# Introduction

ΜΥΥ 801
ΔΙΚΤΥΑ ΥΠΟΛΟΓΙΣΤΩΝ ΙΙ

Liaskos Christos
UoI CSE

# Course Details

**Instructor:** Christos Liaskos
**Email:** cliaskos@uoi.gr

**Class Hours:**
Thu: 16:00-19:00 (Theory - Αμφ. 1)
Fri: 14:00-16:00 (Labs)

**Contact:**
via email (office hours TBA)

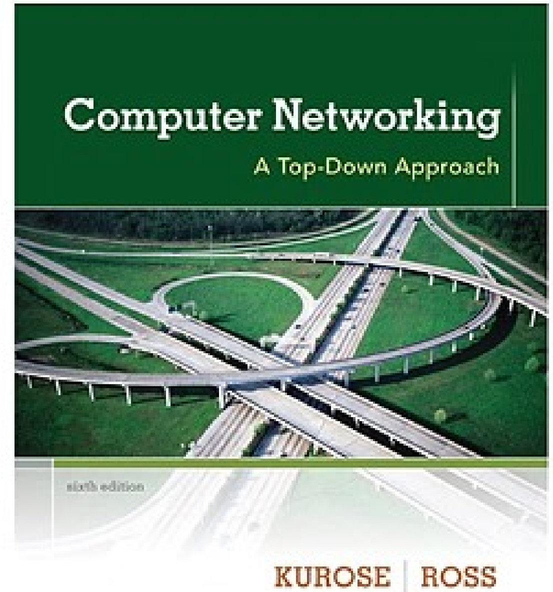
# Outline

- Course Info
- Introduction
- Some basic concepts
- History of popular wireless systems

# Textbook

Slides used/adapted from the original material by the book authors.






*Computer Networking: A Top Down Approach*
7th edition
Jim Kurose, Keith Ross
Addison-Wesley
March 2012

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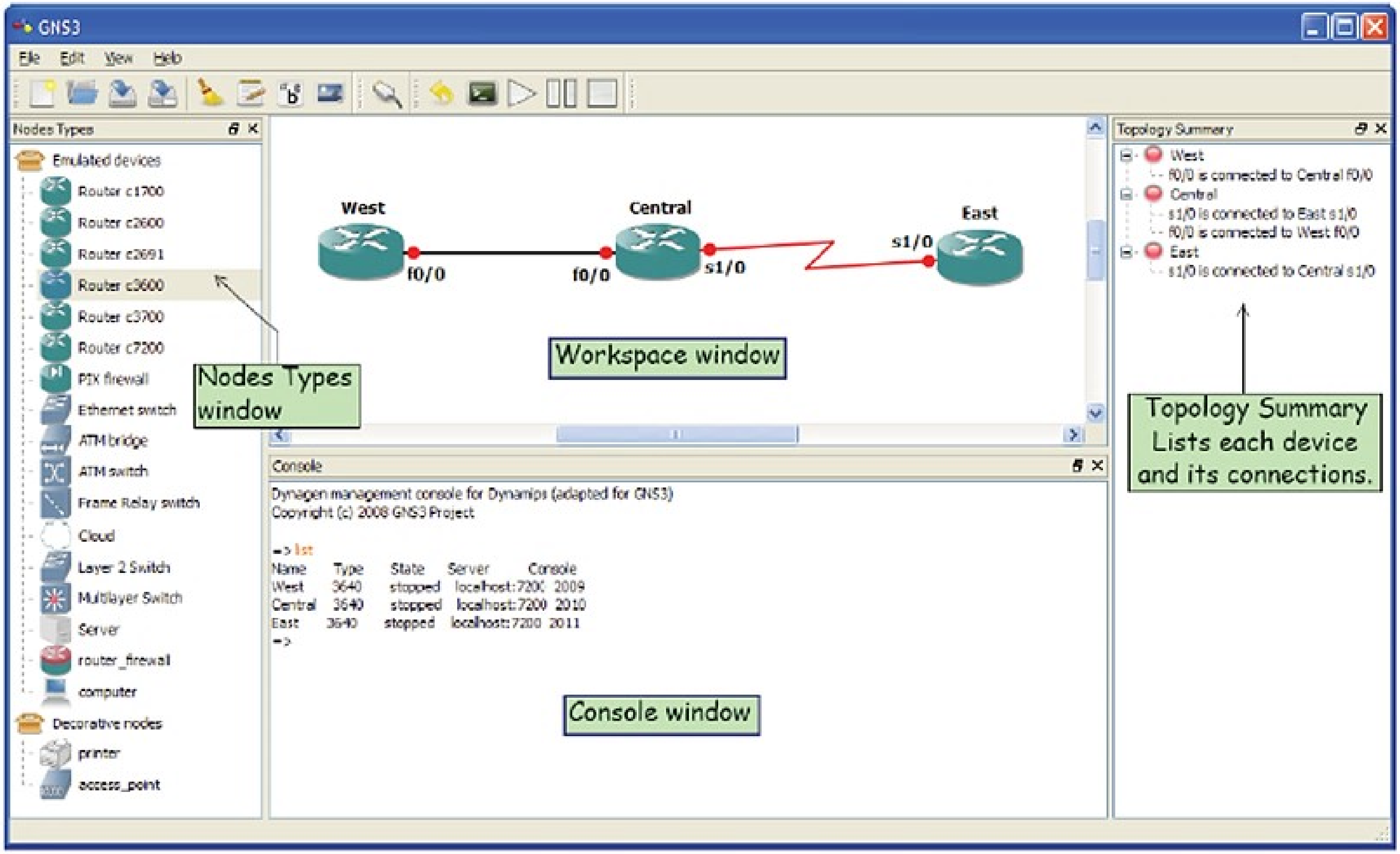
# Textbook outline

- Chapter 1 Computer Networks and the Internet
- Chapter 2 Application Layer — How do applications send data to each other?
- Chapter 3 Transport Layer — How does the network multiplexes the data?
- Chapter 4 The Network Layer — How does the network perform routing?
- Chapter 5 The Link Layer: Links, Access Networks, and LANs — How are frames delivered in a LAN?
- Chapter 6 Wireless and Mobile Networks
- Chapter 7 Multimedia Networking
- Chapter 8 Security in Computer Networks → We will see some recent DDoS attack types
- Chapter 9 Network Management → We will survey a few things about SDN

# Grading

- There will be one final course exam
  - The usual stuff..
- There will be 1 lab exam.
  - It will count as fixed part of the overall grade.
    - E.g.,
      - If you pass with honors, you get 2 pts, the rest 8 pts via the final exam.
      - If you fail, you go to the exams with a -2pt handicap (max 8).
  - Lab exercises: based on GNS3
    - Graphical Network Simulator-3.
    - Really cool, realistic network simulator.
    - We will see several networking aspects.
    - You will be examined in much simpler things.

# GNS3


GNS3
File Edit View Help
Nodes Types
Emulated devices
Router c1700
Router c2600
Router c2691
Router c3600
Router c3700
Router c7200
PIX firewall
Ethernet switch
ATM bridge
ATM switch
Frame Relay switch
Cloud
Layer 2 Switch
Multilayer Switch
Server
router_firewall
computer
Decorative nodes
printer
access_point
Nodes Types window
West
Central
East
f0/0
f0/0
s1/0
s1/0
Workspace window
Topology Summary
West
f0/0 is connected to Central f0/0
Central
s1/0 is connected to East s1/0
f0/0 is connected to West f0/0
East
s1/0 is connected to Central s1/0
Topology Summary Lists each device and its connections.
Console
Dynagen management console for Dynamips (adapted for GNS3)
Copyright (c) 2008 GNS3 Project
=> list
Name Type State Server Console
West 3640 stopped localhost:7200 2009
Central 3640 stopped localhost:7200 2010
East 3640 stopped localhost:7200 2011
=>
Console window

# GNS3

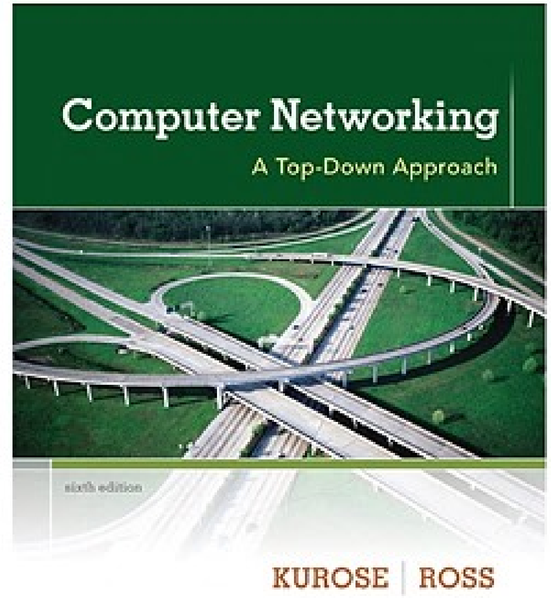
- Everything we need will be available at the CSE Labs.
- You are encouraged to use this tool on your own as well!
  - E.g. at your home PC
  - You will need a decent 8-core PC / 8 GB ram.
- Lots and lots of educational material, tutorials, YouTube channels on how to install, use, etc.

# Course/Lab Announcements

- Via my web-site
  - https://www.cse.uoi.gr/~cliaskos/

# Chapter 1 Introduction



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# Chapter 1: 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
- network core
- access net, physical media
- Internet/ISP structure
- performance: loss, delay
- protocol layers, service models
- network modeling

# Chapter 1: roadmap

1.1 What *is* the Internet?

1.2 Network edge

1.3 Network core

1.4 Network access and physical media

1.5 Internet structure and ISPs

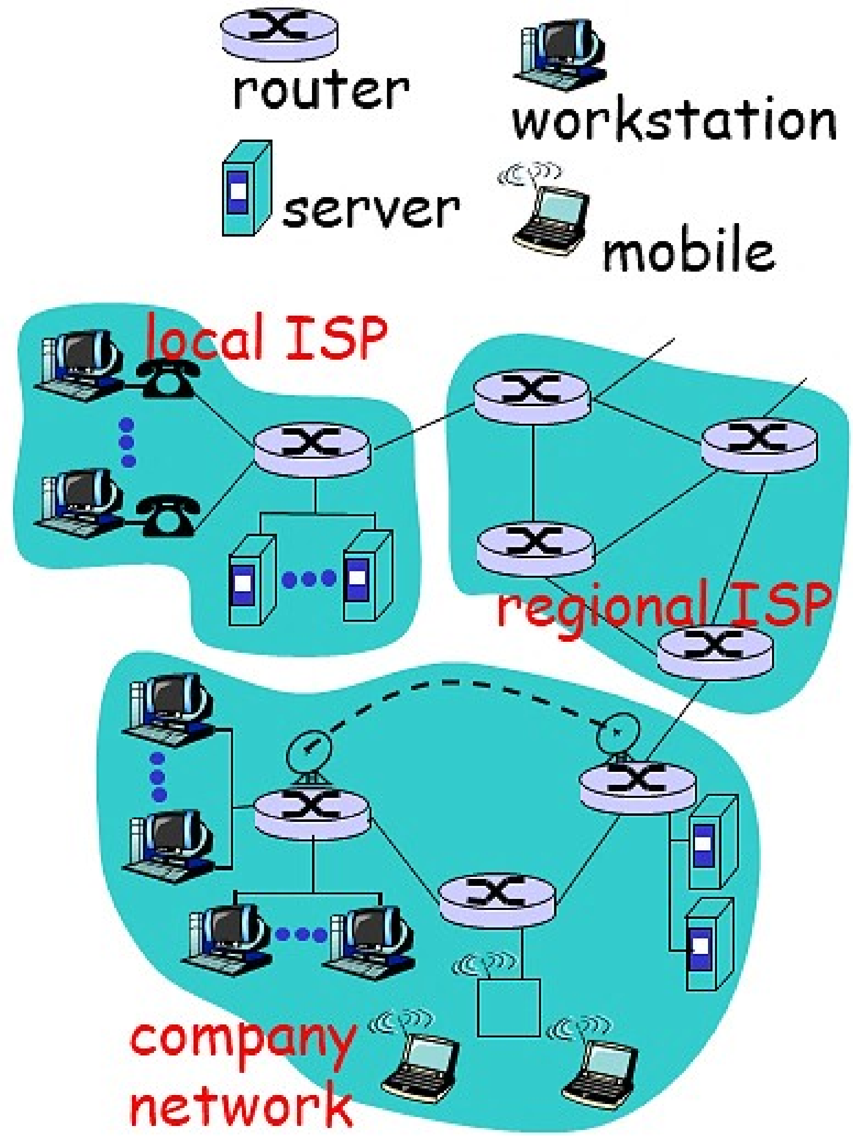
1.6 Delay & loss in packet-switched networks

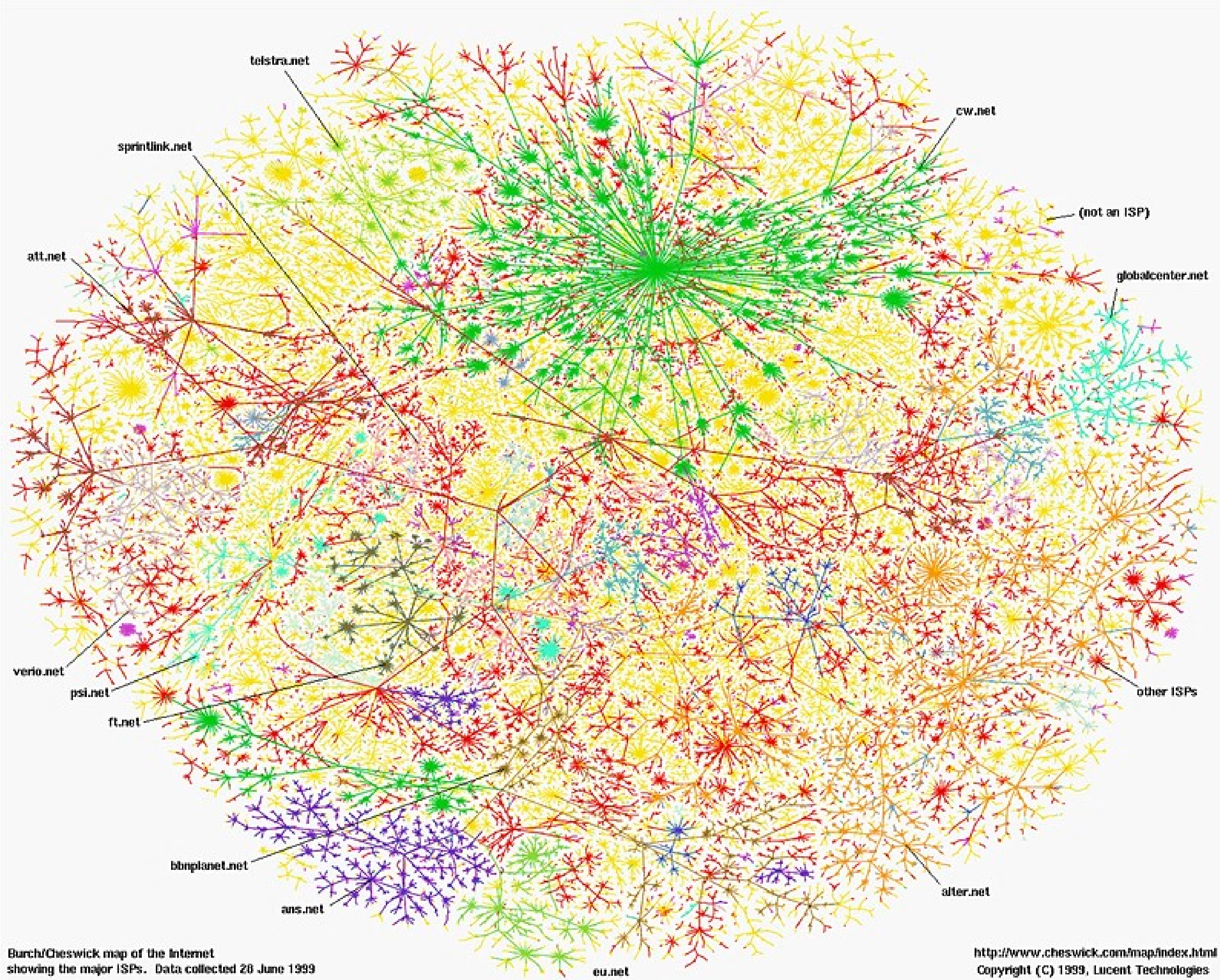
1.7 Protocol layers, service models

1.8 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***
- *routers:* forward packets (chunks of data)

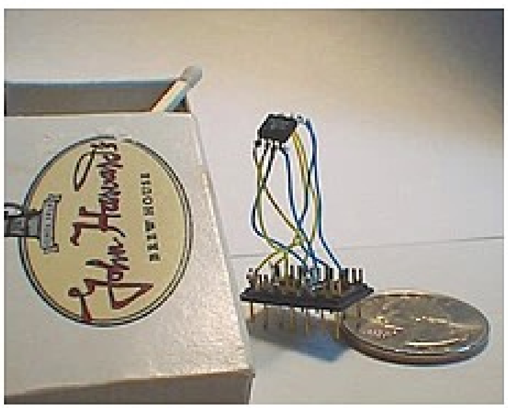



telstra.net
cw.net
sprintlink.net
(not an ISP)
att.net
globalcenter.net
verio.net
psi.net
ft.net
other ISPs
bbnplanet.net
alter.net
ans.net
Burch/Cheswick map of the Internet
showing the major ISPs. Data collected 28 June 1999
eu.net
http://www.cheswick.com/map/index.html
Copyright (C) 1999, Lucent Technologies

# "Cool" old internet appliances

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

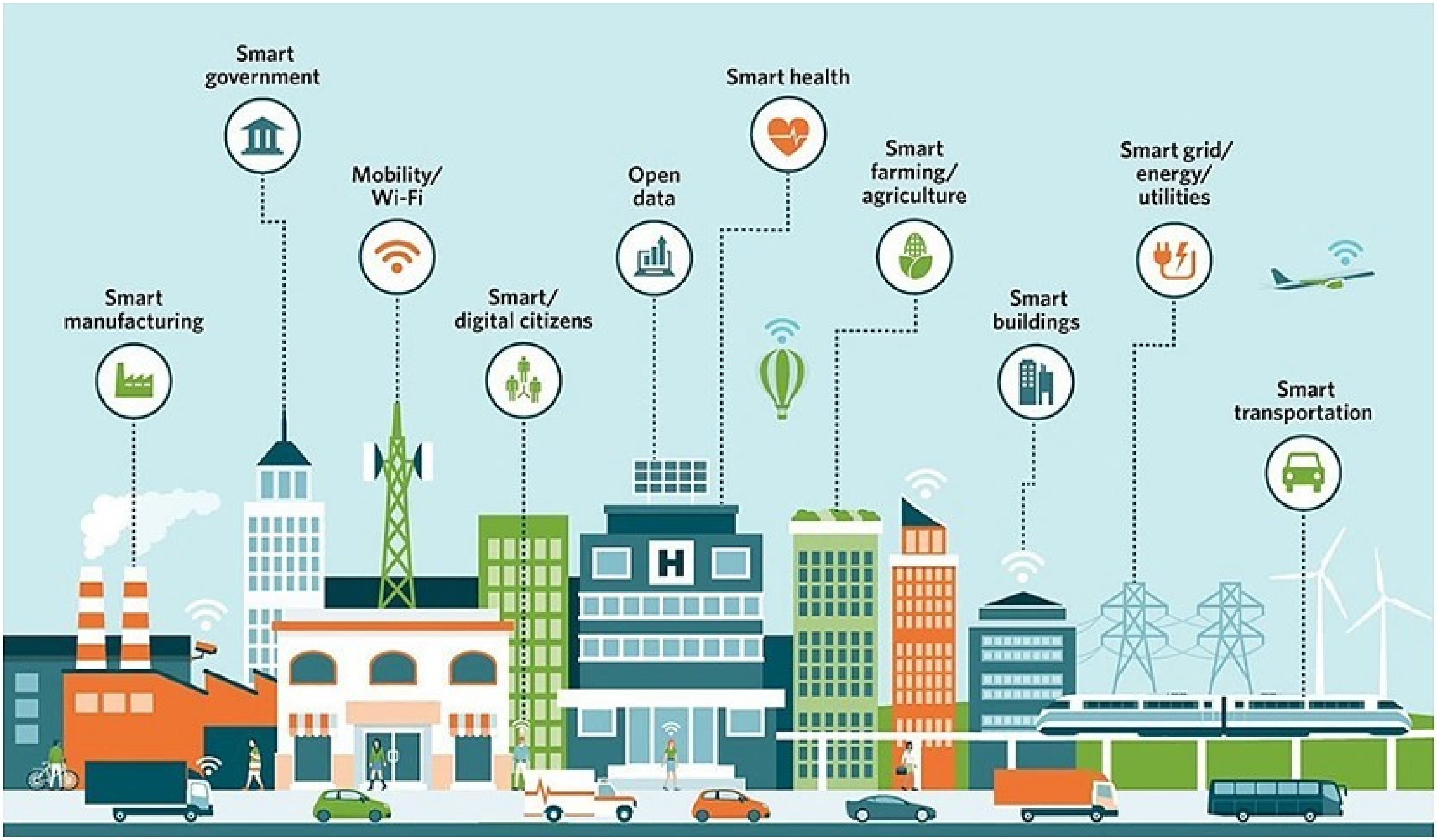
Web-enabled toaster +
weather forecaster



