

Network Performance

These slides have been adapted from the Pearson slides. S. Thomson 01/2017.

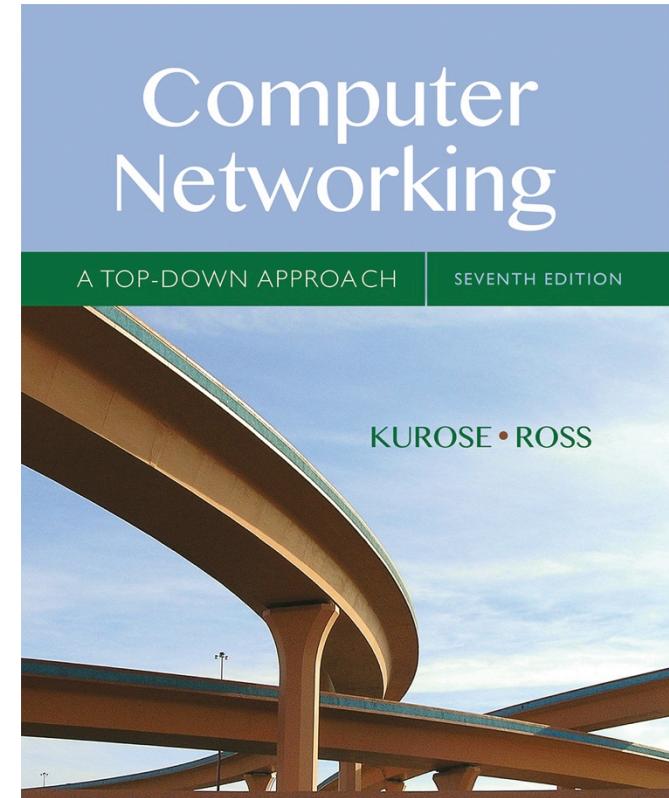
A note on the use of these Powerpoint slides:

We're making these slides freely available to all (faculty, students, readers). They're in PowerPoint form so you see the animations; and can add, modify, and delete slides (including this one) and slide content to suit your needs. They obviously represent a *lot* of work on our part. In return for use, we only ask the following:

- 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!)
- If you post any slides on a www site, that you note that they are adapted from (or perhaps identical to) our slides, and note our copyright of this material.

Thanks and enjoy! JFK/KWR

© All material copyright 1996-2016
J.F Kurose and K.W. Ross, All Rights Reserved



*Computer
Networking: A Top
Down Approach*

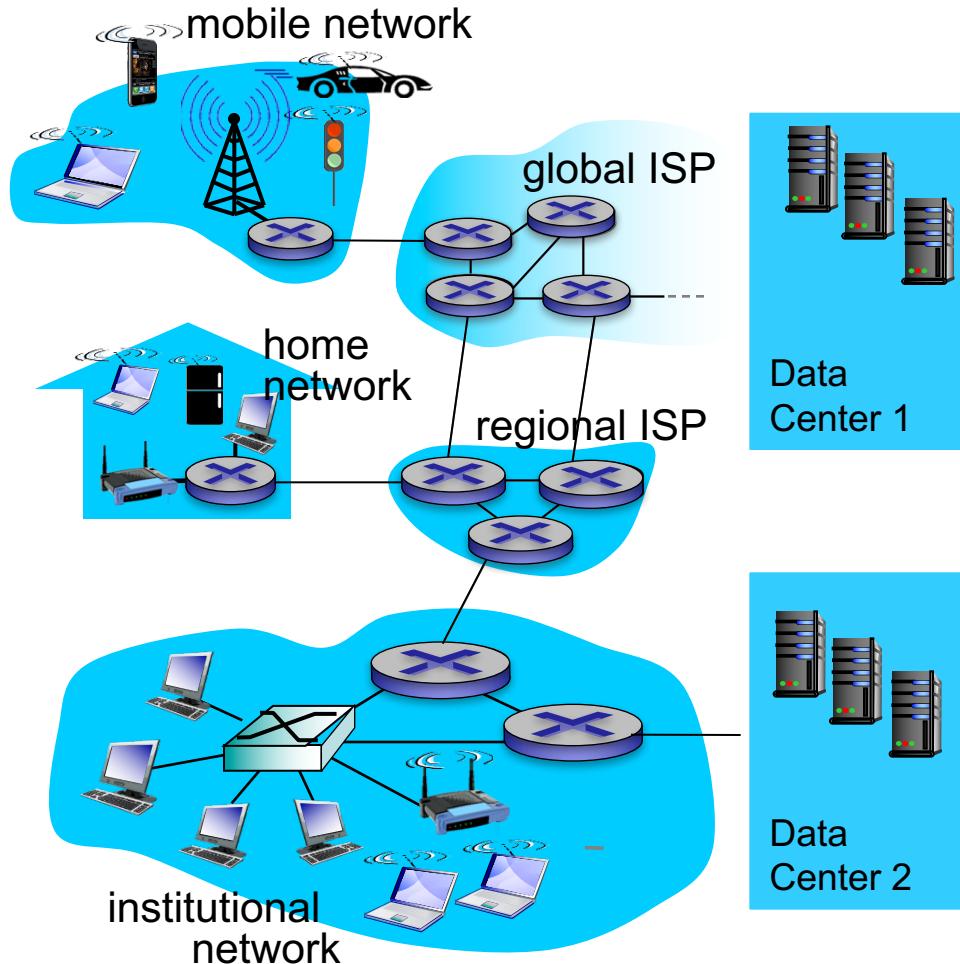
7th edition
Jim Kurose, Keith Ross
Pearson/Addison Wesley
April 2016

Outline

- More on Topology
 - Access Networks
 - Core Networks
- Network Performance
 - Loss
 - Delay
 - Throughput

A closer look at network structure:

- ***network edge:***
 - hosts: clients and servers
 - servers often in data centers
- ***access networks, physical media:*** wired, wireless communication links
- ***network core:***
 - interconnected routers
 - network of networks



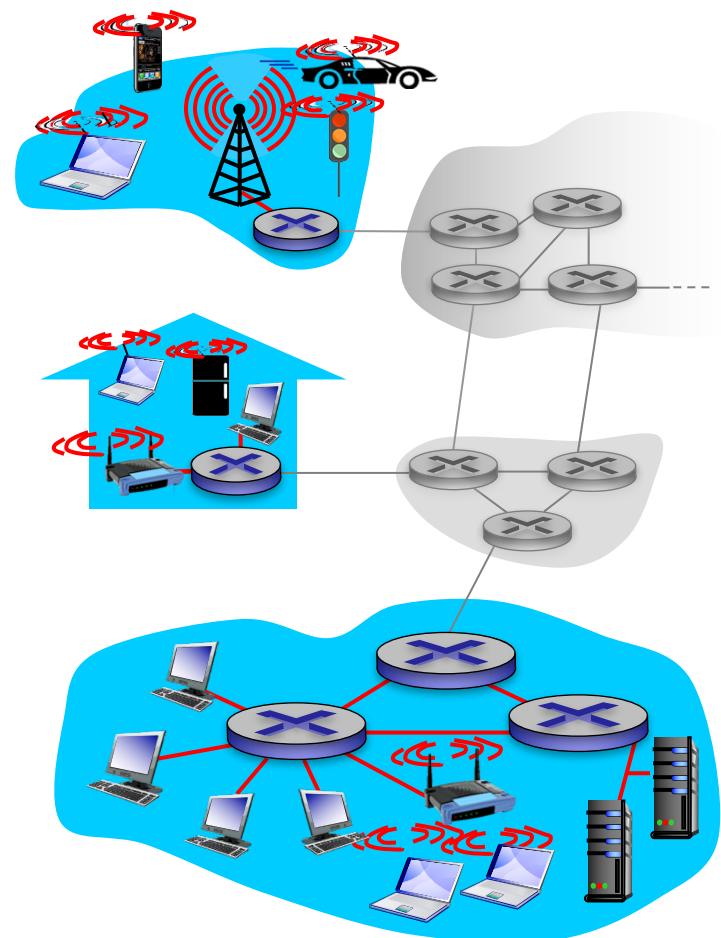
Access networks and physical media

Q: How to connect end systems to edge router?

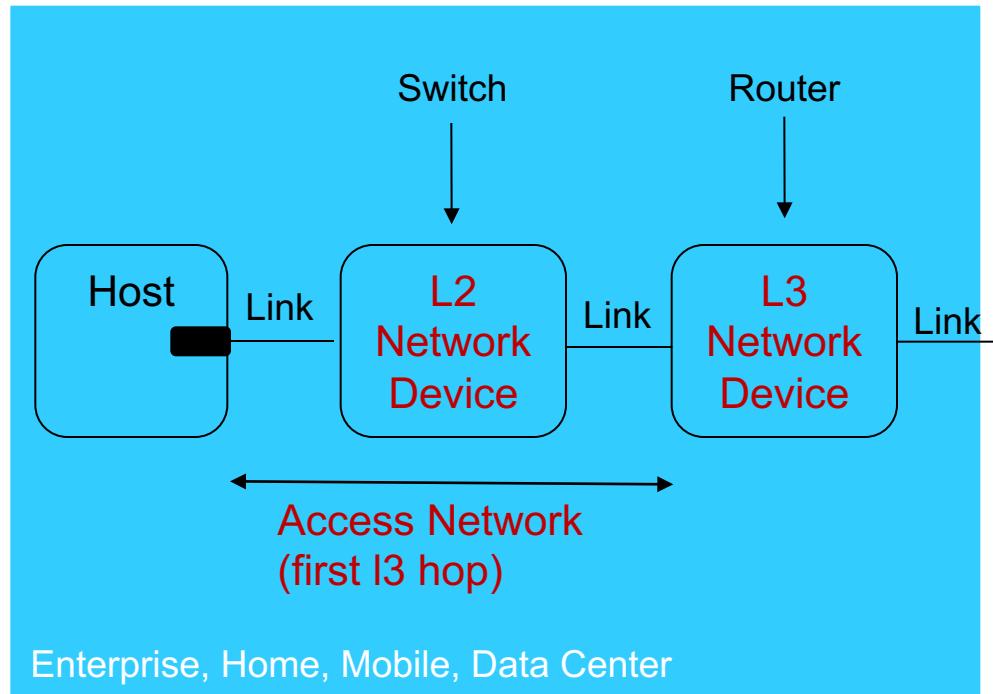
- residential access nets
- institutional access networks (school, company)
- mobile access networks

keep in mind:

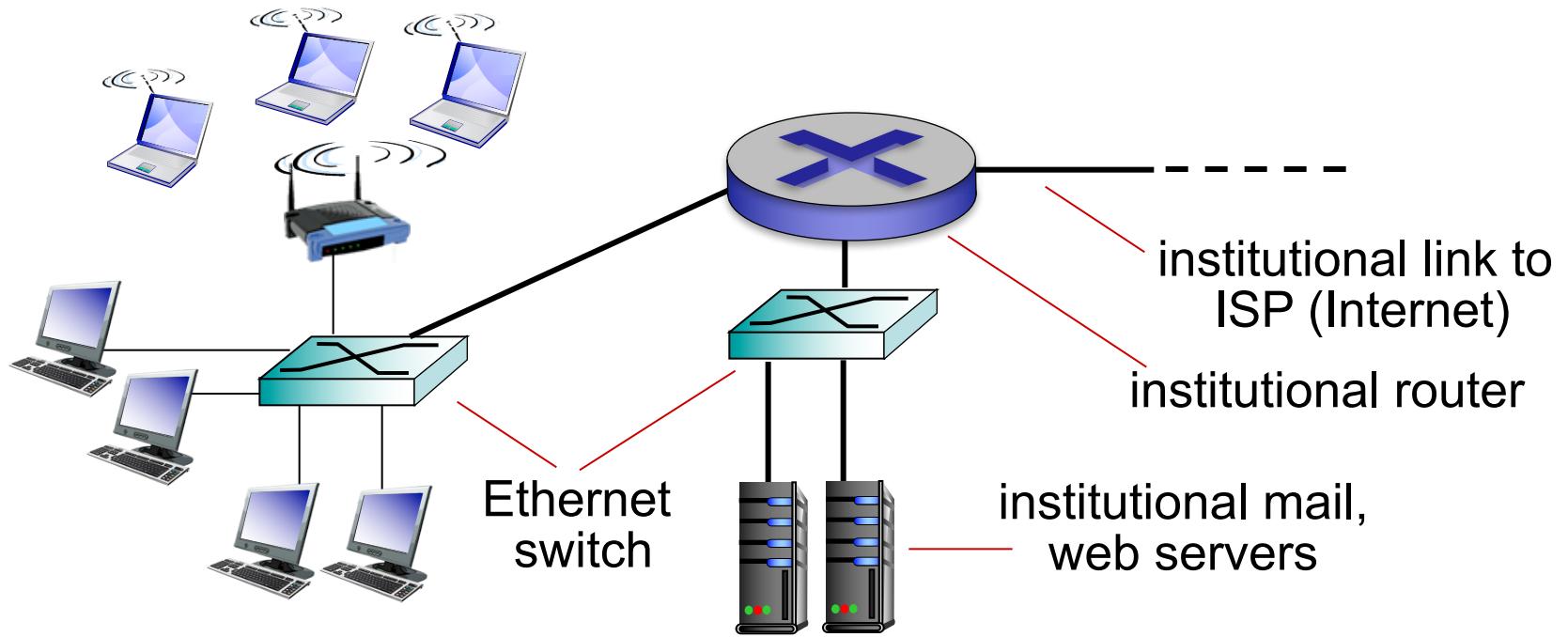
- bandwidth (bits per second) of access network?
- shared or dedicated?
- Symmetric or asymmetric?



