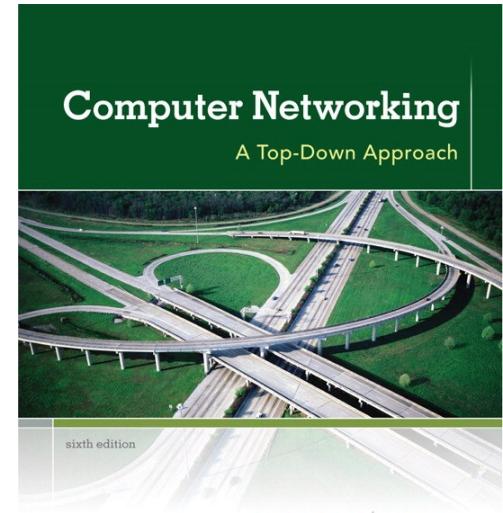


# Computer Networking



Lecturer: Pham Manh Linh, PhD.

*Computer  
Networking: A Top  
Down Approach*  
6<sup>th</sup> edition  
Jim Kurose, Keith Ross  
Addison-Wesley  
March 2012

# Lecturer

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  - Agrotechnology
  - CI/CD
- Publications:
  - <https://scholar.google.com/citations?hl=en&user=WVPZOGIAAAAJ>
- Website:
  - <https://uet.vnu.edu.vn/~linhmp/>

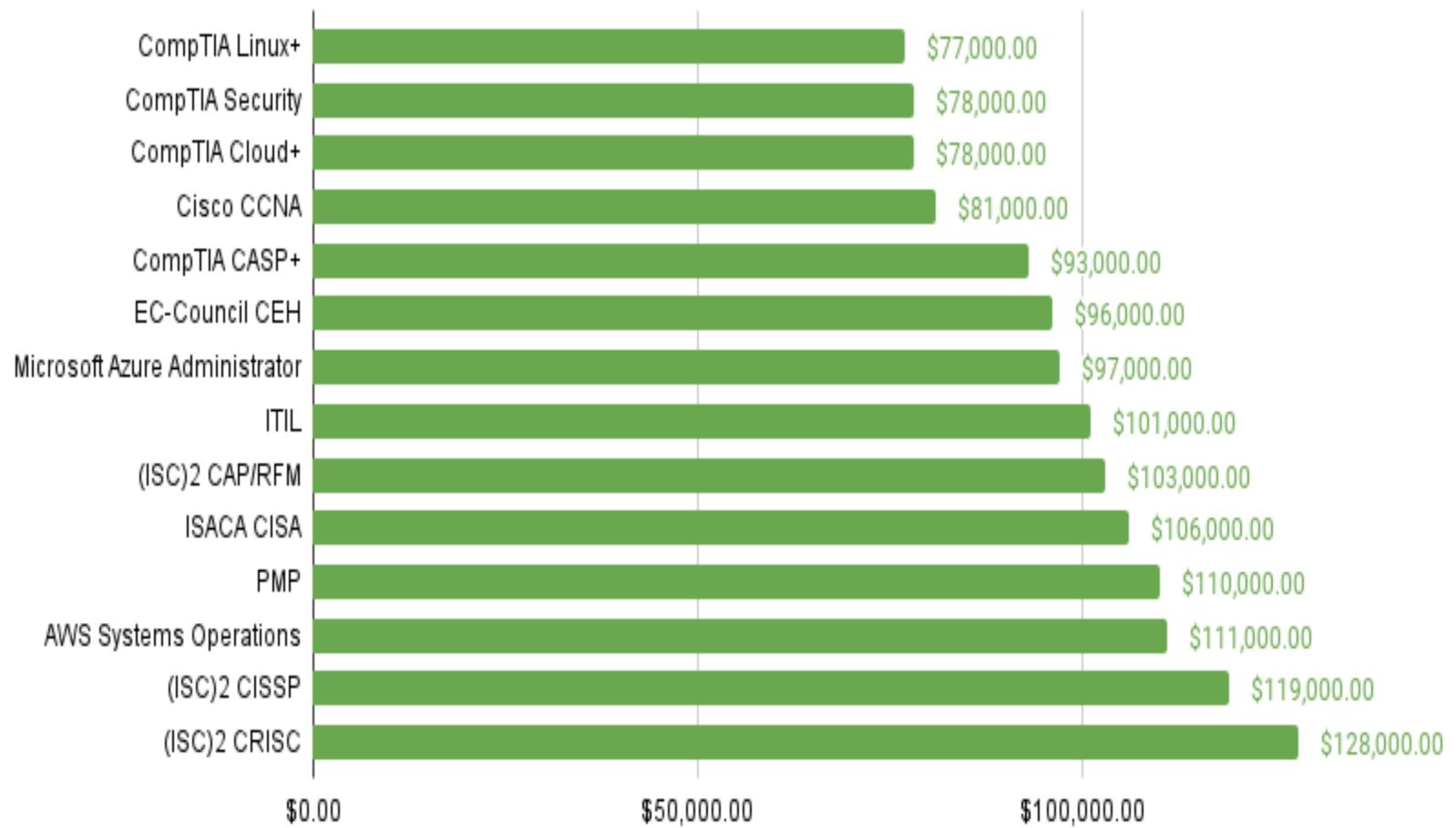
# Syllabus

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- INT2209 - 3 credits || INT2213 – 4 credits
- 2-hour theoretical & 3-hour practical classes
- Objective
  - Knowledge: Networking fundamental, focus on Internet
  - Skill: hands-on x 3.14
  - Attitude: Attendance & Interaction
- Evaluation:
  - Final exam: 60%
  - Hands-on lab + [Midterm exam]: 35%
  - Attendance + Interaction: 5%; > 4 times => fail



## Average Annual Salary per Certification (2022)



For more information visit [blog.trainace.com](http://blog.trainace.com)

**ANY  
QUESTIONS ??**

# 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

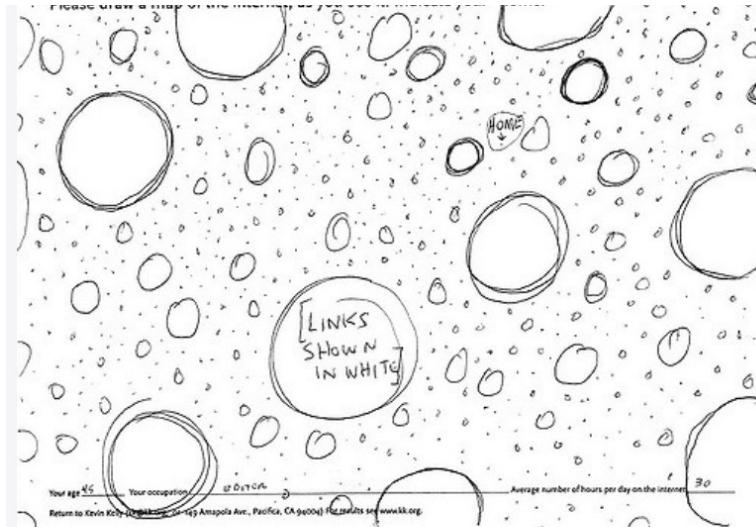
# What's the Internet: newbie

**Draw Your Concept of the Internet**

<https://kk.org/mt-files/internet-mapping/index.html>

By Kevin Kelly

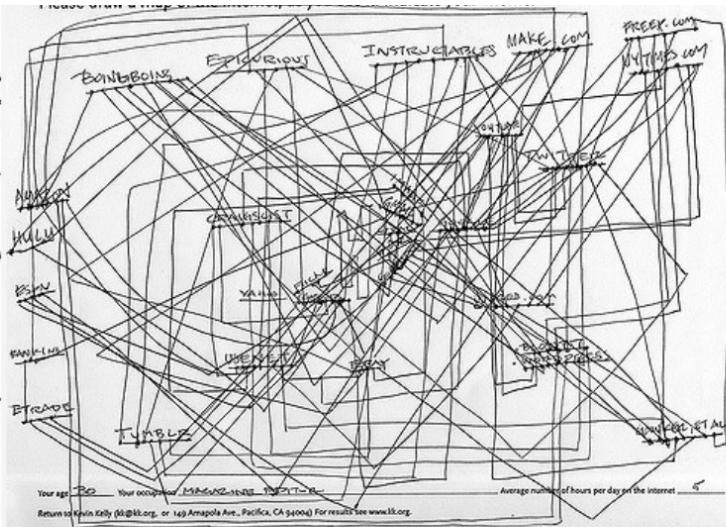
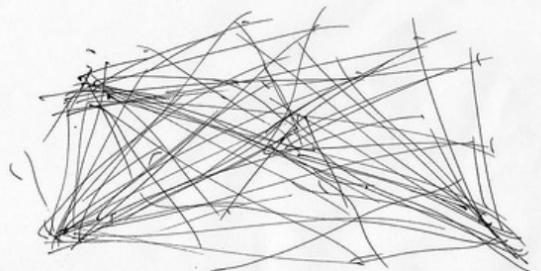
# What's the Internet: newbie



## THE INTERNET MAPPING PROJECT

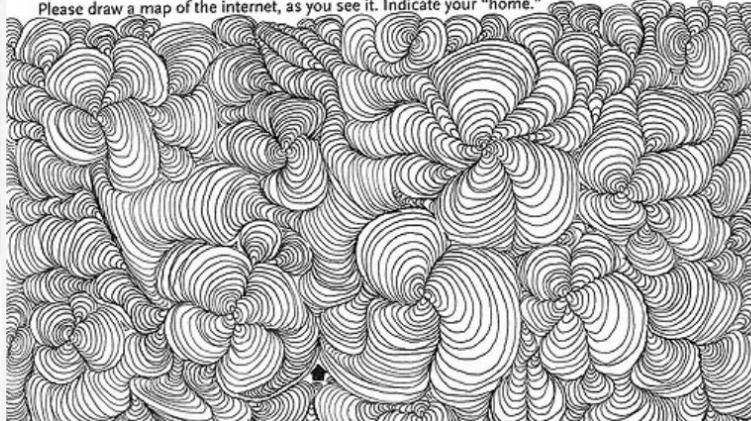
Please draw a map of the internet, as you see it. Indicate your "home."

Hand to draw. To me, it's a Klein bottle,  
ie, more than 3 dimensions

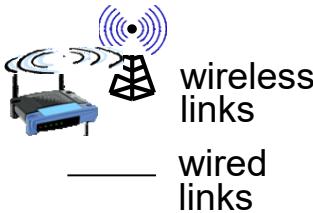


## THE INTERNET MAPPING PROJECT

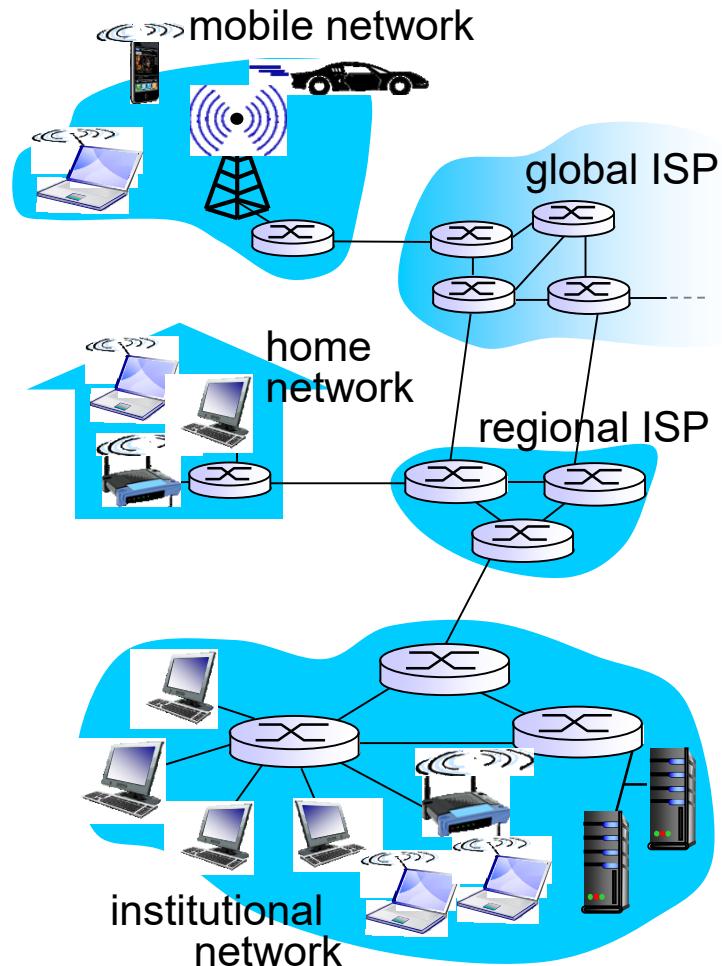
Please draw a map of the internet, as you see it. Indicate your "home."



# 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 appliances



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



Web-enabled toaster +  
weather forecaster



Internet  
refrigerator



Slingbox: watch,  
control cable TV remotely



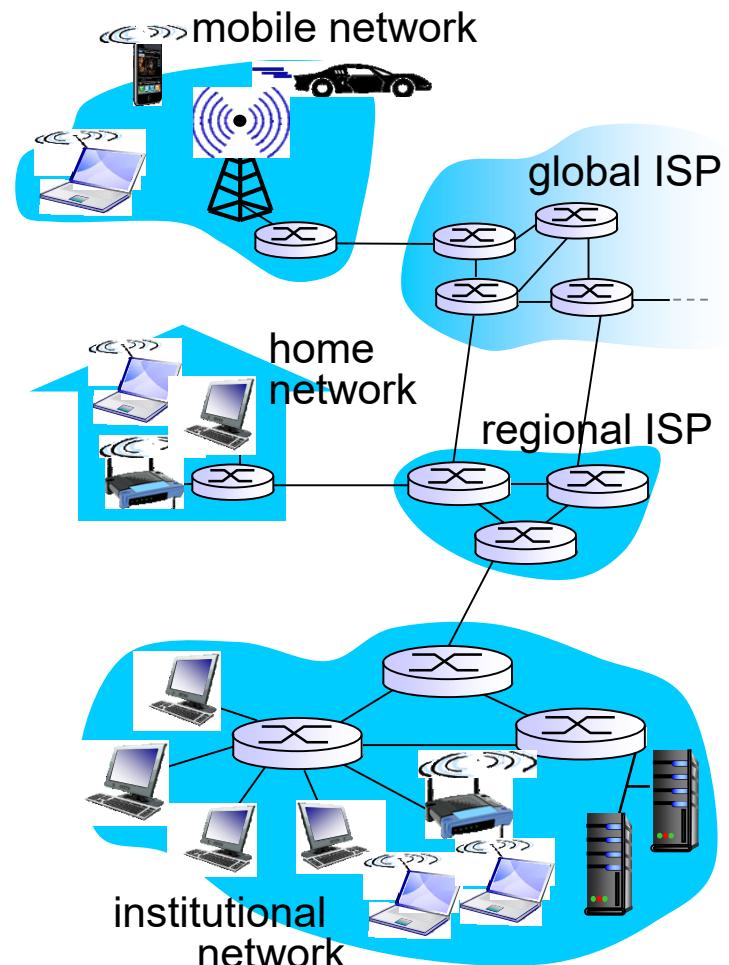
Internet phones



Tweet-a-watt:  
monitor energy use

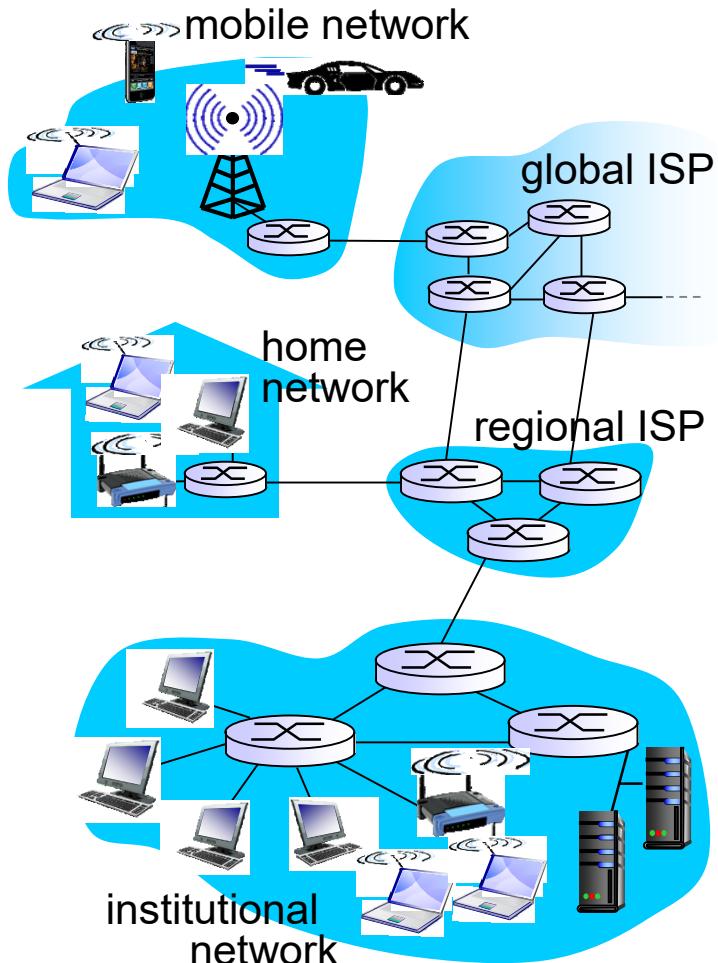
# What's the Internet: “nuts and bolts” view