World's smallest web server
http://www-ccs.cs.umass.edu/~shri/iPic.html

Internet phones

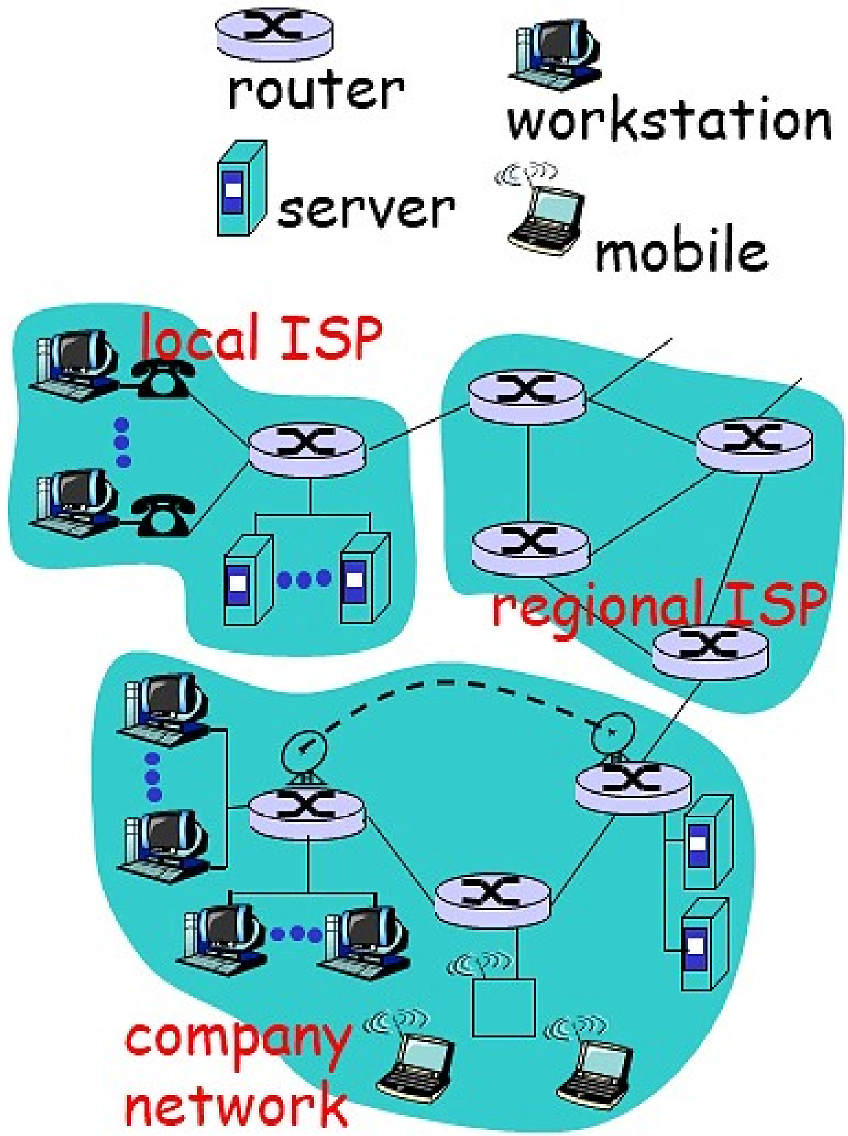
# Towards IoE



Smart government
Smart health
Mobility/ Wi-Fi
Open data
Smart farming/ agriculture
Smart grid/ energy/ utilities
Smart manufacturing
Smart/ digital citizens
Smart buildings
Smart transportation
H

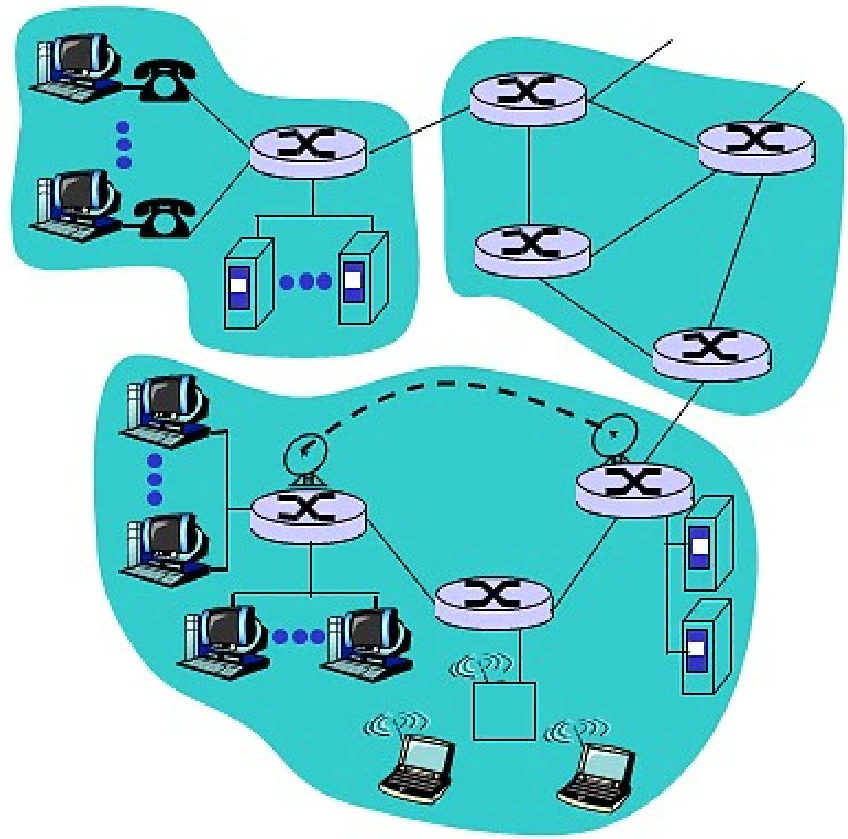
# What's the Internet: "nuts and bolts" view

- *protocols* control sending, receiving of msgs
  - e.g., TCP, IP, HTTP, FTP, PPP
- *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, email, games, e-commerce, file sharing
- communication services provided to apps:
  - Connectionless unreliable
  - connection-oriented reliable



# 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

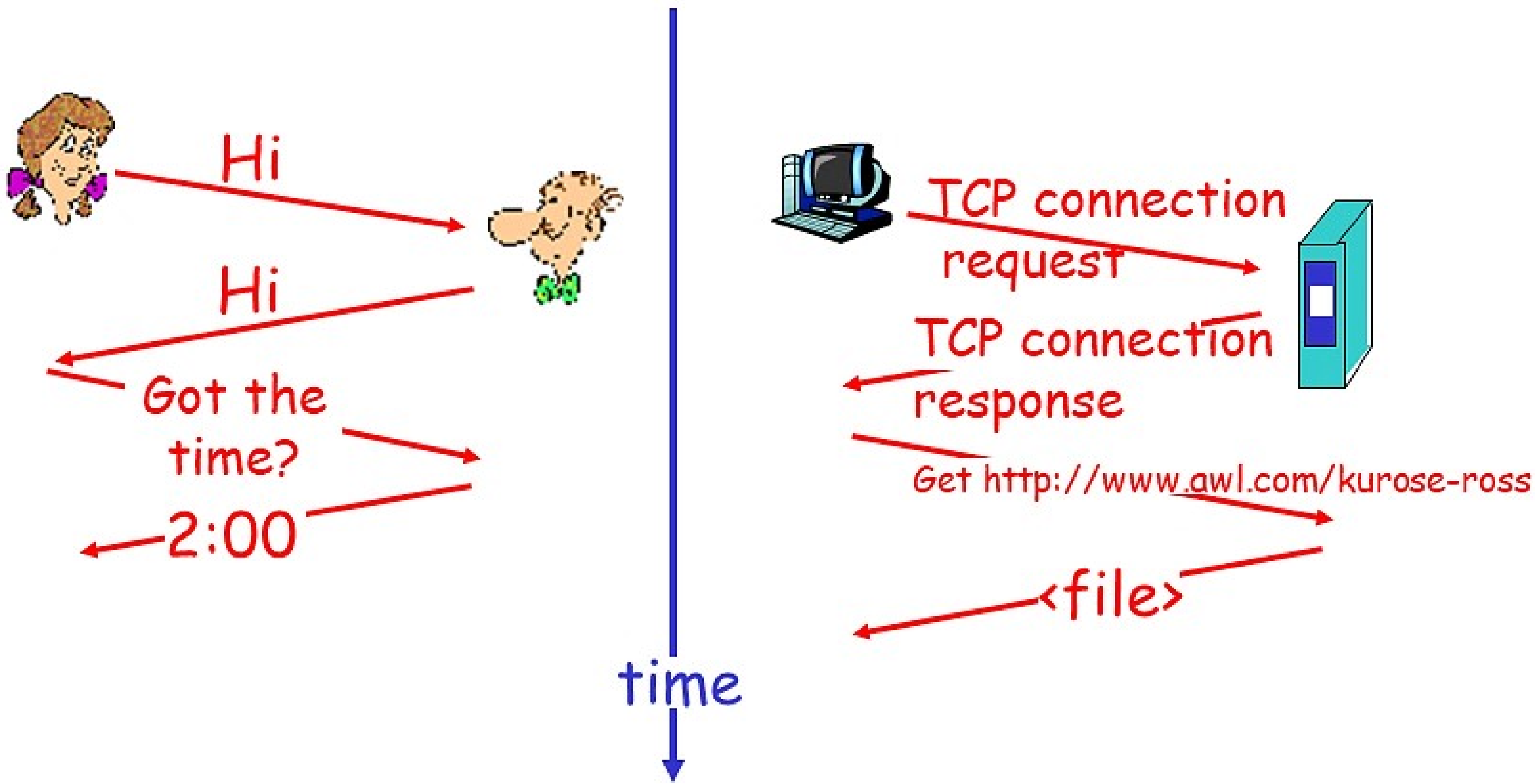
## network protocols:

- 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

1.3 Network core

1.4 Network access and physical media

1.5 Internet structure and ISPs

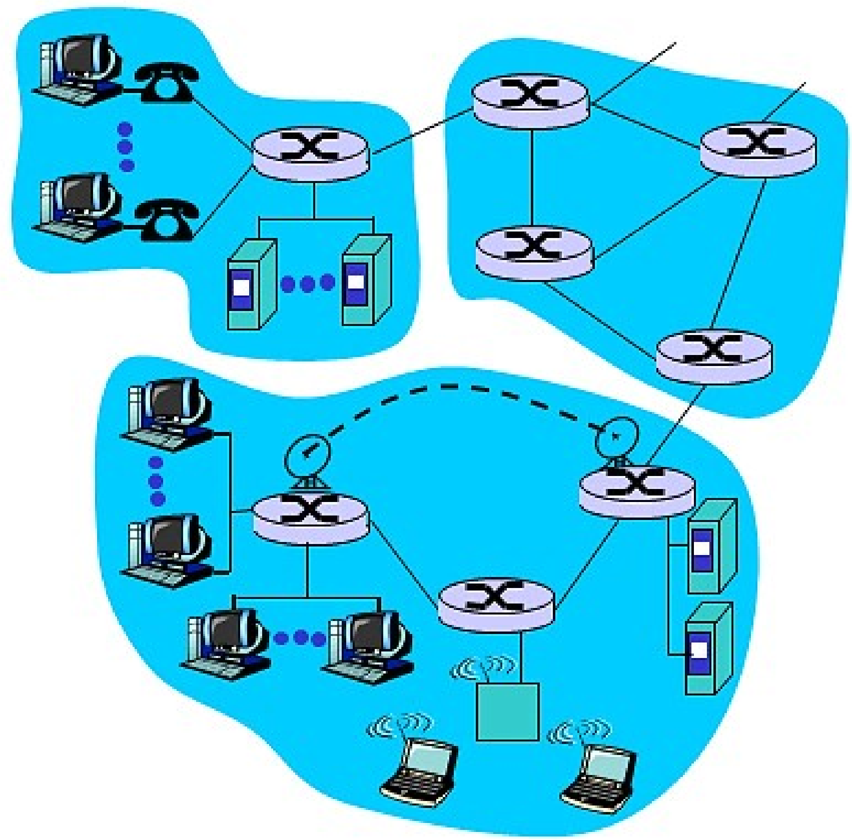
1.6 Delay & loss in packet-switched networks

1.7 Protocol layers, service models

1.8 History

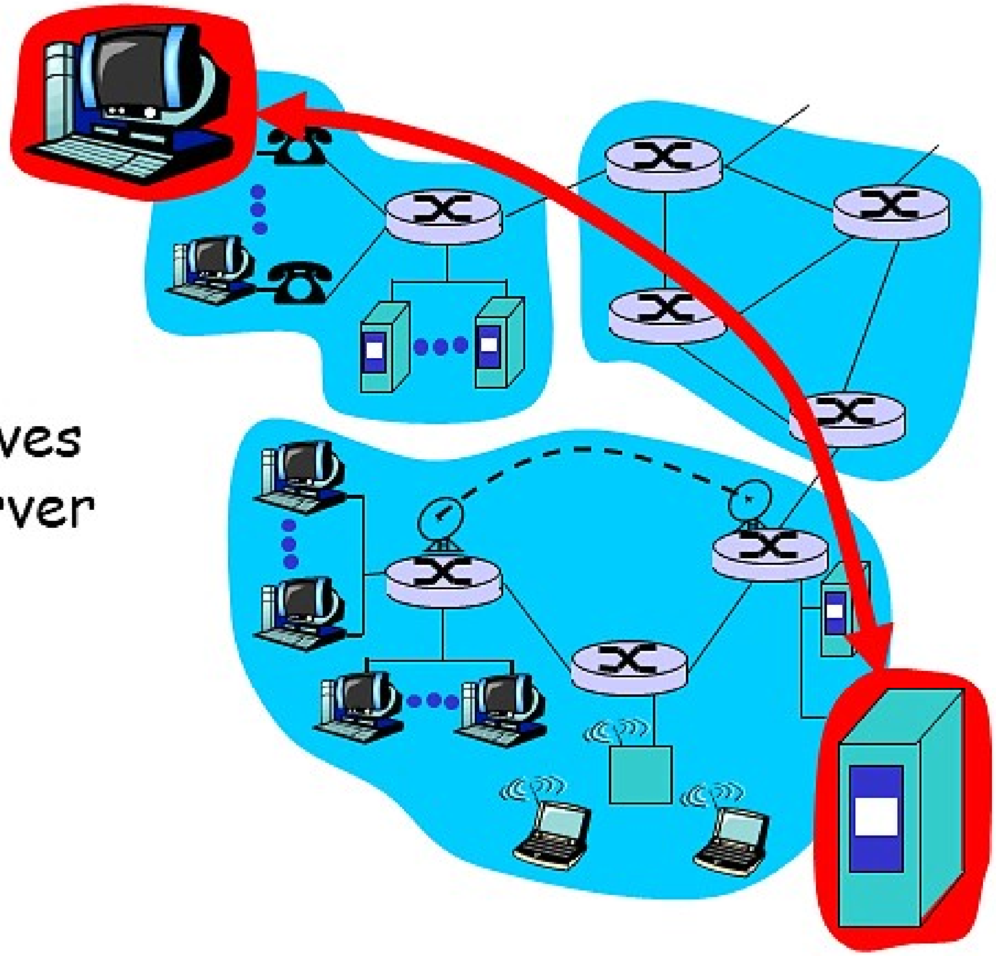
# A closer look at network structure:

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



# 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: connection-oriented 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 connection-oriented 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: connectionless 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

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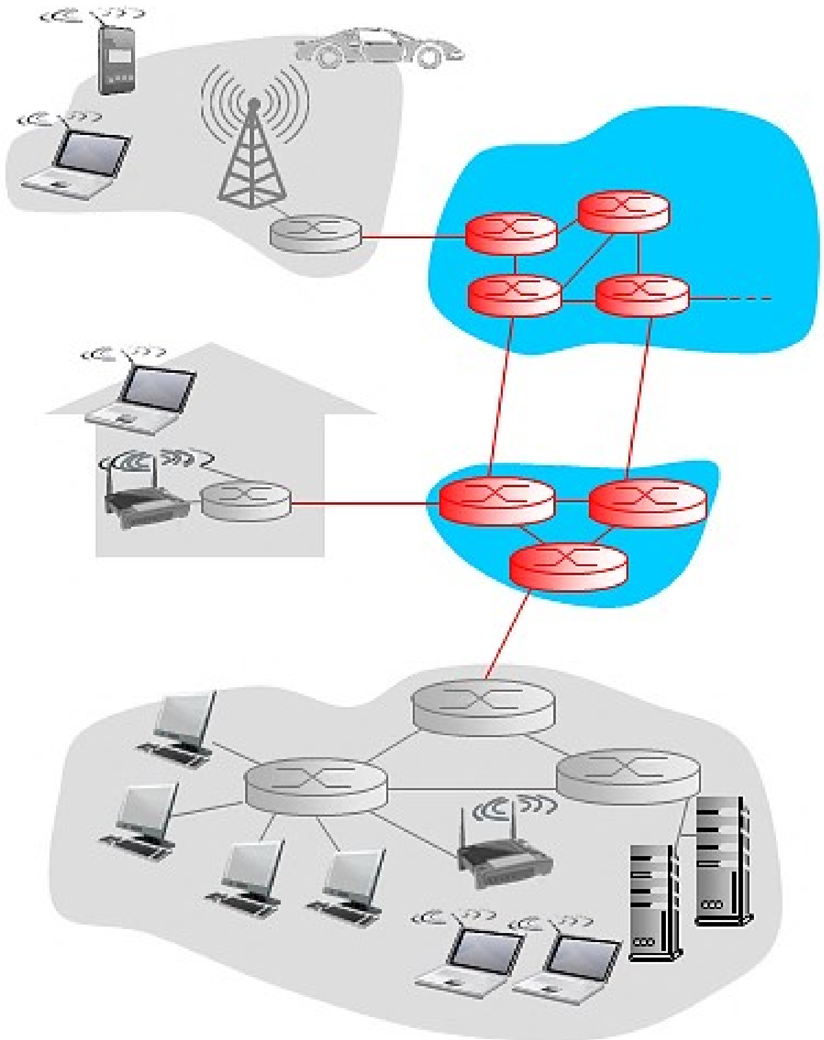
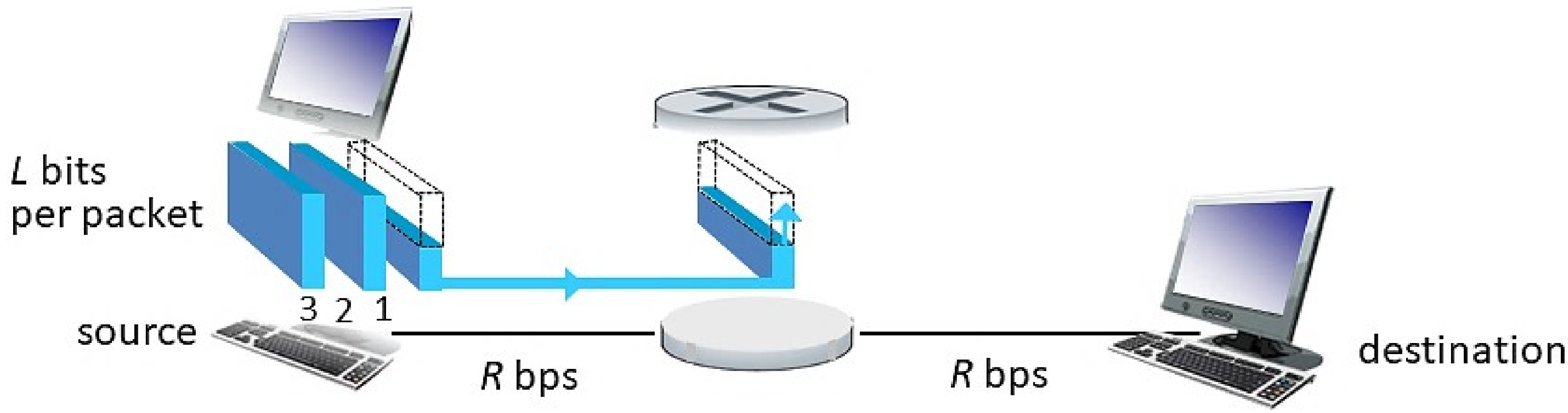
# The network core

