

Chapter I

Introduction

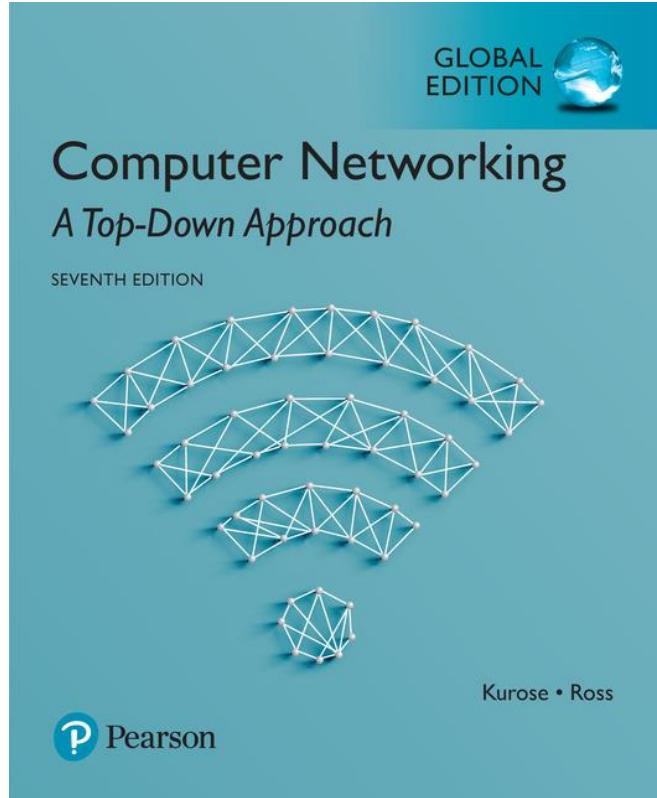
A note on the use of these ppt slides:

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*

Chapter I: introduction

our goal:

- ❖ get “feel” and terminology
- ❖ more depth, detail *later in course*
- ❖ approach:
 - use Internet as example

overview:

- ❖ what’s the Internet?
- ❖ what’s a protocol?
- ❖ network edge; hosts, access net, physical media
- ❖ network core: packet/circuit switching, Internet structure
- ❖ performance: loss, delay, throughput
- ❖ security
- ❖ protocol layers, service models
- ❖ history

Chapter I: roadmap

I.1 what *is* the Internet?

I.2 network edge

- end systems, access networks, links

I.3 network core

- packet switching, circuit switching, network structure

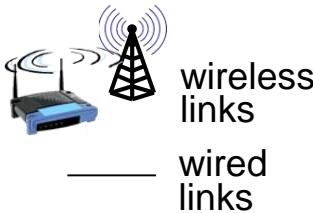
I.4 delay, loss, throughput in networks

I.5 protocol layers, service models

I.6 networks under attack: security

I.7 history

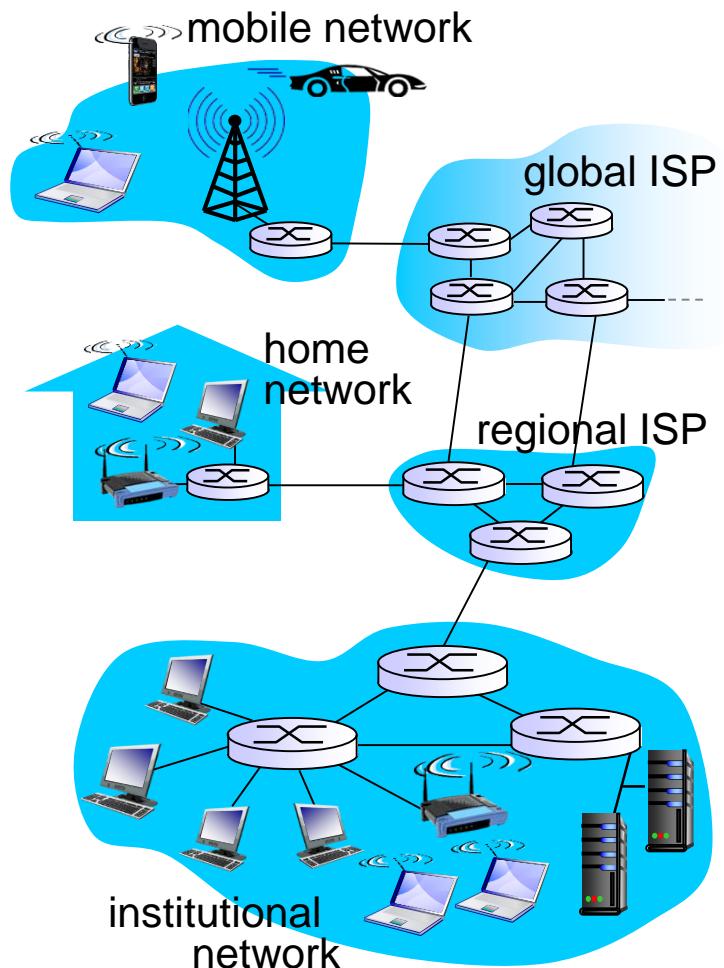
What's the Internet: “nuts and bolts” view



- ❖ millions of connected computing devices:
 - *hosts = end systems*
 - running *network apps*

- ❖ communication links
 - fiber, copper, radio, satellite
 - transmission rate: *bandwidth*

- ❖ *Packet switches: forward packets (chunks of data)*
 - *routers and switches*



“Fun” Internet-connected devices



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



Internet refrigerator



Slingbox: watch,
control cable TV remotely



sensorized,
bed
mattress



Web-enabled toaster +
weather forecaster



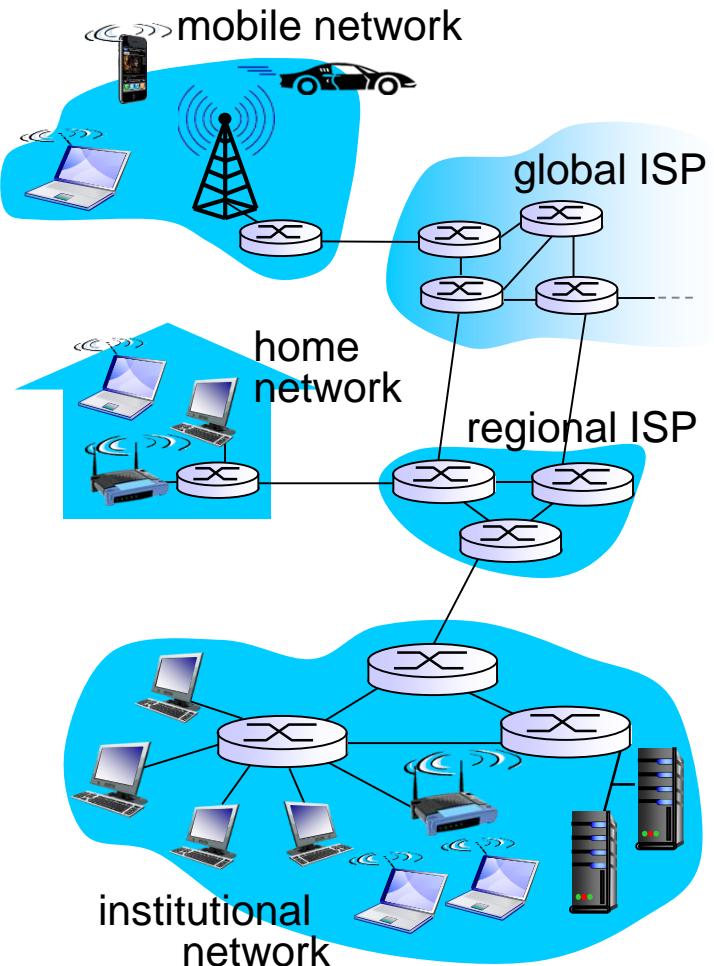
Tweet-a-watt:
monitor energy use



Internet phones

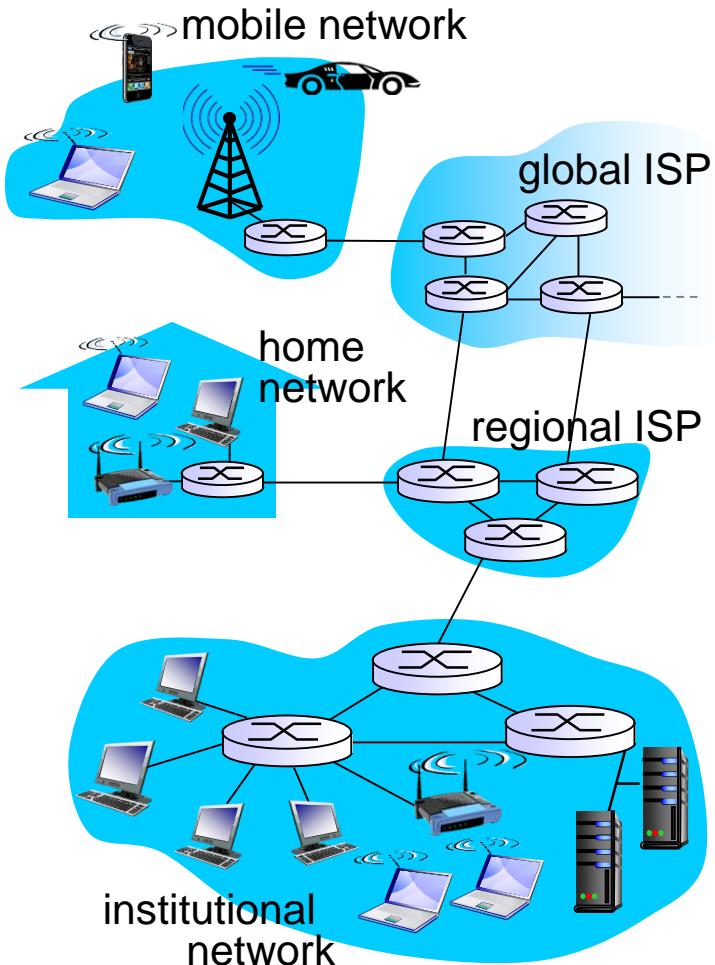
What's the Internet: “nuts and bolts” view

- ❖ *Internet: “network of networks”*
 - Interconnected ISPs
- ❖ *protocols* control sending, receiving of msgs
 - e.g., TCP, IP, HTTP, Skype, 802.11
- ❖ *Internet standards*
 - RFC: Request for comments
 - IETF: Internet Engineering Task Force



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



What's a protocol?

human protocols:

- ❖ “what’s the time?”
- ❖ “I have a question”
- ❖ introductions

... specific msgs sent

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

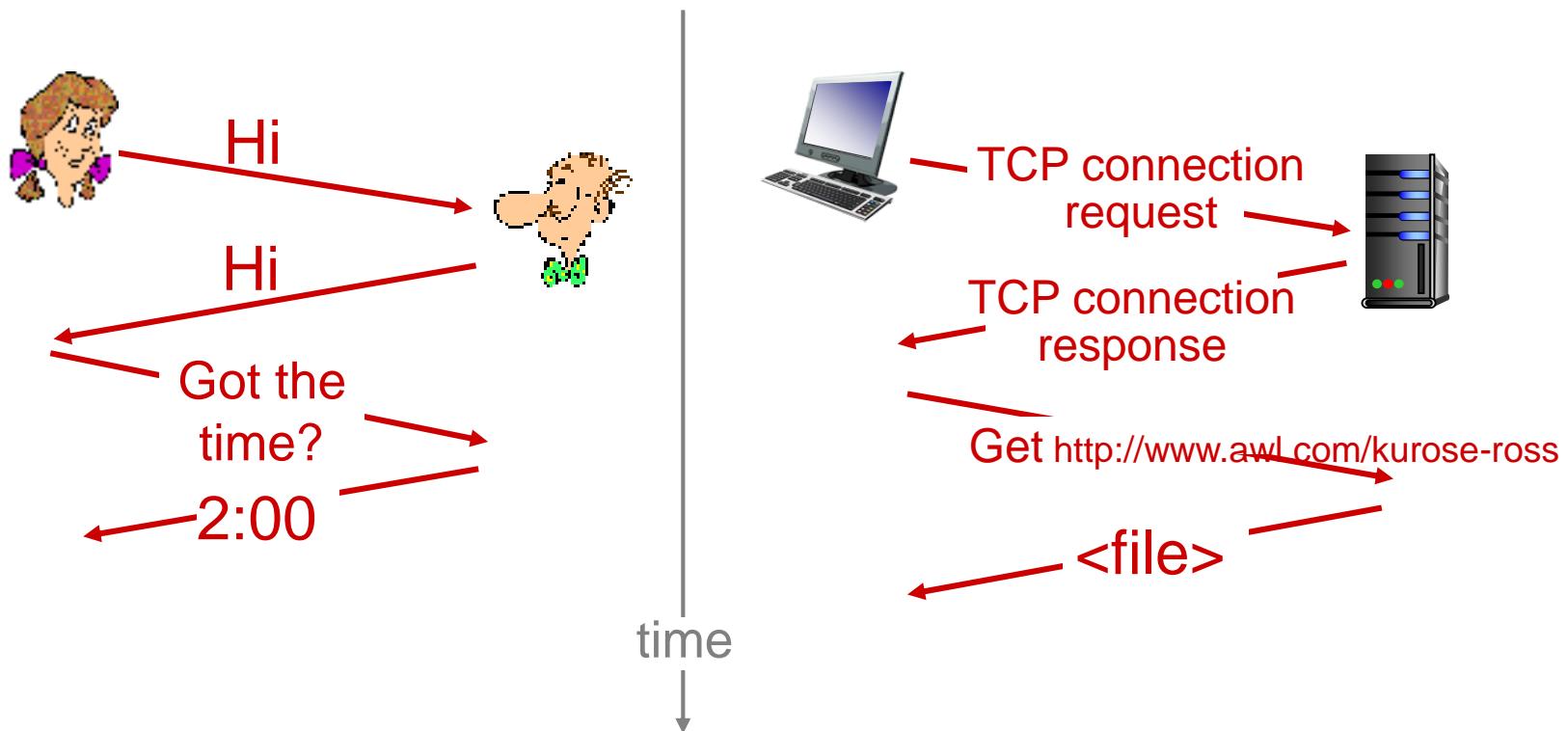
network protocols:

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

*protocols define format, order
of msgs sent and received
among network entities,
and actions taken on msg
transmission, receipt*

What's a protocol?

a human protocol and a computer network protocol:



Q: other human protocols?

Chapter I: roadmap

I.1 what *is* the Internet?

I.2 network edge

- end systems, access networks, links

I.3 network core

- packet switching, circuit switching, network structure

I.4 delay, loss, throughput in networks

I.5 protocol layers, service models

I.6 networks under attack: security

I.7 history

A closer look at network structure:

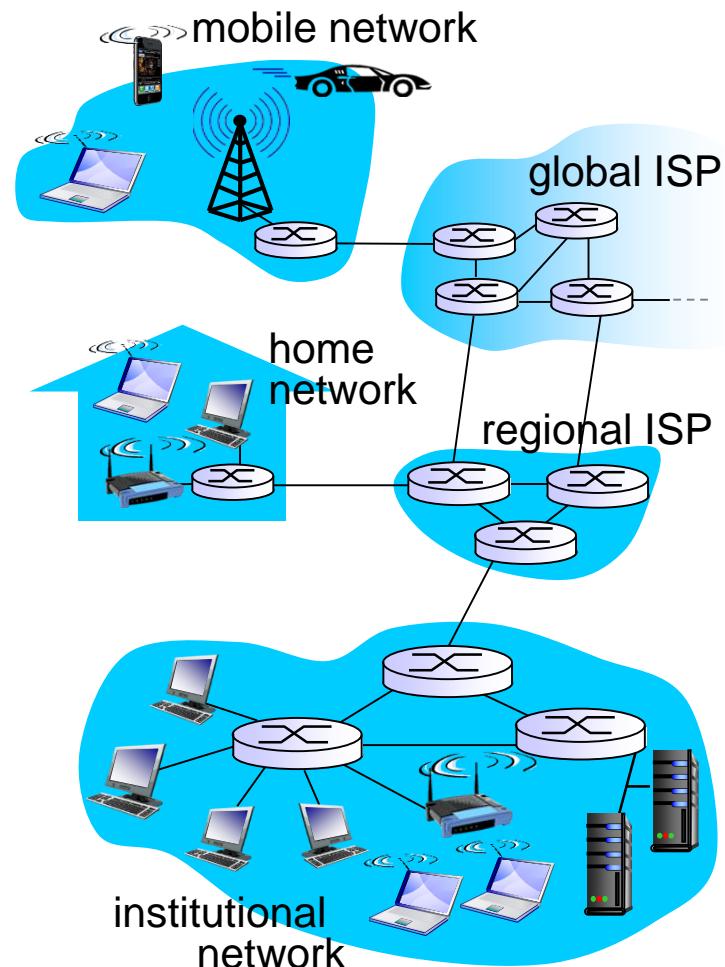
❖ *network edge:*

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

❖ *access networks, physical media:* wired, wireless communication links

❖ *network core:*

- interconnected routers
- network of networks



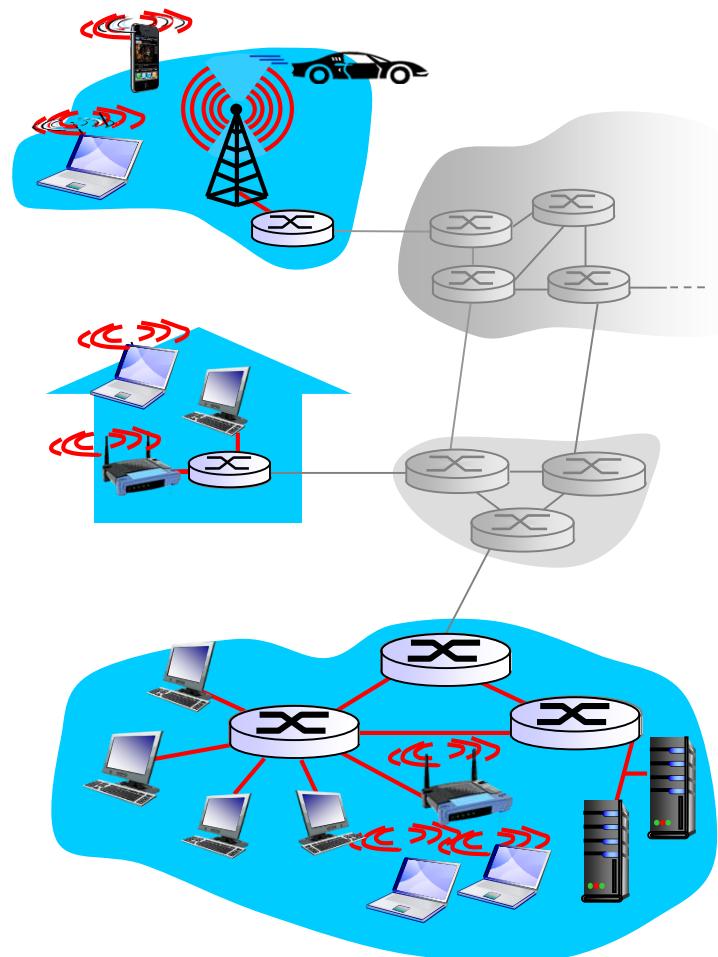
Access networks and physical media

Q: How to connect end systems to edge router?