- ❖ *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

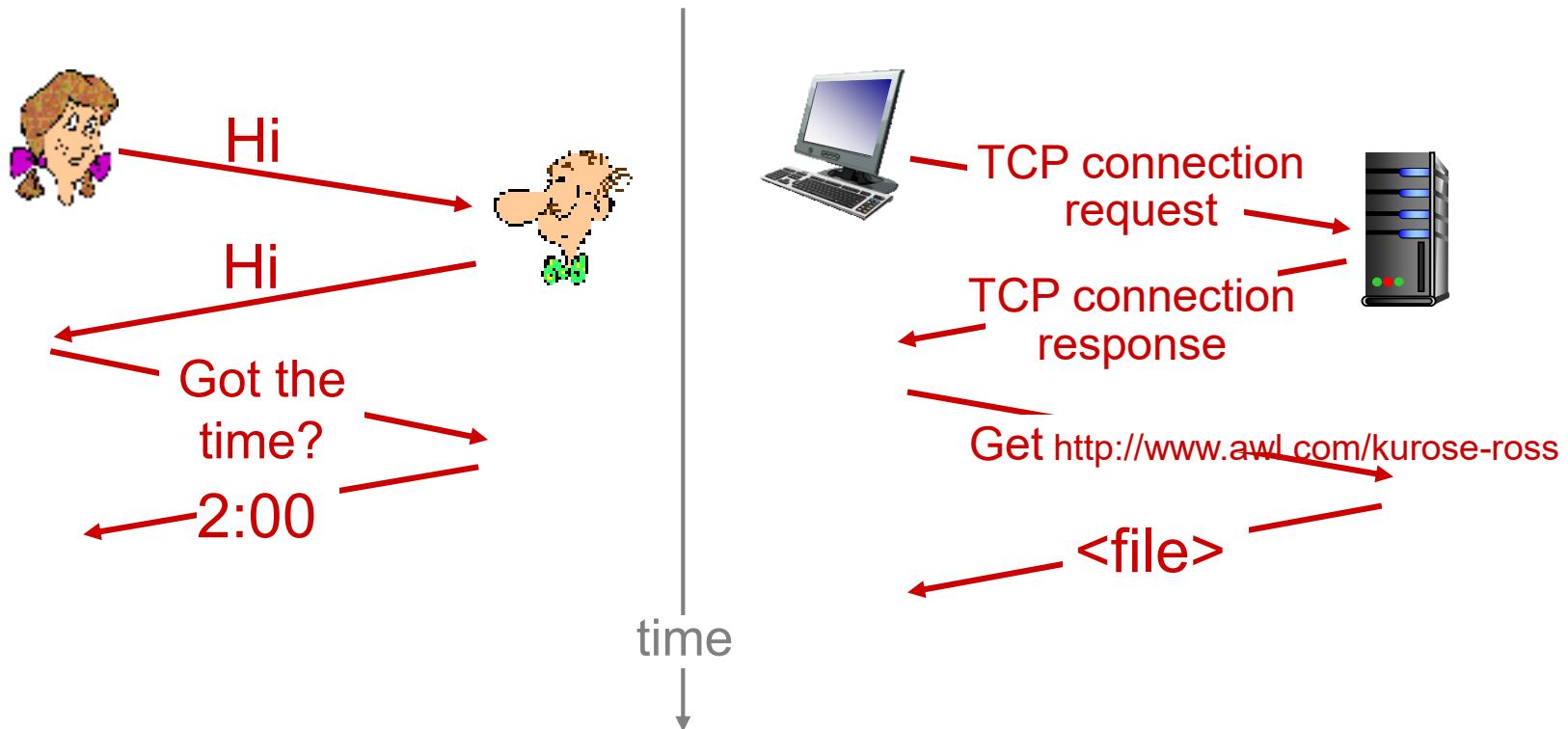
## *network protocols:*

- ❖ 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

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- 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:

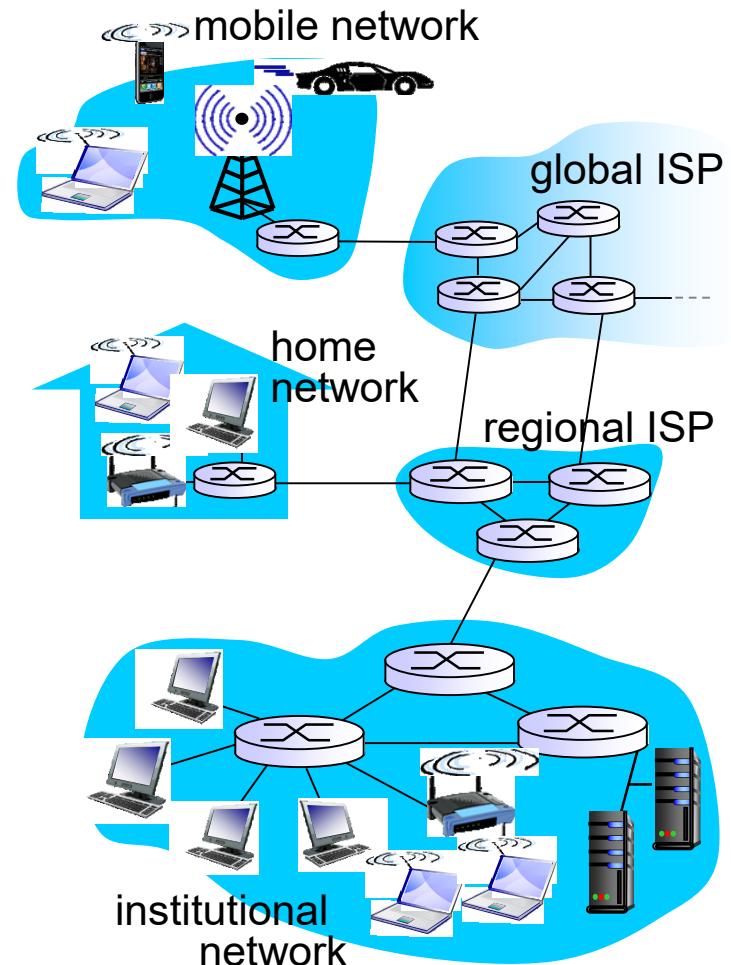
- ❖ **network edge:**

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

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

- ❖ **network core:**

- interconnected routers
- network of networks



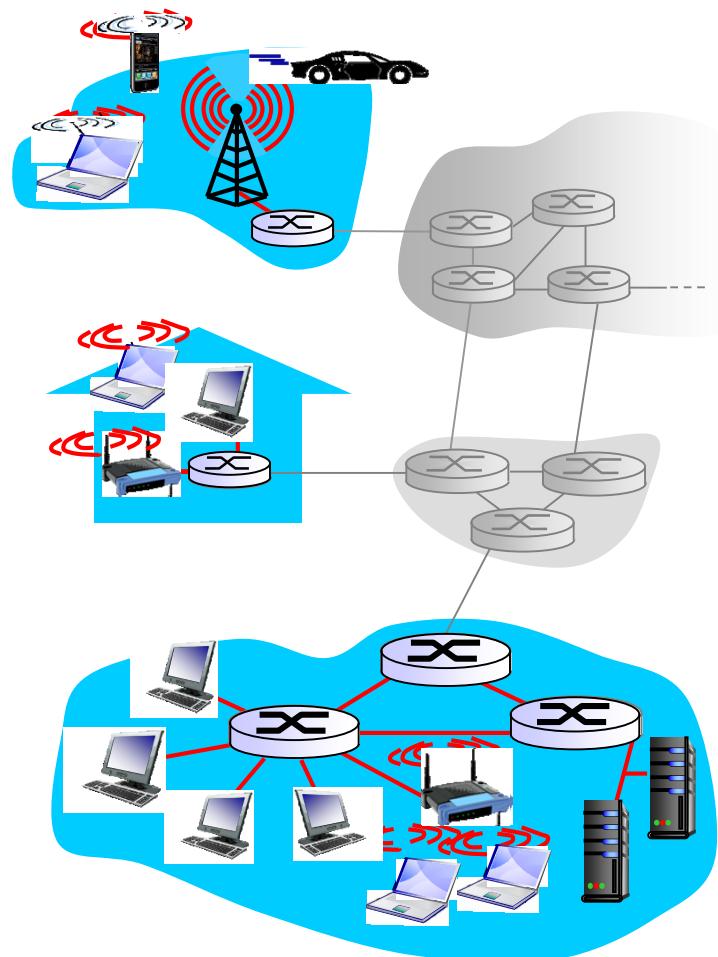
# Access networks and physical media

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

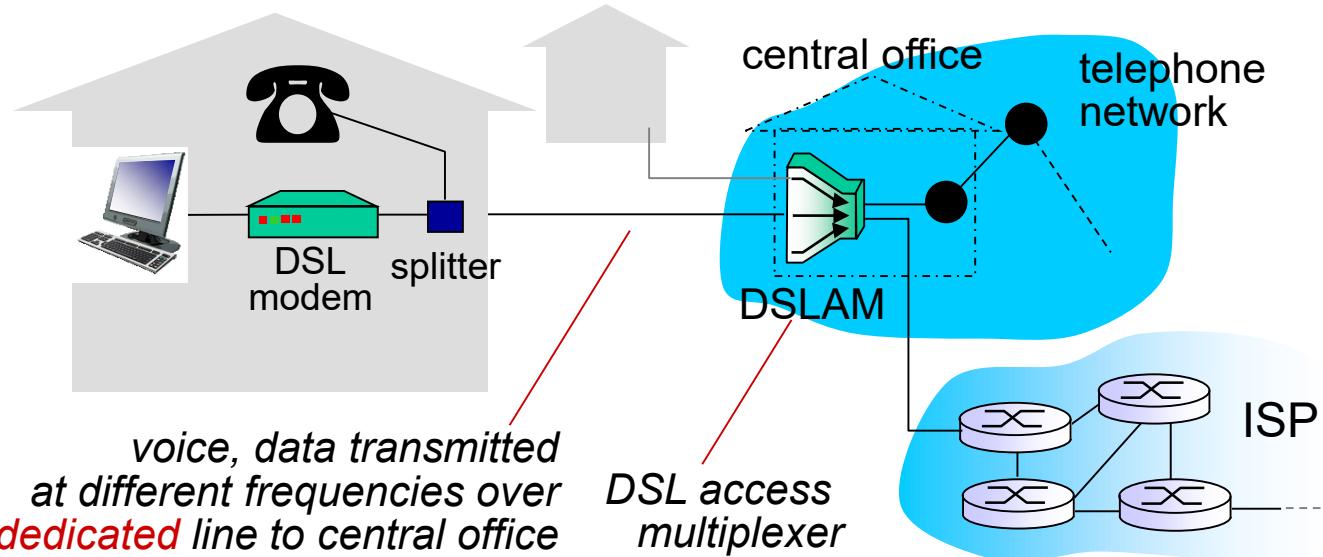
- ❖ residential access nets
- ❖ institutional access networks (school, company)
- ❖ mobile access networks

*keep in mind:*

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

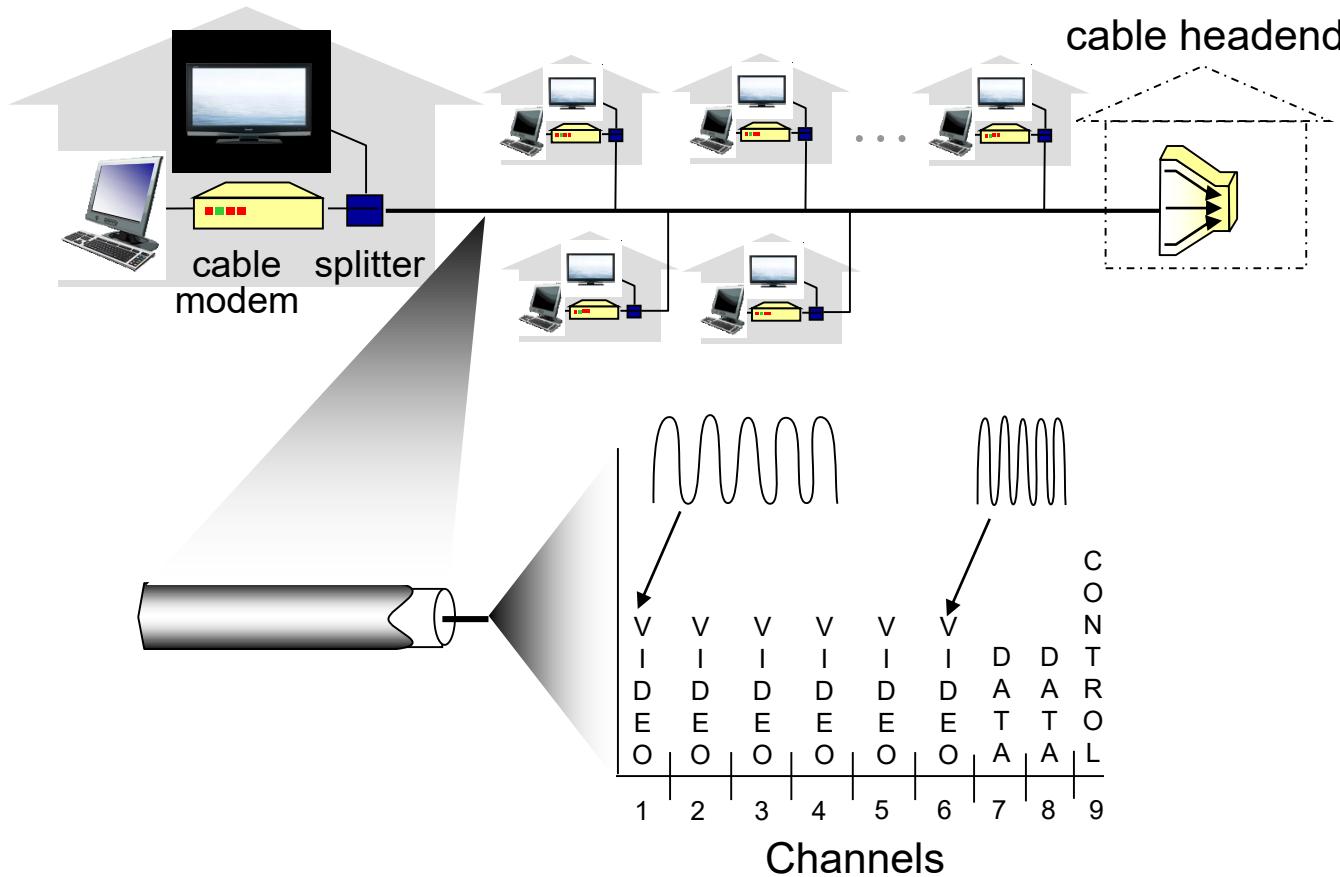


# Access net: digital subscriber line (DSL)



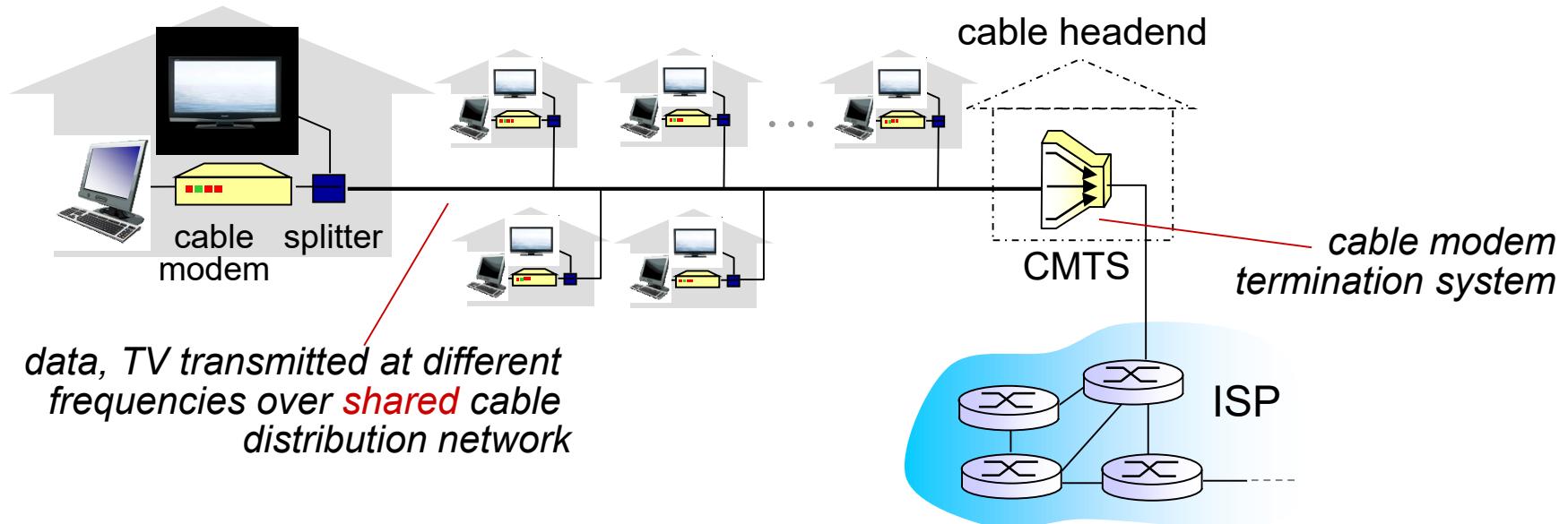
- ❖ use **existing** telephone line to central office DSLAM
  - data over DSL phone line goes to Internet
  - voice over DSL phone line goes to telephone net
- ❖ < 2.5 Mbps upstream transmission rate (typically < 1 Mbps)
- ❖ < 24 Mbps downstream transmission rate (typically < 10 Mbps)

