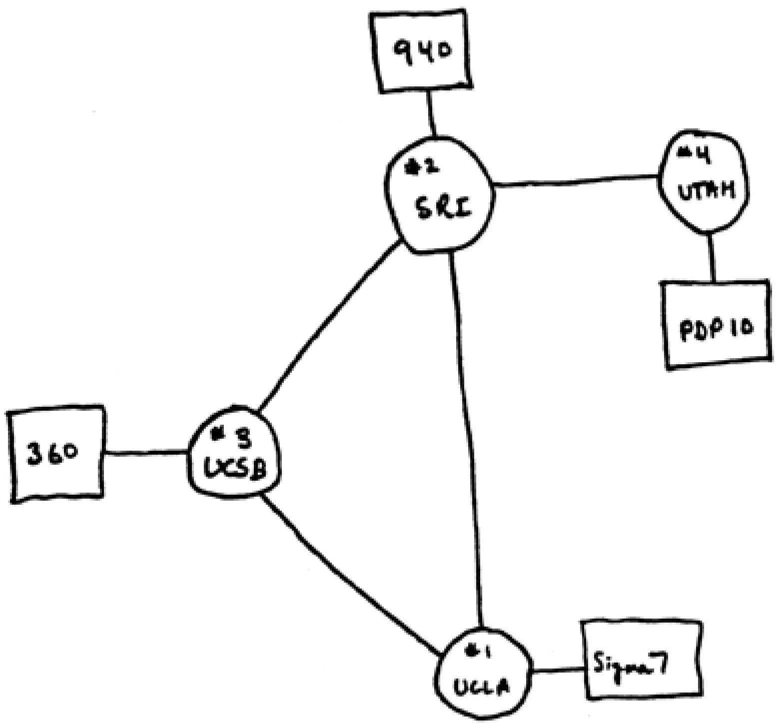
CSCE 560
Introduction to Computer Networking



The first four nodes that formed the ARPANET – Dec 1969

http://www.computerhistory.org/

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Chapter 1: Introduction

Our goal:

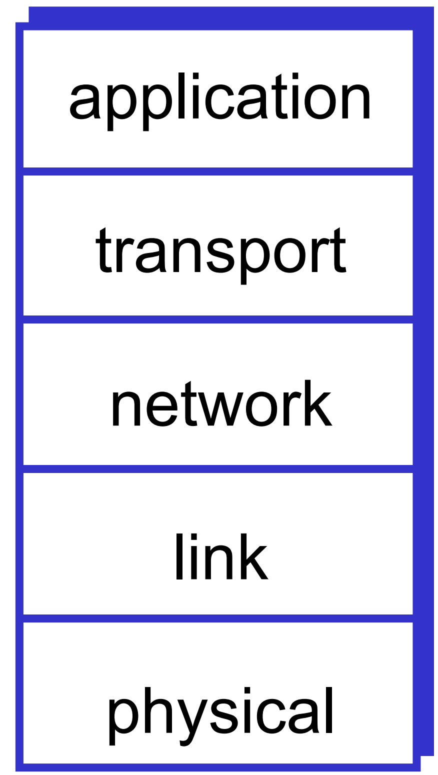
- Get "feel" and terminology
- More depth and details *later* in course
- Approach:
  - Use Internet as example

Overview:

- What's the Internet
- What's a protocol?
- Network edge
- Network core
- Access net, physical media
- Internet/ISP structure
- Performance: loss, delay, throughput
- Protocol layers, service models

How to Teach Networks?

- Traditional Bottom-up approach
    - Tanenbaum book
- Top-down approach
    - Kurose/Ross book
    - Applications motivate networks
- Will try to follow top-down approach



Chapter 1: Roadmap

1.1 What is the Internet? → See supplemental slides

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 → See supplemental slides

1.7 History → See supplemental slides

What's a Protocol?

Human protocols:

- "What's the time?"
- "I have a question"
- Introductions

Network protocols:

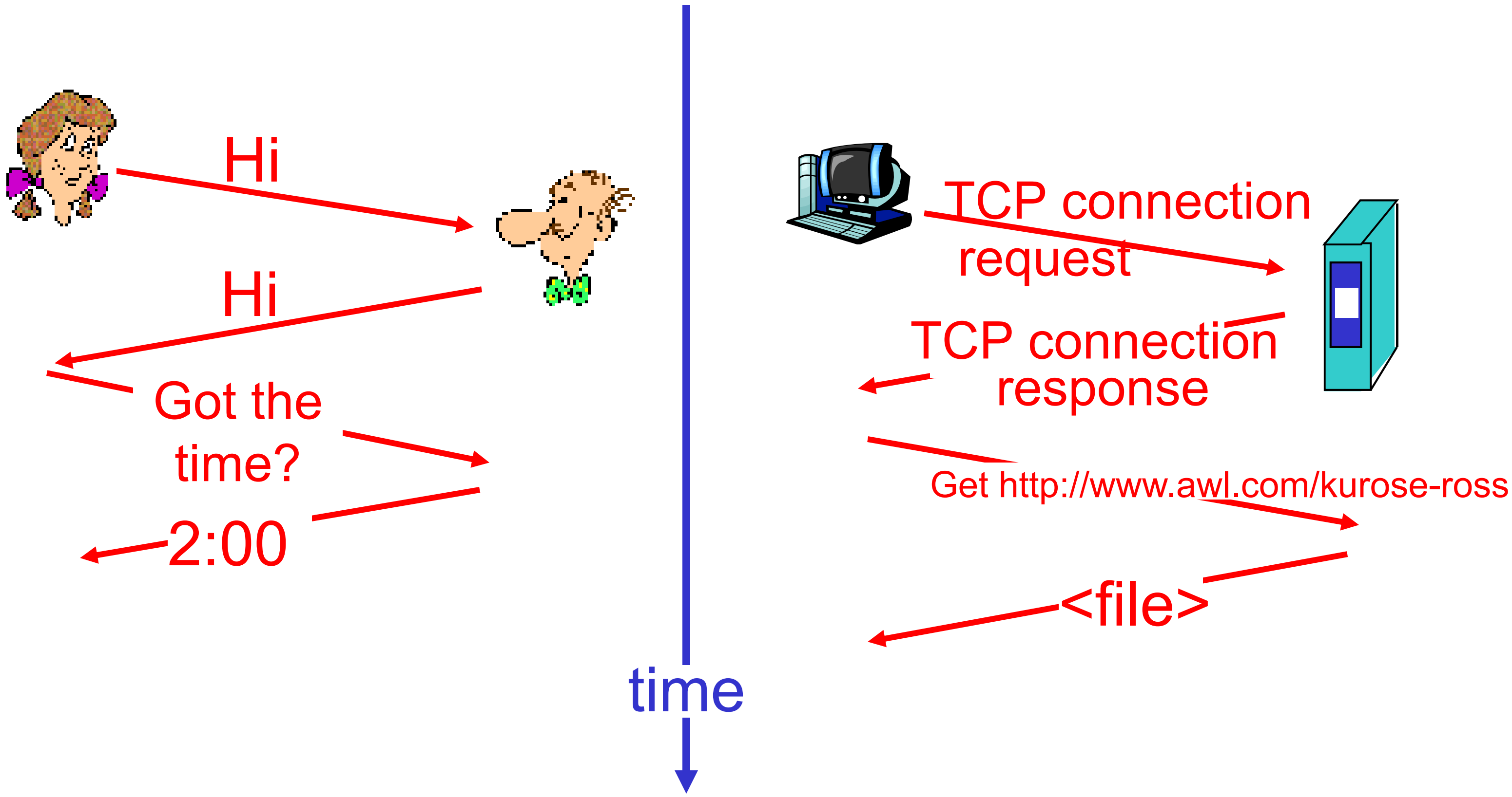
- Machines rather than humans
- All communication activity in Internet governed by protocols

Protocols define

- ✓ *format*
- ✓ *order of msgs sent and received among network entities*
- ✓ *actions taken on msg transmission & receipt*

What's a Protocol?

A human protocol and a computer network protocol:



Q: What if the two protocols are different?

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

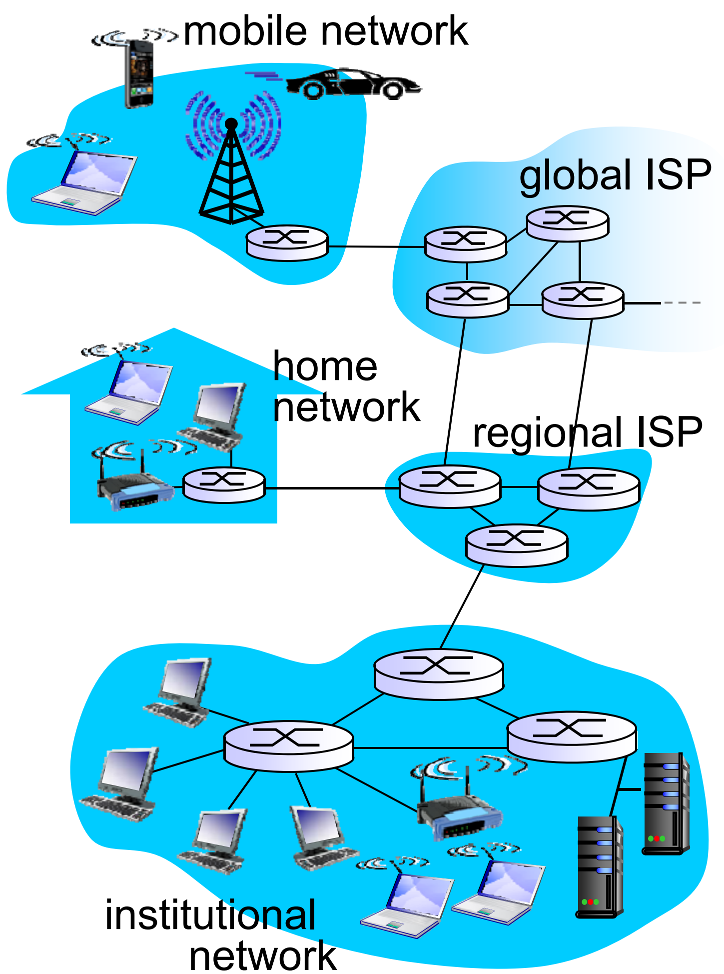
1.5 Protocol layers, service models

1.6 Networks under attack: security

1.7 History

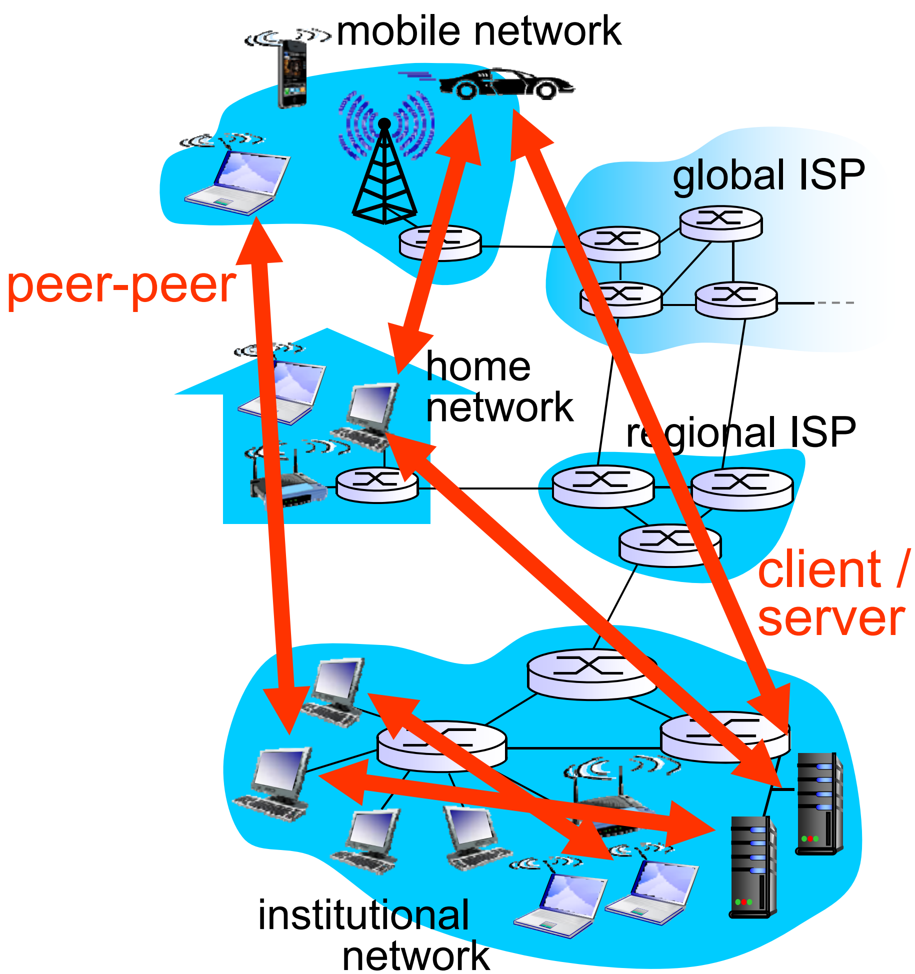
A Closer Look At Network Structure

- Network edge:
  - Applications
  - Hosts: clients and servers
  - Servers often in data centers
- Network core:
  - Interconnected routers
  - Network of networks
- Access networks, physical media:
  - Wired, wireless communication links



The Network Edge

- End systems (hosts):
  - Your computer
  - Run application programs
    - Web, email
  - At the “edge of network”
- Client/Server model
  - Client requests and receives service from always-on server
  - Web browser/server
  - Email client/server
- Peer-peer model:
  - Minimal (or no) use of dedicated servers
  - Gnutella, KaZaA, Skype



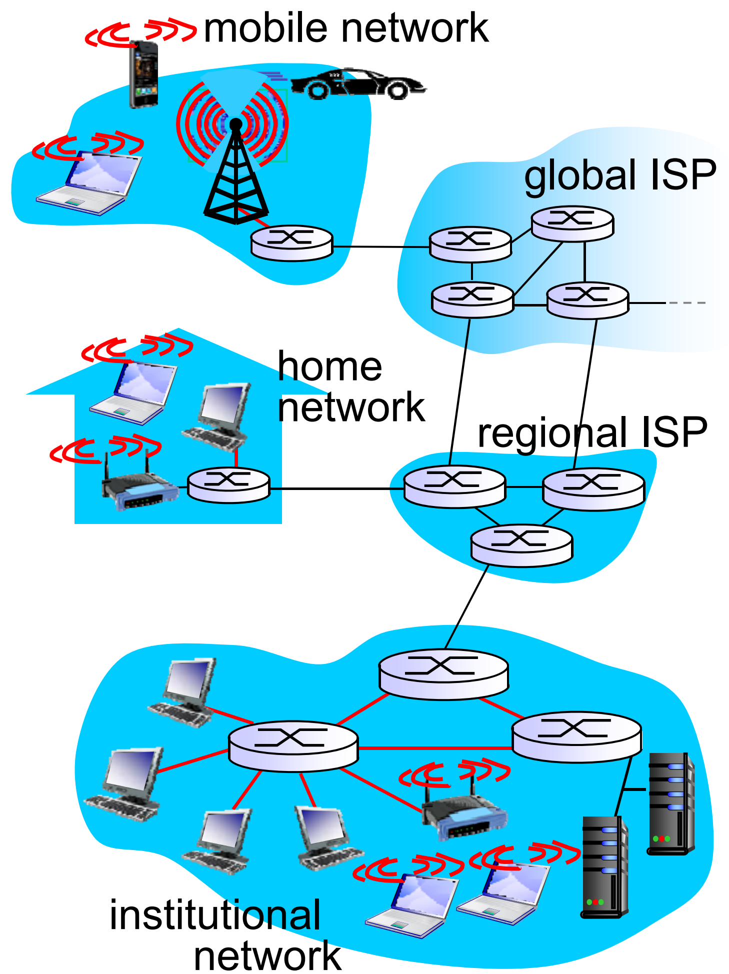
Access Networks and Physical Media

Q: How to connect end systems to edge router?

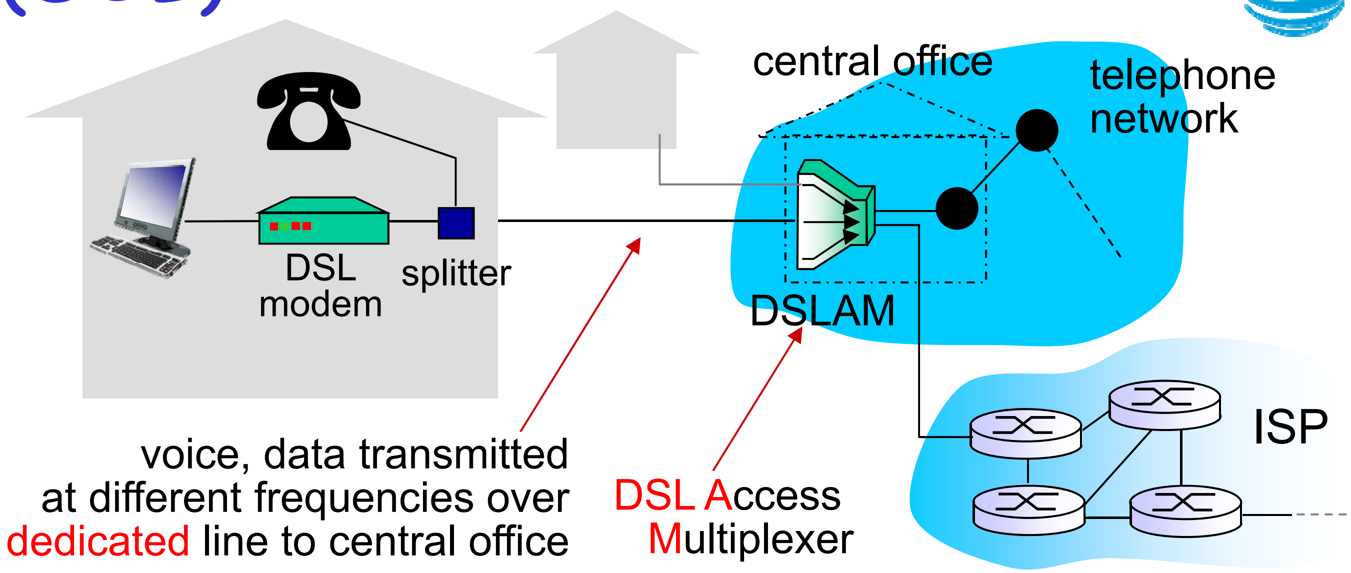
- Residential access nets
- Institutional access networks (school, company)
- Mobile access networks

Keep in mind:

- Bandwidth (bits per second) of access network?
- Shared or dedicated?



