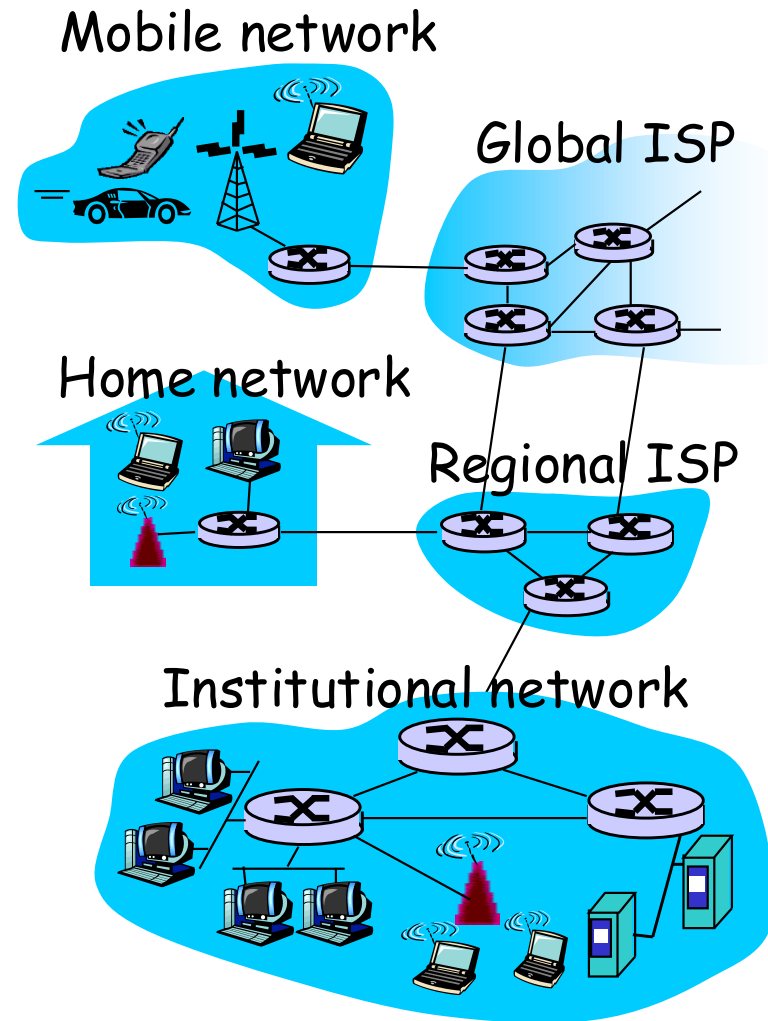
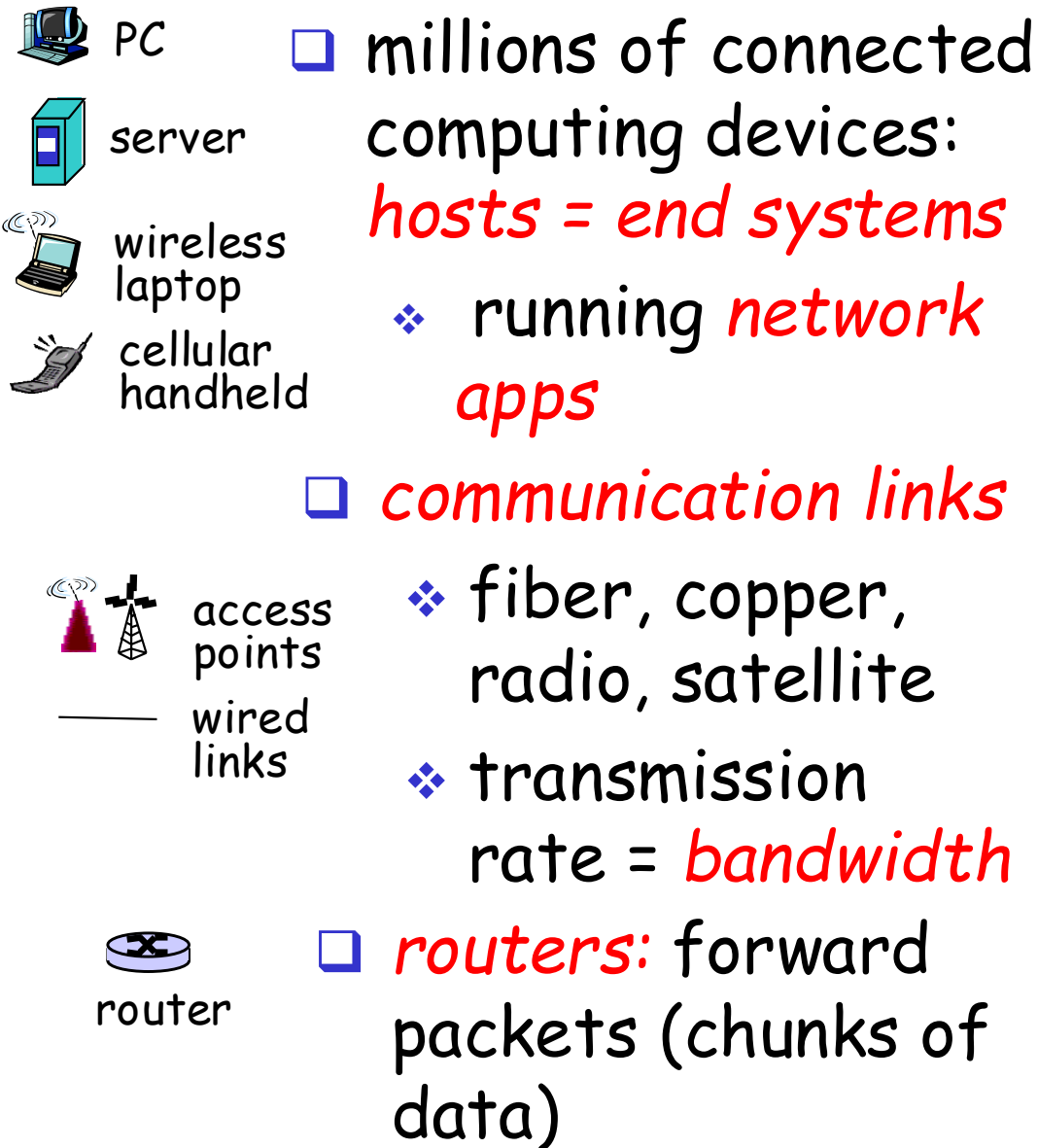


Chapter 1: Introduction

Overview:

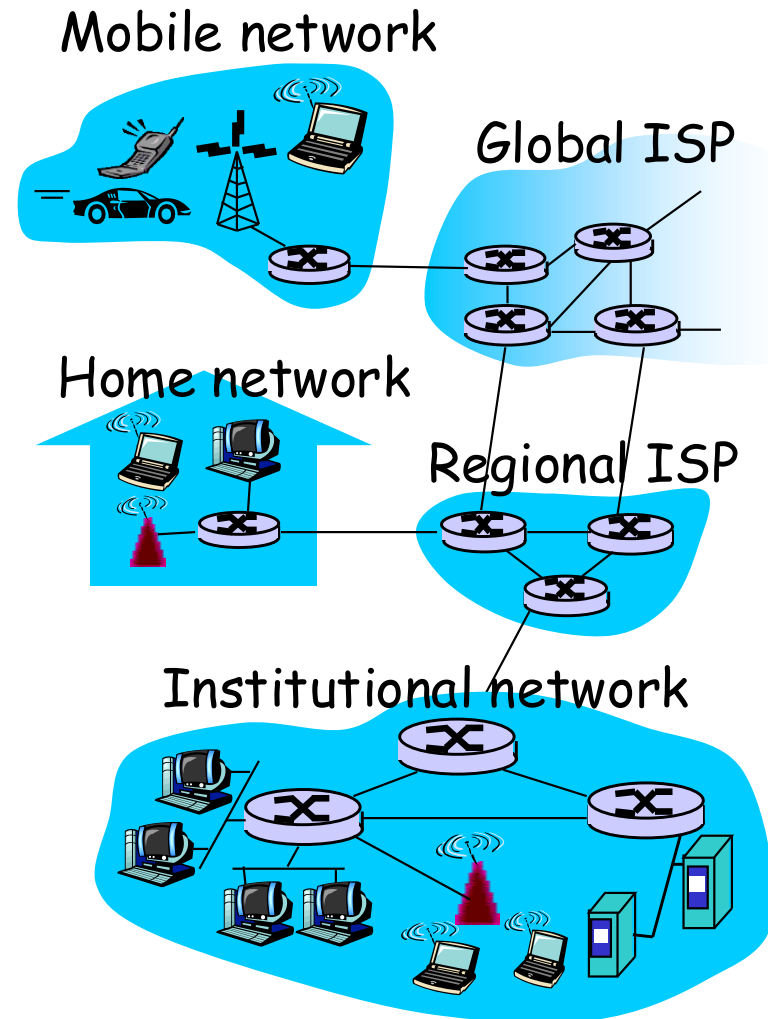
- ❑ what's the Internet?
- ❑ what's a protocol?
- ❑ network edge; hosts, access net, physical media
- ❑ network core: packet/circuit switching, Internet structure
- ❑ performance: loss, delay, throughput
- ❑ security
- ❑ protocol layers, service models
- ❑ history

What's the Internet: "nuts and bolts" view



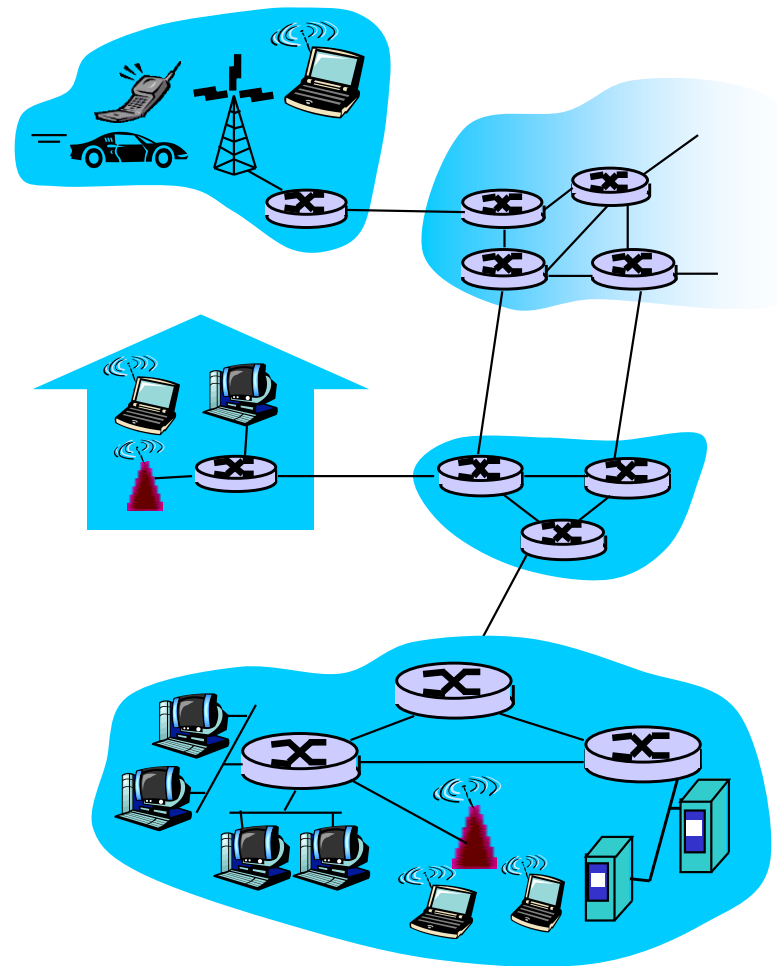
What's the Internet: "nuts and bolts" view

- *protocols* control sending, receiving of msgs
 - ❖ e.g., TCP, IP, HTTP, Skype, Ethernet
- *Internet: "network of networks"*
 - ❖ loosely hierarchical
 - ❖ public Internet versus private intranet
- Internet standards
 - ❖ RFC: Request for comments
 - ❖ IETF: Internet Engineering Task Force



What's the Internet: a service view

- **communication infrastructure** enables distributed applications:
 - ❖ Web, VoIP, email, games, e-commerce, file sharing
- **communication services provided to apps:**
 - ❖ reliable data delivery from source to destination
 - ❖ "best effort" (unreliable) data delivery