# Access net: cable network



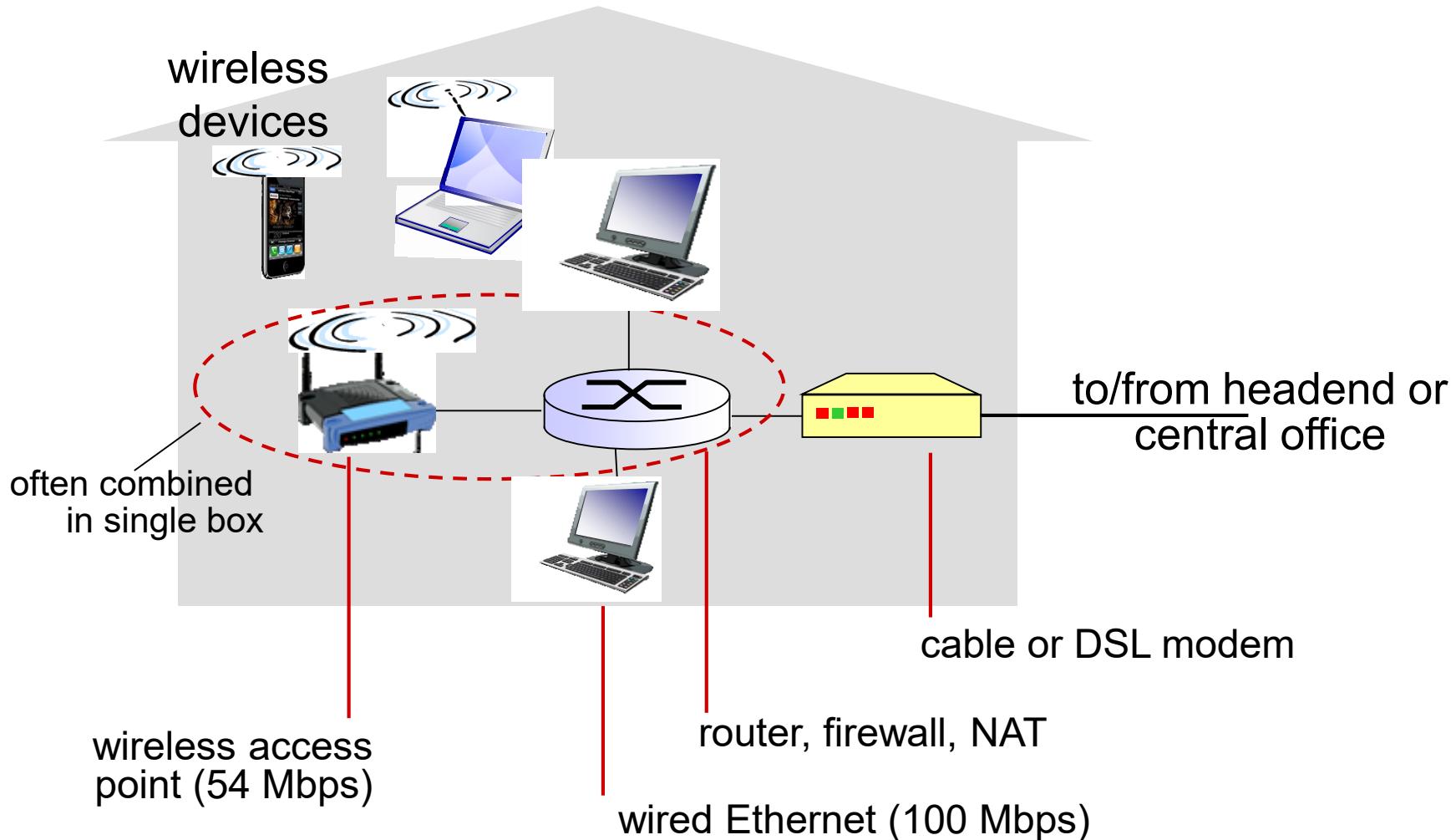
*frequency division multiplexing:* different channels transmitted in different frequency bands

# Access net: cable network

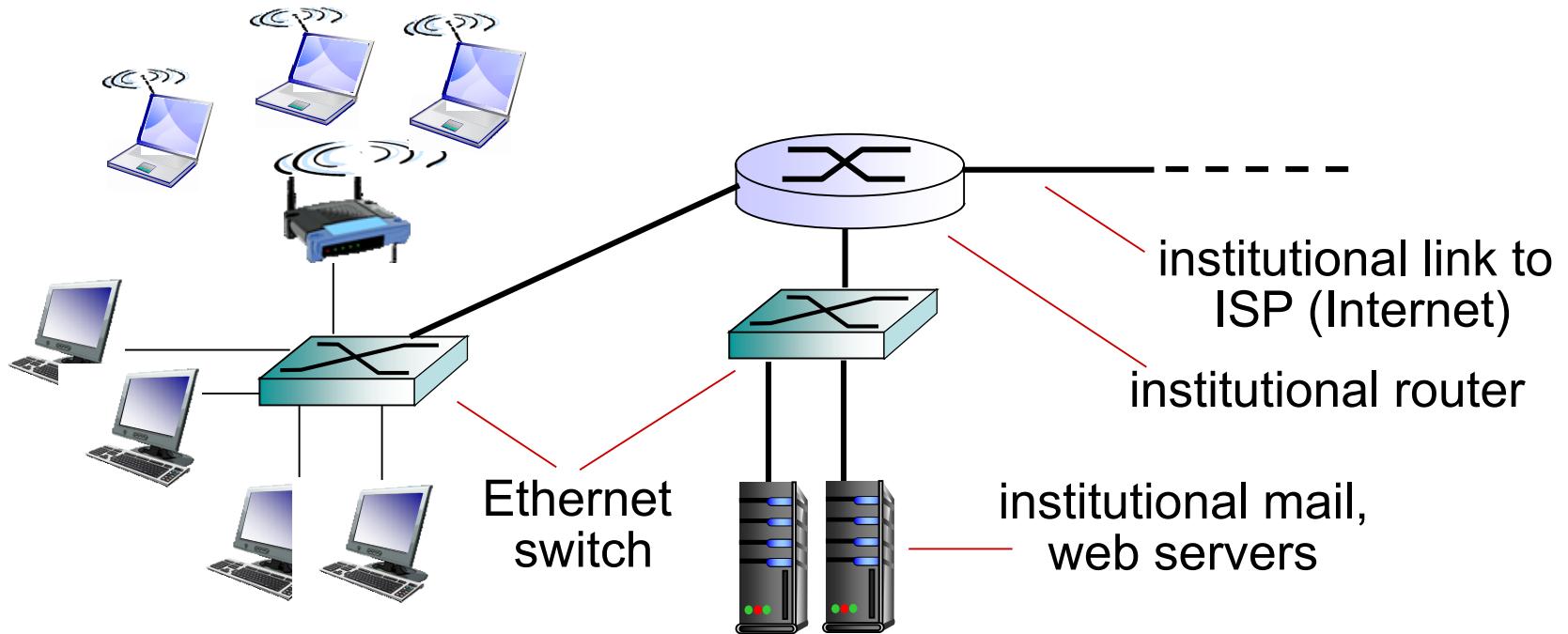


- ❖ HFC: hybrid fiber coax
  - asymmetric: up to 30Mbps downstream transmission rate, 2 Mbps upstream transmission rate
- ❖ network of cable, fiber attaches homes to ISP router
  - homes **share access network** to cable headend
  - unlike DSL, which has dedicated access to central office

# Access net: home network



# Enterprise access networks (Ethernet)



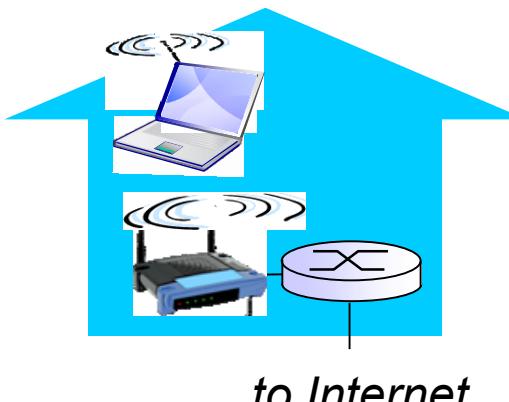
- ❖ typically used in companies, universities, etc
- ❖ 10 Mbps, 100Mbps, 1Gbps, 10Gbps transmission rates
- ❖ today, end systems typically connect into Ethernet switch

# Wireless access networks

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

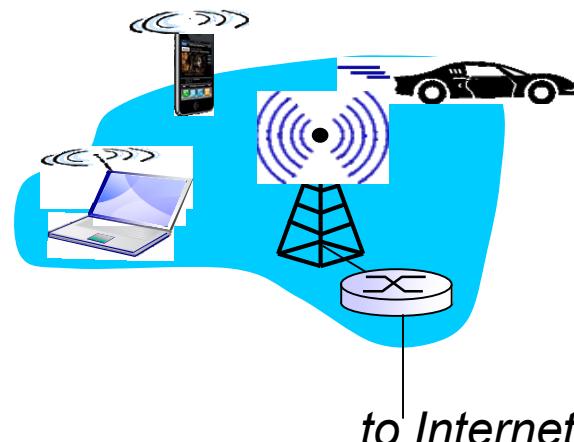
## wireless LANs:

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



## wide-area wireless access

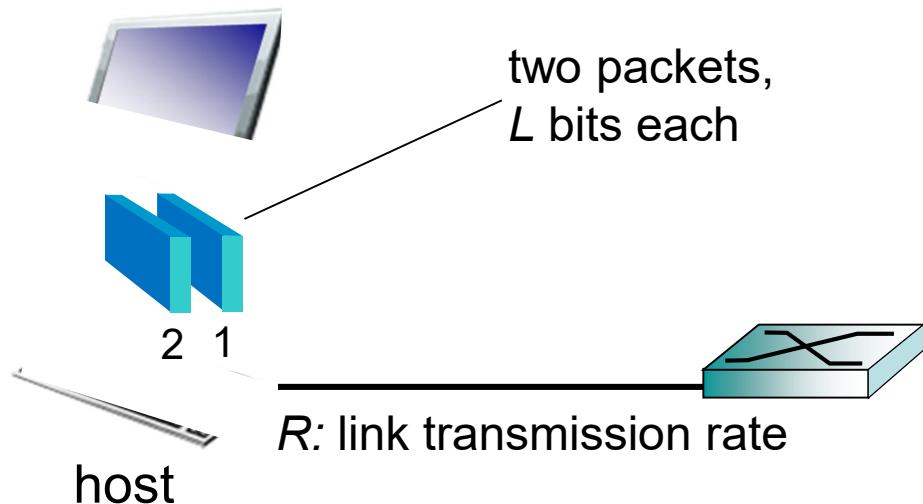
- provided by telco (cellular) operator, 10's km
- between 1 and 10 Mbps
- 3G, 4G: LTE



# Host: sends packets of data

host sending function:

- ❖ takes application message
- ❖ breaks into smaller chunks, known as *packets*, of length  $L$  bits
- ❖ transmits packet into access network at *transmission rate R*
  - link transmission rate, aka link *capacity*, aka *link bandwidth*



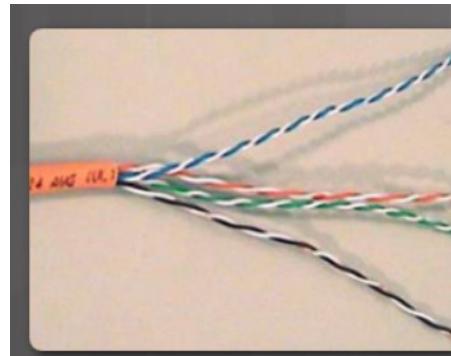
$$\text{packet transmission delay} = \frac{\text{time needed to transmit } L\text{-bit packet into link}}{R \text{ (bits/sec)}}$$

# 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
- ❖ UTP and STP
  - Category 5: 100 Mbps, 1 Gbps Ethernet
  - Category 6: 10Gbps



Unshielded Twisted-Pair (UTP) Cable

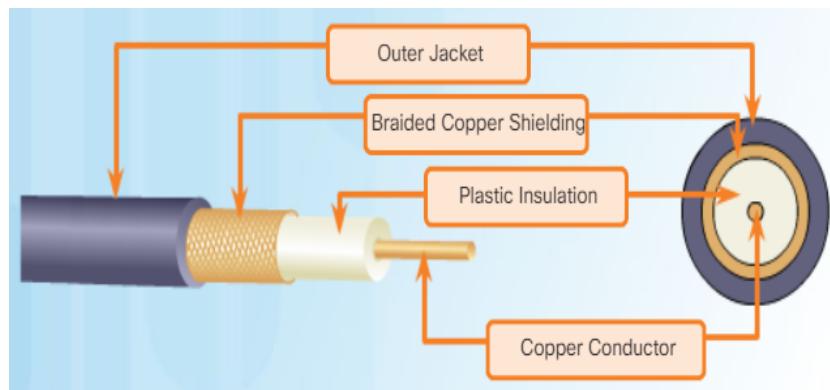


Shielded Twisted-Pair (STP) Cable

# Physical media: coax, fiber

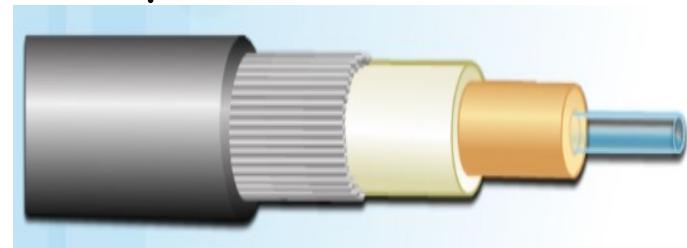
## *coaxial cable:*

- ❖ 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)
  - Single-mode vs Multimode
- ❖ low error rate:
  - repeaters spaced far apart
  - immune to electromagnetic



# 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

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I.3 network core

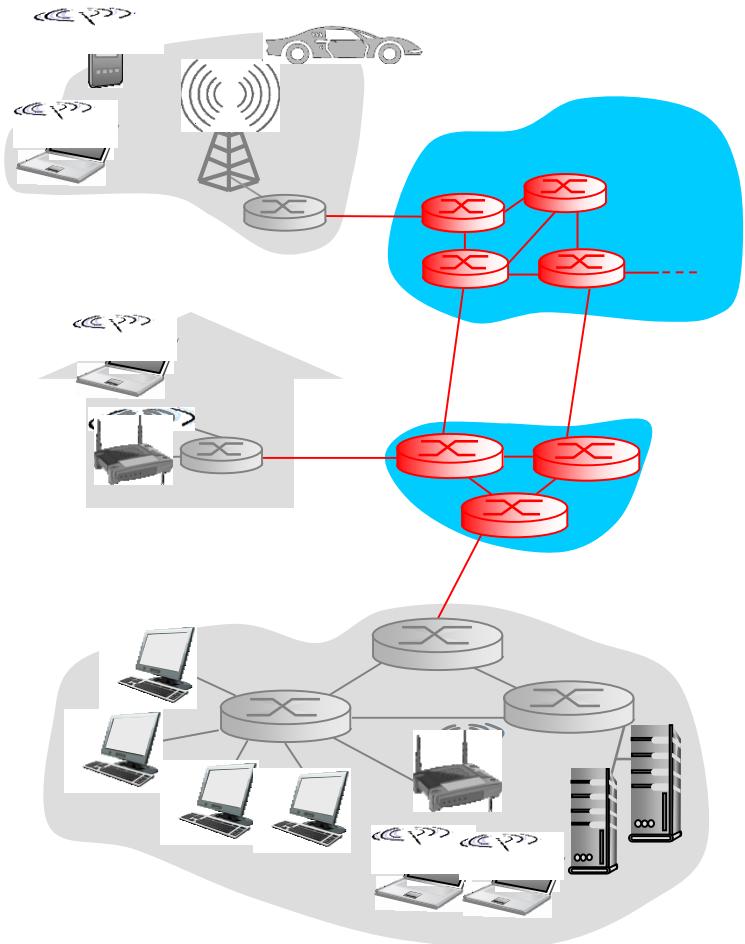
- packet switching, circuit switching, network structure