- 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



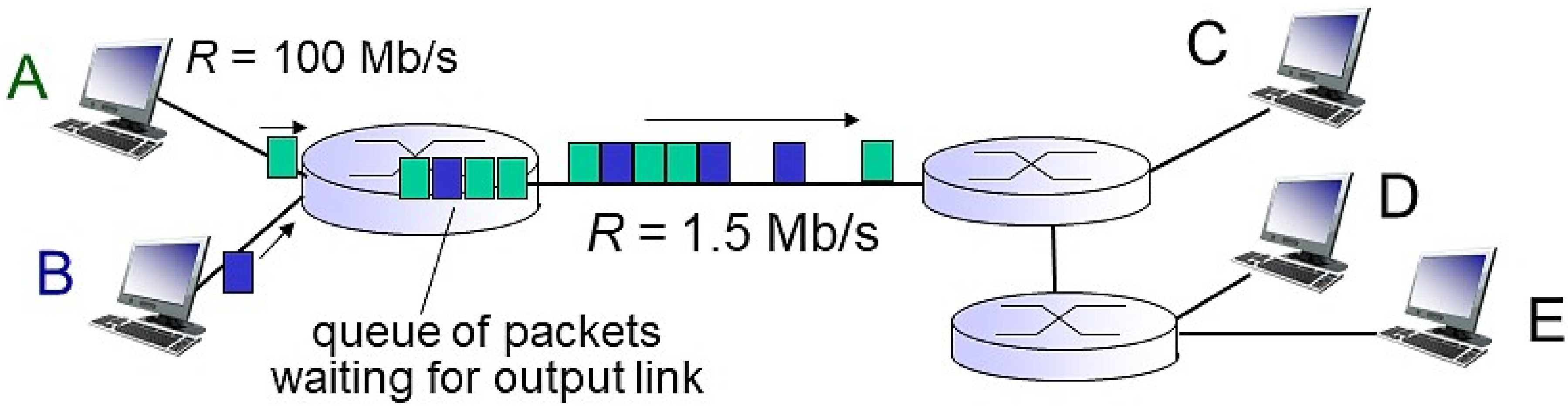

- takes $L/R$ seconds to transmit (push out) $L$-bit packet into link at $R$ bps
- *store and forward:* entire packet must arrive at router before it can be transmitted on next link
- end-end delay = $2L/R$ (assuming zero propagation delay)

more on delay shortly …

*one-hop numerical example:*

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

# Packet Switching: queueing delay, loss




## queuing and loss:

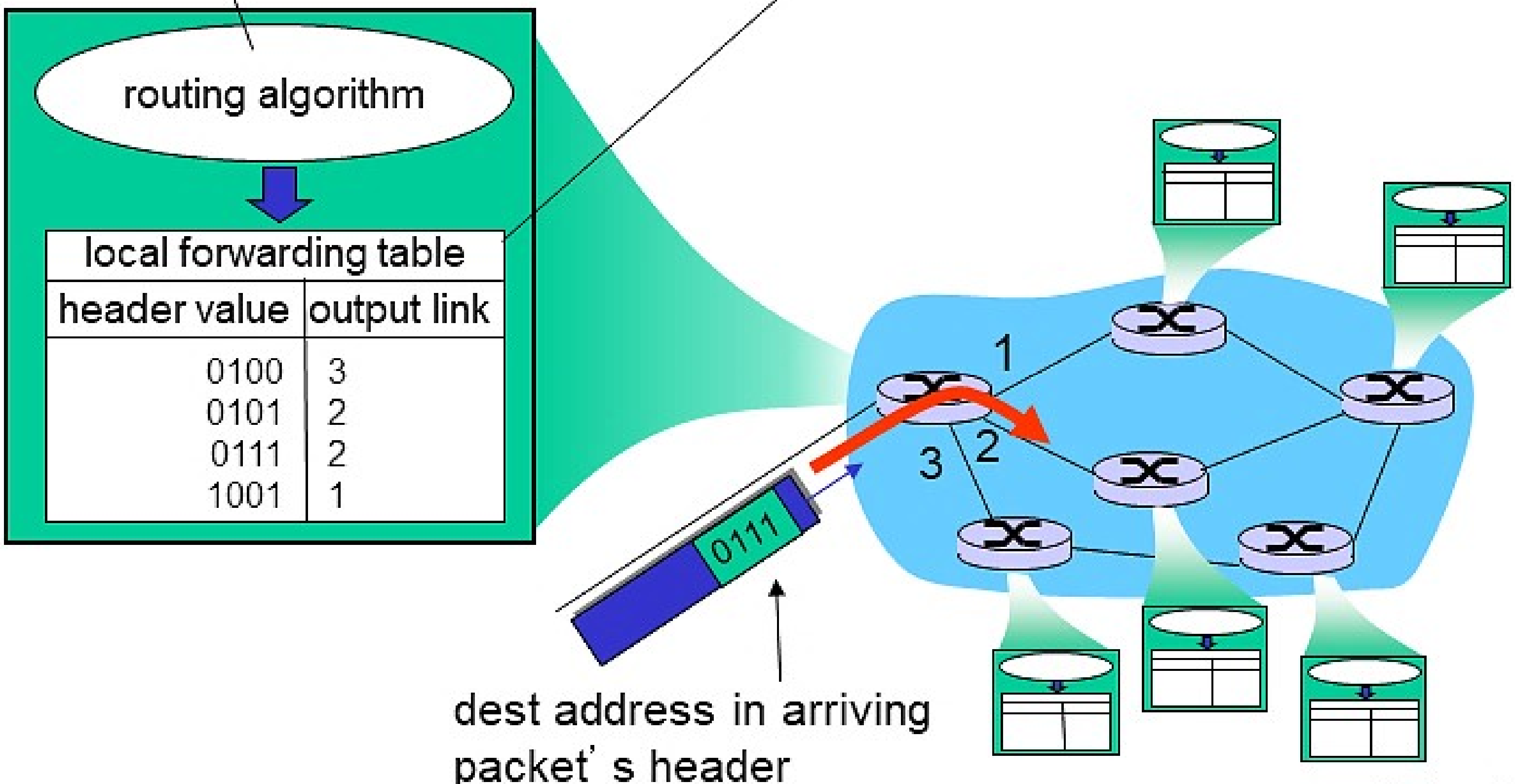
- If arrival rate (in bits) to link exceeds transmission rate of link for a period of time:
  - packets will queue, wait to be transmitted on link
  - packets can be dropped (lost) if memory (buffer) fills up

# Two key network-core functions

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

- *routing algorithms*

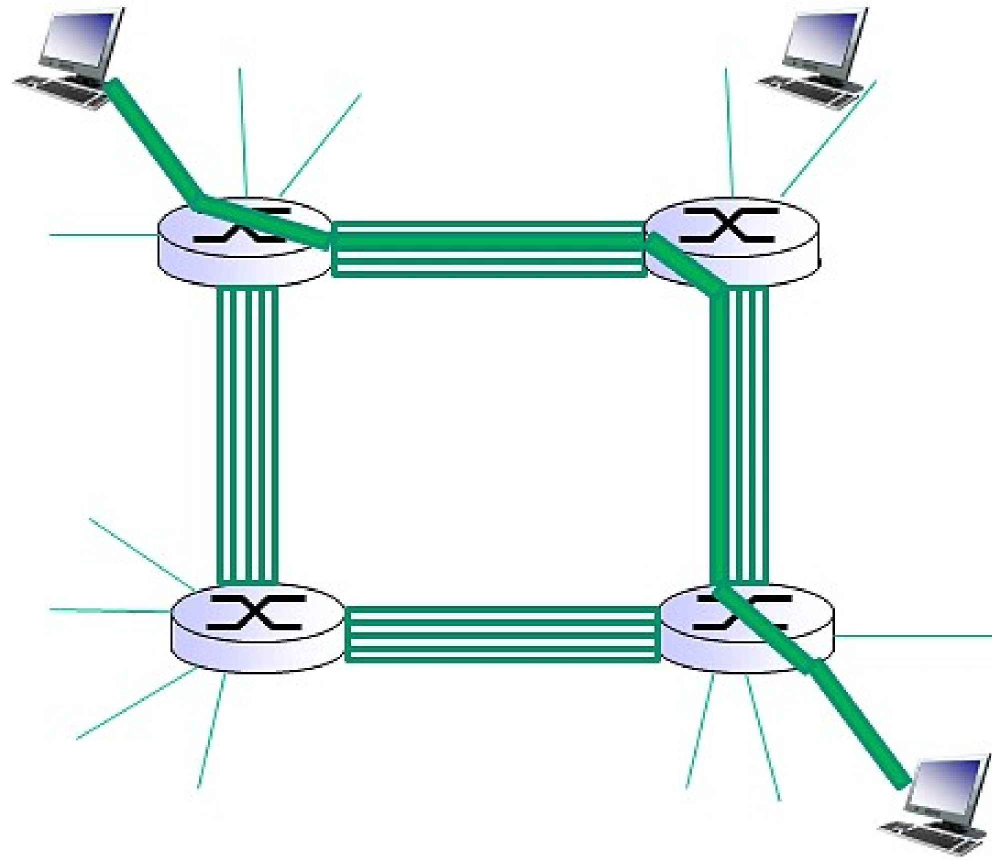
*forwarding:* move packets from router's input to appropriate router output



# Alternative core: circuit switching

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

- In diagram, each link has four circuits.
  - call gets 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

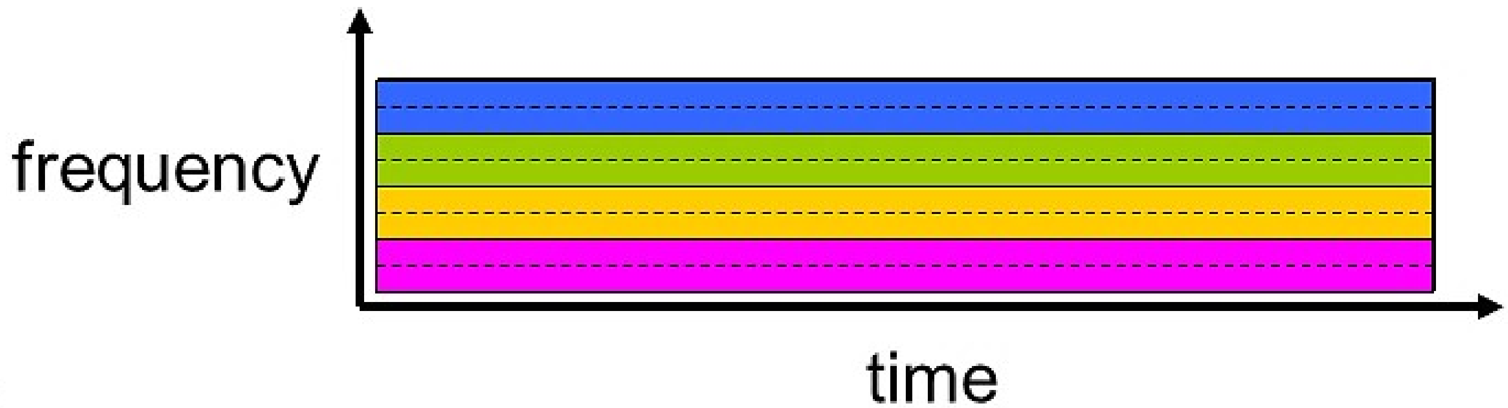


# Circuit switching: FDM versus TDM

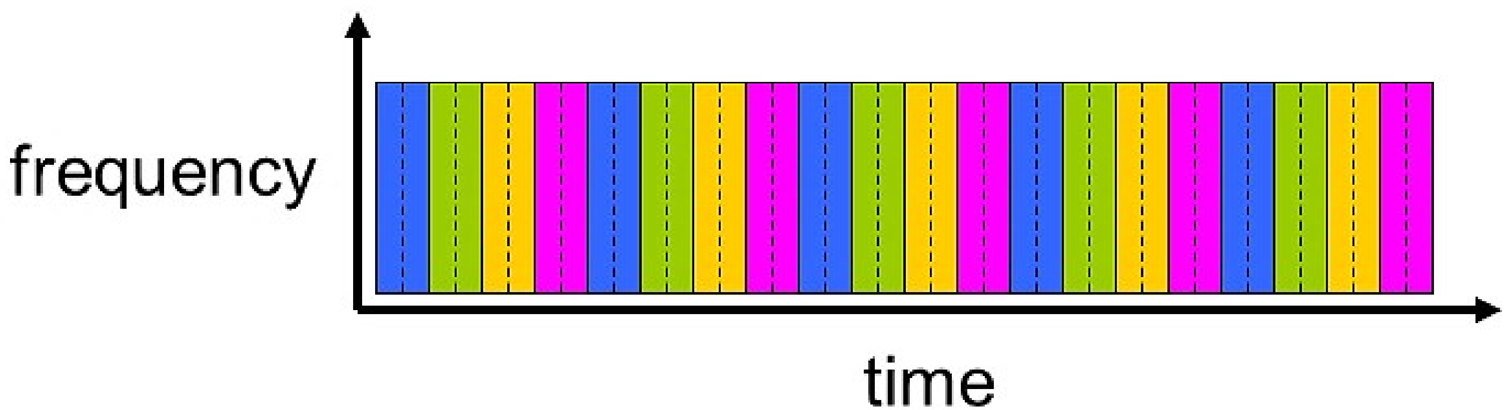
Example:

4 users

FDM




TDM

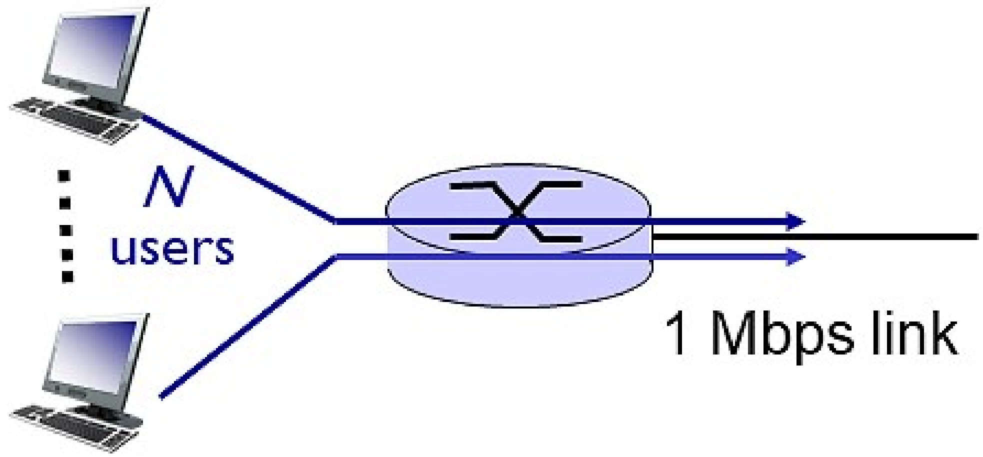


# Packet switching versus circuit switching

*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)?

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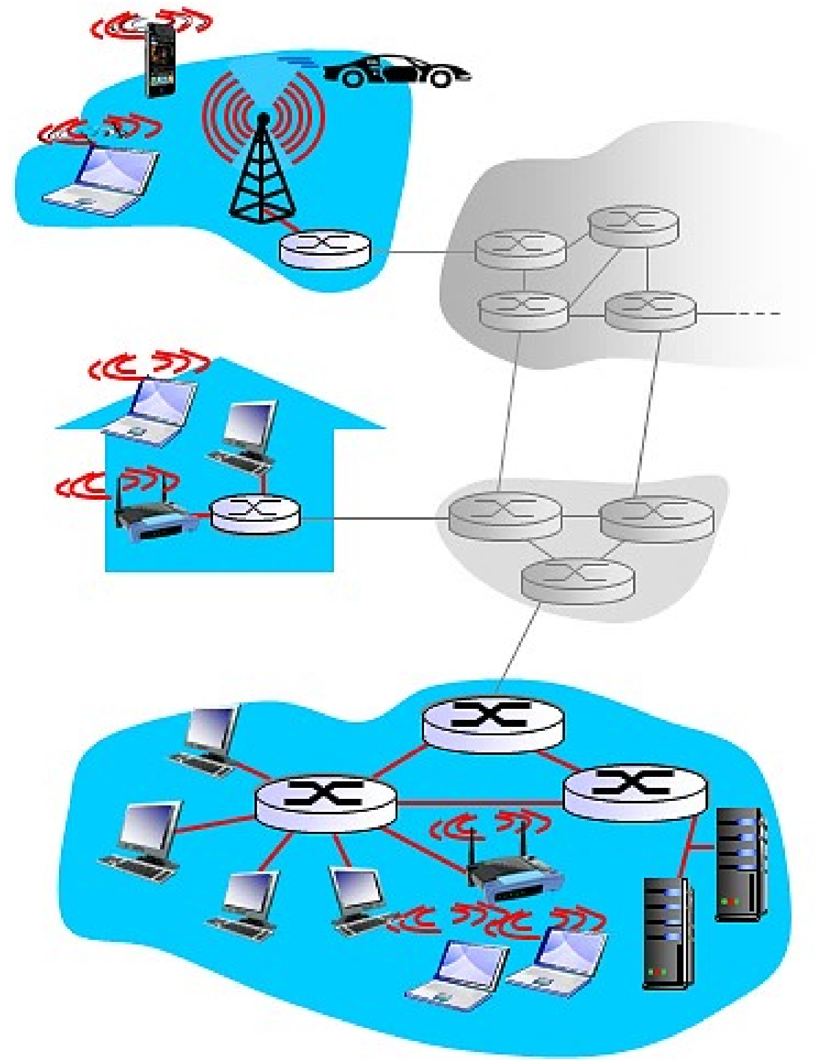
# Access networks and physical media