Access Network: Components

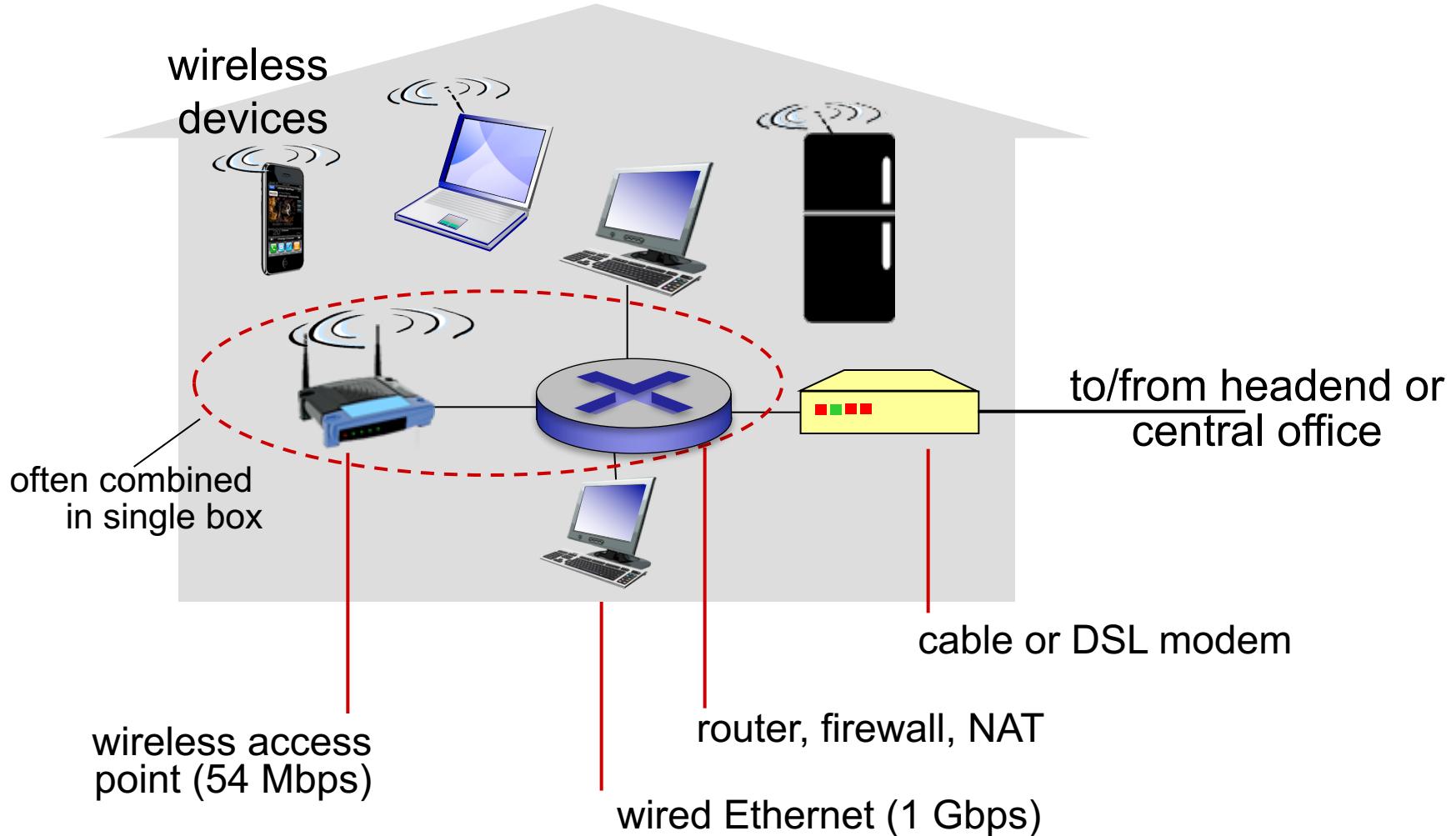


Enterprise access networks (Ethernet)

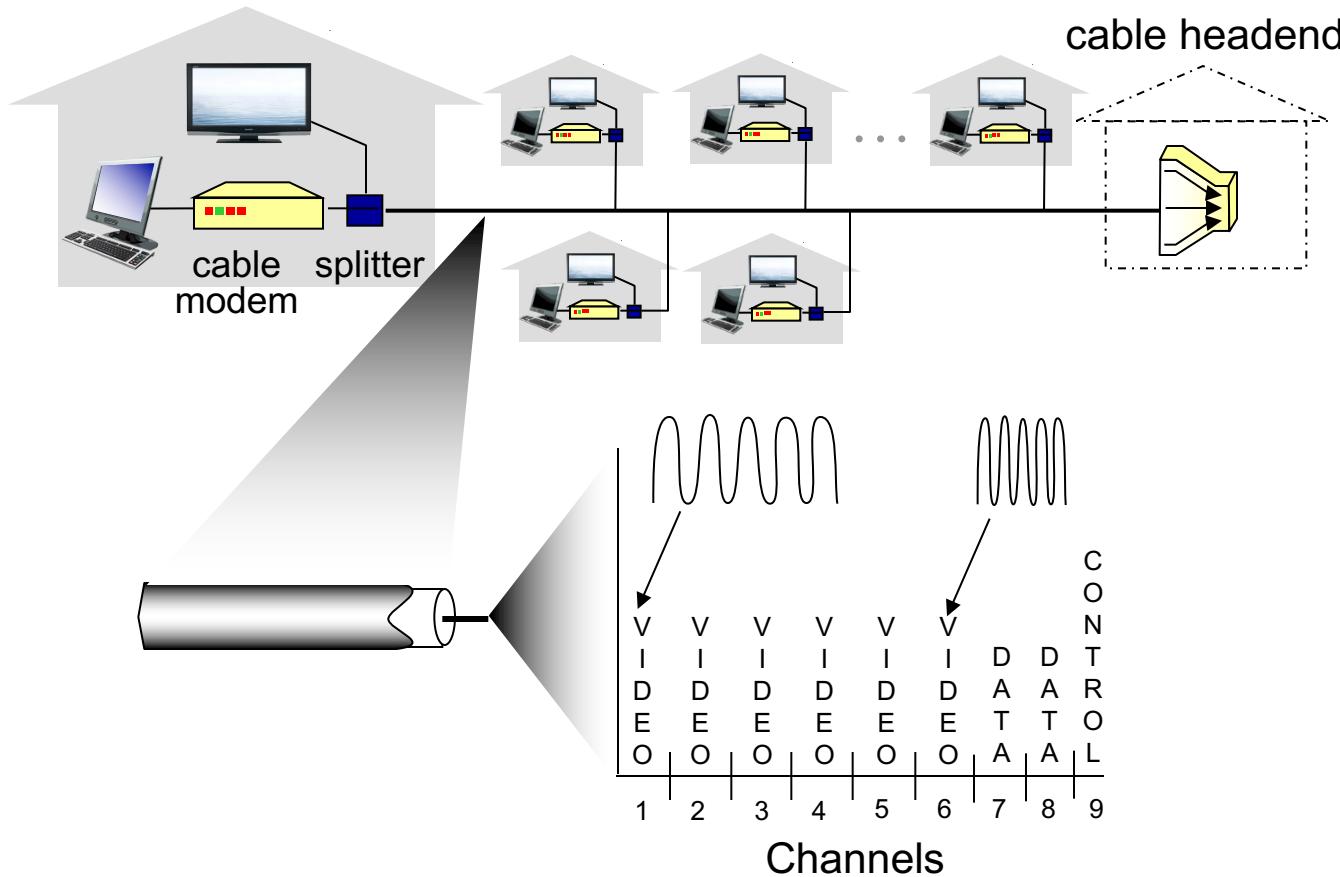


- typically used in companies, universities, etc.
- 10 Mbps, 100Mbps, 1Gbps, 10Gbps transmission rates
- today, end systems typically connect into Ethernet switch

Access network: home network

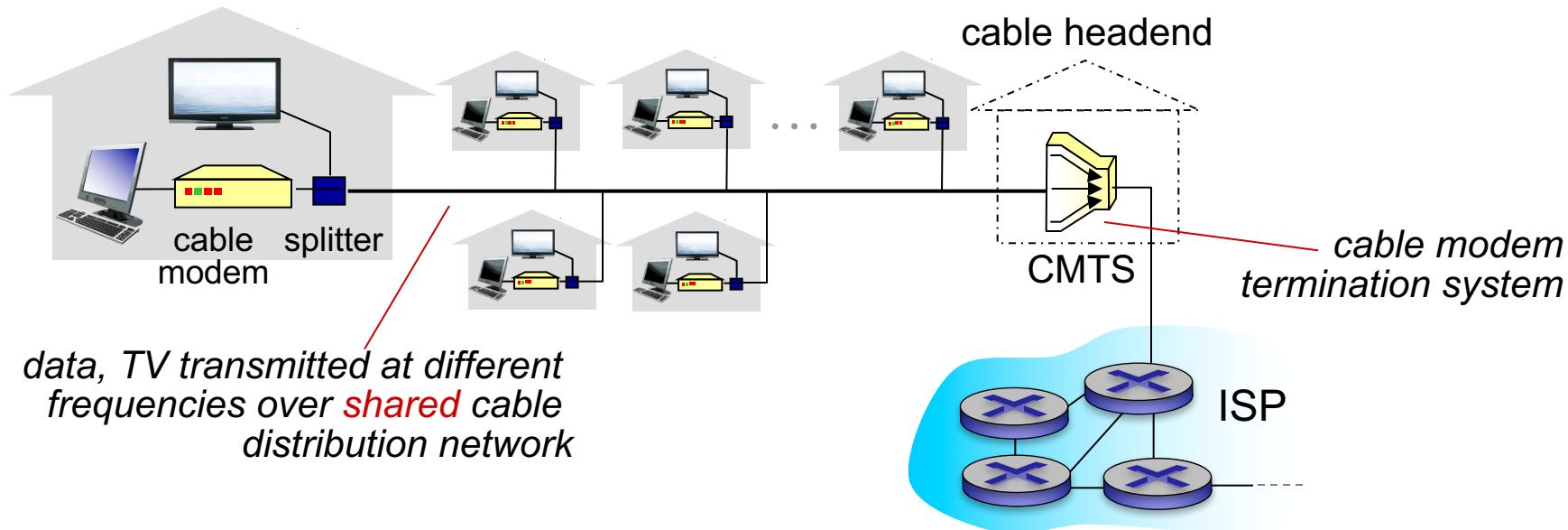


Access network: cable network



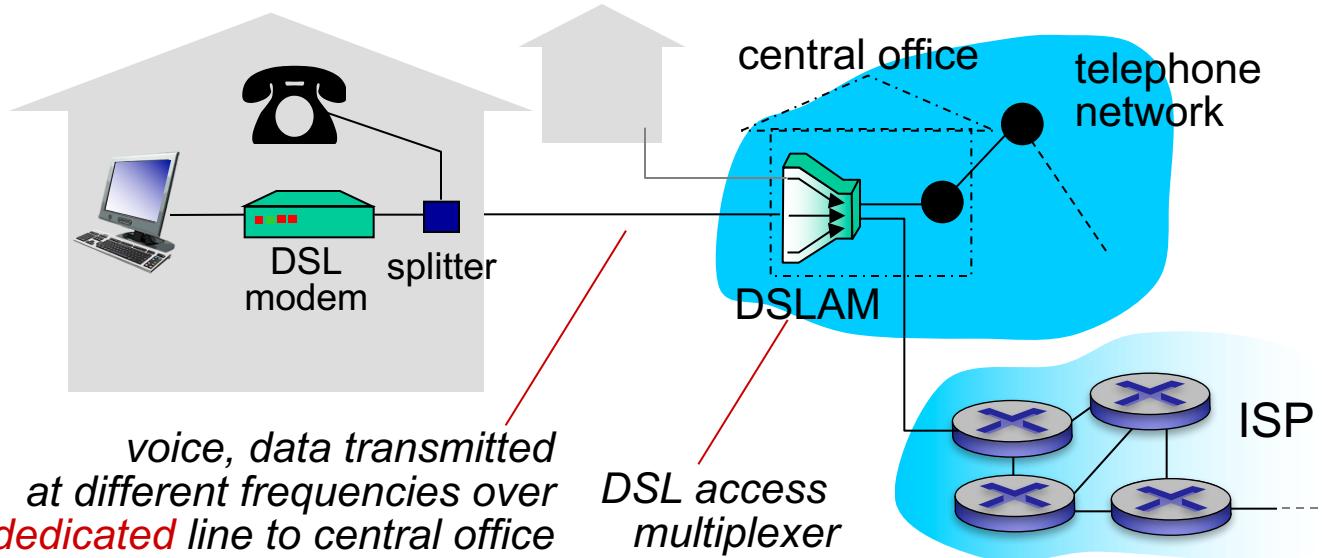
frequency division multiplexing: different channels transmitted in different frequency bands

Access network: cable network



- HFC: hybrid fiber coax
 - asymmetric: up to 30Mbps 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 network: digital subscriber line (DSL)