I.4 delay, loss, throughput in networks

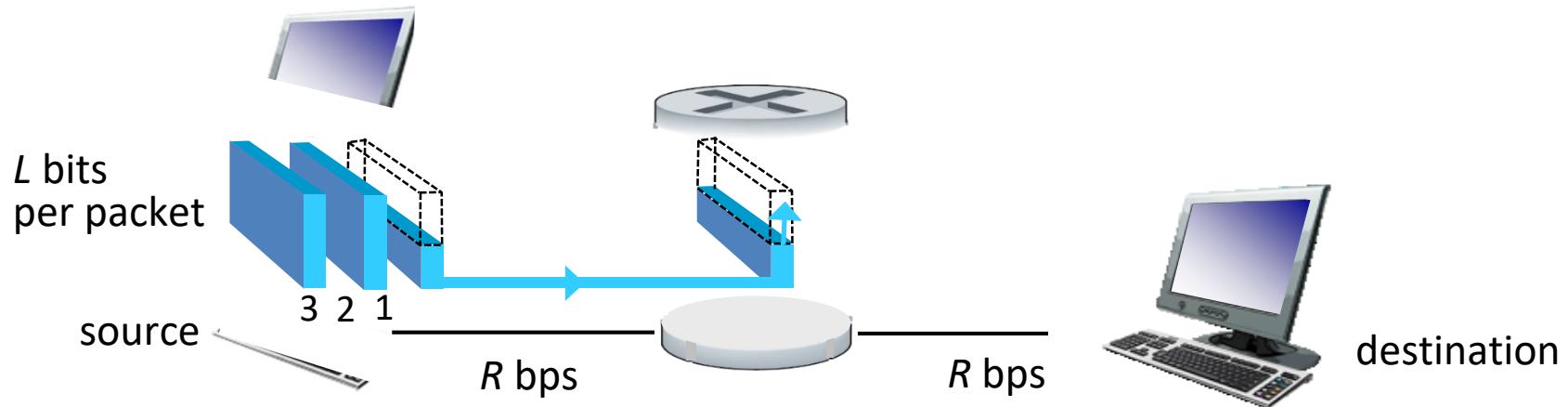
I.5 protocol layers, service models

# 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



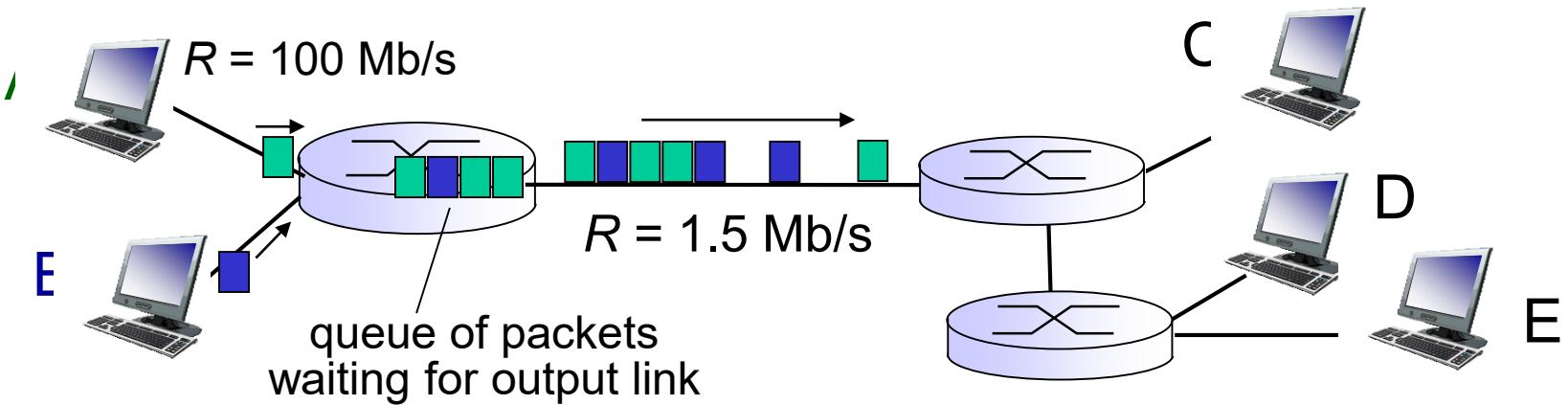
# Packet-switching: store-and-forward



- ❖ 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:*
- $L = 7.5 \text{ Mbits}$
  - $R = 1.5 \text{ Mbps}$
  - one-hop transmission delay = 5 sec
- } more on delay shortly ...

# Packet Switching: queueing delay, loss



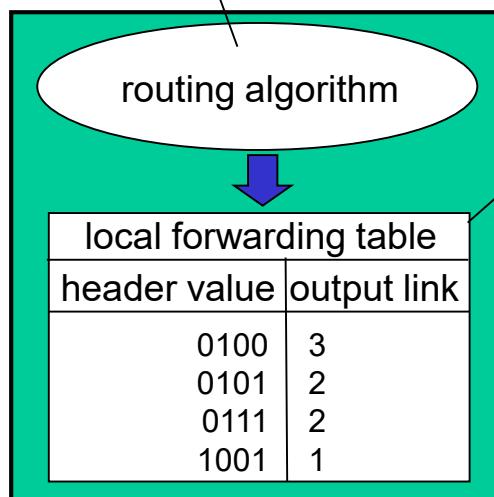
## queuing and loss:

- ❖ 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

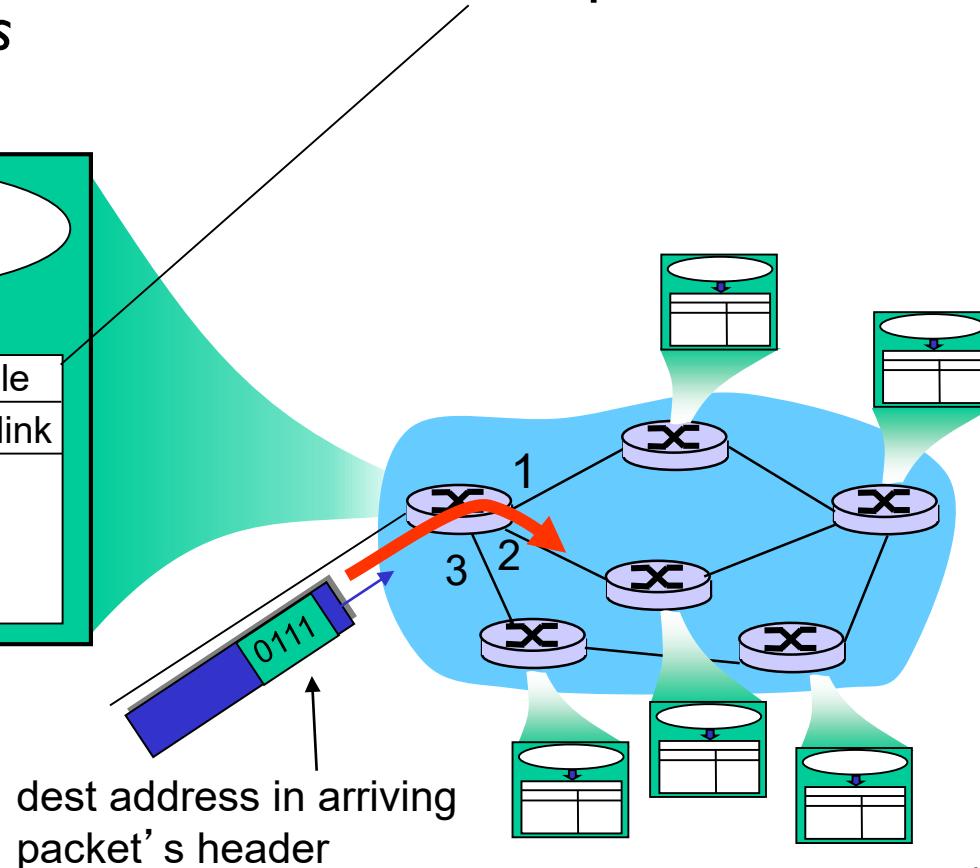
# Two key network-core functions

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

- *routing algorithms*



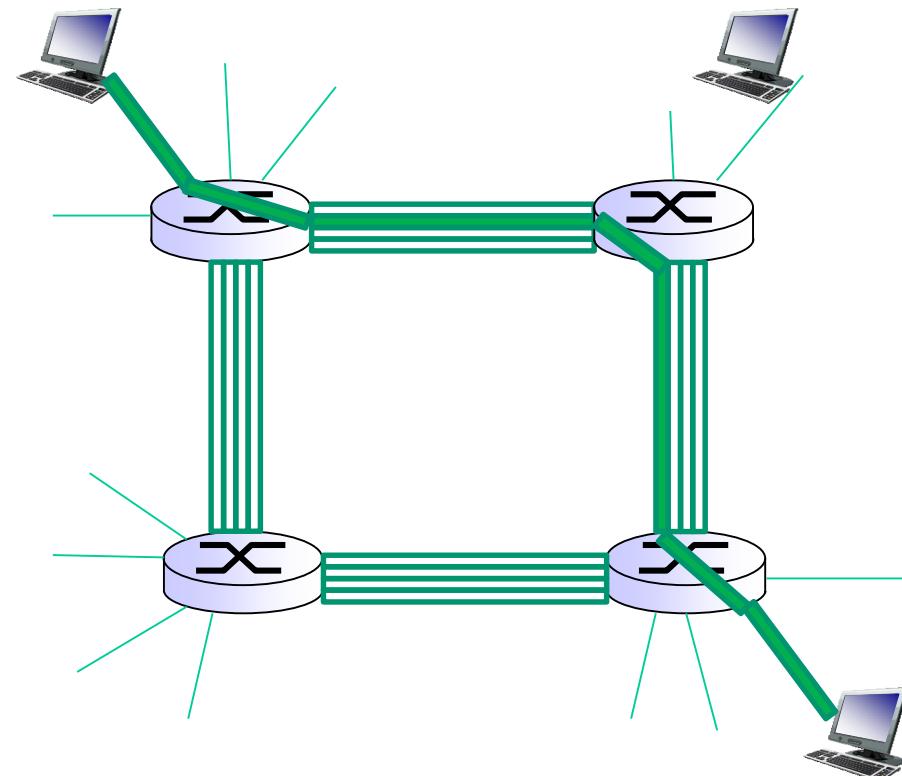
**forwarding:** move packets from router's input to appropriate router output



# Alternative core: circuit switching

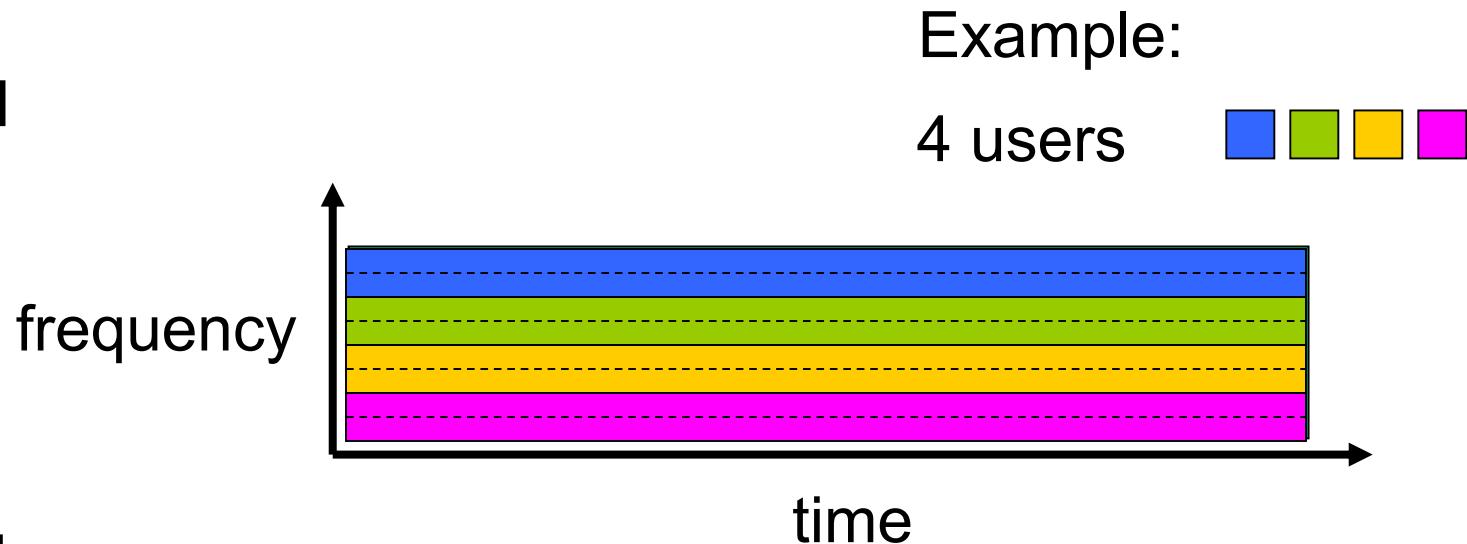
end-end resources allocated to, reserved for “call” between source & dest:

- ❖ In diagram, each link has four circuits.
  - call gets 2<sup>nd</sup> circuit in top link and 1<sup>st</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

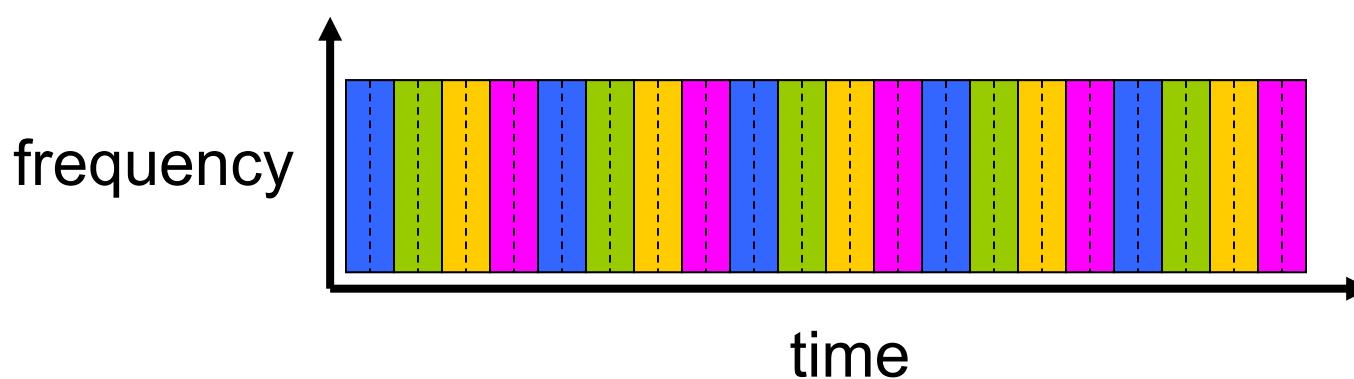


# Circuit switching: FDM versus TDM

FDM



TDM

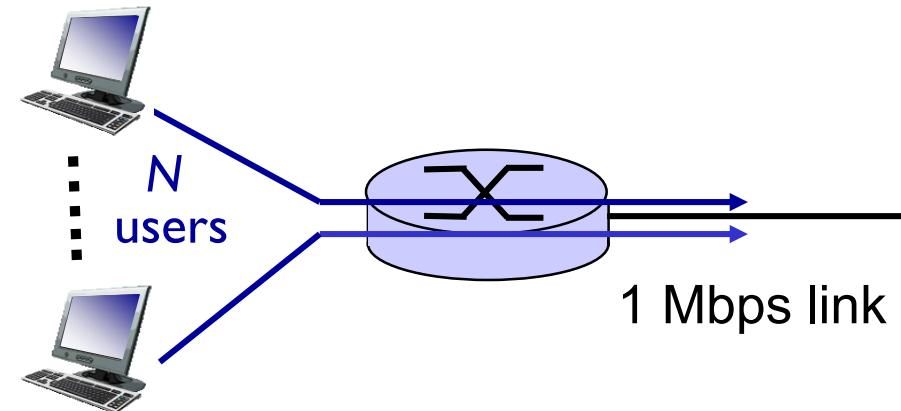


# Packet switching versus circuit switching

*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 \*

Q: how did we get value 0.0004?

Q: what happens if > 35 users ?