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

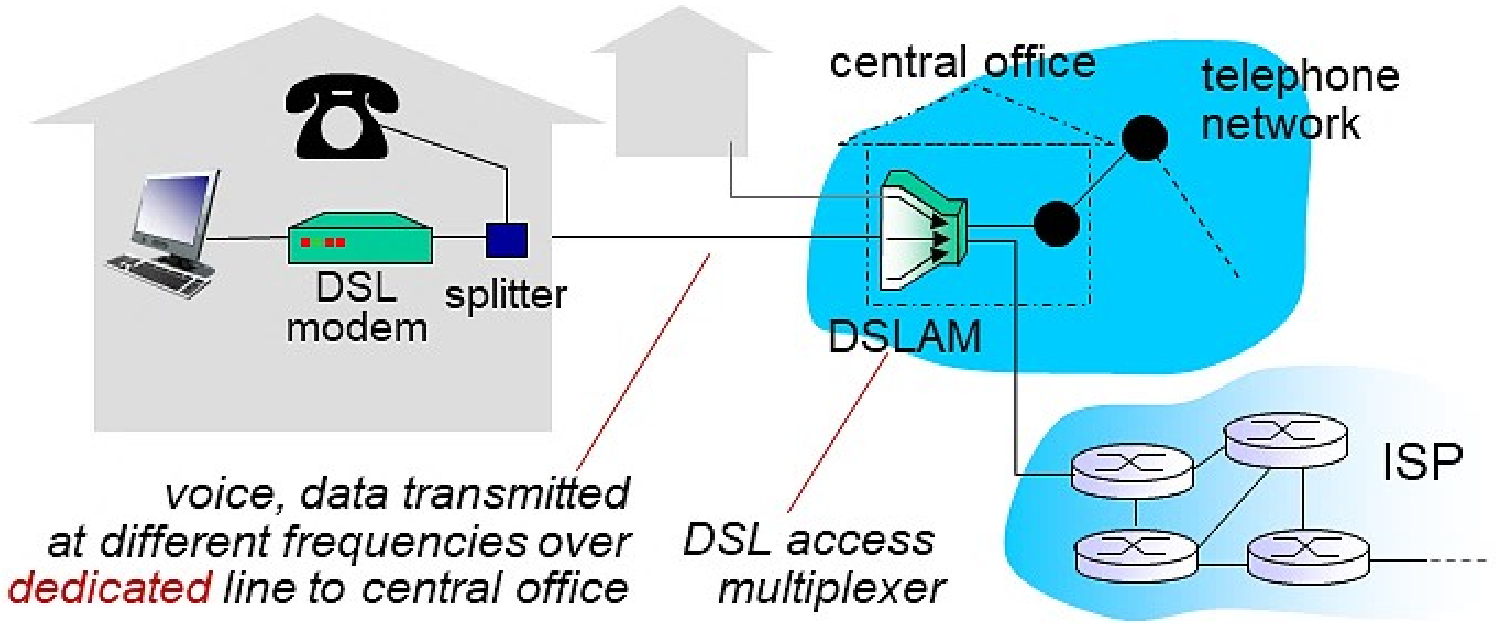
- residential access nets
- institutional access networks (school, company)
- mobile access networks

*keep in mind:*

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

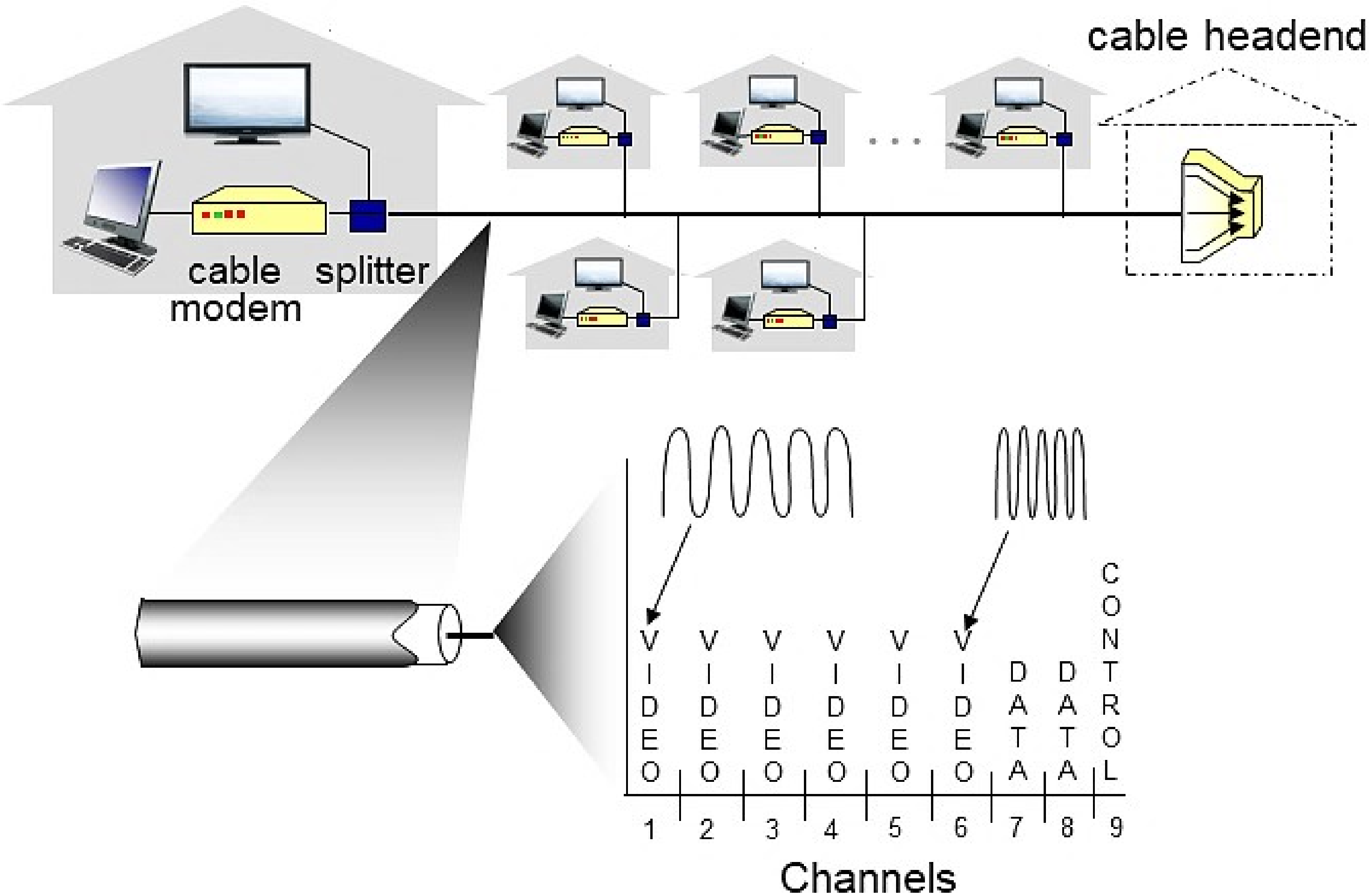


# Access net: digital subscriber line (DSL)



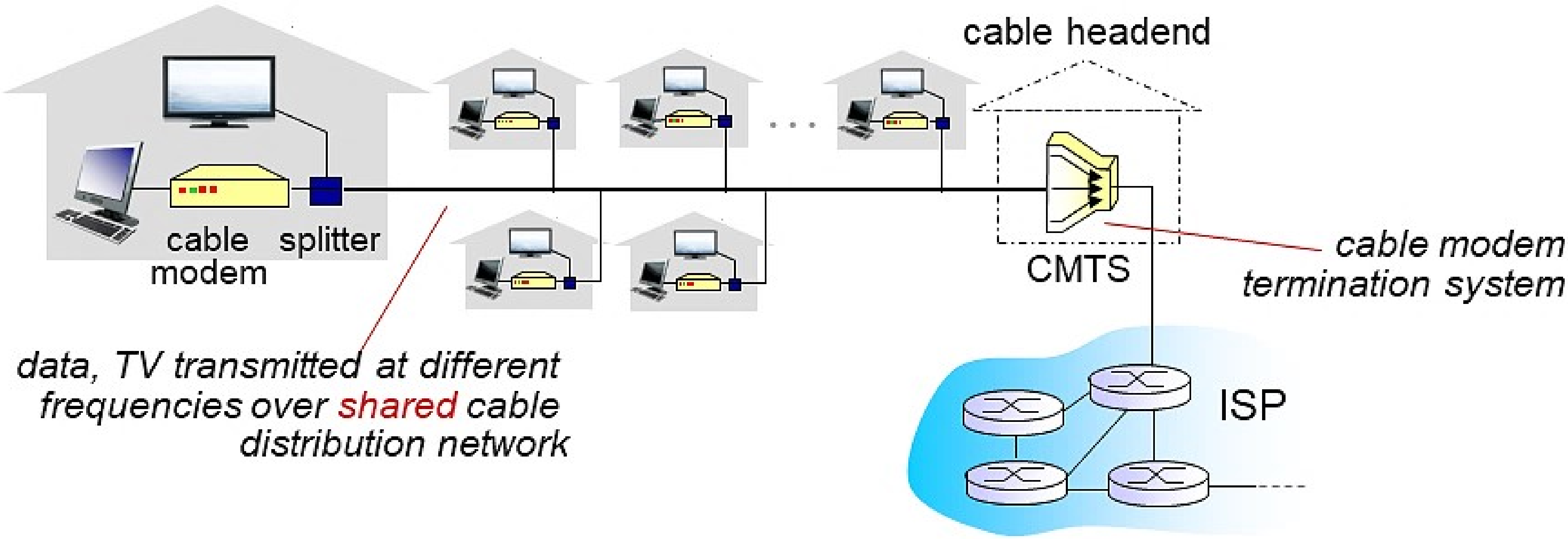

- use *existing* telephone line to central office DSLAM
  - data over DSL phone line goes to Internet
  - voice over DSL phone line goes to telephone net
- < 2.5 Mbps upstream transmission rate (typically < 1 Mbps)
- < 24 Mbps downstream transmission rate (typically < 10 Mbps)

# Access net: cable network



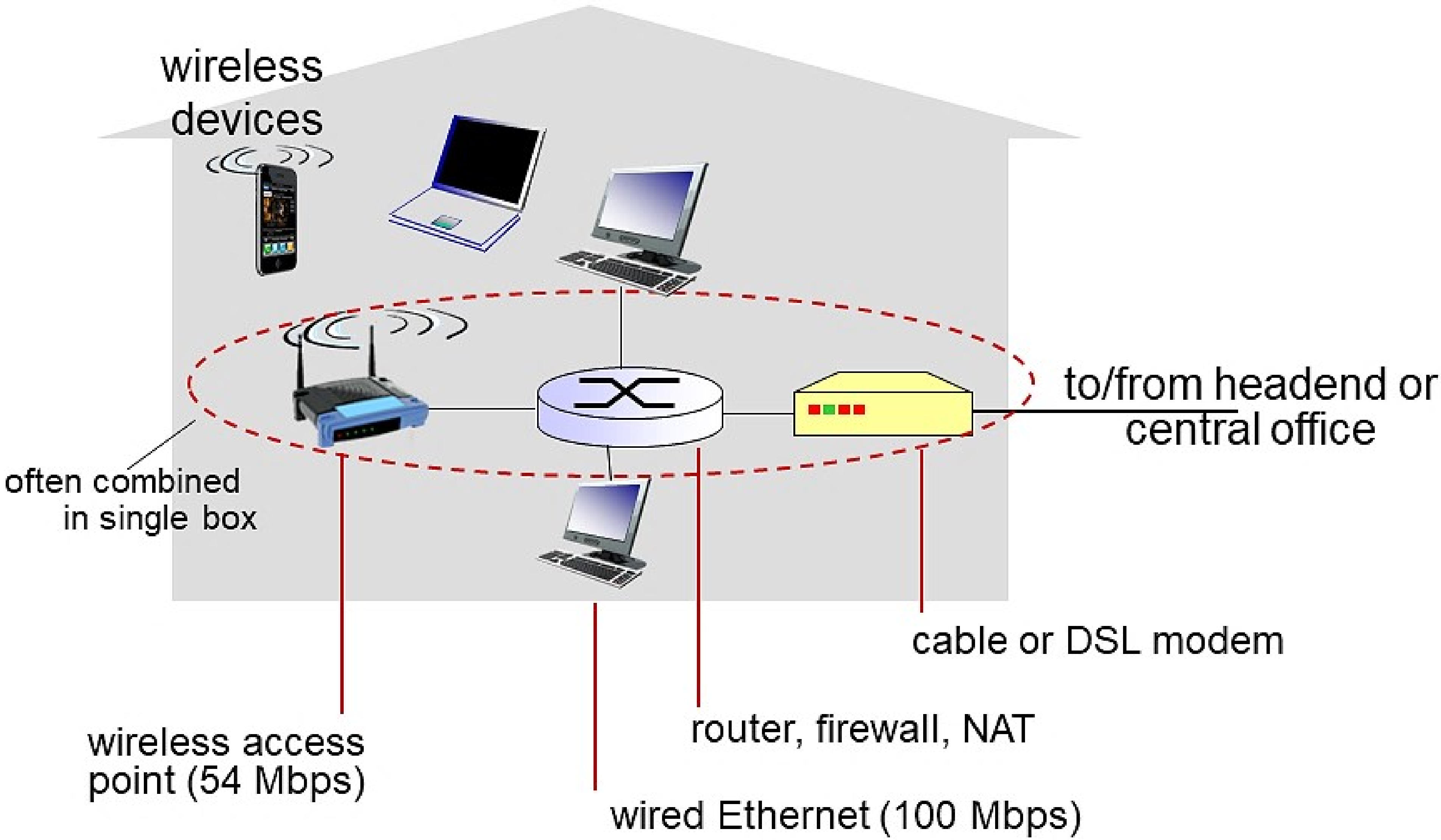

*frequency division multiplexing:* different channels transmitted in different frequency bands

# Access net: cable network

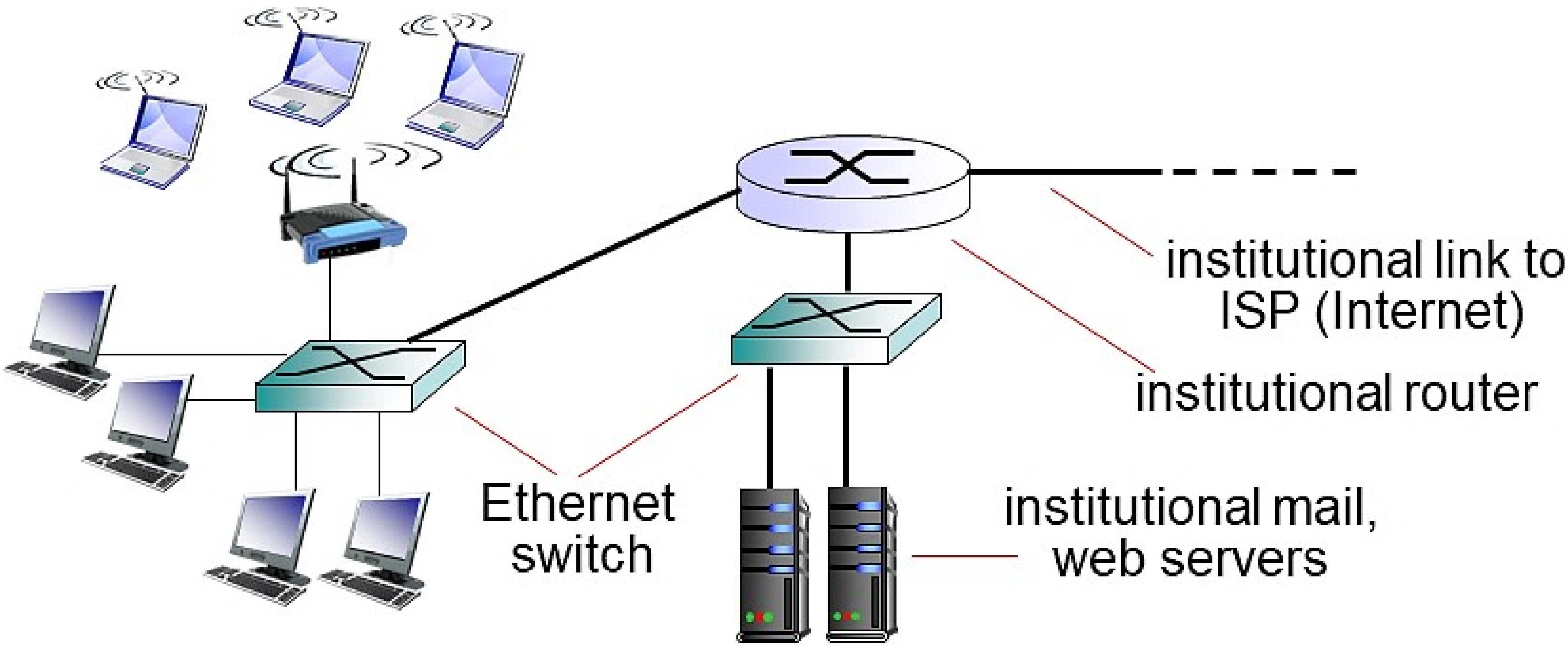



- HFC: hybrid fiber coax
  - asymmetric: up to 30Mbps downstream transmission rate, 2 Mbps upstream transmission rate
- network of cable, fiber attaches homes to ISP router
  - homes *share access network* to cable headend
  - unlike DSL, which has dedicated access to central office

# 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

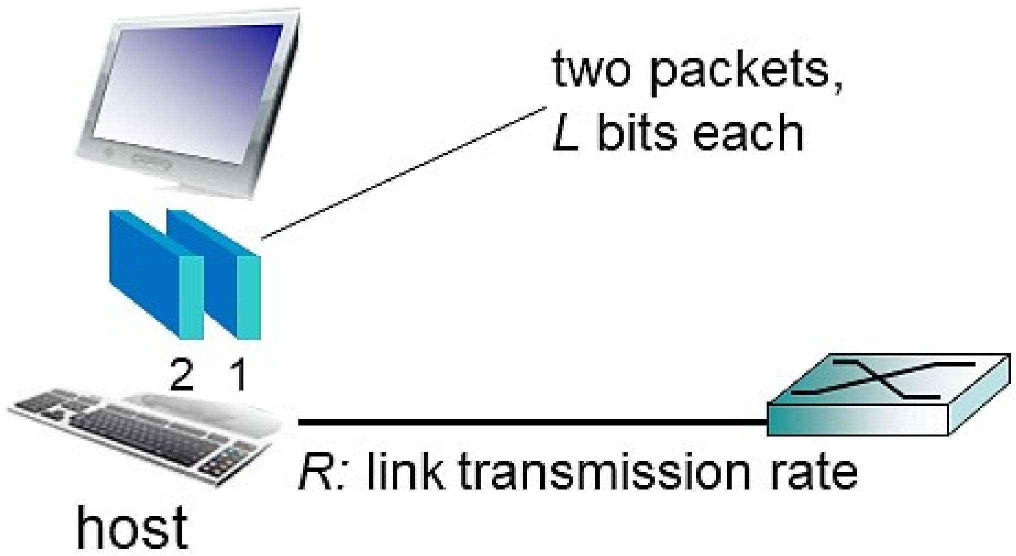

wide-area wireless access

- 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*




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

# 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 Gpbs 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 Gpbs 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

