CSCI 450
Data Communication
& Network Programming

Computer Networks and the Internet

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(Adapted from "Computer Networking: A Top Down Approach Featuring the Internet", 6th edition. Copyrighted by Jim Kurose, Keith Ross)

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: hosts, access net, physical media
- Network core: packet/circuit switching, Internet structure
- Performance: loss, delay, throughput
- Security
- Protocol layers, service models
- History

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

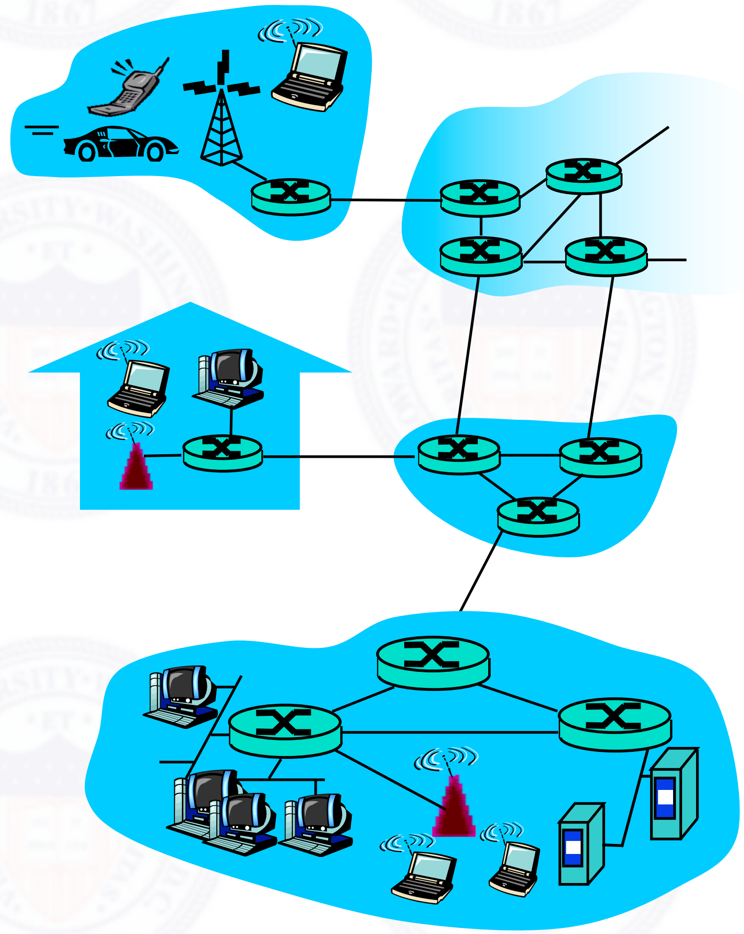
1.5 Protocol layers, service models

1.6 Networks under attack: security

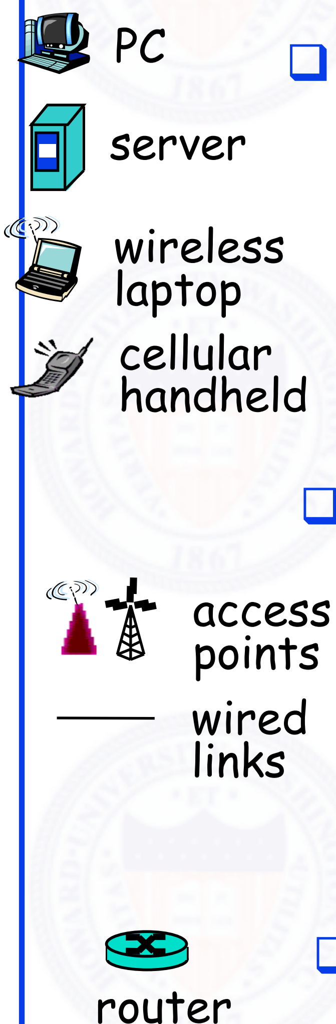
1.7 History

What's the Internet: A Service View

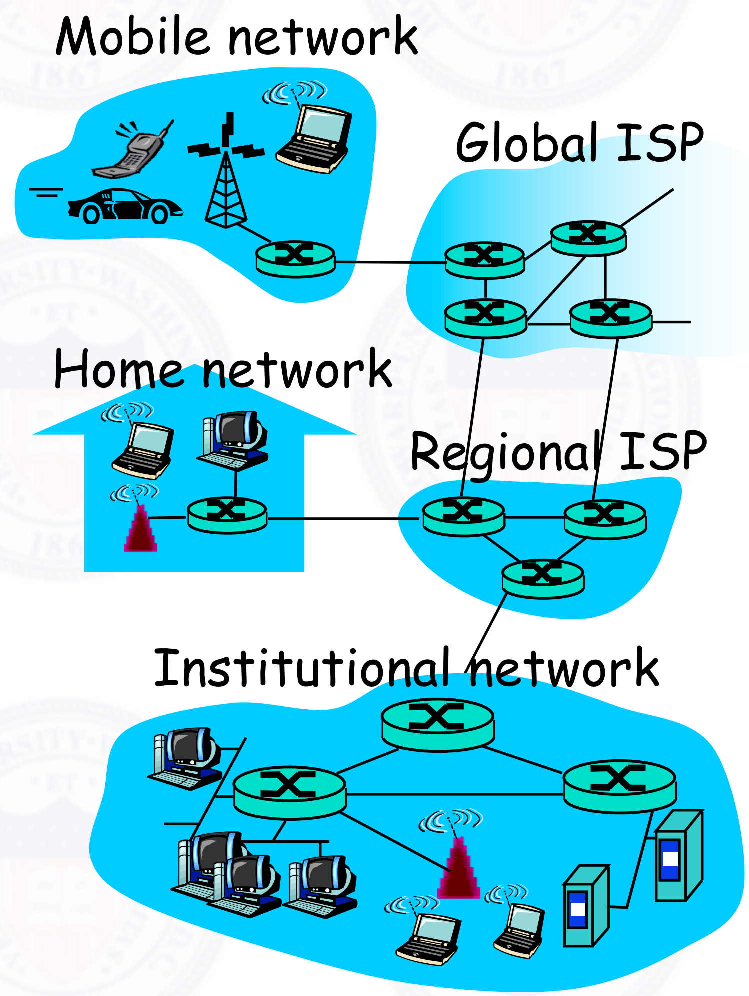
- Communication *infrastructure* enables distributed applications:
  - Web, VoIP, email, games, e-commerce, file sharing
- Communication *services* provided to apps:
  - Reliable data delivery from source to destination
  - "Best effort" (unreliable) data delivery
- Applications access the service on hosts via API



What's the Internet: "nuts and bolts" view (1)



- Millions of connected computing devices: *hosts = end systems*
  - Running *network apps*
- *Communication links*
  - Fiber, copper, radio, satellite
  - Transmission rate = *bandwidth*
- *Switches and routers:* forward packets (chunks of data)