\* Check out the online interactive exercises for more examples

# 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)

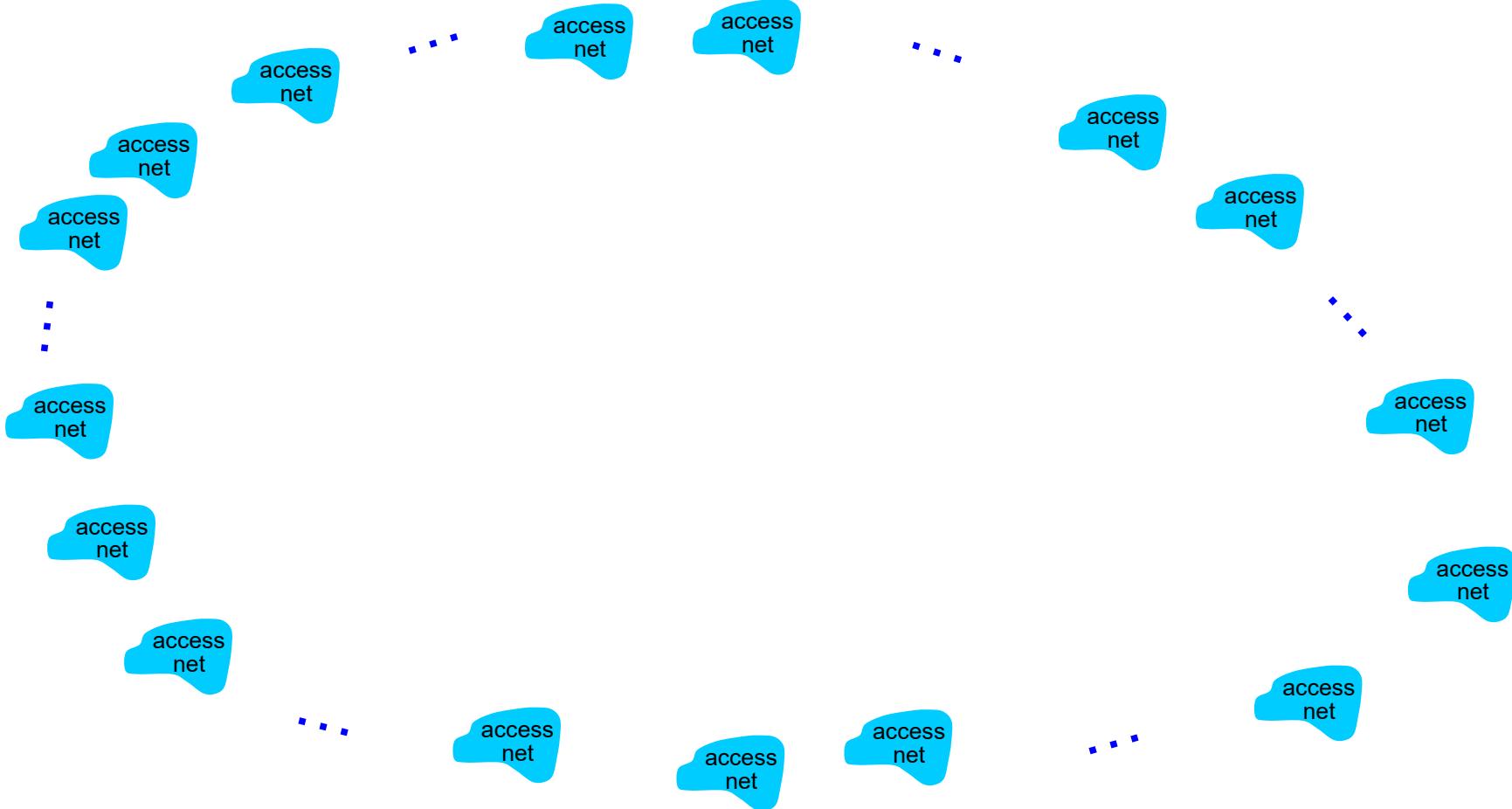
Q: human analogies of reserved resources (circuit switching)  
versus on-demand allocation (packet-switching)?

# 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

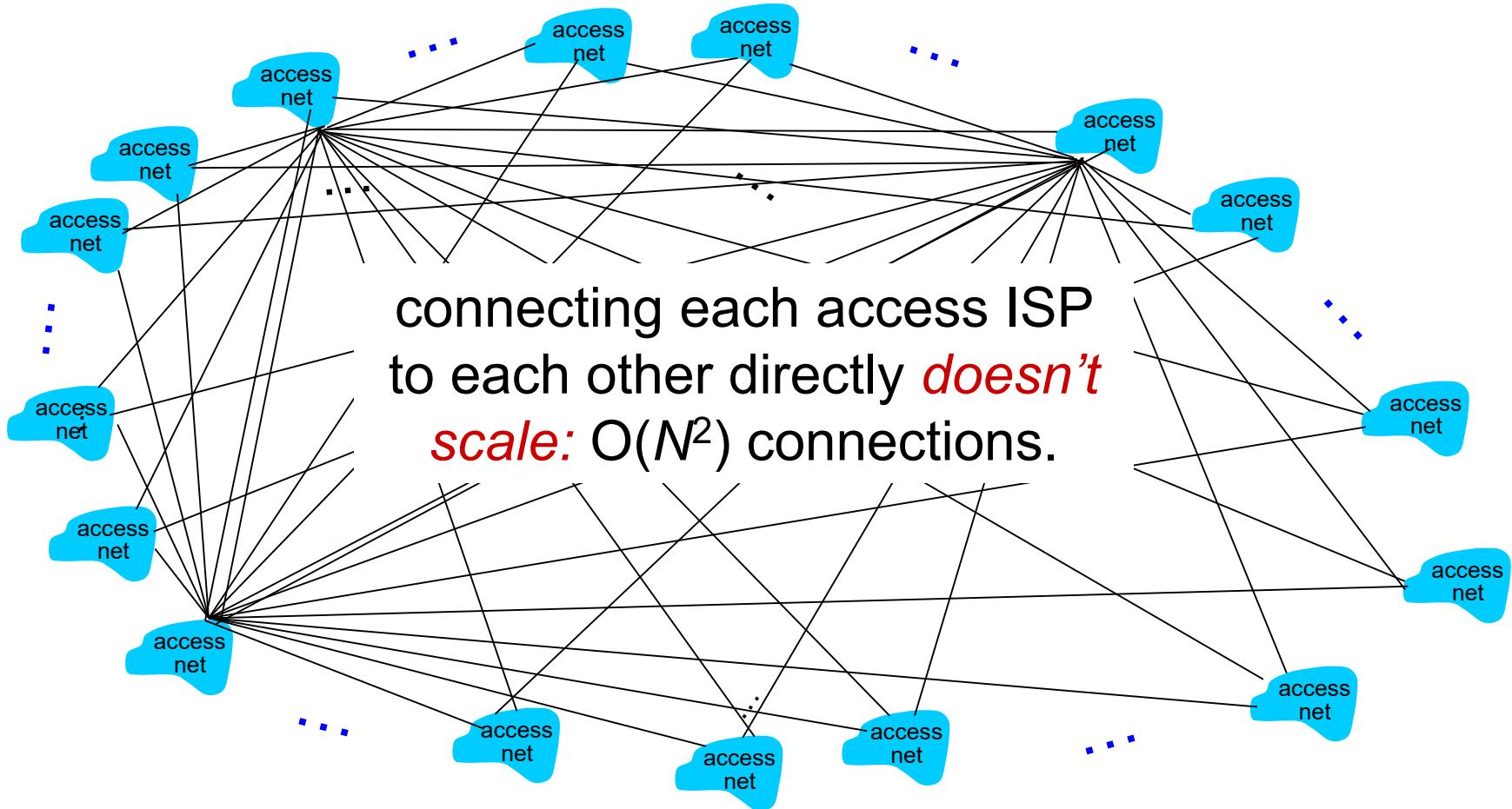
# Internet structure: network of networks

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



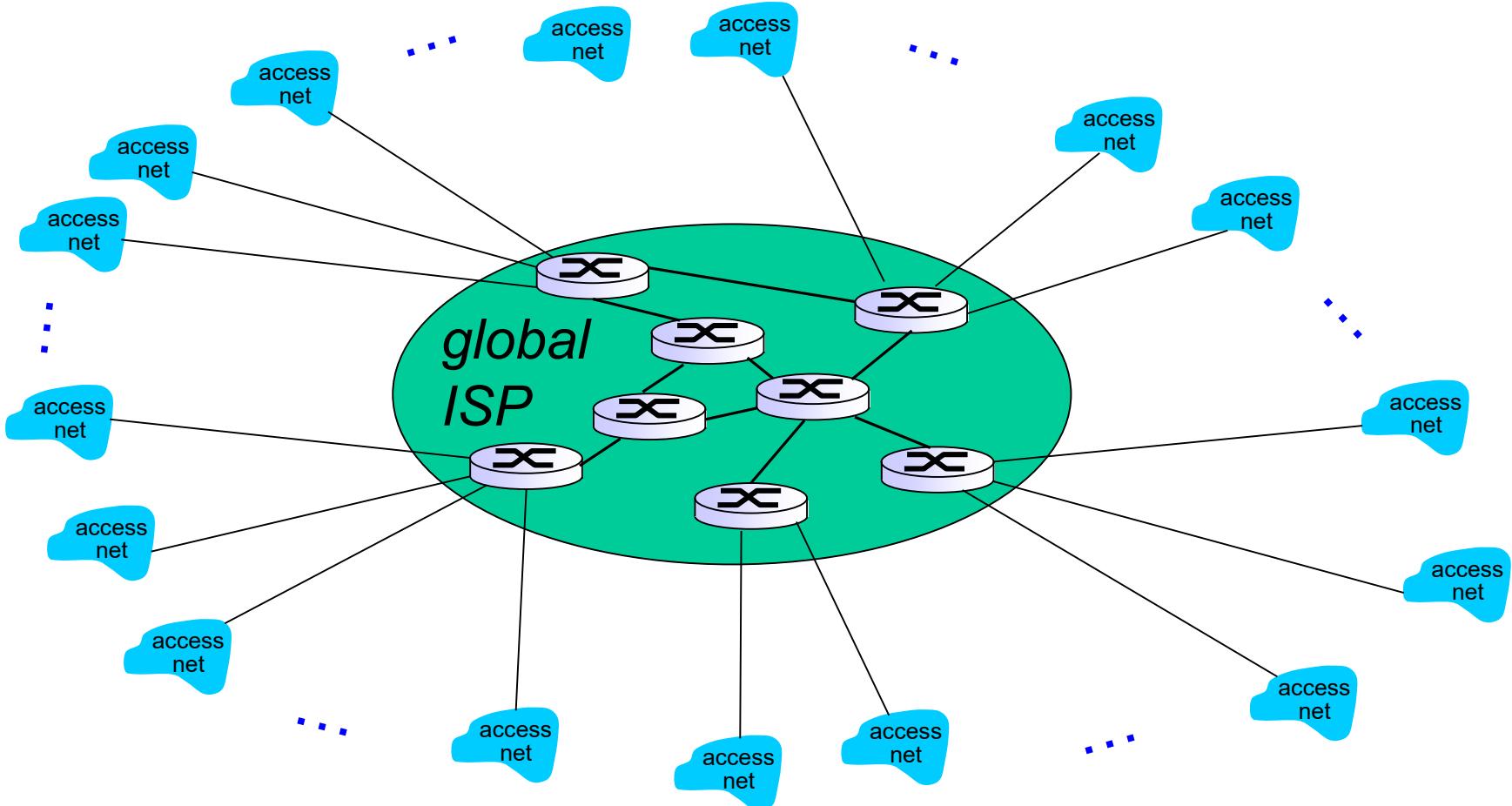
# Internet structure: network of networks

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



# Internet structure: network of networks

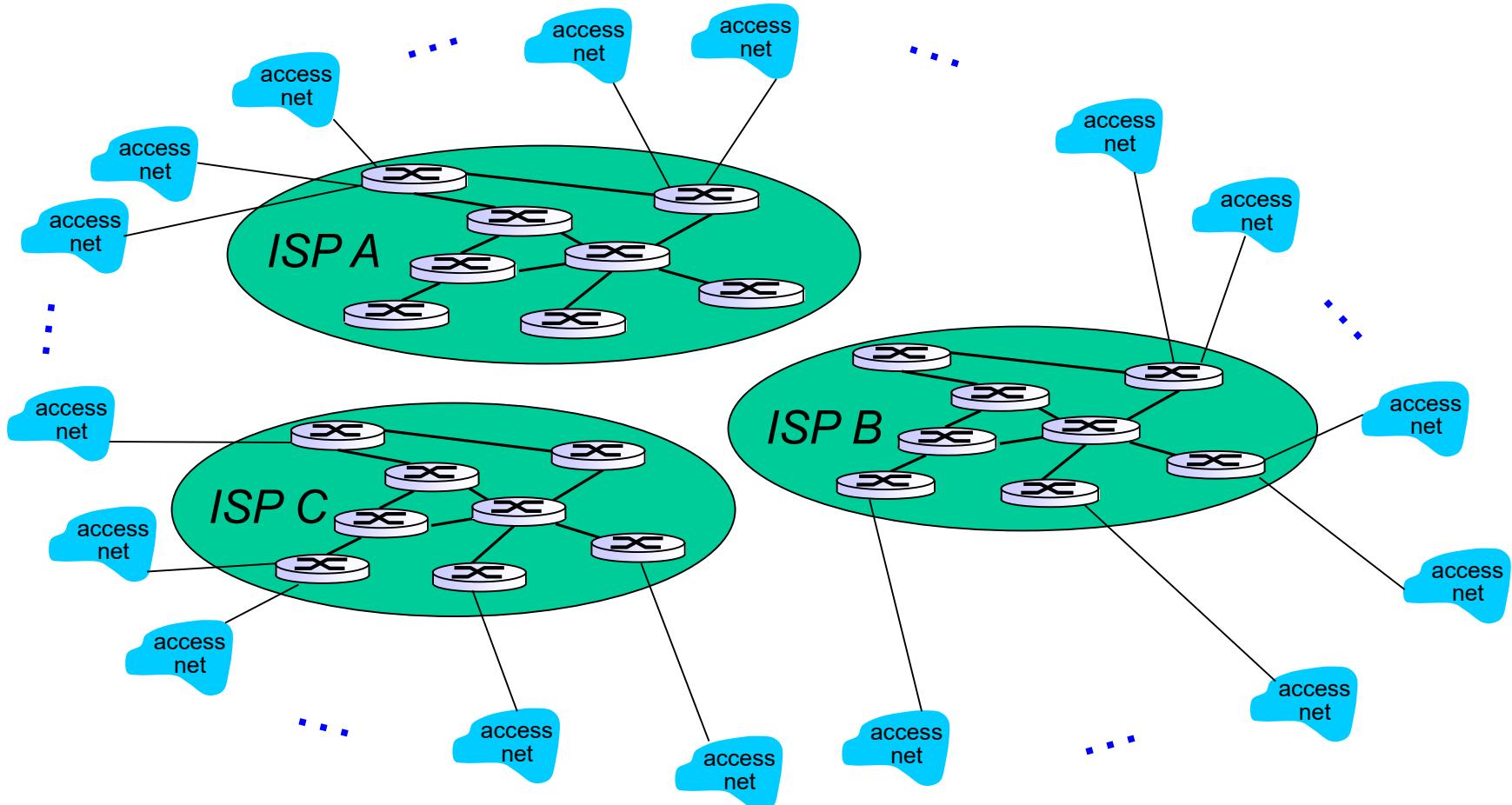
*Option: connect each access ISP to a global transit ISP? Customer and provider ISPs have economic agreement.*



# Internet structure: network of networks

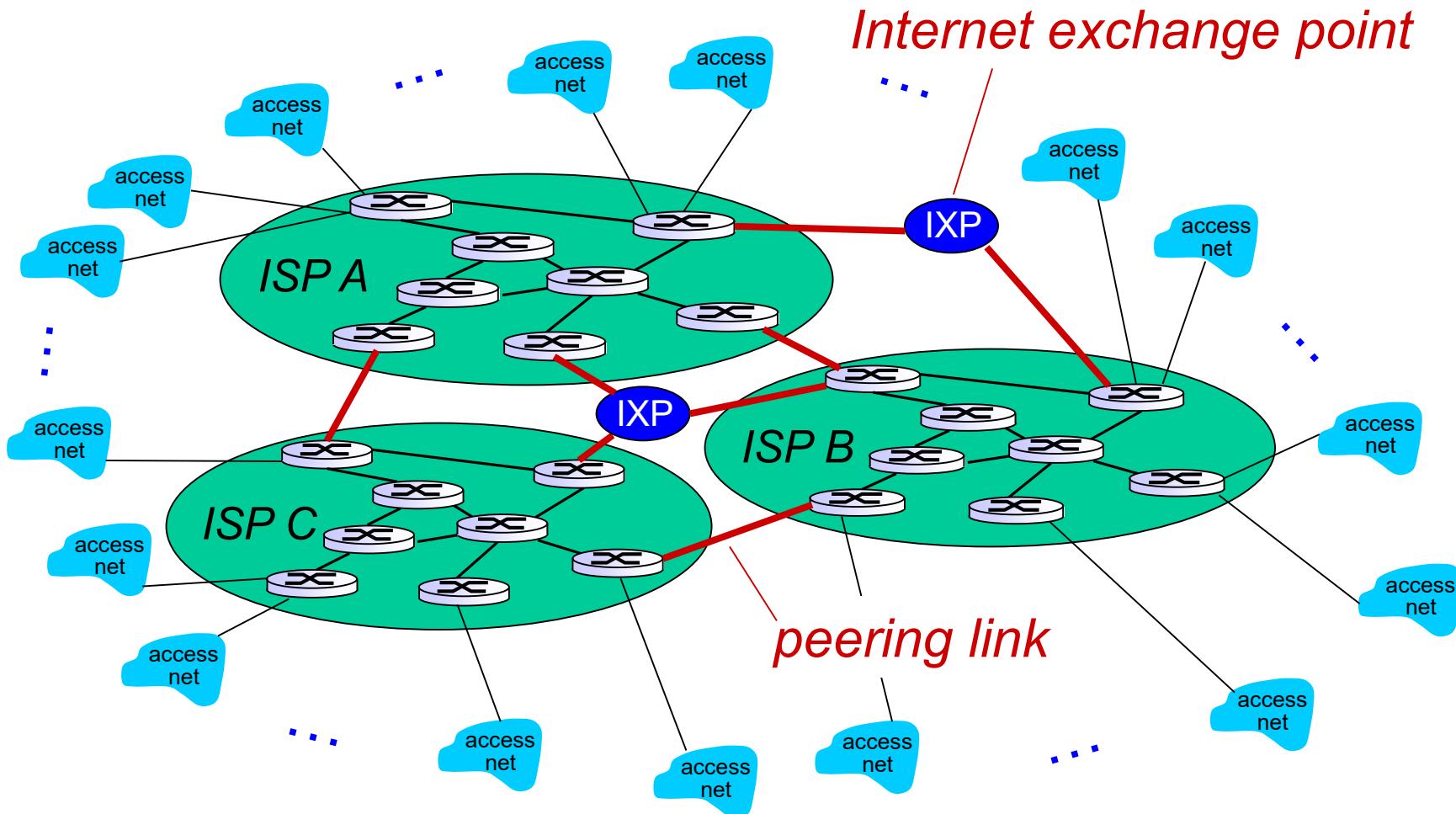
But if one global ISP is viable business, there will be competitors

....