Residential Access: Digital Subscriber Line (DSL)



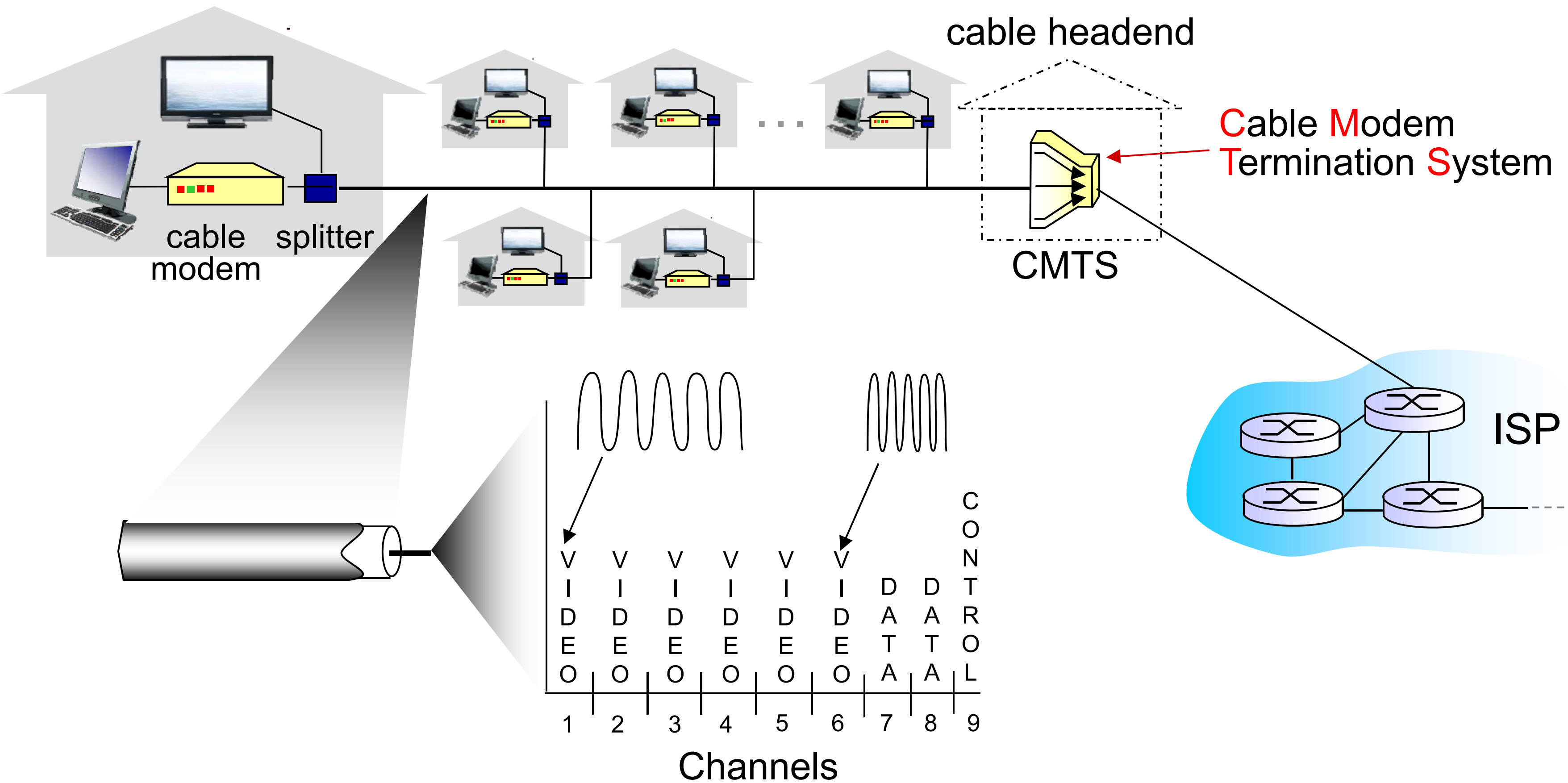
- Uses existing phone lines but limits distance btw user & ISP modem
  - Data over DSL phone line goes to Internet
  - Voice over DSL phone line goes to telephone net
- 2.5 Mbps upstream transmission rate (typically < 1 Mbps)
- 24 Mbps downstream transmission rate (typically < 10 Mbps)

Residential Access: Cable Modems

- HFC: Hybrid Fiber Coax
  - Asymmetric:
    - 100 Mbps downstream
    - 5 Mbps upstream
- Network of cable and fiber attaches homes to ISP router
  - Homes share access network to cable headend
    - That's why your cable modem activity light blinks even when you are not using the modem ☺
- Deployment: available via cable companies

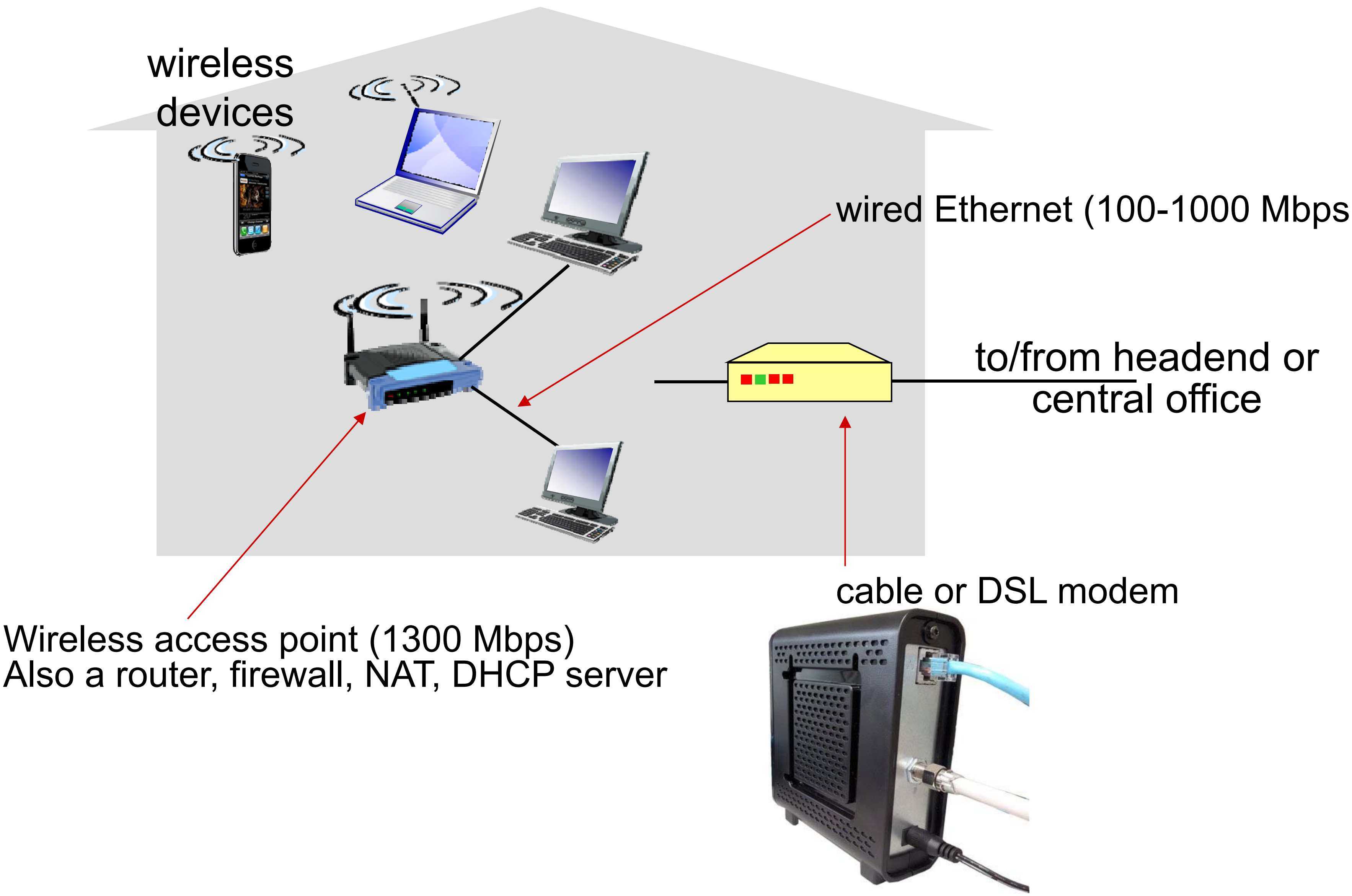
Spectrum

Residential Access: Cable Modems



frequency division multiplexing: different channels transmitted in different frequency bands

Home Networks



High Speed Networking!
56 Kbps Access

***WRIGHT-PATT MAIN EXCHANGE**

HAPPY HOLIDAYS!

INTERNET ADDRESS @http://www.aaf

SPORTSTER 56K INT.2X FAXMODM

73816800615 179.95

TOTAL $ 179.95

MASTERCARD $ 179.95

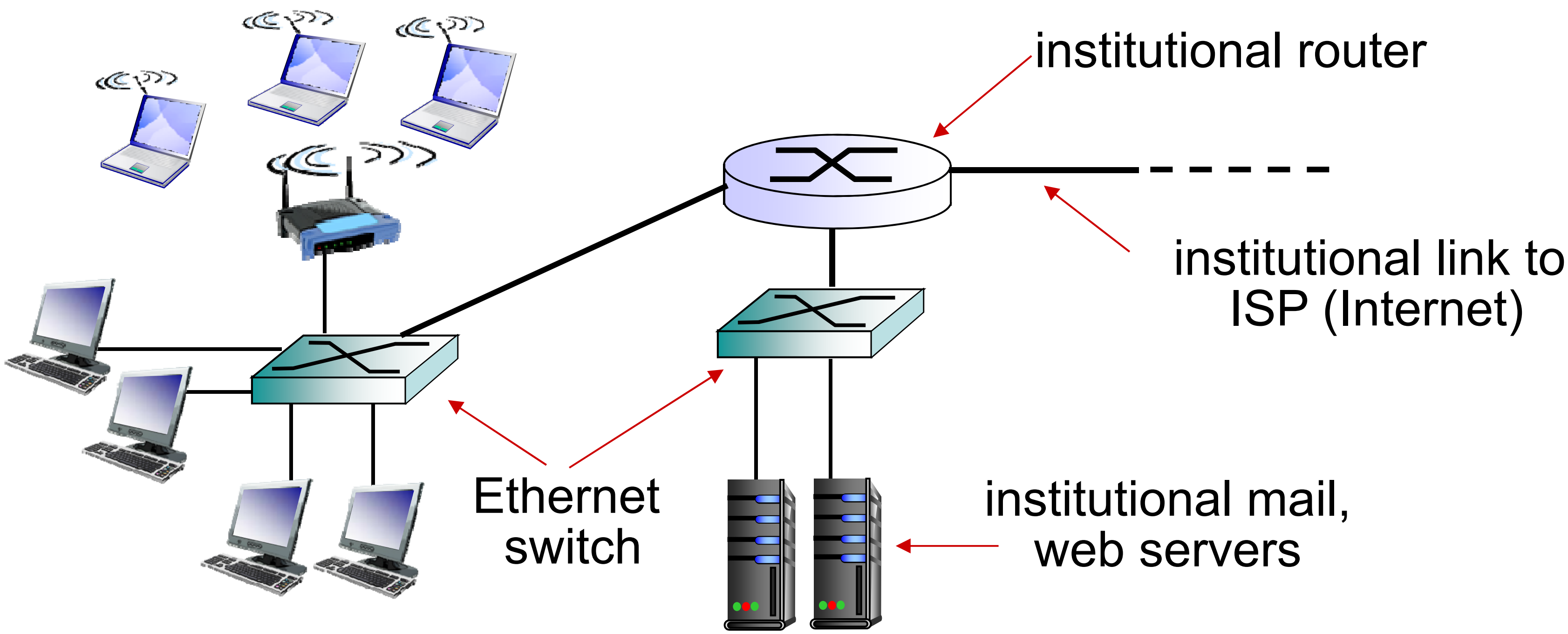
EXPIRY: 01/98 SWIPED BANK

AUTH# :00527

ITEMS 1

12/05/1997 19:31 1010 14 000114 3701

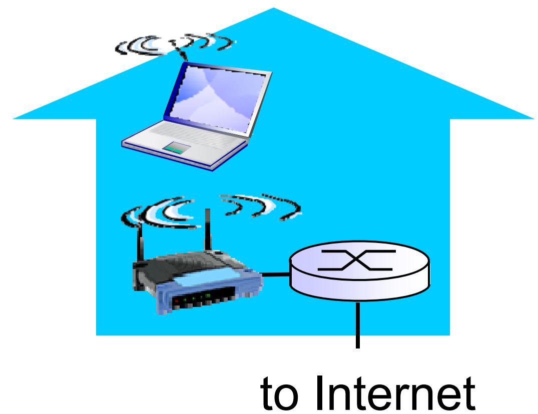
Enterprise Access Networks (Ethernet)



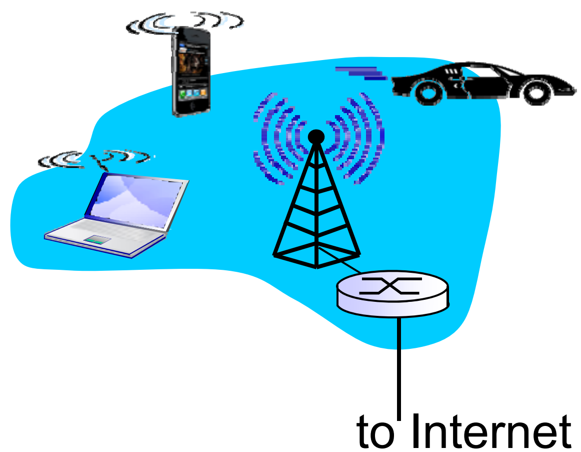
- Typically used in companies, universities, etc.
- 100 Mbps, 1 Gbps, 10 Gbps transmission rates
- Today, end systems typically connect into Ethernet switch

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 (WiFi) 11 Mbps
  - 802.11a,g 54 Mbps
  - 802.11n 150 Mbps
  - 802.11ac 1300 Mbps



- Wide-area wireless access
  - Provided by telco operator
  - 3G and 4G over wide area
  - Covered in CSCE 660

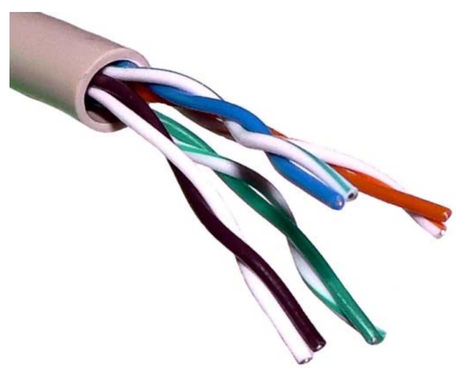


Physical Media

- 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 in free space
    - e.g., radio

Twisted Pair (TP)

- Two insulated copper wires
  - Cat 3: traditional phone wires, 10 Mbps Ethernet
  - Cat 5: 100-1000 Mbps Ethernet
  - Cat 6: 10 Gbps Ethernet

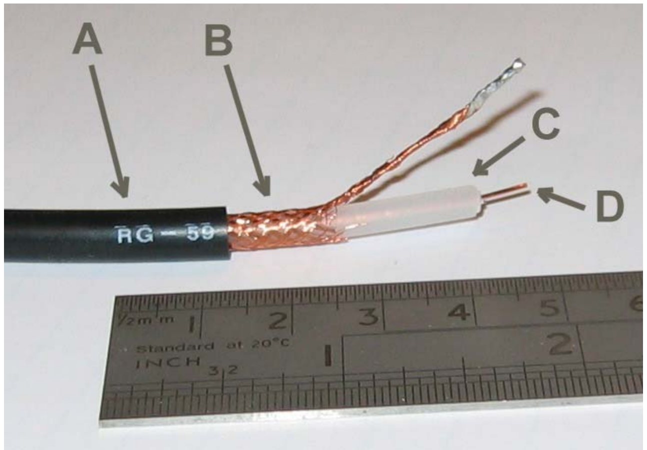


Unshielded twisted pair cable

Physical Media: Coax, Fiber

Coaxial cable:

- Two concentric copper conductors
- Bidirectional
- Baseband:
  - Single channel on cable
  - Legacy Ethernet
- Broadband:
  - Multiple channels on cable
  - Cable TV

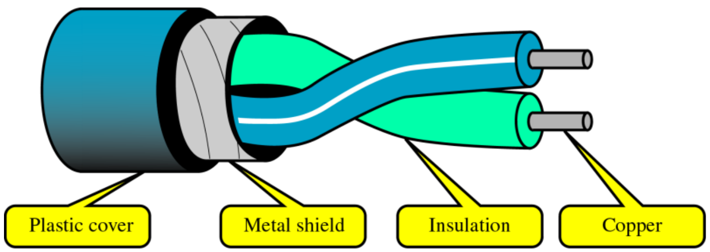


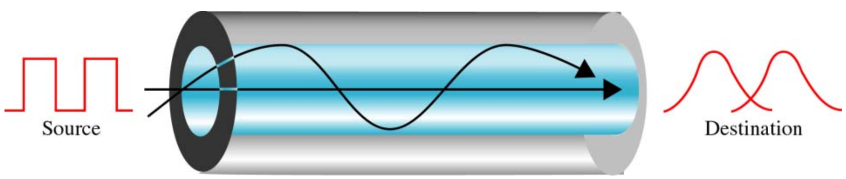
Fiber optic cable:

- Glass fiber carrying light pulses, each pulse = bit
- High-speed operation:
  - High-speed point-to-point transmission
  - 10's-100's Gbps
- Low error rate: repeaters spaced far apart; immune to electromagnetic noise

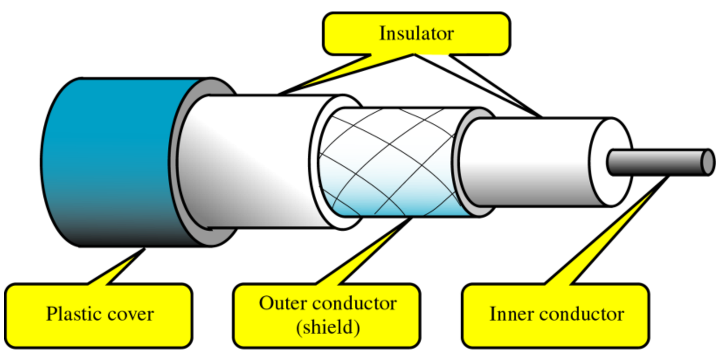
Physical Media: Cables

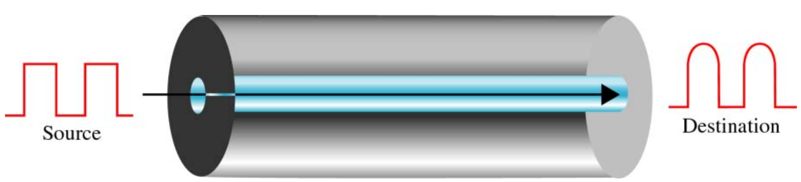
Cable	Typical Bandwidth	Distances
Cat 5 (BASE T)	10-100 Mbps	100 m
Cat 5e (BASE T)	1000 Mbps	100 m
Thin-net coax (BASE2)	10-100 Mbps	200 m
Thick-net coax (BASE5)	10-100 Mbps	500 m
Multimode fiber	100 Mbps / 10 Gbps	2 km / 550m
Single mode fiber	10 Gbps	80 km





Multimode (50-80 microns)
Orange cable





Single mode (7-10 microns)
Yellow cable

Physical Media: Radio

- Signal carried in electromagnetic spectrum
- Bidirectional
- Effects of propagation:
  - Reflection
  - Obstruction by objects
  - Interference

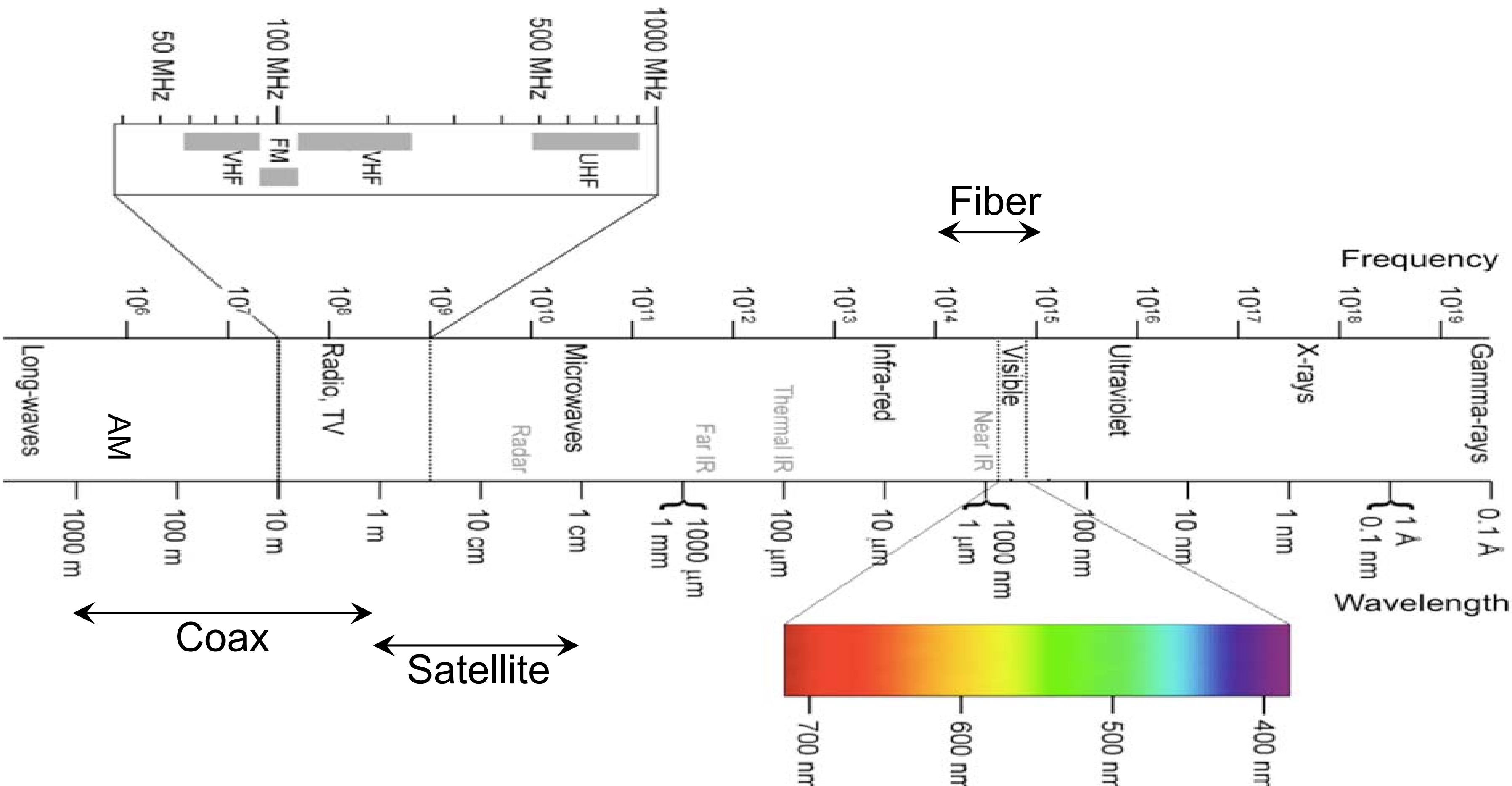
Radio link types:

- Terrestrial microwave
  - Up to 45 Mbps channels
- LAN (e.g., WiFi)
  - 2, 11, 54, 1300 Mbps
- Wide-area (e.g., cellular)
  - 3G : ~ 500 Kbps
  - 4G : ~ 5 Mbps
  - 5G : ~ 100 Mbps (goal)
- Satellite
  - Kbps to 45 Mbps channel
  - ~ 270 msec end-end prop. delay
  - Geosynchronous vs low orbit

Physical Media: Radio

2.4 GHz → 12.5 cm
~5 in

- Relationship between speed of light (c), frequency (f), and wavelength (λ)
  - $\lambda = c/f$ where $c = 3 \times 10^8$ m/s (air); 2×10^8 m/s (wire)



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

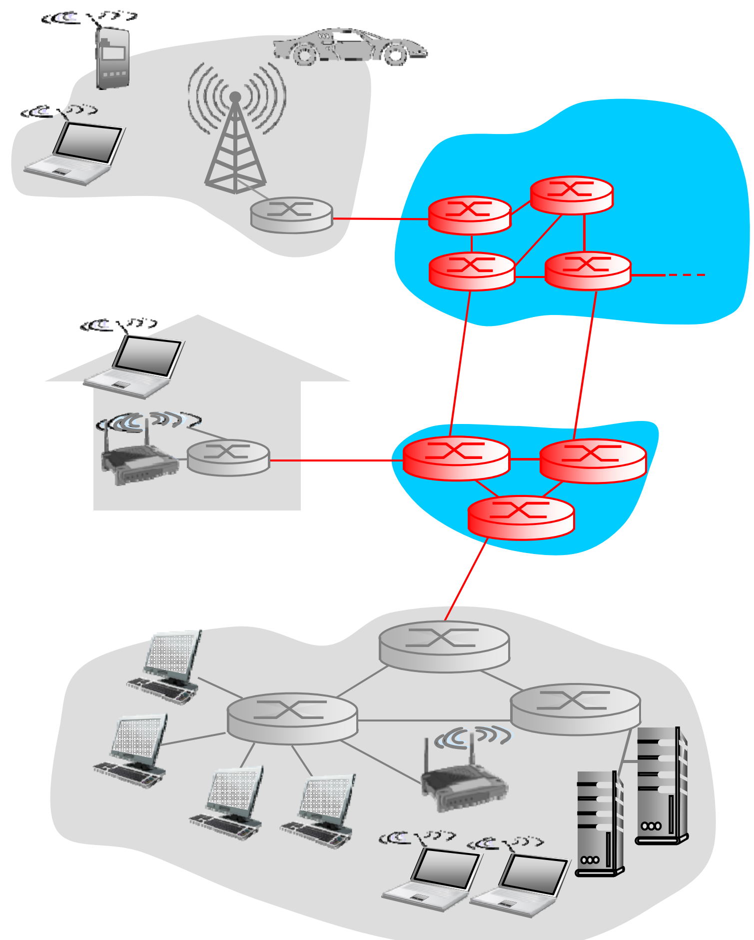
1.5 Protocol layers, service models

1.6 Networks under attack: security

1.7 History

The Network Core

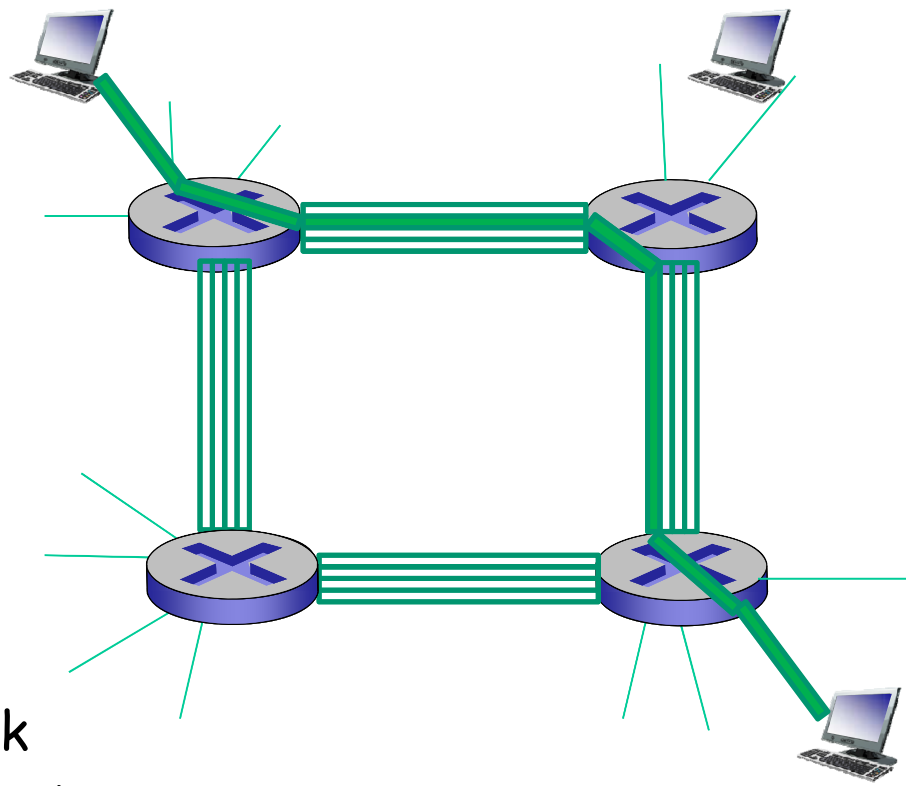
- Interconnected routers
- *The* fundamental question: how is data transferred through the network?
  - Circuit switching: dedicated circuit per call
    - Telephone network
  - Packet switching: data sent thru net in discrete "chunks"



Network Core: Circuit Switching

End-end resources reserved for "call"

- 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
- Call setup required
- Public Switched Telephone Network
  - Plain old telephone service (POTS)

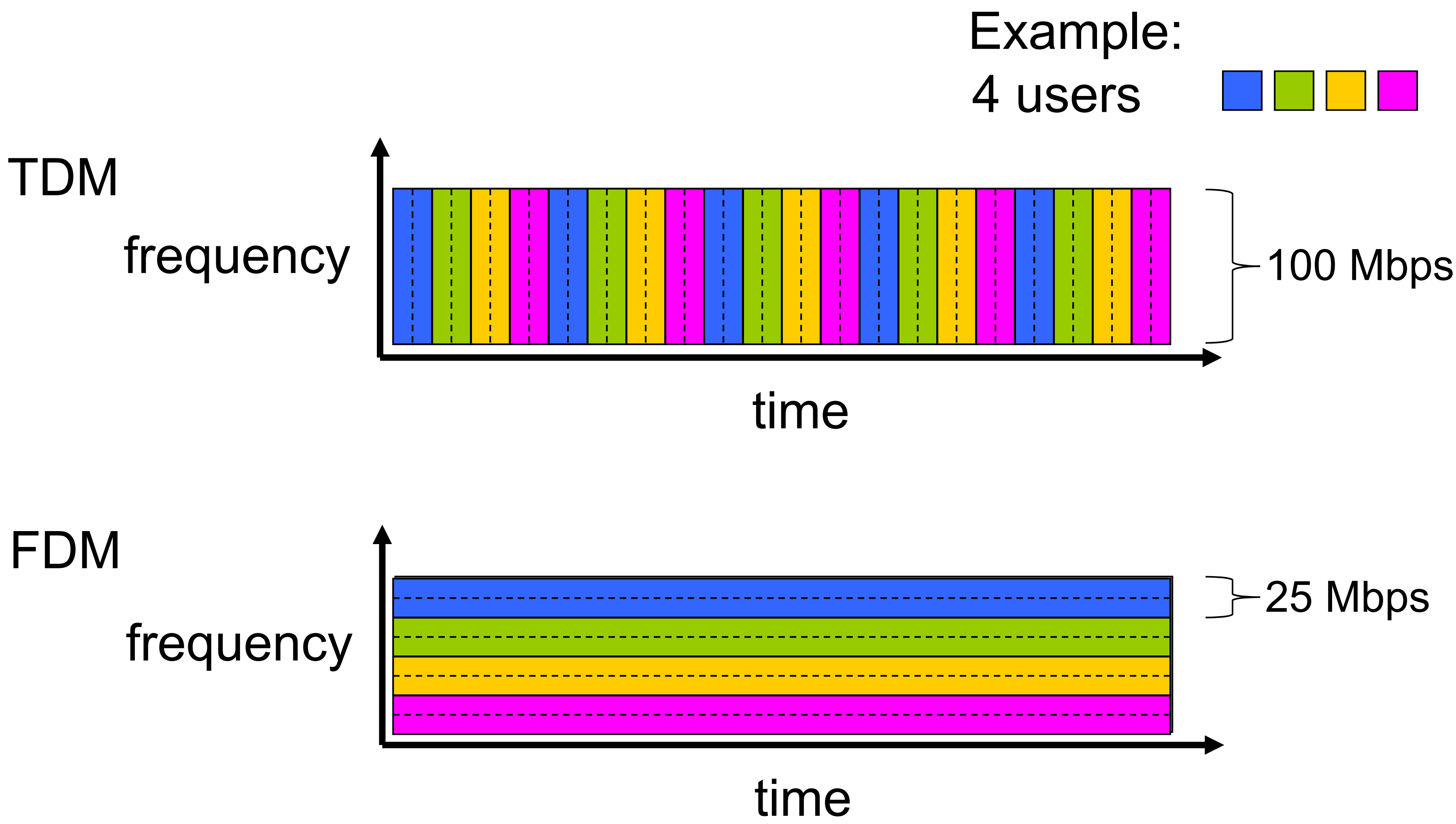


Network Core: Circuit Switching

- Network resources (e.g., link bandwidth) divided into "pieces"
- Pieces allocated to calls
- Resource piece idle if not used by owning call (no sharing)

- Dividing link bandwidth into "pieces" -- multiplex different calls
  - Time division multiplexing (TDM)
  - Frequency division multiplexing (FDM)

Circuit switching: TDM versus FDM



Circuit Switching 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

Transmission rate:	1.536 Mbps / 24 = 64 kbps
Transmission time:	640,000 bits / 64 kbps = 10 sec
Total time:	10 sec + 500 msec = 10.5 sec

Ignores propagation delay

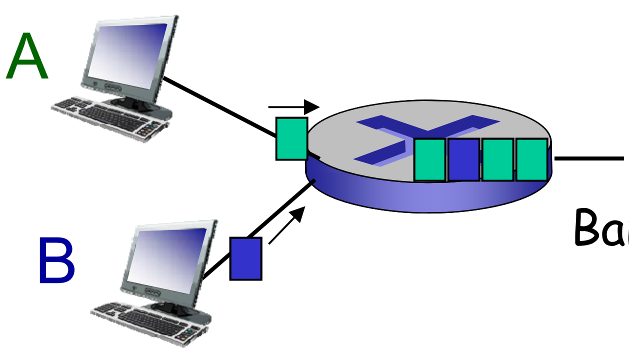
Network Core: Packet Switching

Each end-end data stream divided into *packets*

- Packets are numbered and addressed and sent through the network one at a time
- A's packets and B's packets *share* network resources
- Each packet uses full link bandwidth
- Resources used *as needed*

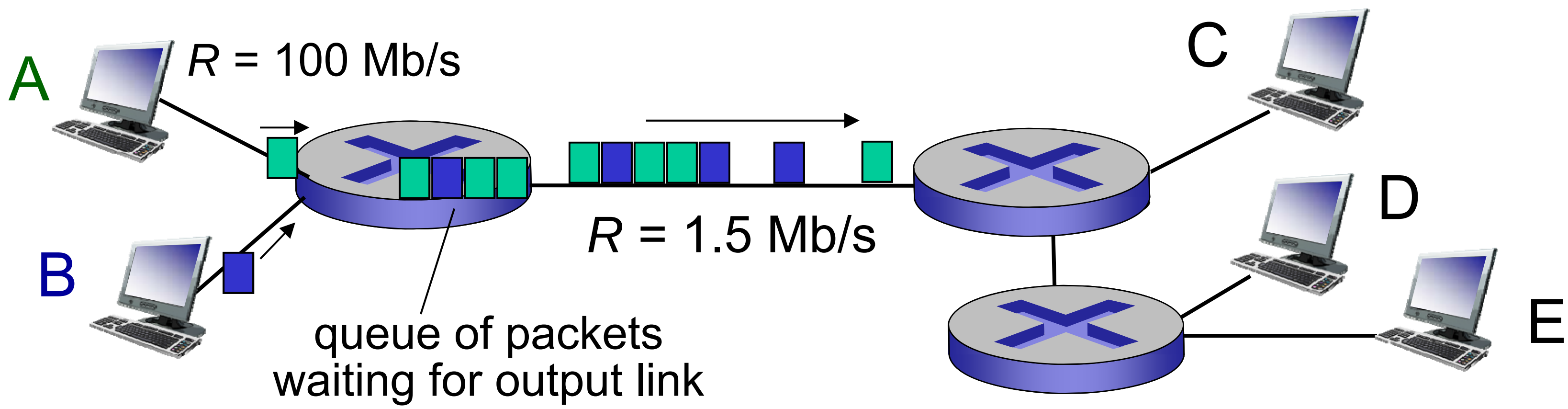
Resource contention:

- Aggregate resource demand can exceed amount available
- Congestion: packets queue, wait for link to become available
- Store and forward: packets move one hop at a time
  - Node receives complete packet before forwarding
  - Allows Pipelining
    - Overlap sending and receiving of packets on multiple links



~~Bandwidth divided into "pieces"~~
~~Dedicated allocation~~
~~Resource reservation~~

Packet Switching: Queuing Delay, Loss



Queuing and Loss:

- If arrival rate (in bits per second) 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

http://media.pearsoncmg.com/aw/aw_kurose_network_2/applets/queuing/queuing.html

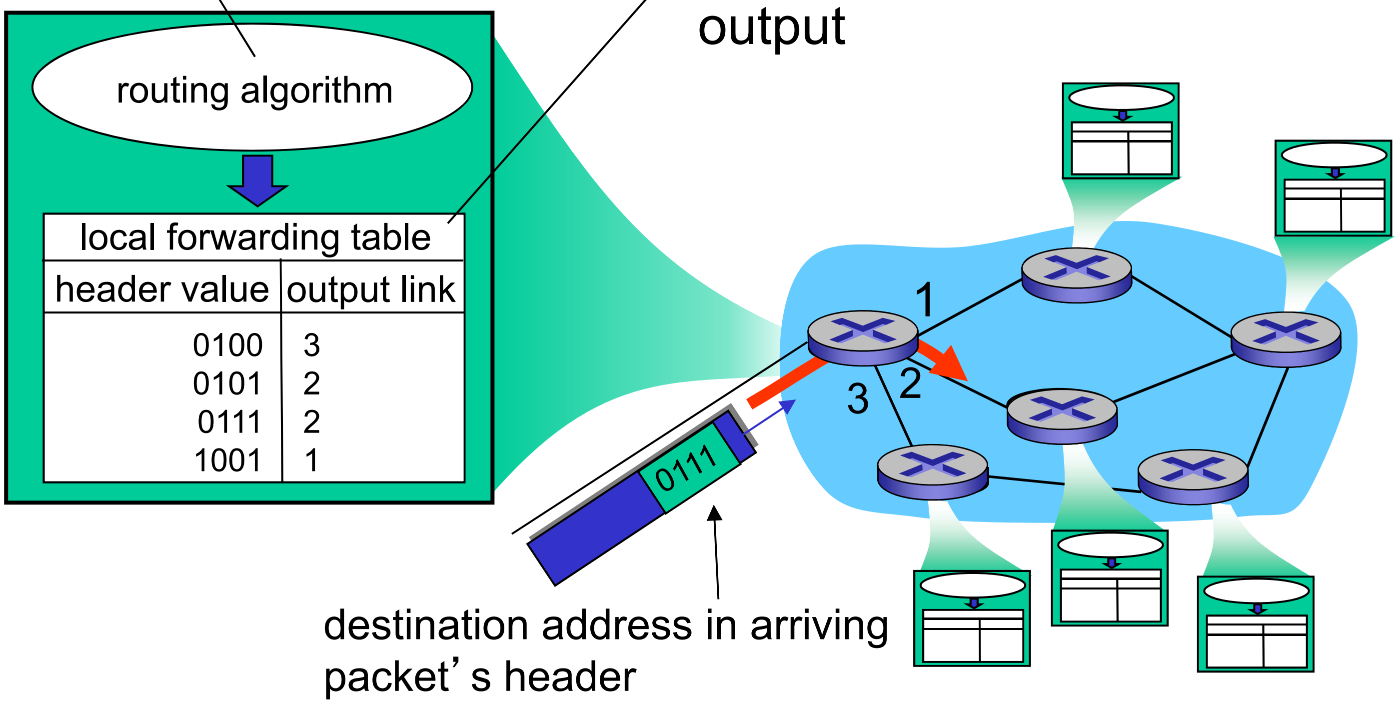
Two Key Network-Core Functions

Goal: move packets through routers from source to destination
Datagram network:

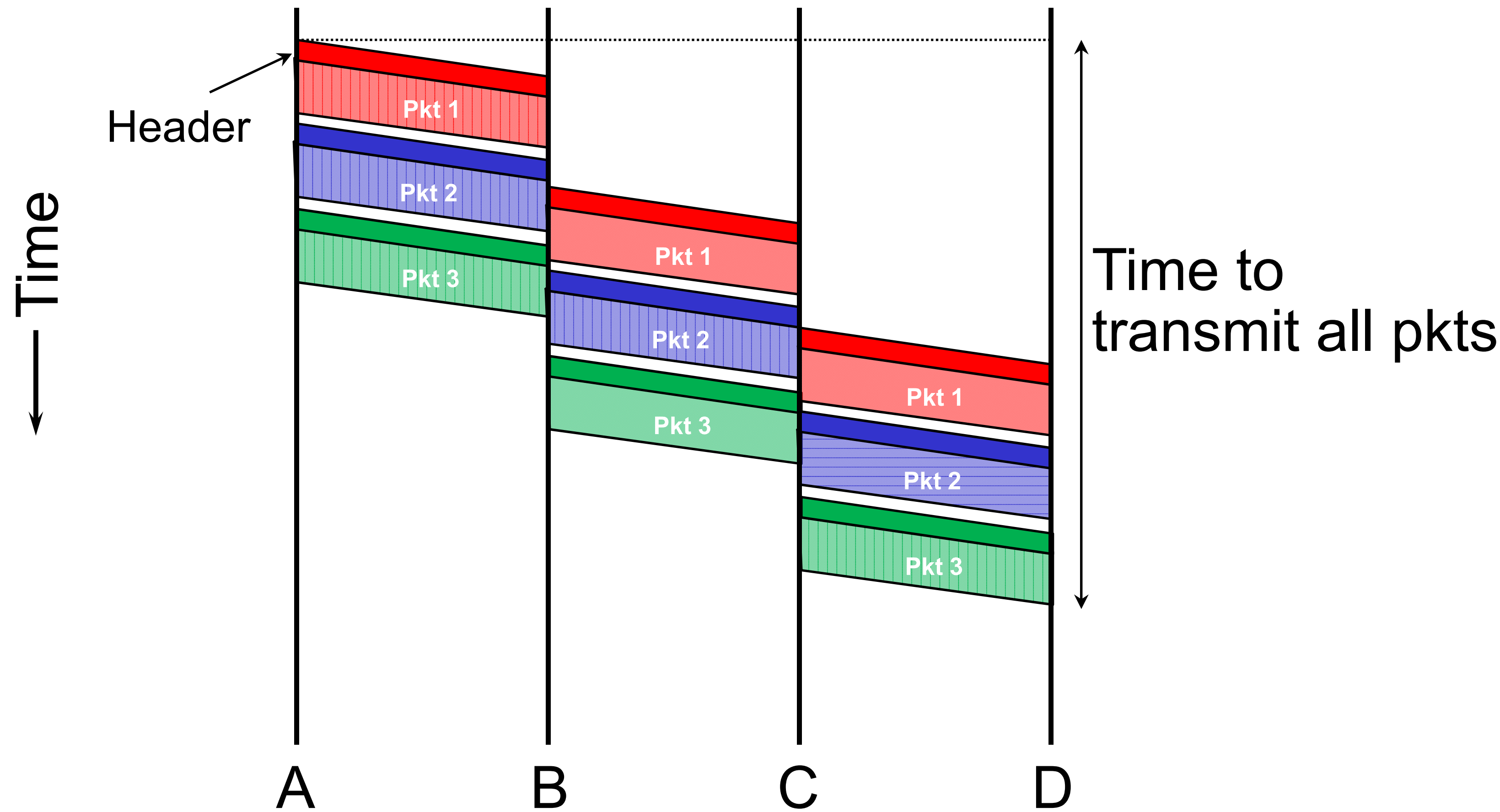
Destination address in packet determines next hop