“Fun” Internet Appliances

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

Web-enabled toaster +
weather forecaster

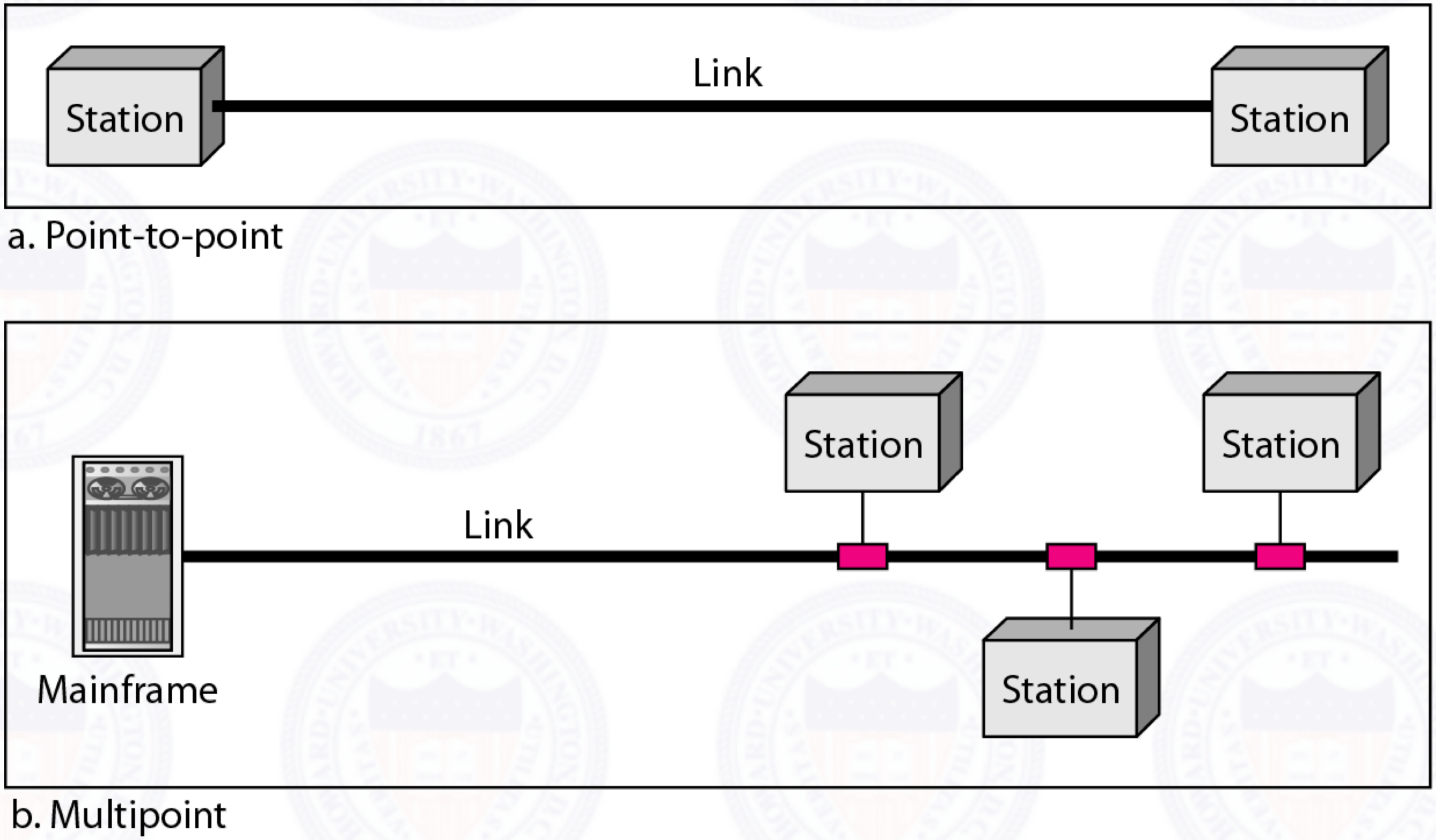
Tweet-a-watt:
monitor energy use

Internet
refrigerator

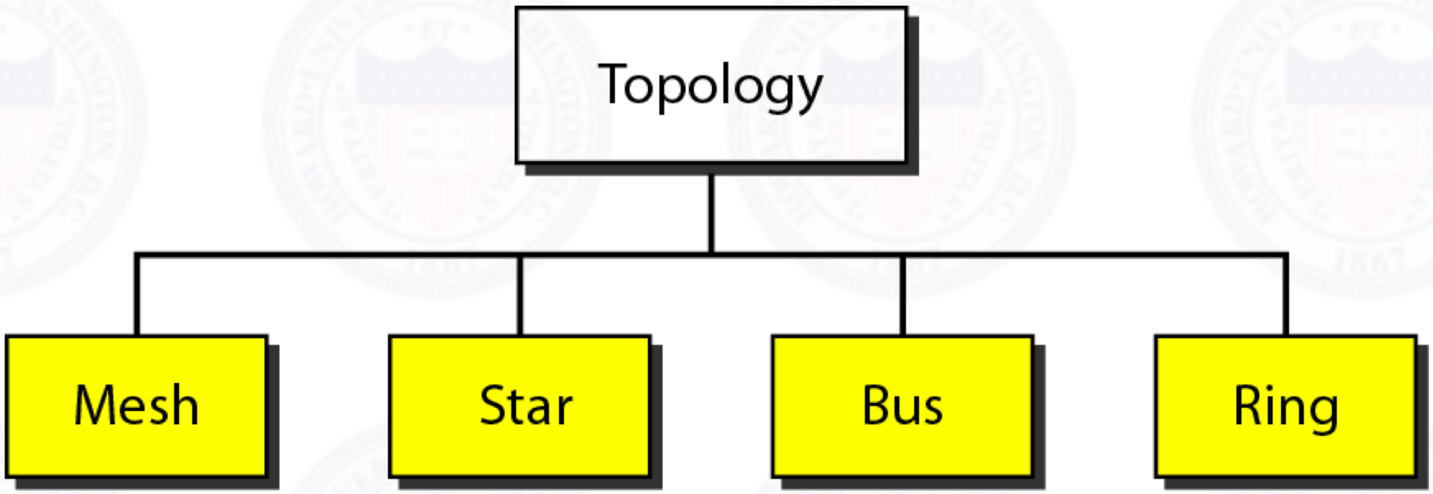
Slingbox: watch,
control cable TV remotely