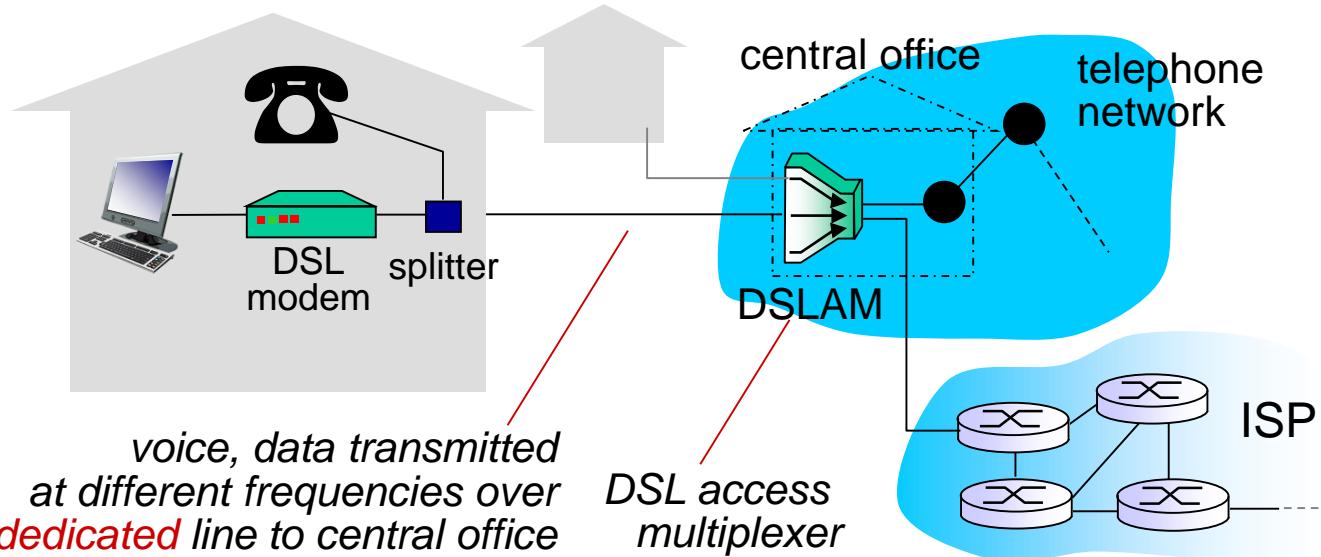
- ❖ residential access nets
- ❖ institutional access networks (school, company)
- ❖ mobile access networks

keep in mind:

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

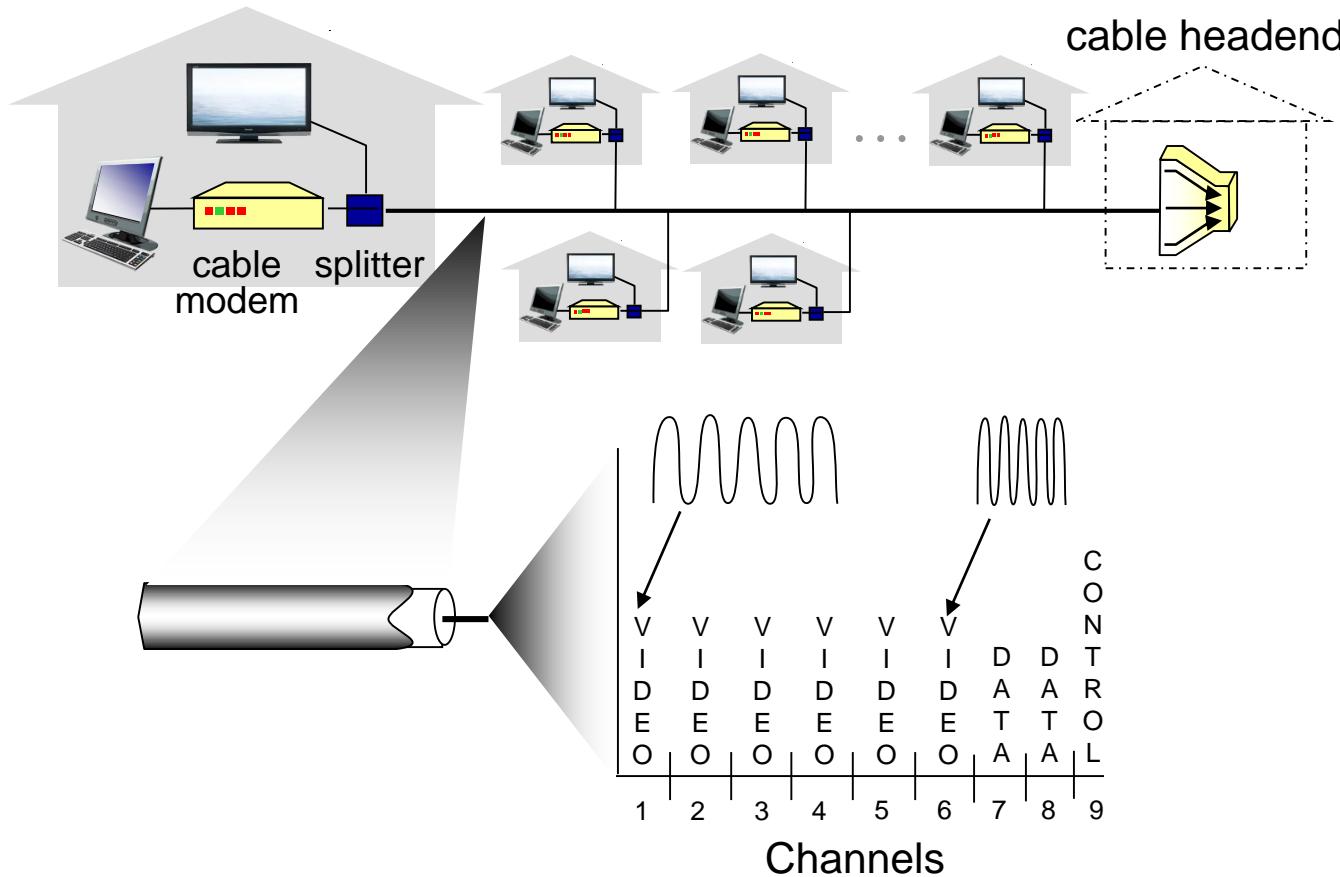


Access net: digital subscriber line (DSL)



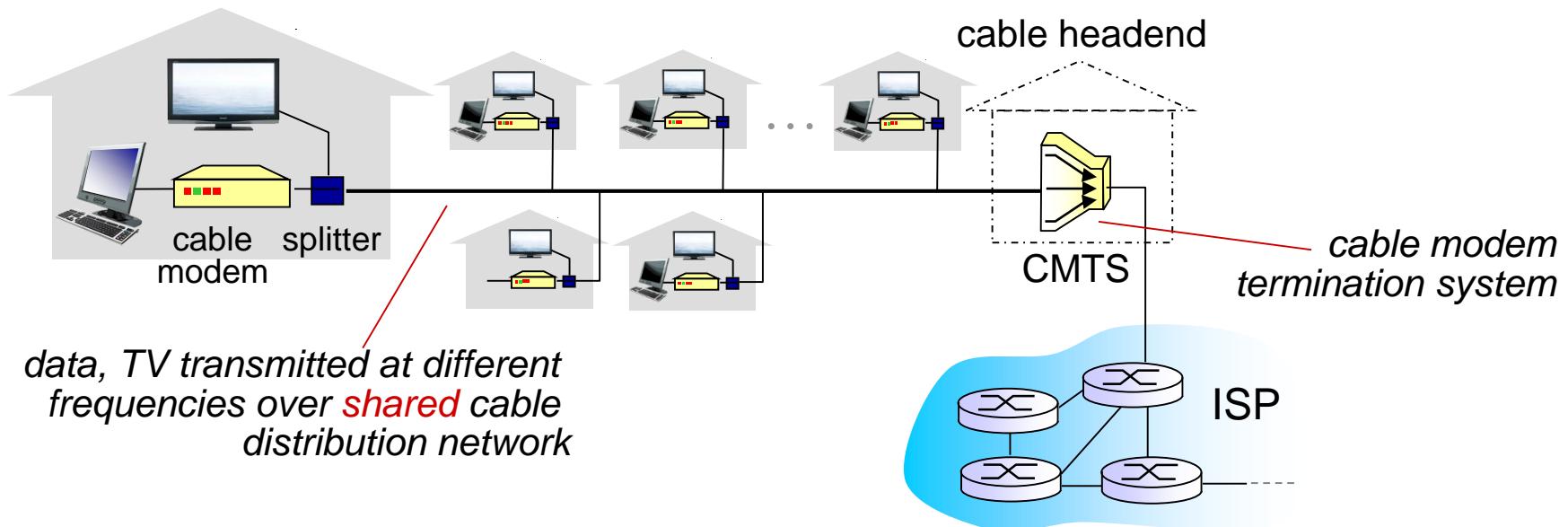
- ❖ use **existing** telephone line to central office DSLAM
 - data over DSL phone line goes to Internet
 - voice over DSL phone line goes to telephone net
- ❖ < 2.5 Mbps upstream transmission rate (typically < 1 Mbps)
- ❖ < 24 Mbps downstream transmission rate (typically < 10 Mbps)

Access net: cable network



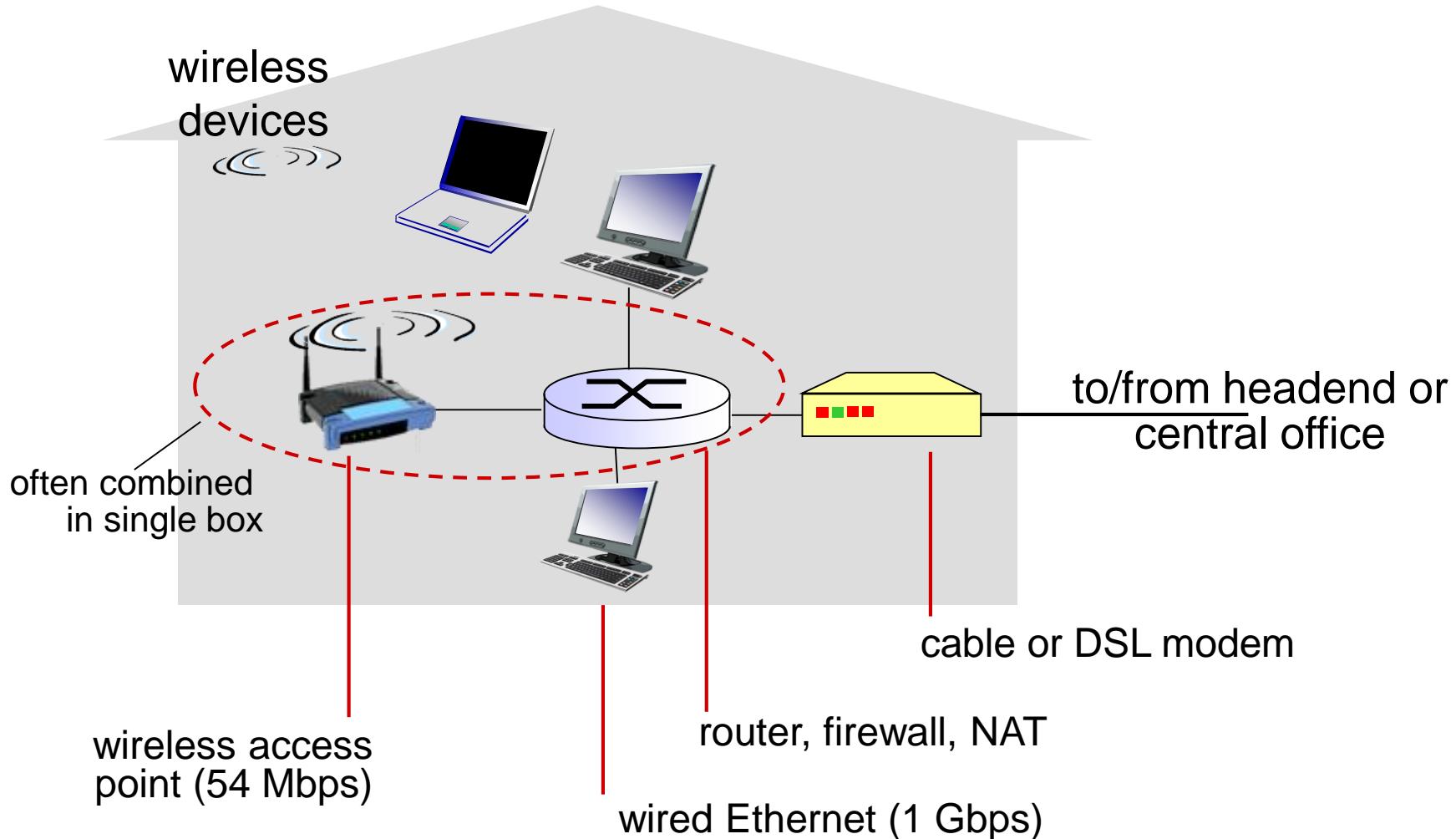
frequency division multiplexing: different channels transmitted in different frequency bands

Access net: cable network

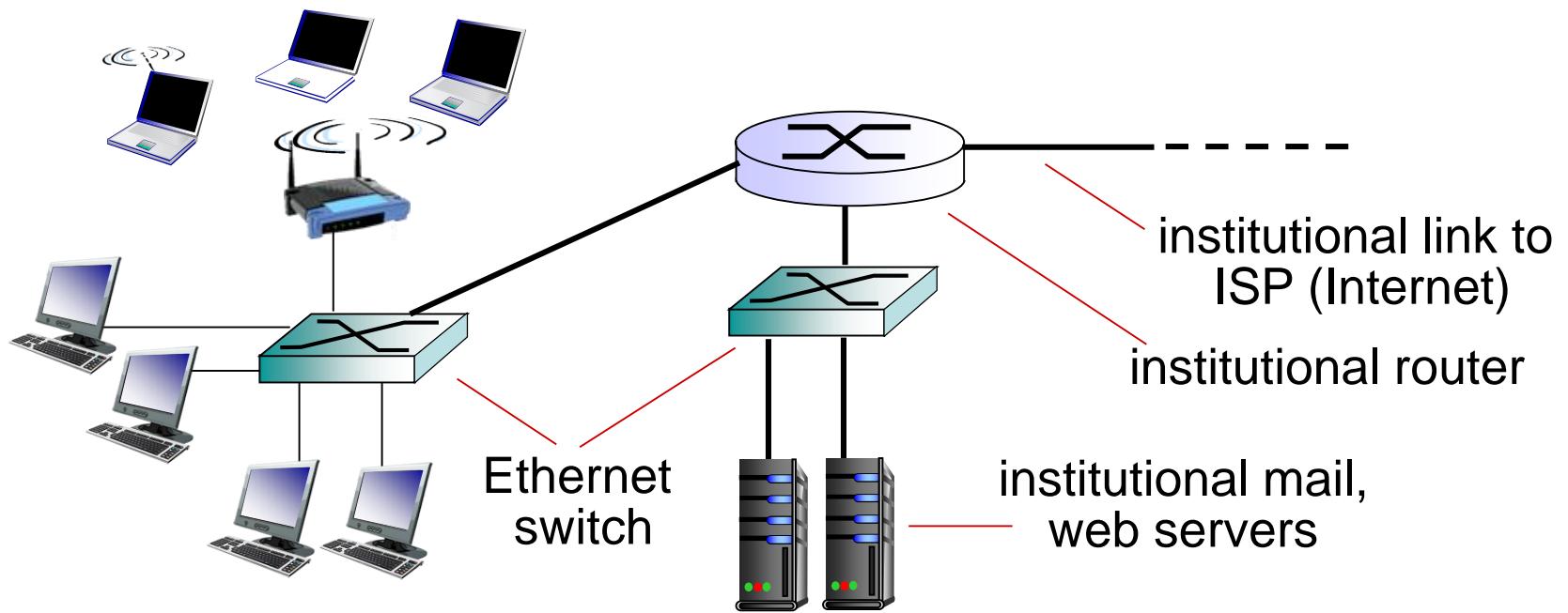


- ❖ HFC: hybrid fiber coax
 - asymmetric: up to 30Mbps downstream transmission rate, 2 Mbps upstream transmission rate
- ❖ network of cable, fiber attaches homes to ISP router
 - homes **share access network** to cable headend
 - unlike DSL, which has dedicated access to central office