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

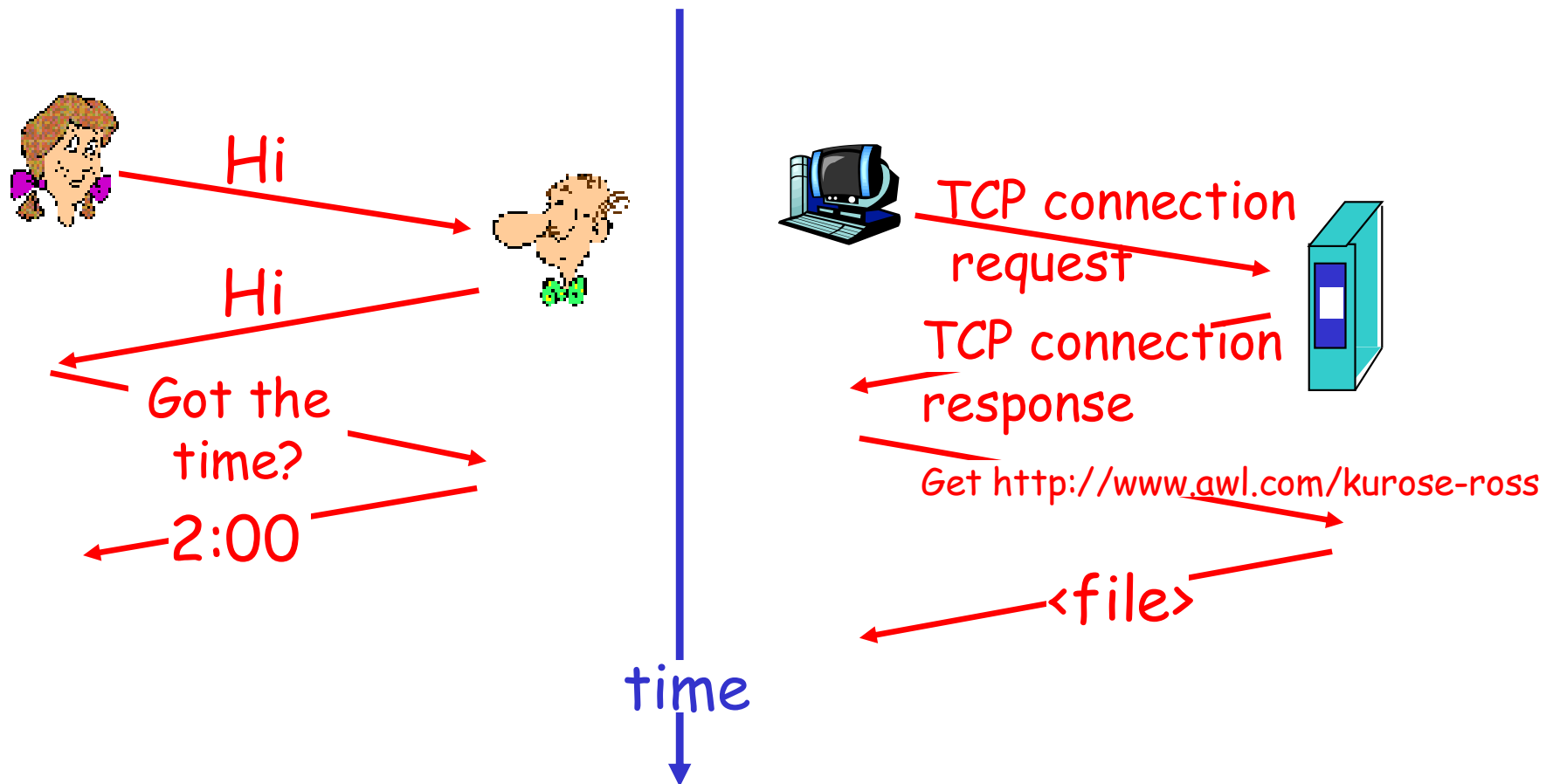
network protocols:

- ❑ 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 1: roadmap

1.1 What is the Internet?

1.2 Network edge

- end systems, access networks, links

1.3 Network core

- circuit switching, packet switching, network structure

1.4 Delay, loss and throughput in packet-switched networks

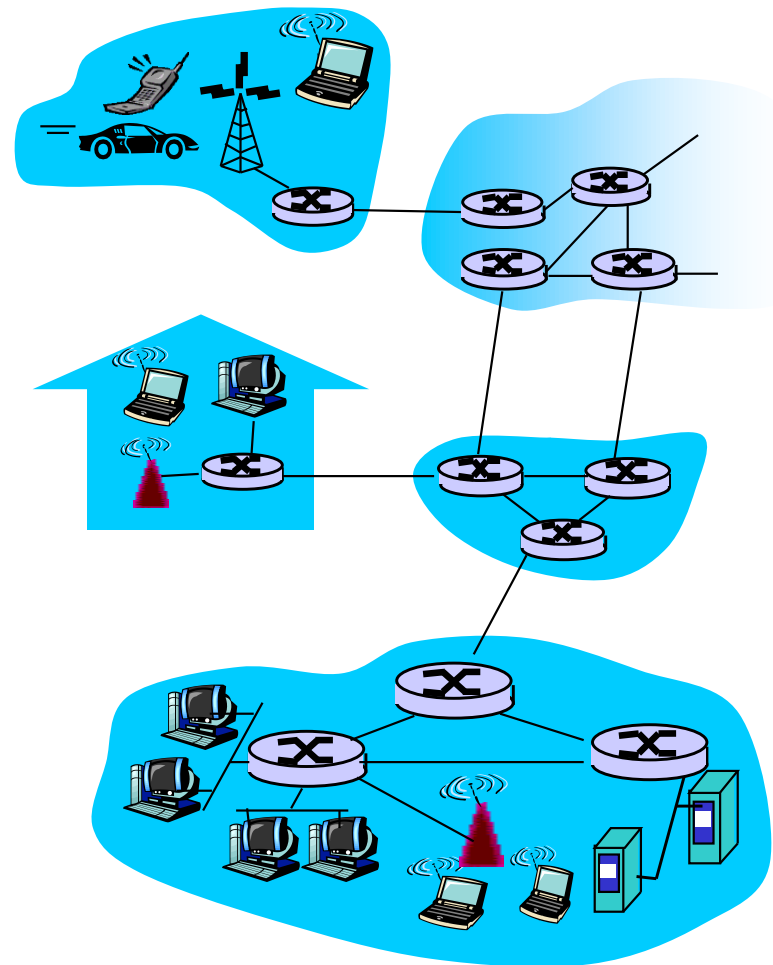
1.5 Protocol layers, service models

1.6 Networks under attack: security

1.7 History

A closer look at network structure:

- **network edge:**
applications and hosts
- **access networks,**
physical media:
wired, wireless communication links
- **network core:**
 - ❖ interconnected routers
 - ❖ network of networks



The network edge:

□ end systems (hosts):

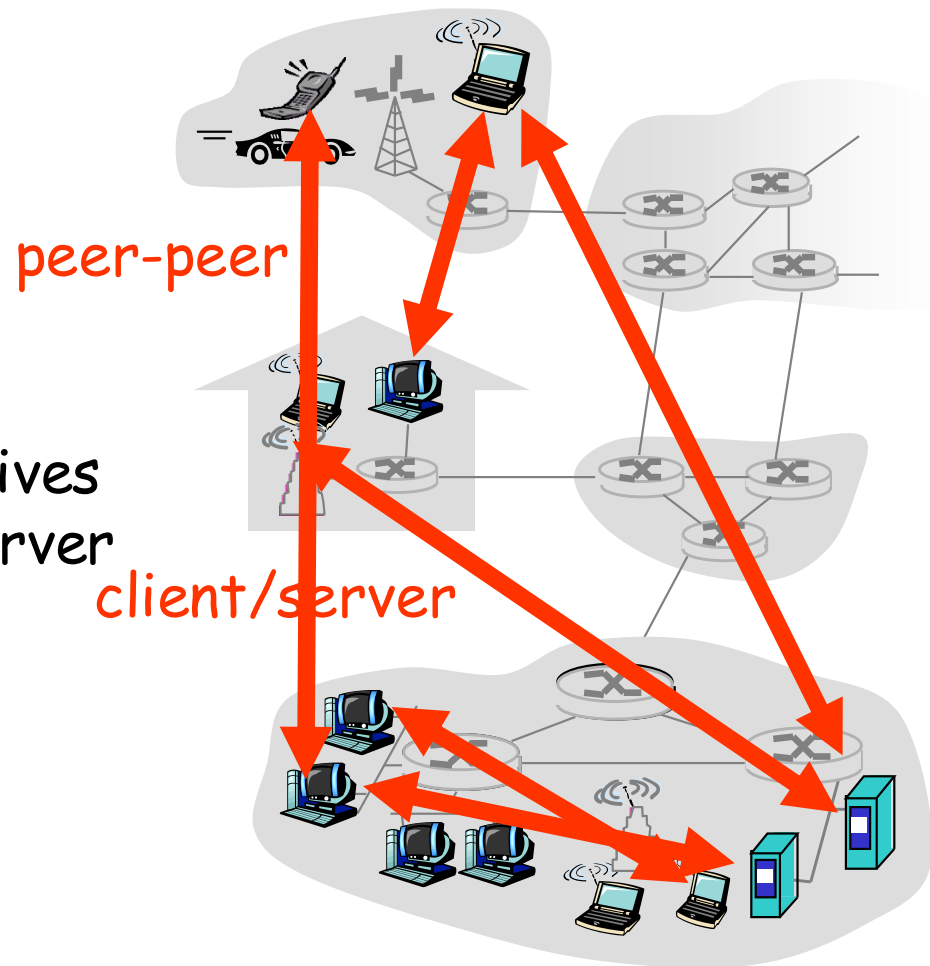
- ❖ run application programs
- ❖ e.g. Web, email
- ❖ at "edge of network"

□ client/server model

- ❖ client host requests, receives service from always-on server
- ❖ e.g. Web browser/server; email client/server

□ peer-peer model:

- ❖ minimal (or no) use of dedicated servers
- ❖ e.g. Skype, BitTorrent



Network edge: reliable data transfer service

- Goal: data transfer between end systems
- ❑ *handshaking*: setup (prepare for) data transfer ahead of time
 - ❖ Hello, hello back human protocol
 - ❖ *set up "state"* in two communicating hosts
 - ❑ TCP - Transmission Control Protocol
 - ❖ Internet's reliable data transfer service

TCP service [RFC 793]

- ❑ *reliable, in-order* byte-stream data transfer
 - ❖ loss: acknowledgements and retransmissions
- ❑ *flow control*:
 - ❖ sender won't overwhelm receiver
- ❑ *congestion control*:
 - ❖ senders "slow down sending rate" when network congested

Network edge: best effort (unreliable) data transfer service

Goal: data transfer
between end systems

- ❖ same as before!

- ❑ **UDP** - User Datagram Protocol [RFC 768]:

- ❖ connectionless
- ❖ unreliable data transfer
- ❖ no flow control
- ❖ no congestion control

App's using TCP:

- ❑ HTTP (Web), FTP (file transfer), Telnet (remote login), SMTP (email)

App's using UDP:

- ❑ streaming media, teleconferencing, DNS, Internet telephony

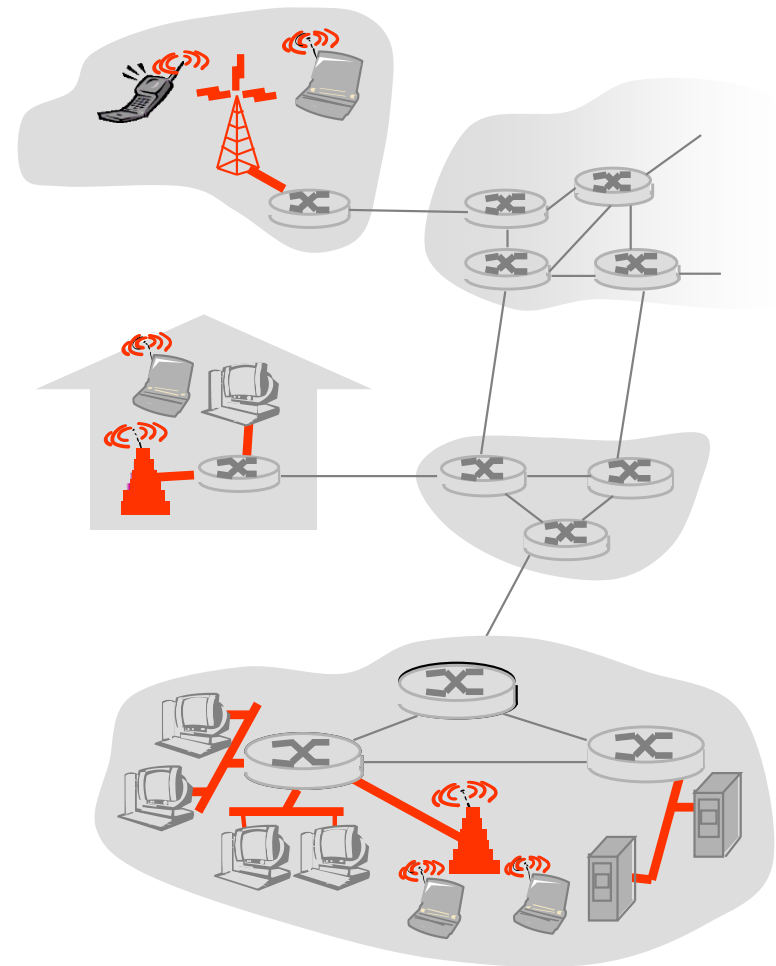
Access networks and physical media

Q: How to connect end systems to edge router?