Internet phones

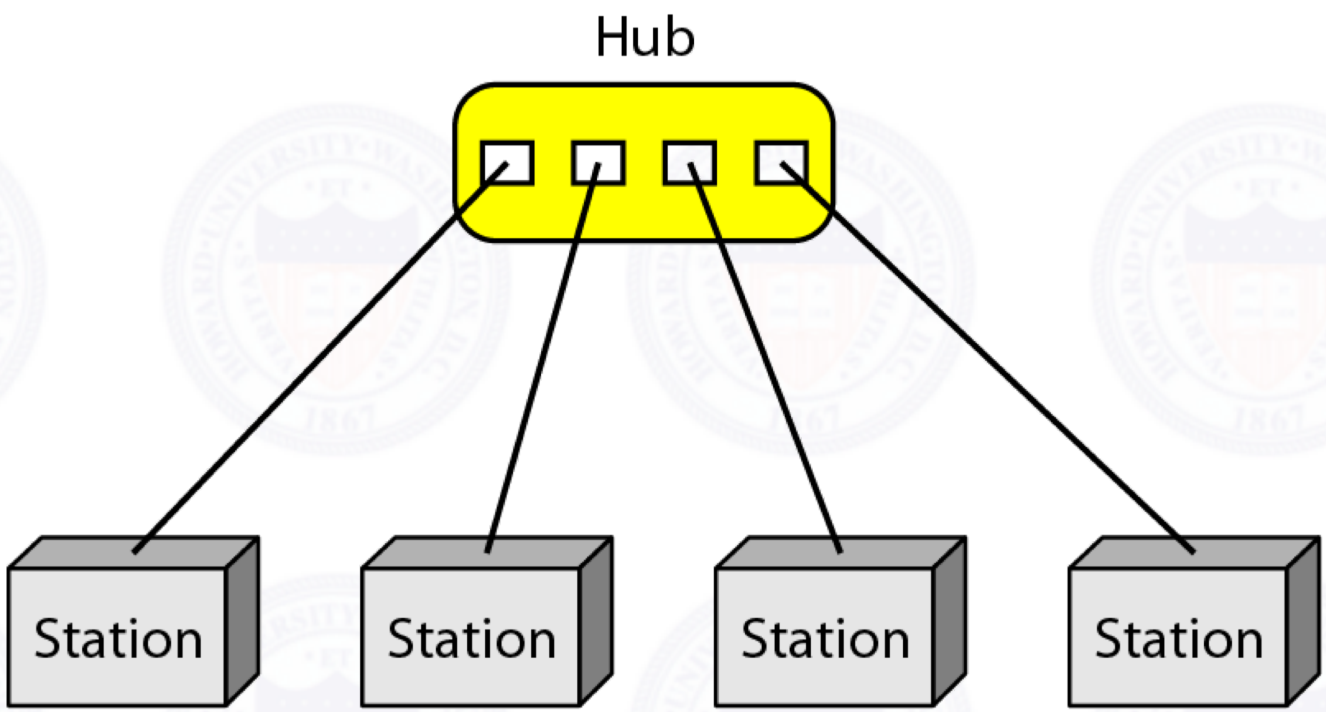
Types of Connections



Categories of Topology

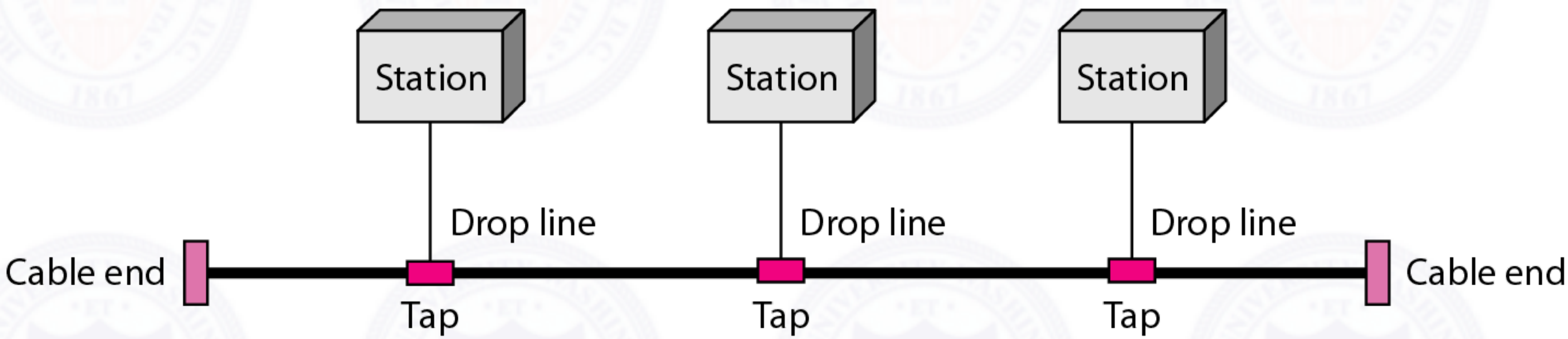


A Star Topology Connecting Four Stations

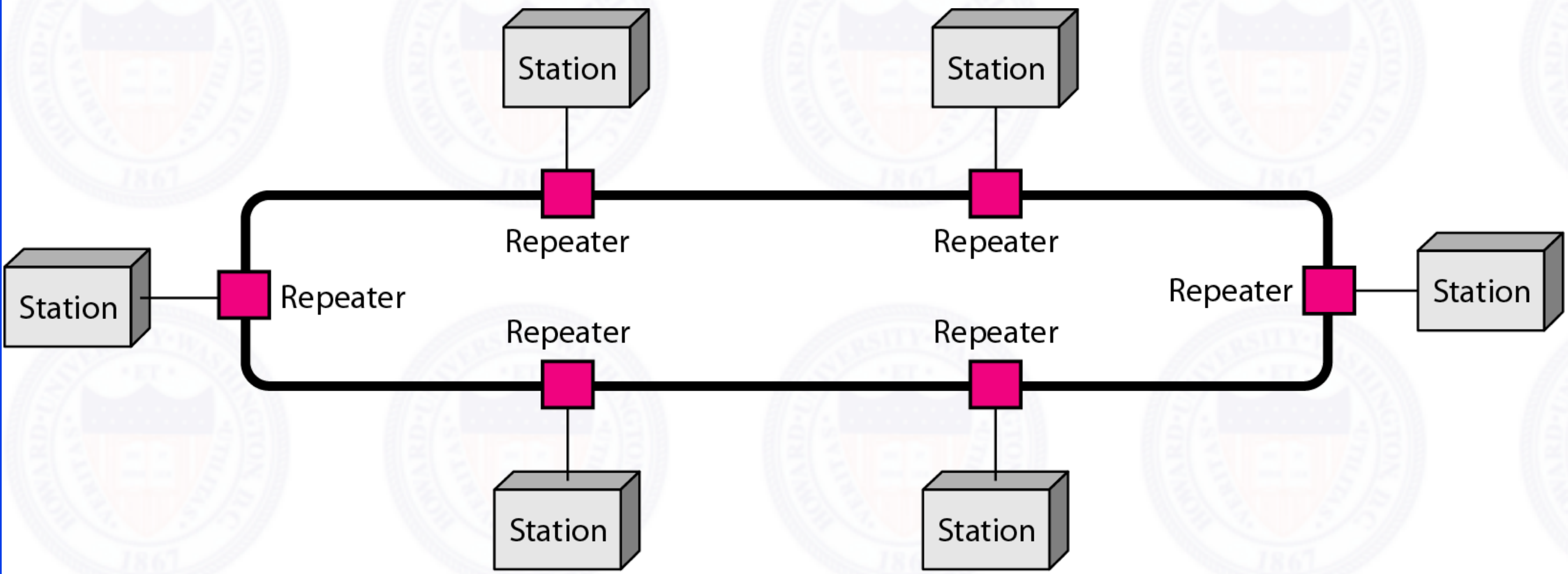


A set of point-to-point connections