Access net: home network



Enterprise access networks (Ethernet)



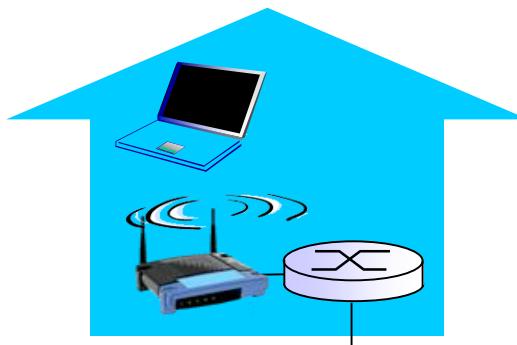
- ❖ typically used in companies, universities, etc
- ❖ 10 Mbps, 100Mbps, 1Gbps, 10Gbps transmission rates
- ❖ today, end systems typically connect into Ethernet switch

Wireless access networks

- ❖ shared wireless access network connects end system to router
 - via base station aka “access point”

wireless LANs:

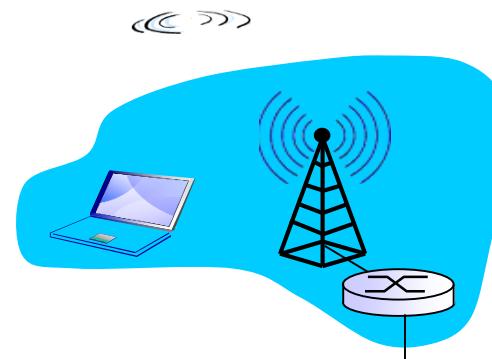
- within building (100 ft)
- 802.11b/g/n (WiFi): 11/54/450 Mbps transmission rate



to Internet

wide-area wireless access

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

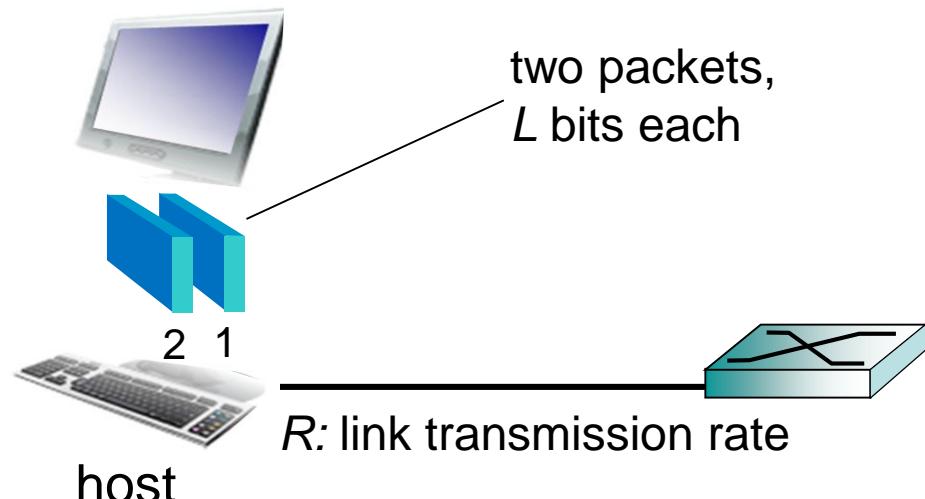


to Internet

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, aka link *capacity*, aka *link bandwidth*



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

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)
 - 11Mbps, 54 Mbps
- ❖ wide-area (e.g., cellular)
 - 3G cellular: ~ few Mbps
- ❖ satellite
 - Kbps to 45Mbps channel (or multiple smaller channels)
 - 270 msec end-end delay
 - geosynchronous versus low altitude

Chapter I: roadmap

I.1 what *is* the Internet?

I.2 network edge

- end systems, access networks, links

I.3 network core

- **packet switching, circuit switching, network structure**

I.4 delay, loss, throughput in networks

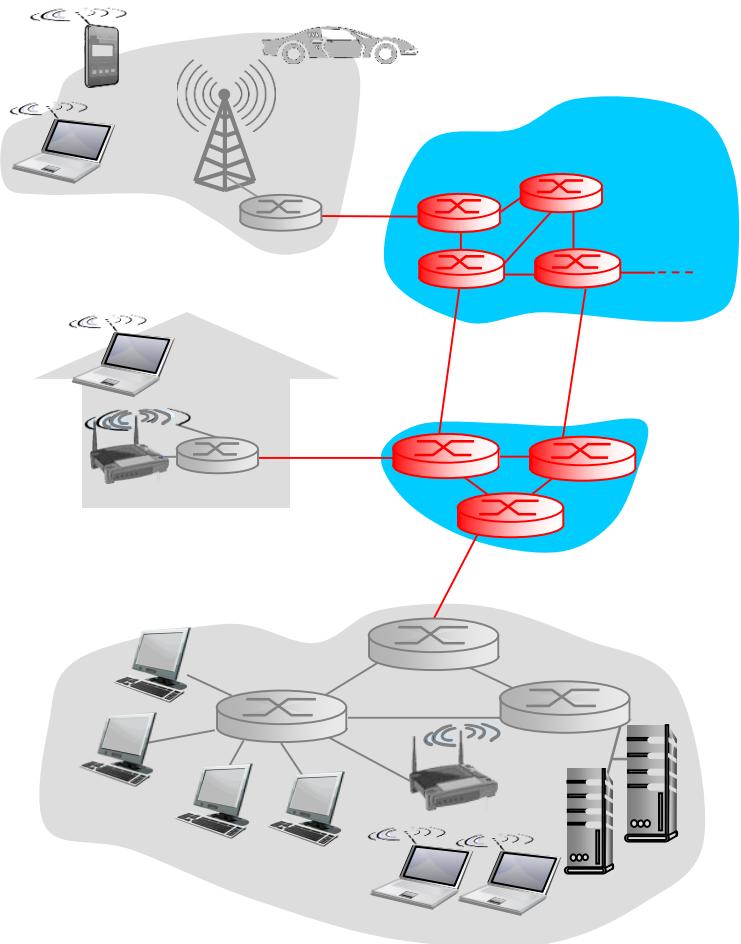
I.5 protocol layers, service models

I.6 networks under attack: security

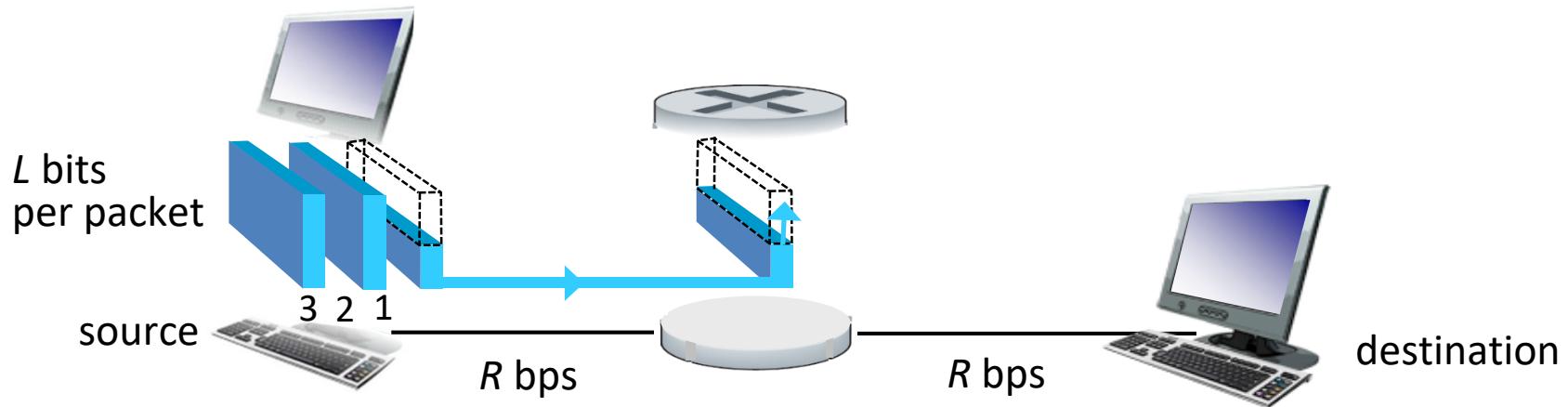
I.7 history

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



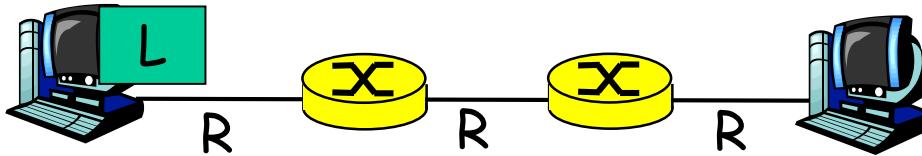
Packet-switching: store-and-forward



- ❖ 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 = 5 sec
- } more on delay shortly ...

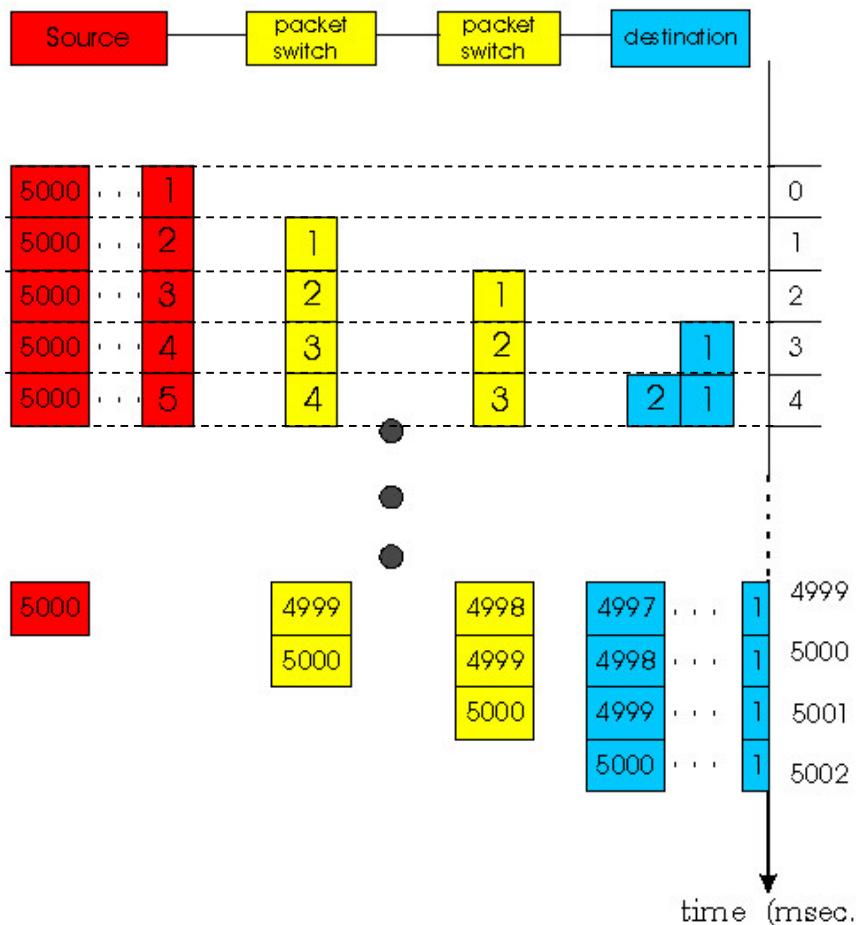
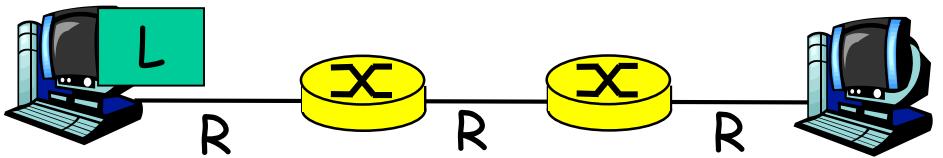
Packet-switching: store-and-forward



Example:

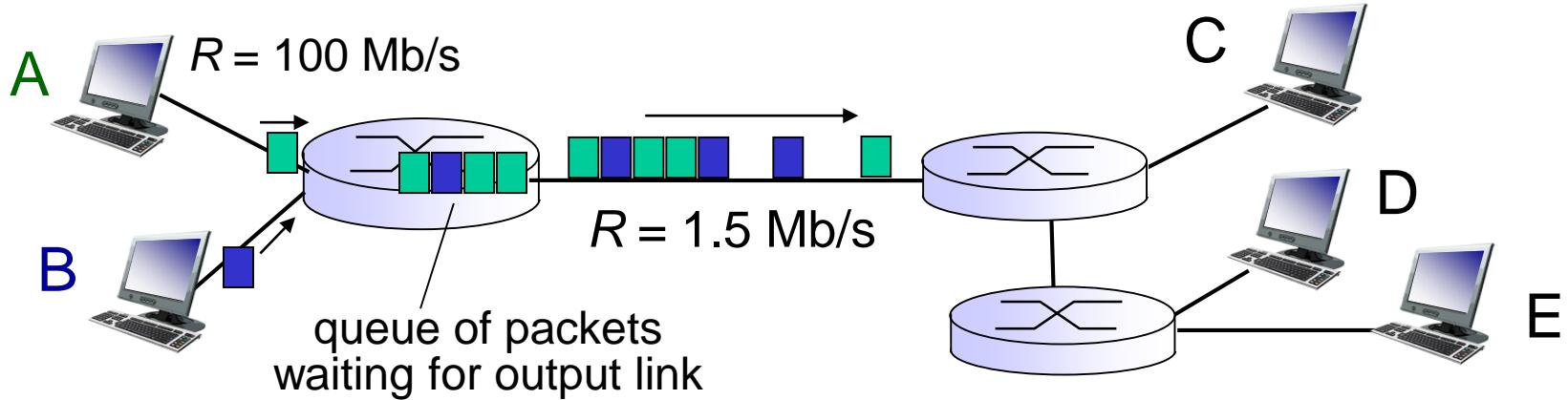
- ❖ $L = 25 \text{ Mbits}$ (big message or file)
- ❖ $R = 5 \text{ Mbps}$
- ❖ Compute the end-to-end delay, assuming that the file is sent as one big chunk (**not possible in practice**)
- ❖ $\text{delay} = 3 \times 25/5 = 15 \text{ sec}$

Packet-switching: store-and-forward



- The same example:
 - $L=25\text{Mbits}$, $R=5 \text{ Mbps}$
- Now, break message or file into smaller chunks: "packets"
- assume the file is divided into 5000 packets of 5000 bits each
 - total delay = 5.002 sec
 - total delay decreased by ~ 67% (however, there is some added overhead)

Packet Switching: queueing delay, loss



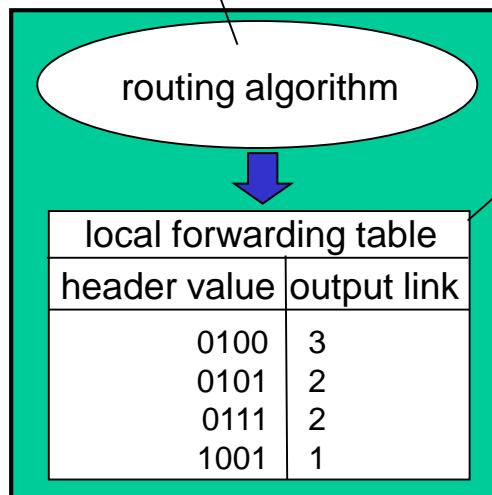
queuing and loss:

- ❖ 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

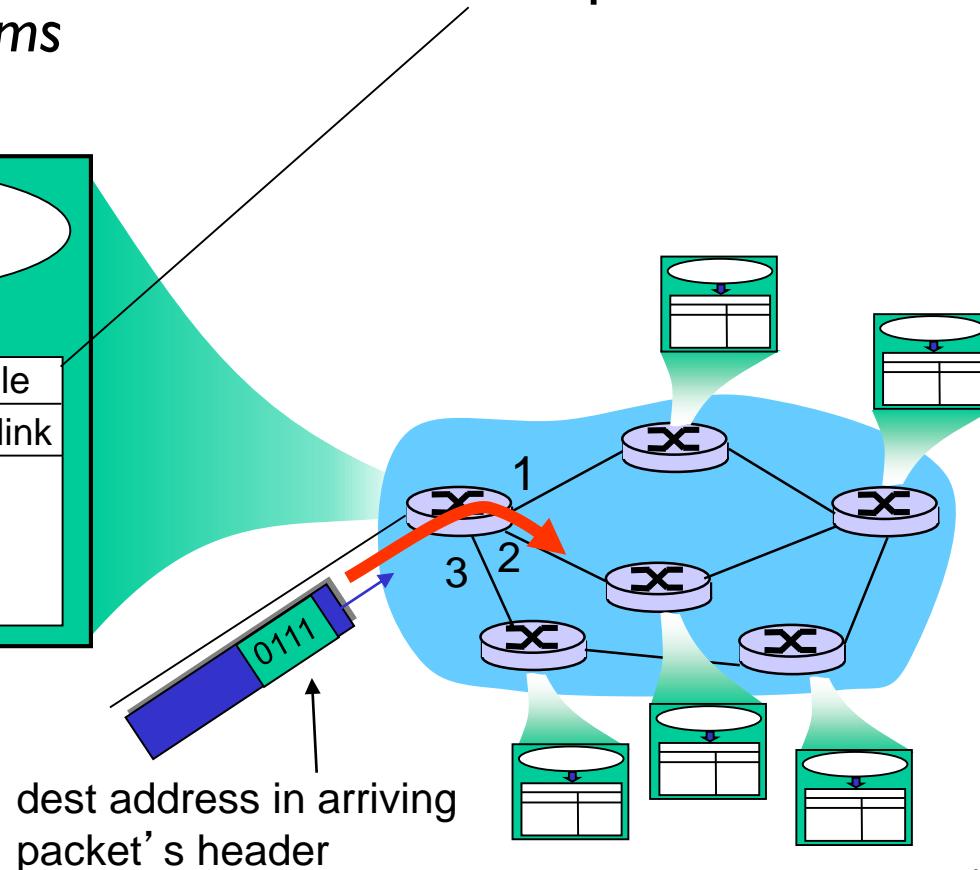
Two key network-core functions

routing: determines the source-destination route taken by packets

- *routing algorithms*



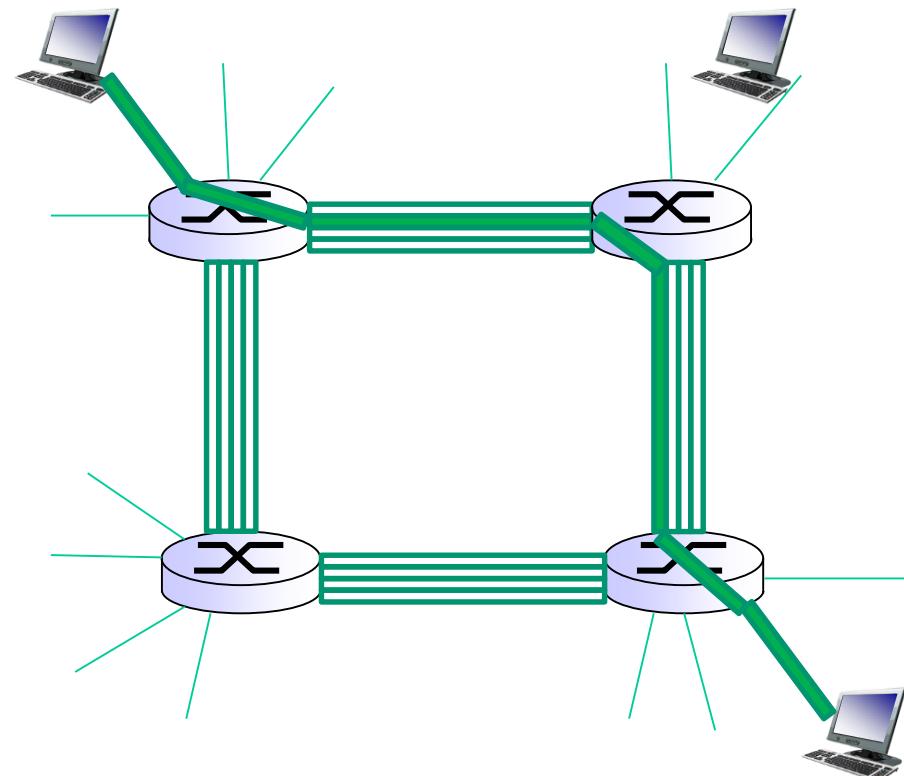
forwarding: move packets from router's input to appropriate router output



Alternative core: circuit switching

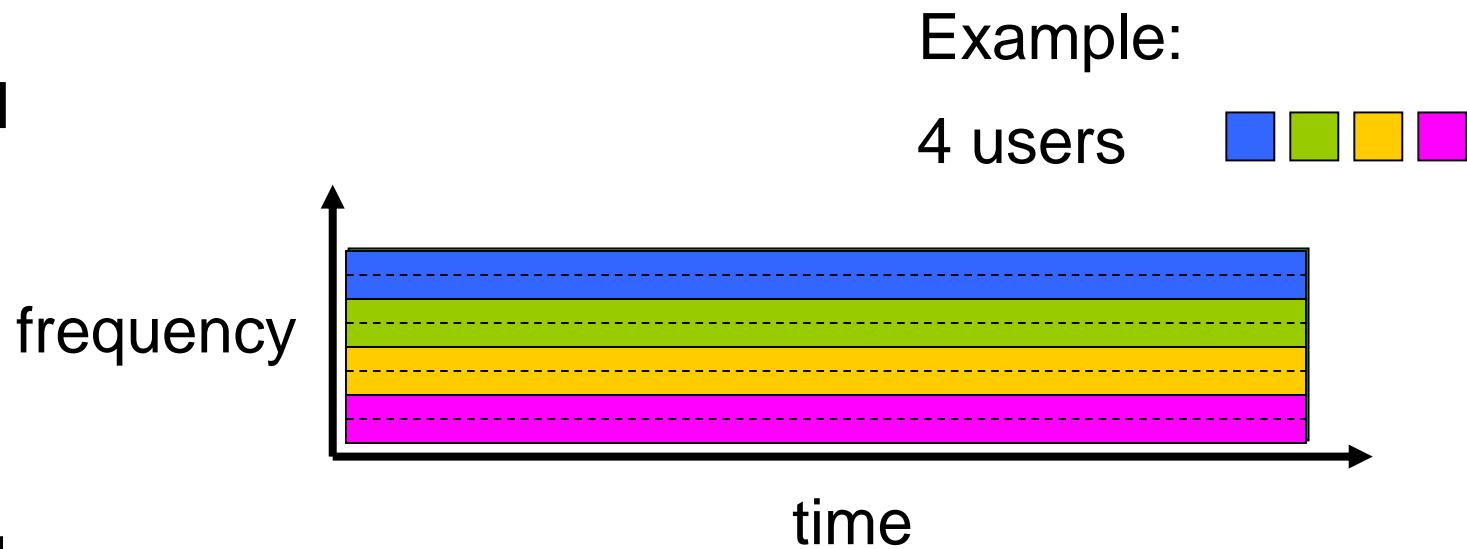
end-end resources allocated to, reserved for “call” between source & dest:

- ❖ 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

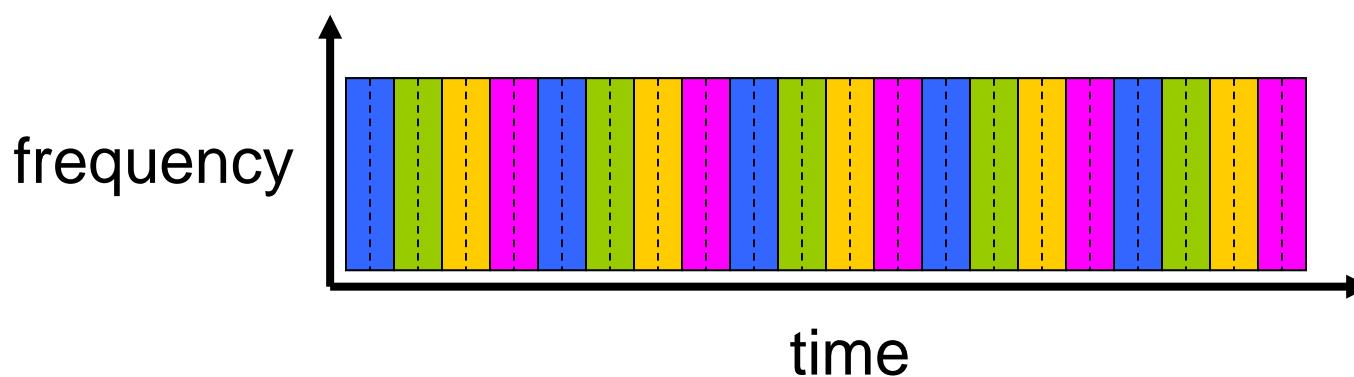


Circuit switching: FDM versus TDM

FDM



TDM



Packet switching versus circuit switching

packet switching allows more users to use network!

example:

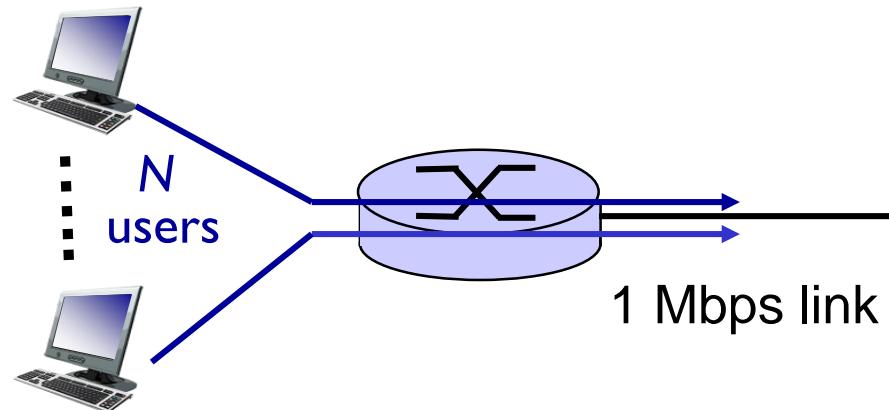
- 1 Mb/s link with N users
- each user:
 - requires 100 kb/s when “active”
 - active 10% of time

❖ *circuit-switching:*

- 10 users ($1M/100k=10$)
- 10% link utilization ☺

❖ *packet switching:*

- with 35 users, the probability that >10 users are active at the same time is less than 0.0004
- near full link utilization ☺



Q: how did we get value 0.0004?

- Binomial Distribution:

$$\sum_{n=11}^{35} \binom{35}{n} (0.1)^n (0.9)^{35-n} = 0.0004$$

Q: what happens if >35 users?

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 8)

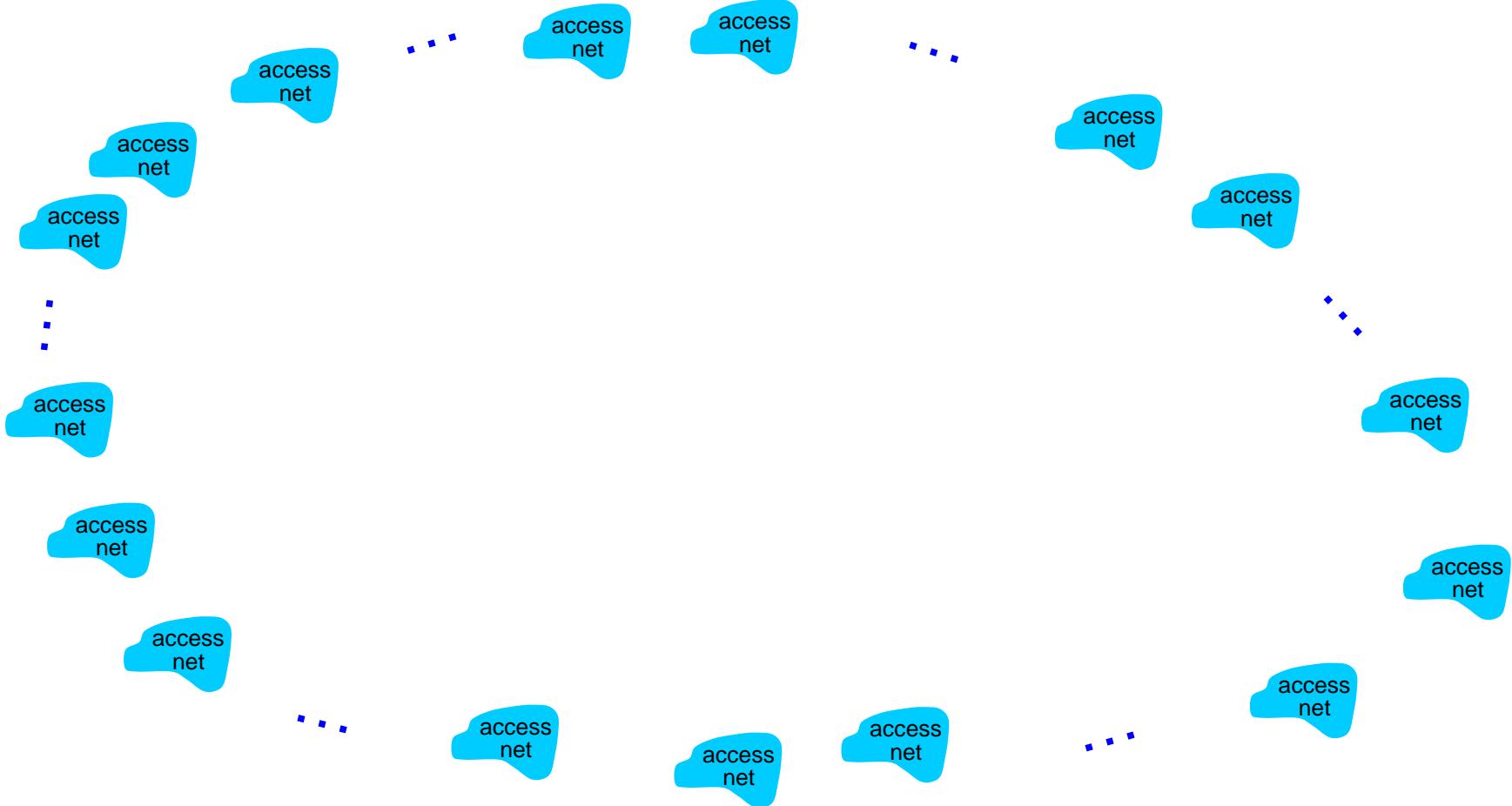
Q: human analogies of reserved resources (circuit switching)
versus on-demand allocation (packet-switching)?