Routing: determines source-destination route taken by packets

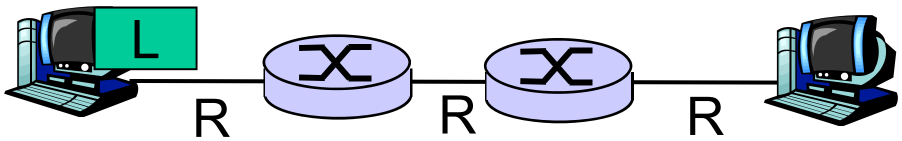
Forwarding: move packets from router's input to appropriate router output



Packet Switching (Exploiting Pipelining)



Packet Switching: Store-and-forward



- Takes L/R seconds to transmit (push out) packet of L bits onto link of 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)

more on prop. delay soon …

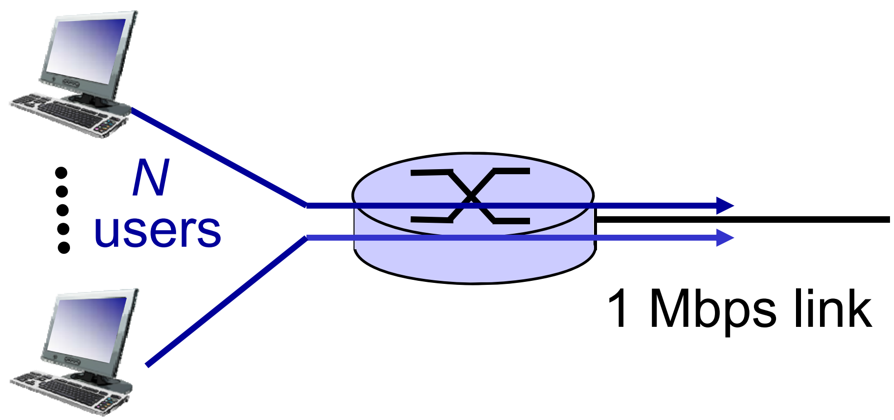
Example:

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

Packet Switching Versus Circuit Switching

Packet switching allows more users to use network!

- Assume:
  - 1 Mbps link
  - Each user:
    - 100 kbps when "active"
    - Active 10% of time
- Circuit-switching:
  - Supports 10 users
- Packet switching:
  - With 35 users, probability of more than 10 users active at once is less than 0.0004



Q: How did we get value 0.0004?
A: See problem 8 in text ☺

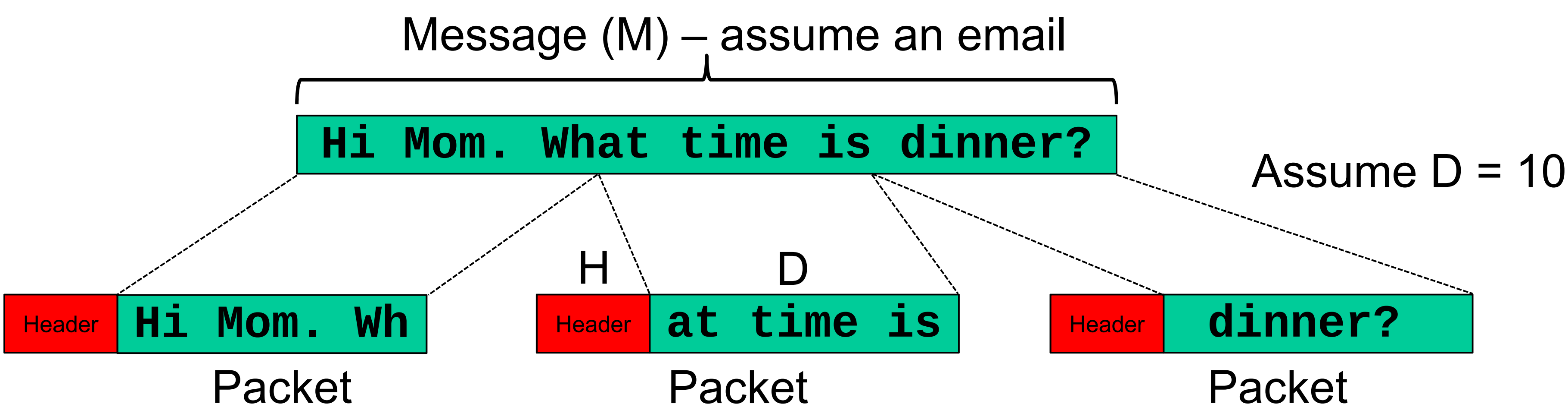
Packet Switching Versus Circuit Switching

Is packet switching a "slam dunk winner?"

- Great for bursty data
  - Resource sharing;   Simpler, no call setup
  - Link fully utilized if there is **any** data to transmit by anyone
  - Delay can be significantly reduced
  - Utilization can be significantly increased
- Excessive congestion → packet delay and loss
  - Protocols needed for reliable data transfer, congestion control
  - Greater variance in delay due to queuing delays
  - *Flow control* needed to prevent buffer overflows
- Q: How to provide circuit-like behavior?
  - Bandwidth guarantees needed for audio/video apps
  - Still an unsolved problem (Chapter 9)

Packet Switching Time

- **Goal:** Determine time required to move a fixed amount of data
  We'll ignore propagation delay in this example
  - Per-link bandwidth: B (bps)
  - Number of switches: S
  - Number of bytes in the message: M (bytes)
  - Size of data within a packet: D (bytes)
  - Size of the header: H (bytes)

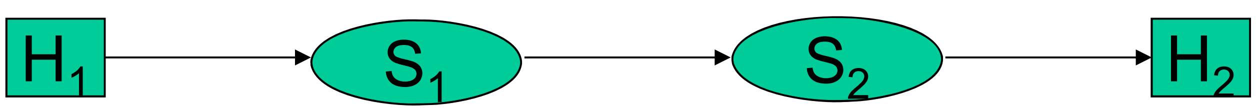


Packet Switching Time

- Delay = Transmission + "Forwarding" delays

- Transmission delay (aka bandwidth delay)
  - Time to push all the packets into the network (from H_1 to S_1)
  - Time required by the NIC to push all bits onto the wire

- "Forwarding" delay
  - Time for the last packet (bit) to cross network



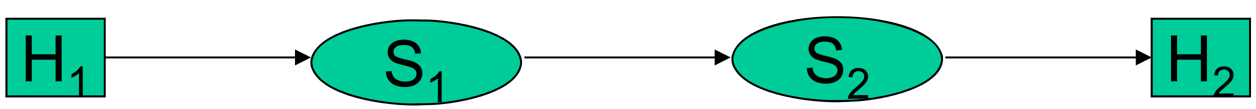
Packet Switching Time

$$\overbrace{\left\lceil \frac{M}{D} \right\rceil \left[\frac{8(D+H)}{B} \right]}^{\text{Transmission delay}} + \overbrace{S \left[\frac{8(D+H)}{B} \right]}^{\text{“Forwarding” delay for last packet}}$$

Number of packets

Number of switches

Time for each packet to be transmitted on each link



Try M=1,500 bytes, D=500 bytes, B=4,000 bps, no header

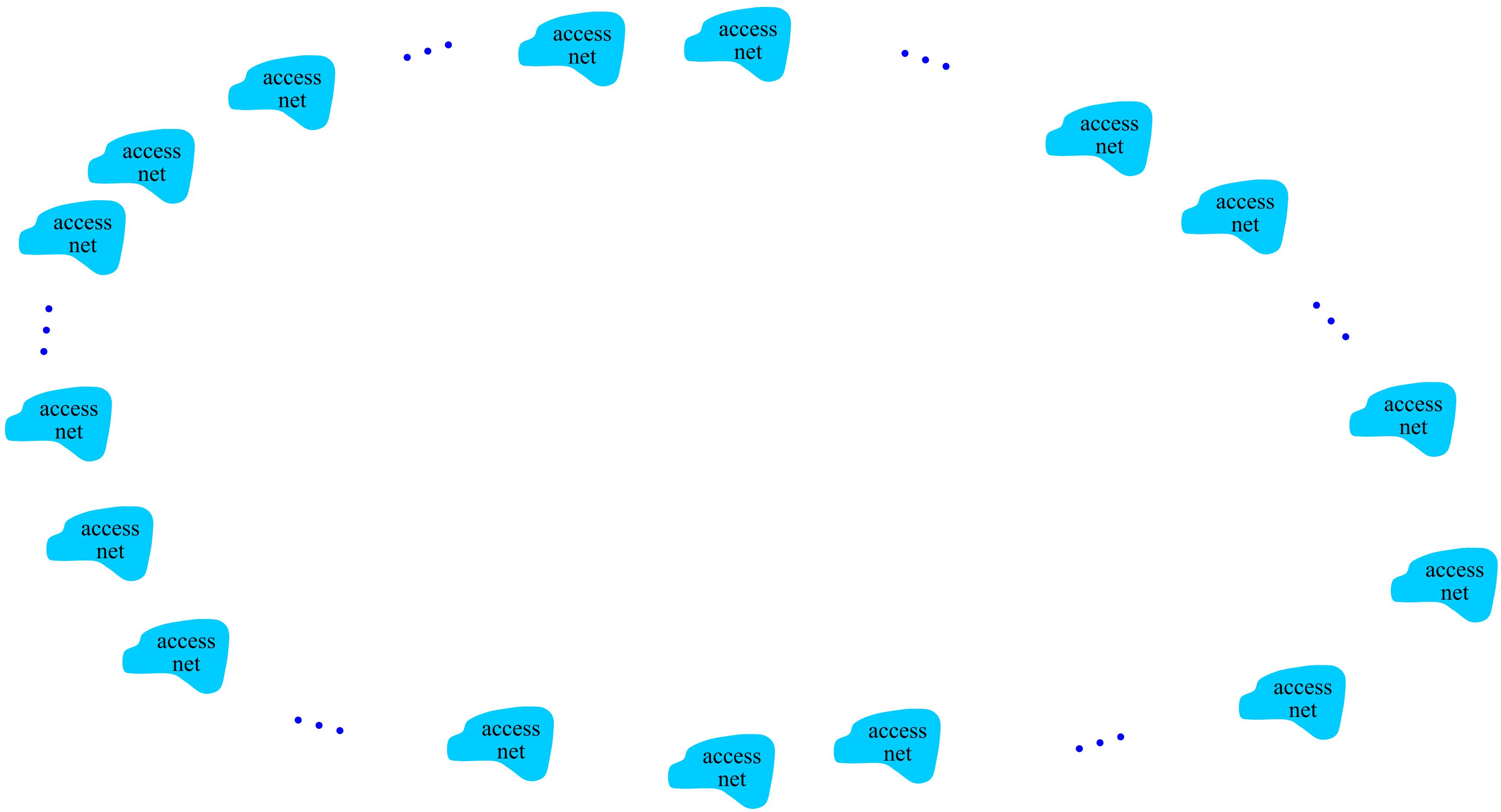
http://media.pearsoncmg.com/aw/aw_kurose_network_2/applets/message/messagesegmentation.html