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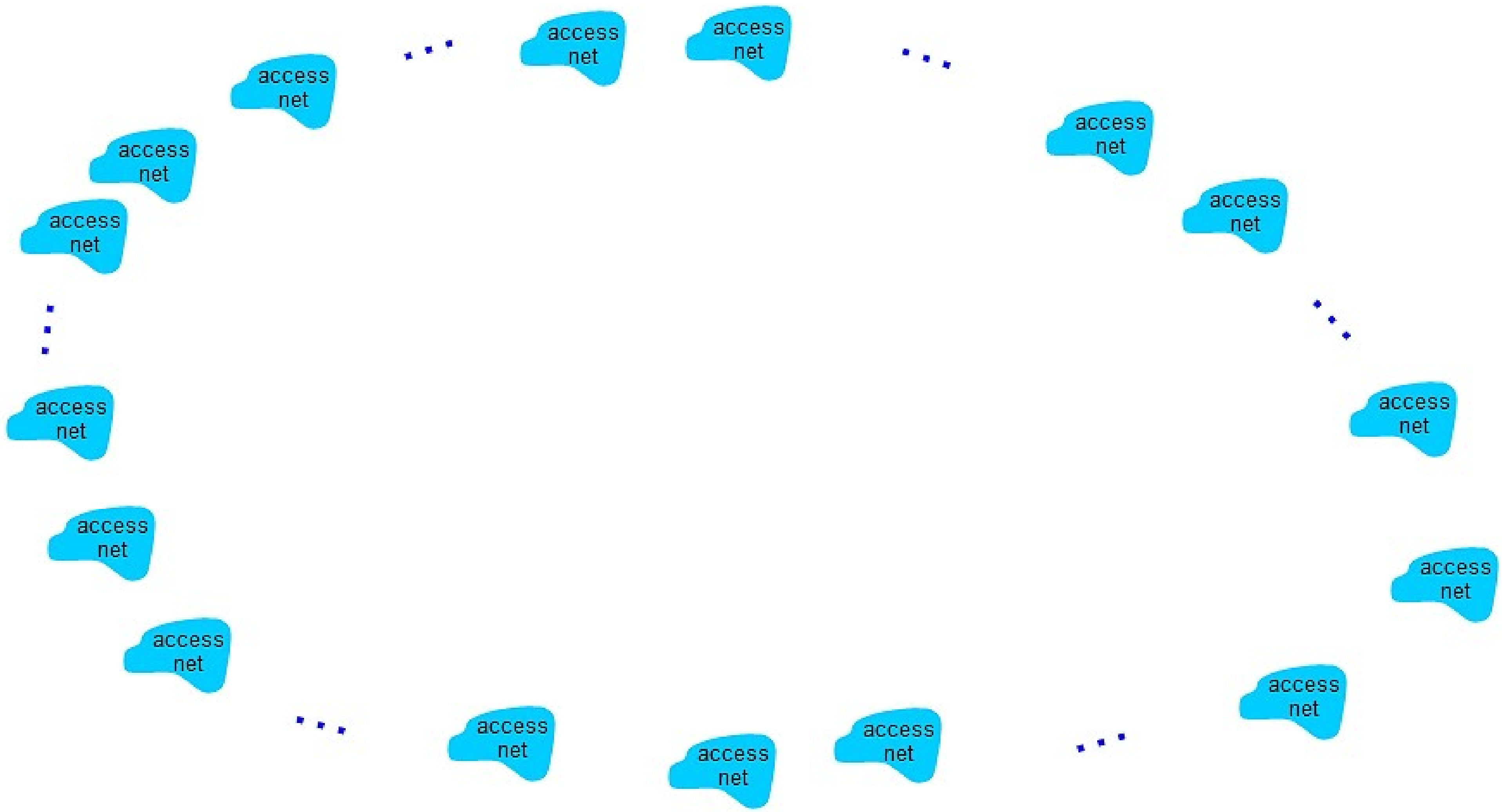
# Internet structure: network of networks

- 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

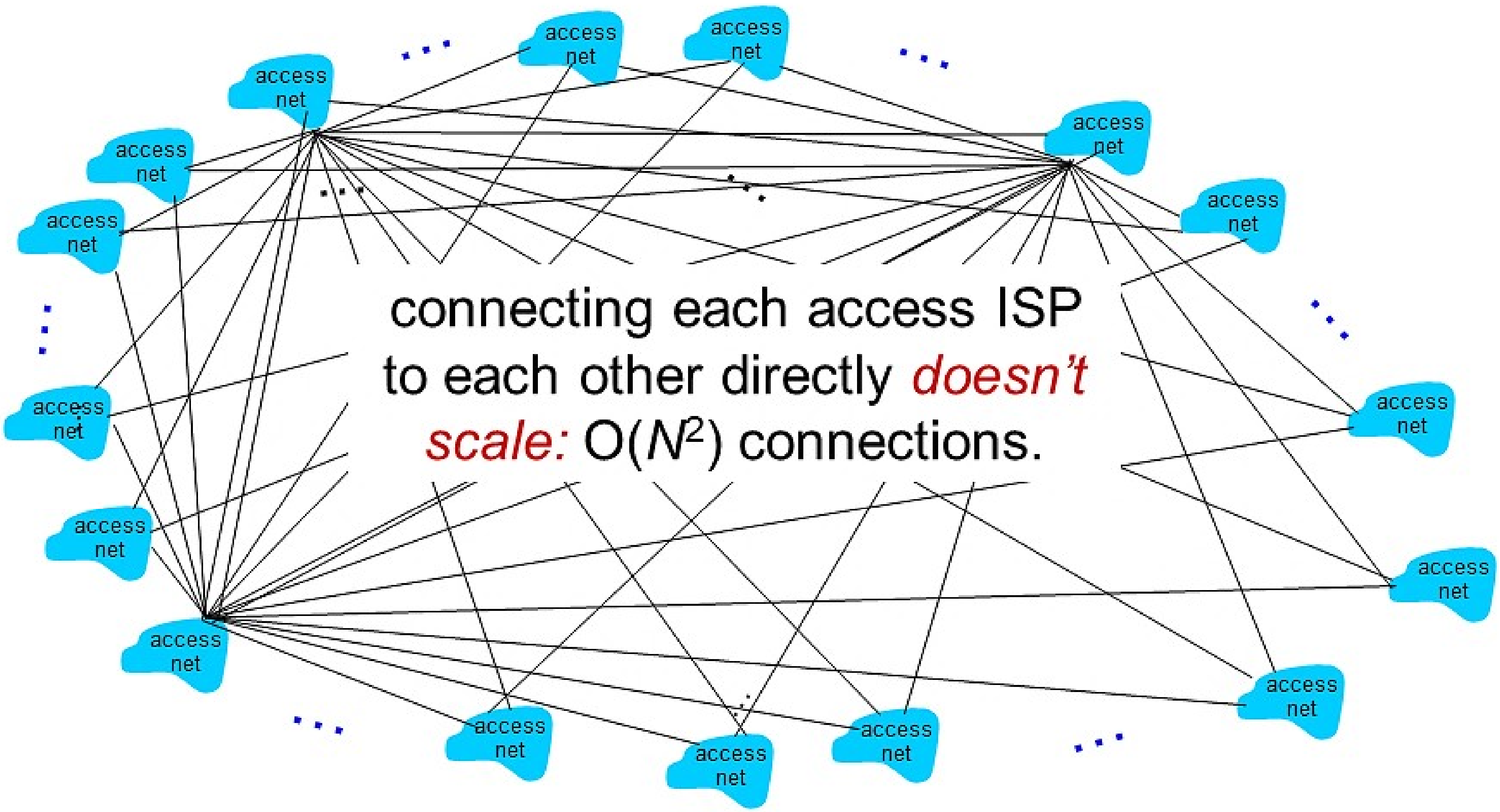
# Internet structure: network of networks

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



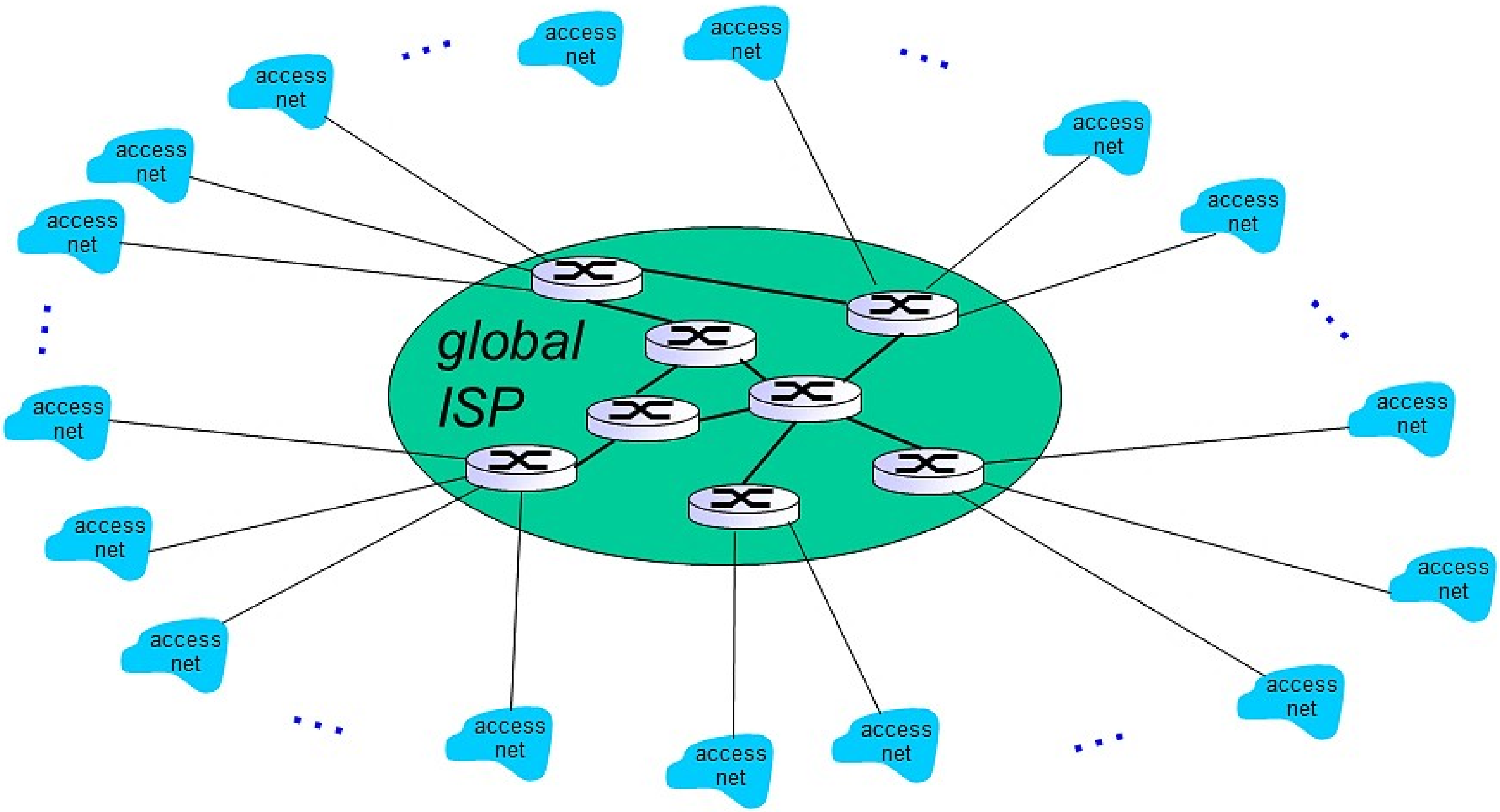
# Internet structure: network of networks

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



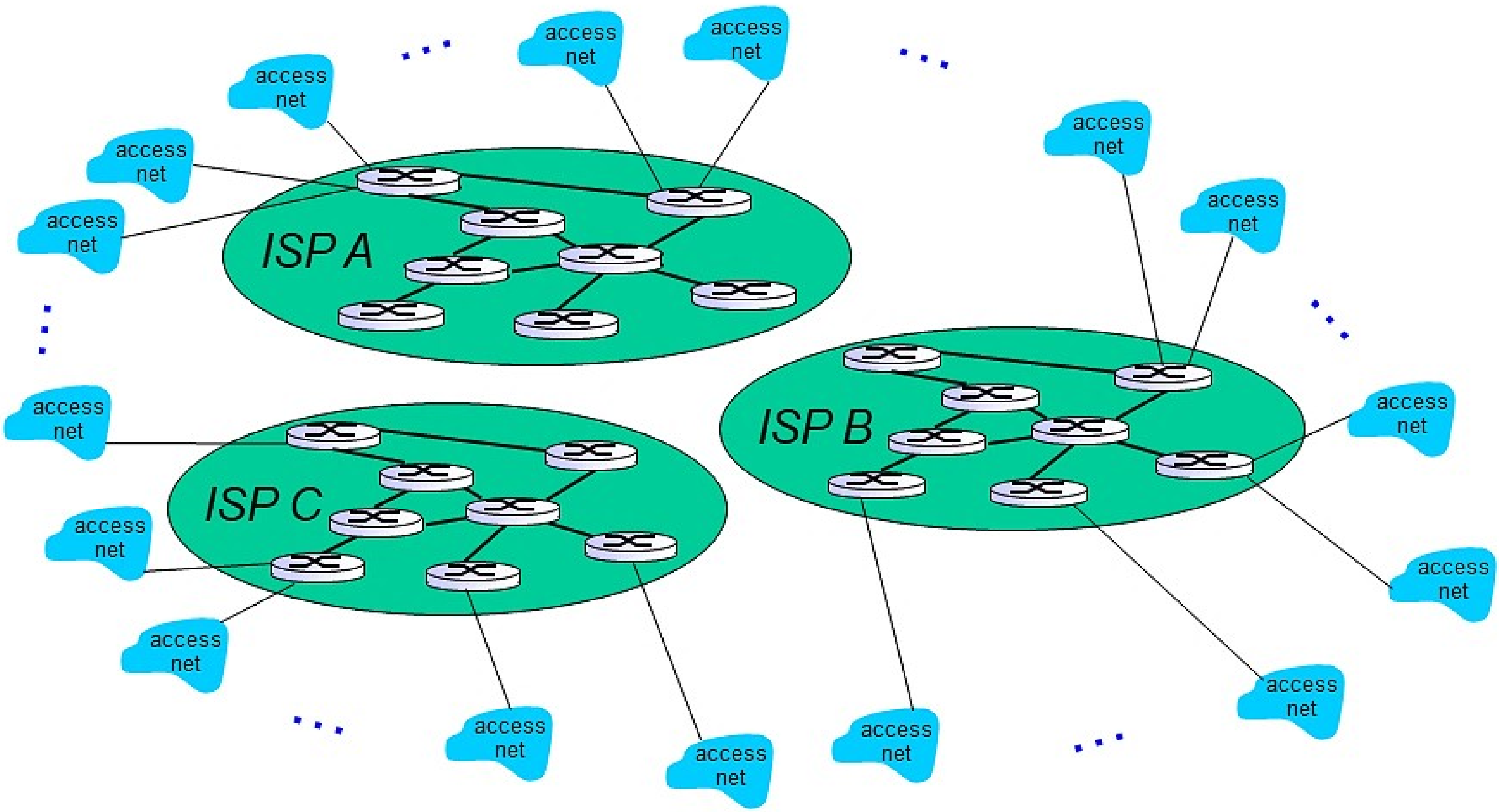
# Internet structure: network of networks

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



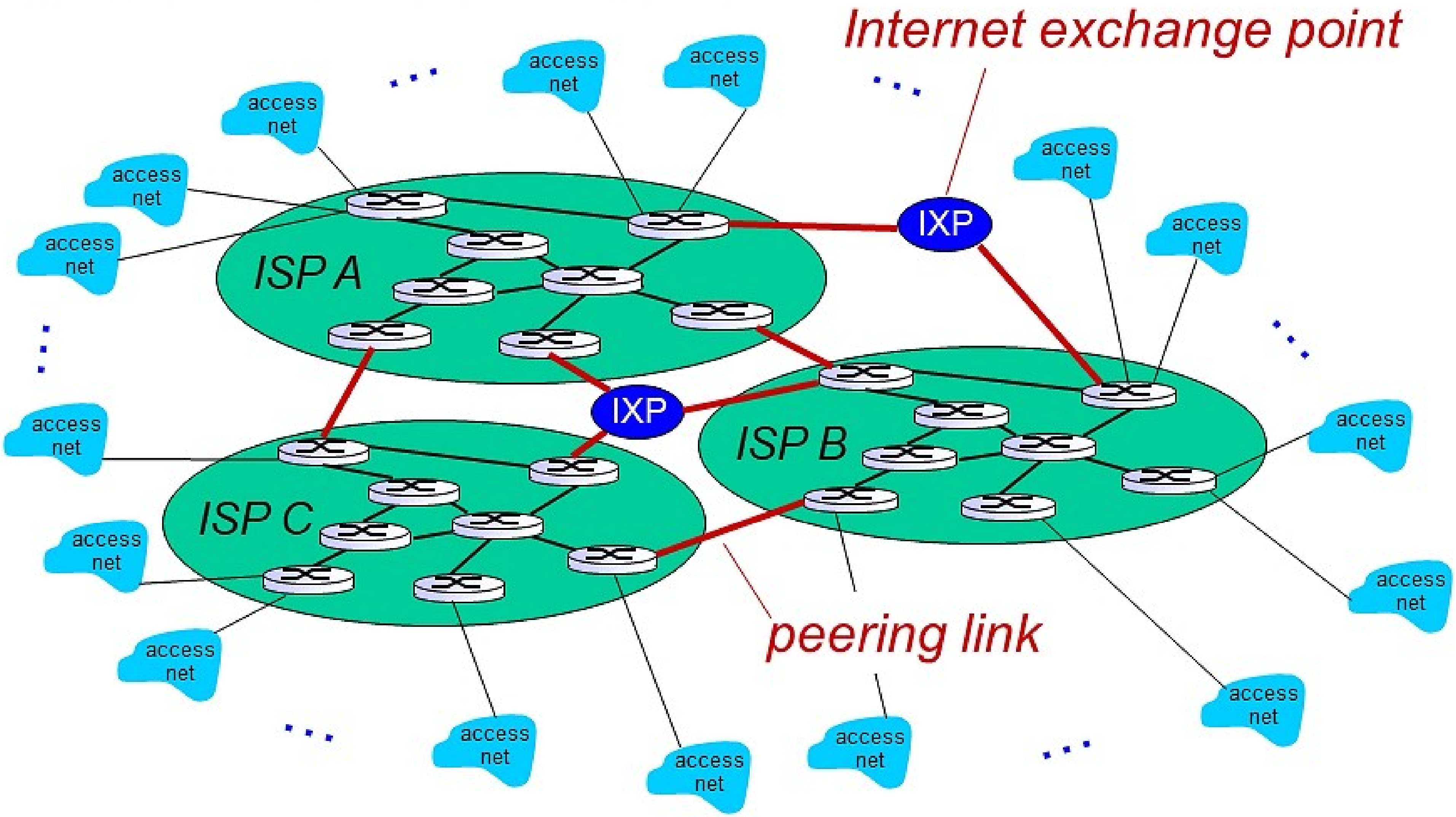
# Internet structure: network of networks