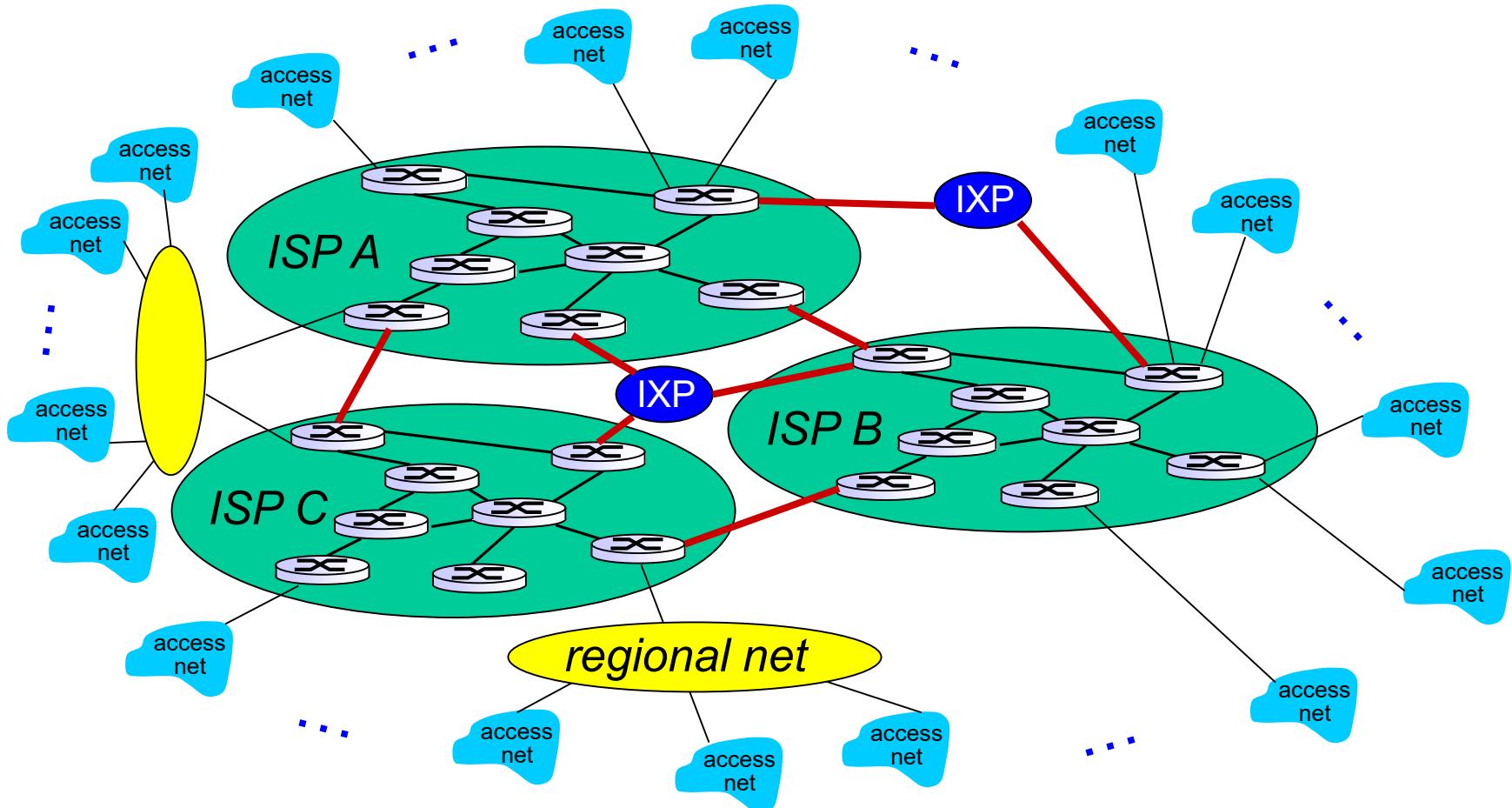
# Internet structure: network of networks

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



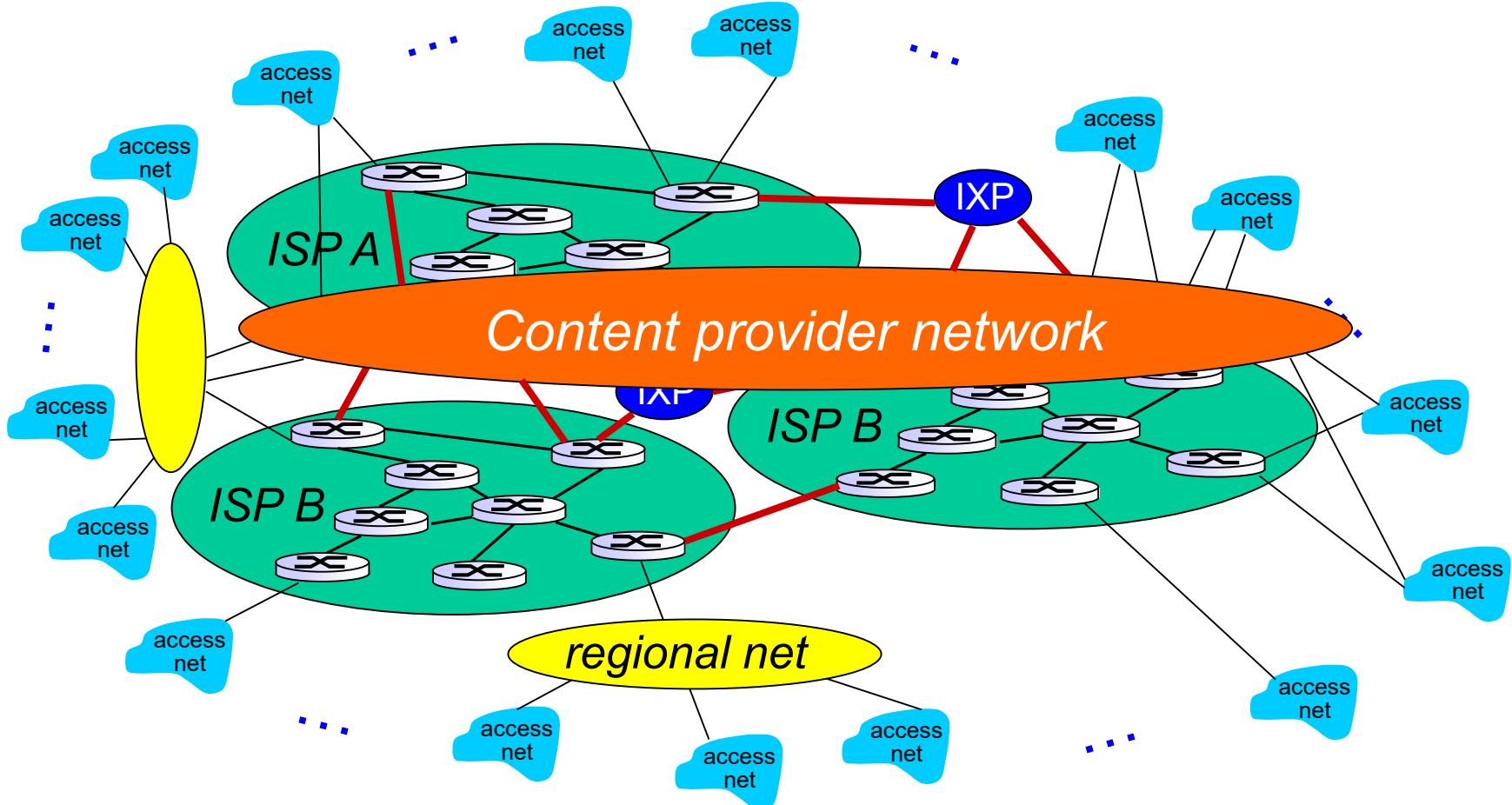
# Internet structure: network of networks

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

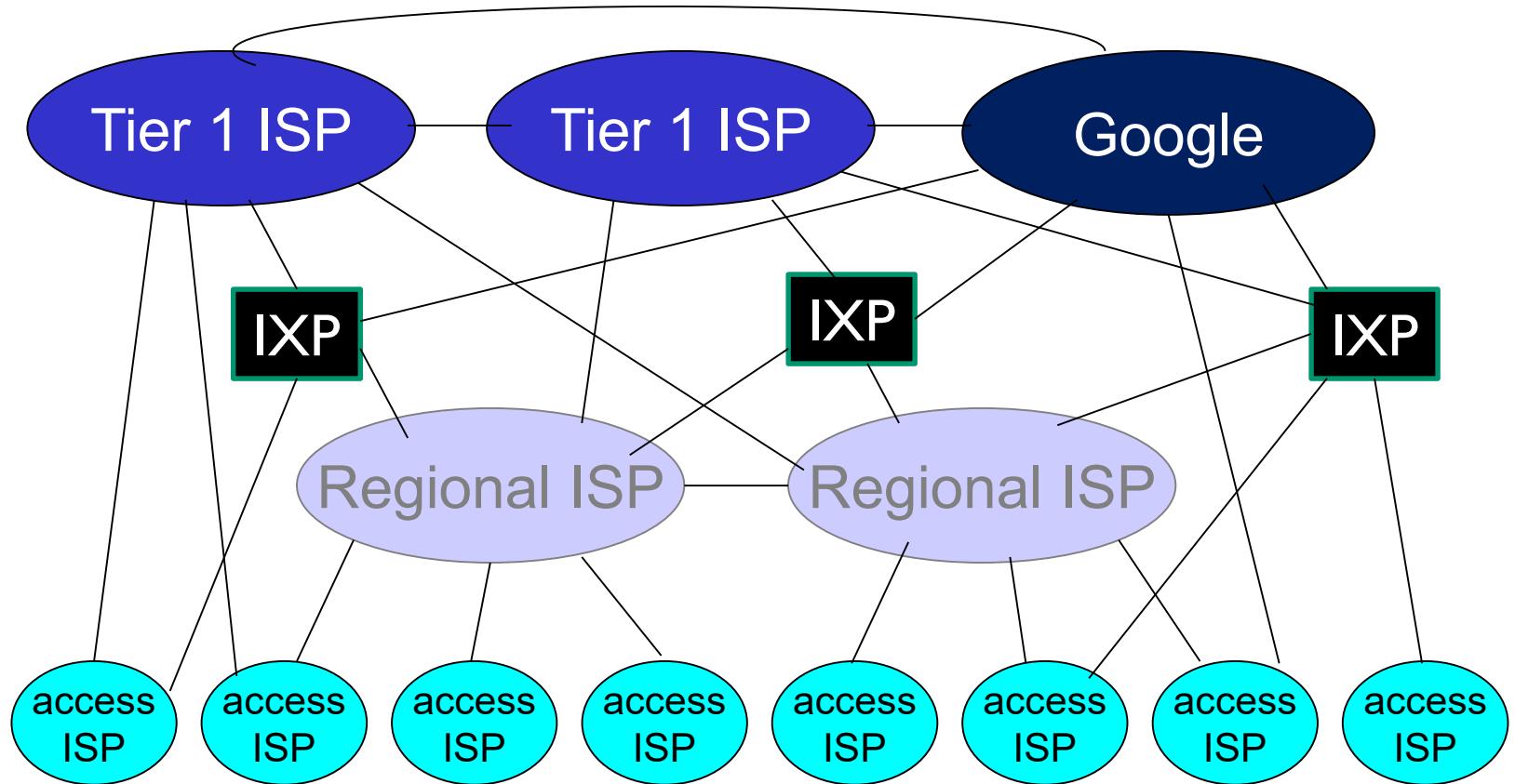


# Internet structure: network of networks

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

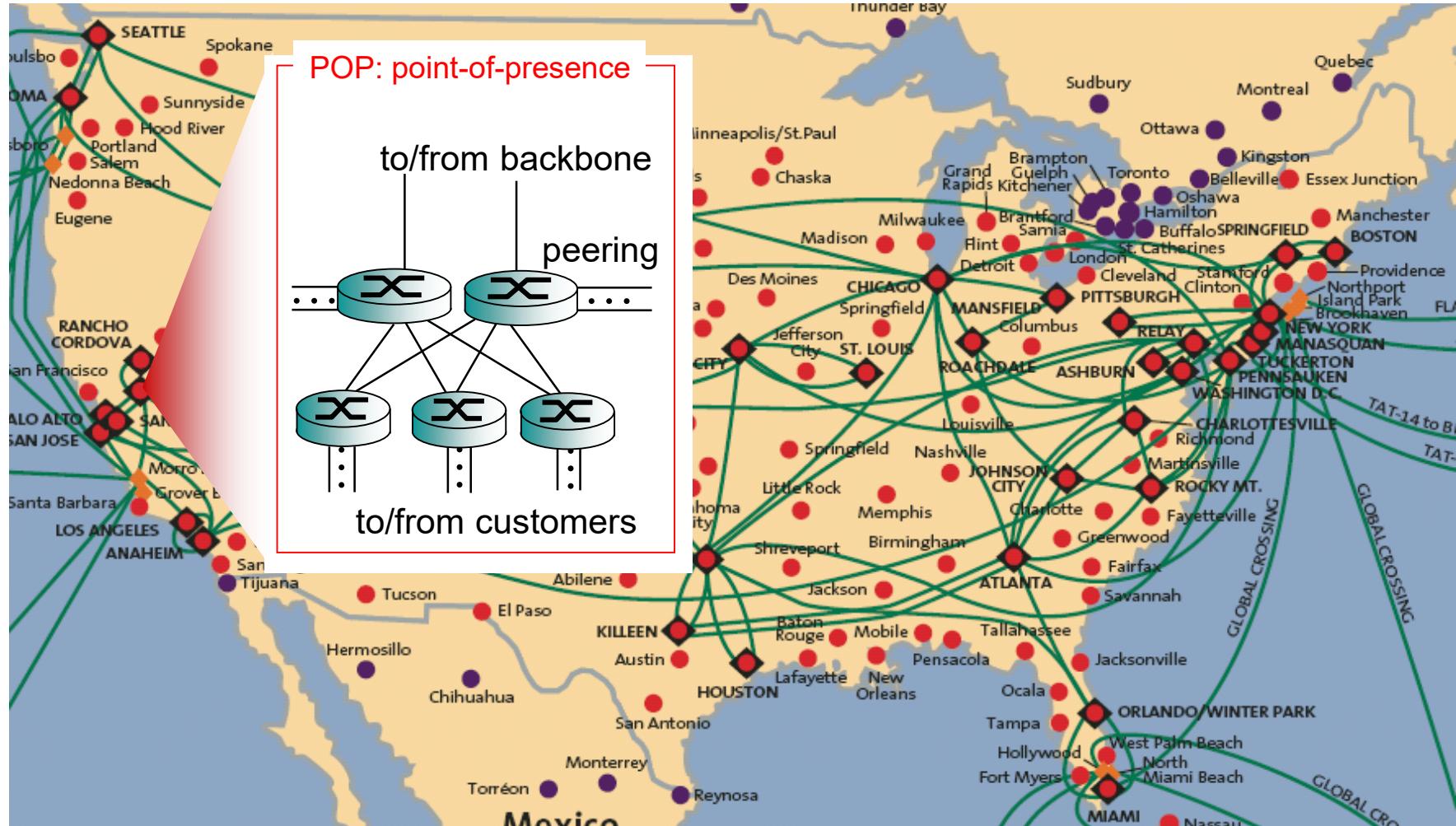


# Internet structure: network of networks



- ❖ at center: small # of well-connected large networks
  - “tier-I” 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-I, regional ISPs