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

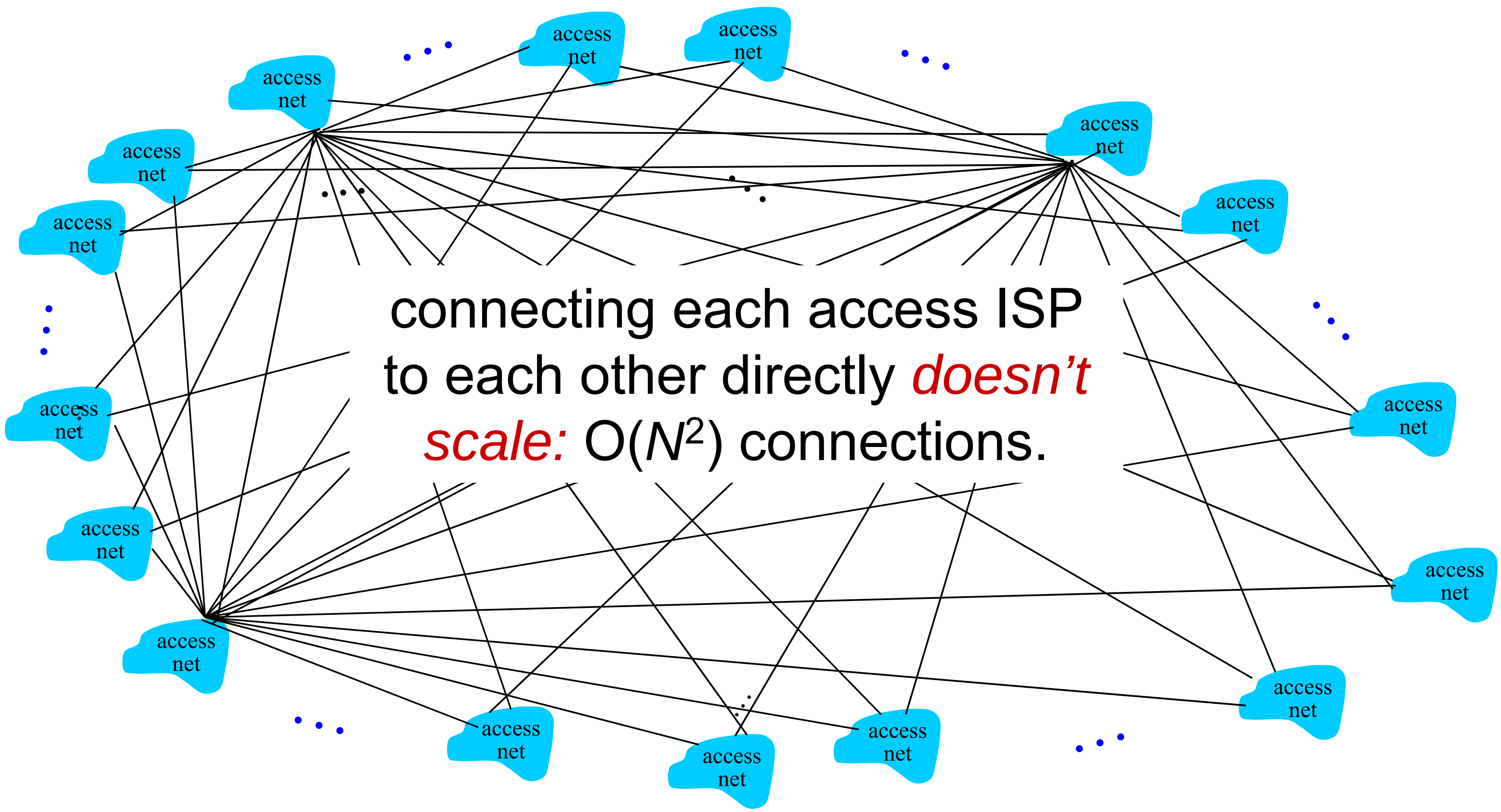
Internet Structure: Network of Networks

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



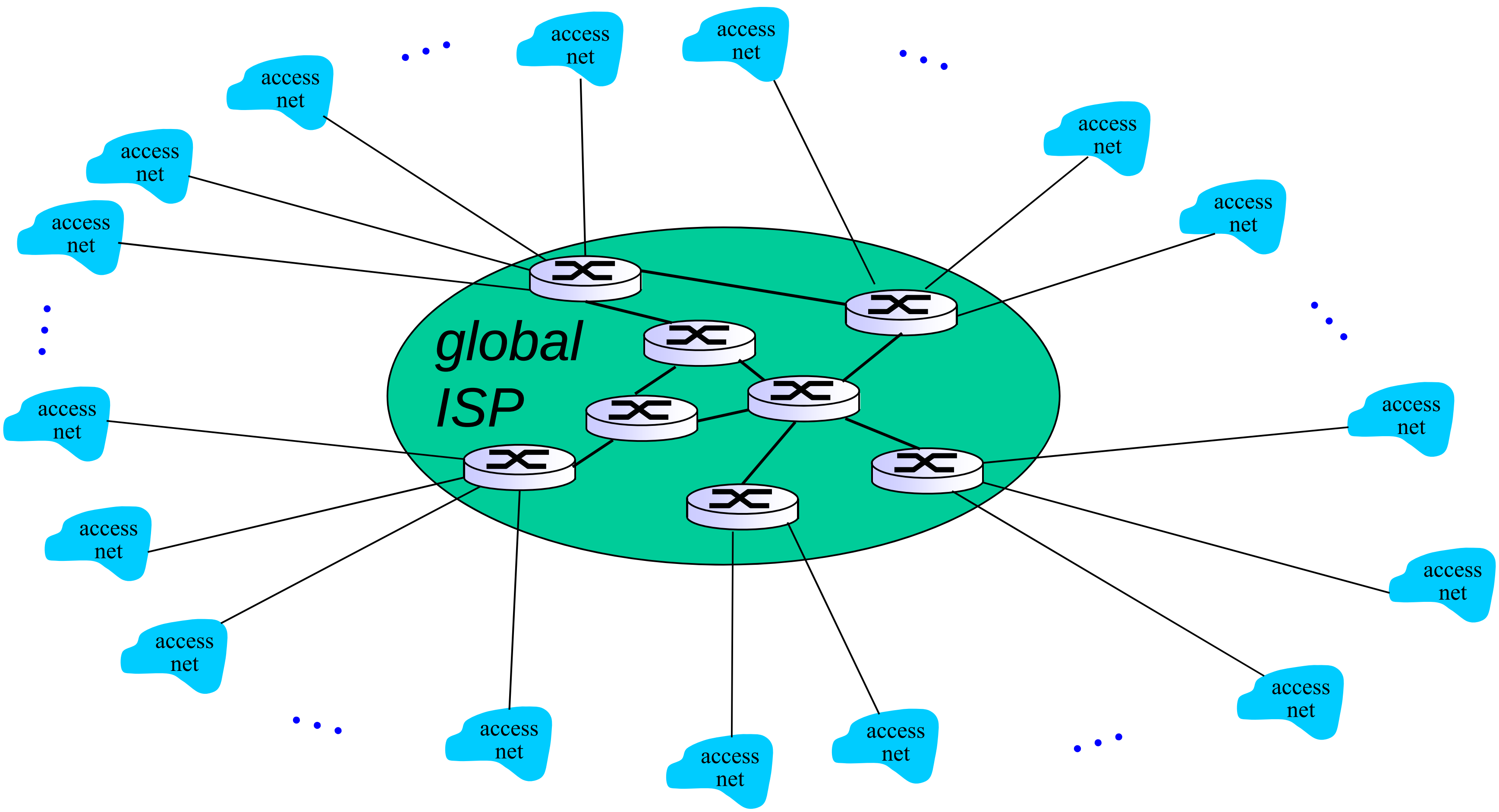
Internet Structure: Network of Networks

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



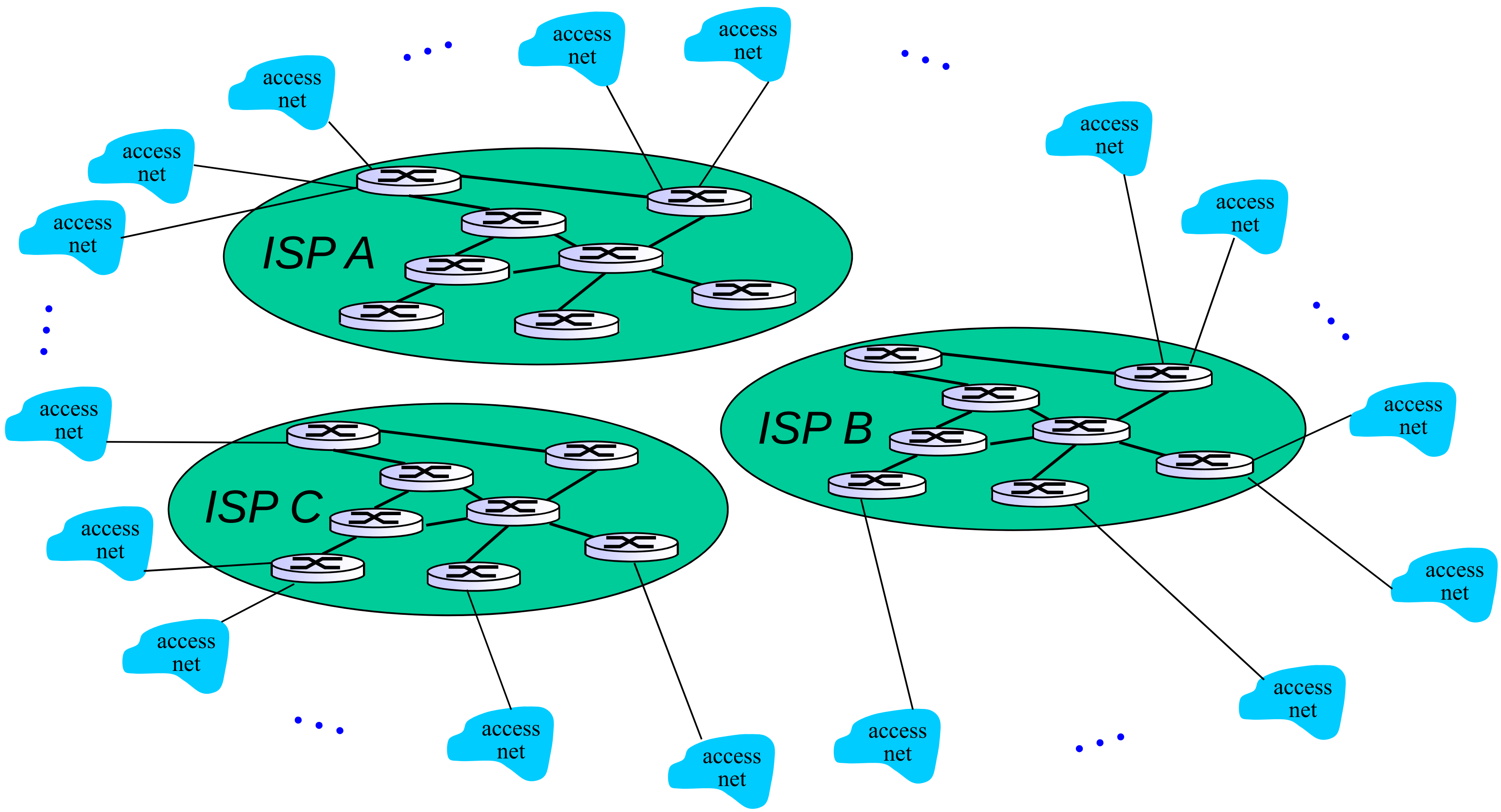
Internet Structure: Network of Networks

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



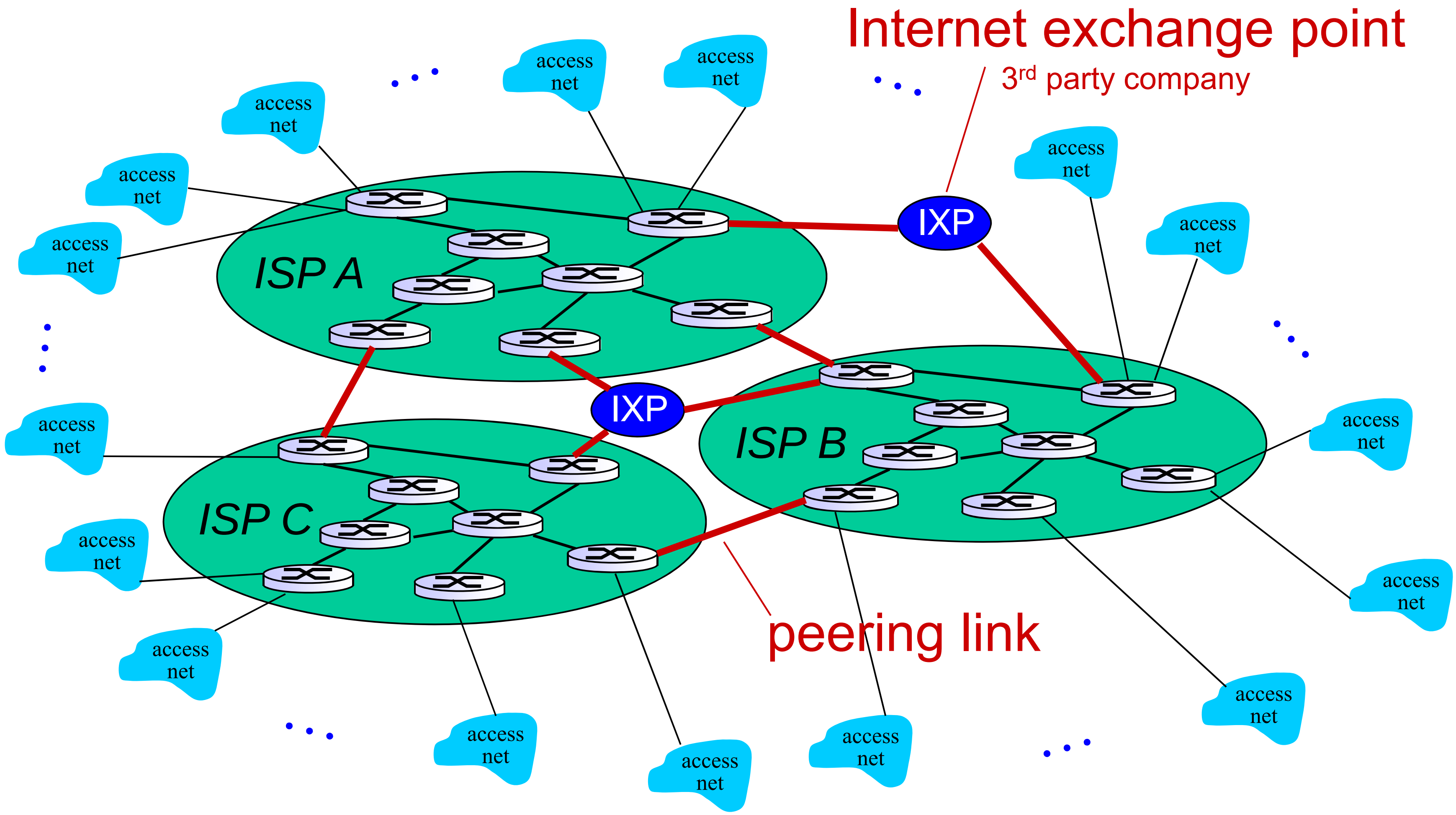
Internet Structure: Network of Networks

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



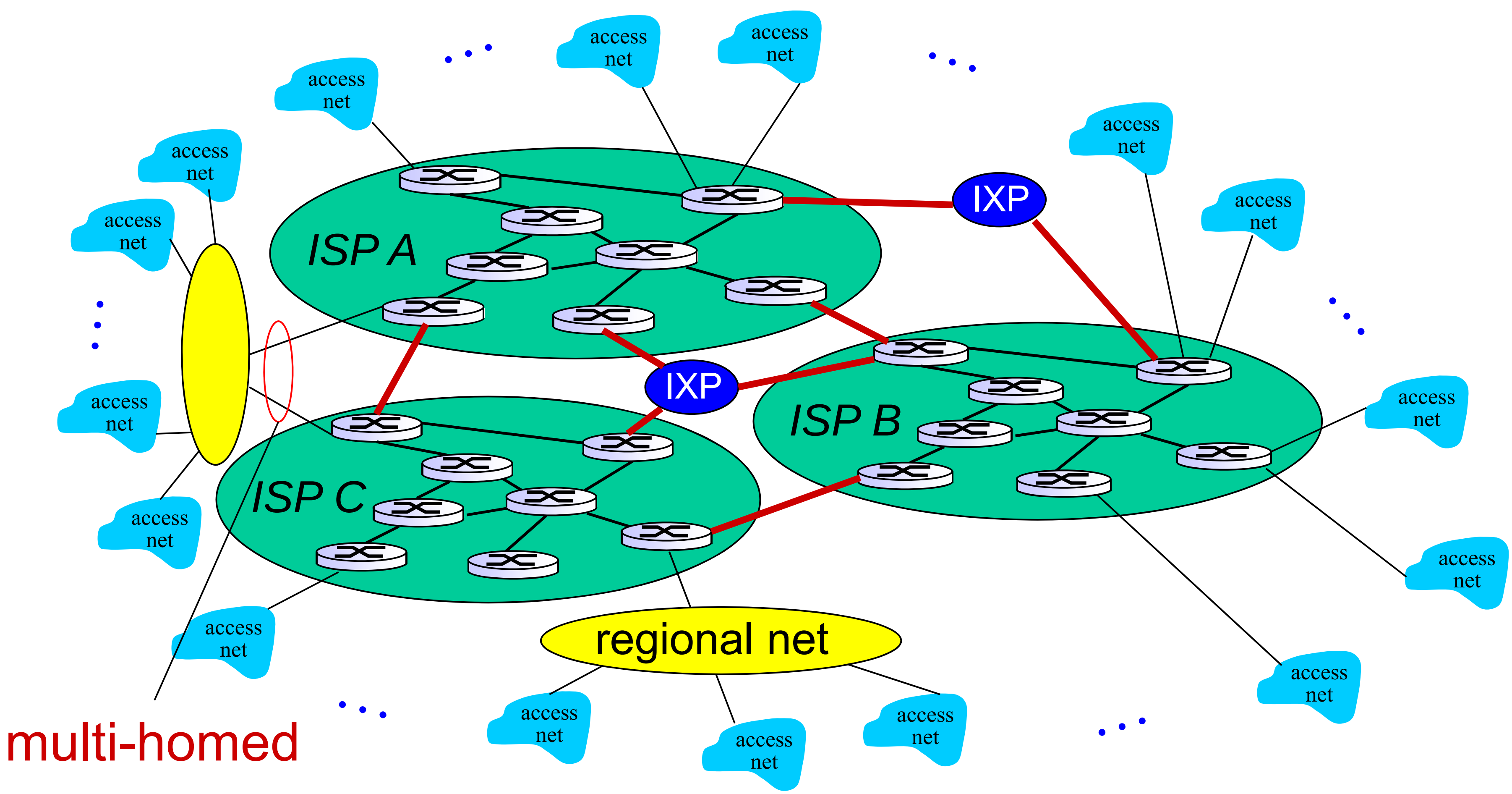
Internet Structure: Network of Networks

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



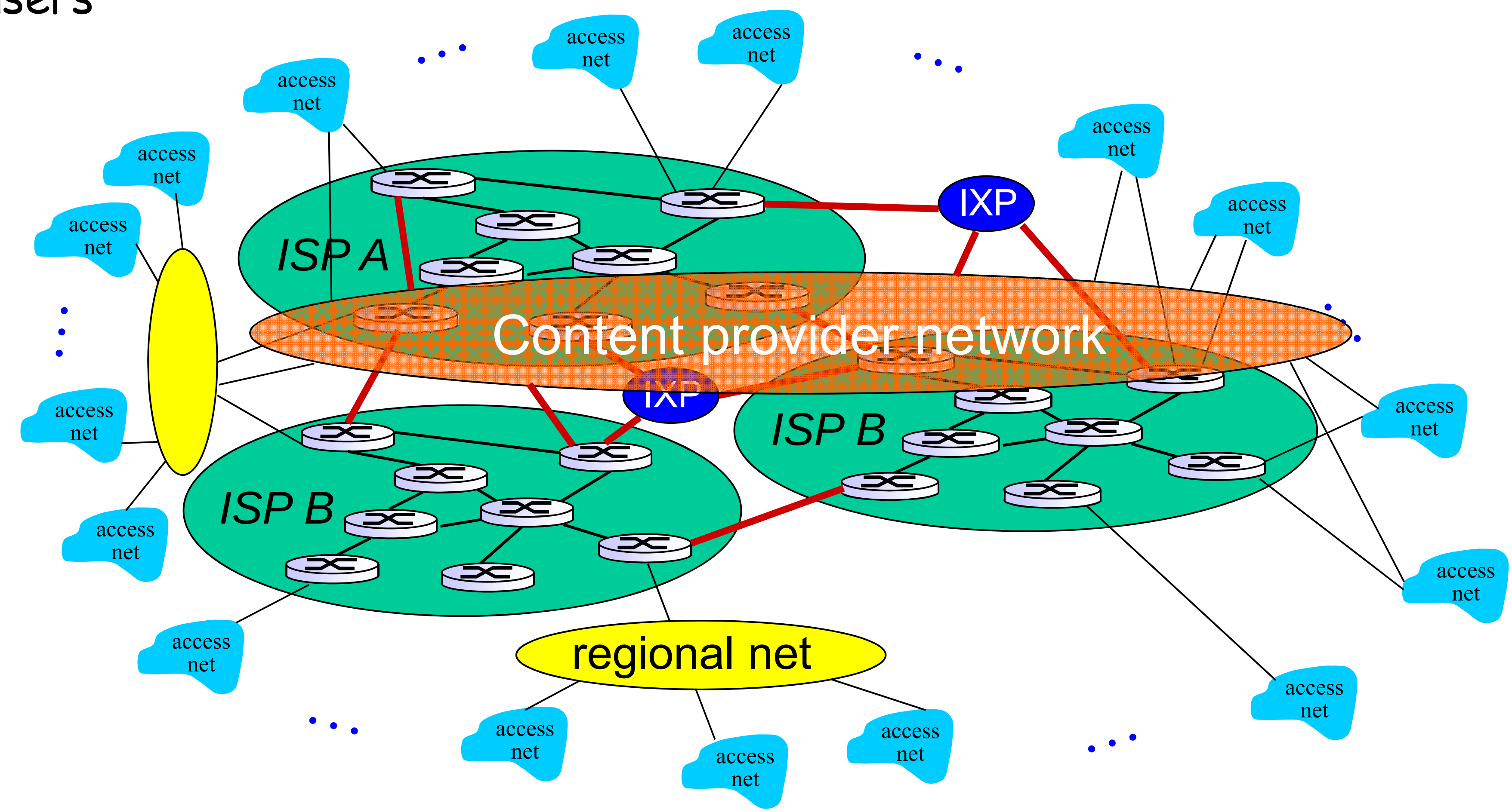
Internet Structure: Network of Networks

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

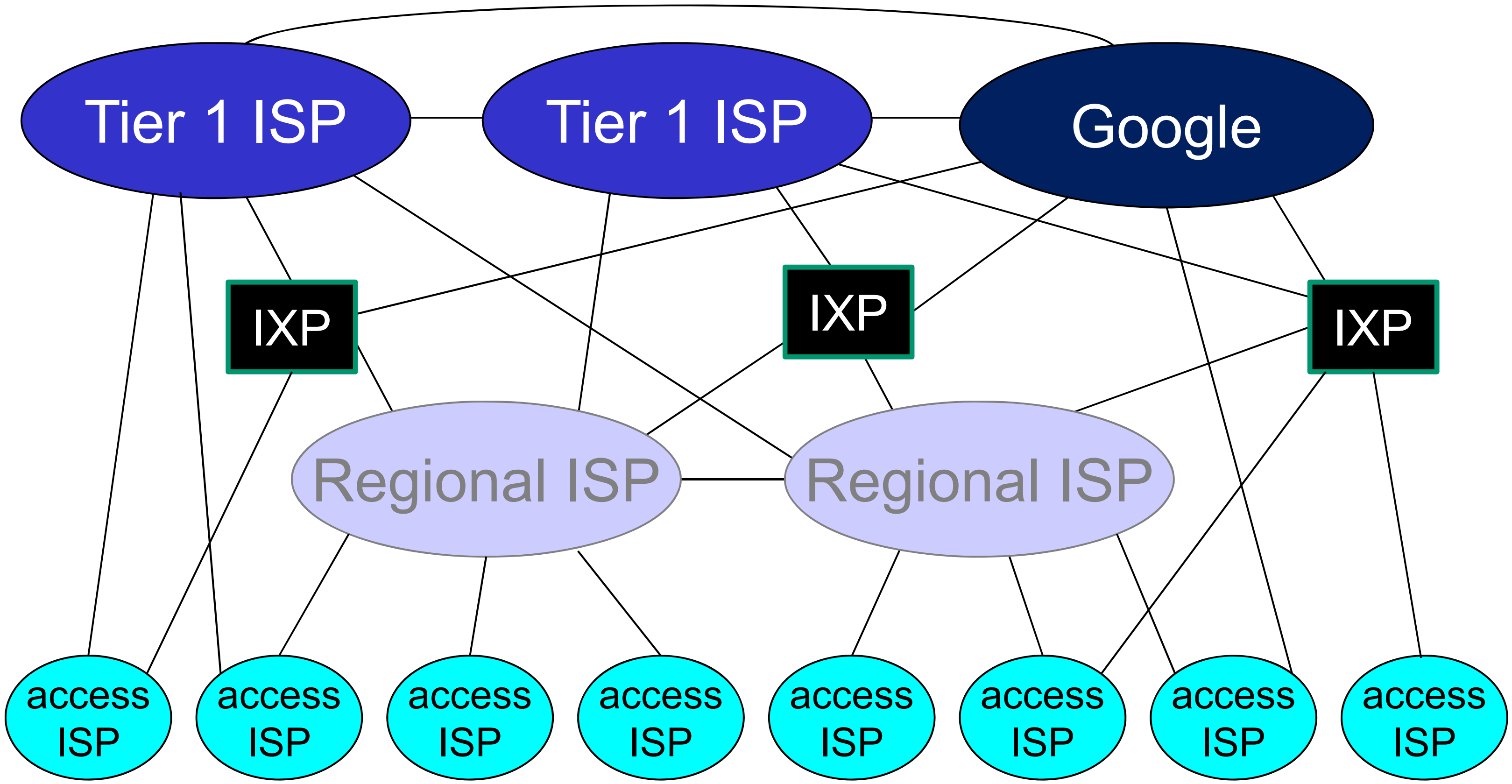


Internet Structure: Network of Networks

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

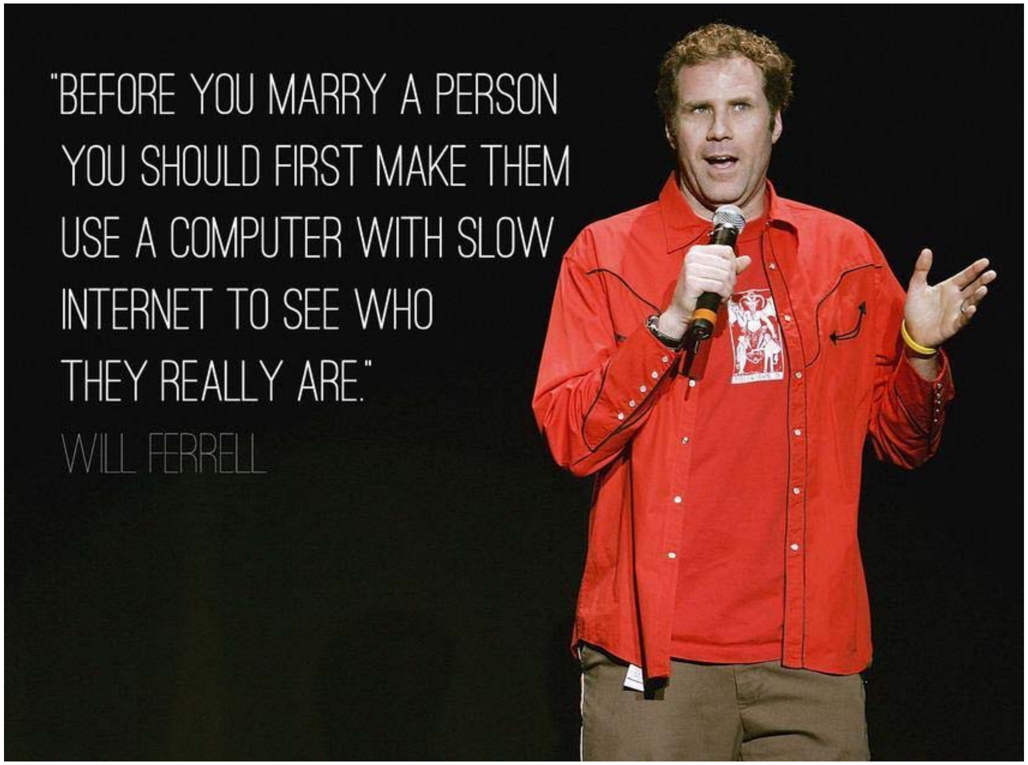


Internet Structure: Network of Networks



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

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

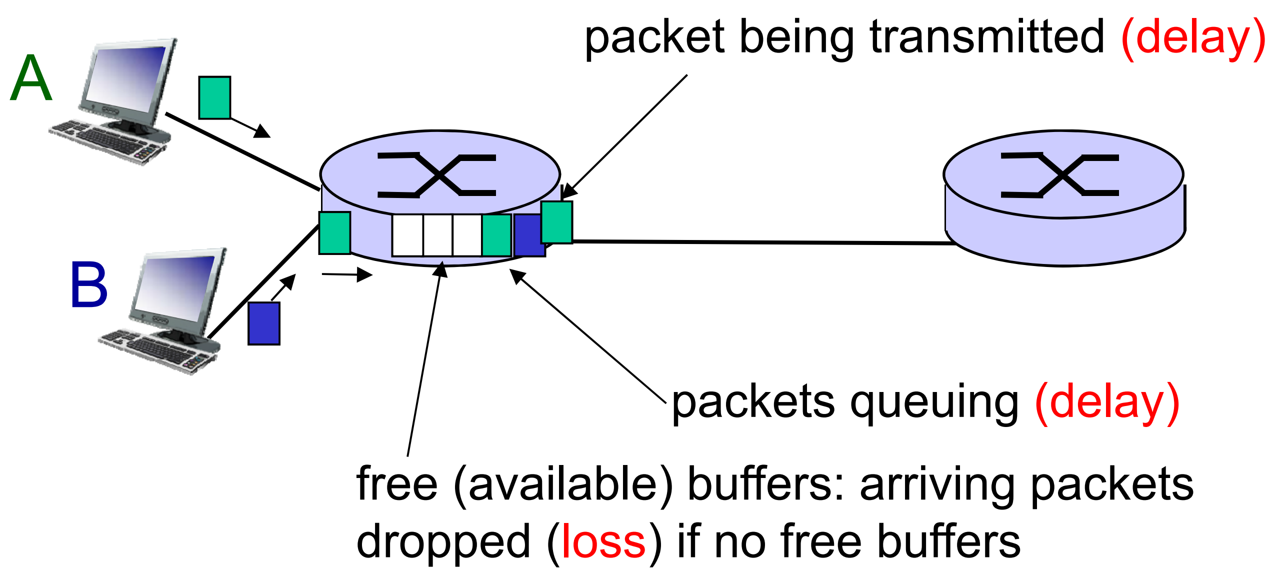
1.6 Networks under attack: security

1.7 History

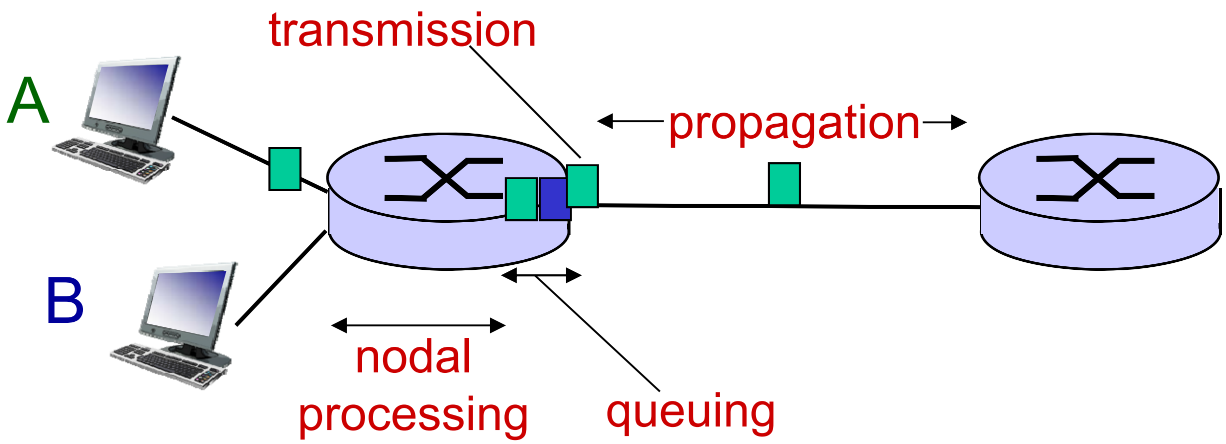
How Do Loss and Delay Occur?

Packets *queue* in router buffers

- Packet arrival rate to link (temporarily) exceeds output link capacity
- Packets queue and wait for turn
- Lost packet may be retransmitted by previous node, by source end system, or not at all



Four Sources Of Packet Delay



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

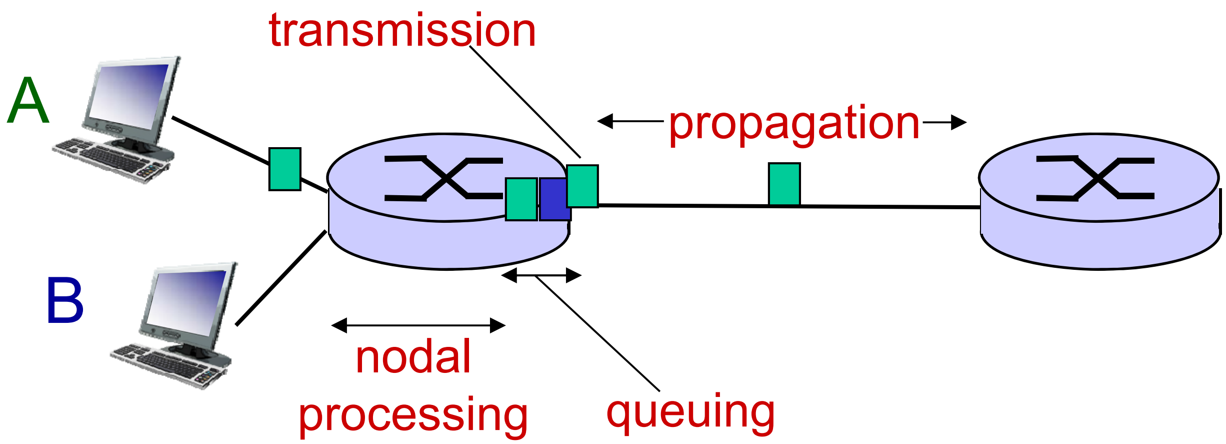
d_{proc}: nodal processing

- Check bit errors
- Determine output link
- Typically << usec
  - Often ignored

d_{queue}: queuing delay

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

Four Sources Of Packet Delay



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

d_{trans}: transmission delay:

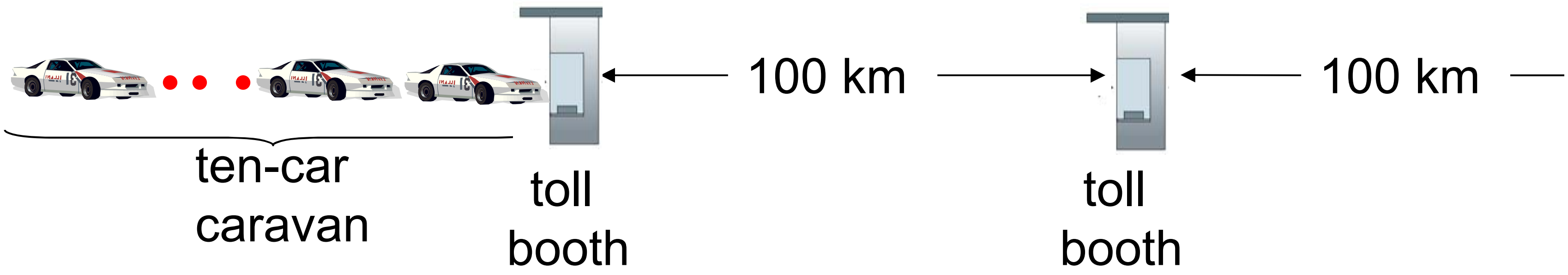
- L: packet length (bits)
- R: link bandwidth (bps)
- $d_{trans} = L/R$

d_{prop}: propagation delay:

- d: length of physical link
- s: propagation speed in medium (~ 2.8×10^8 m/sec)
- $d_{prop} = d/s$

d_{trans} and d_{prop} very different

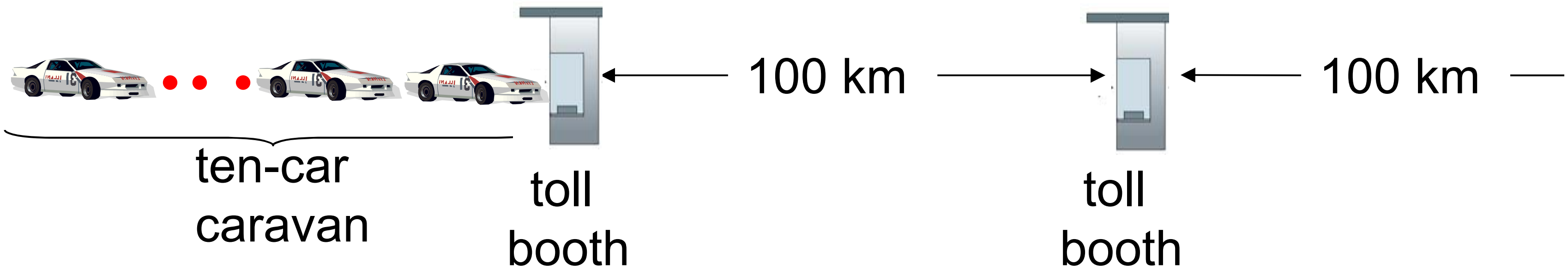
Caravan Analogy



- Car ~ bit; caravan ~ packet
- Cars "propagate" at 100 km/hr
  - Propagation delay
- Toll booth takes 12 sec to service a car
  - Transmission delay
- 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
  - Transmission delay
- Time for last car to propagate from 1st to 2nd toll booth:

  100km / (100km/hr) = 1 hr
  - Propagation delay
- 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 at 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!