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

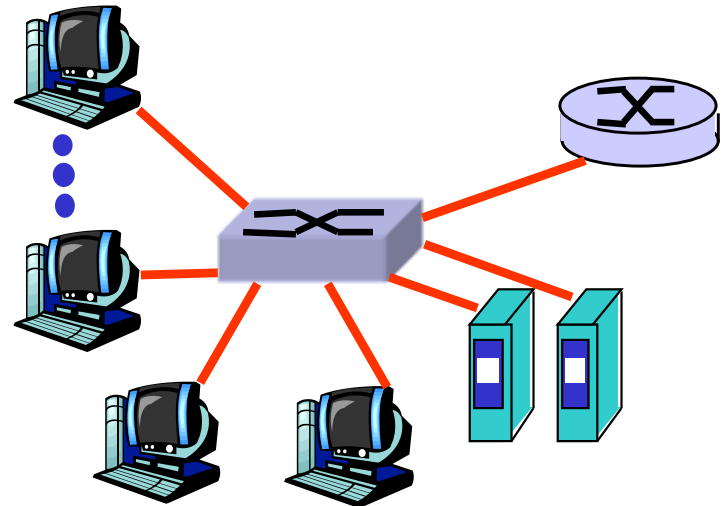
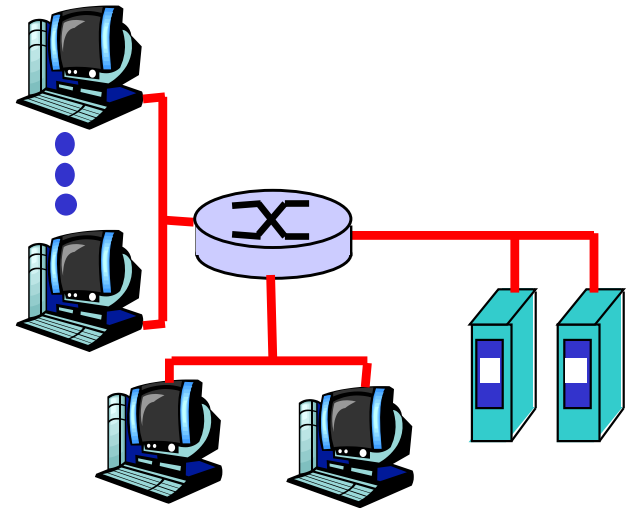
Keep in mind:

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



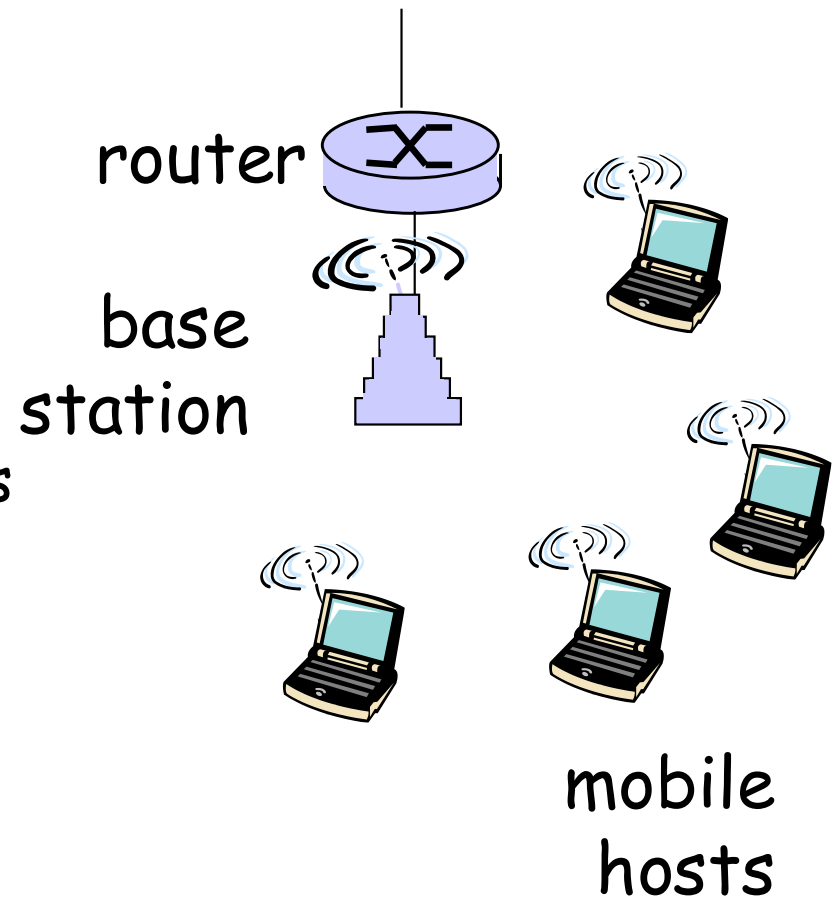
Company access: local area networks

- ❑ company/univ **local area network** (LAN) connects end system to edge router
- ❑ **Ethernet:**
 - ❖ 10 Mbs, 100Mbps, 1Gbps, 10Gbps Ethernet
 - ❖ modern configuration: end systems connect into *Ethernet switch*
- ❑ LANs: chapter 5



Wireless access networks

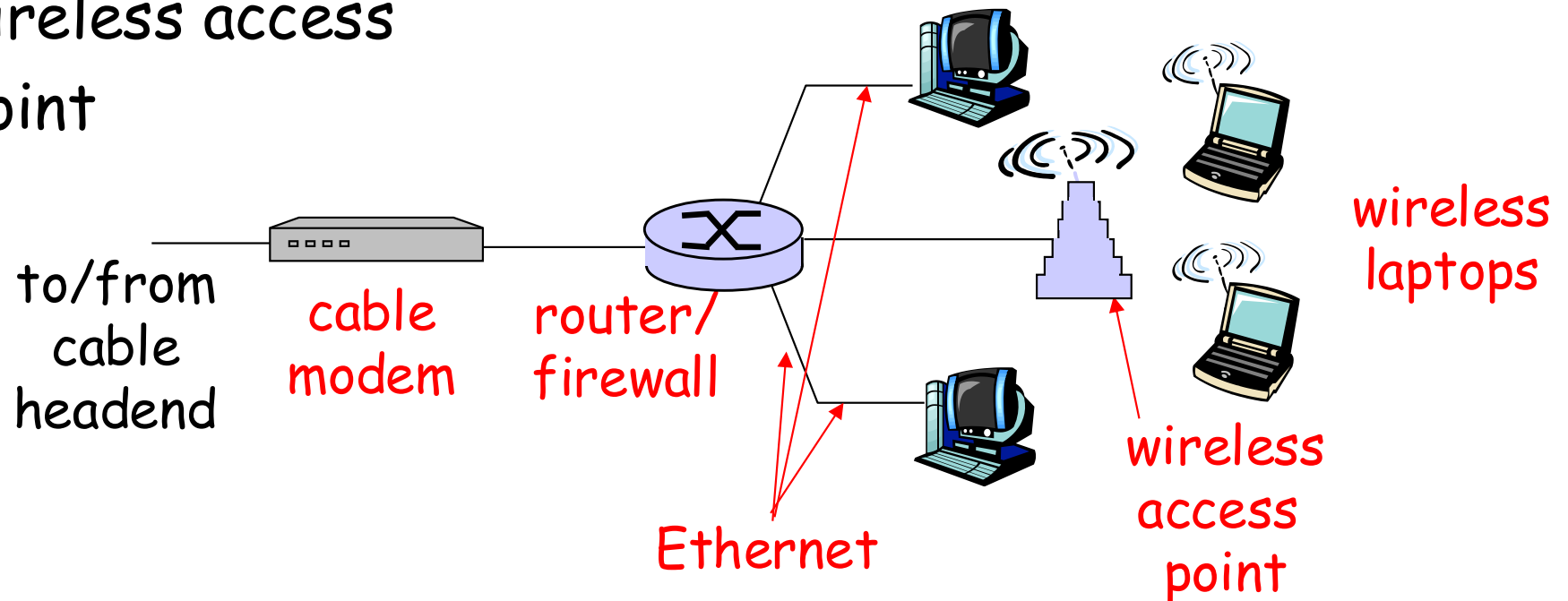
- ❑ shared *wireless* access network connects end system to router
 - ❖ via base station aka "access point"
- ❑ **wireless LANs:**
 - ❖ 802.11b/g (WiFi): 11 or 54 Mbps
- ❑ **wider-area wireless access**
 - ❖ provided by telco operator
 - ❖ ~1Mbps over cellular system
 - ❖ next up (?): WiMAX (10's Mbps) over wide area



Home networks

Typical home network components:

- ❑ DSL or cable modem
- ❑ router/firewall/NAT
- ❑ Ethernet
- ❑ wireless access point



Physical Media

- ❑ **Bit:** propagates between transmitter/rcvr 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)

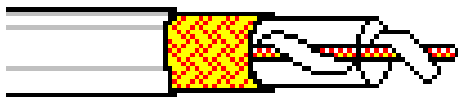
- ❑ two insulated copper wires
 - ❖ Category 3: traditional phone wires, 10 Mbps Ethernet
 - ❖ Category 5: 100Mbps Ethernet



Physical Media: coax, fiber

Coaxial cable:

- ❑ two concentric copper conductors
- ❑ bidirectional
- ❑ baseband:
 - ❖ single channel on cable
 - ❖ legacy Ethernet
- ❑ 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 Gps)
- ❑ 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: ~ 1 Mbps
- ❑ **satellite**
 - ❖ Kbps to 45Mbps channel (or multiple smaller channels)
 - ❖ 270 msec end-end delay
 - ❖ geosynchronous versus low altitude

Chapter 1: roadmap

1.1 What is the Internet?

1.2 Network edge

- end systems, access networks, links

1.3 Network core

- circuit switching, packet switching, network structure

1.4 Delay, loss and throughput in packet-switched networks

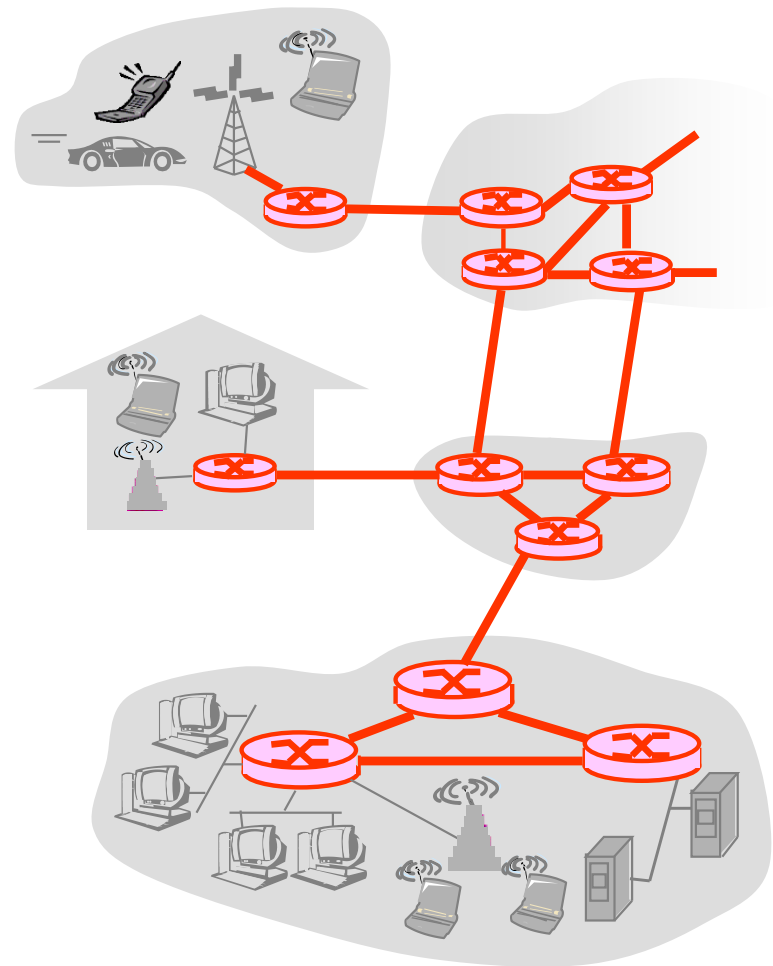
1.5 Protocol layers, service models

1.6 Networks under attack: security

1.7 History

The Network Core

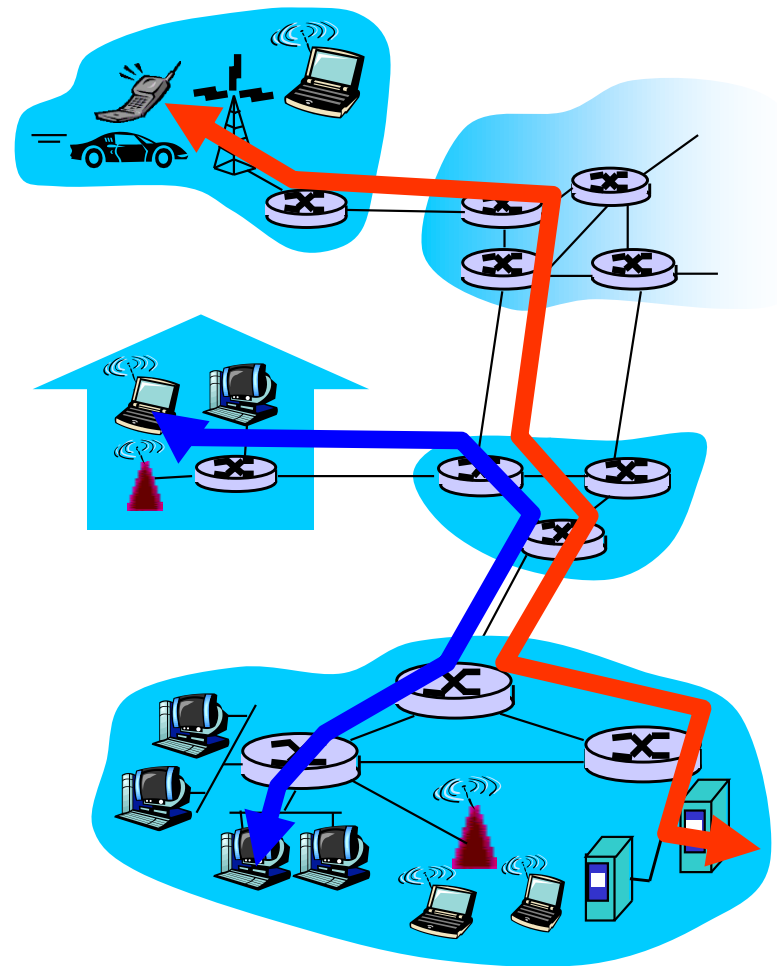
- mesh of interconnected routers
- the fundamental question: how is data transferred through net?
 - ❖ circuit switching: dedicated circuit per call: telephone net
 - ❖ packet-switching: data sent thru net in discrete "chunks"