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



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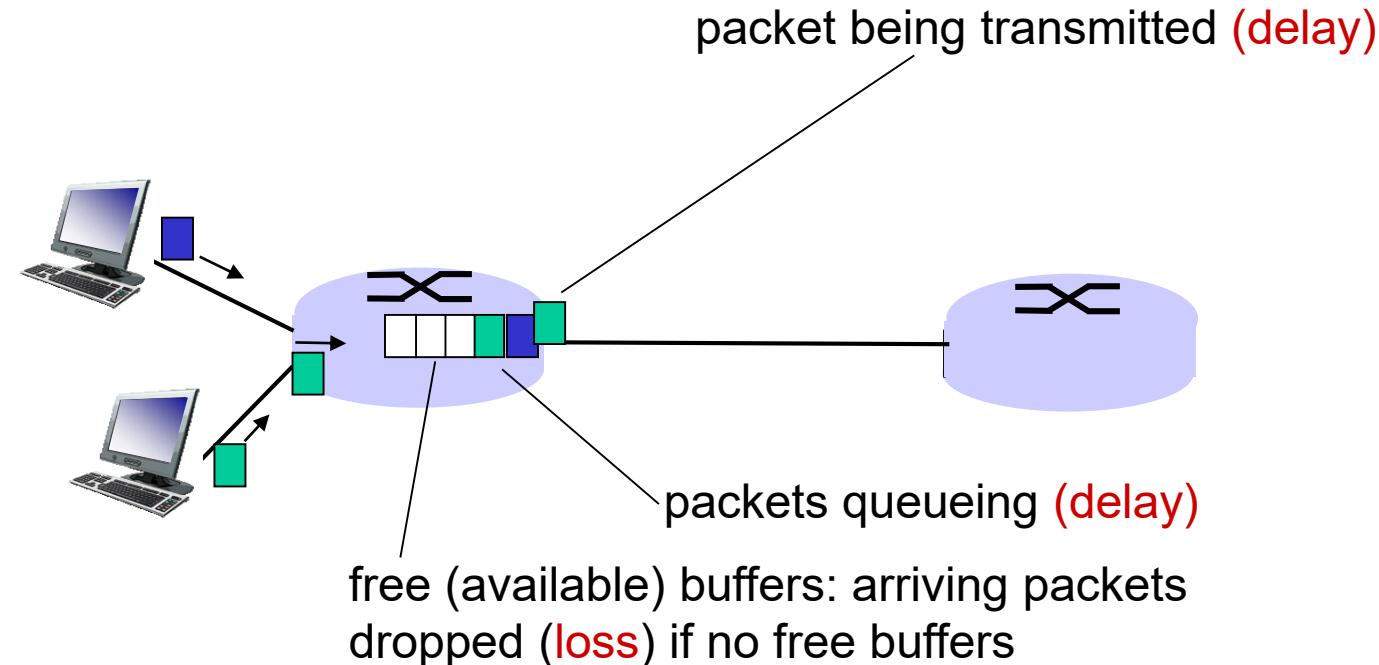
I.4 delay, loss, throughput in networks

I.5 protocol layers, service models

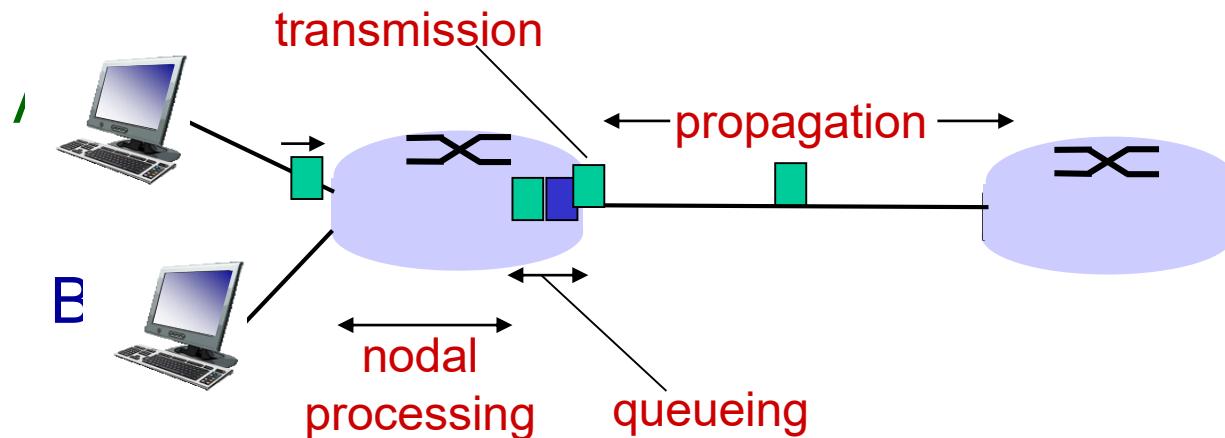
# How do loss and delay occur?

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



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

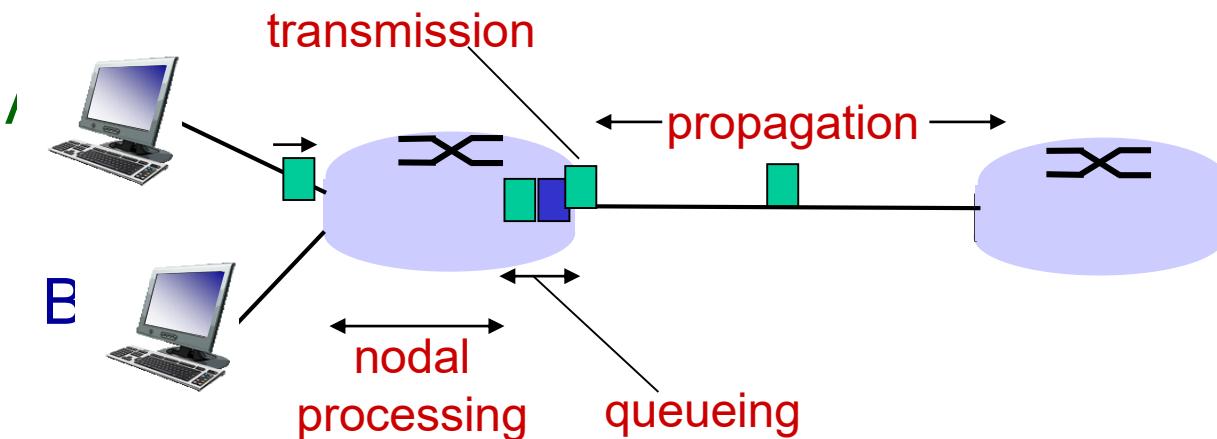
$d_{\text{proc}}$ : nodal processing

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

$d_{\text{queue}}$ : queueing delay

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

# Four sources of packet delay



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

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

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

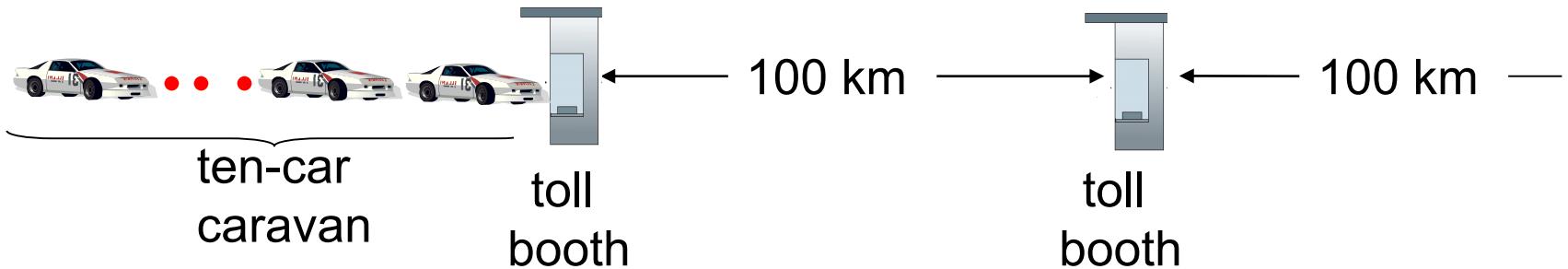
$d_{\text{trans}}$  and  $d_{\text{prop}}$   
very different

$d_{\text{prop}}$ : 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

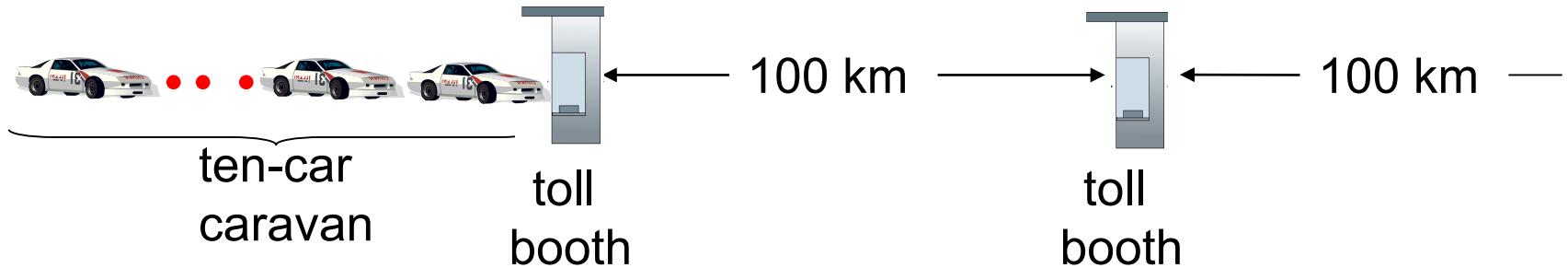
# Caravan analogy



- ❖ 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

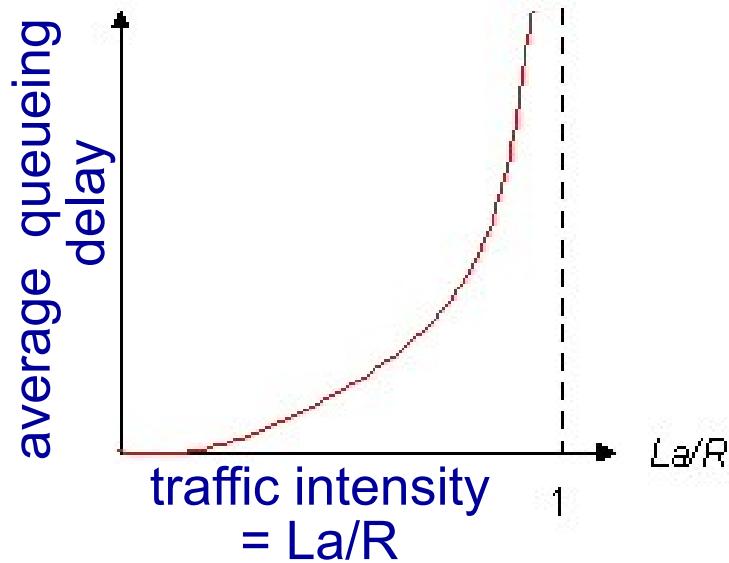
# Caravan analogy (more)



- ❖ 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.

# Queueing delay (revisited)

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



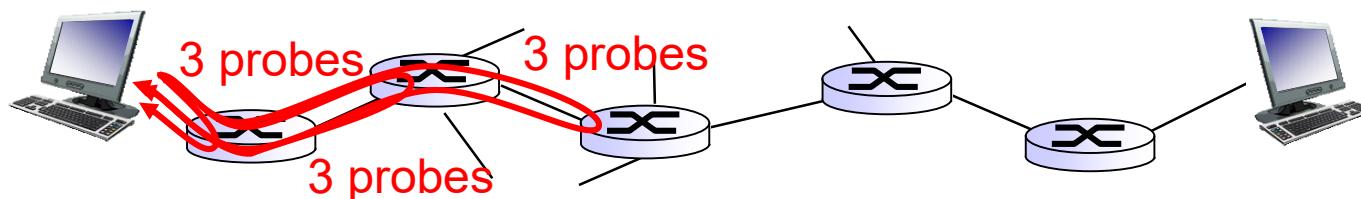
- ❖  $La/R \sim 0$ : avg. queueing delay small
- ❖  $La/R \rightarrow 1$ : avg. queueing delay large
- ❖  $La/R > 1$ : more “work” arriving than can be serviced, average delay infinite!



\* 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

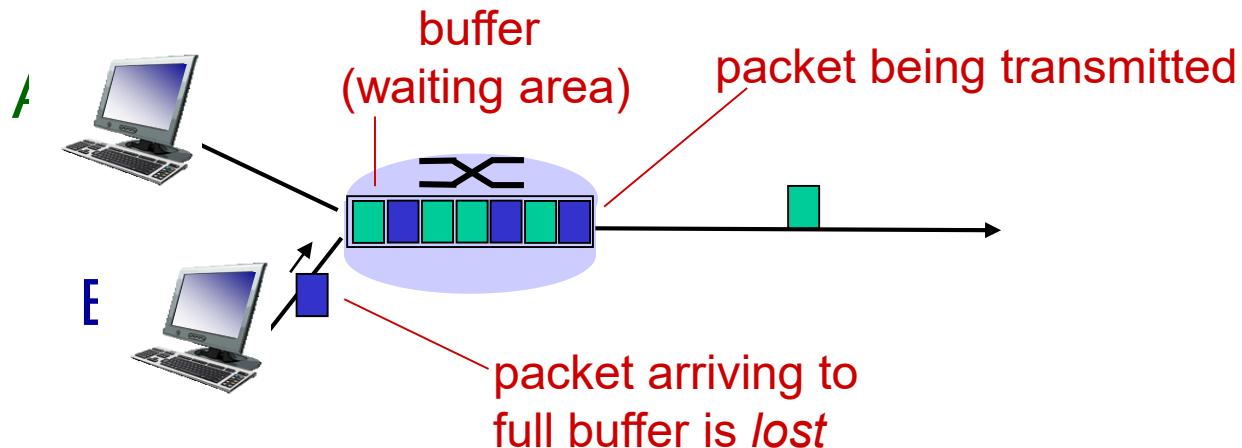
1	cs-gw (128.119.240.254)	1 ms	1 ms	2 ms
2	border1-rt-fa5-1-0.gw.umass.edu (128.119.3.145)	1 ms	1 ms	2 ms
3	cht-vbns.gw.umass.edu (128.119.3.130)	6 ms	5 ms	5 ms
4	jn1-at1-0-0-19.wor.vbns.net (204.147.132.129)	16 ms	11 ms	13 ms
5	jn1-so7-0-0-0.wae.vbns.net (204.147.136.136)	21 ms	18 ms	18 ms
6	abilene-vbns.abilene.ucaid.edu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

# Packet loss

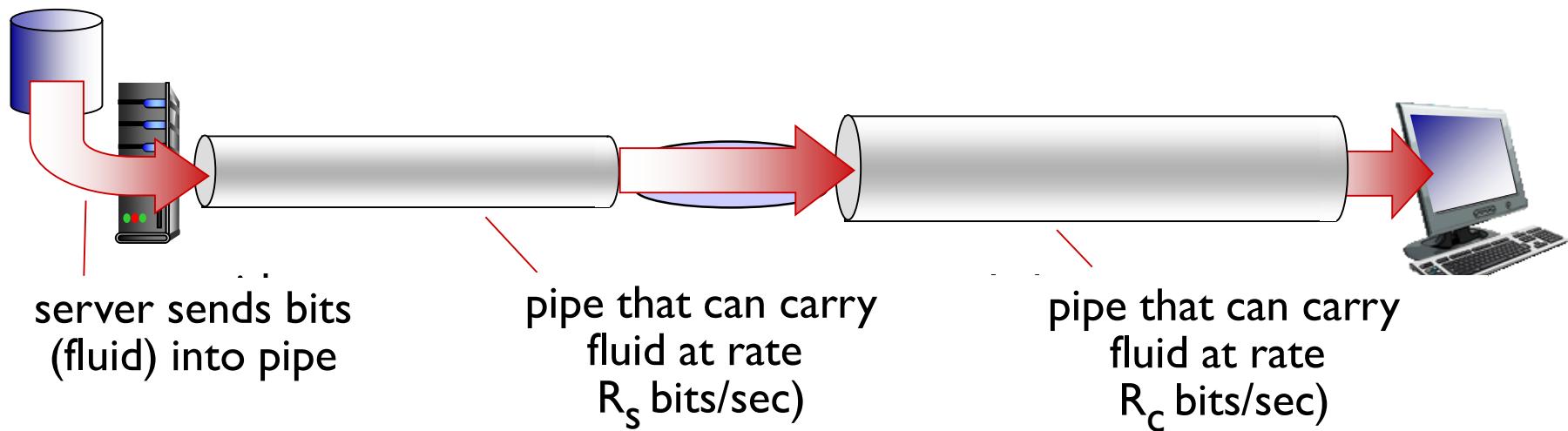
- ❖ queue (aka buffer) preceding link in buffer has finite capacity
- ❖ packet arriving to full queue dropped (aka lost)
- ❖ lost packet may be retransmitted by previous node, by source end system, or not at all