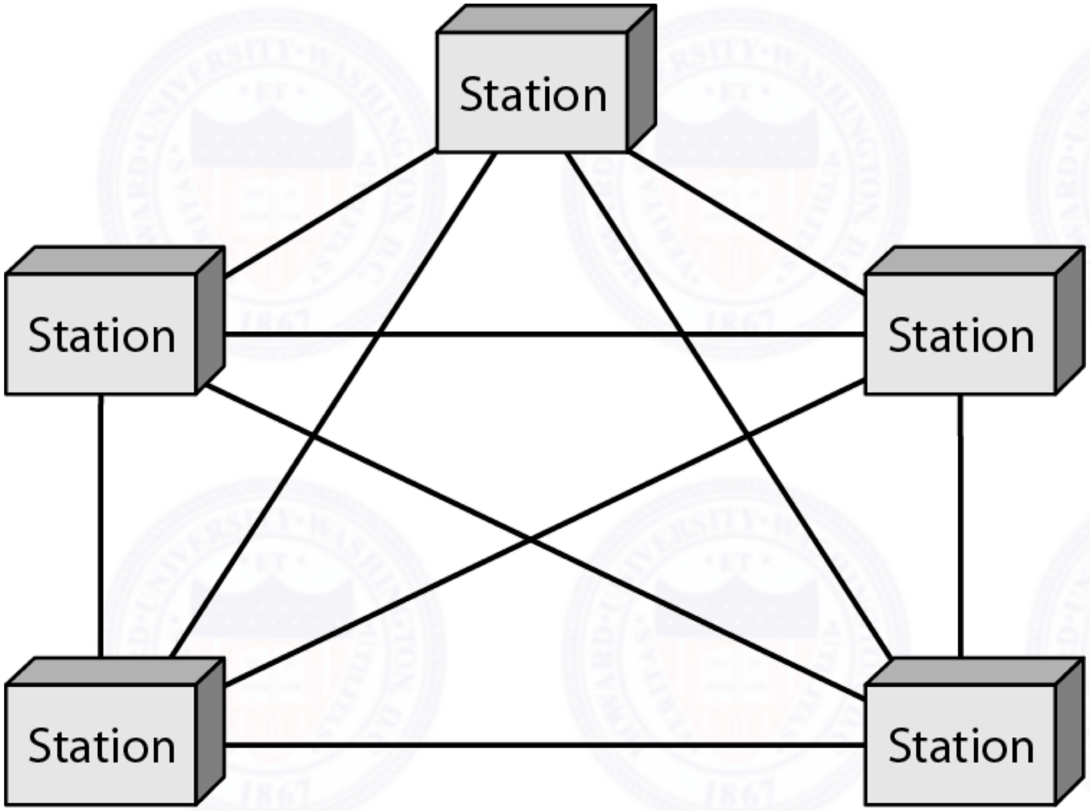
A Bus Topology Connecting Three Stations



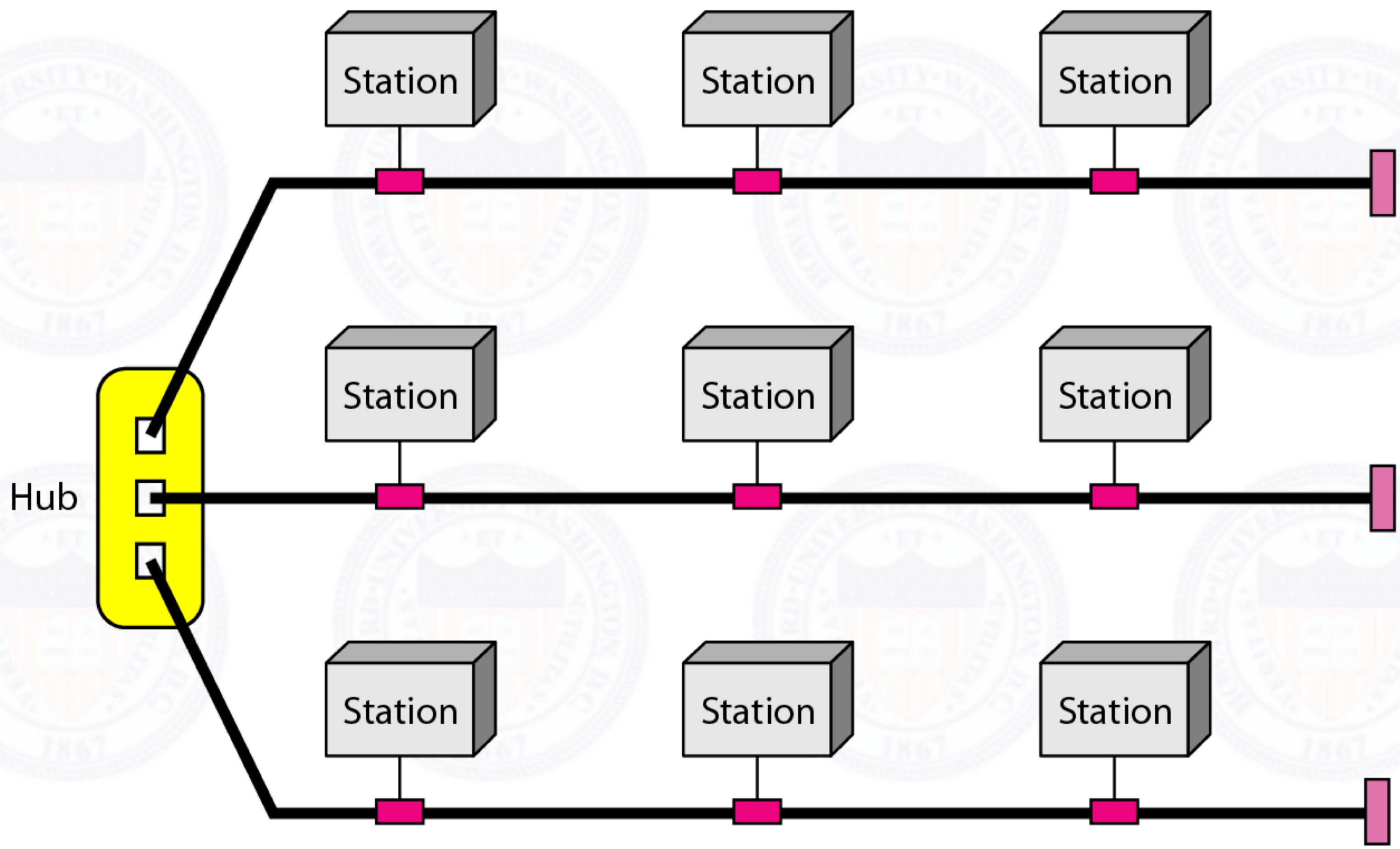
A Ring Topology Connecting Six Stations



A Fully Connected Mesh Topology



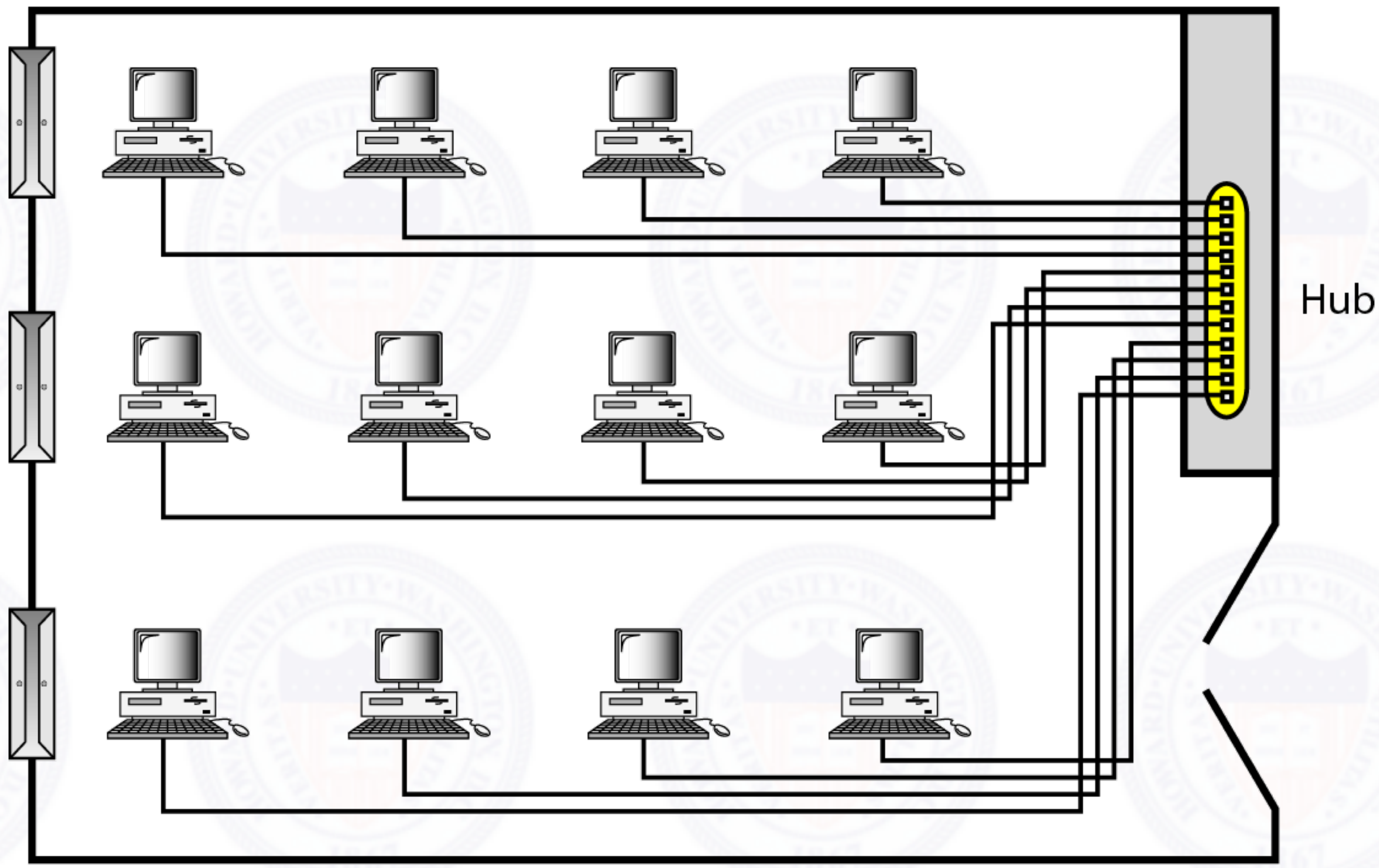
A Hybrid Topology: A Star Backbone with Three Bus Networks