http://www.ccs-labs.org/teaching/rn/animations/propagation/

Nodal Delay Using Flow Control

- If we are using some type of flow control
  - ARQ (Automatic Repeat reQuest) or windowing, delay is:

$$d_{nodal} = d_{proc} + d_{queue} + d_{trans} + 2d_{prop} + d_{ack}$$

where d_{ack} is the time for the receiver to generate and transmit an acknowledgement

Delay Considerations (Example)

- Processing overhead -- assume d_{proc} = 1 μs
- Queuing delay -- assume d_{queue} = 0
- Transmission time
  - Assume L = 1,000 bit message
  - Assume C = 10 Mbps link
  - Transmission time: $d_{trans} = L/C$ = 100 μs
- Propagation delay
  - Speed of light is $c = 2\times10^8$ m/s in optical fiber
  - Assume D = 1 km (1000 m)
  - Propagation delay $d_{prop} = D/c$ = 5 μs

- Latency is d_{nodal} = 1 + 0 + 100 + 5 = 106 μs
  - Transmission time dominates in this example

Delay Considerations

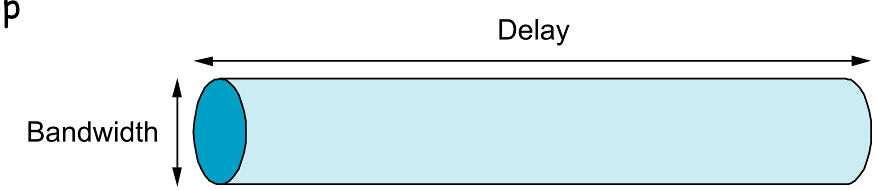
- What happens at high speeds (gigabit speeds)?
  - The tradeoff between bandwidth and latency (delay) changes
    - Latency does not improve at the same rate as bandwidth
    - Speed-of-light limitations
      - Round-trip propagation delay the same for 1 Mbps and 1 Gbps links
  - Bandwidth available on the network starts to rival bandwidth available *inside* the computers that are connected to the network

    PCI express bus – 5 Gbps

    - Potential bottlenecks are now within the host

Bandwidth x Delay Product

- If acks are not required
  - Volume is the number of bits the pipe (link) holds
  - Delay = d_{prop}

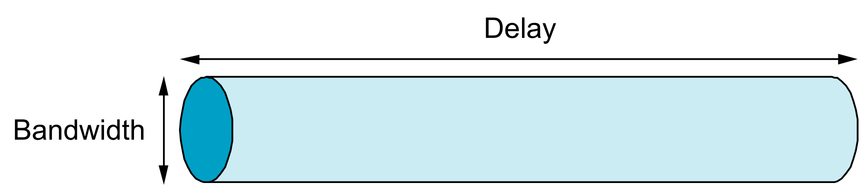


B-D without acks	Bandwidth (bps)	Delay (ms) (made up examples)	b x d in bytes
Gigabit Ethernet	1G	0.150	18,750
100 Mbit Ethernet	100M	0.7	8,750
Dialup Modem+Internet	56K	180	1,260
Cable Modem+Internet	4M	180	67,500

Bandwidth x Delay Product

- If acks are required
  - Volume corresponds to number of bits sender should send before acknowledgement is received by sender
  - Delay = round trip time (RTT) = $2d_{prop}$

- Sender should attempt to send BxD bits to fill the pipe to fully utilize the network



Bandwidth-Delay Product with Acks

- Send a 64 KB file on 1 Gbps link
  64 KB = 64 x 2^{10} =
  65,536 B = 524,288 bits

- Transmit time = 524,288/1x10^9 =
  524.288 μsec

- This protocol requires an acknowledgment for each byte

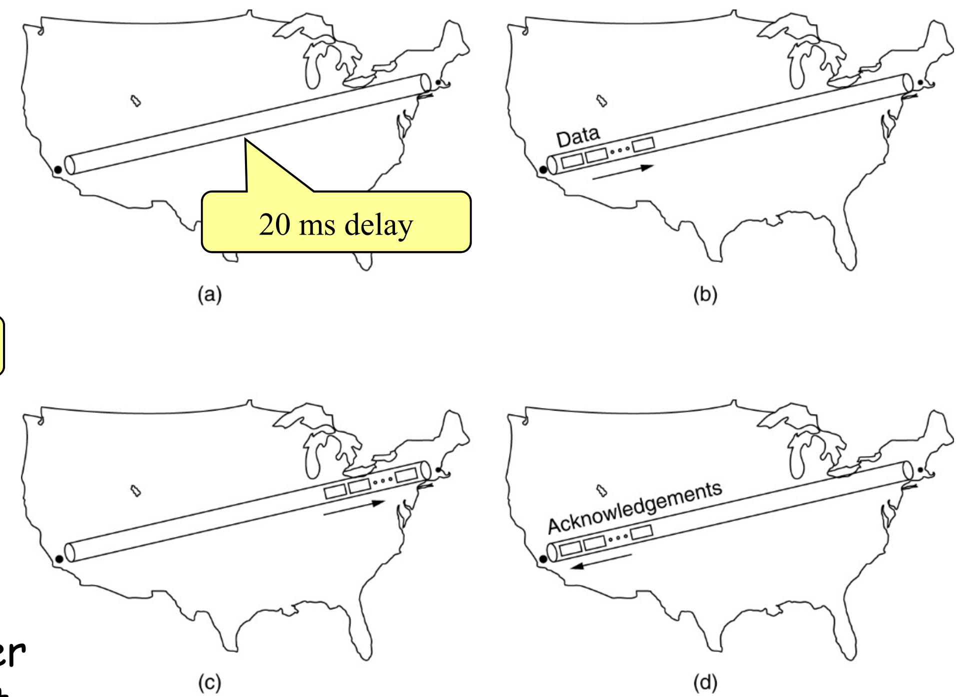
Unrealistic

RTT = 20 ms * 2

- B-D product is
  1x10^9 bps x 40 ms = 40 Mb
  - Corresponds to number of bits sender should send before acknowledgement is received by sender

- We only used 524,288 b = 512 Kb

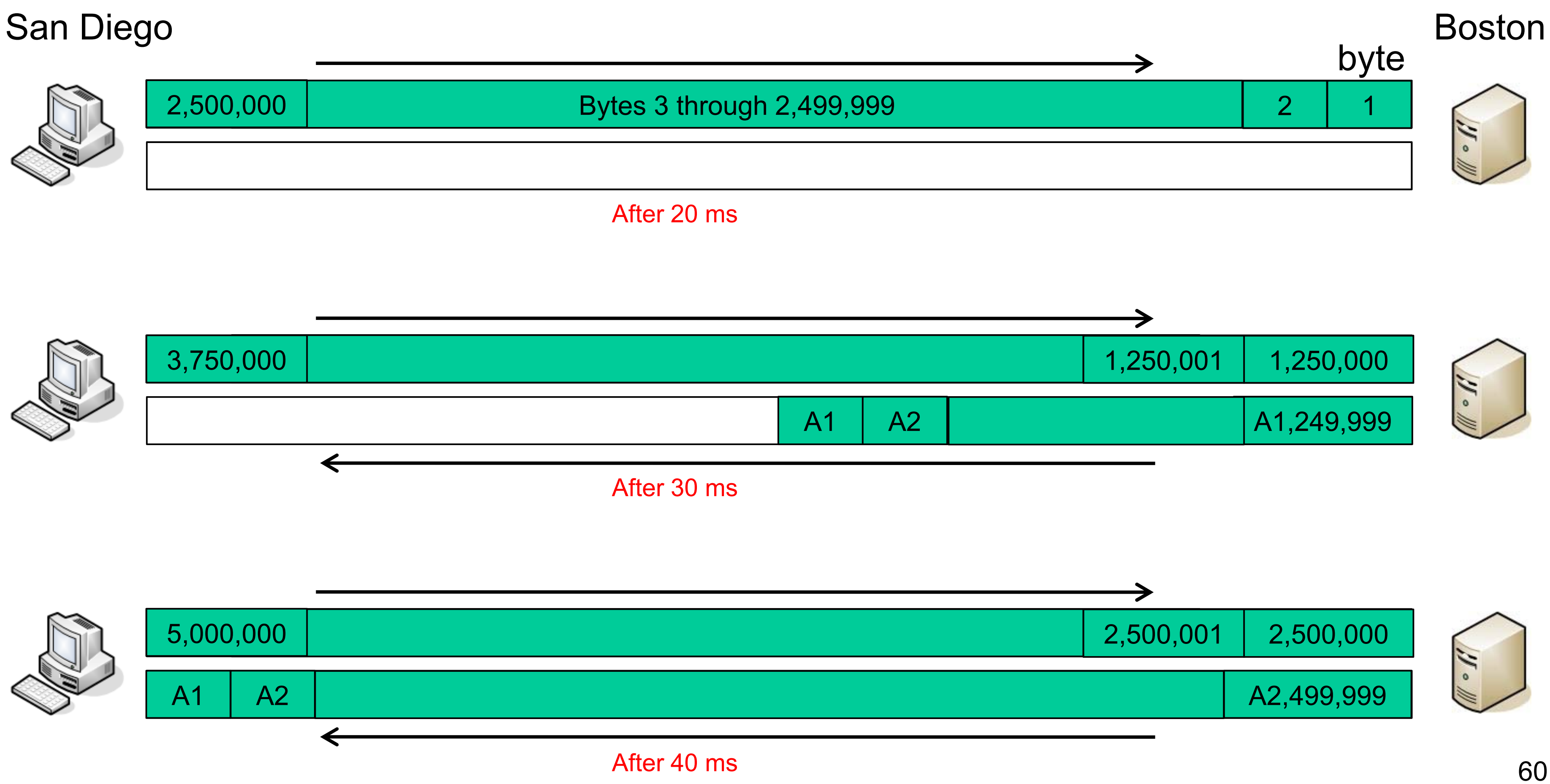
- 1.3% efficient ← 524,288/40 M



The state of transmitting 524,288 bits from San Diego to Boston
(a) At t = 0, (b) After 524 μsec,
(c) After 20 msec, (d) after 40 msec.