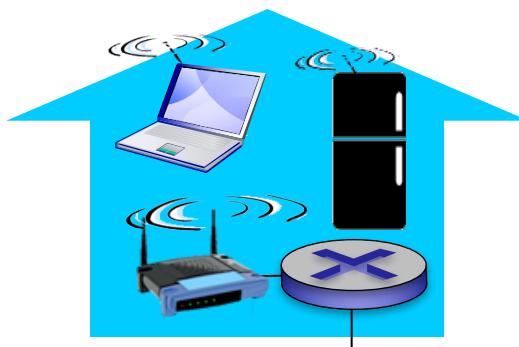
- use **existing** telephone line to central office DSLAM
 - data over DSL phone line goes to Internet
 - voice over DSL phone line goes to telephone net
- < 2.5 Mbps upstream transmission rate (typically < 1 Mbps)
- < 24 Mbps downstream transmission rate (typically < 10 Mbps)

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

wide-area wireless access

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



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



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

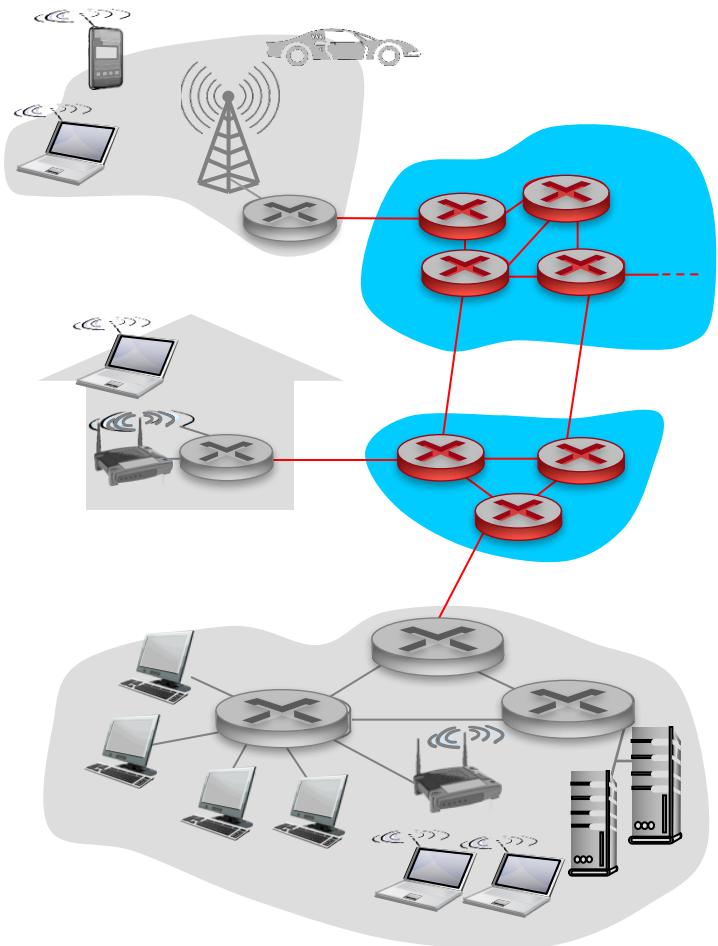
- signal carried in electromagnetic spectrum
- no physical “wire”
- bidirectional
- propagation environment effects:
 - reflection
 - obstruction by objects
 - interference

radio link types:

- terrestrial microwave
 - e.g. up to 45 Mbps channels
- LAN (e.g., WiFi)
 - 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

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

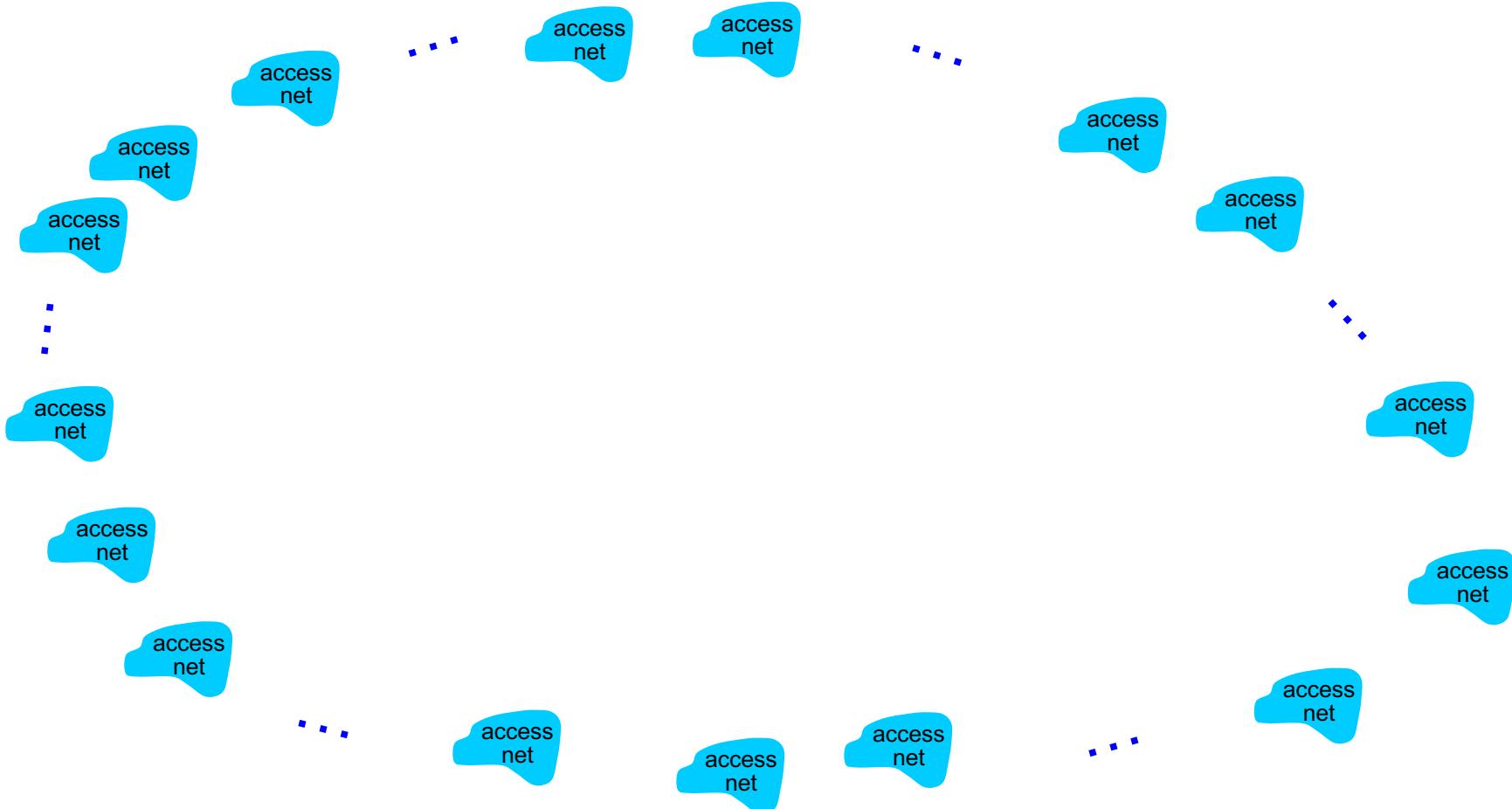


Internet structure: network of networks

- 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

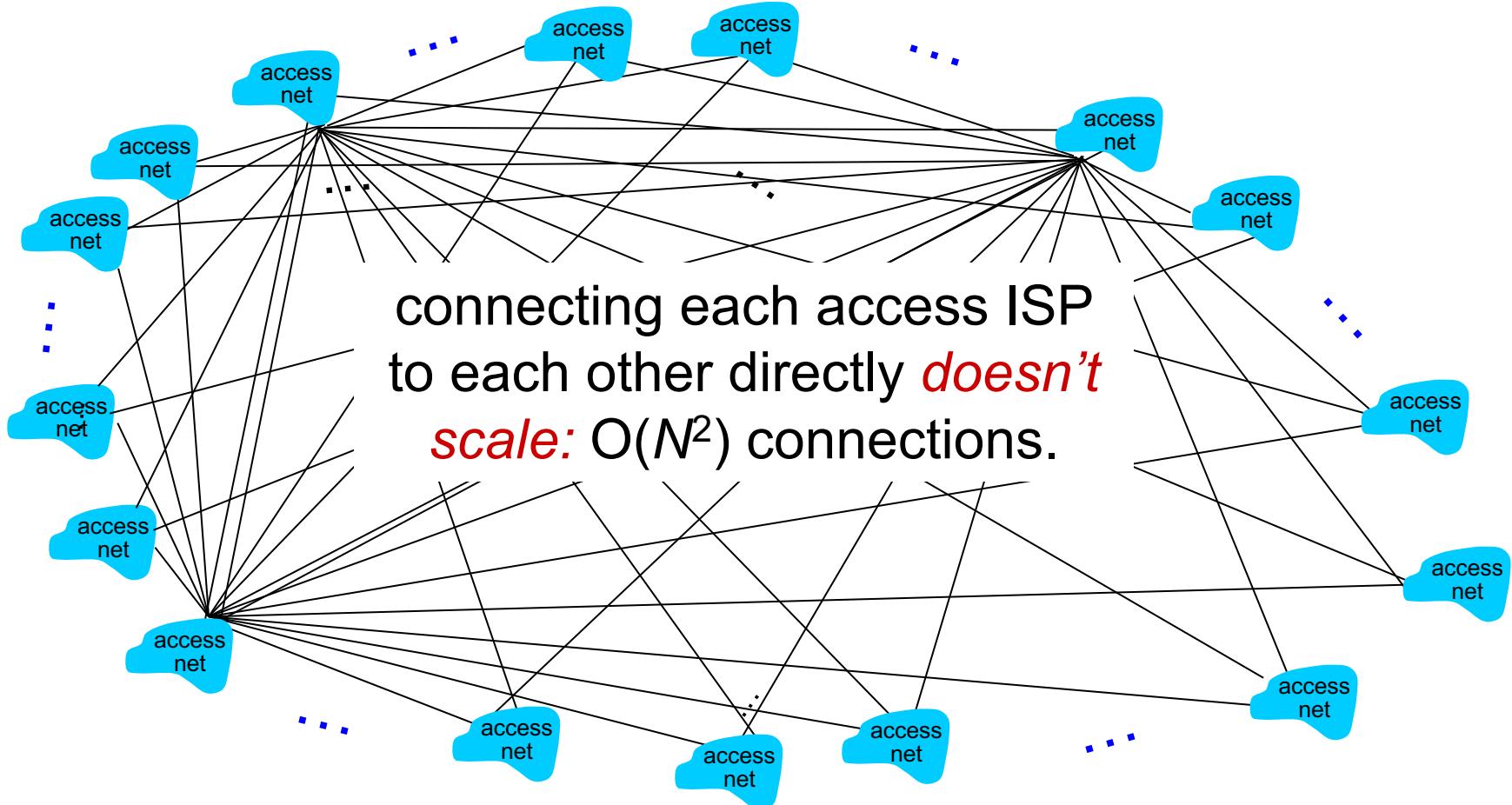
Internet structure: network of networks

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



Internet structure: network of networks

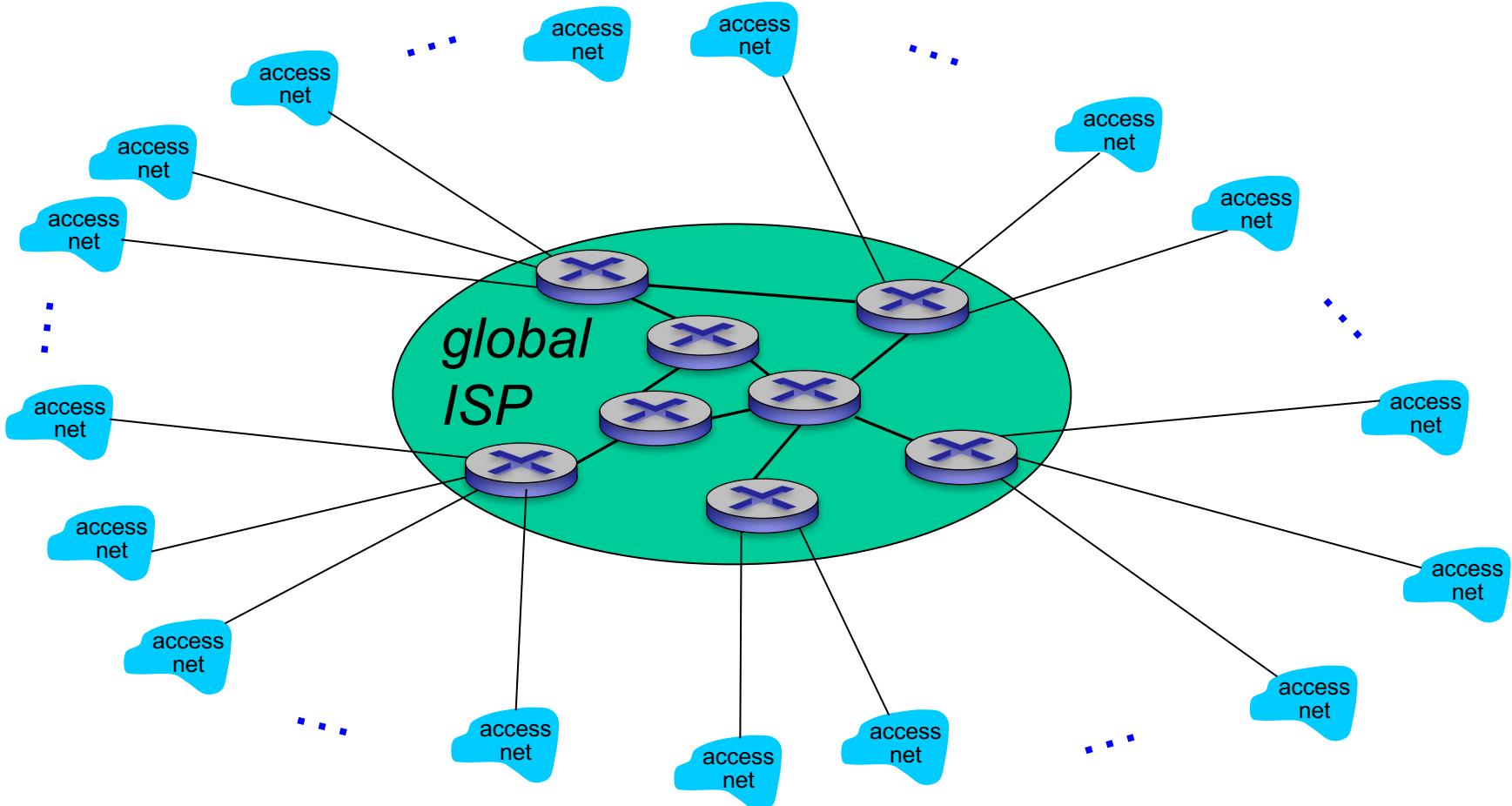
Option: connect each access ISP to every other access ISP?