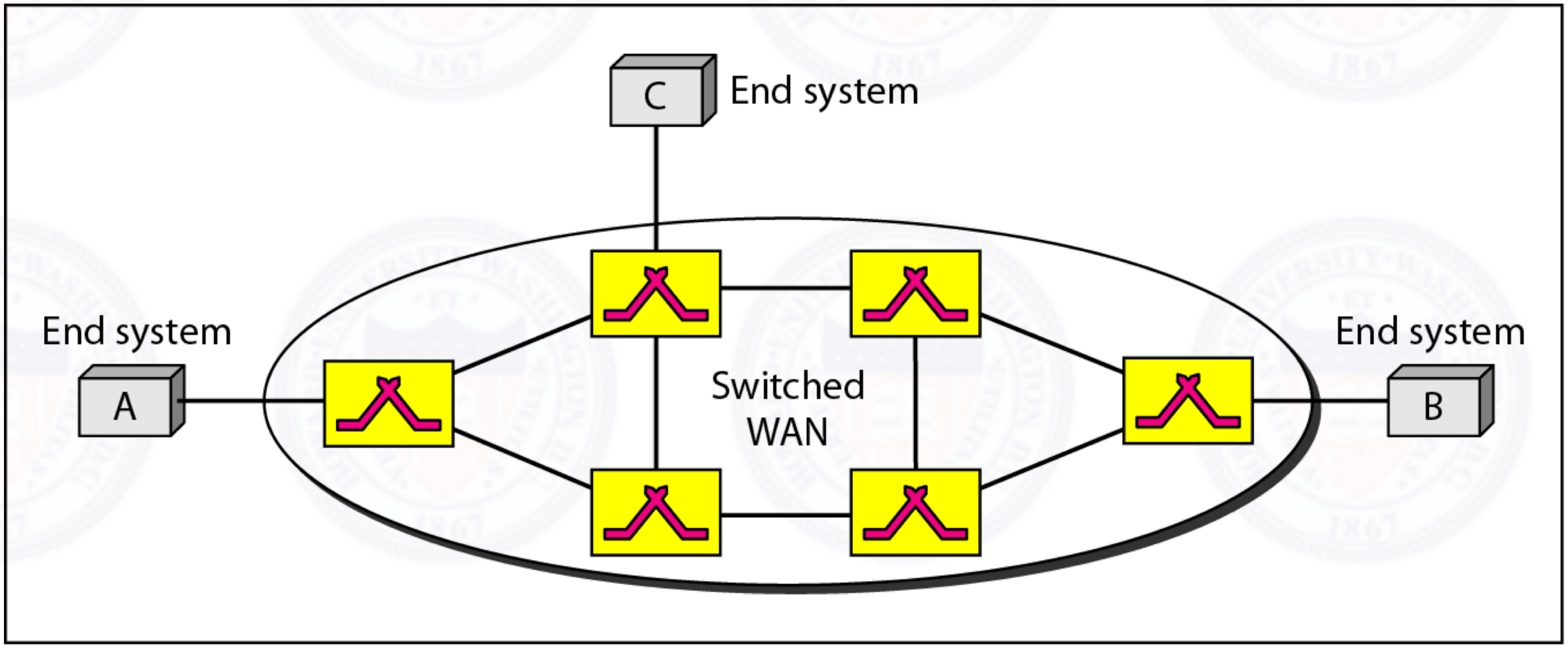
LANs and WANs

- LAN
  - Local Area Network
  - Network in a building or of an institution
- WAN
  - Wide Area Network
  - Network over a large area (e.g. across multiple cities)

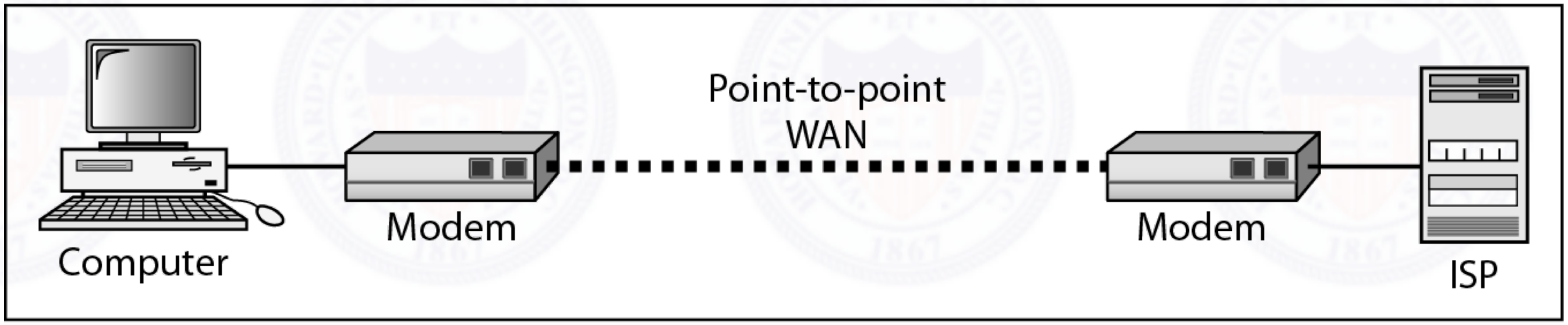
An Isolated LAN Connecting 12 Computers to A Hub in A Closet