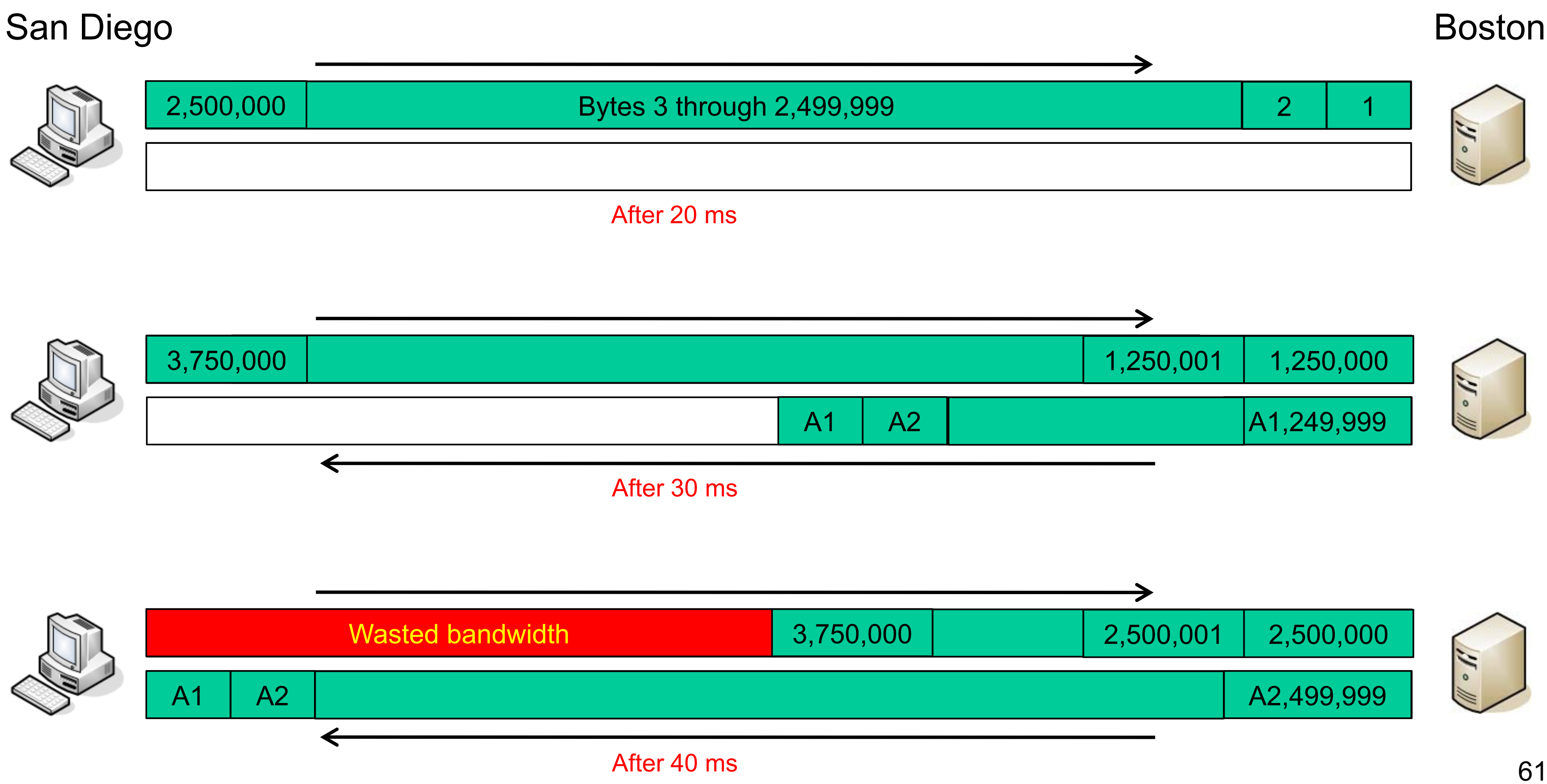
Bandwidth-Delay Product with Acks

- Best performance → make sender's window as large as B-D product
  - Sender has permission to send 40 Mb (5 MB) before receiving the ACK for the first byte



Bandwidth-Delay Product with Acks

- What happens if the sender's window is smaller than B-D product?
  - Let window = 30 Mb (3.75 MB)



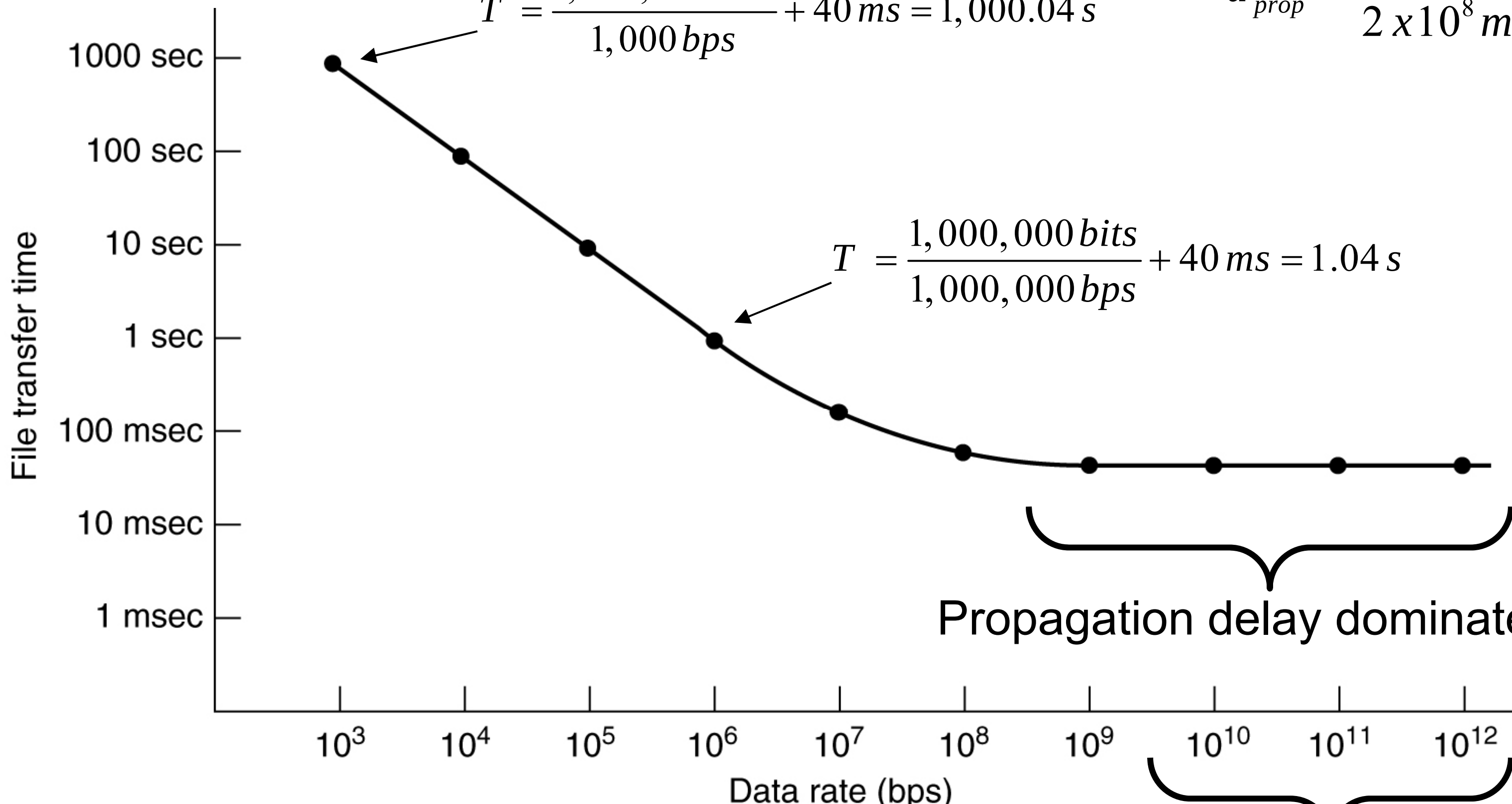
Protocols for Gigabit Networks: B-D in Action

Time to transfer & acknowledge a 1,000,000 bit file over a 4000-km line

$$d_{prop} = \frac{2\,x\,4000km}{2\,x\,10^8\,m/s} = 40ms$$

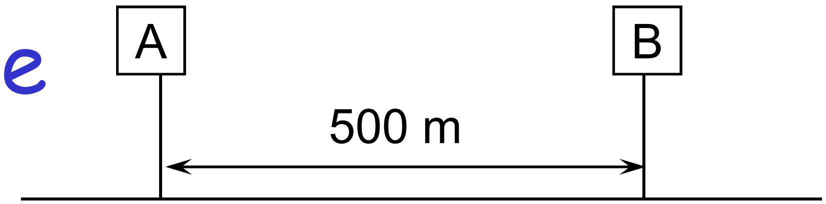
$$T = \frac{1,000,000\,bits}{1,000\,bps} + 40\,ms = 1,000.04\,s$$

$$T = \frac{1,000,000\,bits}{1,000,000\,bps} + 40\,ms = 1.04\,s$$



No need to spend more money for a faster connection

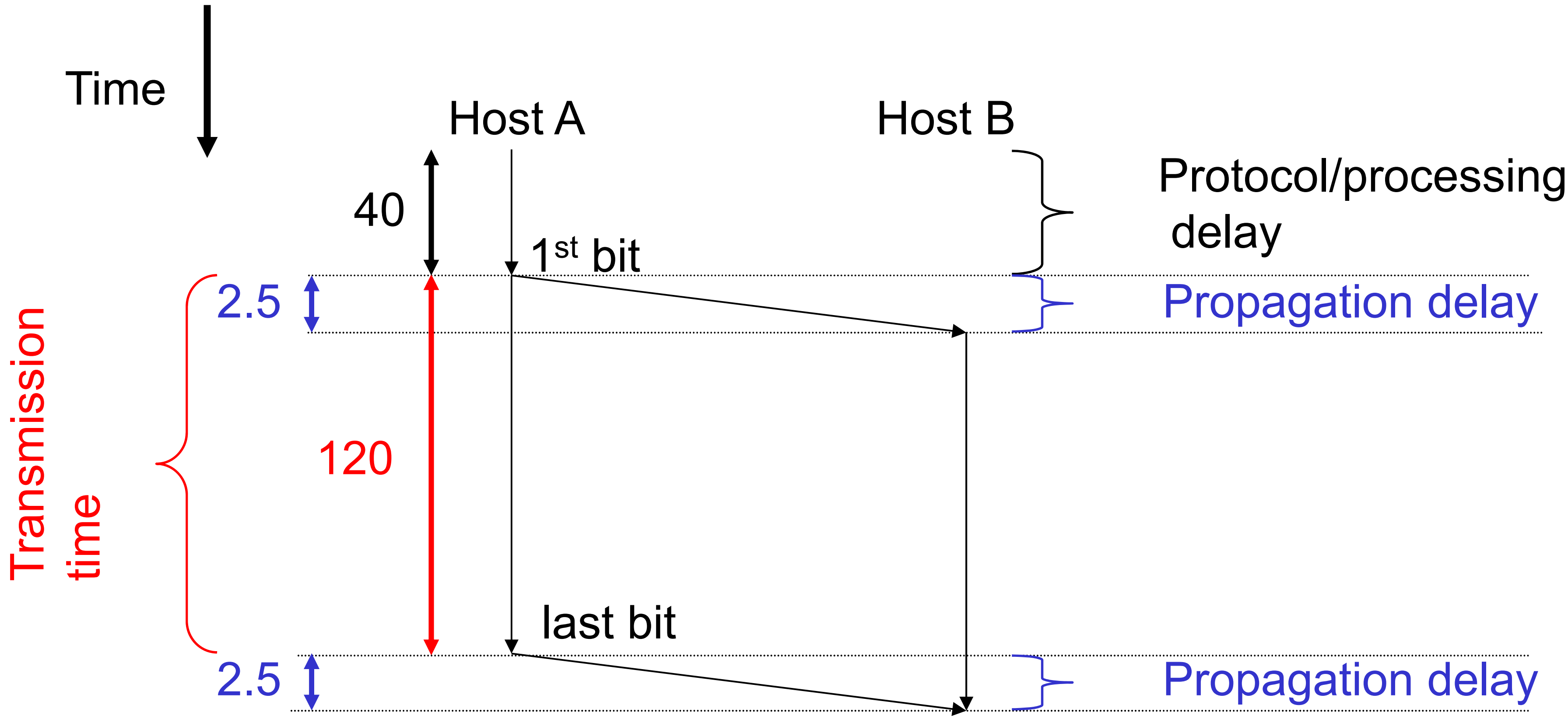
Processing Delay Example



- Given
  - Protocol processing time = 40×10^{-6} s
  - Packet length = 1500 bytes
  - Channel capacity = 100 Mbps
  - Propagation delay factor = 5×10^{-6} s/km (aka 2×10^{8} m/s)

- How long to format the data, add header, and calculate CRC?
  - Given in the problem definition 40×10^{-6} s
- How long does it take a single bit to travel on the link from A to B?
  - Propagation delay = 500 m / 2×10^{8} m/s = 2.5×10^{-6} s
- How long does it take A to transmit an entire packet onto the link?
  - (1500 bytes * 8 bits/byte) / 100×10^{6} bps = 120×10^{-6} s

Processing Delay Example (2)

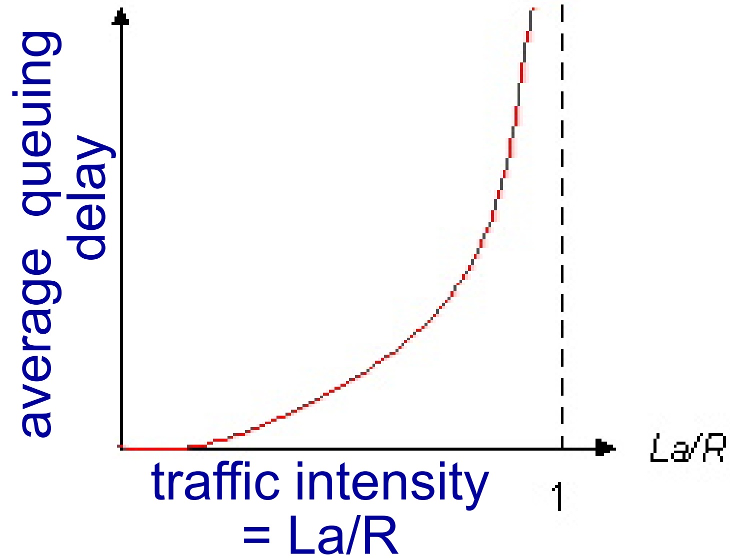


Total time: 40 + 120 + 2.5 = 162.5 x 10^{-6} sec

Queuing Delay

- R = link bandwidth (bps)
- L = packet length (bits)
- a = average packet arrival rate
- I = La/R = traffic intensity

- I ~ 0: average queuing delay small
- I -> 1: delays become large
- I > 1: more "work" arriving than can be serviced, average delay infinite!

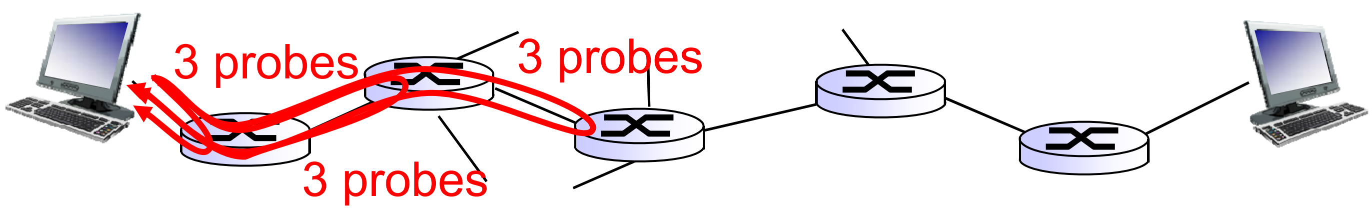


La/R ~ 0

La/R -> 1

"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 drop the packet and return a special ICMP packet to sender
  - Sender times interval between transmission and ICMP reply