Internet structure: network of networks

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

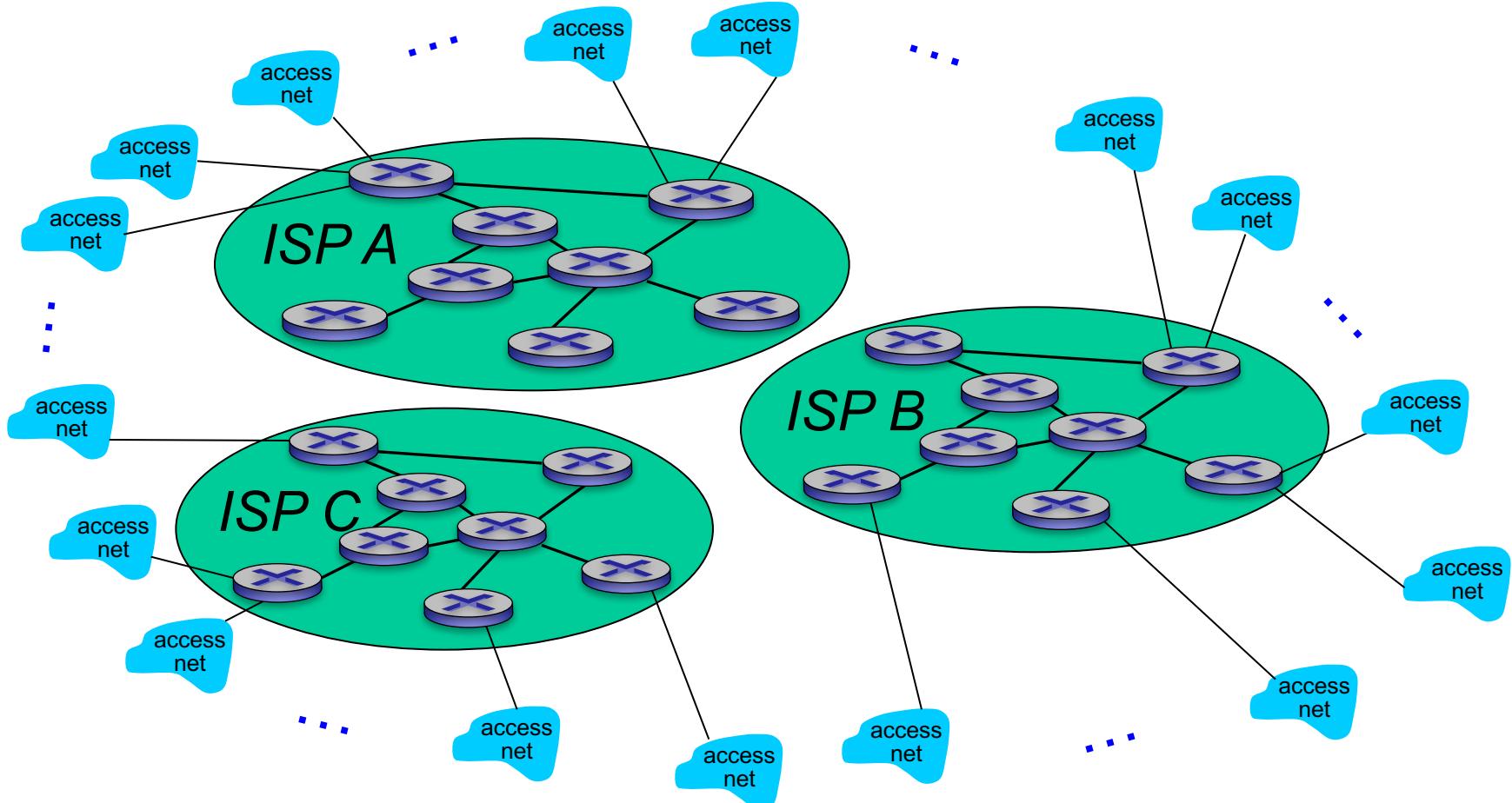
Customer and provider ISPs have economic agreement.



Internet structure: network of networks

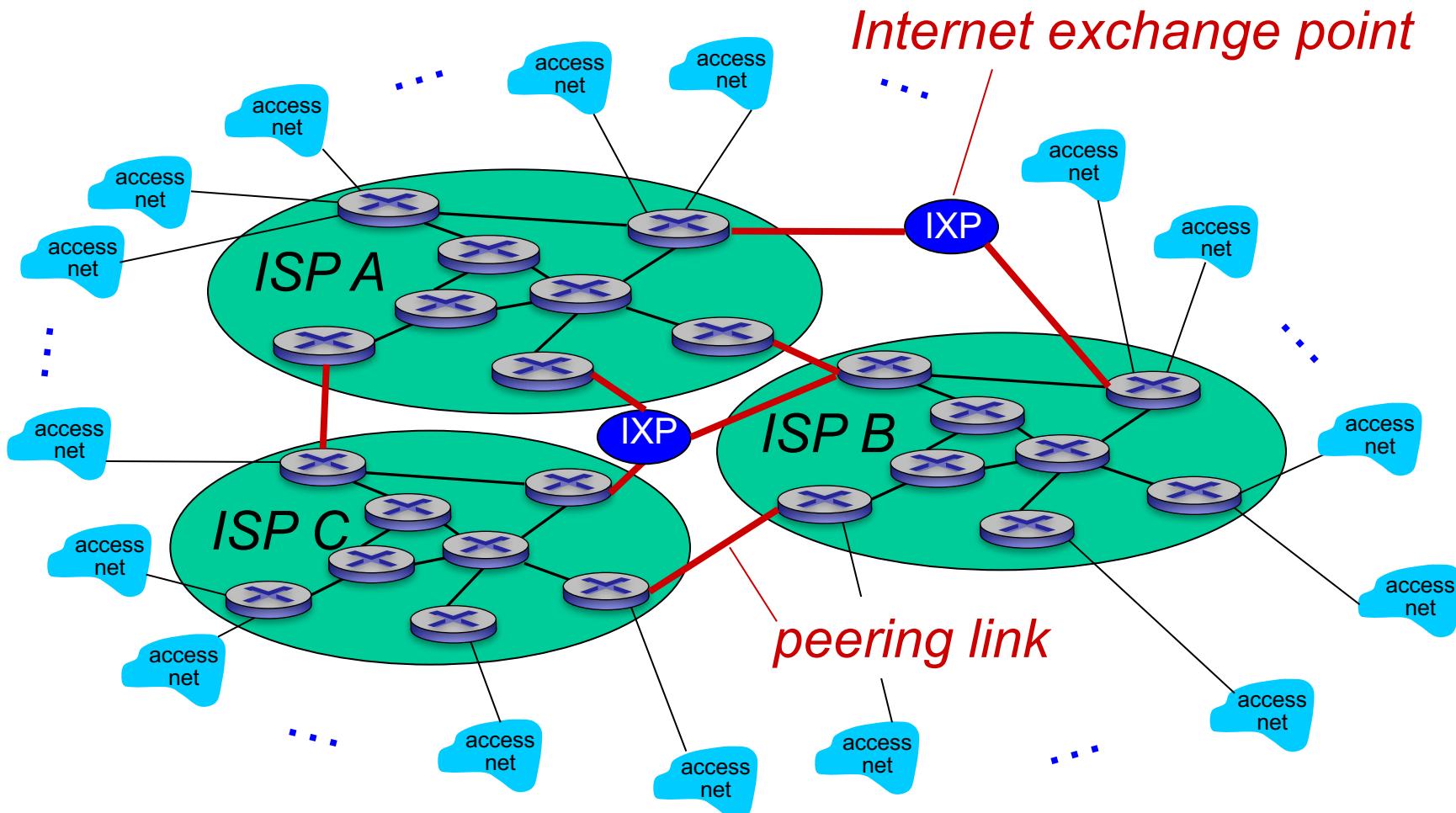
But if one global ISP is viable business, there will be competitors

....