WANs: A Switched WAN and A Point-to-Point WAN

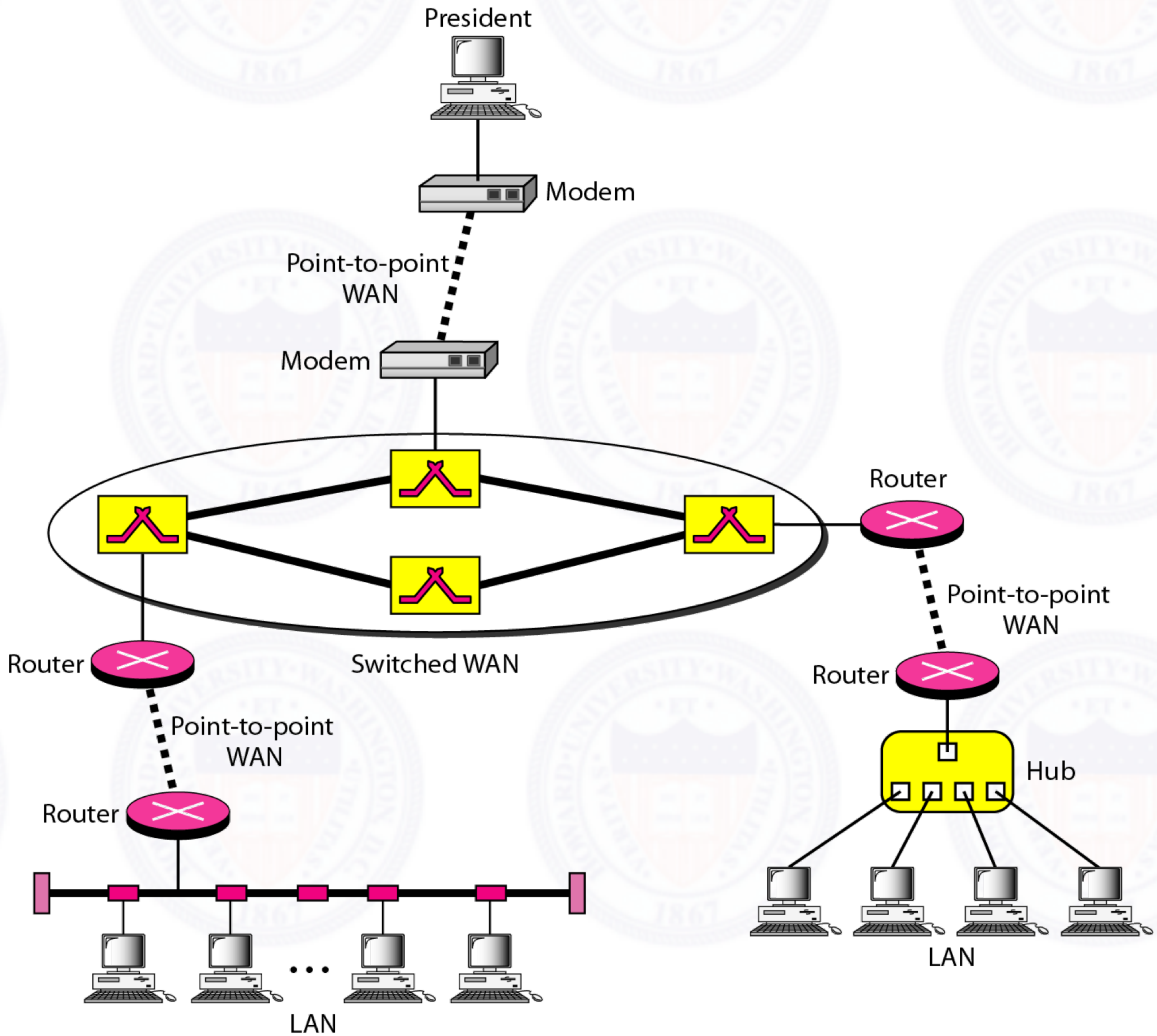


a. Switched WAN



b. Point-to-point WAN

A Heterogeneous Network Made of 4 WANs and 2 LANs



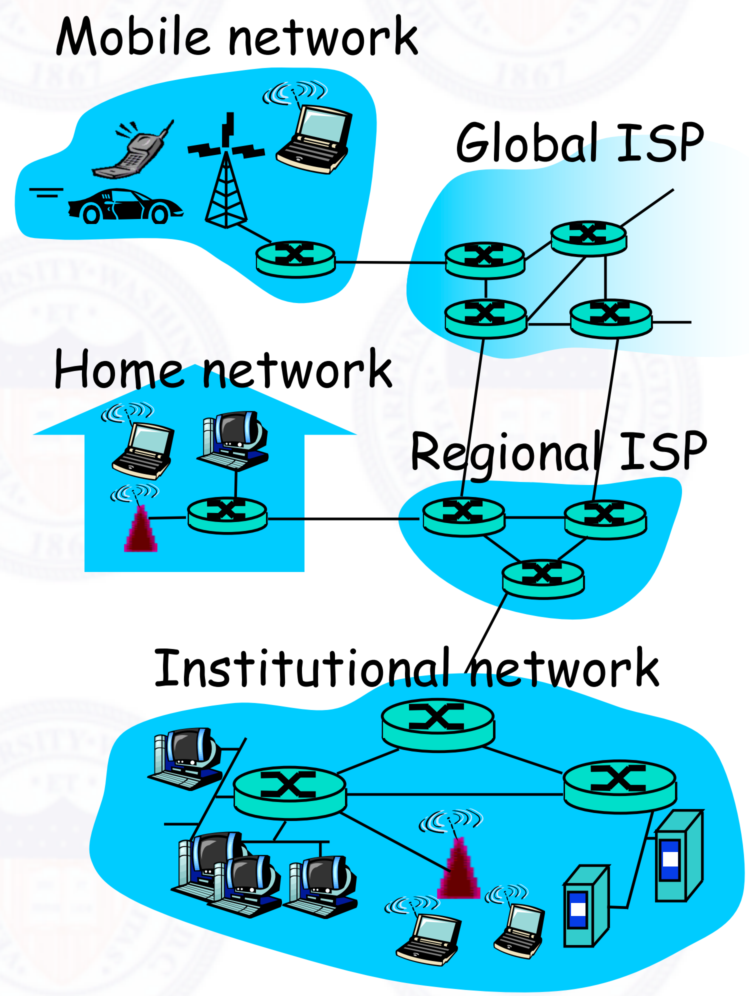
Internet: "network of networks"

- Loosely hierarchical
- Public Internet versus private intranet

What's the Internet: "nuts and bolts" view (2)

- *Protocols* control sending, receiving of msgs
  - e.g., TCP, IP, HTTP, Skype, 802.11
- Internet standards
  - RFC: Request for comments
  - IETF: Internet Engineering Task Force

Much of this course is about protocols



What's a protocol?