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

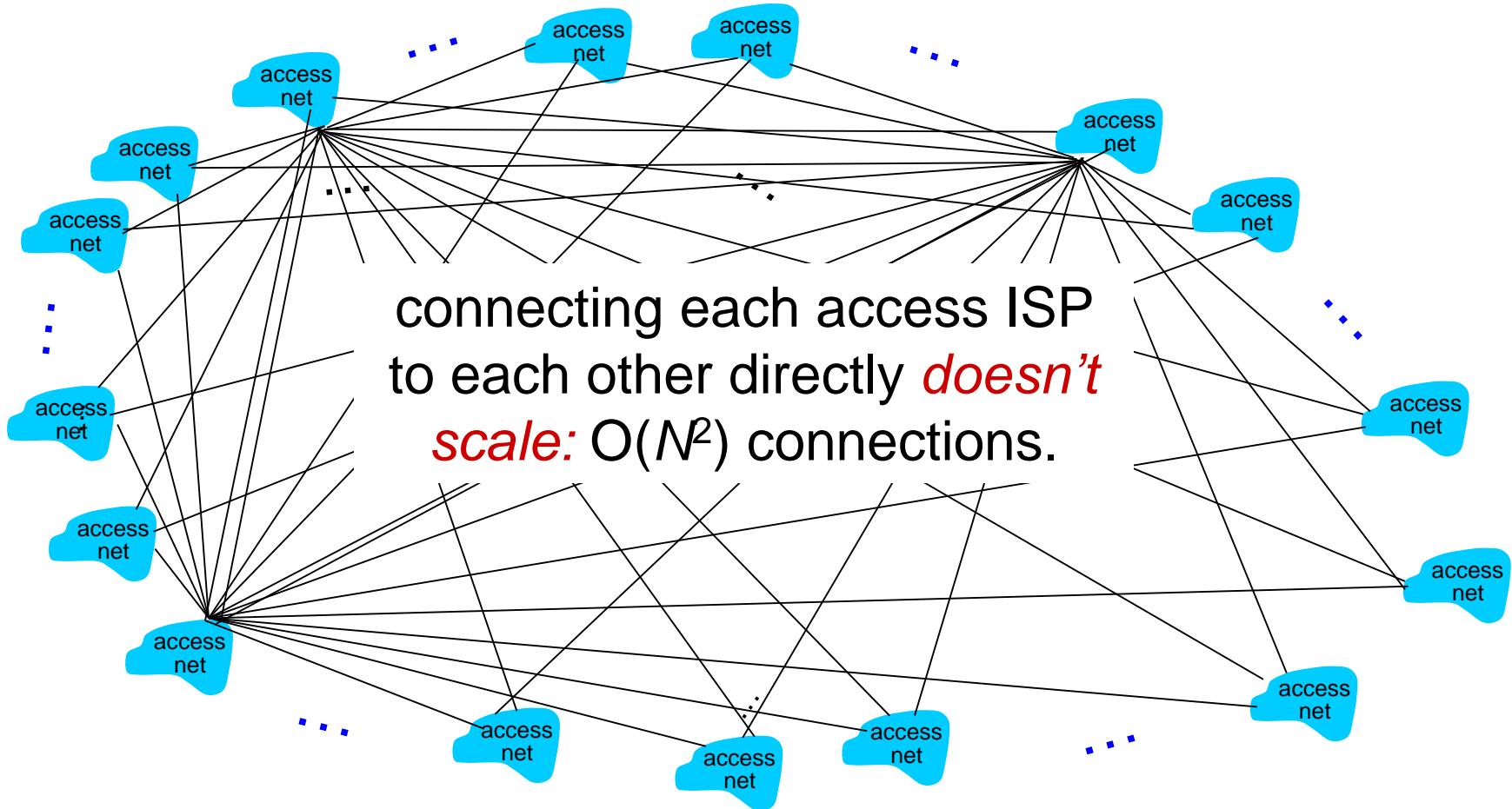
Internet structure: network of networks

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



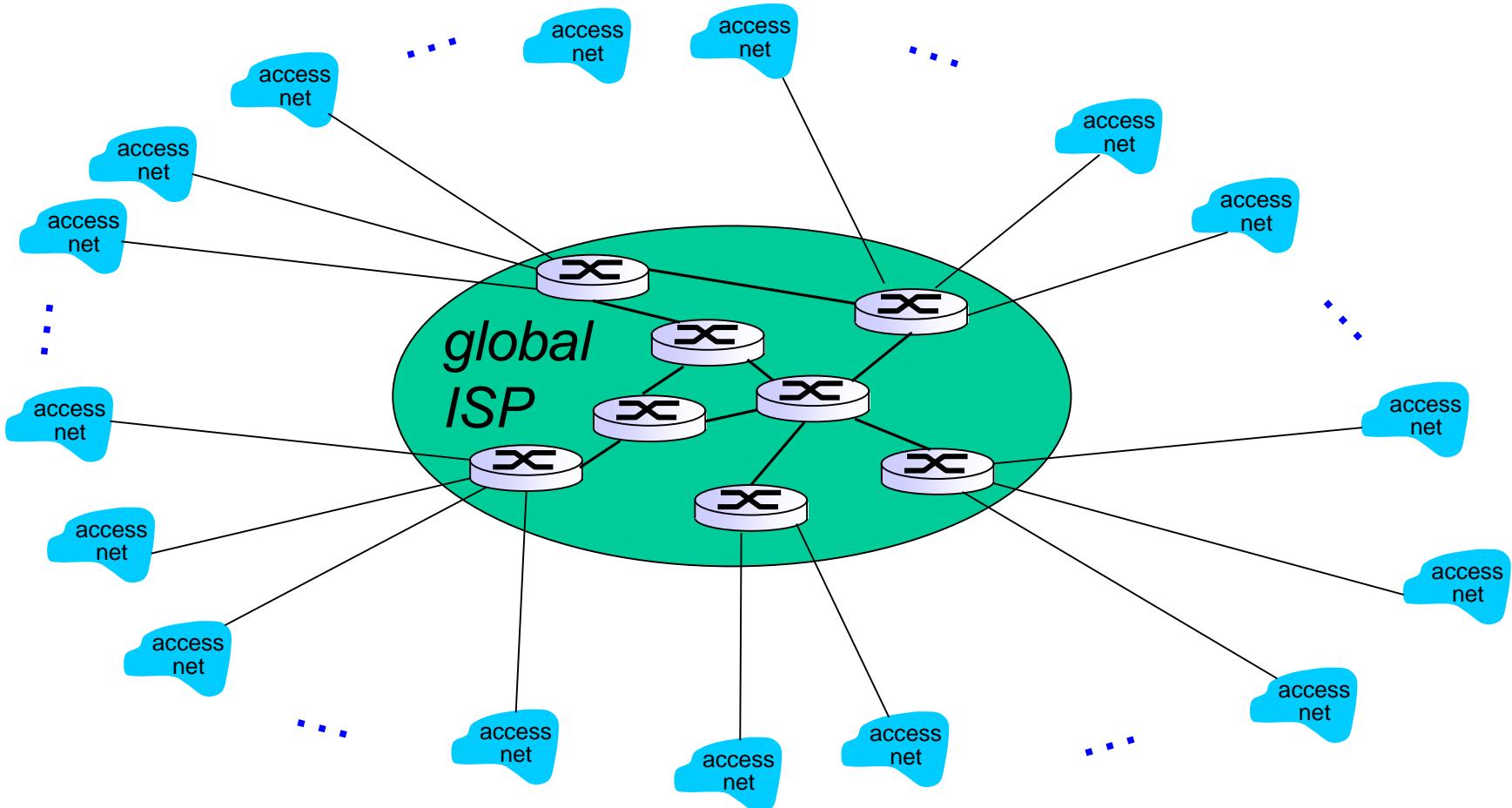
Internet structure: network of networks

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



Internet structure: network of networks

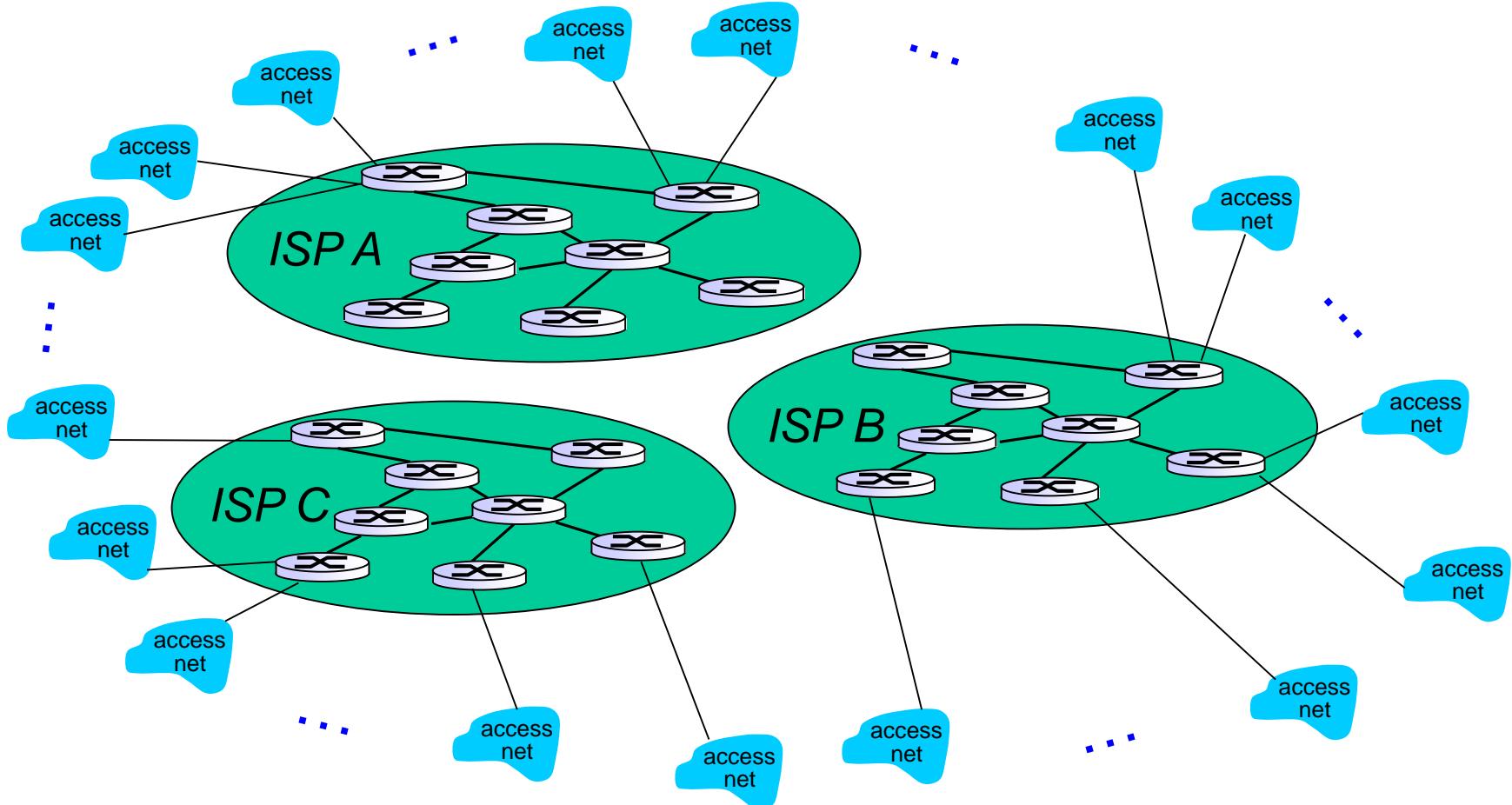
Option: connect each access ISP to a global transit ISP? *Customer and provider ISPs have economic agreement.*



Internet structure: network of networks

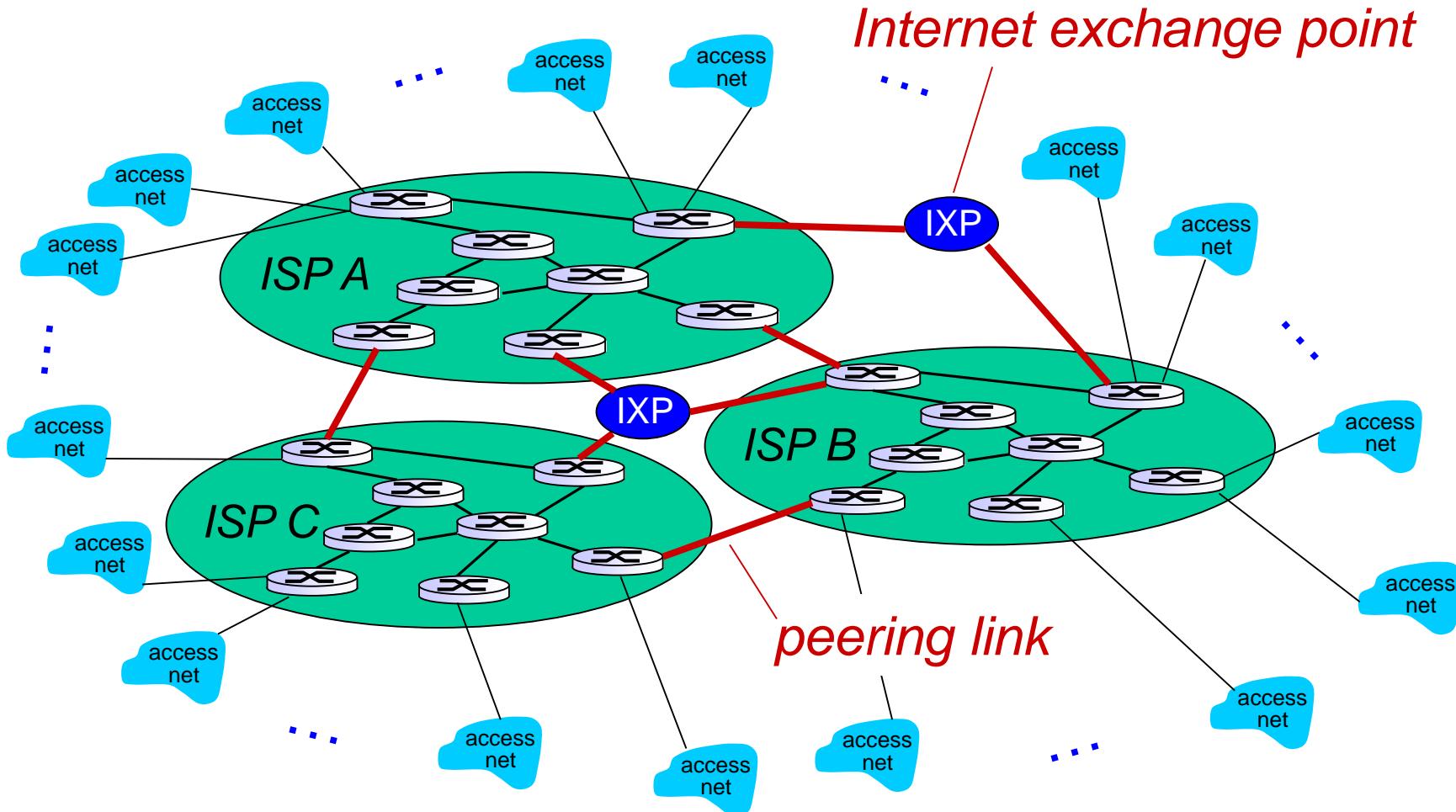
But if one global ISP is viable business, there will be competitors

....