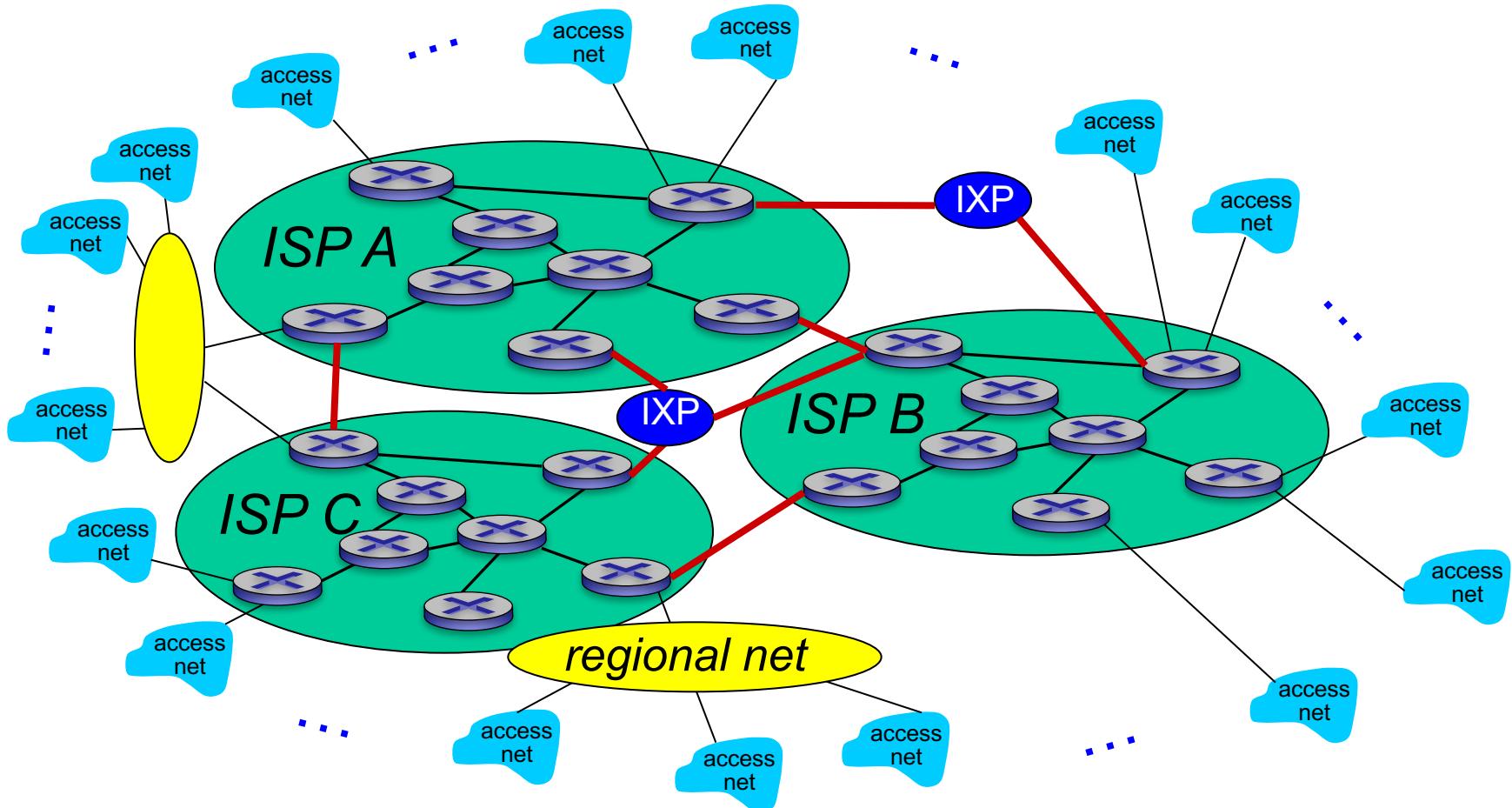
Internet structure: network of networks

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



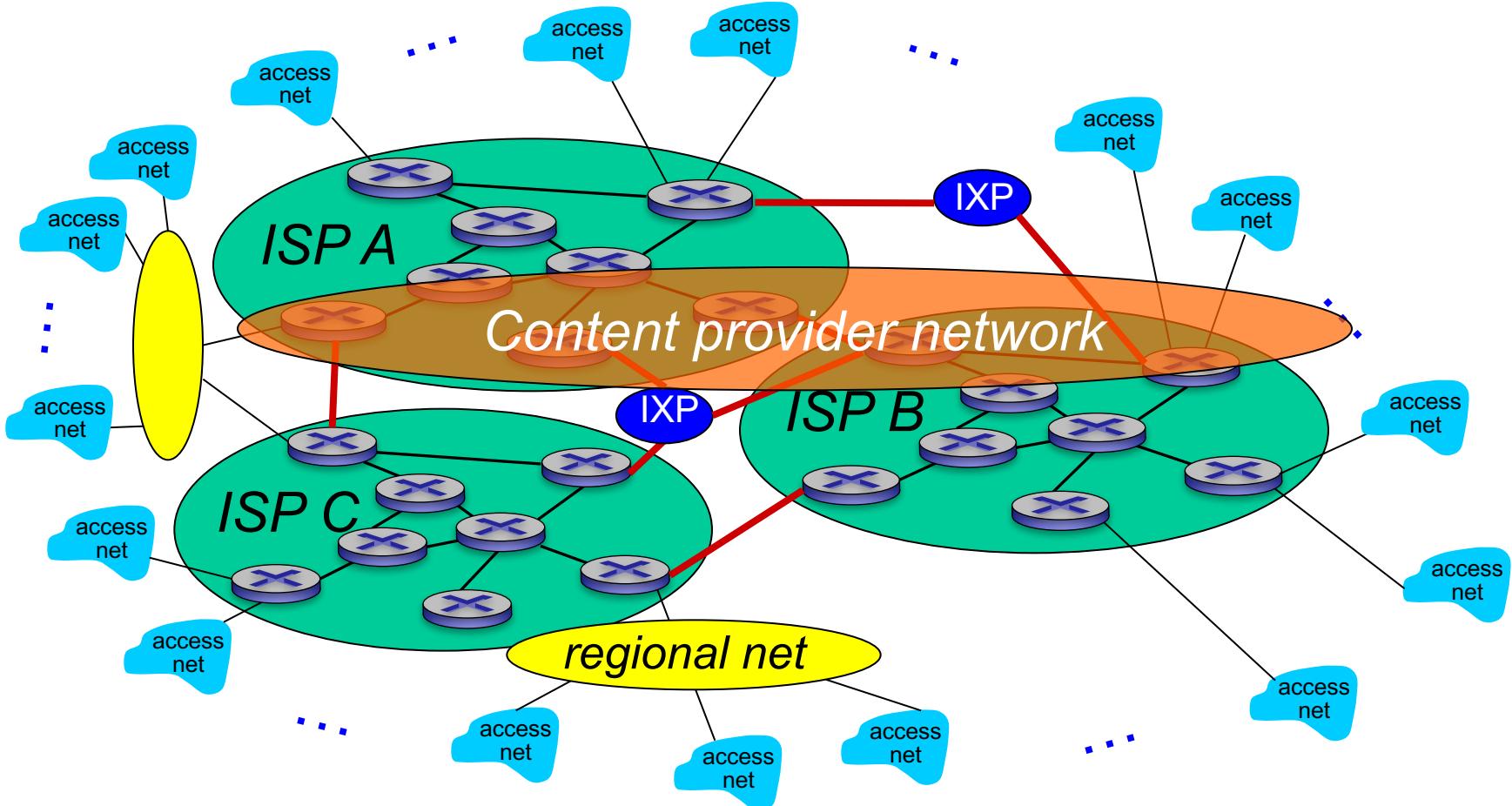
Internet structure: network of networks

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

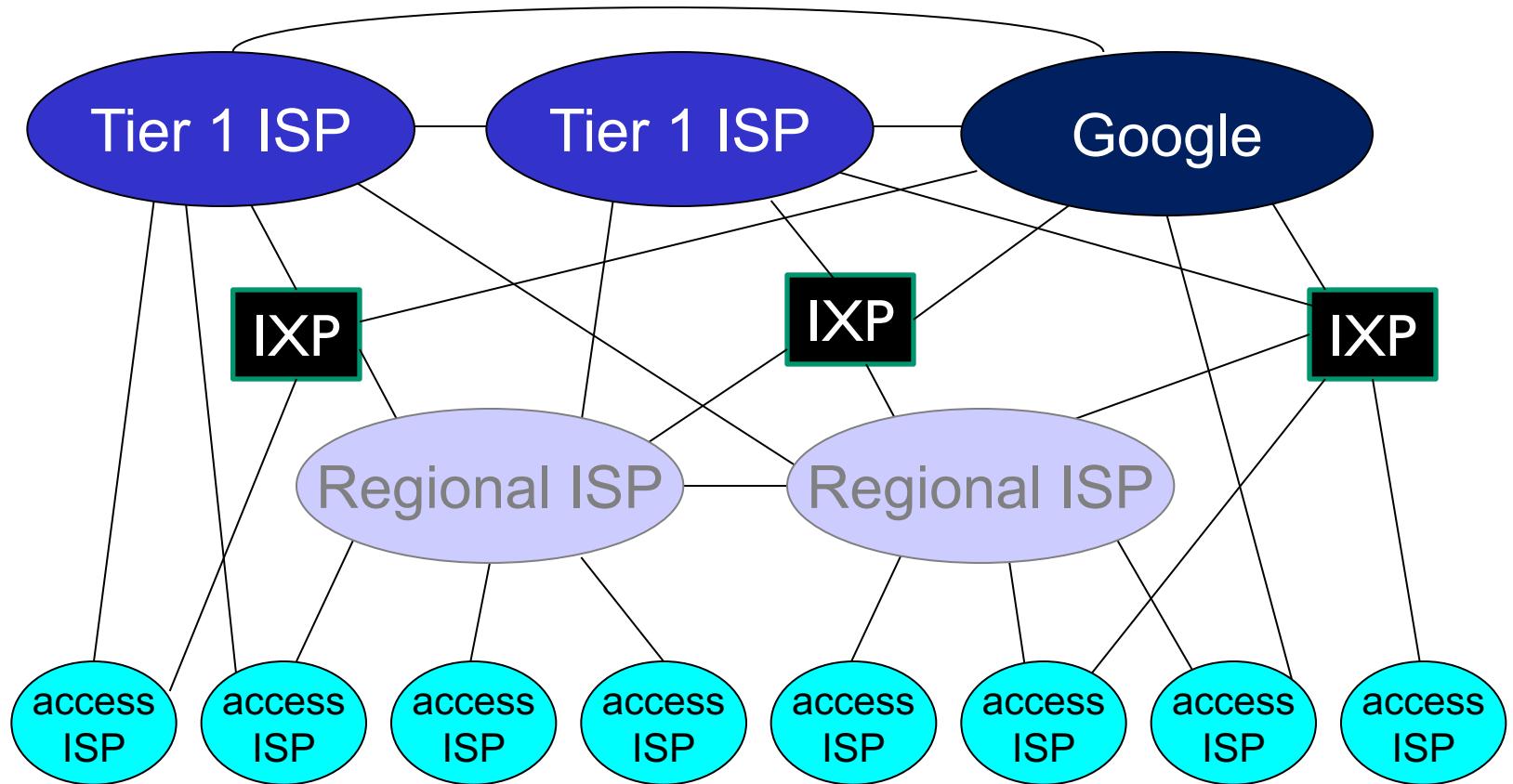


Internet structure: network of networks

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

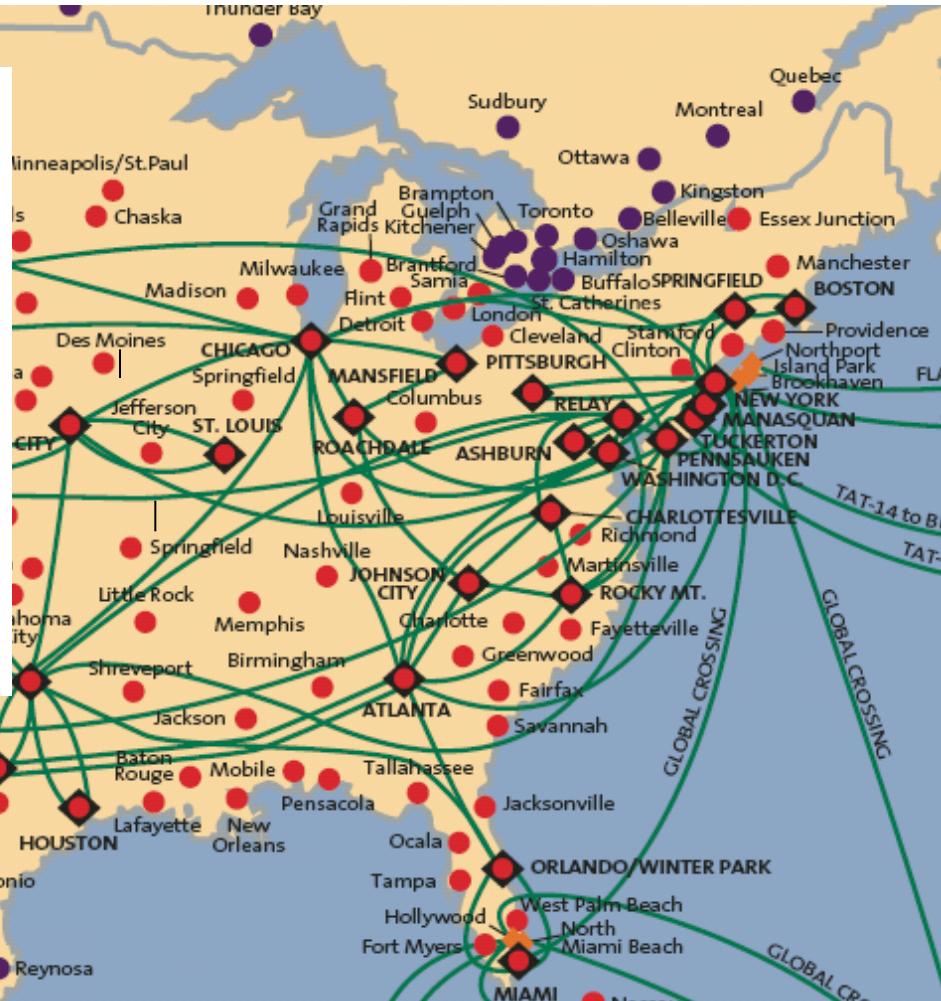
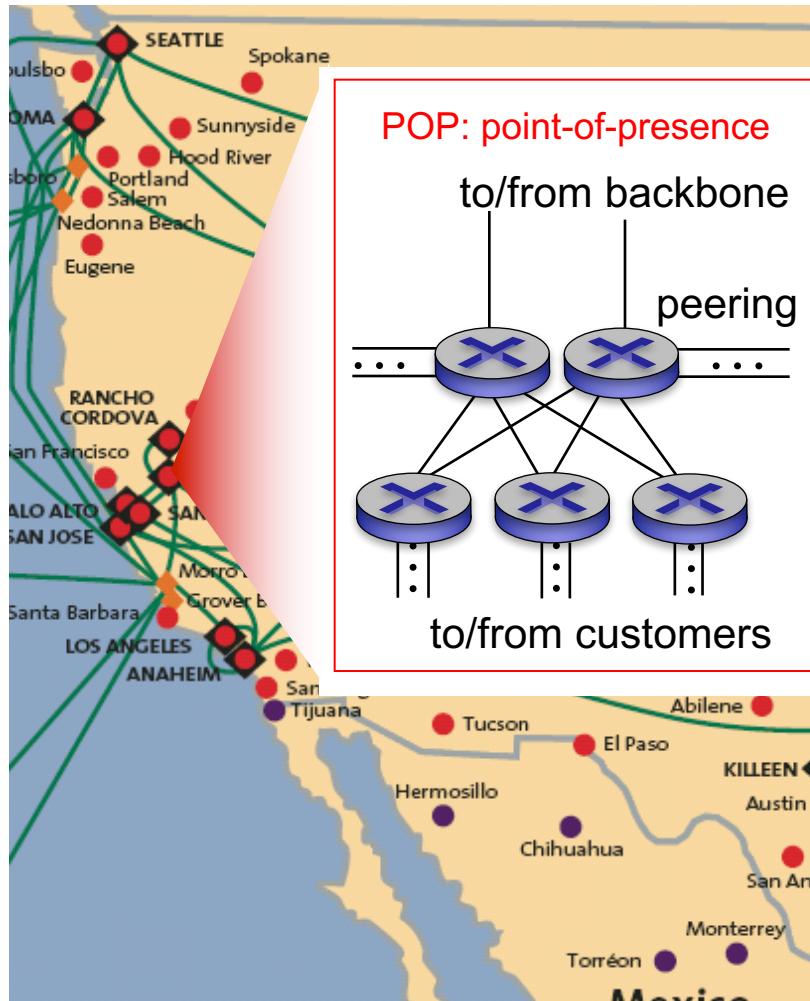


Internet structure: network of networks



- 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 its data centers to Internet, often bypassing tier-1, regional ISPs