<u>Human protocols:</u>

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

… specific msgs sent

… specific actions taken when msgs received, or other events

Protocol:
A set of rules

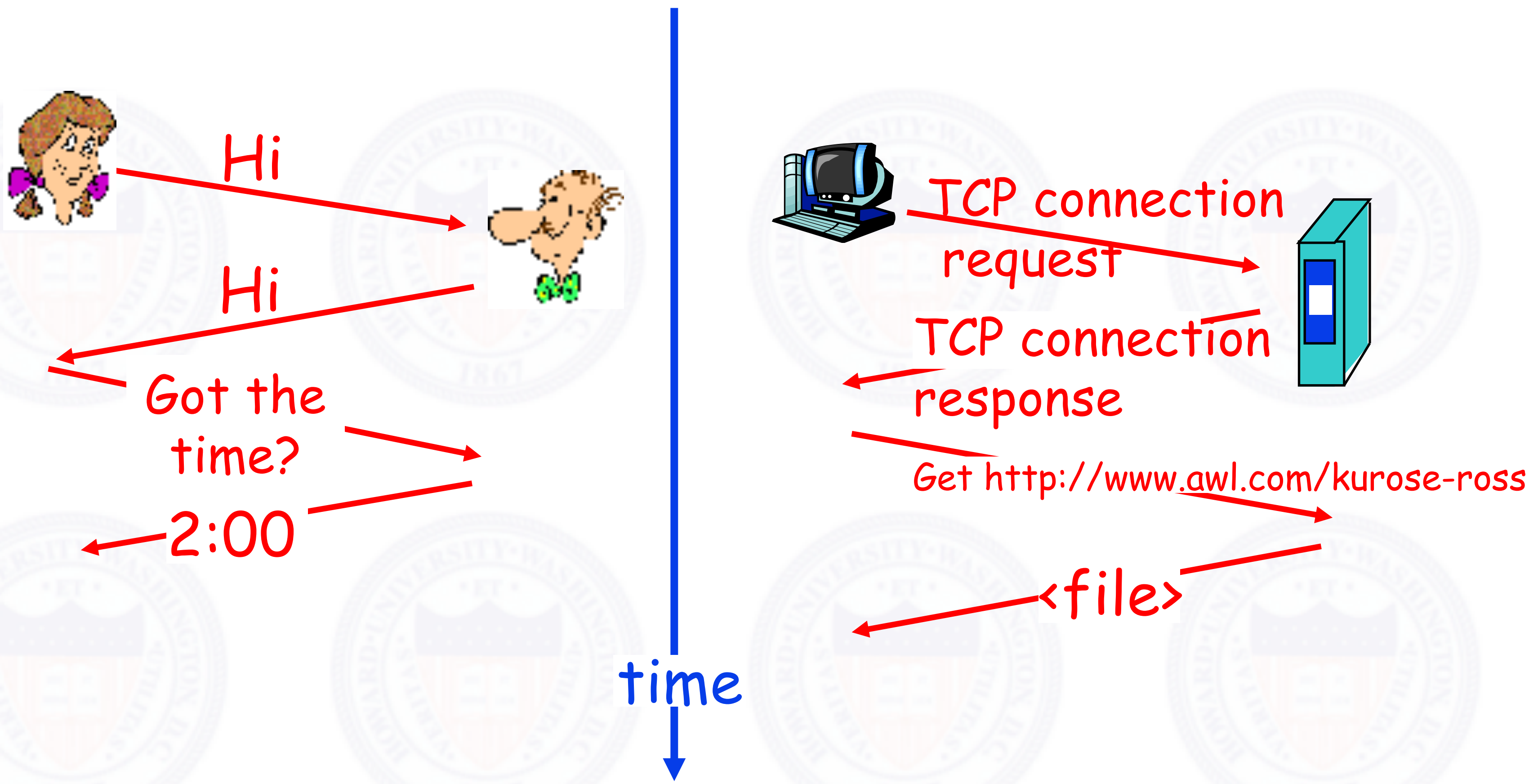
<u>Network protocols:</u>

- 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

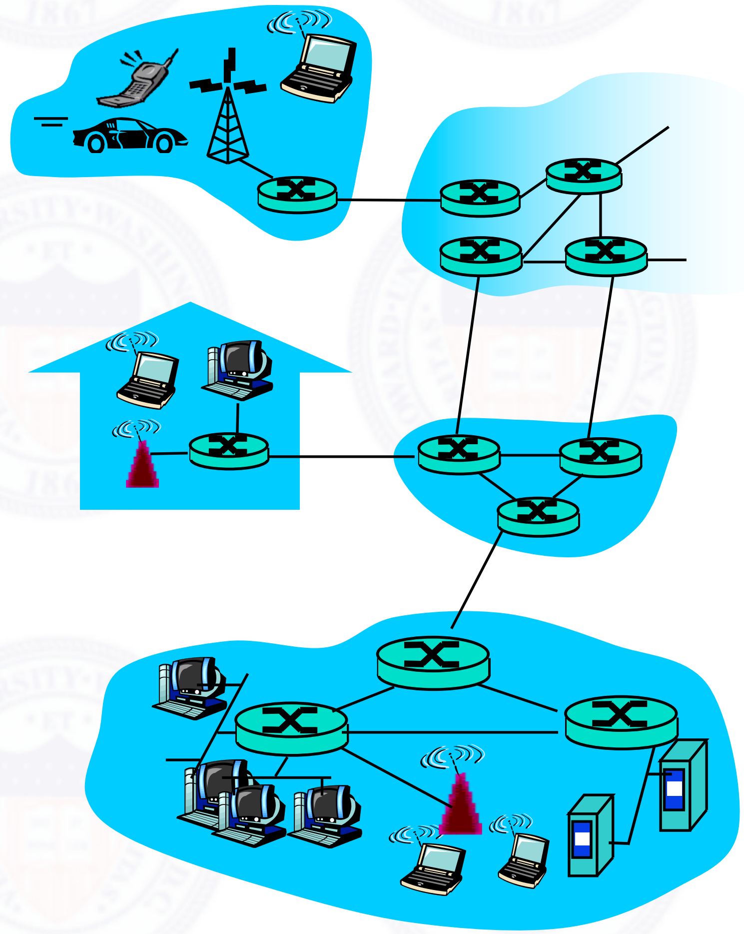
1.5 Protocol layers, service models

1.6 Networks under attack: security

1.7 History

A Closer Look at Network Structure

- Network edge:
  - hosts: clients and servers
  - servers often in data centers
- Access networks, physical media wired, wireless communication links
- Network core:
  - Interconnected routers
  - Network of networks



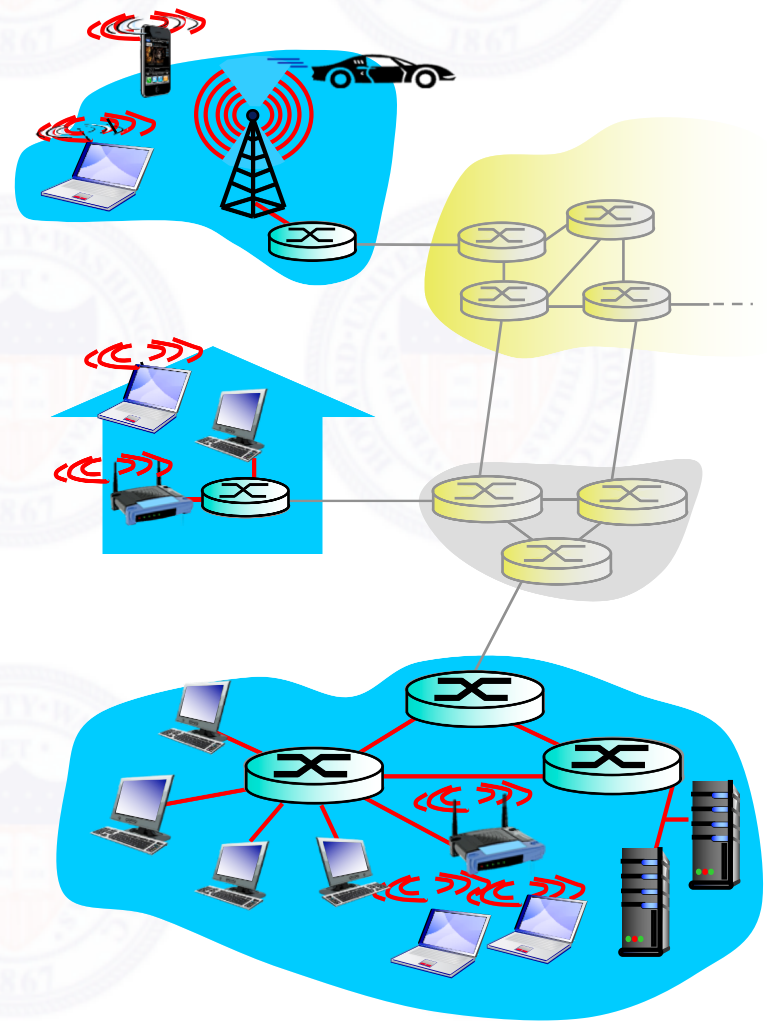
Access networks and physical media

Q: How to connect end systems to edge router?