Network Core: Circuit Switching

End-end resources
reserved for "call"

- ❑ link bandwidth, switch capacity
- ❑ dedicated resources:
no sharing
- ❑ circuit-like
(guaranteed)
performance
- ❑ call setup required



Network Core: Circuit Switching

network resources
(e.g., bandwidth)
divided into "pieces"

- ❑ pieces allocated to calls
- ❑ resource piece *idle* if not used by owning call (*no sharing*)

- ❑ dividing link bandwidth into "pieces"
 - ❖ frequency division
 - ❖ time division

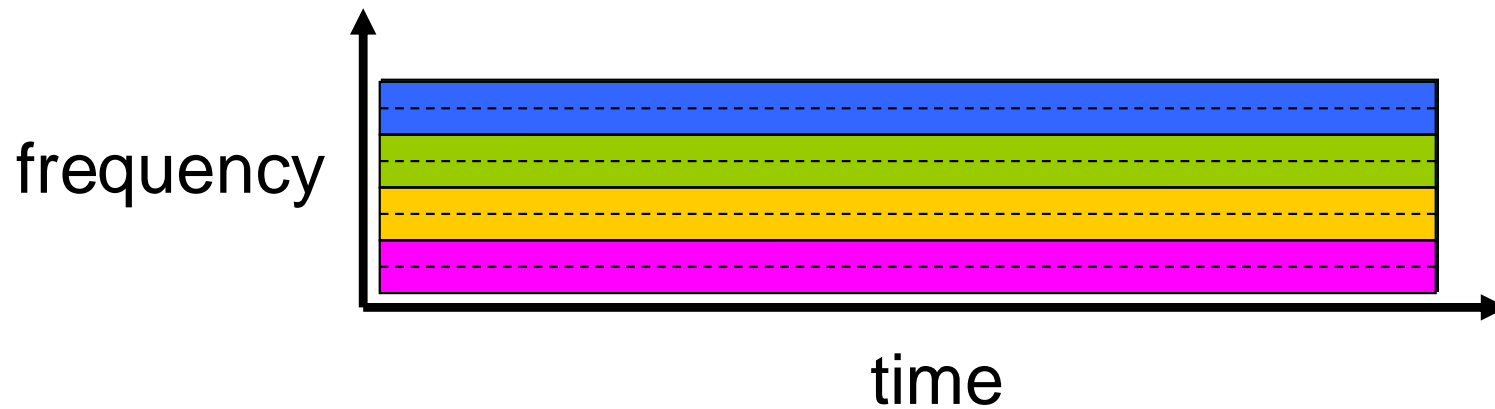
Circuit Switching: FDM and TDM

Example:

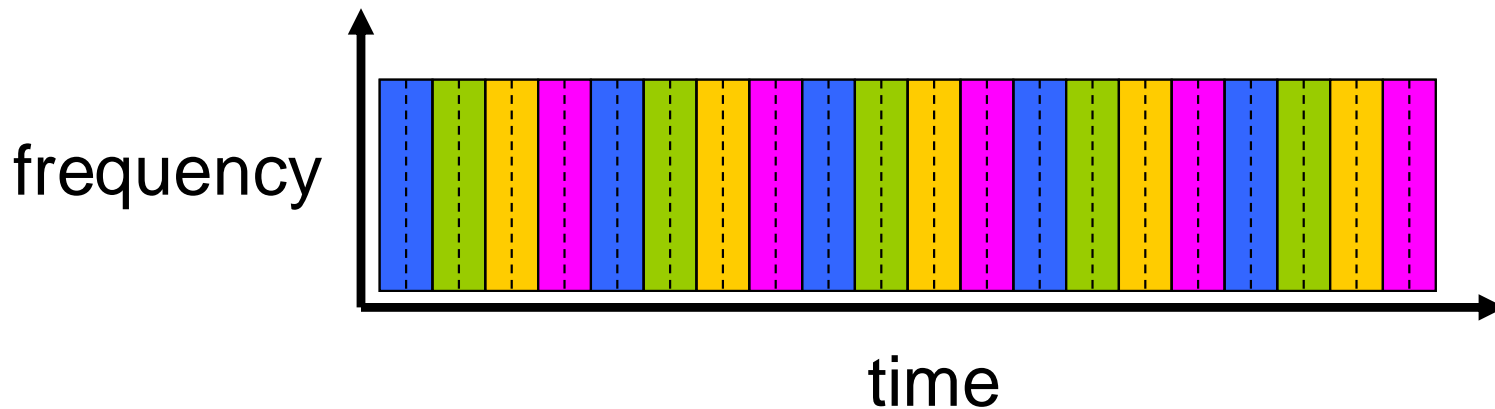
4 users



FDM



TDM



Numerical example

- How long does it take to send a file of 640,000 bits from host A to host B over a circuit-switched network?
 - ❖ All links are 1.536 Mbps
 - ❖ Each link uses TDM with 24 slots/sec
 - ❖ 500 msec to establish end-to-end circuit


Let's work it out!

Network Core: Packet Switching

each end-end data stream
divided into *packets*

- ❑ user A, B packets *share* network resources
- ❑ each packet uses full link bandwidth
- ❑ resources used *as needed*

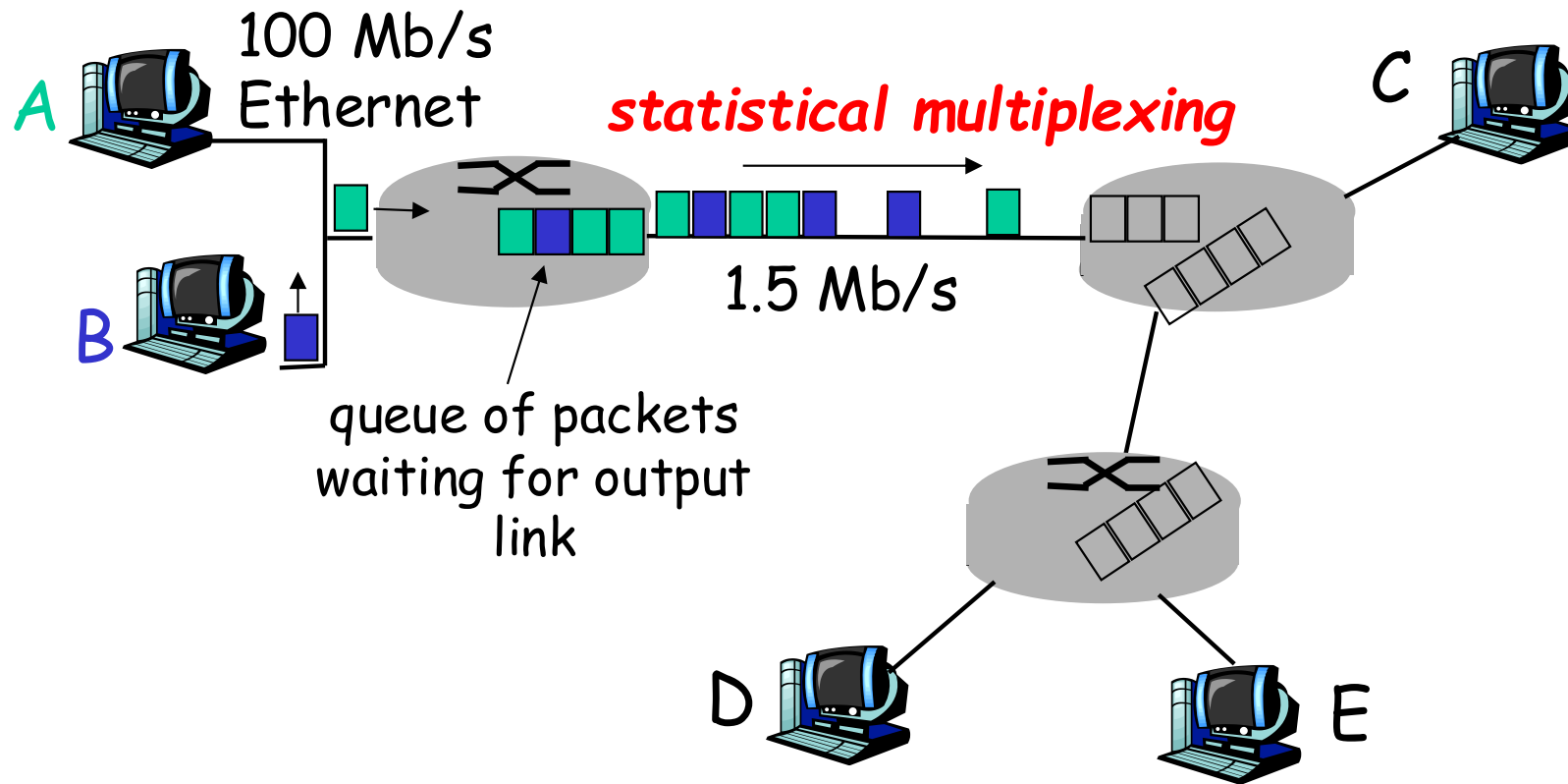
Bandwidth division into "pieces"
Dedicated allocation
Resource reservation



resource contention:

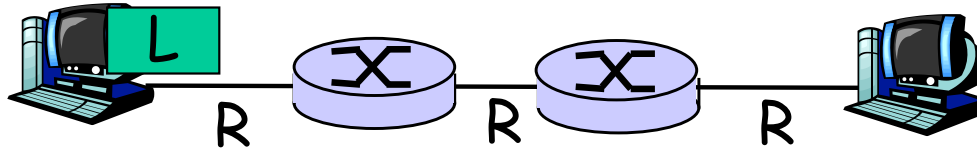
- ❑ aggregate resource demand can exceed amount available
- ❑ congestion: packets queue, wait for link use
- ❑ store and forward: packets move one hop at a time
 - ❖ Node receives complete packet before forwarding

Packet Switching: Statistical Multiplexing



Sequence of A & B packets does not have fixed pattern,
bandwidth shared on demand □ **statistical multiplexing**.
TDM: each host gets same slot in revolving TDM frame.

Packet-switching: store-and-forward



- takes L/R seconds to transmit (push out) packet of L bits on to link at R bps
- *store and forward*: entire packet must arrive at router before it can be transmitted on next link
- delay = $3L/R$ (assuming zero propagation delay)

Example:

- $L = 7.5$ Mbits
- $R = 1.5$ Mbps
- transmission delay = 15 sec

} more on delay shortly ...

Packet switching versus circuit switching

Packet switching allows more users to use network!

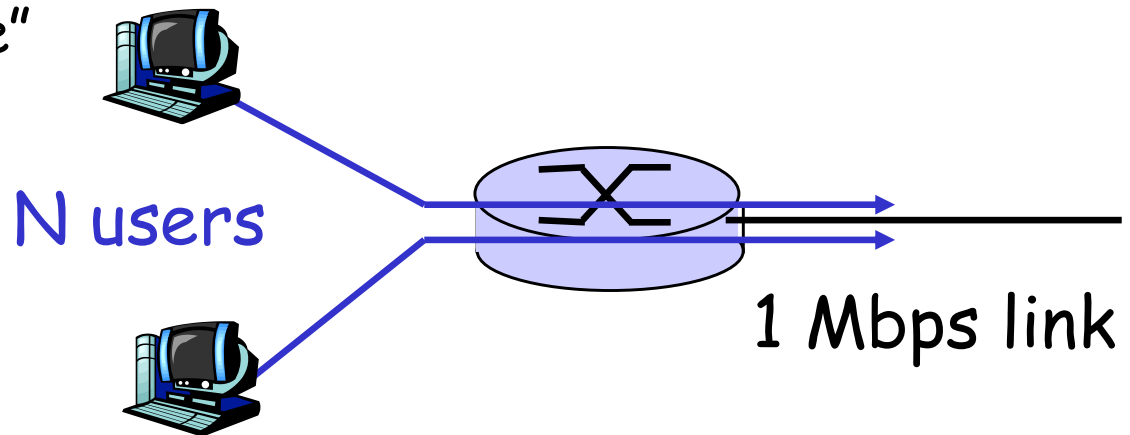
- ❑ 1 Mb/s link
- ❑ each user:
 - ❖ 100 kb/s when “active”
 - ❖ active 10% of time

- ❑ *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?