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



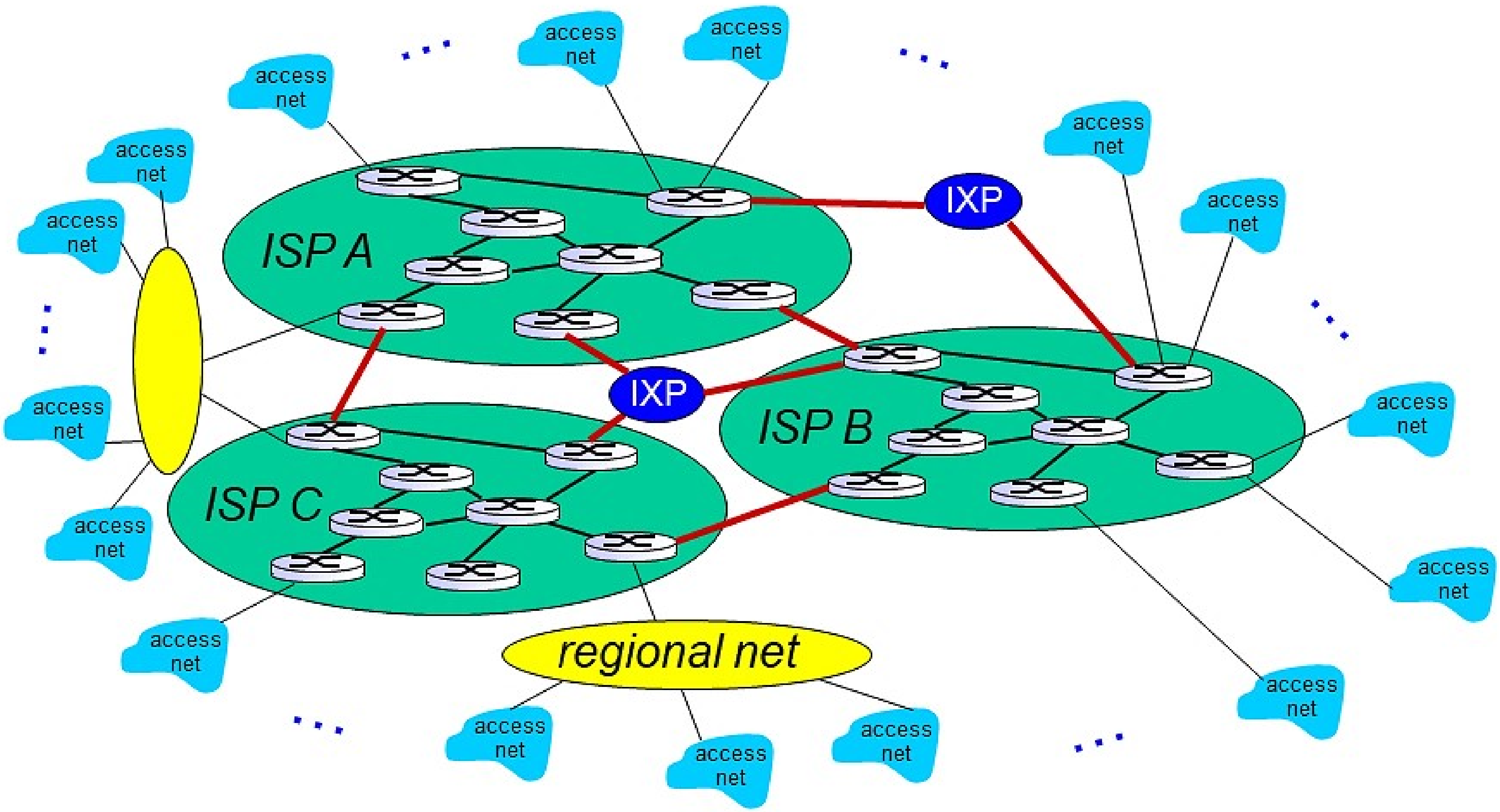
# Internet structure: network of networks

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



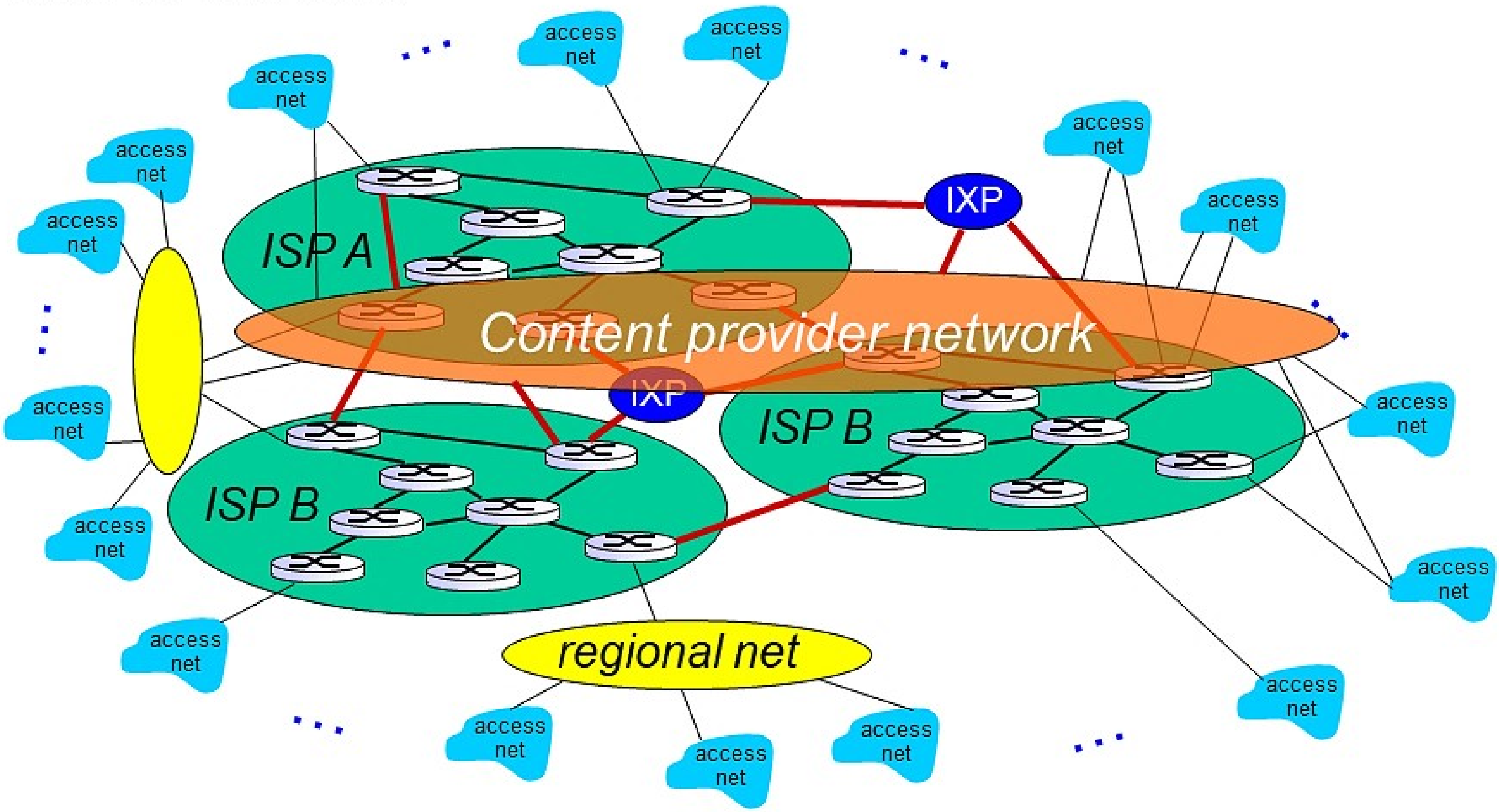
# Internet structure: network of networks

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

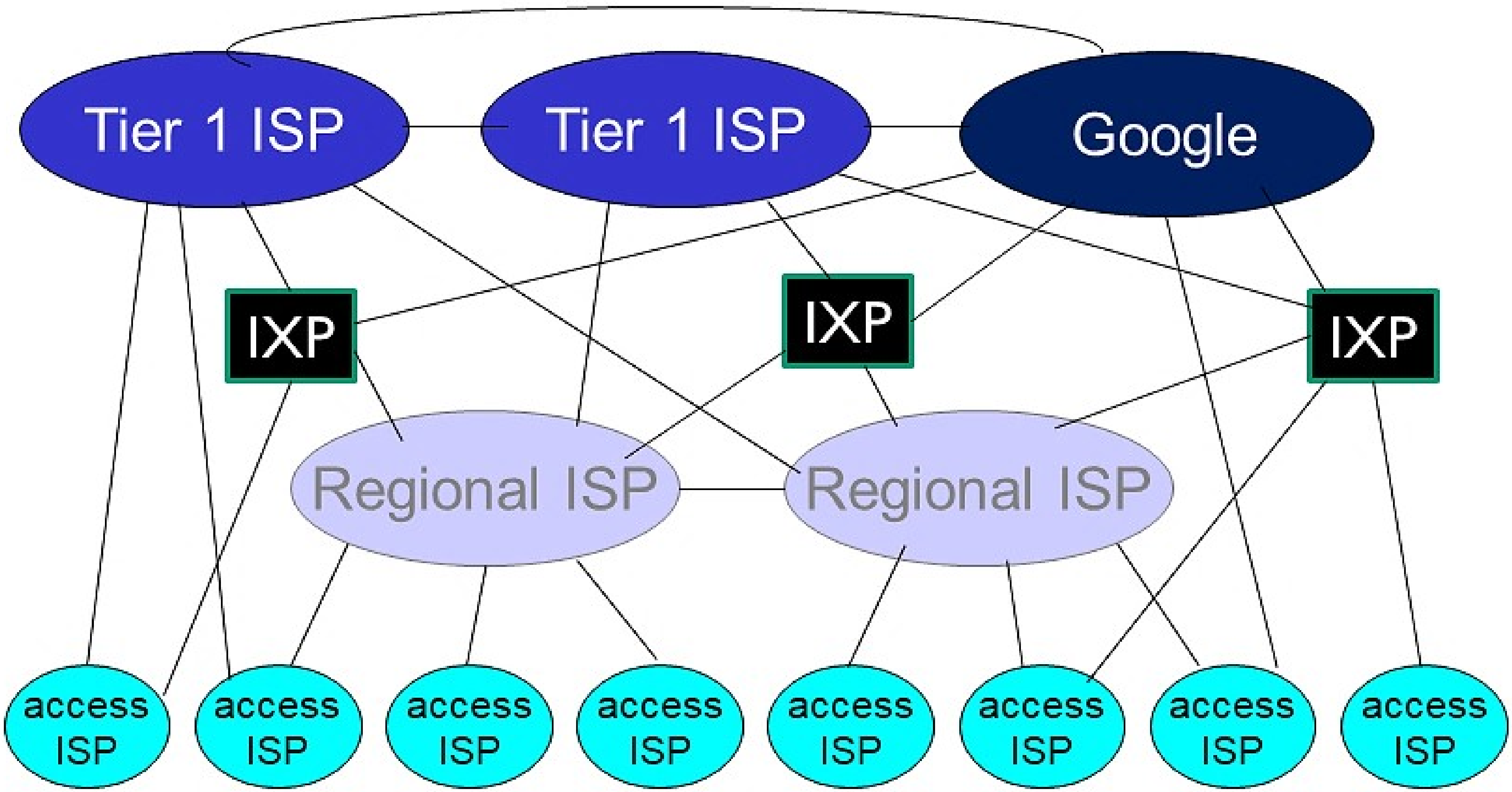


# Internet structure: network of networks

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

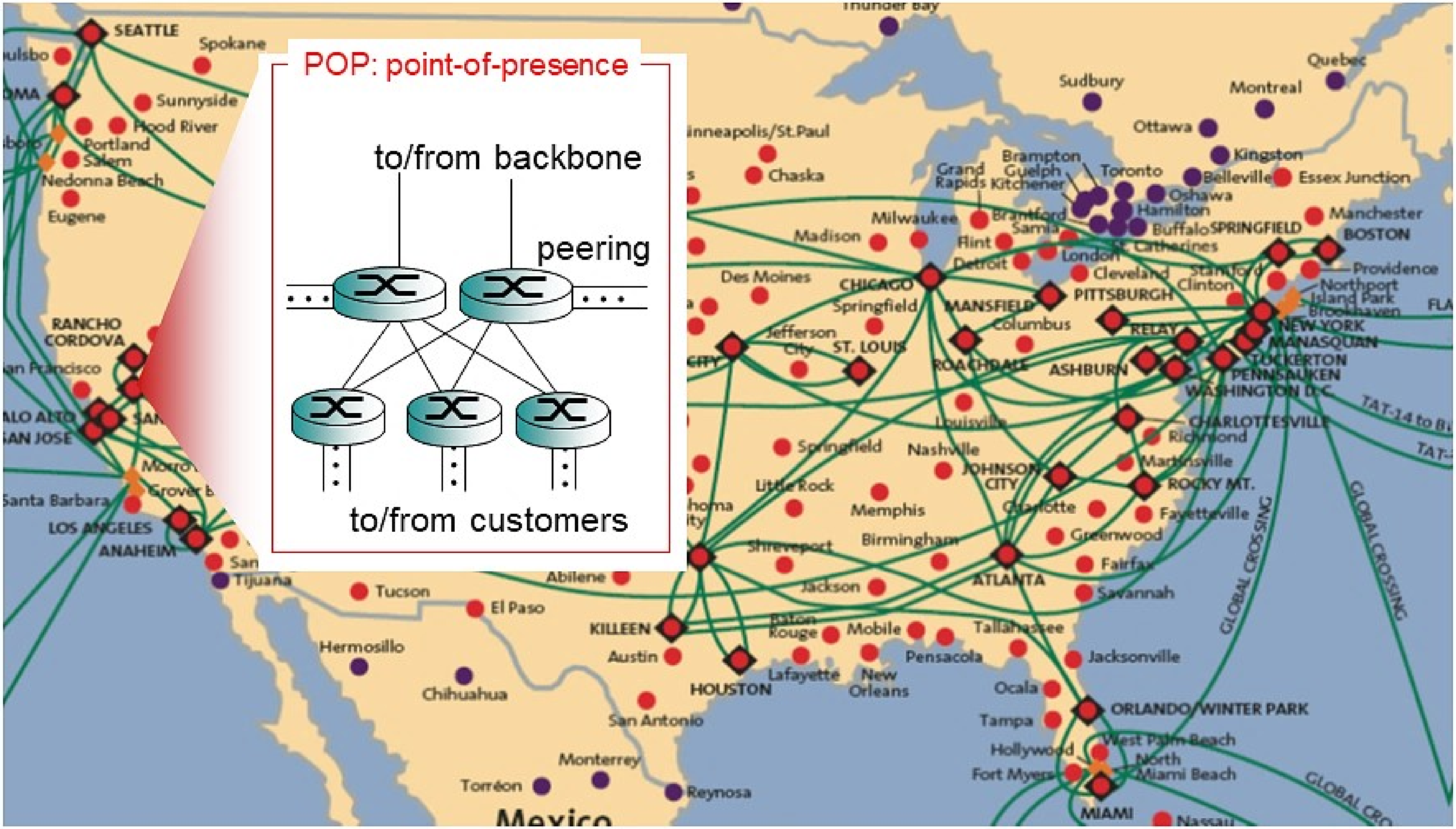


# Internet structure: network of networks

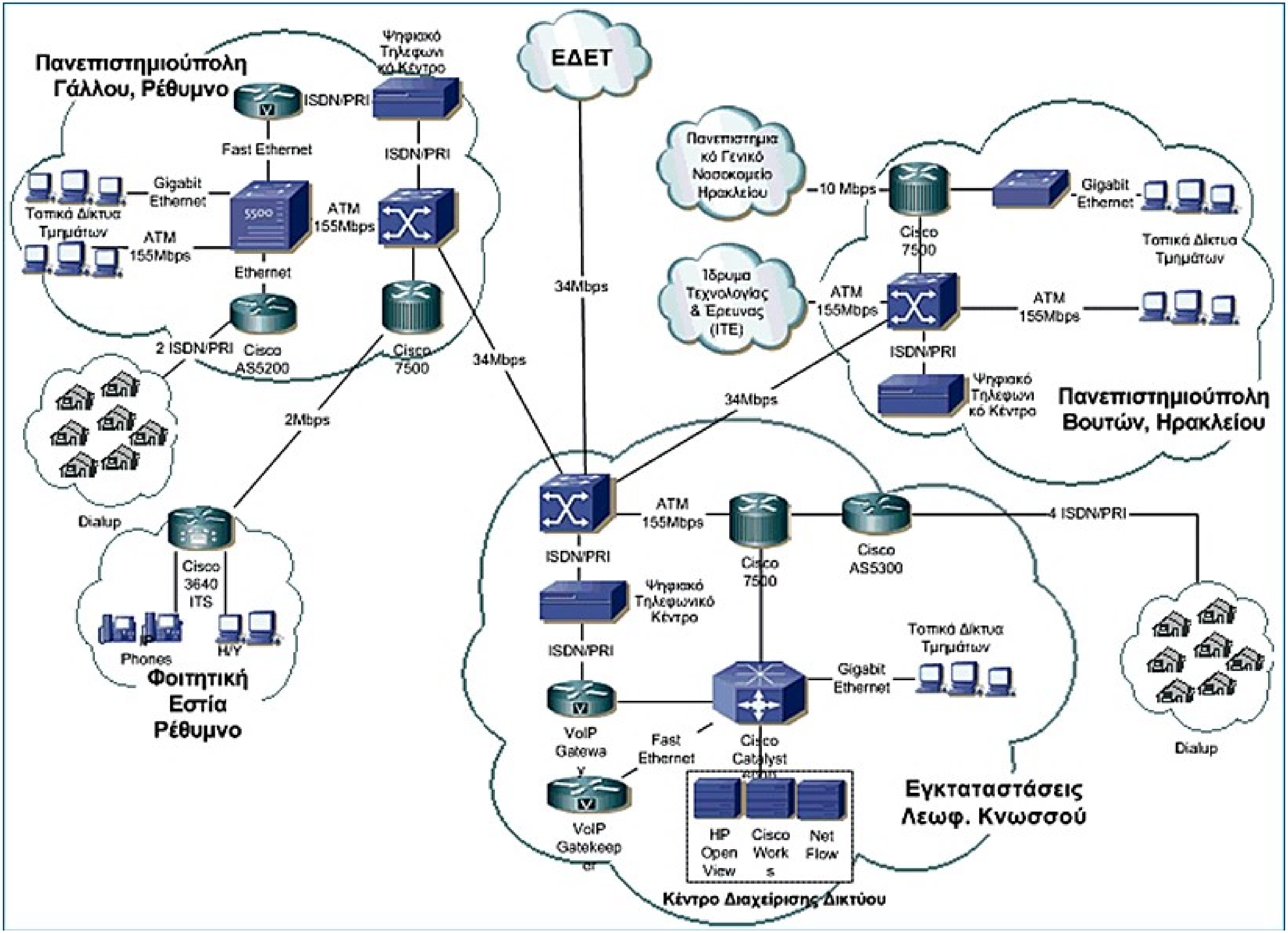



- at center: small # of well-connected large networks
  - "tier-1" commercial ISPs (e.g., Level 3, Sprint, AT&T, NTT), national & international coverage
  - content provider network (e.g, Google): private network that connects it data centers to Internet, often bypassing tier-1, regional ISPs