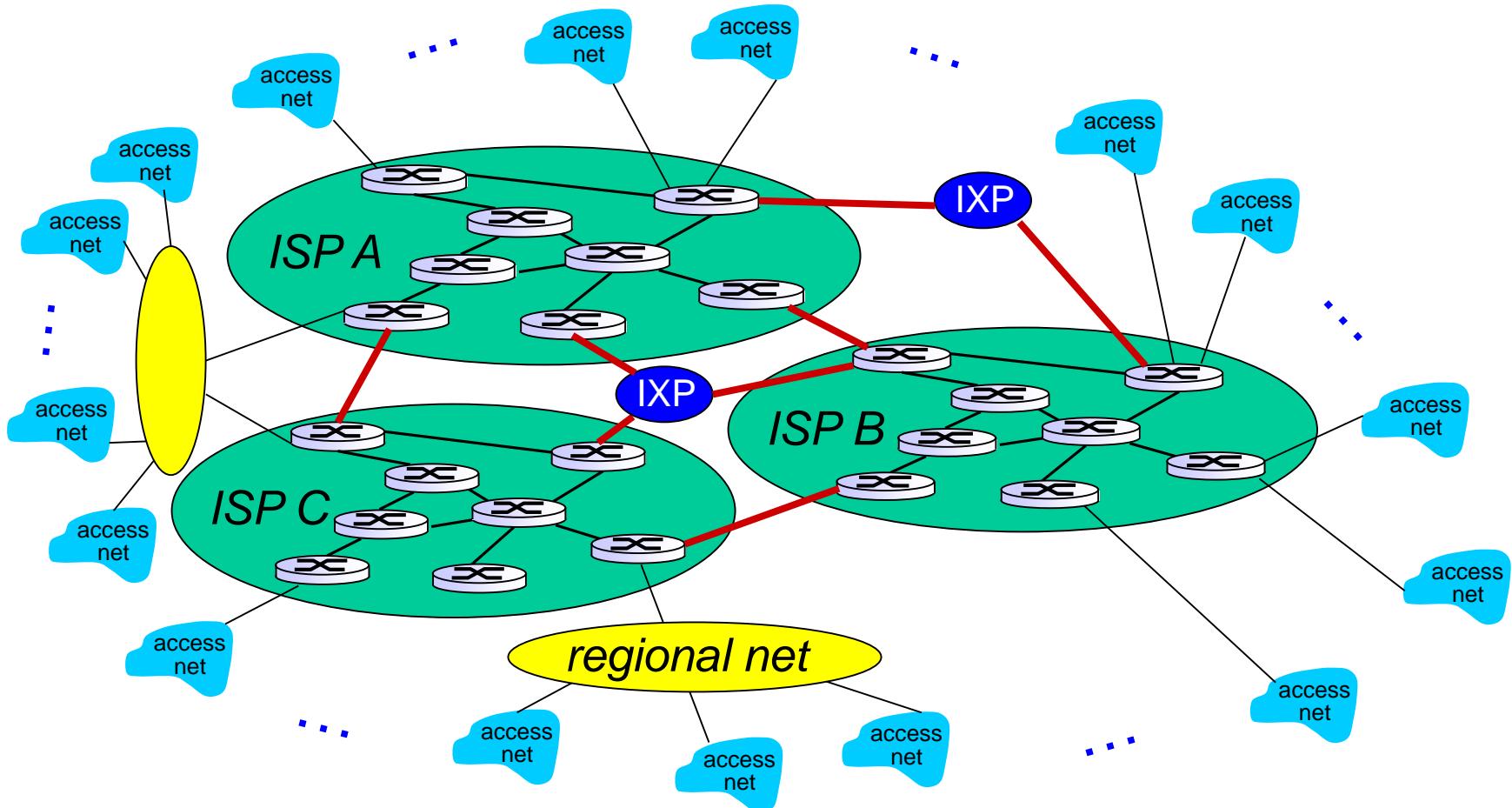
Internet structure: network of networks

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



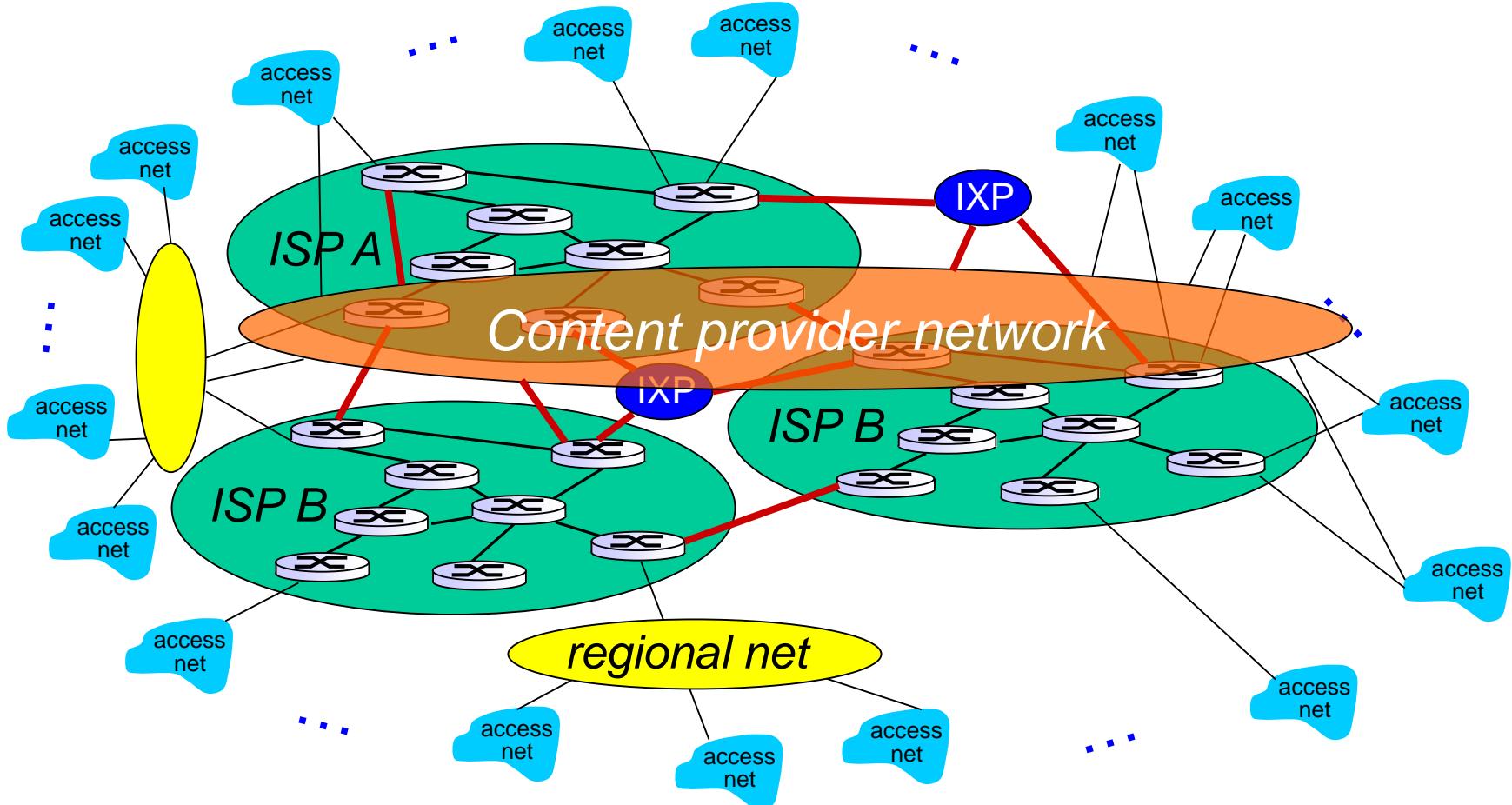
Internet structure: network of networks

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

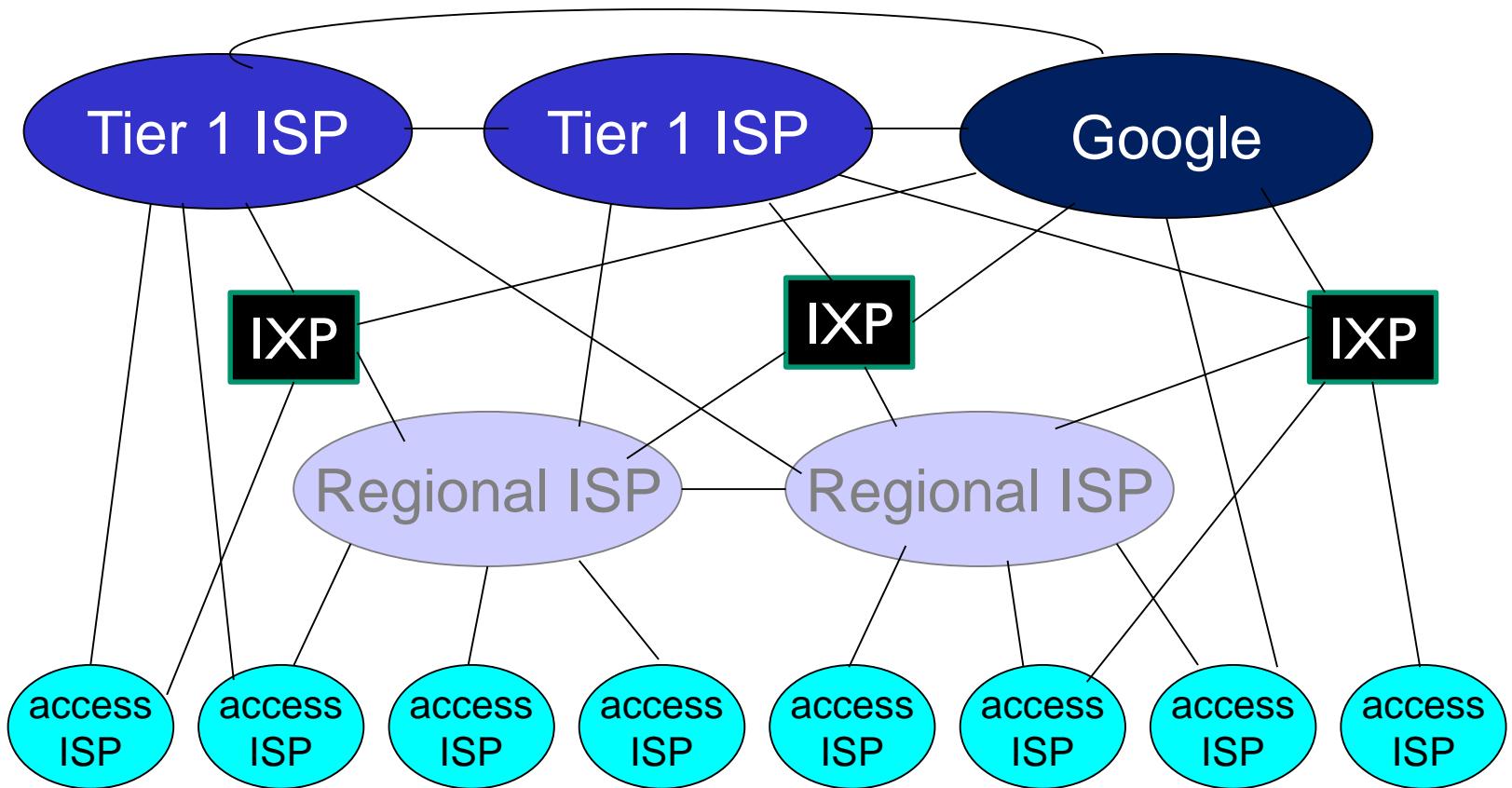


Internet structure: network of networks

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

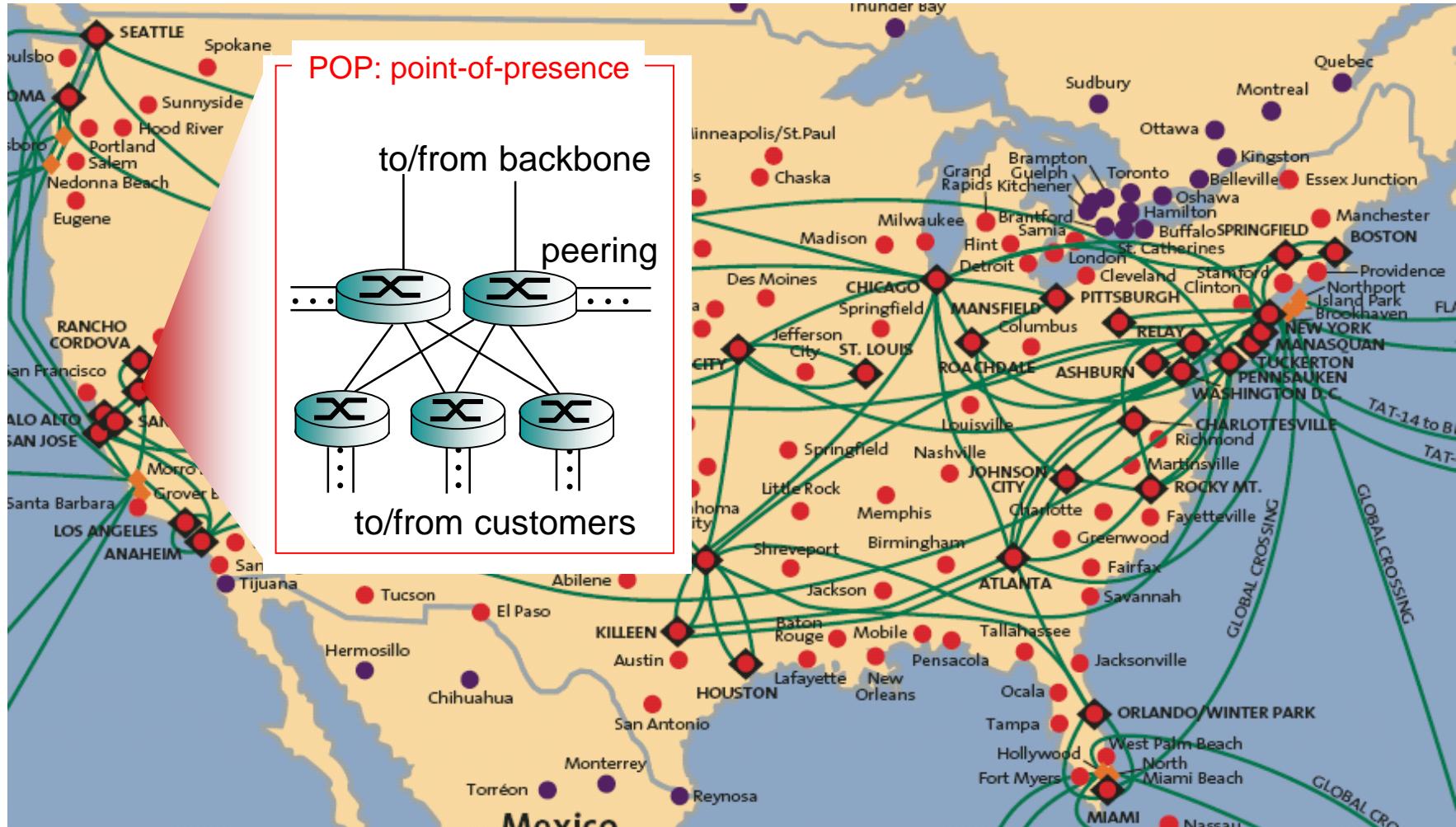


Internet structure: network of networks



- ❖ 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-1 ISP: e.g., Sprint



Chapter I: roadmap

I.1 what *is* the Internet?

I.2 network edge

- end systems, access networks, links

I.3 network core

- packet switching, circuit switching, network structure

I.4 delay, loss, throughput in networks

I.5 protocol layers, service models

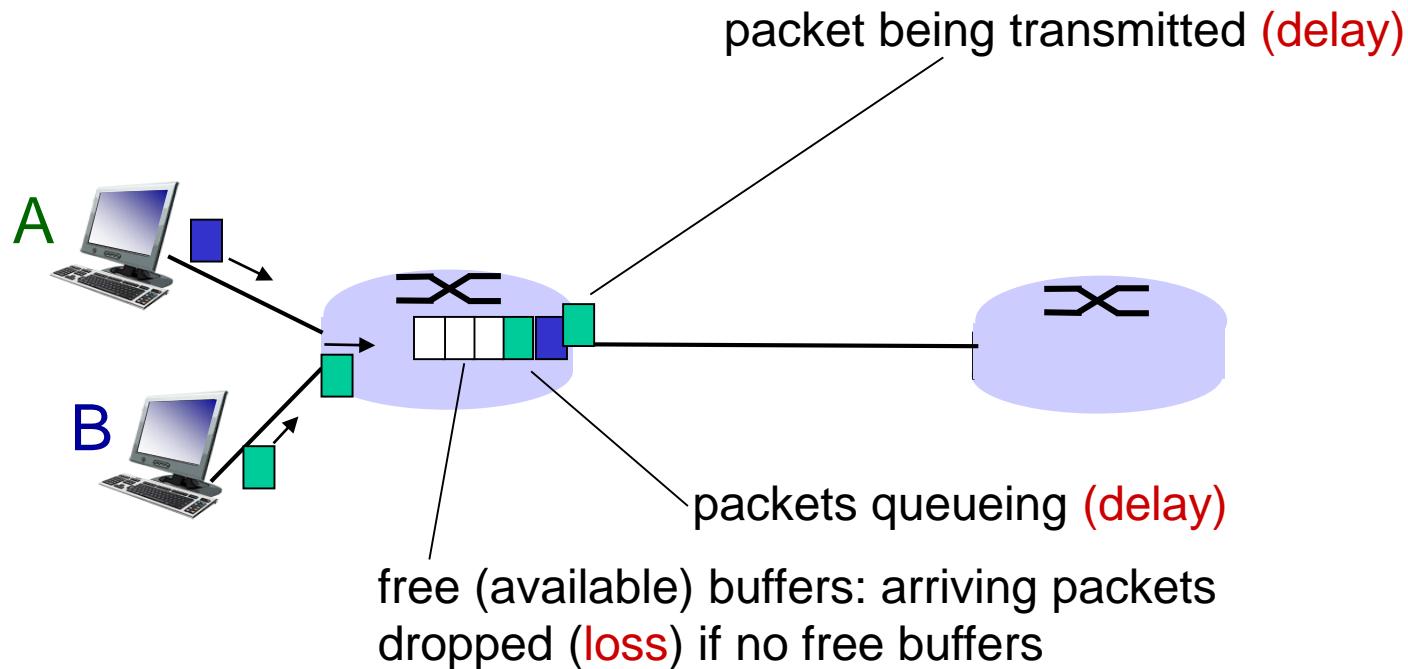
I.6 networks under attack: security

I.7 history

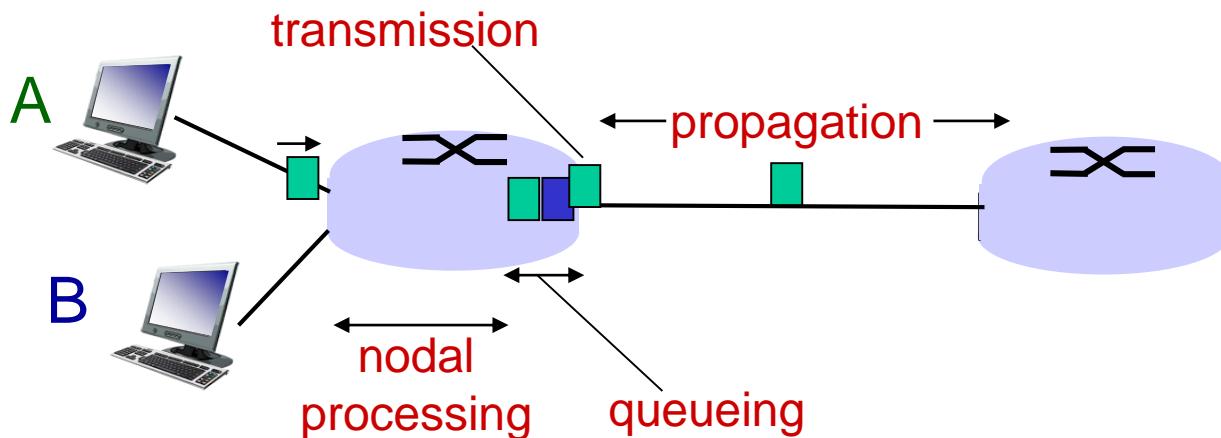
How do loss and delay occur?