Packet switching versus circuit switching

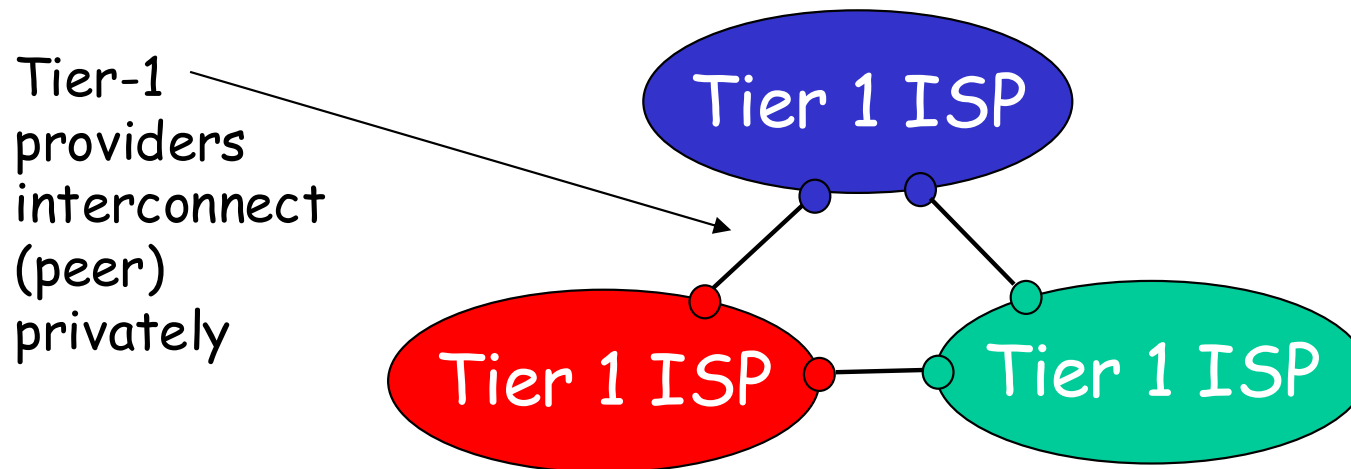
Is packet switching a “slam dunk winner?”

- great for bursty data
 - ❖ resource sharing
 - ❖ simpler, no call setup
- **excessive congestion:** 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)

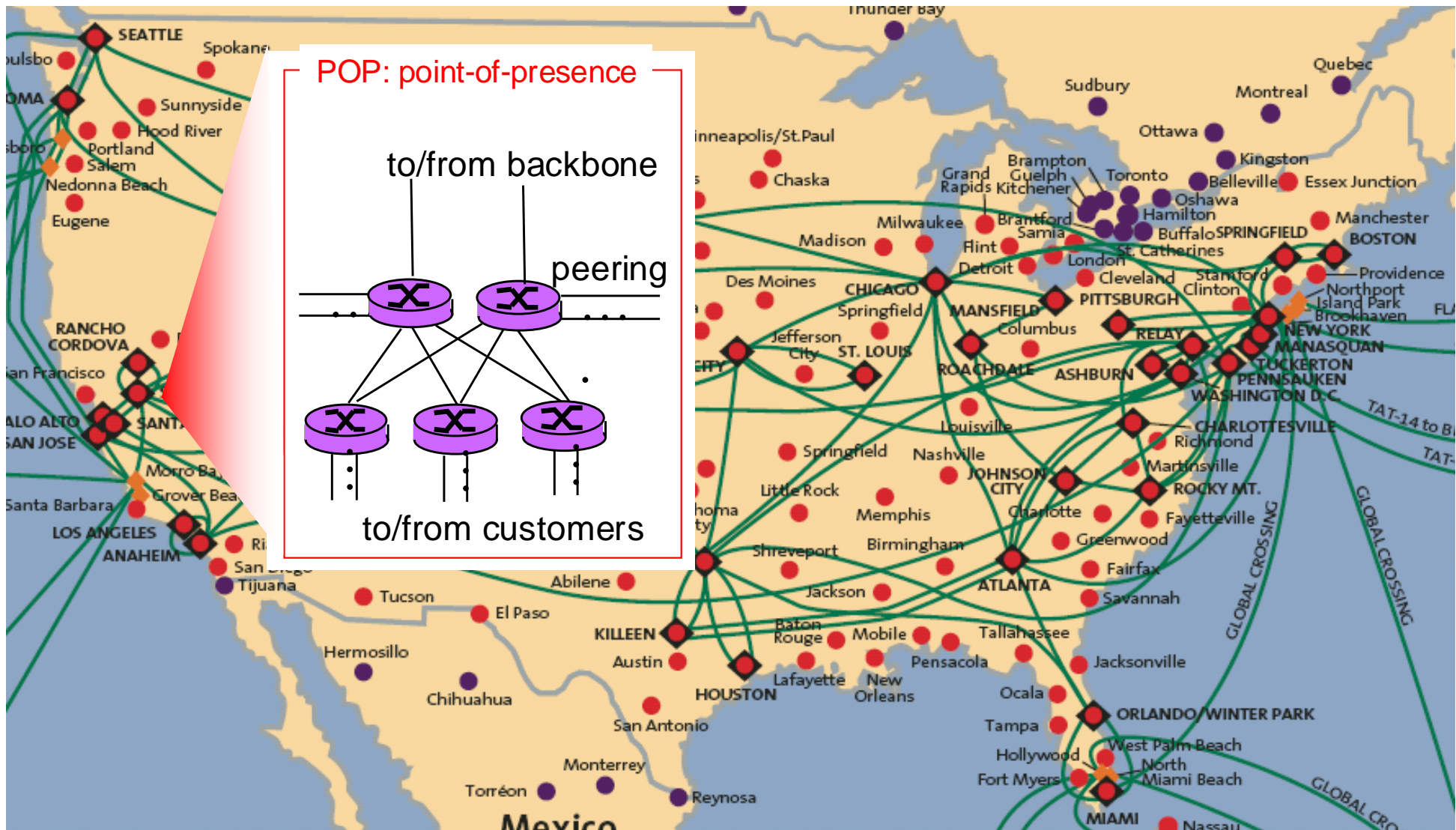
Q: human analogies of reserved resources (circuit switching) versus on-demand allocation (packet-switching)?

Internet structure: network of networks

- ❑ roughly hierarchical
- ❑ **at center: "tier-1" ISPs** (e.g., Verizon, Sprint, AT&T, Cable and Wireless), national/international coverage
 - ❖ treat each other as equals



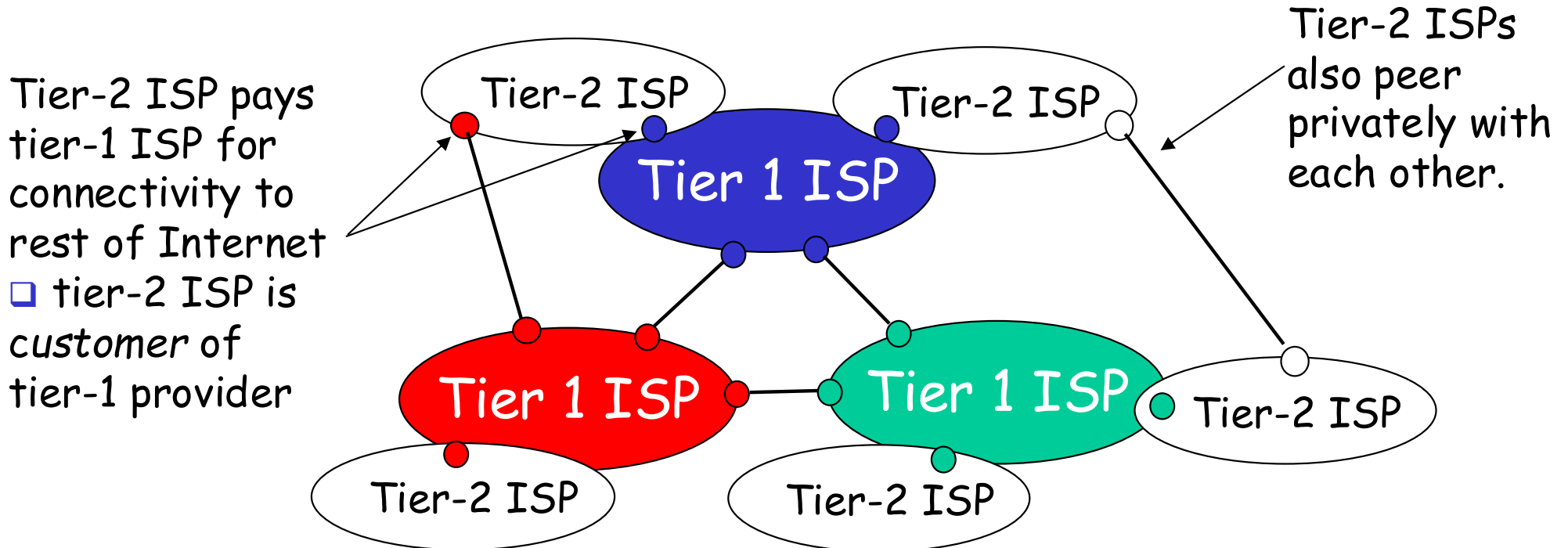
Tier-1 ISP: e.g., Sprint



Internet structure: network of networks

❑ "Tier-2" ISPs: smaller (often regional) ISPs

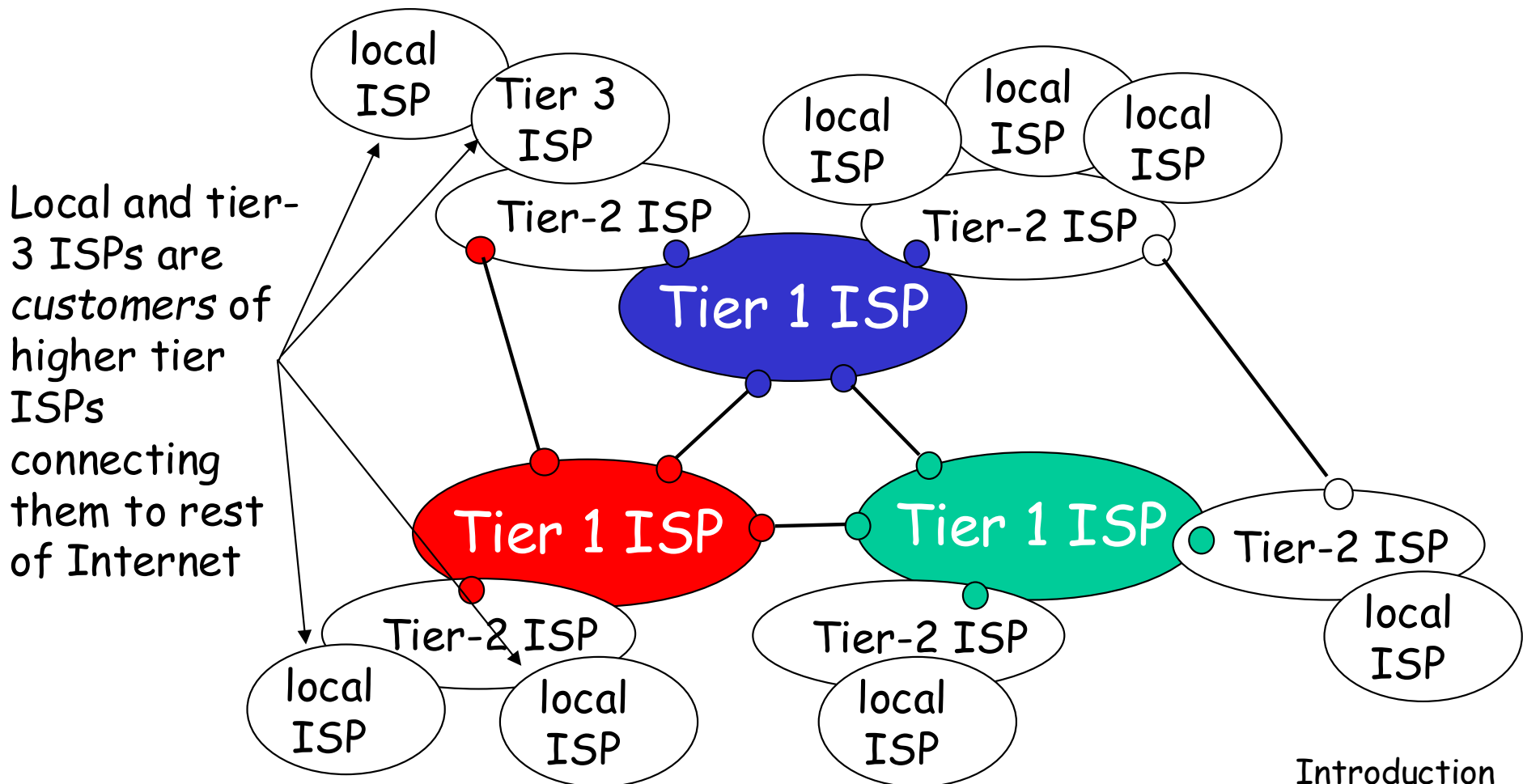
- ❖ Connect to one or more tier-1 ISPs, possibly other tier-2 ISPs



