delay large
- *La/R* > 1: more "work" arriving than can be serviced, average delay infinite!

La/R ~ 0

*La/R* -> 1

* Check online interactive animation on queuing and loss

"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.

3 probes   3 probes

3 probes
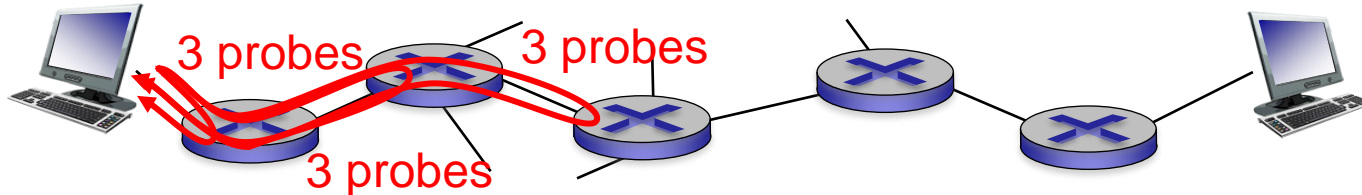
"Real" Internet delays, routes

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
```
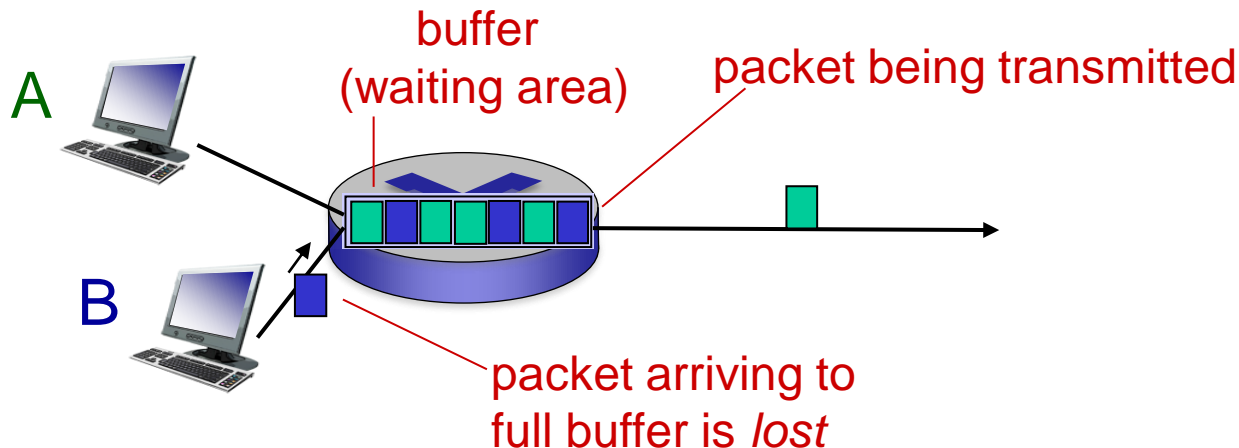
trans-oceanic
link

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

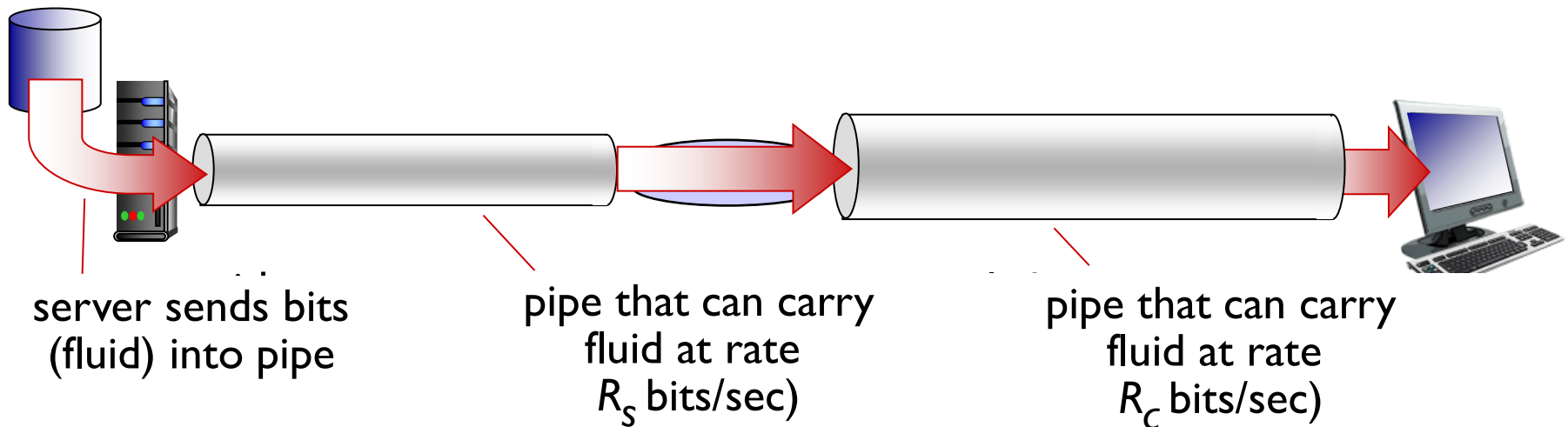* Do some traceroutes from exotic countries at www.traceroute.org

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
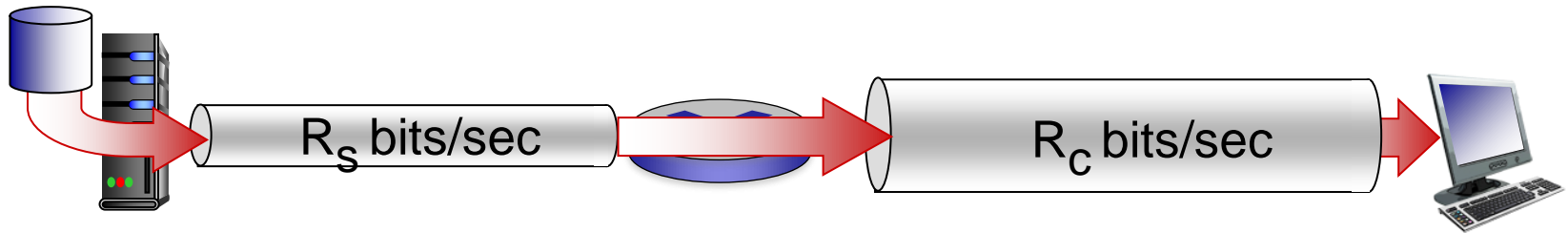
A

B

buffer
(waiting area)

packet being transmitted