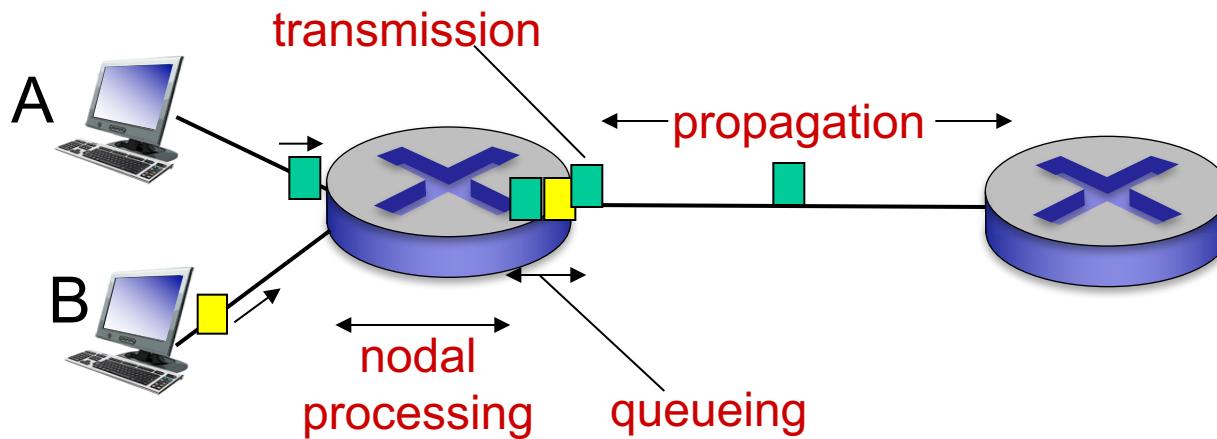
Tier-I ISP: e.g., Sprint



Network Performance

- Packet Delay
- Packet Loss
- Throughput

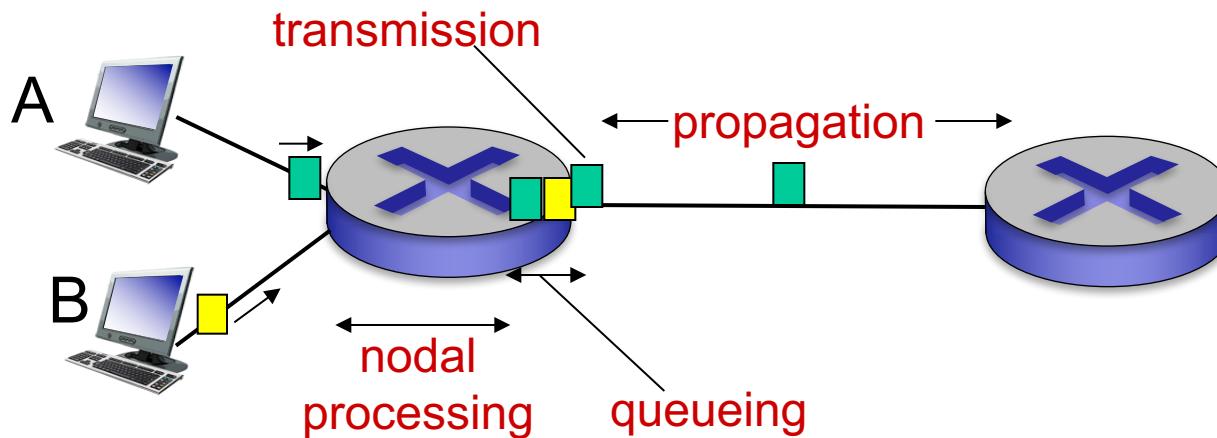
Four sources of packet delay



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

- * 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

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)
- $d_{\text{trans}} = L/R$

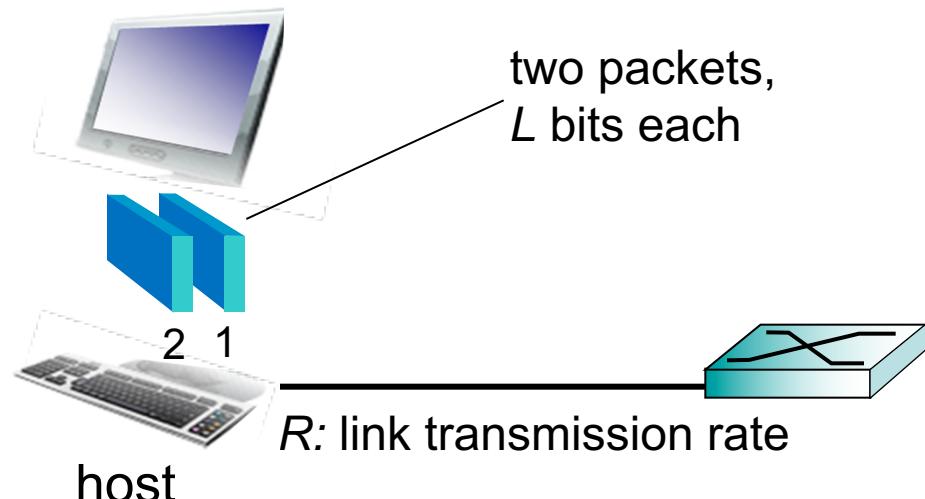
* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/interactive/

* Check out the Java applet for an interactive animation on trans vs. prop delay

Transmission Delay (d_{trans})

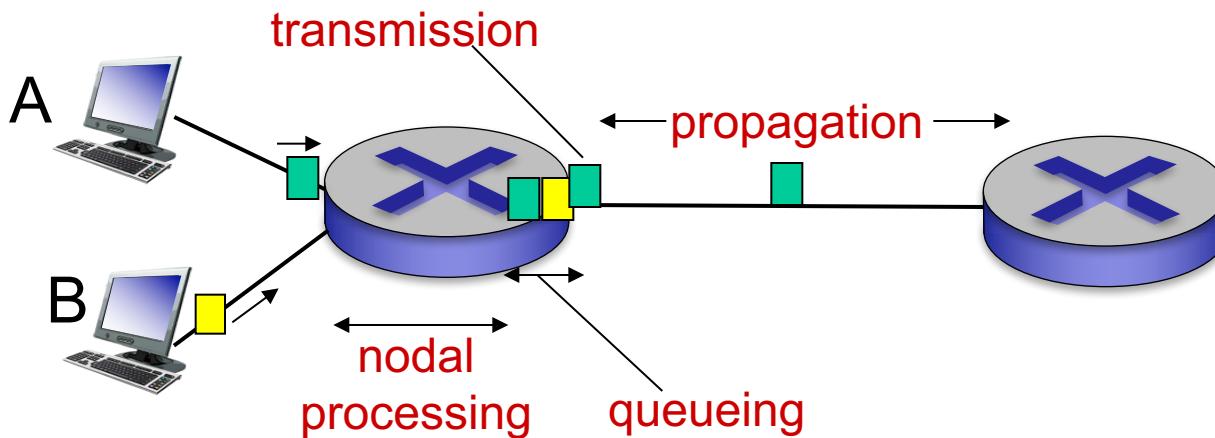
host sending function:

- 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*



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

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)
- $d_{\text{trans}} = L/R$ ← d_{trans} and d_{prop} →
very different

d_{prop} : propagation delay:

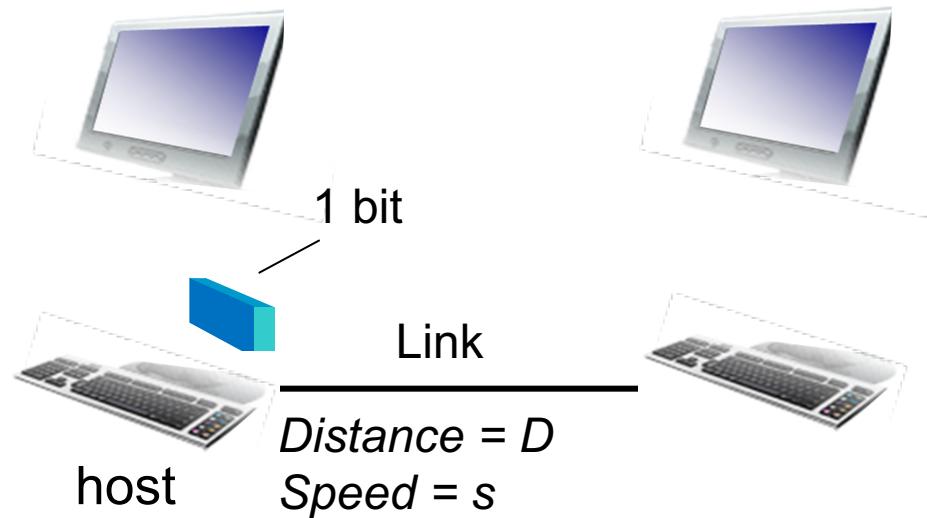
- d : length of physical link
- s : propagation speed ($\sim 2 \times 10^8$ m/sec)
- $d_{\text{prop}} = d/s$

* 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

Propagation Delay (d_{prop})

Propagation delay : Time to propagate one bit across link from source to destination

- Depends on distance (D) and
- Speed (s)
 - Depends on physical medium
 - Typically between 2×10^8 meters per second and 3×10^8 meters/sec



$$\text{Propagation delay} = \frac{\text{time needed to transmit 1-bit}}{\text{Across link}} = \frac{D \text{ (meters)}}{s \text{ (meters/sec)}}$$

Simple Example: Single Link

$$d_{\text{trans}} = L/R$$

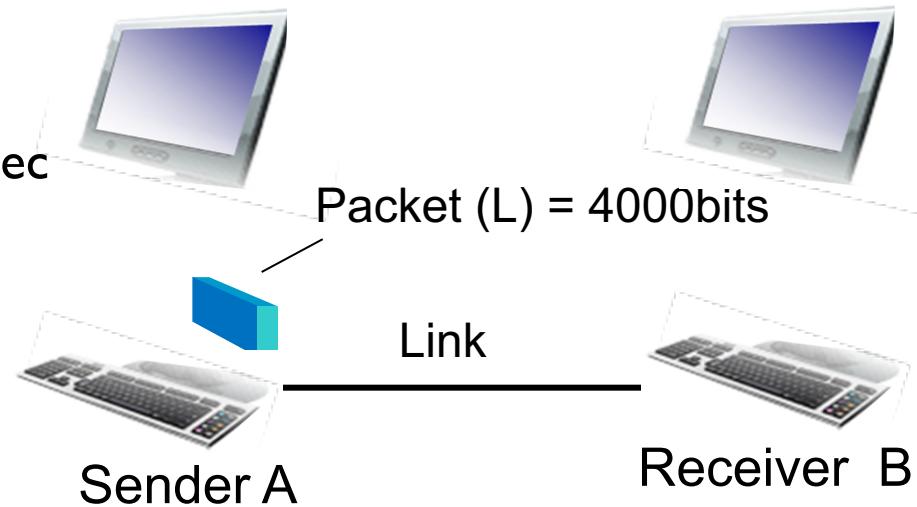
$$= 4,000 \text{ bits} / 1,000,000 \text{ bits/sec}$$