Internet structure: network of networks

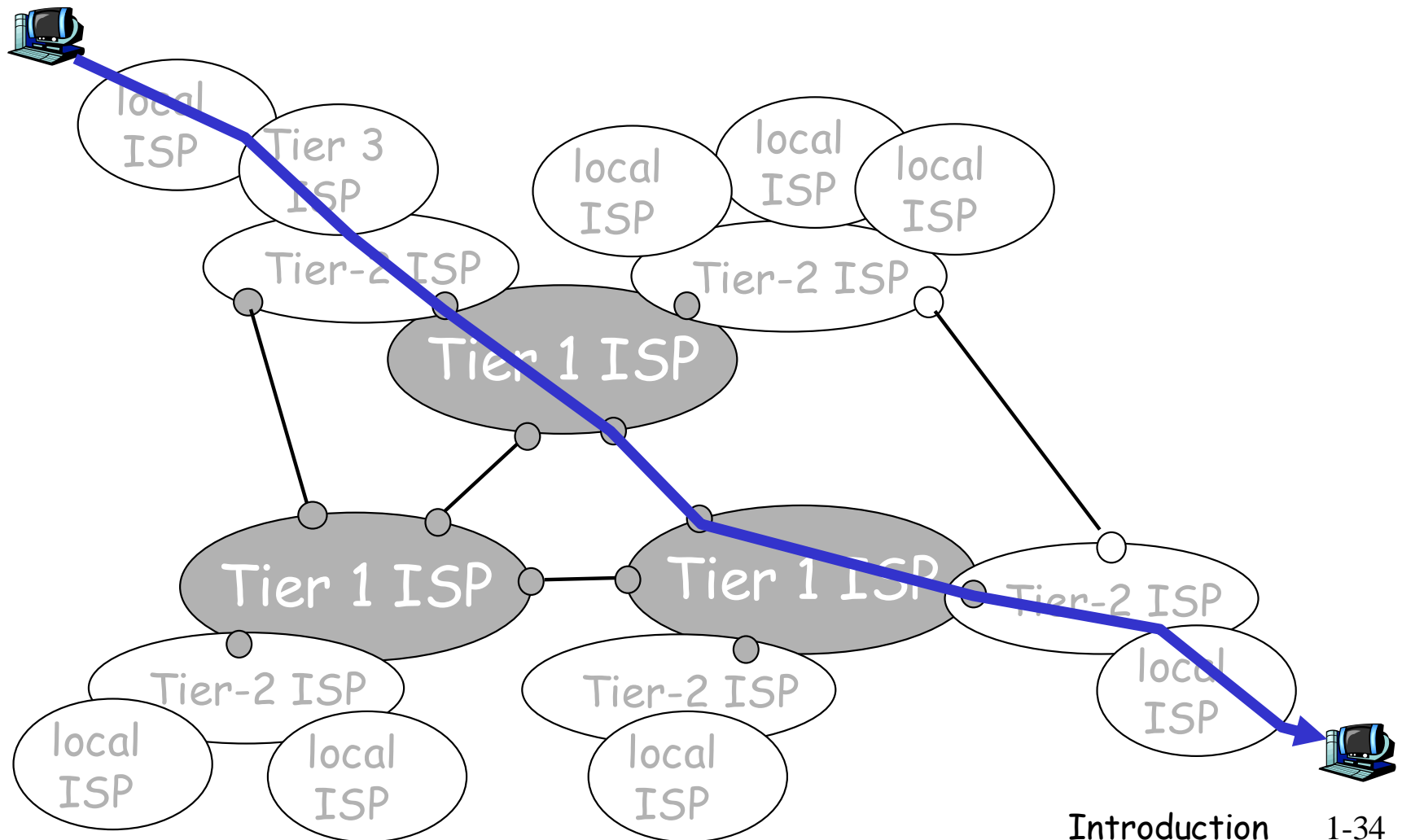
❑ "Tier-3" ISPs and local ISPs

❖ last hop ("access") network (closest to end systems)



Internet structure: network of networks

- a packet passes through many networks!



Chapter 1: roadmap

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1.4 Delay, loss and throughput in packet-switched networks

1.5 Protocol layers, service models

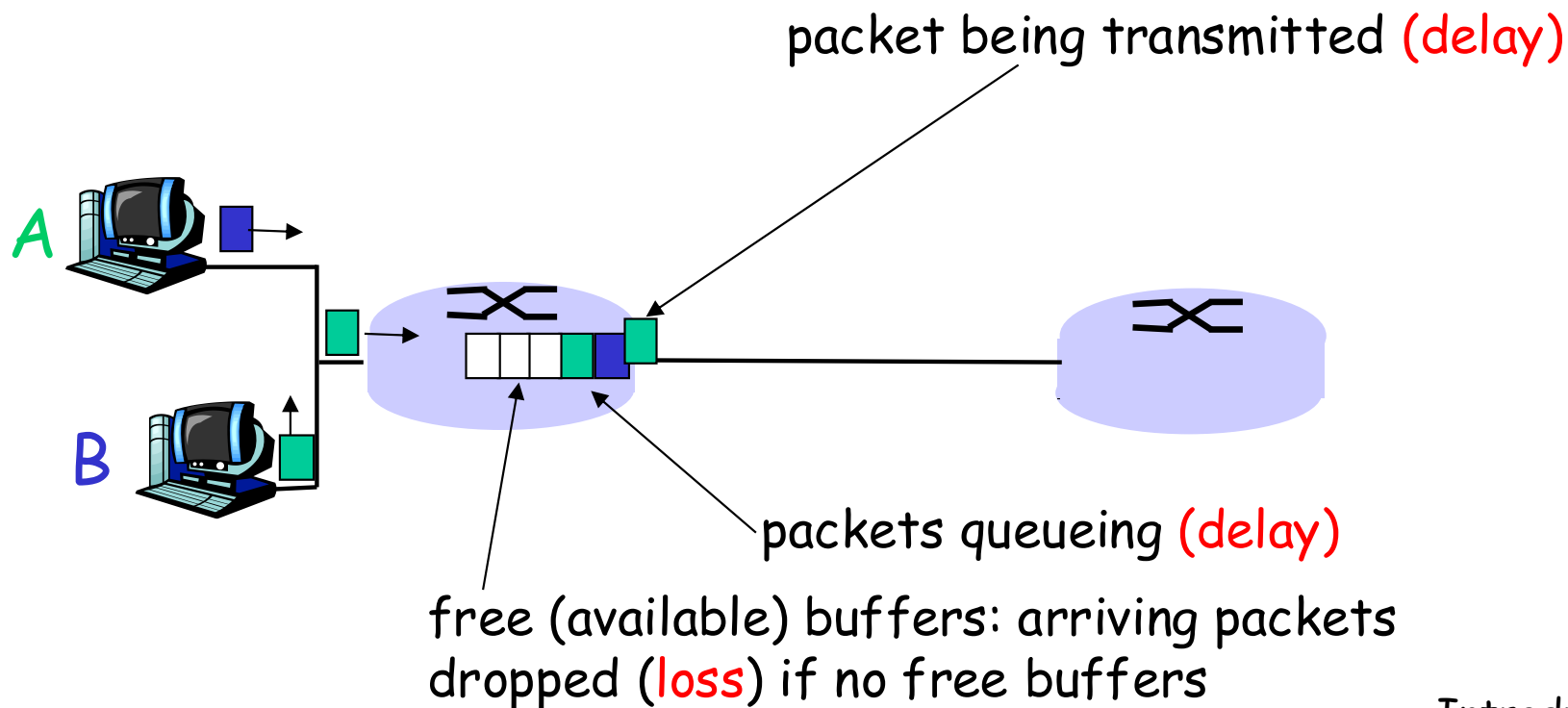
1.6 Networks under attack: security

1.7 History

How do loss and delay occur?

packets *queue* in router buffers

- ❑ packet arrival rate to link exceeds output link capacity
- ❑ packets queue, wait for turn



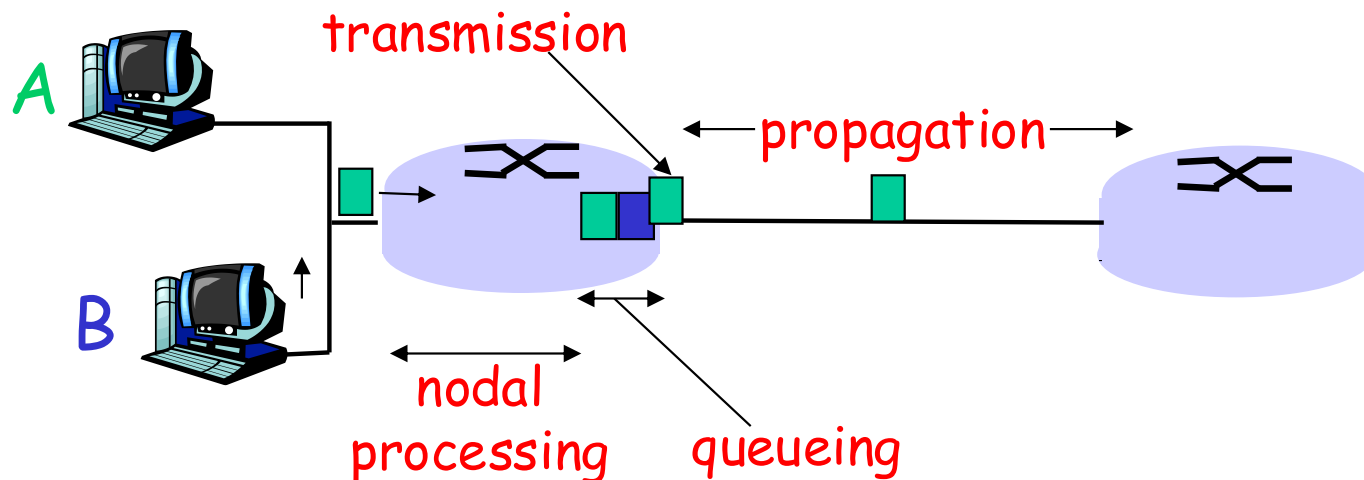
Four sources of packet delay

❑ 1. nodal processing:

- ❖ check bit errors
- ❖ determine output link

❑ 2. queueing

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



Delay in packet-switched networks

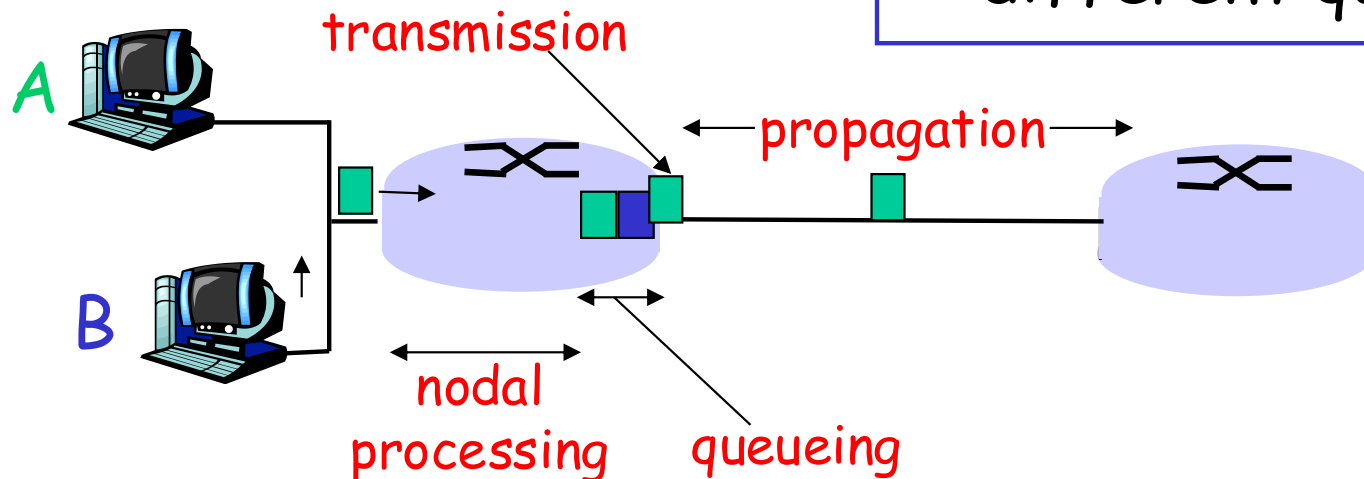
3. Transmission delay:

- ❑ R = link bandwidth (bps)
- ❑ L = packet length (bits)
- ❑ time to send bits into link = L/R

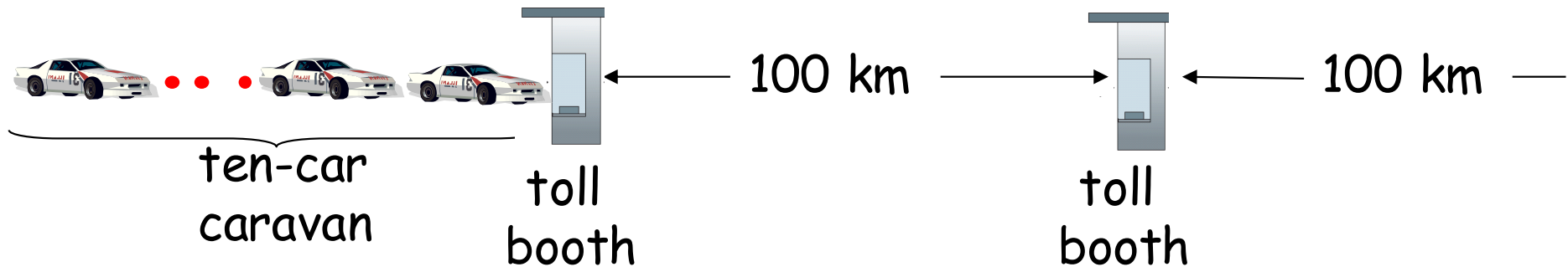
4. Propagation delay:

- ❑ d = length of physical link
- ❑ s = propagation speed in medium ($\sim 2 \times 10^8$ m/sec)
- ❑ propagation delay = d/s

Note: s and R are very different quantities!