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



# Univ of Crete Campus Network



# Chapter 1: roadmap

1.1 What *is* the Internet?
1.2 Network edge
1.3 Network core
1.4 Network access and physical media
1.5 Internet structure and ISPs
1.6 Delay & loss in packet-switched networks
1.7 Protocol layers, service models
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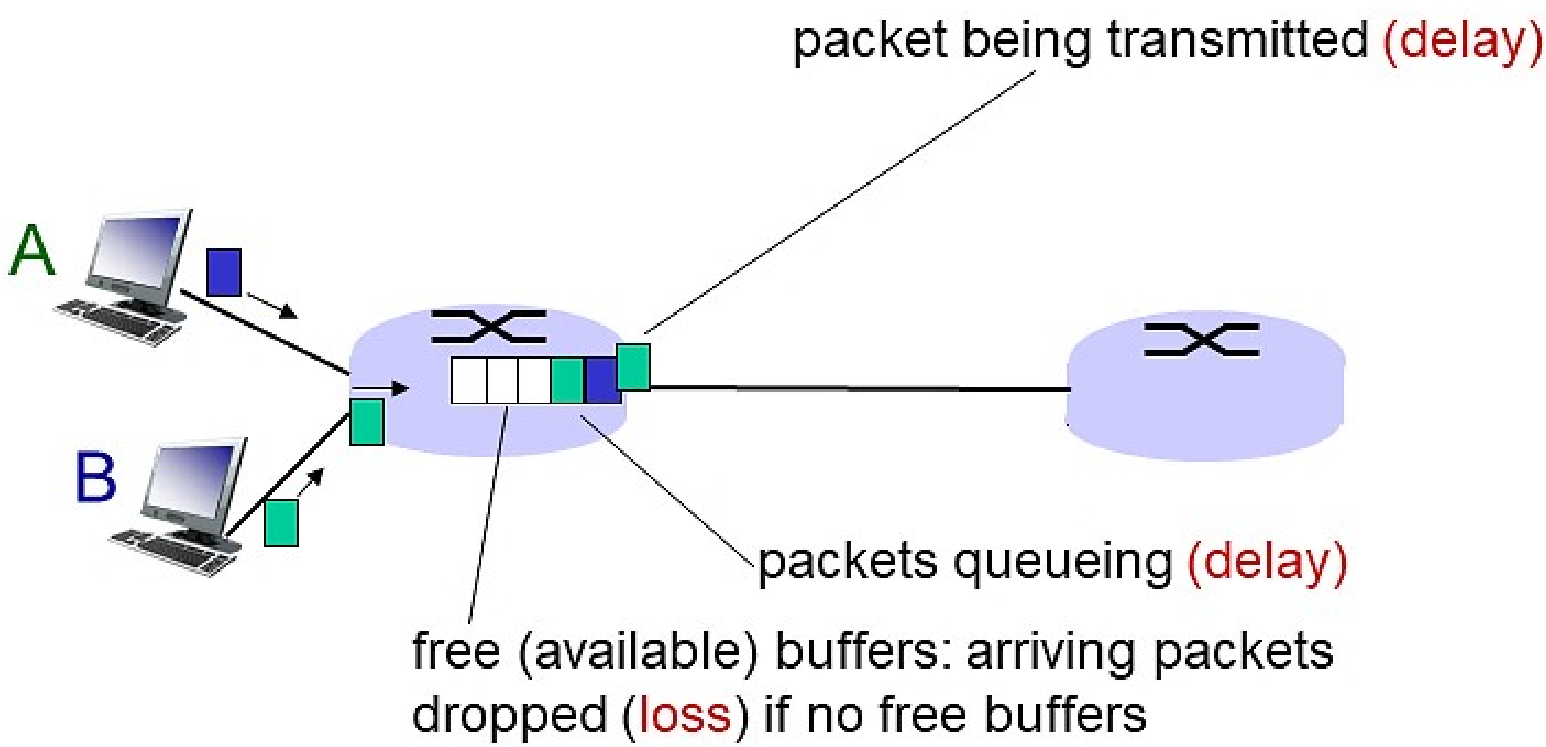
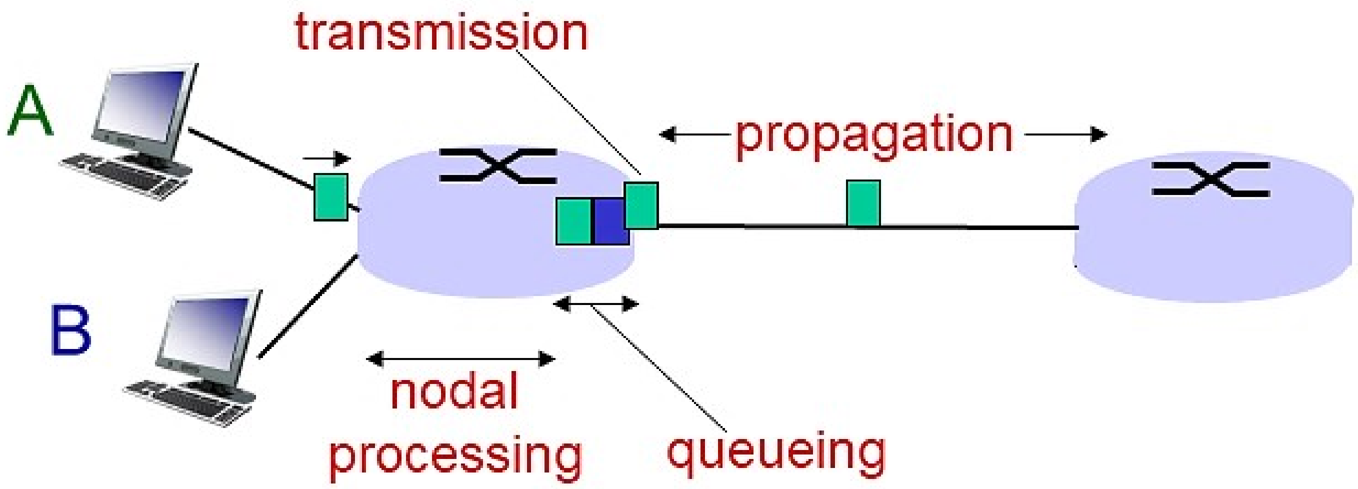
# How do loss and delay occur?

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




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

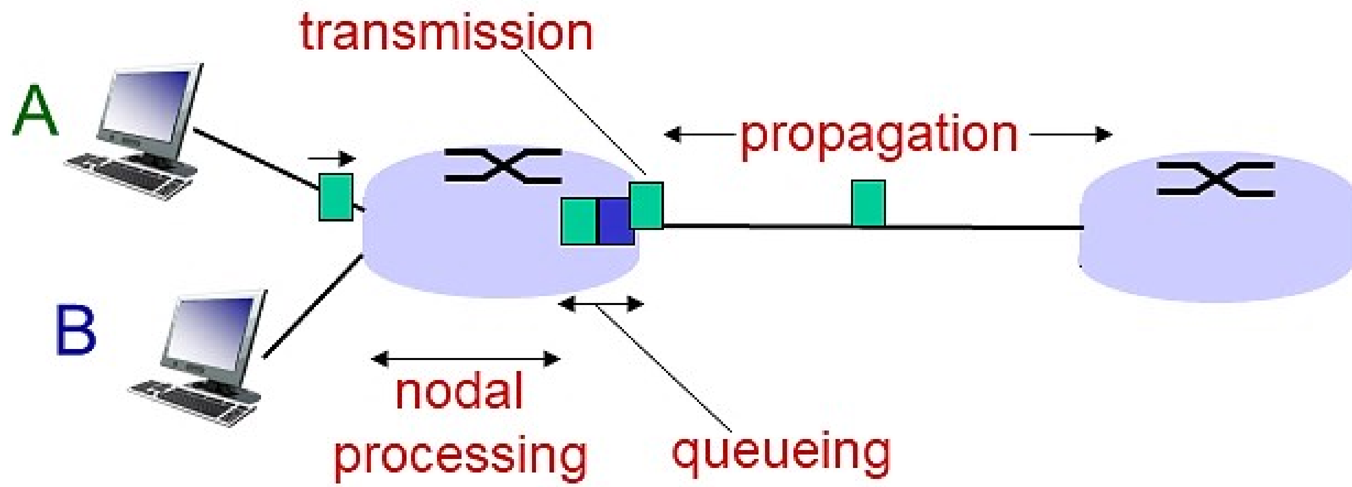
### $d_{proc}$: nodal processing

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

### $d_{queue}$: queueing delay

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

# Four sources of packet delay




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

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

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

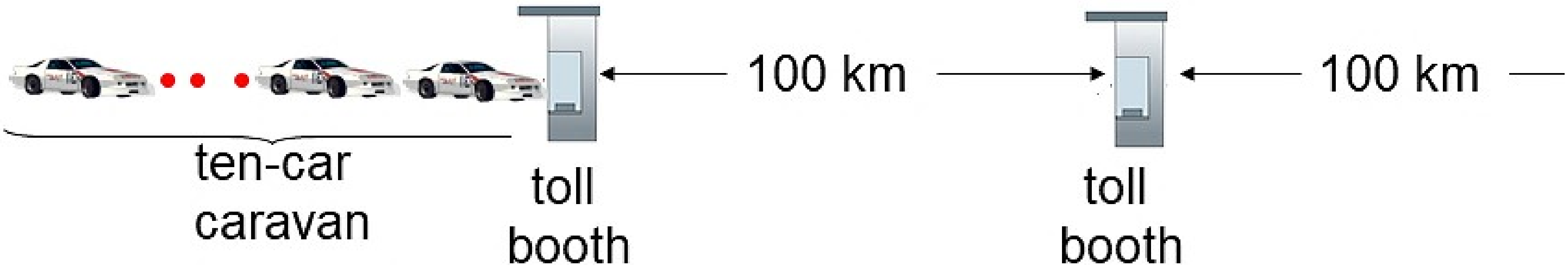
$d_{\mathrm{prop}}$: propagation delay:

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

$d_{\mathrm{trans}}$ and $d_{\mathrm{prop}}$ *very* different

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

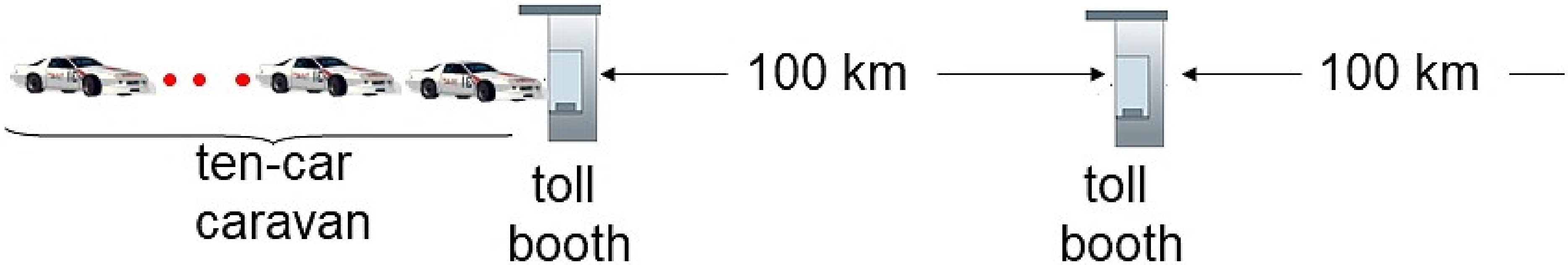
# Caravan analogy




- 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: 100km/(100km/hr)= 1 hr
- *A:* 62 minutes

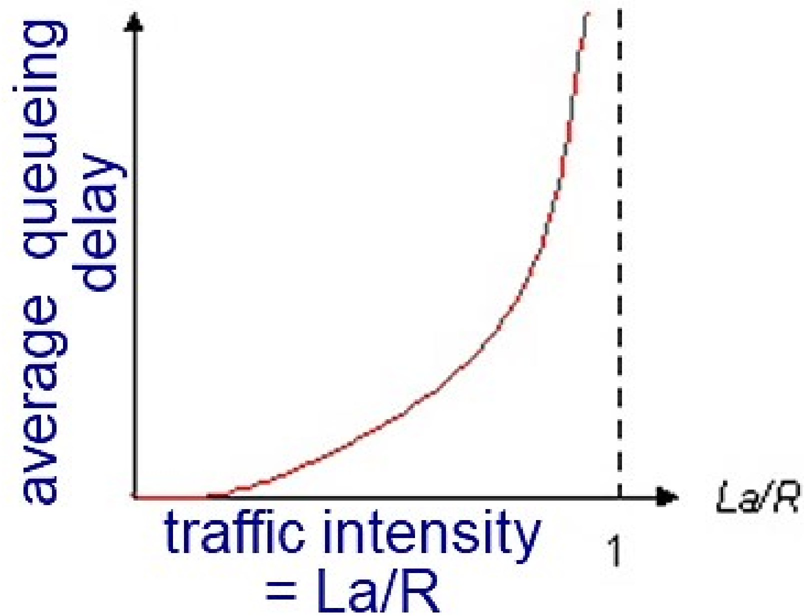
# Caravan analogy (more)



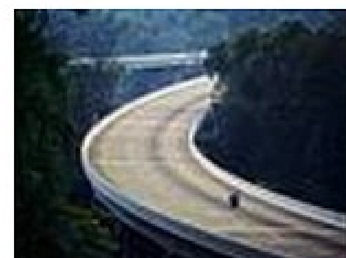

- suppose cars now "propagate" at 1000 km/hr
- and suppose toll booth now takes one min to service a car
- *Q:* Will cars arrive to 2nd booth before all cars serviced at first booth?
  - *A: Yes!* after 7 min, 1st car arrives at second booth; three cars still at 1st booth.

# Queueing delay (revisited)

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




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



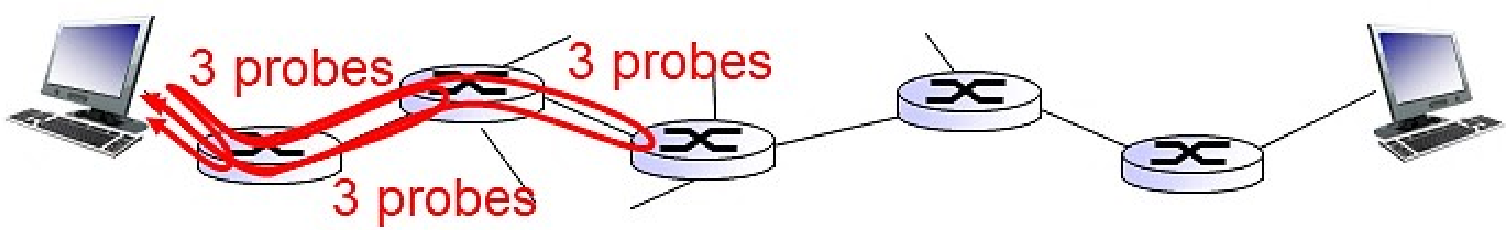
La/R ~ 0

La/R -> 1

* Check 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 * * *
19 fantasia.eurecom.fr (193.55.113.142) 132 ms 128 ms 136 ms

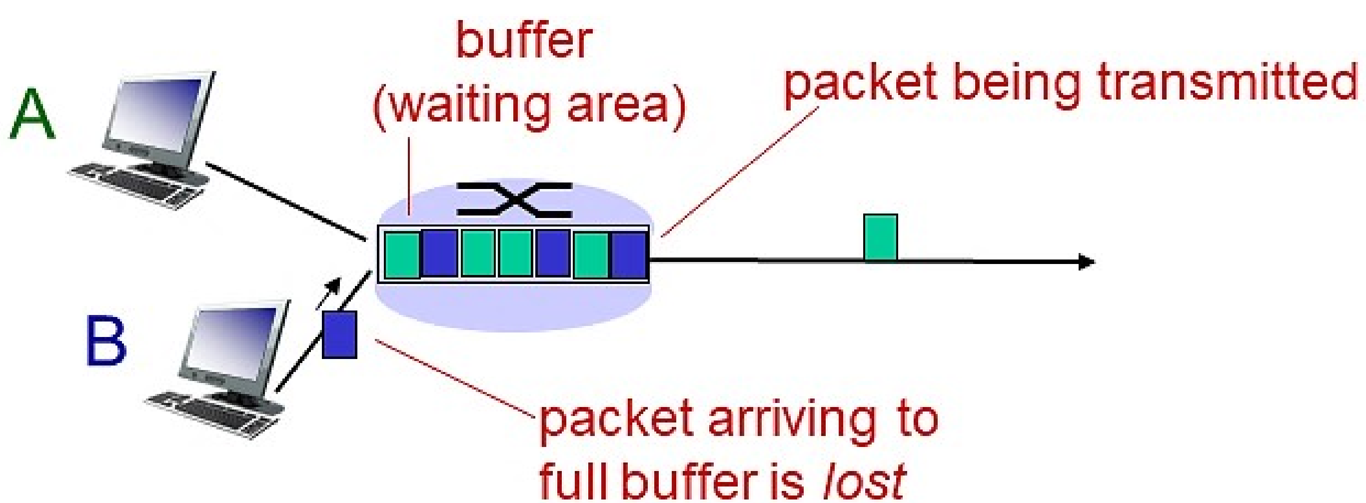
trans-oceanic link

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

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

# Packet loss

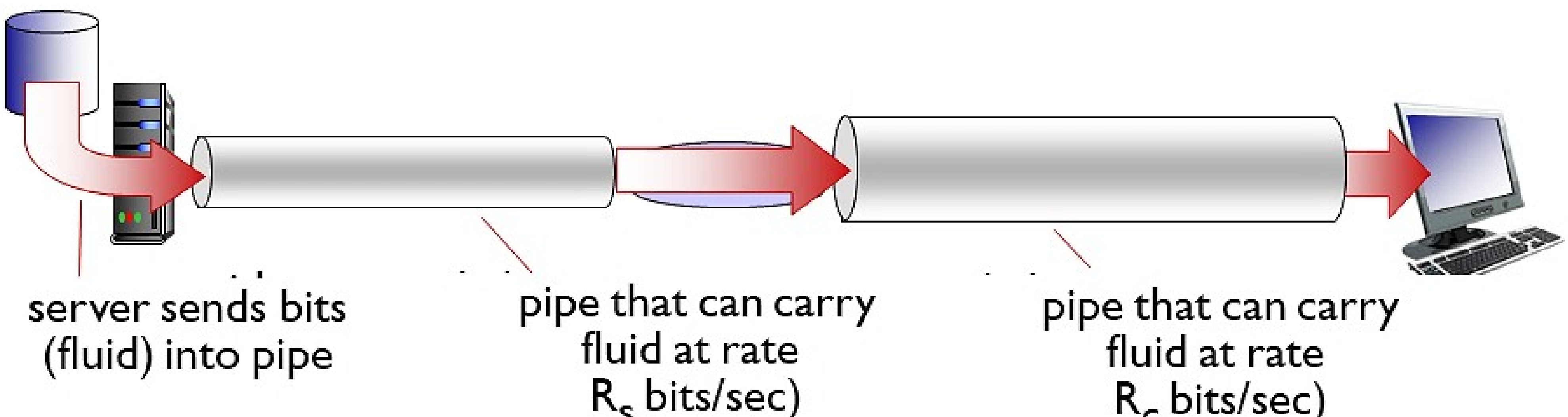
- queue (aka buffer) preceding link in buffer has finite capacity
- packet arriving to full queue dropped (aka lost)
- lost packet may be retransmitted by previous node, by source end system, or not at all