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

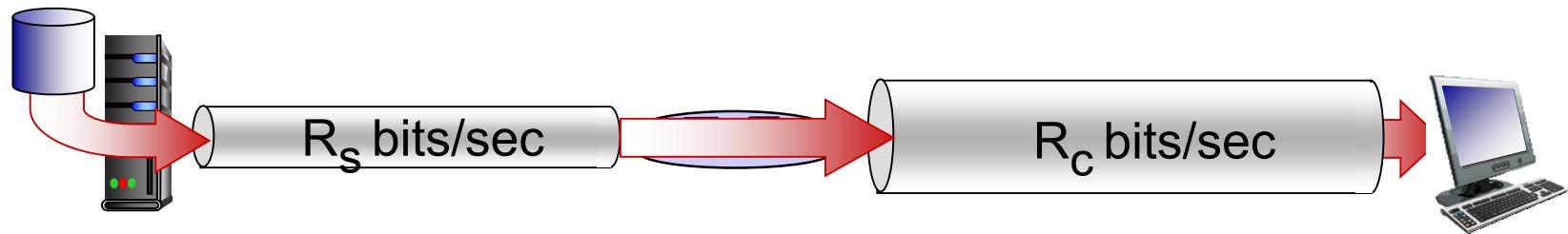
# Throughput

- ❖ **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

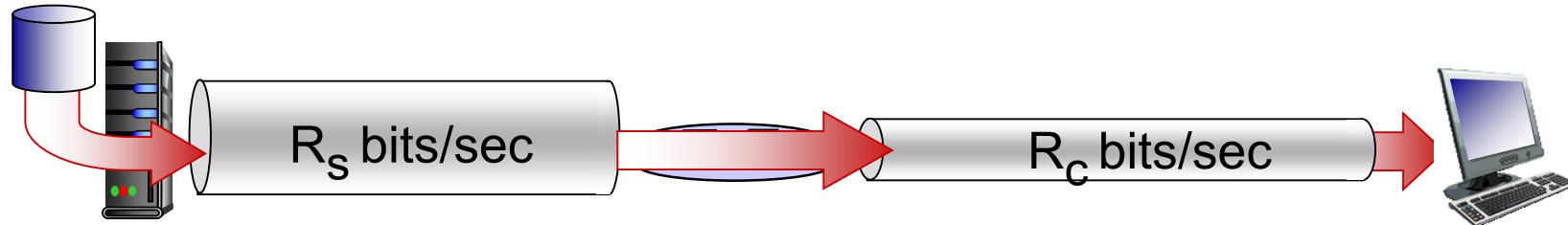


# Throughput (more)

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



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

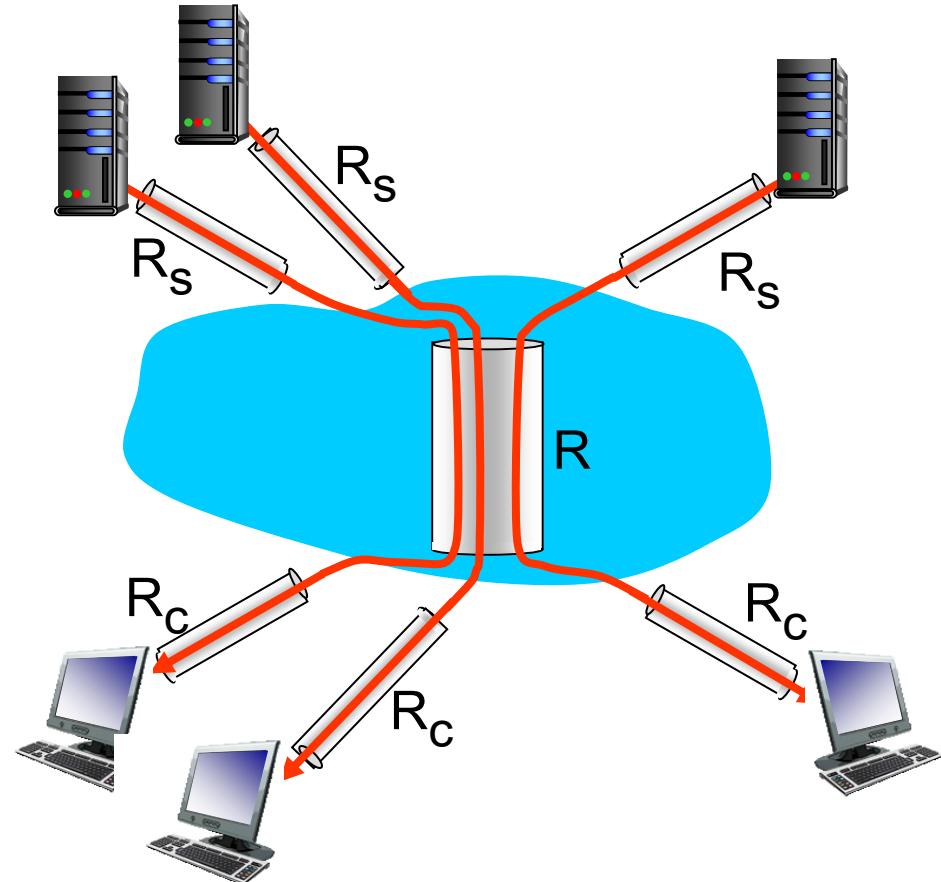


*bottleneck link*

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

# 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

# Protocol “layers”

*Networks are complex,  
with many “pieces”:*

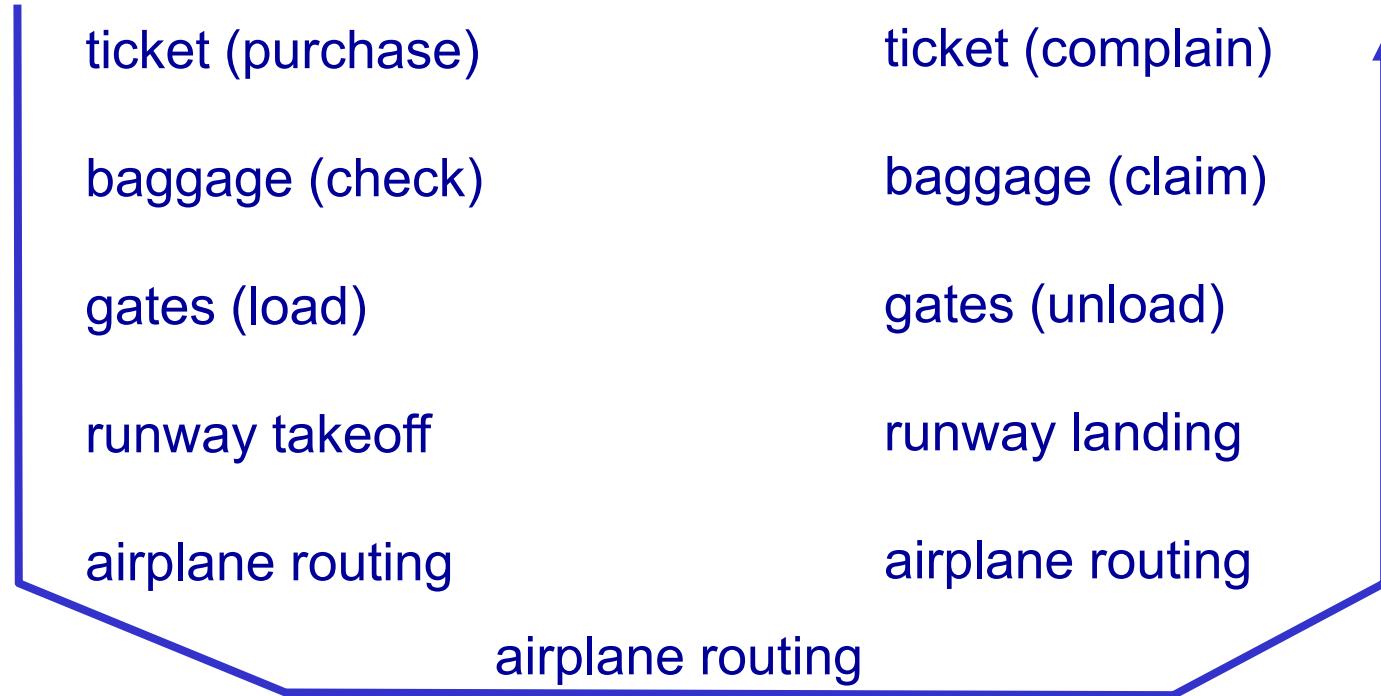
- hosts
- routers
- links of various media
- applications
- protocols
- hardware, software

*Question:*

is there any hope of  
organizing structure of  
network?

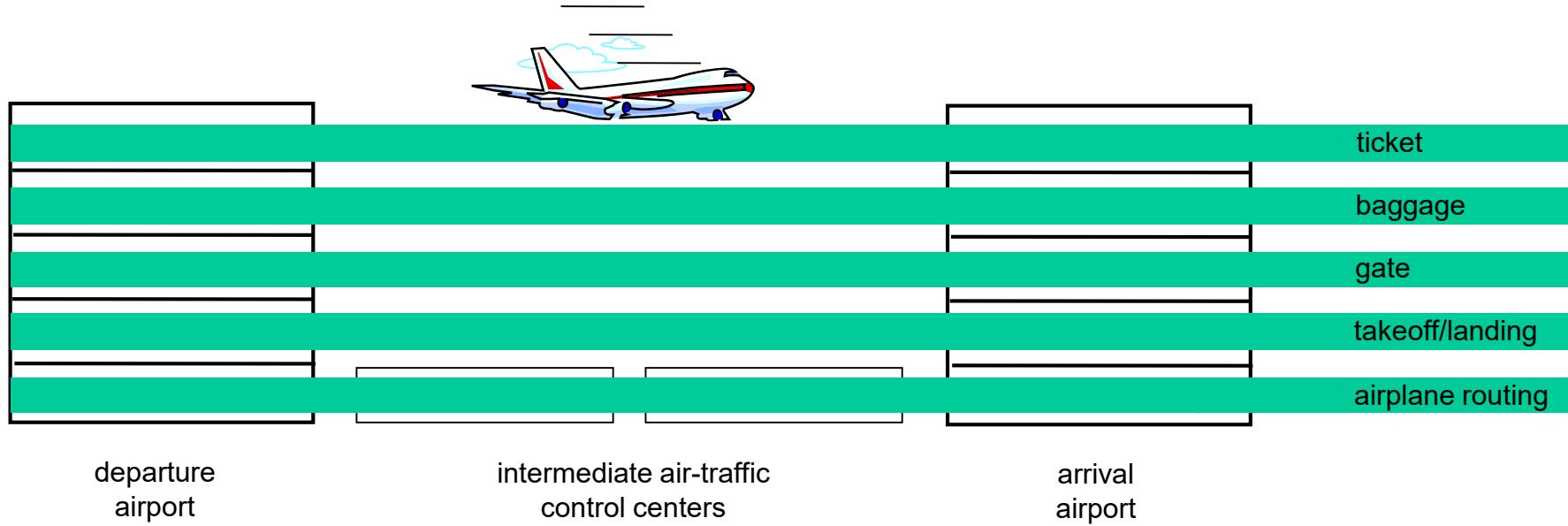
.... or at least our  
discussion of networks?

# 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

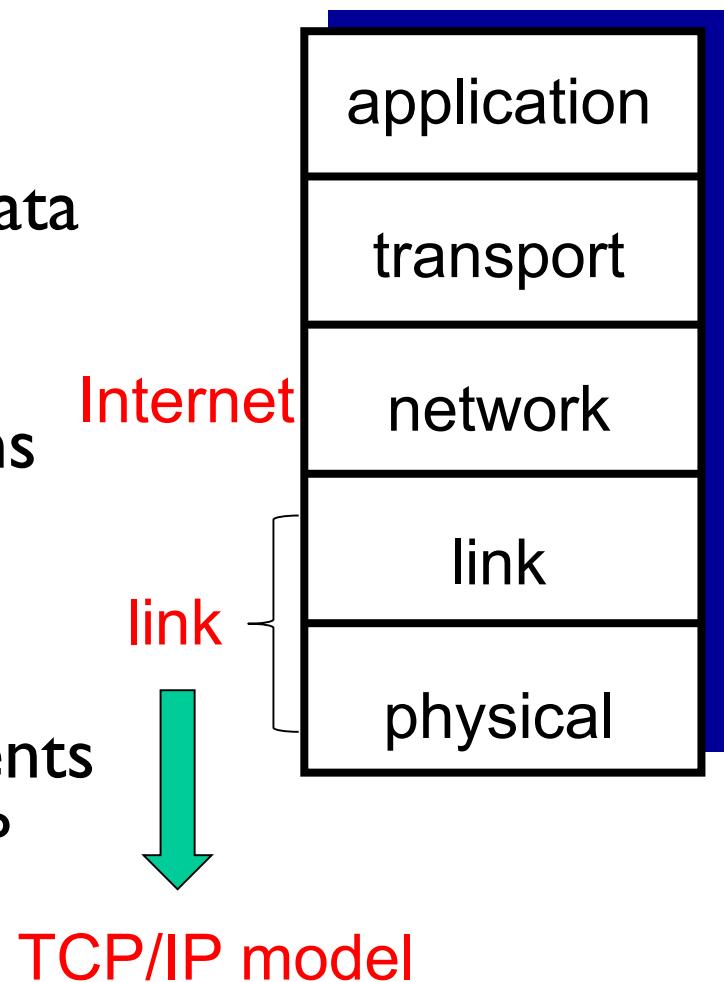
# Why layering?

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?

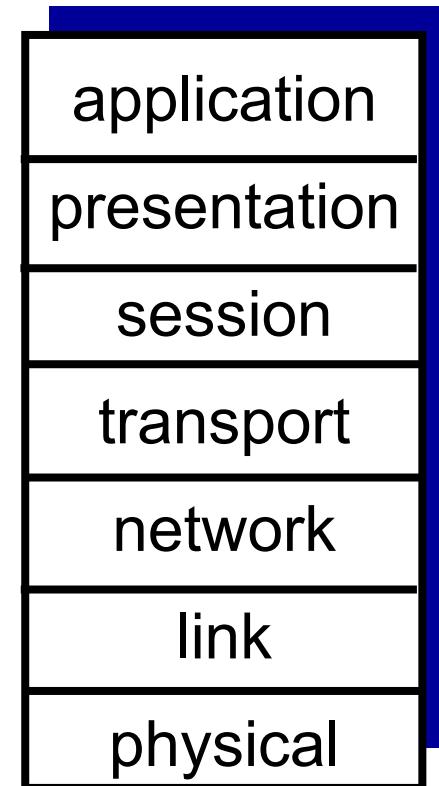
# Internet protocol stack

- ❖ *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”

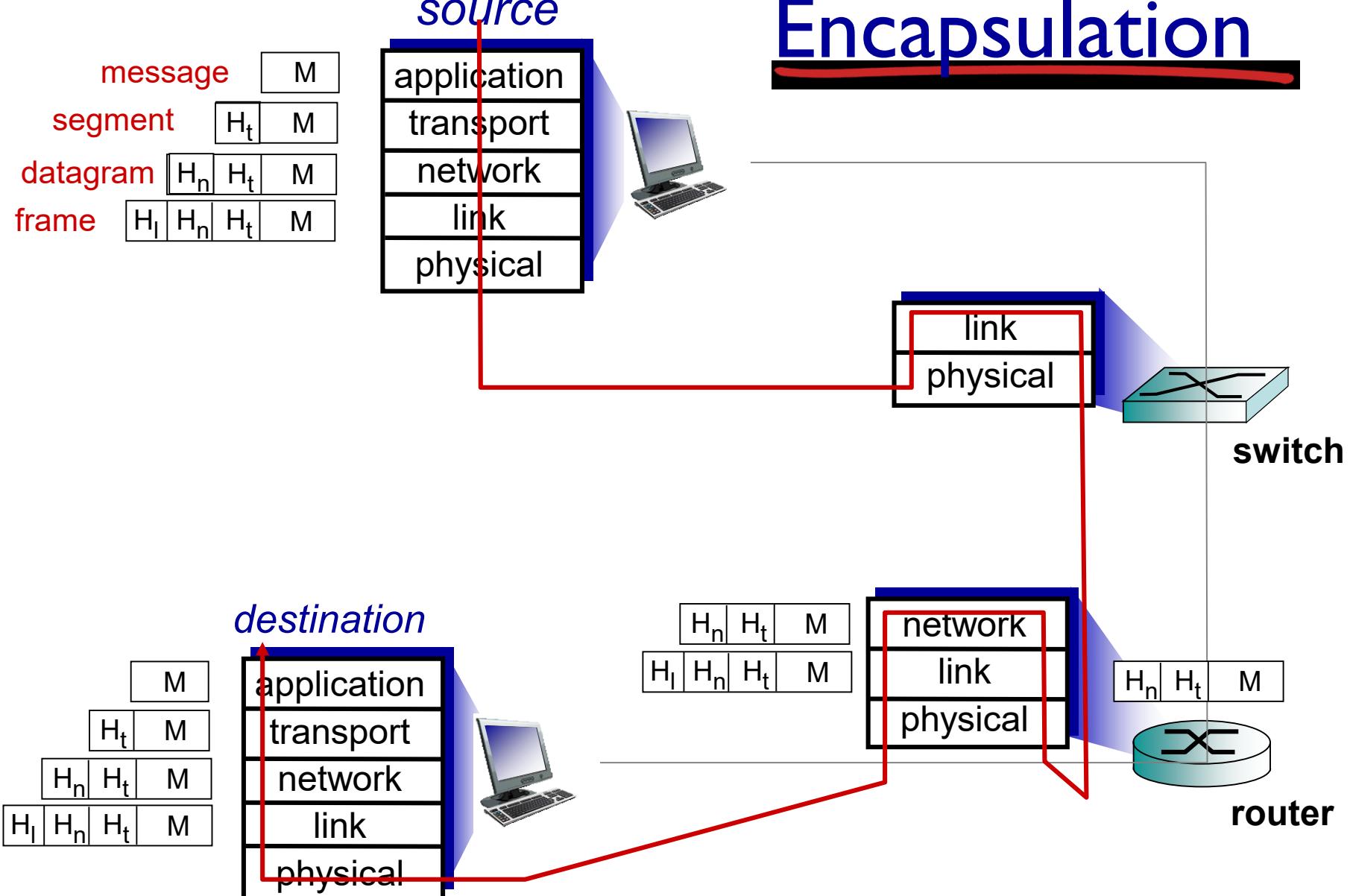


# ISO/OSI reference model

- ❖ ***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



# 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

*you now have:*

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