$$= 4 \text{ milliseconds}$$

$$d_{\text{prop}} = D/s$$

$$= 2.5 \times 10^6 \text{ m} / 2.5 \times 10^8 \text{ m/sec}$$

$$= 0.01 \text{ sec} = 10 \text{ ms}$$

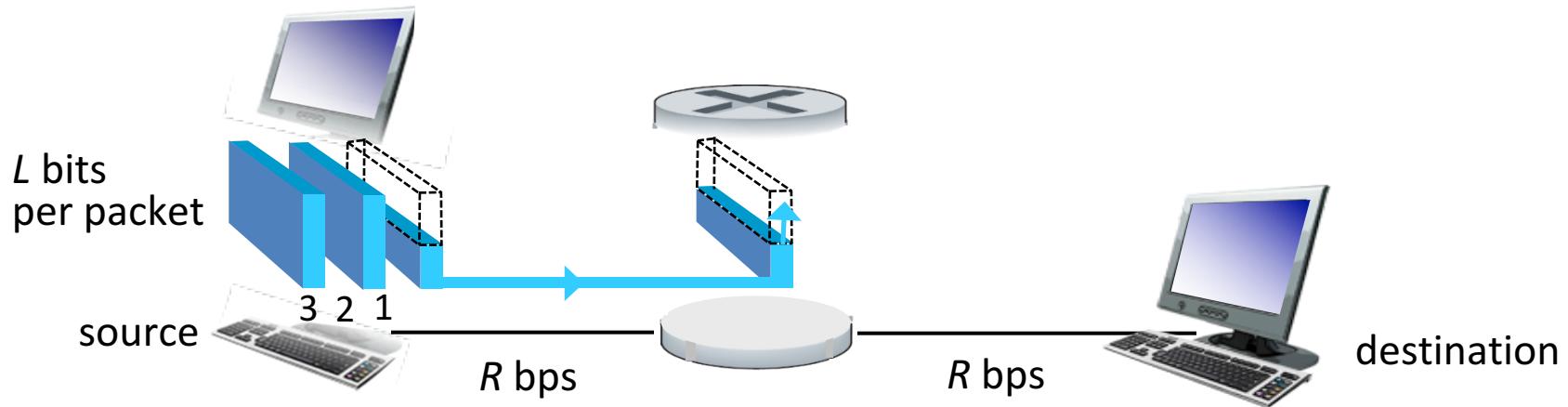


$$\text{Distance } (D) = 2500 \text{ km}$$

$$\text{Speed } (s) = 2.5 \times 10^8 \text{ m/sec}$$

$$\text{Transmission Rate } (R) = 1 \text{ Mbits/sec}$$

Transmission Delay – Multiple Links

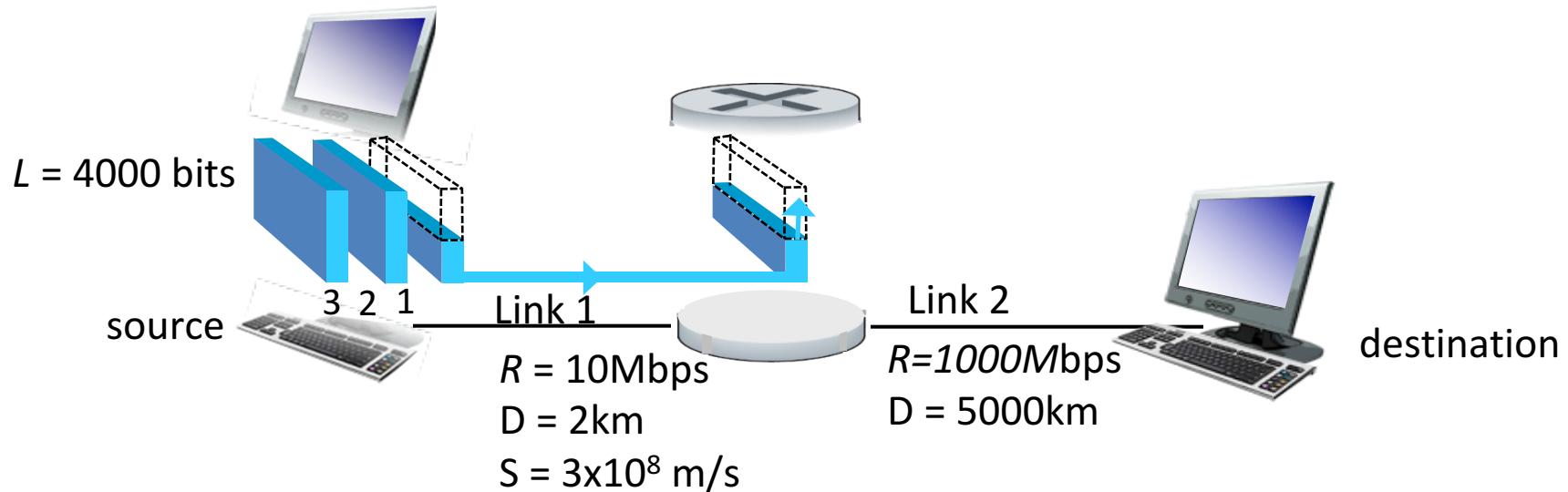


- takes L/R seconds to transmit (push out) L -bit packet into link at R bps
- **store and forward:** entire packet must arrive at router before it can be transmitted on next link
- end-end delay = $2L/R$ (assuming zero propagation delay)

one-hop numerical example:

- $L = 7.5 \text{ Mbits}$
- $R = 1.5 \text{ Mbps}$
- one-hop transmission delay = 5 sec

Simple Example: Multiple Links



Link 1:

$$\begin{aligned}d_{\text{trans}} &= L/R \\&= 4,000 \text{ bits} / 10 \text{ Mbits/sec} \\&= 0.4 \text{ milliseconds}\end{aligned}$$

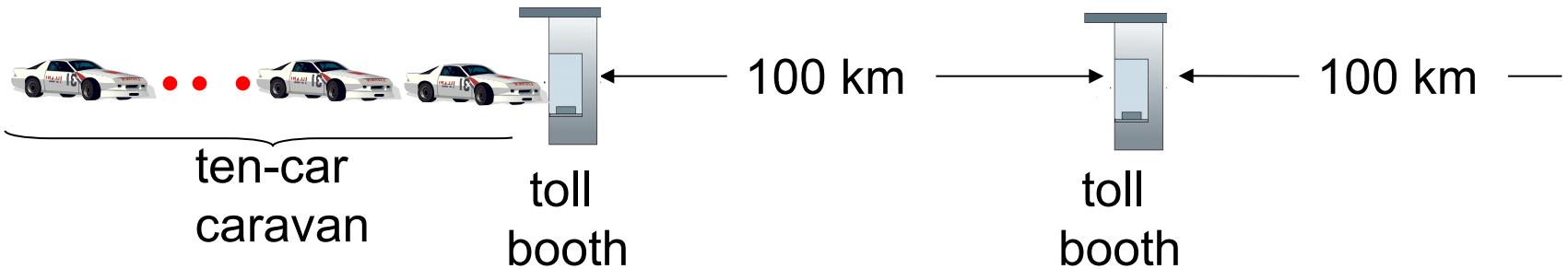
$$\begin{aligned}d_{\text{prop}} &= D/s \\&= 2 \times 10^3 \text{ m} / 3 \times 10^8 \text{ m/sec} \\&= 0.00667 \text{ msec}\end{aligned}$$

Link 2:

$$\begin{aligned}d_{\text{trans}} &= L/R \\&= 4,000 \text{ bits} / 1000 \text{ Mbits/sec} \\&= 0.004 \text{ milliseconds}\end{aligned}$$

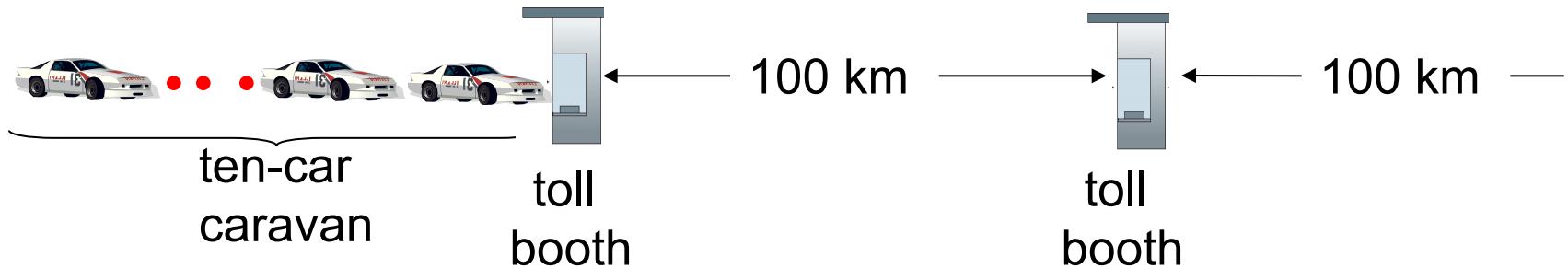
$$\begin{aligned}d_{\text{prop}} &= D/s \\&= 5 \times 10^6 \text{ m} / 3 \times 10^8 \text{ m/sec} \\&= 16.667 \text{ msec}\end{aligned}$$

Caravan analogy



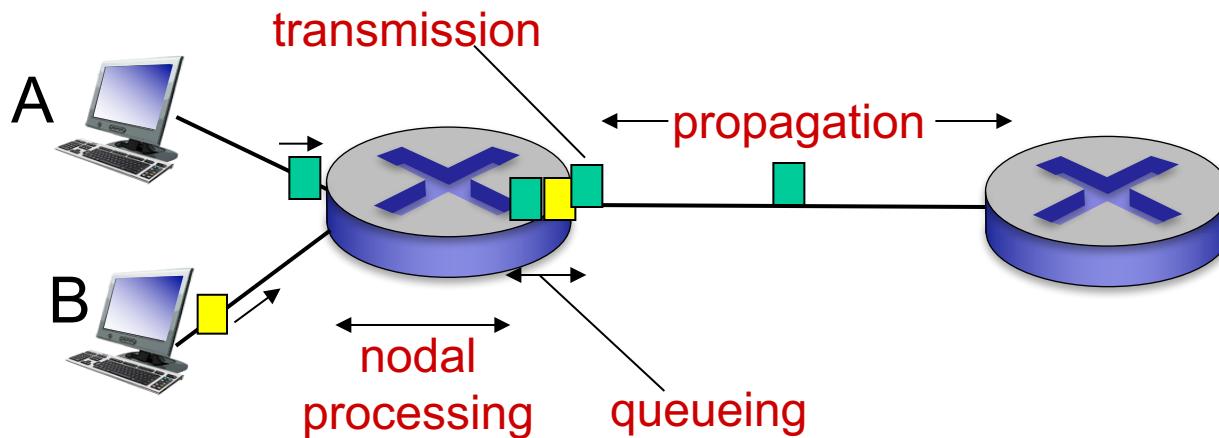
- cars “propagate” at 100 km/hr
- toll booth takes 12 sec to service car (bit transmission time)
- car ~ bit; caravan ~ packet
- Q: How long until caravan is lined up before 2nd toll booth?
A: 62 minutes
- time to “push” entire caravan through toll booth onto highway = $12*10 = 120$ sec
- time for last car to propagate from 1st to 2nd toll both:
 $100\text{km}/(100\text{km/hr})= 1\text{ hr}$

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 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

Four sources of packet delay



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

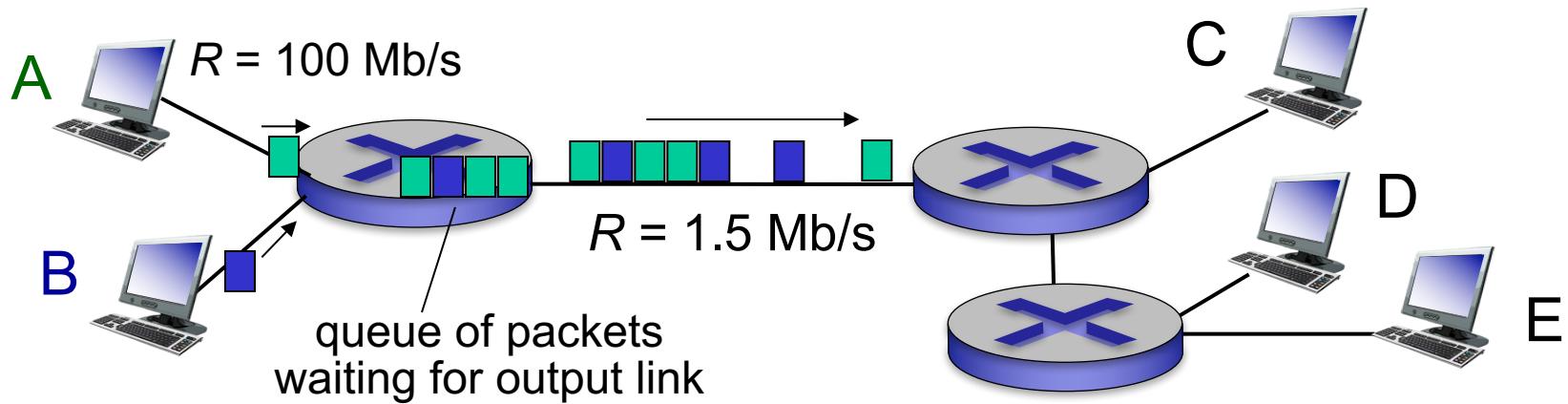
d_{proc} : nodal processing

- 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 Switching: queueing delay, loss



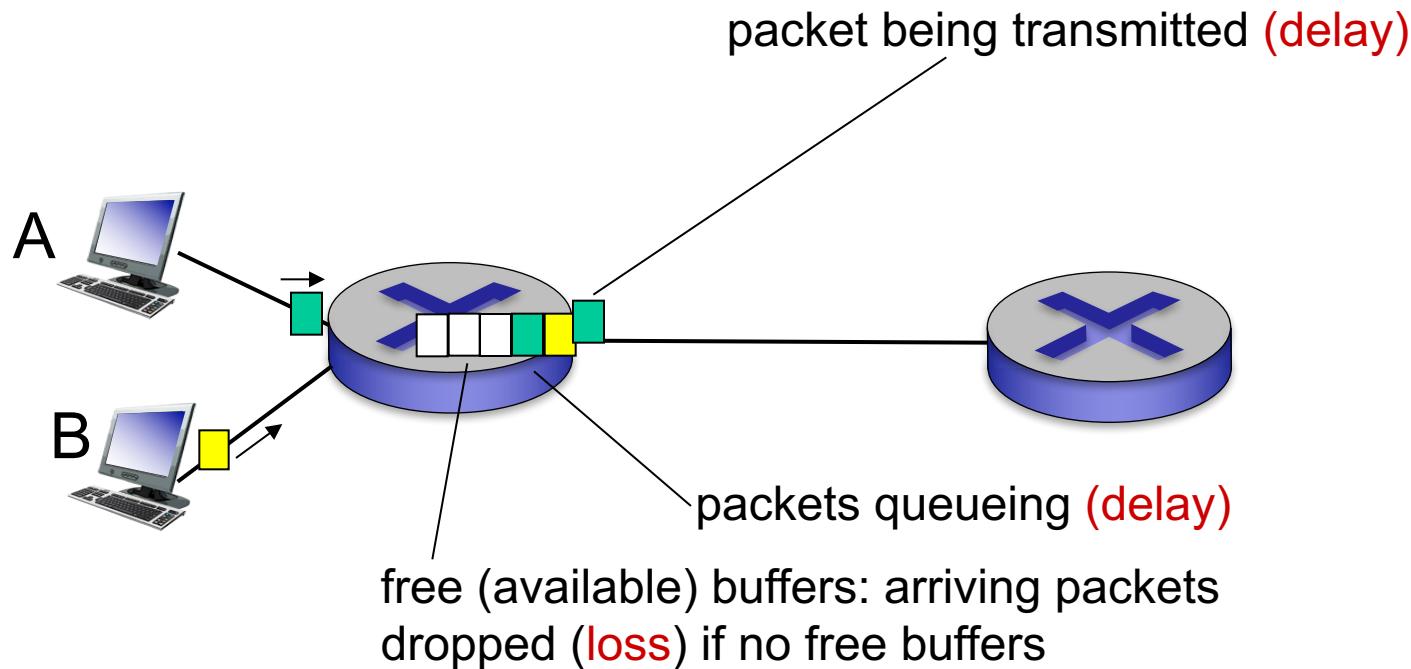
queuing and loss:

- 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

How do loss and other delays occur?