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

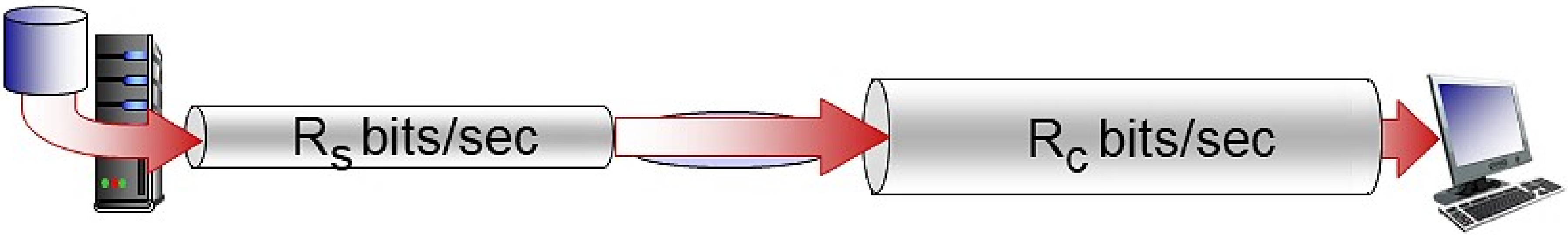
# Throughput

- *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

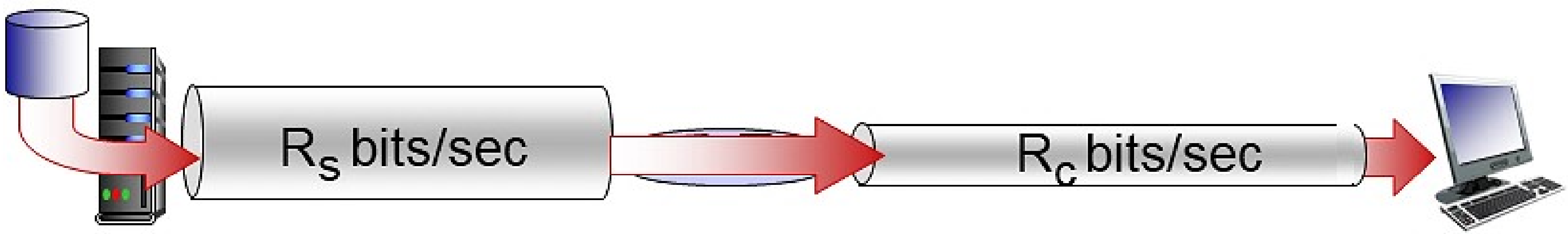


# Throughput (more)

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




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

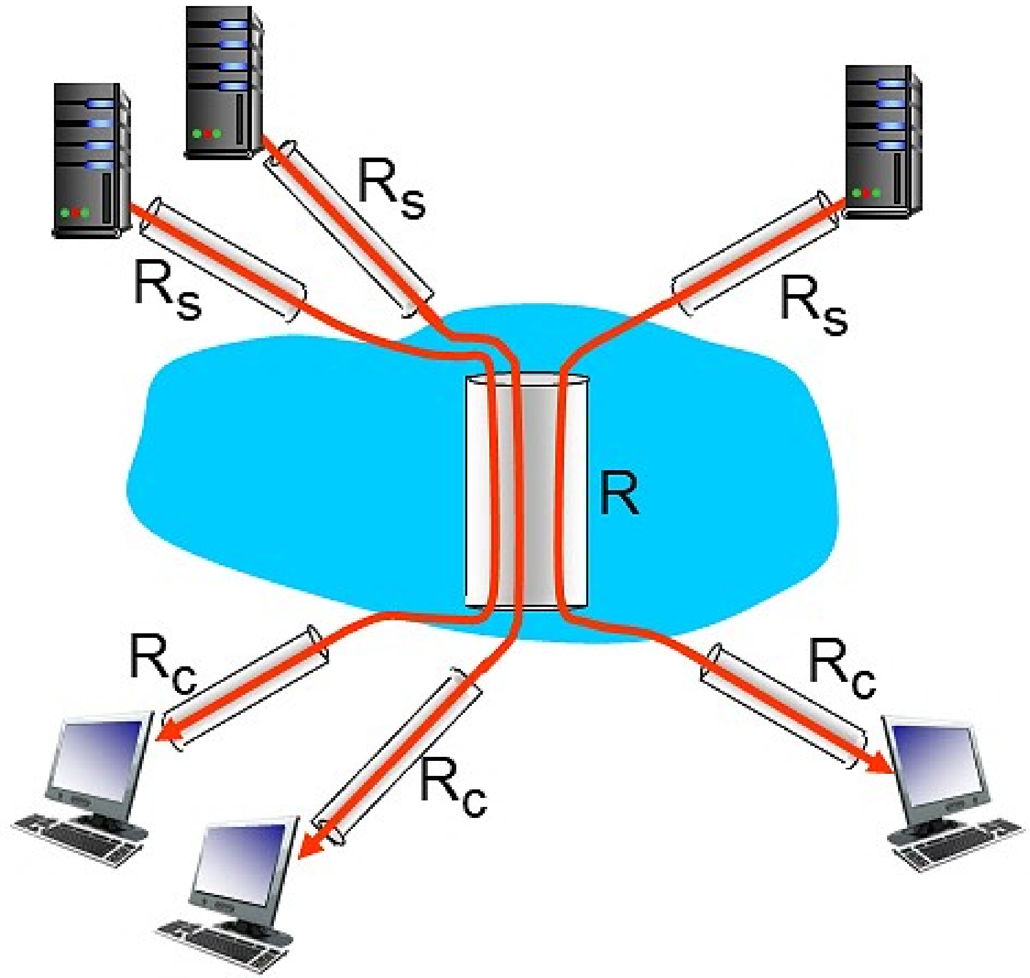



*bottleneck link*

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

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# Protocol "layers"

*Networks are complex,*
*with many "pieces":*

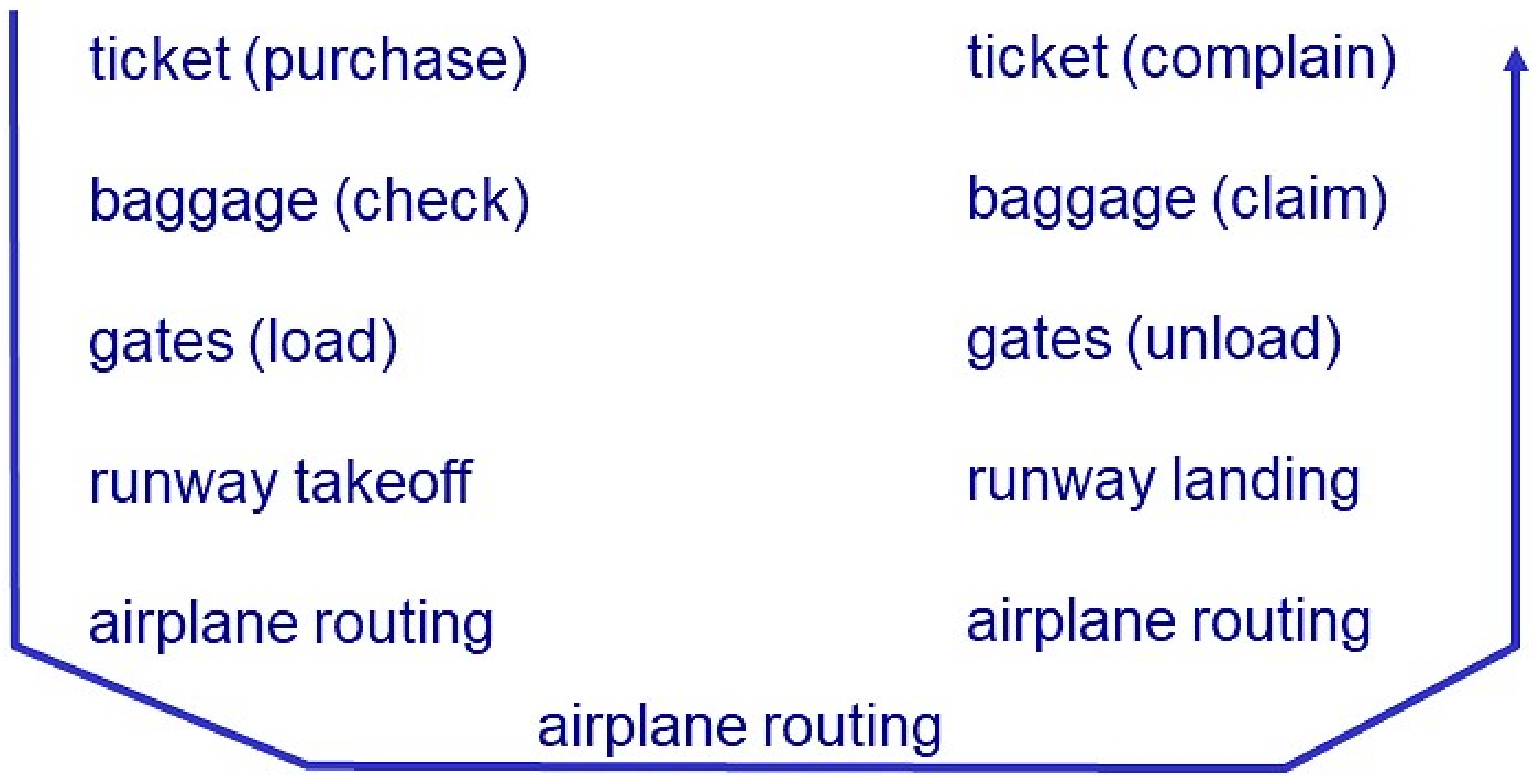
- hosts
- routers
- links of various media
- applications
- protocols
- hardware, software

*Question:*

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

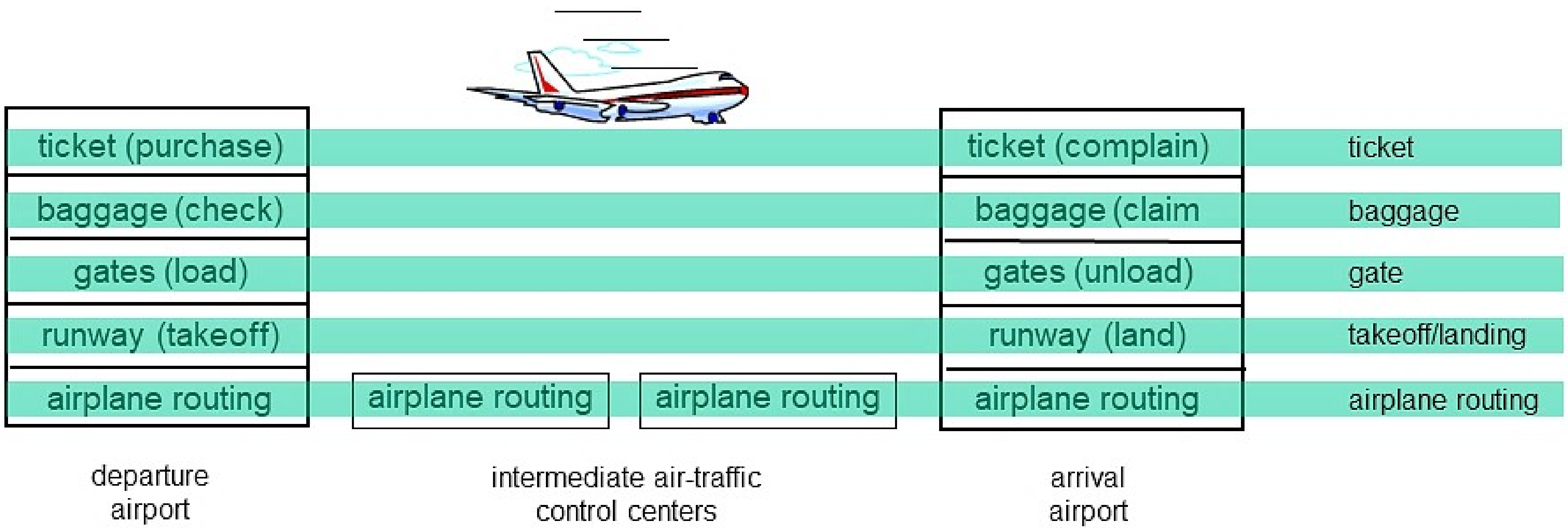
…. or at least our discussion of networks?

# 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

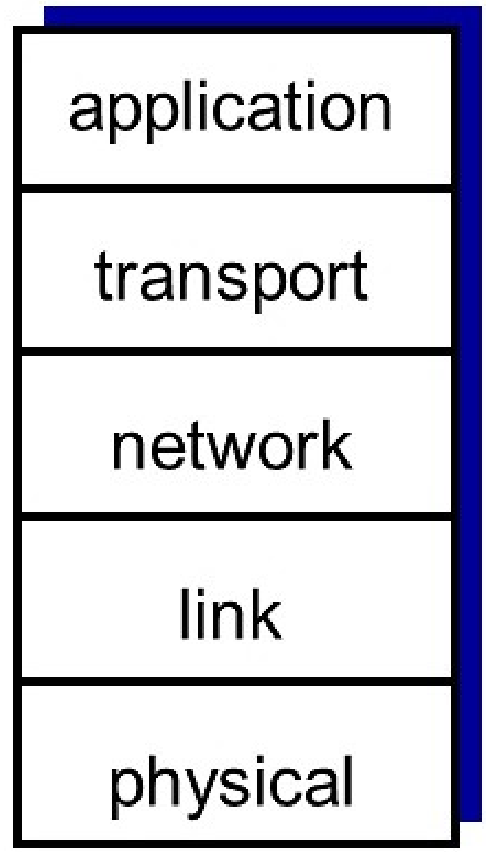
# Why layering?

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?

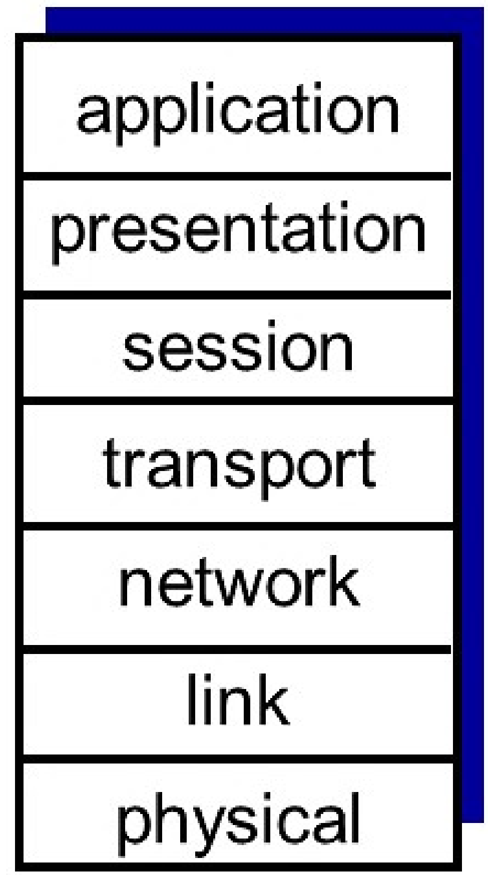
# Internet protocol stack

- *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"

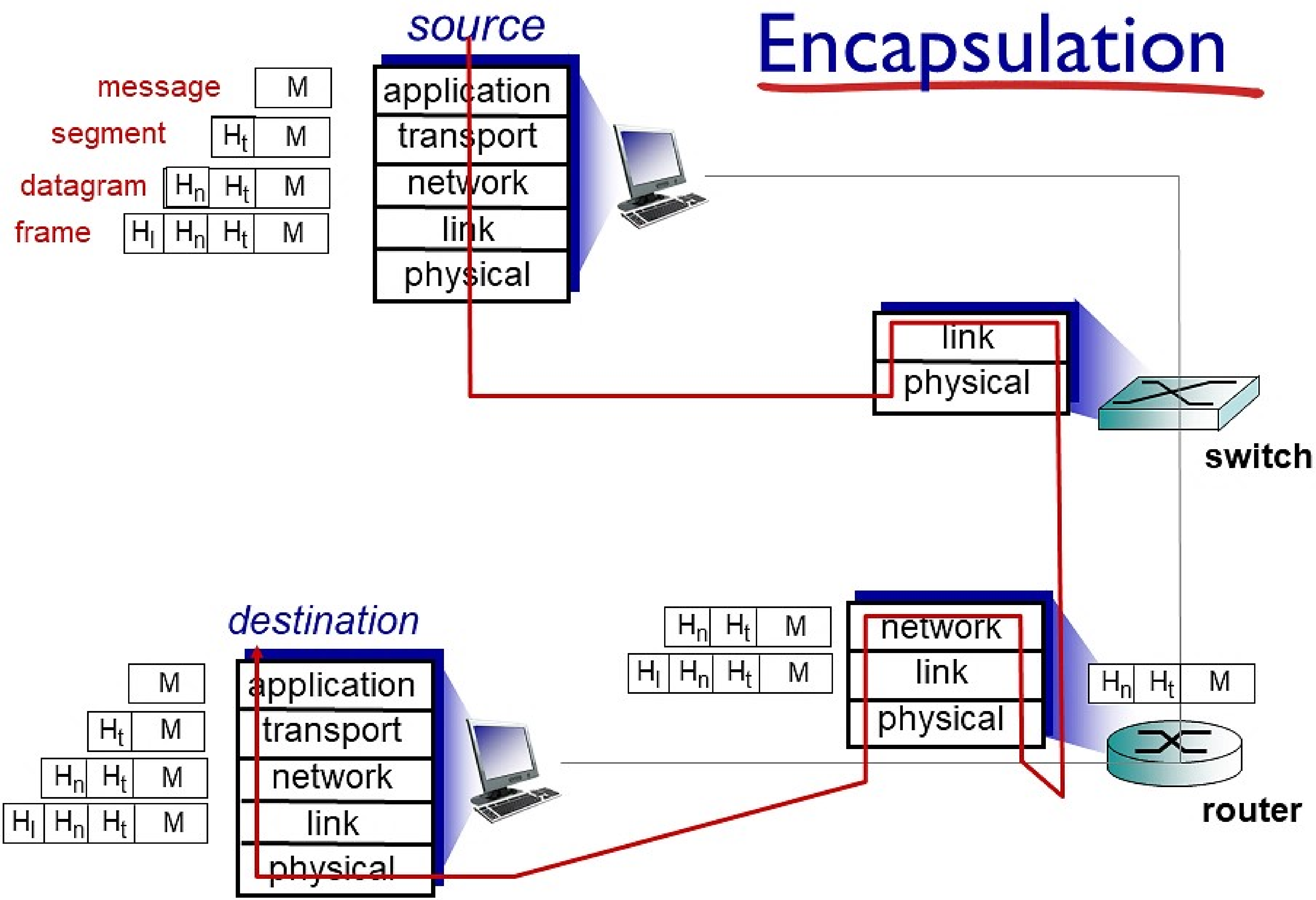


# ISO/OSI reference model

- *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



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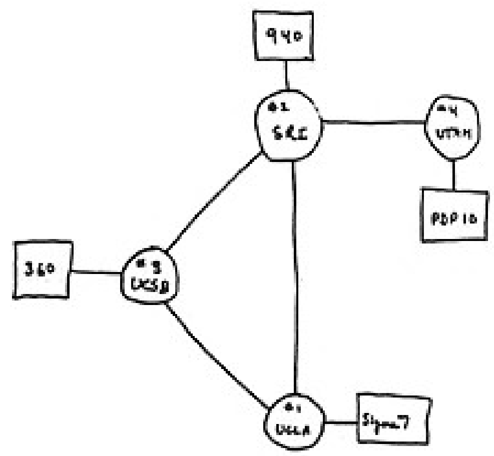
# Internet history

## *1961-1972: Early packet-switching principles*

- 1961: Kleinrock - queueing theory shows effectiveness of packet-switching
- 1964: Baran - packet-switching in military nets
- 1967: ARPAnet conceived by Advanced Research Projects Agency
- 1969: first ARPAnet node operational

- 1972:
  - ARPAnet public demo
  - NCP (Network Control Protocol) first host-host protocol
  - first e-mail program
  - ARPAnet has 15 nodes




THE ARPA NETWORK

# Internet history

*1972-1980: Internetworking, new and proprietary nets*

- 1970: ALOHAnet satellite network in Hawaii
- 1974: Cerf and Kahn - architecture for interconnecting networks
- 1976: Ethernet at Xerox PARC
- late70's: proprietary architectures: DECnet, SNA, XNA
- late 70's: switching fixed length packets (ATM precursor)
- 1979: ARPAnet has 200 nodes

Cerf and Kahn's internetworking principles:

- minimalism, autonomy - no internal changes required to interconnect networks
- best effort service model
- stateless routers
- decentralized control

define today's Internet architecture

# Internet history

*1980-1990: new protocols, a proliferation of networks*

- 1983: deployment of TCP/IP
- 1982: smtp e-mail protocol defined
- 1983: DNS defined for name-to-IP-address translation
- 1985: ftp protocol defined
- 1988: TCP congestion control

- new national networks: Csnet, BITnet, NSFnet, Minitel
- 100,000 hosts connected to confederation of networks

# Internet history

*1990, 2000's: commercialization, the Web, new apps*

- early 1990's: ARPAnet decommissioned
- 1991: NSF lifts restrictions on commercial use of NSFnet (decommissioned, 1995)
- early 1990s: Web
  - hypertext [Bush 1945, Nelson 1960's]
  - HTML, HTTP: Berners-Lee
  - 1994: Mosaic, later Netscape
  - late 1990's: commercialization of the Web

late 1990's – 2000's:

- more killer apps: instant messaging, P2P file sharing
- network security to forefront
- est. 50 million host, 100 million+ users
- backbone links running at Gbps

# Internet history

*2005-present*

- ~750 million hosts
  - Smartphones and tablets
- Aggressive deployment of broadband access
- Increasing ubiquity of high-speed wireless access
- Emergence of online social networks:
  - Facebook: soon one billion users
- Service providers (Google, Microsoft) create their own networks
  - Bypass Internet, providing "instantaneous" access to search, emai, etc.
- E-commerce, universities, enterprises running their services in "cloud" (eg, Amazon EC2)