"Real" Internet Delays and Routes

tracert - Windows   traceroute - Linux

On gaia.cs.umass.edu computer, author opened command shell

 # traceroute 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
```

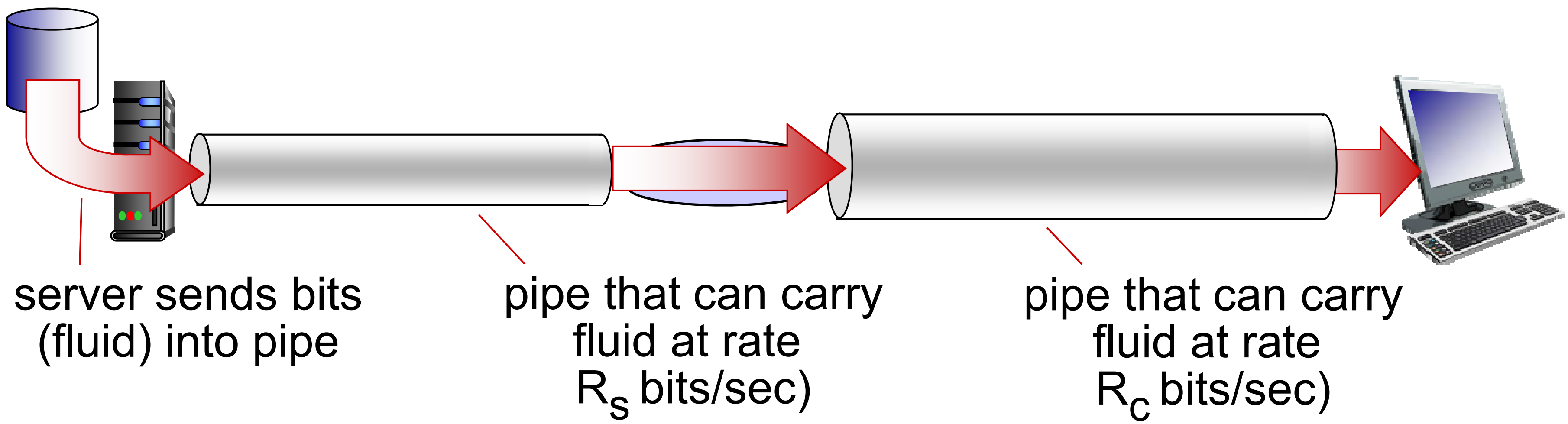
trans-oceanic link

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

Throughput

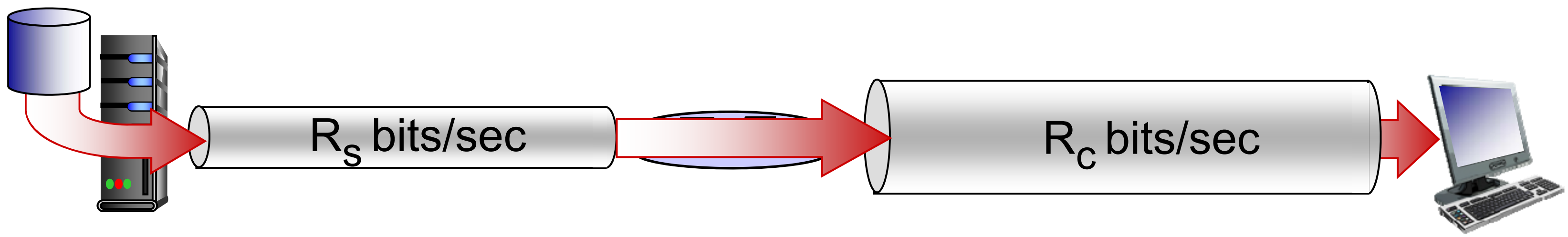
Throughput: rate (bits/time unit) at which bits transferred between sender/receiver

- *Instantaneous:* rate at given point in time
- *Average:* rate over long(er) period of time

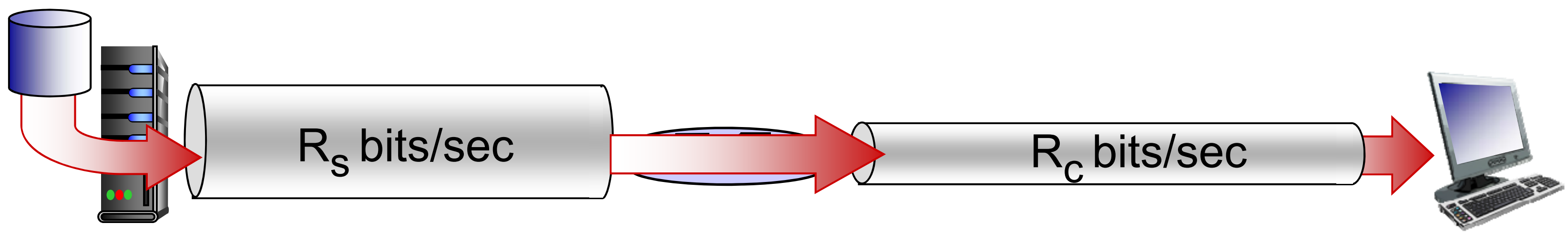


Throughput (more)

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



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

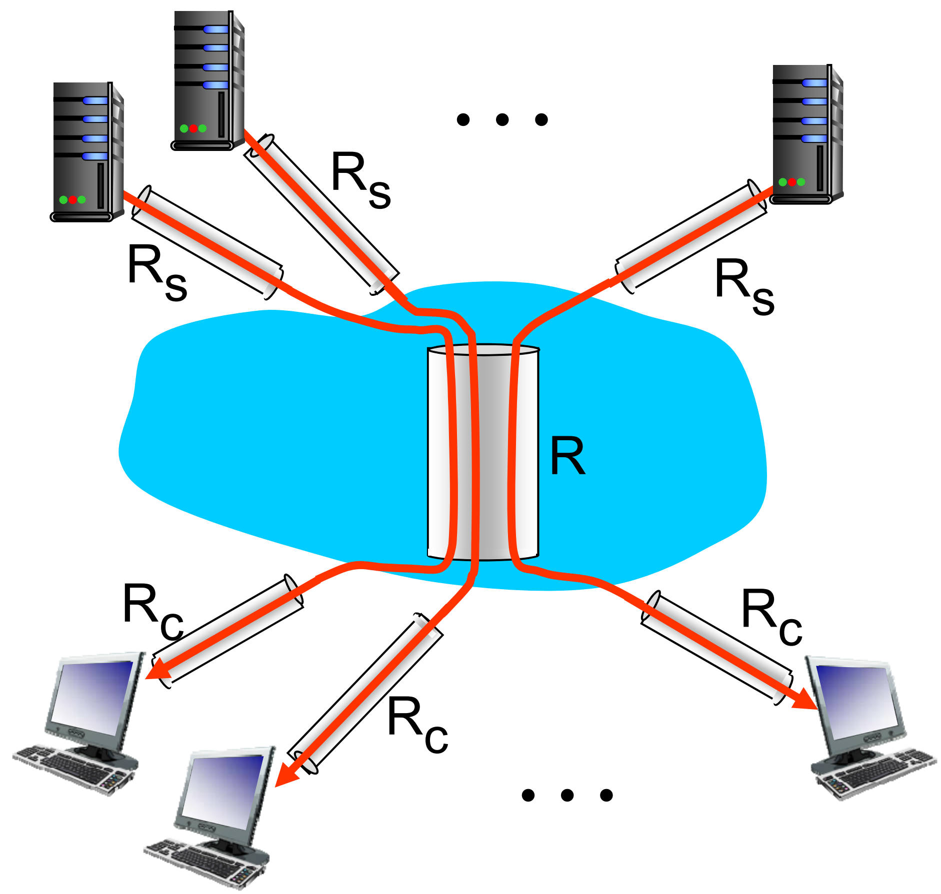


bottleneck link

Link on end-end path that constrains end-end throughput

Throughput: Internet Scenario

- Per-connection end-end throughput is $\min(R_c, R_s, R/10)$
- In practice: R_c or R_s is often bottleneck



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

Chapter 1: Roadmap

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?

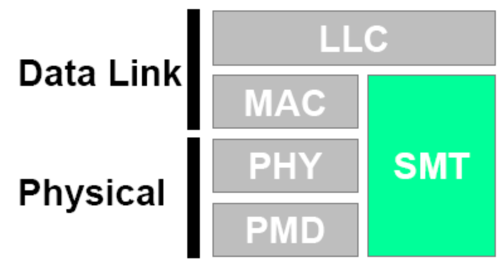
Why Layering?

Dealing with complex systems:

- Explicit structure allows identification, relationship of complex system's pieces
  - Provides a layered reference model for discussion
- Modularization eases maintenance, updating of system
  - Change of implementation of a layer's service transparent to rest of system
  - System can evolve since layers can be changed (as long as service and interface do not change)

Arguments Against Layering

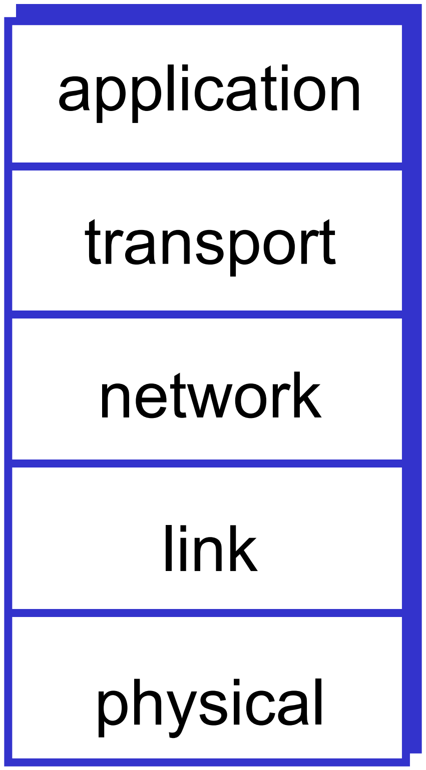
- Design
  - Some functions don't fit in one layer
    - Fiber Distributed Data Interface (FDDI) station management--needs to access and operate at multiple layers
    - Generally: network management
- Performance
  - Possible performance penalties from crossing layers:
    - memory-to-memory copies



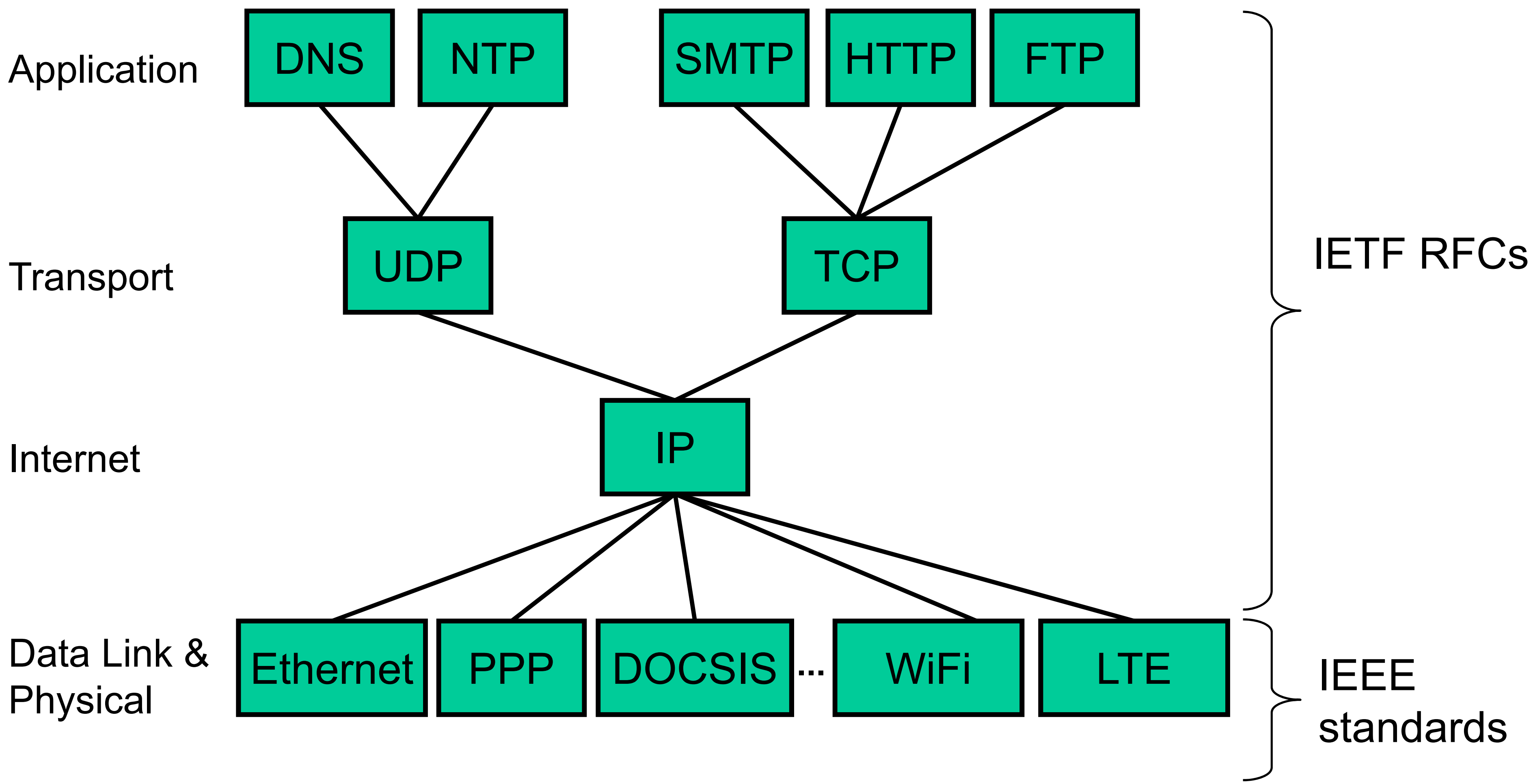
LLC	Logical Link Control
MAC	Media Access Control
PHY	Physical
PMD	Physical Media Dependent
SMT	Station Management

Internet Protocol Stack

- Application: supporting network applications
  - FTP, SMTP, HTTP, DNS
- Transport: process - process data transfer
  - TCP, UDP
- Network: routing of datagrams from source host to destination host
  - IP, routing protocols
- Link: data transfer between neighboring network elements
  - Ethernet, IEEE 802.11 (WiFi), PPP
- Physical: bits "on the wire"



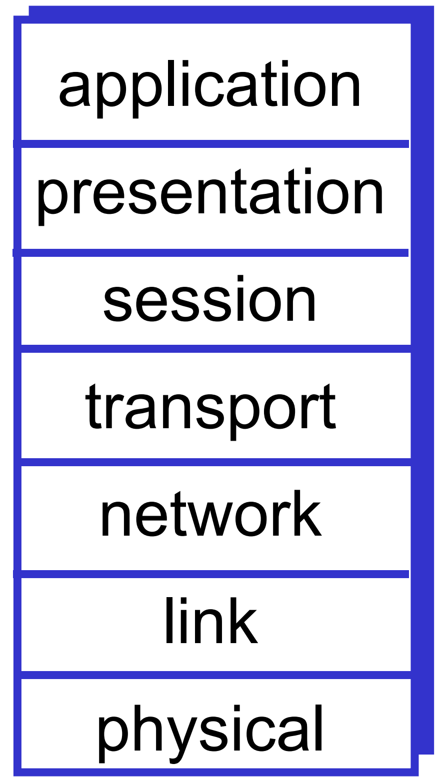
TCP/IP Hourglass View



DOCSIS - Data Over Cable Service Interface Specification
IETF - Internet Engineering Task Force
IEEE – Institute of Electrical and Electronics Engineers

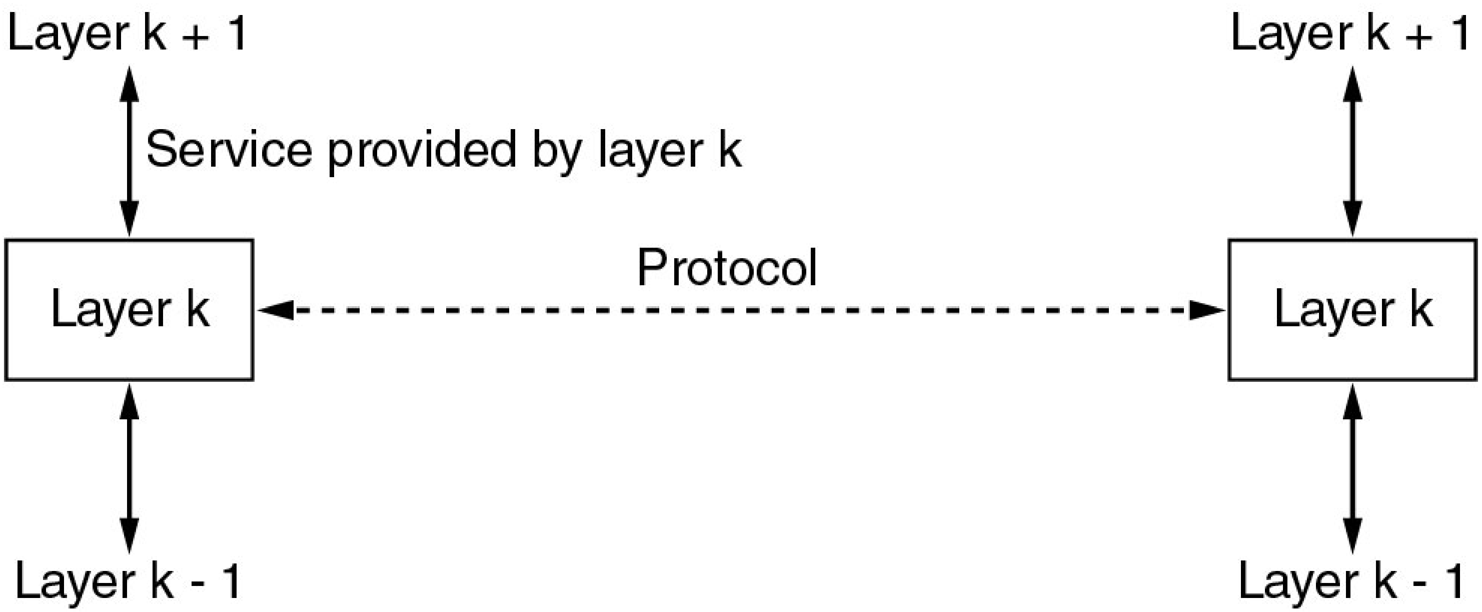
ISO/OSI Reference Model

- Presentation: allow applications to interpret meaning of data,
  - 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



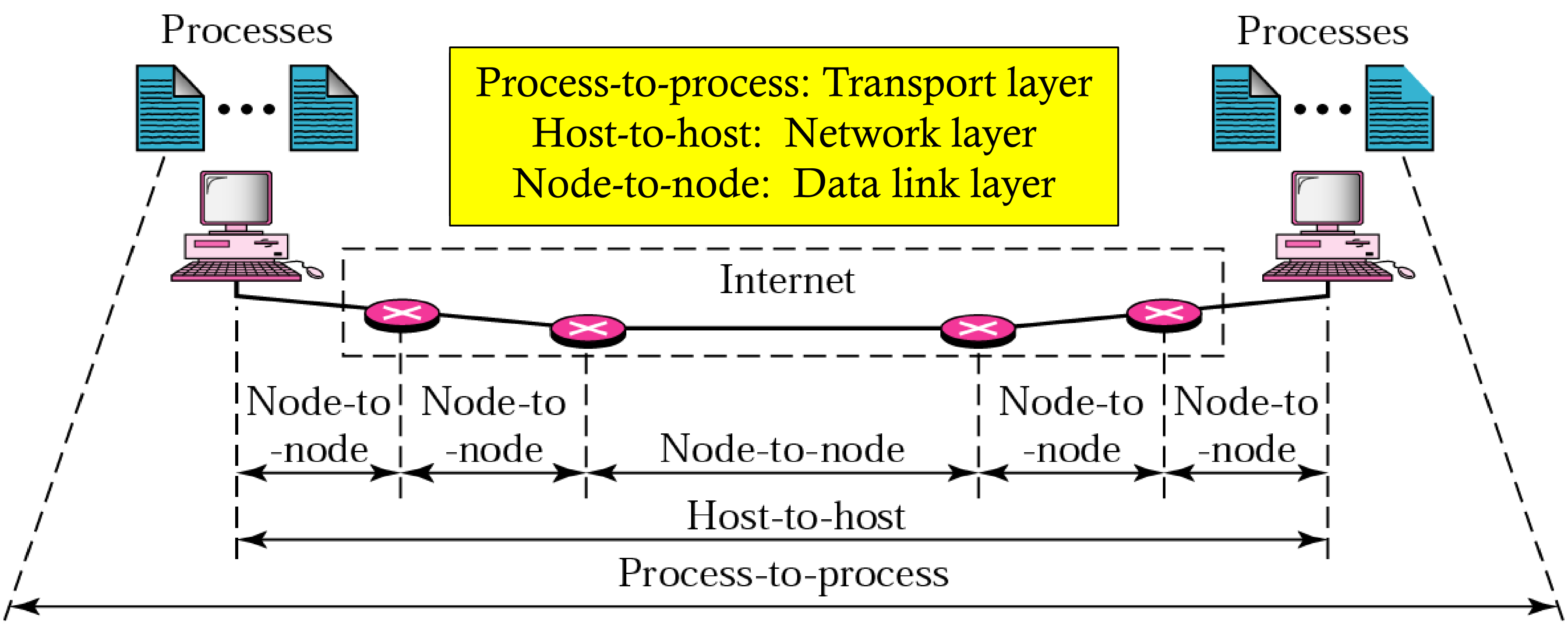
Checkpointing - technique to add fault tolerance

Services vs. Protocols

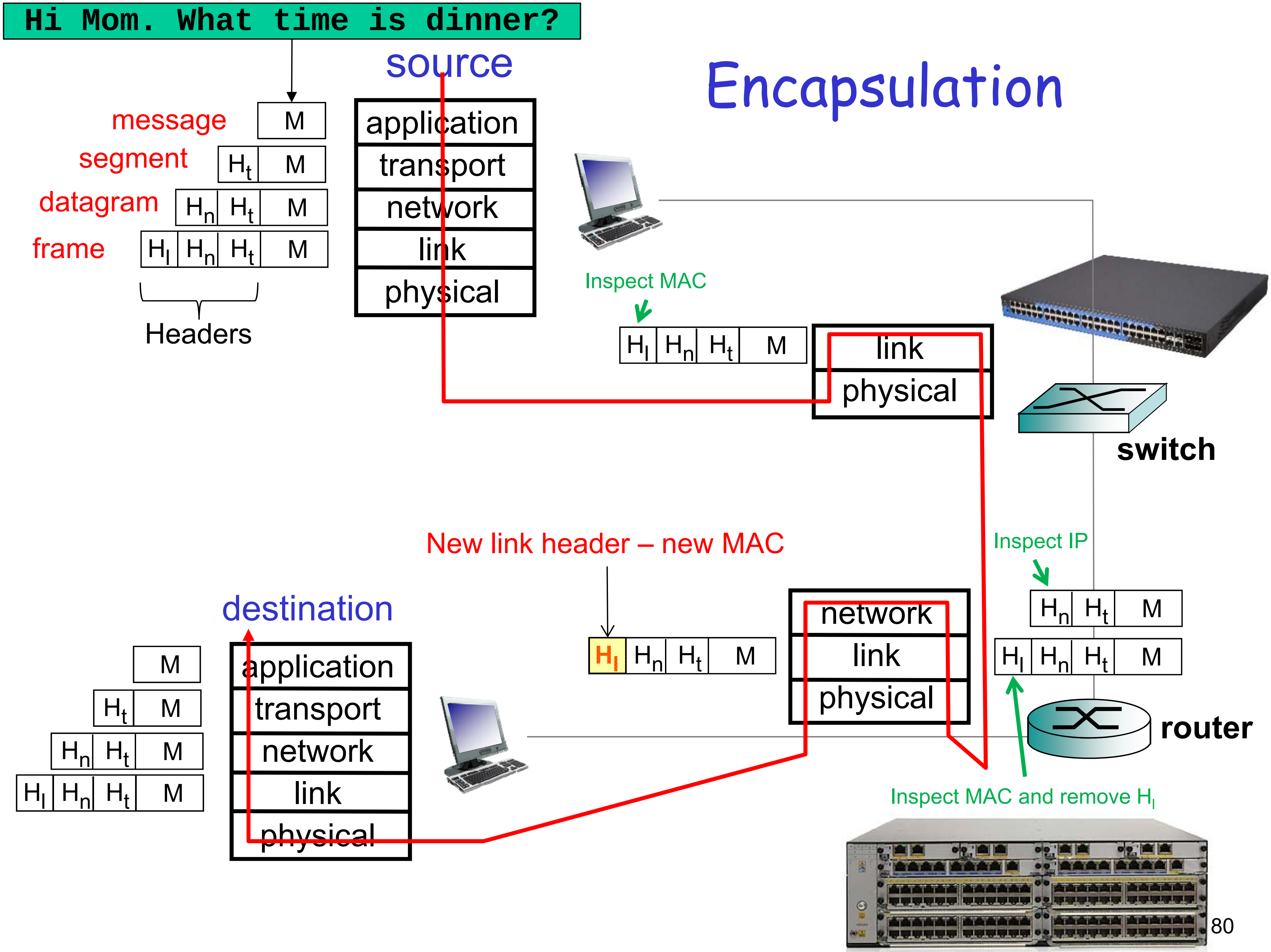


- Vertical component (Interface/Service between layers)
  - Layer k provides services to layer k+1 and uses services provided by k-1
- Horizontal component (Protocol between peers)
  - Layer k may interact with peer layer k only via protocols

Internet Protocol Relationships



Encapsulation



Encapsulation