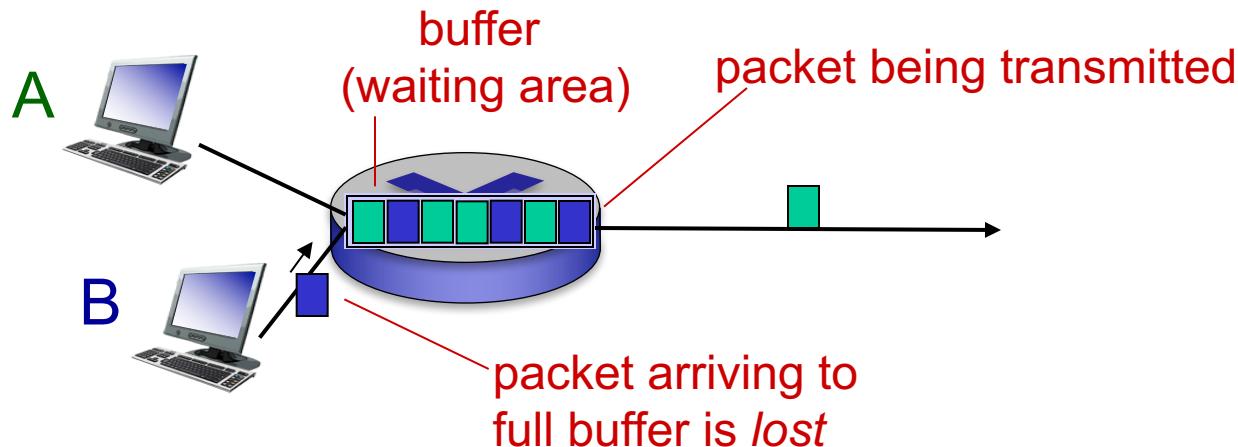
packets queue in router buffers

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



Packet loss

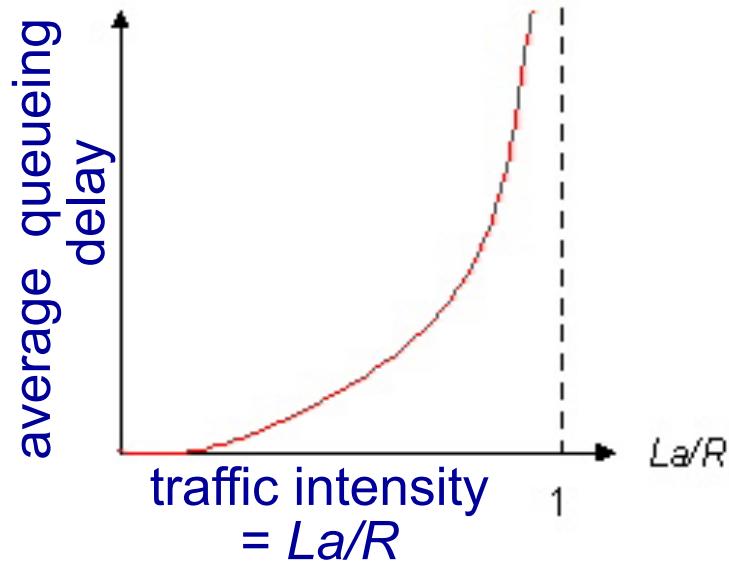
- queue (aka buffer) preceding link in buffer has finite capacity
- packet arriving to full queue dropped (aka lost)
- lost packet may be retransmitted by previous node, by source end system, or not at all



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

Queueing delay (revisited)

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



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



$La/R \sim 0$



$La/R \rightarrow 1$

Processing Delay (d_{proc})

- Time for packet processing in node
- In routers, includes time to examine IP header and make a forwarding decision (where to send the packet next)
 - Typically order of microseconds or less

Network Performance

End-to-end Delay

- Total Nodal Delay = processing delay + queuing delay + transmission delay + propagation delay

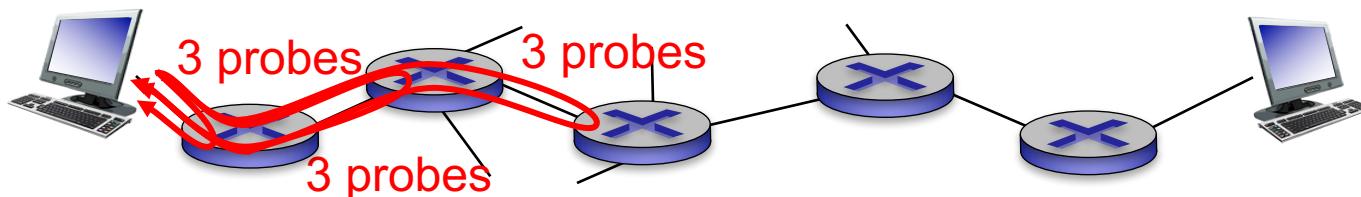
$$d_{nodal} = d_{proc} + d_{queue} + d_{trans} + d_{prop}$$

- For $n-1$ routers on homogenous path and negligible queuing, end-to-end delay is:

$$d_{end-to-end} = N(d_{proc} + d_{trans} + d_{prop})$$

“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

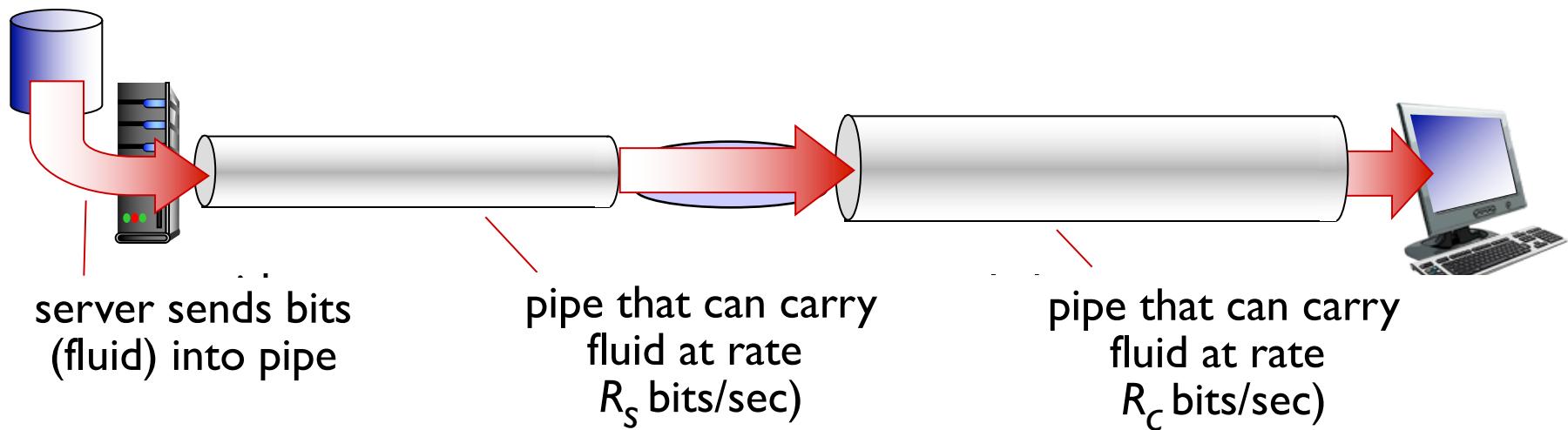
1	cs-gw (128.119.240.254)	1 ms	1 ms	2 ms
2	border1-rt-fa5-1-0.gw.umass.edu (128.119.3.145)	1 ms	1 ms	2 ms
3	cht-vbns.gw.umass.edu (128.119.3.130)	6 ms	5 ms	5 ms
4	jn1-at1-0-0-19.wor.vbns.net (204.147.132.129)	16 ms	11 ms	13 ms
5	jn1-so7-0-0-0.wae.vbns.net (204.147.136.136)	21 ms	18 ms	18 ms
6	abilene-vbns.abilene.ucaid.edu (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	***	* means no response (probe lost, router not replying)		
19	fantasia.eurecom.fr (193.55.113.142)	132 ms	128 ms	136 ms

trans-oceanic link

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

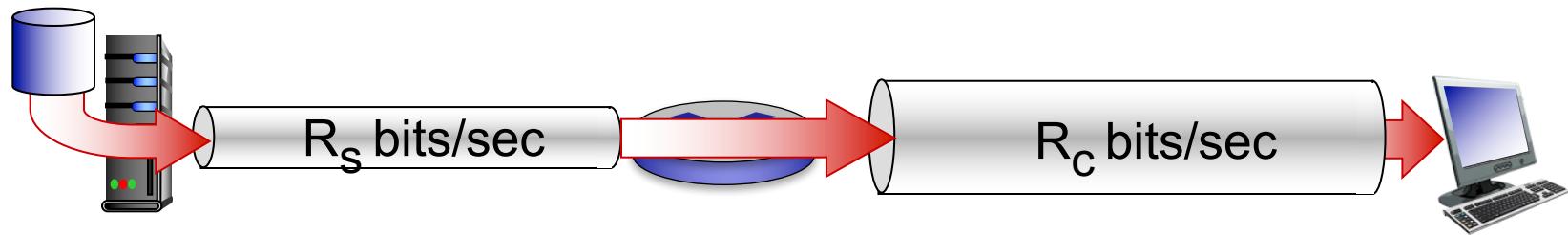
Throughput

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

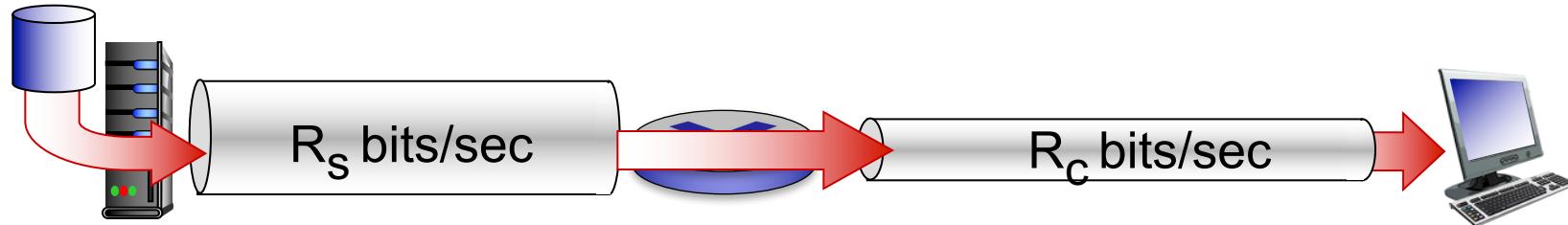


Throughput (more)

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



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

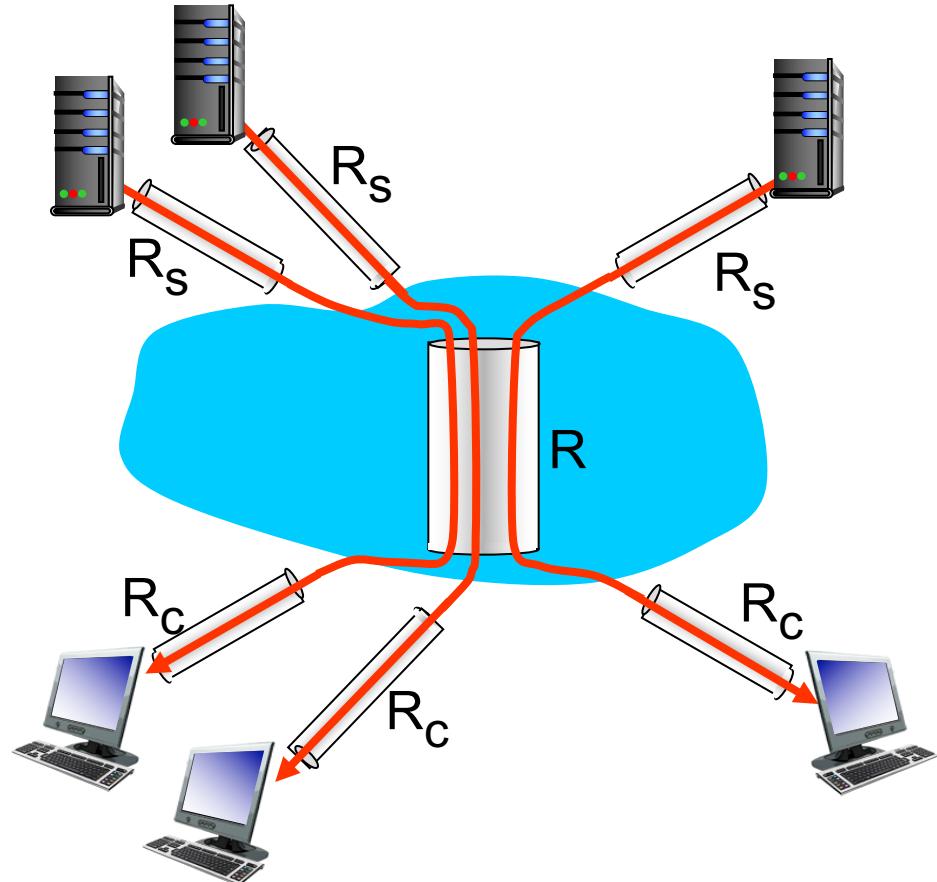


bottleneck link

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



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