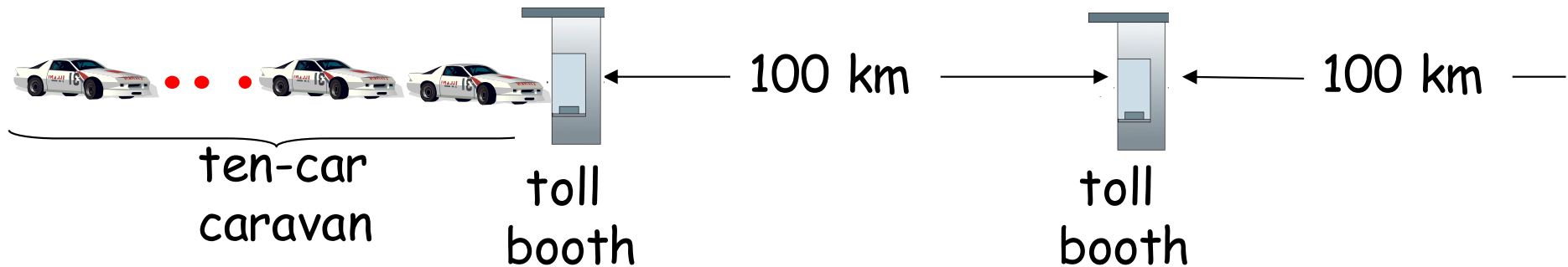


Caravan analogy



- ❑ cars "propagate" at 100 km/hr
- ❑ toll booth takes 12 sec to service car (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 = $12 \times 10 = 120$ sec
- ❑ Time for last car to propagate from 1st to 2nd toll booth: $100\text{km} / (100\text{km/hr}) = 1$ hr
- ❑ A: 62 minutes

Caravan analogy (more)



- ❑ Cars now "propagate" at 1000 km/hr
- ❑ Toll booth now takes 1 min to service a car
- ❑ **Q: Will cars arrive to 2nd booth before all cars serviced at 1st booth?**

- ❑ **Yes!** After 7 min, 1st car at 2nd booth and 3 cars still at 1st booth.
- ❑ 1st bit of packet can arrive at 2nd router before packet is fully transmitted at 1st router!
 - ❖ See Ethernet applet at AWL Web site

Nodal delay

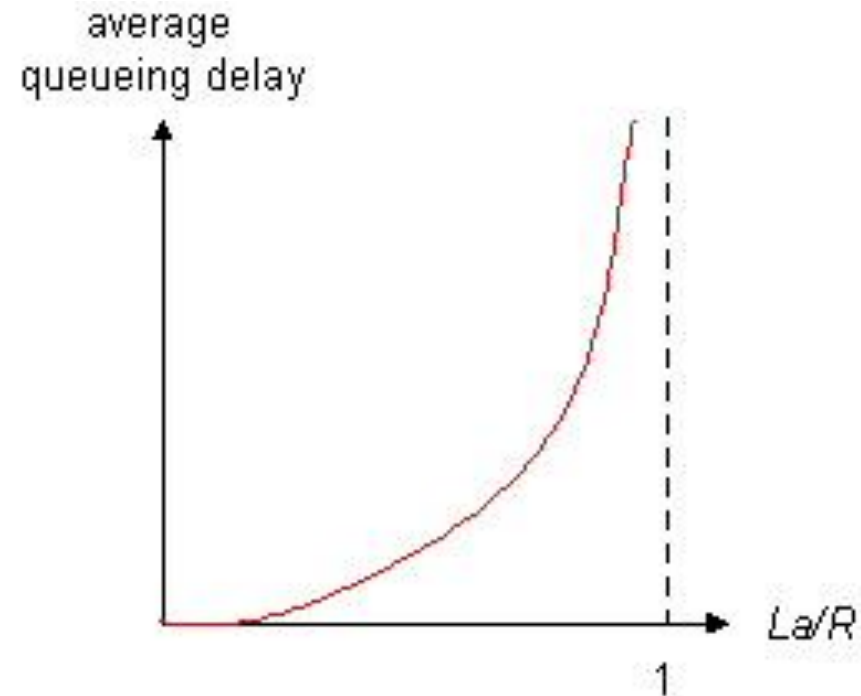
$$d_{\text{nodal}} = d_{\text{proc}} + d_{\text{queue}} + d_{\text{trans}} + d_{\text{prop}}$$

- d_{proc} = processing delay
 - ❖ typically a few microsecs or less
- d_{queue} = queuing delay
 - ❖ depends on congestion
- d_{trans} = transmission delay
 - ❖ $= L/R$, significant for low-speed links
- d_{prop} = propagation delay
 - ❖ a few microsecs to hundreds of msecs

Queueing delay (revisited)

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

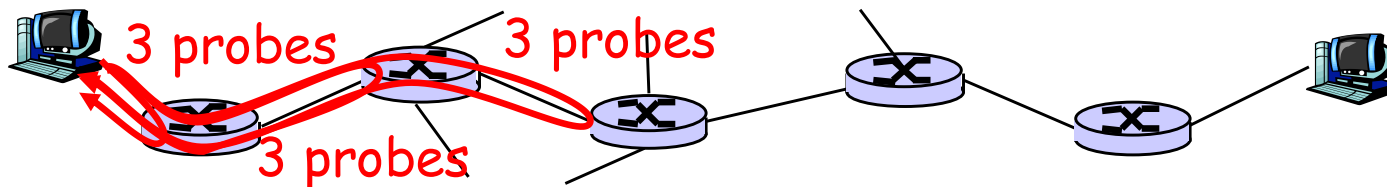
traffic intensity = La/R



- $La/R \sim 0$: average queueing delay small
- $La/R \rightarrow 1$: delays become large
- $La/R > 1$: more "work" arriving than can be serviced, average delay infinite!

"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 and routes

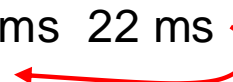
traceroute: gaia.cs.umass.edu to www.eurecom.fr

Three delay measurements from
gaia.cs.umass.edu to cs-gw.cs.umass.edu




1 cs-gw (128.119.240.254) 1 ms 1 ms 2 ms
2 border1-rt-fa5-1-0.gw.umass.edu (128.119.3.145) 1 ms 1 ms 2 ms
3 cht-vbns.gw.umass.edu (128.119.3.130) 6 ms 5 ms 5 ms
4 jn1-at1-0-0-19.wor.vbns.net (204.147.132.129) 16 ms 11 ms 13 ms
5 jn1-so7-0-0-0.wae.vbns.net (204.147.136.136) 21 ms 18 ms 18 ms
6 abilene-vbns.abilene.ucaid.edu (198.32.11.9) 22 ms 18 ms 22 ms
7 nycm-wash.abilene.ucaid.edu (198.32.8.46) 22 ms 22 ms 22 ms
8 62.40.103.253 (62.40.103.253) 104 ms 109 ms 106 ms
9 de2-1.de1.de.geant.net (62.40.96.129) 109 ms 102 ms 104 ms
10 de.fr1.fr.geant.net (62.40.96.50) 113 ms 121 ms 114 ms
11 renater-gw.fr1.fr.geant.net (62.40.103.54) 112 ms 114 ms 112 ms
12 nio-n2.cssi.renater.fr (193.51.206.13) 111 ms 114 ms 116 ms
13 nice.cssi.renater.fr (195.220.98.102) 123 ms 125 ms 124 ms
14 r3t2-nice.cssi.renater.fr (195.220.98.110) 126 ms 126 ms 124 ms
15 eurecom-valbonne.r3t2.ft.net (193.48.50.54) 135 ms 128 ms 133 ms
16 194.214.211.25 (194.214.211.25) 126 ms 128 ms 126 ms
17 * * *
18 * * *
19 fantasia.eurecom.fr (193.55.113.142) 132 ms 128 ms 136 ms

trans-oceanic link

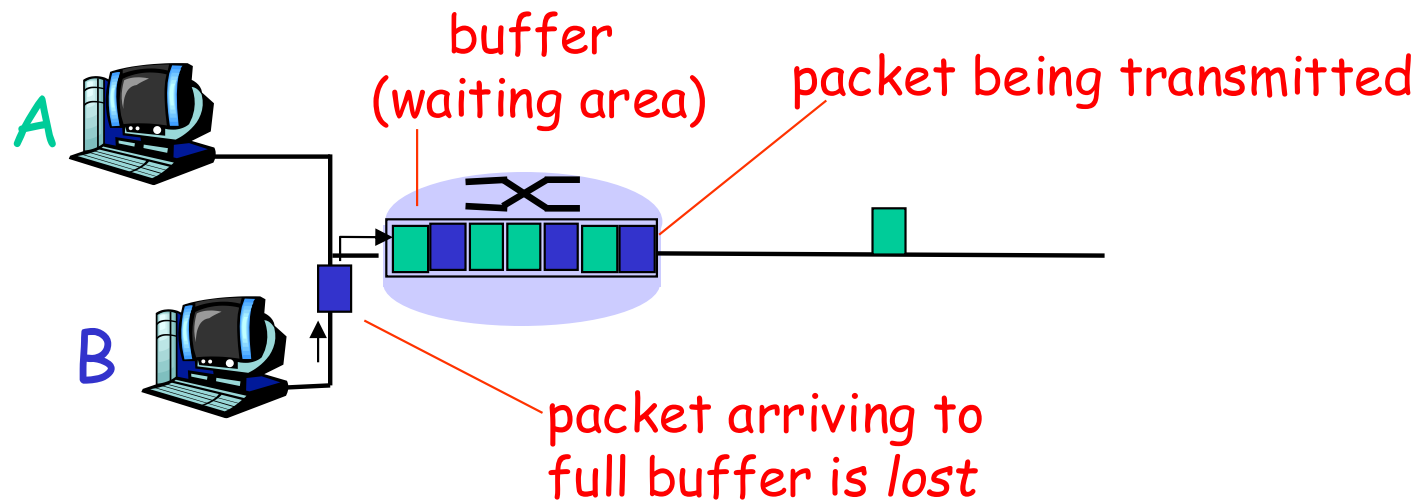


* means no response (probe lost, router not replying)



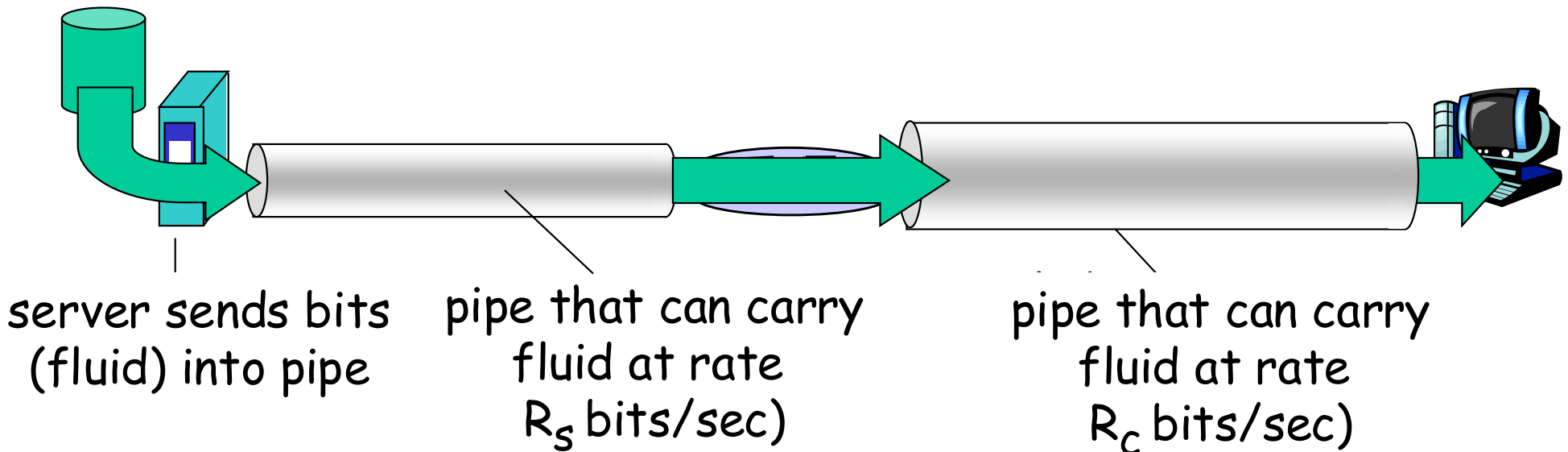
Packet loss

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



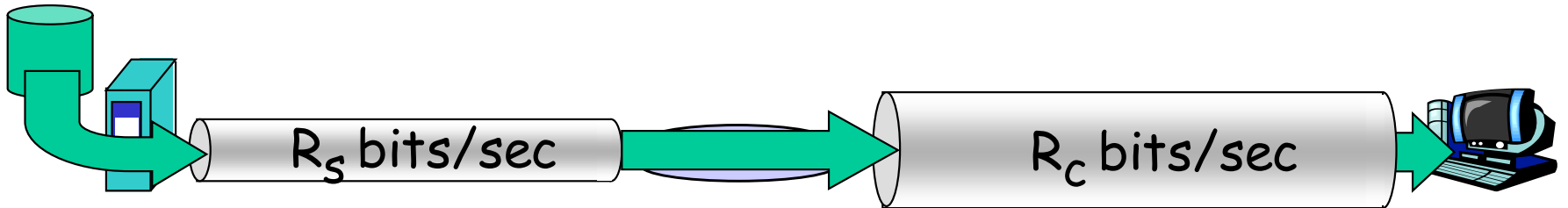
Throughput

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

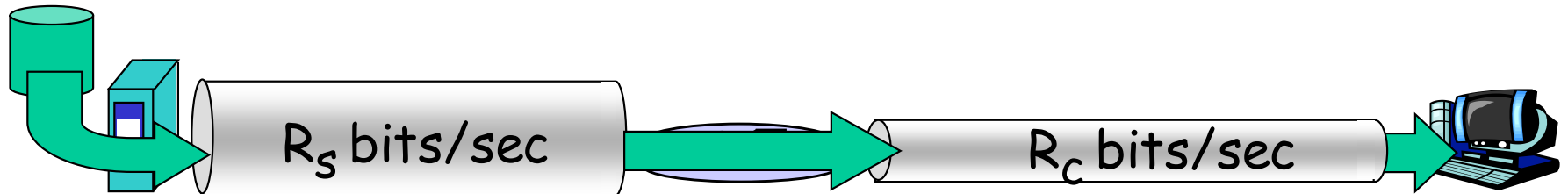


Throughput (more)