packet arriving to
full buffer is *lost*

* Check out the Java applet for an interactive animation on queuing and loss

Throughput

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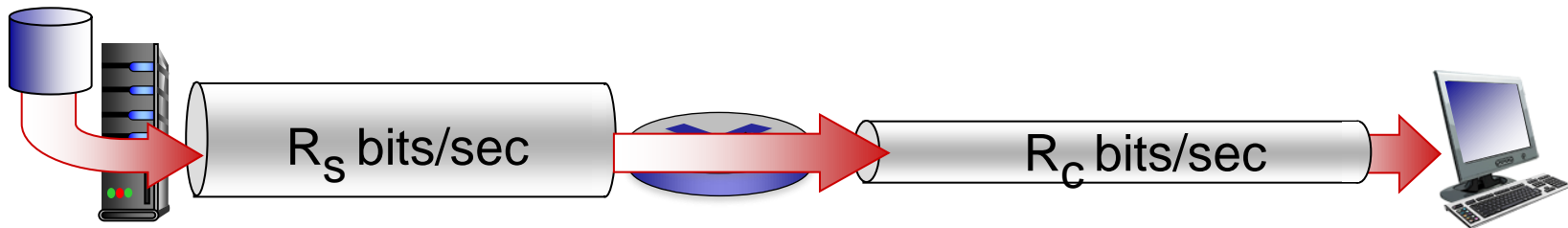 - *average:* rate over longer period of time

server sends bits
(fluid) into pipe

pipe that can carry
fluid at rate
R_s bits/sec)

pipe that can carry
fluid at rate
R_c bits/sec)

Throughput (more)

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

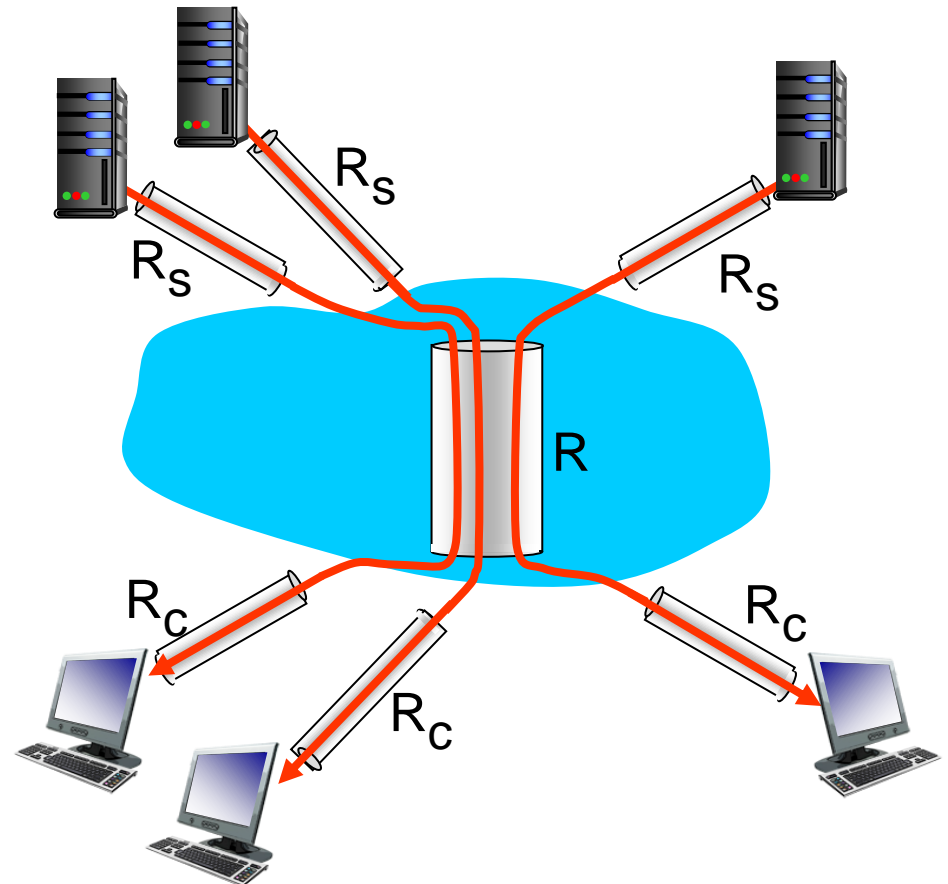- $R_s > R_c$ What is average end-end throughput?

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

R_s

R_s

R_s

R

R_c

R_c

R_c

10 connections (fairly) share backbone bottleneck link R bits/sec

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