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



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

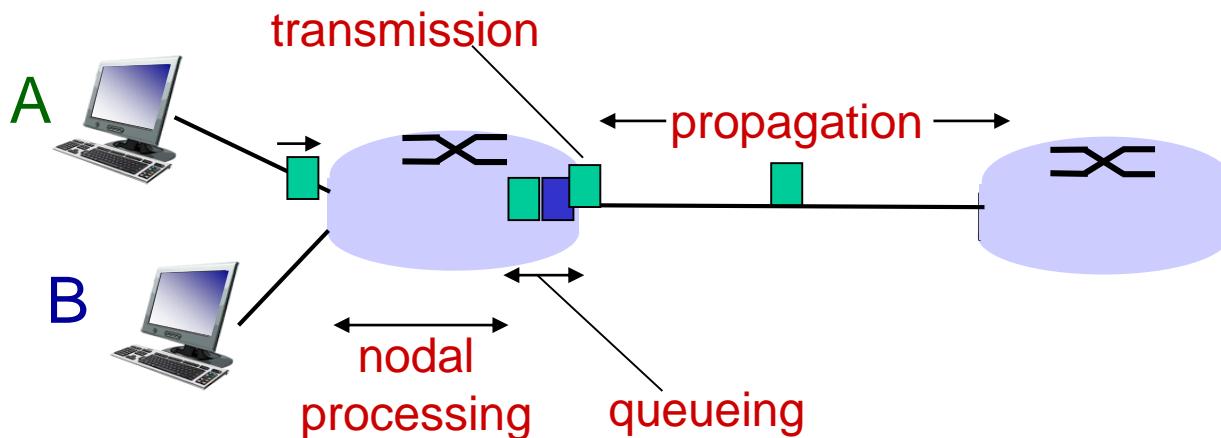
d_{proc} : nodal processing

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

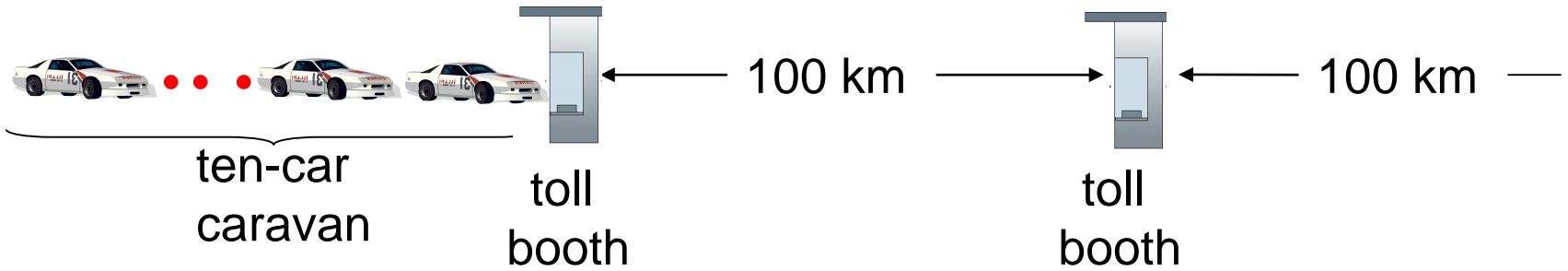
d_{trans} and d_{prop}
very different

d_{prop} : propagation delay:

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

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

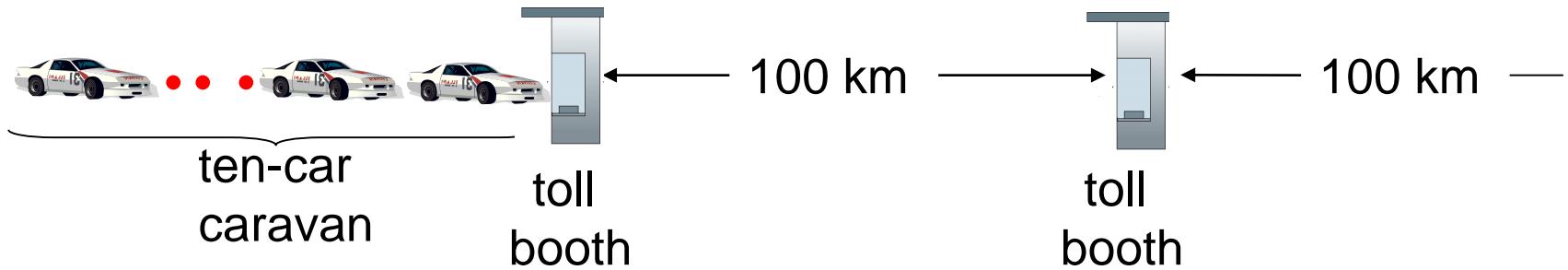
Caravan analogy



- ❖ 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 both:
 $100\text{km}/(100\text{km/hr}) = 1\text{ hr}$
- A: 62 minutes

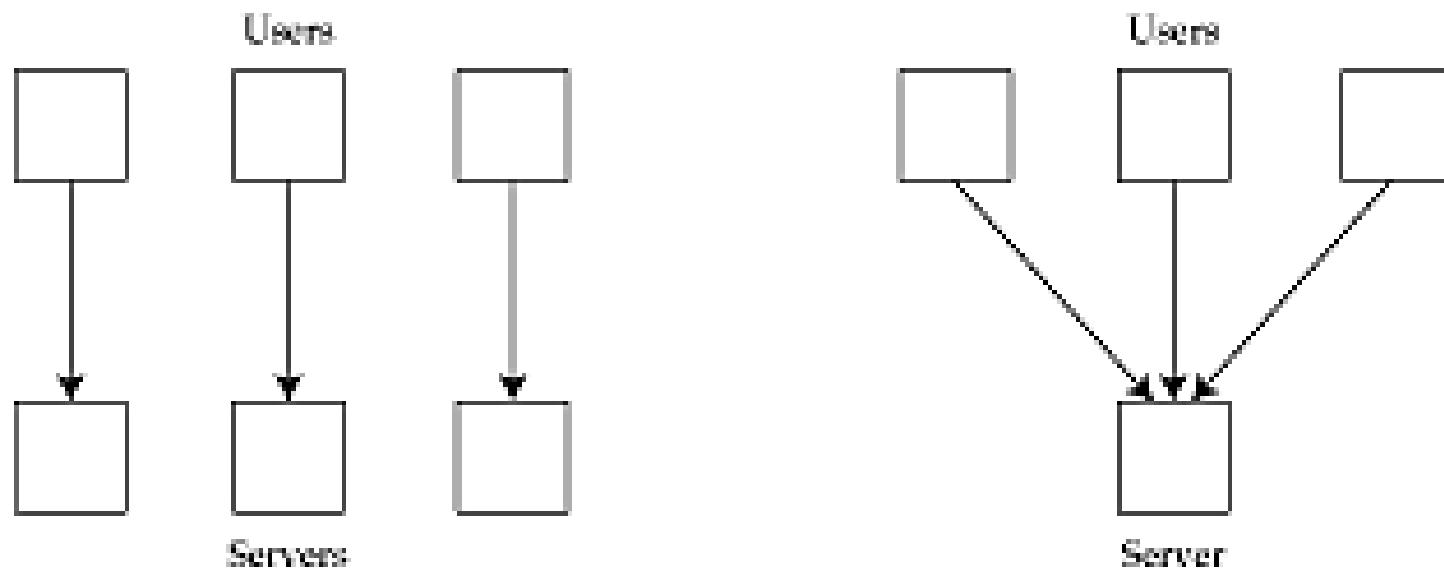
Caravan analogy (more)



- ❖ 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, 1st car arrives at second booth; three cars still at 1st booth.

Multiplexing

- ❖ Multiplexing = sharing resources
 - Trading off time and space for money
 - Cost: waiting time, buffer space & packet loss
 - Gain: Money → less overall system costs

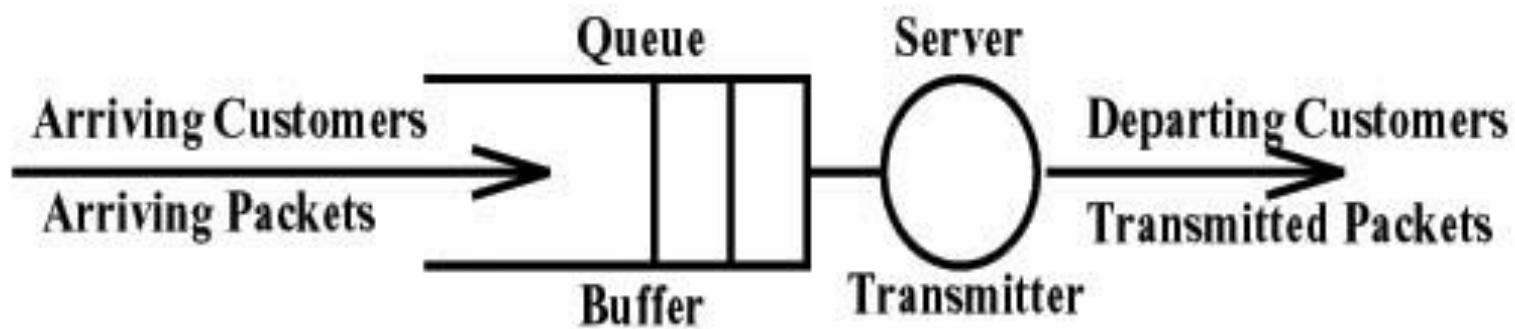


Statistical Multiplexing

- ❖ Reduce resource requirements by *exploiting statistical knowledge* of the system
 - E.g.; average rate \leq service rate \leq peak rate
 - If the service rate $<$ the average rate, then the system becomes unstable
 - First, design to ensure system stability
 - Then, for a stable multiplexed system:
 - Gain = peak rate/service rate
 - Cost: buffering, queuing delays, and data loss

Stability of a Multiplexed System

Average Input Rate > Average Output Rate
→ System will become unstable!



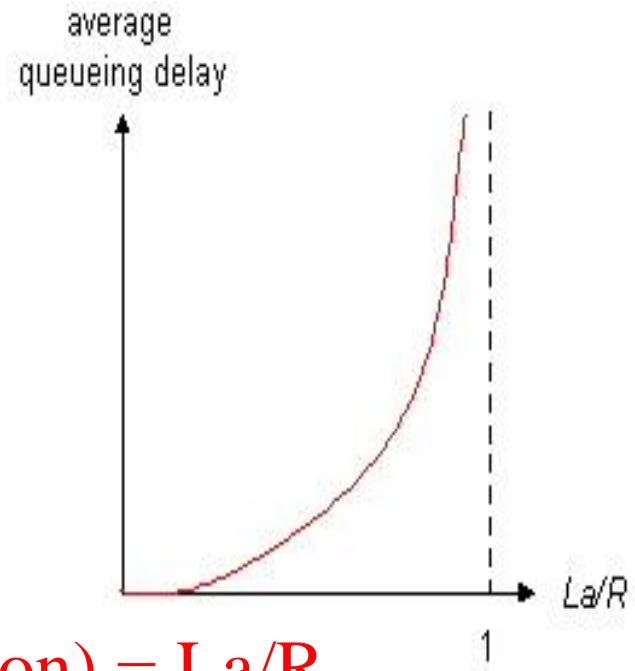
How to ensure stability?

1. Reserve enough capacity so that the average demand is less than the reserved capacity
2. Dynamically detect overload and adapt either the demand or the capacity to resolve the overload

What is a performance tradeoff?

- A situation where you cannot get something for nothing
- Also known as a zero-sum game

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

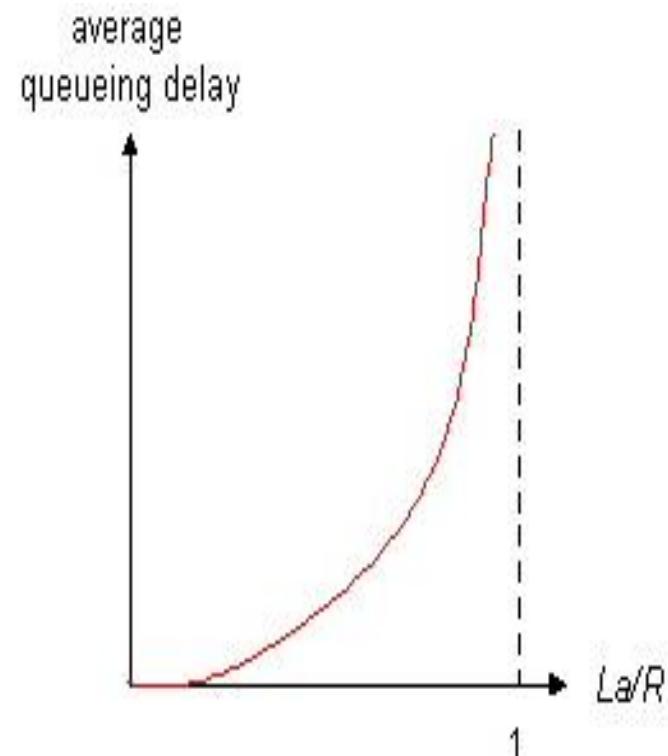


Traffic Intensity (or Link Utilization) = La/R

(Average traffic divided by the link capacity)

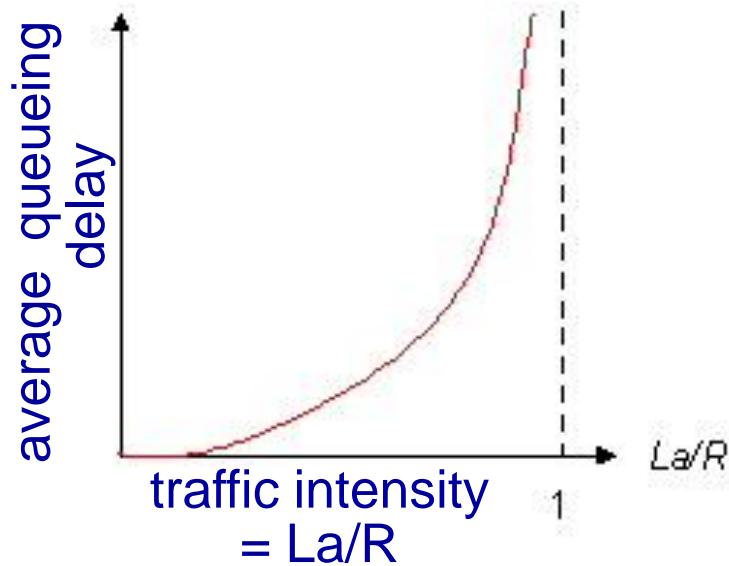
What is a performance tradeoff?

- ❖ $La/R \sim 0$
 - Average queueing delay small
 - Wasteful Design
- ❖ $La/R \rightarrow 1$
 - Delay becomes large
- ❖ $La/R > 1$
 - Infinite average delay
 - Service degrades unboundedly → instability
- ❖ Statistics suggest that the best tradeoff is when $La/R \sim 0.8$



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!



$La/R \sim 0$

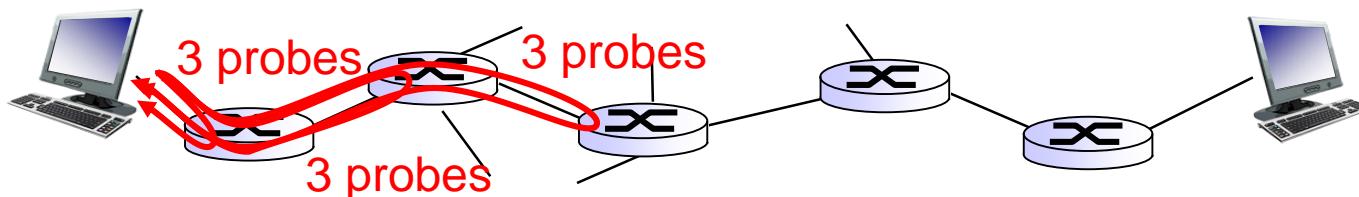


$La/R \rightarrow 1$

* Check out the Java applet for an 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.