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



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

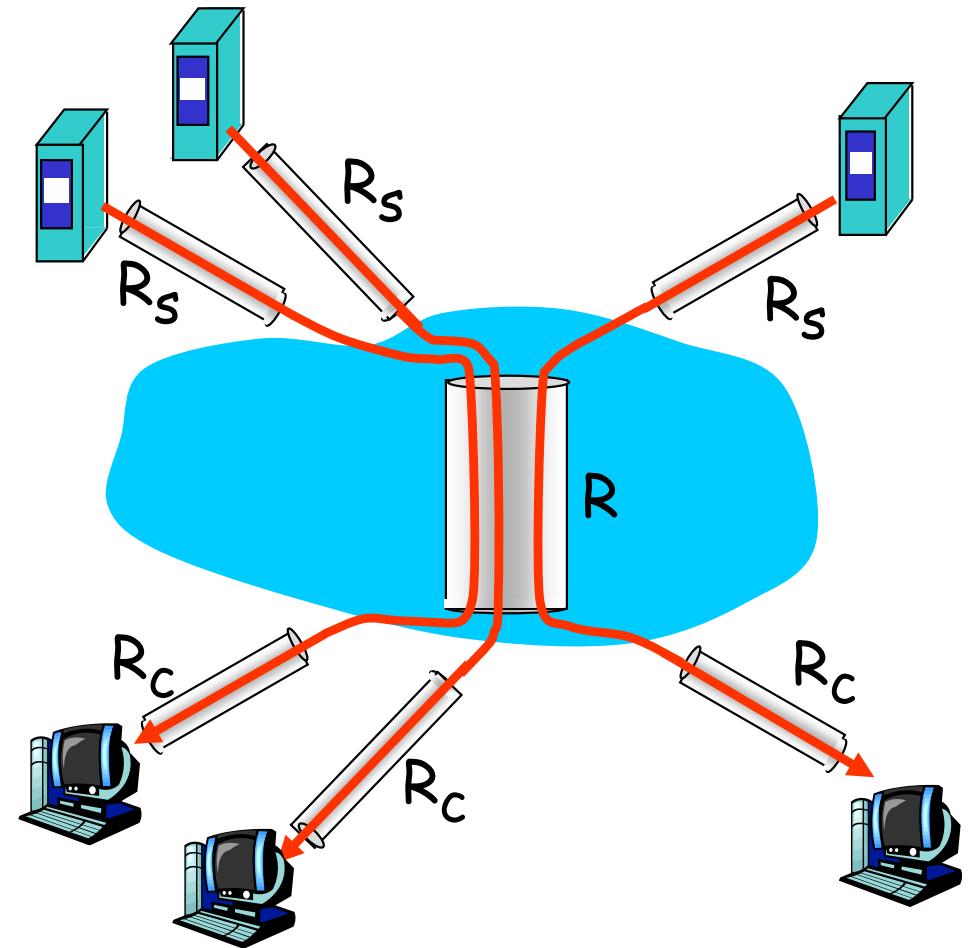


bottleneck link

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 1: roadmap

1.1 What is the Internet?

1.2 Network edge

- end systems, access networks, links

1.3 Network core

- circuit switching, packet switching, network structure

1.4 Delay, loss and throughput in packet-switched networks

1.5 Protocol layers, service models

1.6 Networks under attack: security

1.7 History

Protocol "Layers"

Networks are complex!

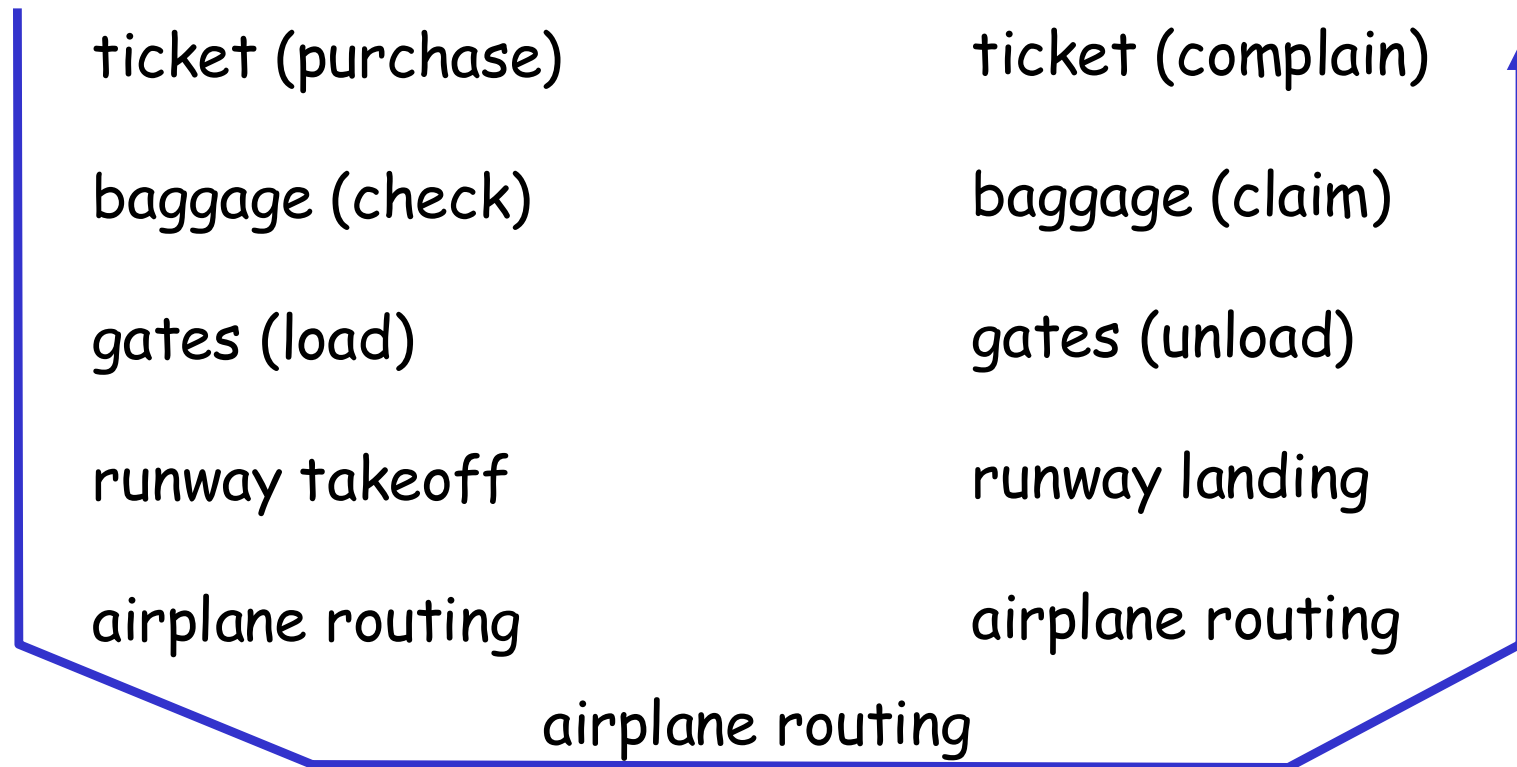
- ❑ many "pieces":
 - ❖ hosts
 - ❖ routers
 - ❖ links of various media
 - ❖ applications
 - ❖ protocols
 - ❖ hardware, software

Question:

Is there any hope of
organizing structure of
network?

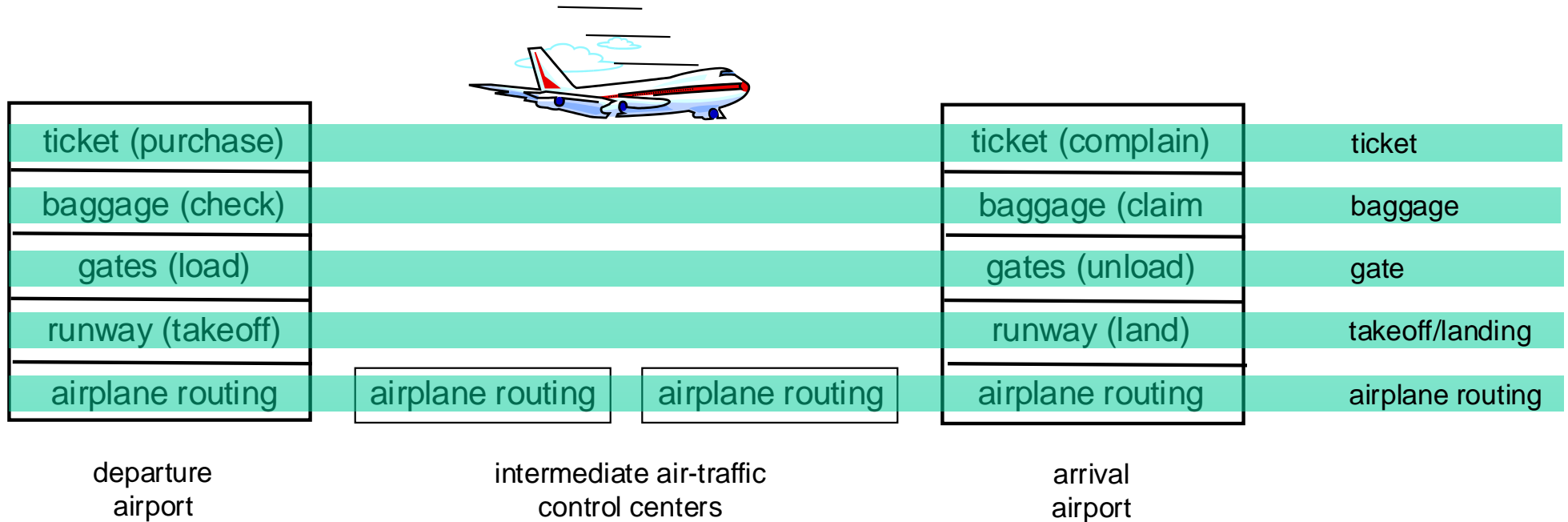
Or at least our discussion
of networks?

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

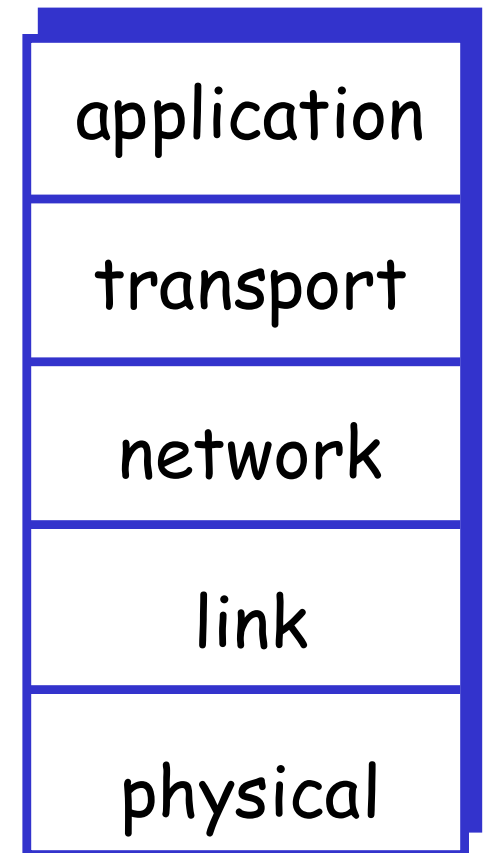
Why layering?

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?

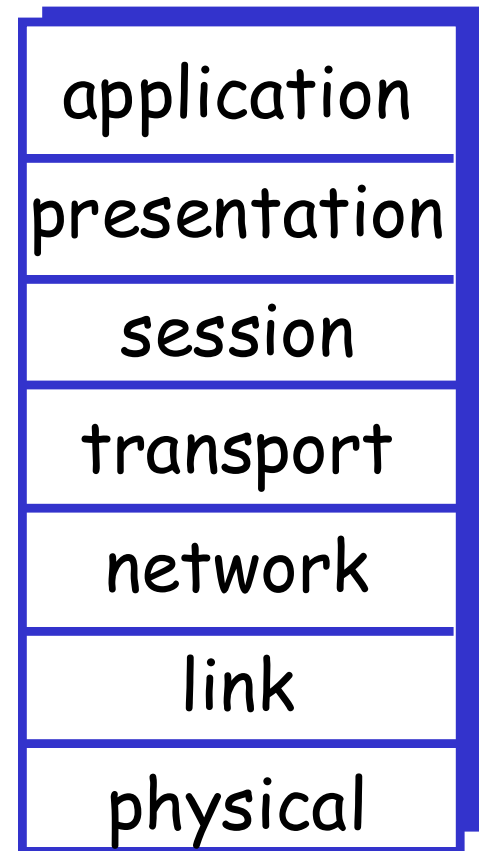
Internet protocol stack

- ❑ **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
 - ❖ PPP, Ethernet
- ❑ **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