“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

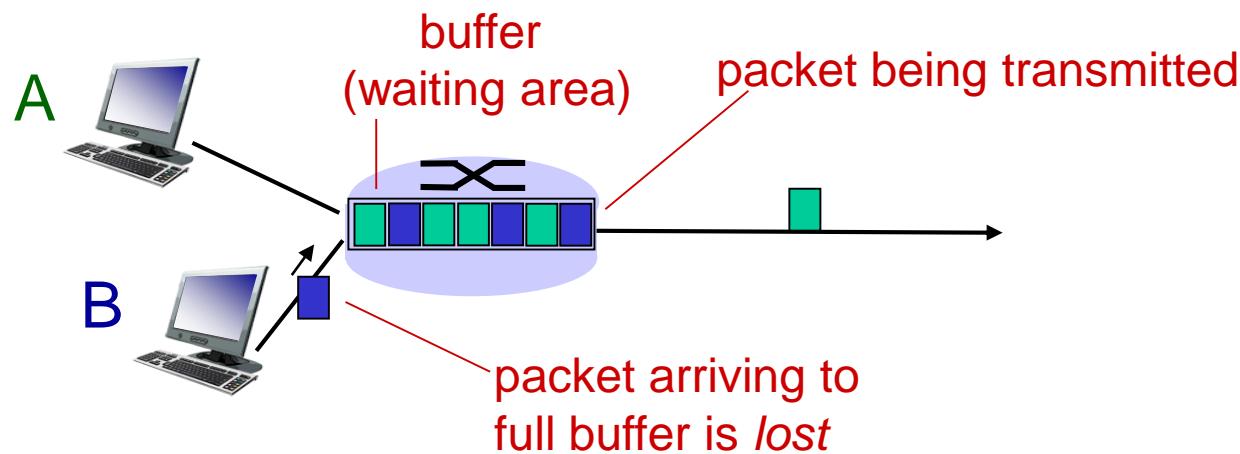
1	cs-gw (128.119.240.254)	1 ms	1 ms	2 ms
2	border1-rt-fa5-1-0.gw.umass.edu (128.119.3.145)	1 ms	1 ms	2 ms
3	cht-vbns.gw.umass.edu (128.119.3.130)	6 ms	5 ms	5 ms
4	jn1-at1-0-0-19.wor.vbns.net (204.147.132.129)	16 ms	11 ms	13 ms
5	jn1-so7-0-0-0.wae.vbns.net (204.147.136.136)	21 ms	18 ms	18 ms
6	abilene-vbns.abilene.ucaid.edu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

Packet loss

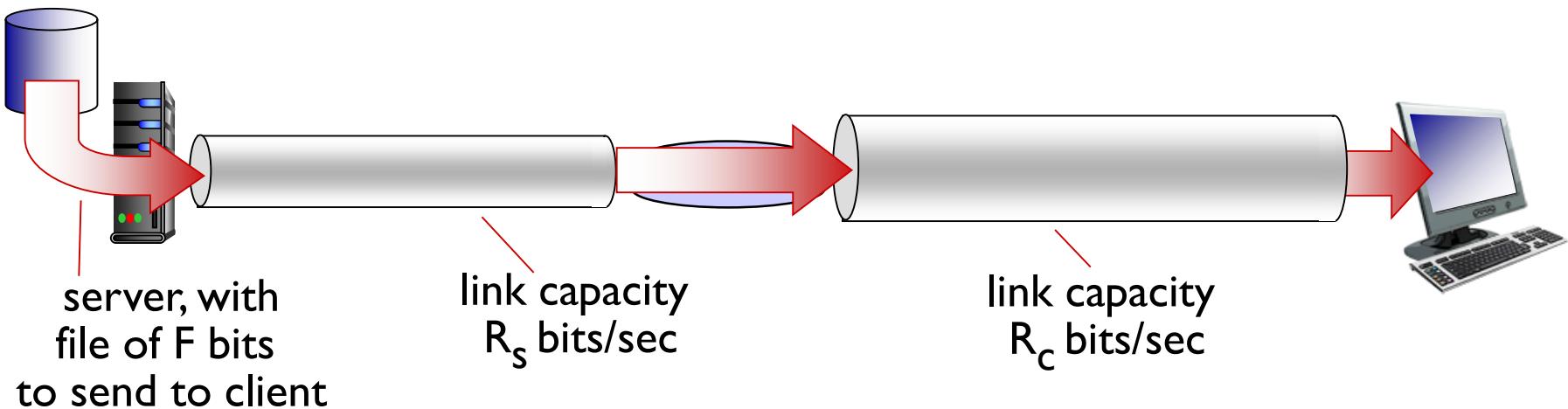
- ❖ queue (aka buffer) preceding link in buffer has finite capacity
- ❖ packet arriving to full queue is dropped (aka lost)
- ❖ lost packet may be retransmitted by previous node, by source end system, or not at all



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

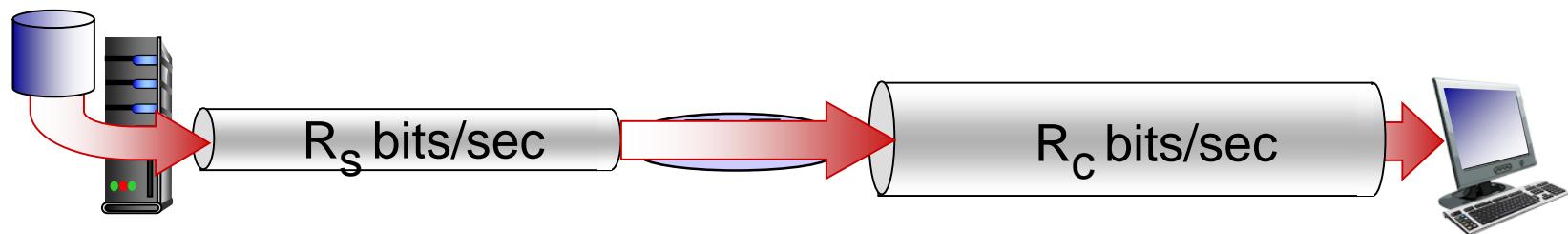
Throughput

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

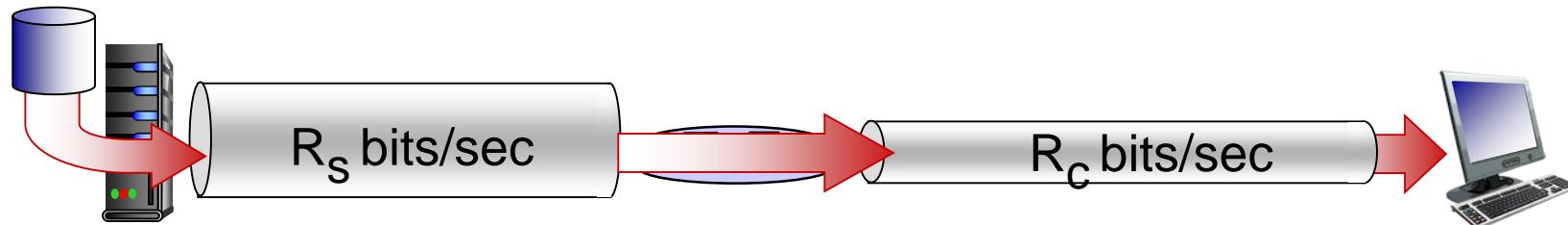


Throughput (more)

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



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

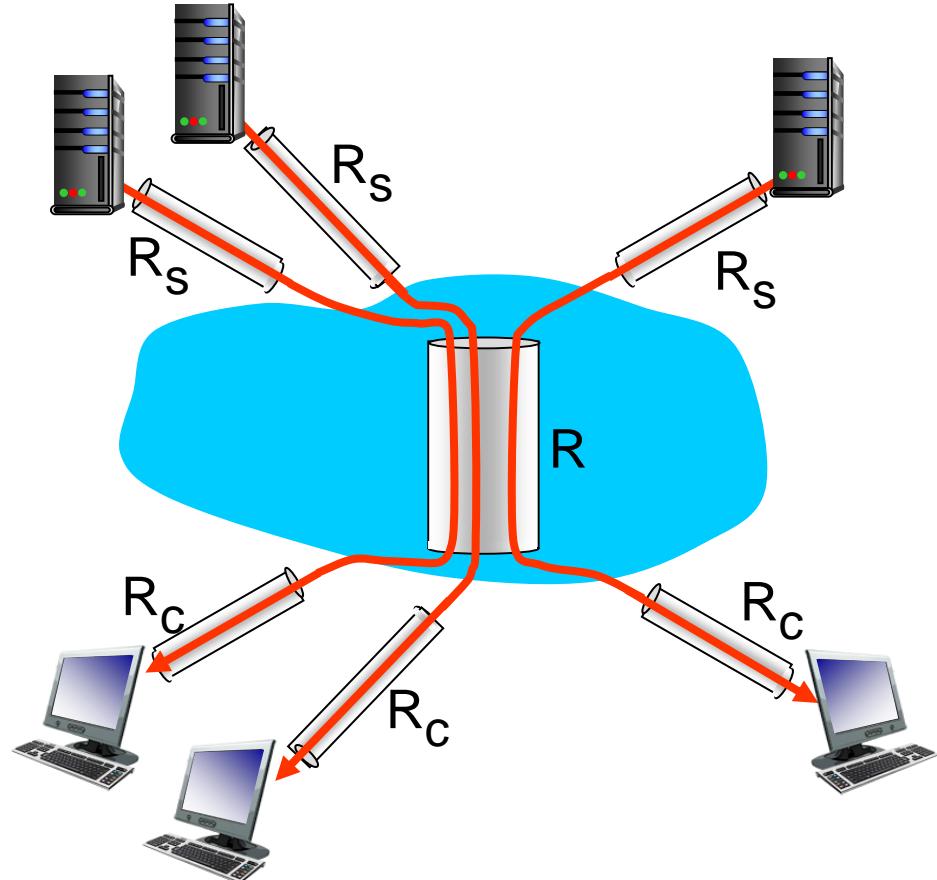


bottleneck link

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 the bottleneck



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

Chapter I: roadmap

I.1 what *is* the Internet?

I.2 network edge

- end systems, access networks, links

I.3 network core

- packet switching, circuit switching, network structure

I.4 delay, loss, throughput in networks

I.5 protocol layers, service models

I.6 networks under attack: security

I.7 history

Protocol “layers”

Networks are complex, with many “pieces”:

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

Question:

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

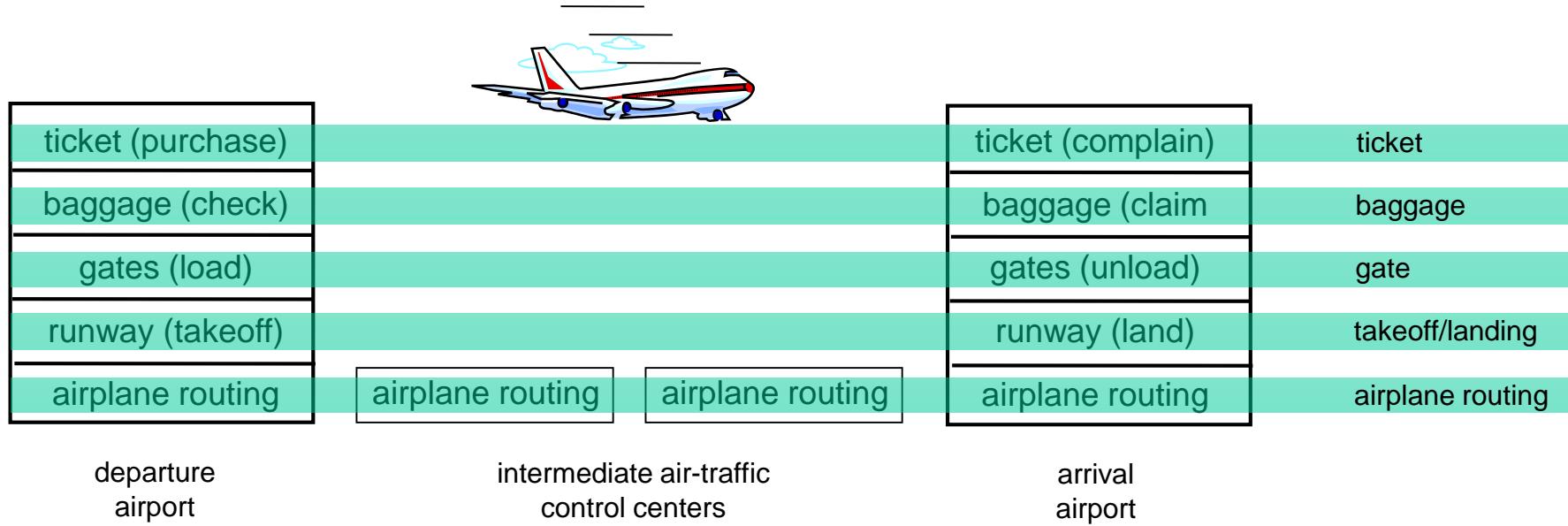
.... or at least our discussion of networks?

Organization of air travel



- ❖ a series of steps

Layering of airline functionality



layers: each layer implements a service

- via its own internal-layer actions
- relying on services provided by layer below

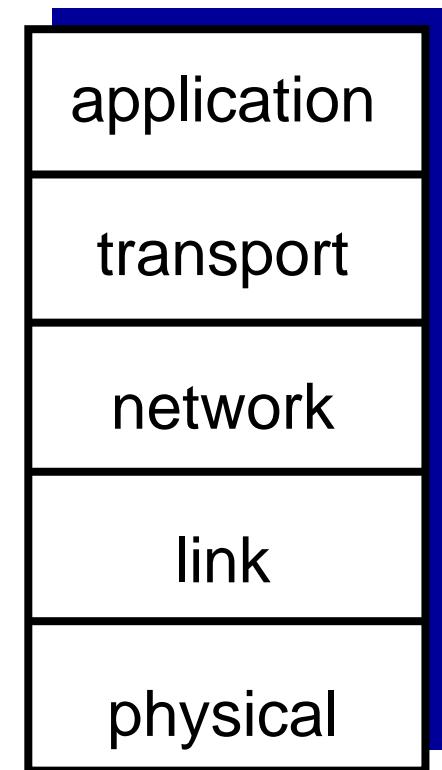
Why layering?

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 gate procedure doesn't affect rest of system
- ❖ layering considered harmful?

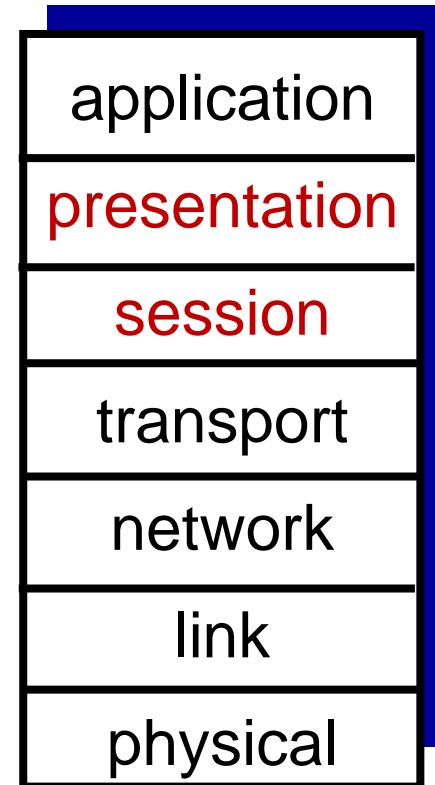
Internet protocol stack

- ❖ *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”



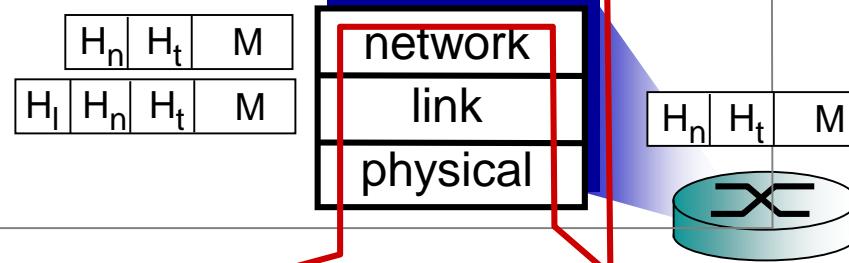
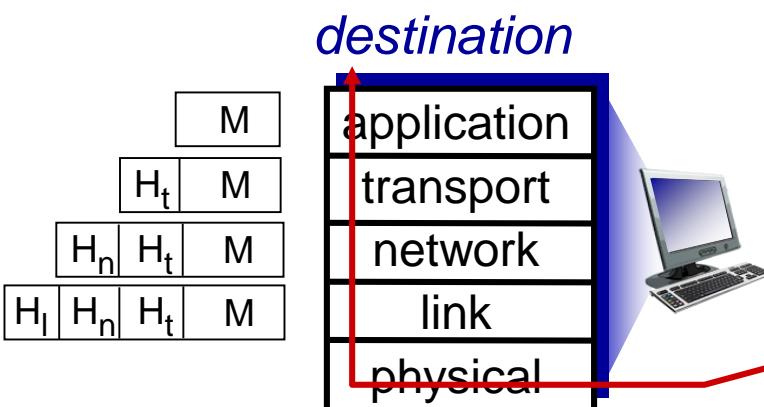
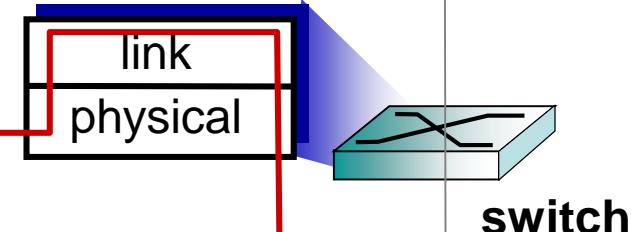
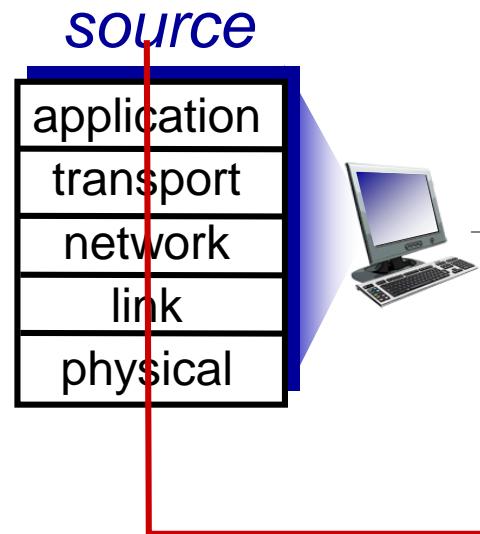
ISO/OSI reference model

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



Encapsulation

message	M
segment	H _t M
datagram	H _n H _t M
frame	H _l H _n H _t M



Introduction: summary

covered a “ton” of material!

- ❖ Internet overview
- ❖ what’s a protocol?
- ❖ network edge, core, access network
 - packet-switching versus circuit-switching
 - Internet structure
- ❖ performance: loss, delay, throughput
- ❖ layering, service models
- ❖ security
- ❖ history

you now have:

- ❖ context, overview, “feel” of networking
- ❖ more depth, detail to follow!