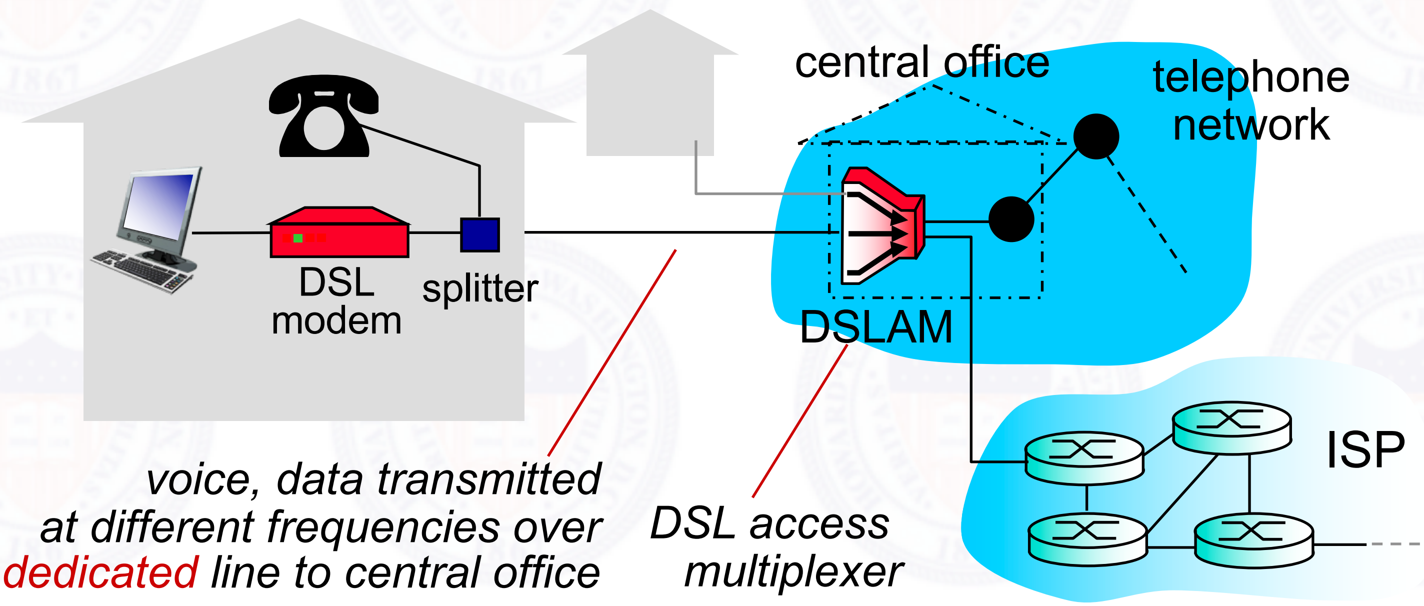
- Residential access nets
- Institutional access networks (school, company)
- Mobile access networks

Keep in mind:

- Bandwidth (bits per second) of access network? (possibly asymmetric: U/L ≠ D/L)
- Shared or dedicated?

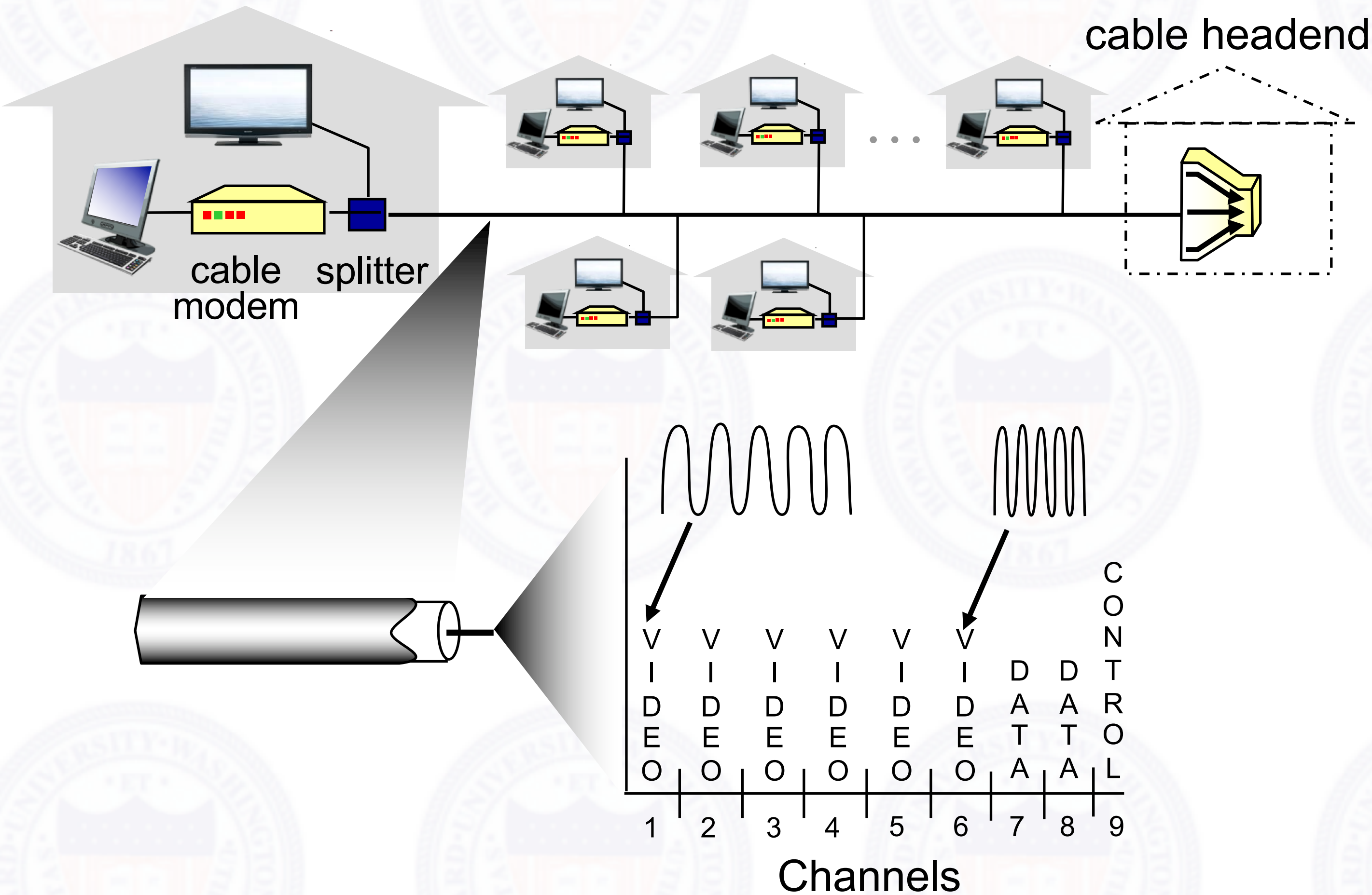


Access net: digital subscriber line (DSL)



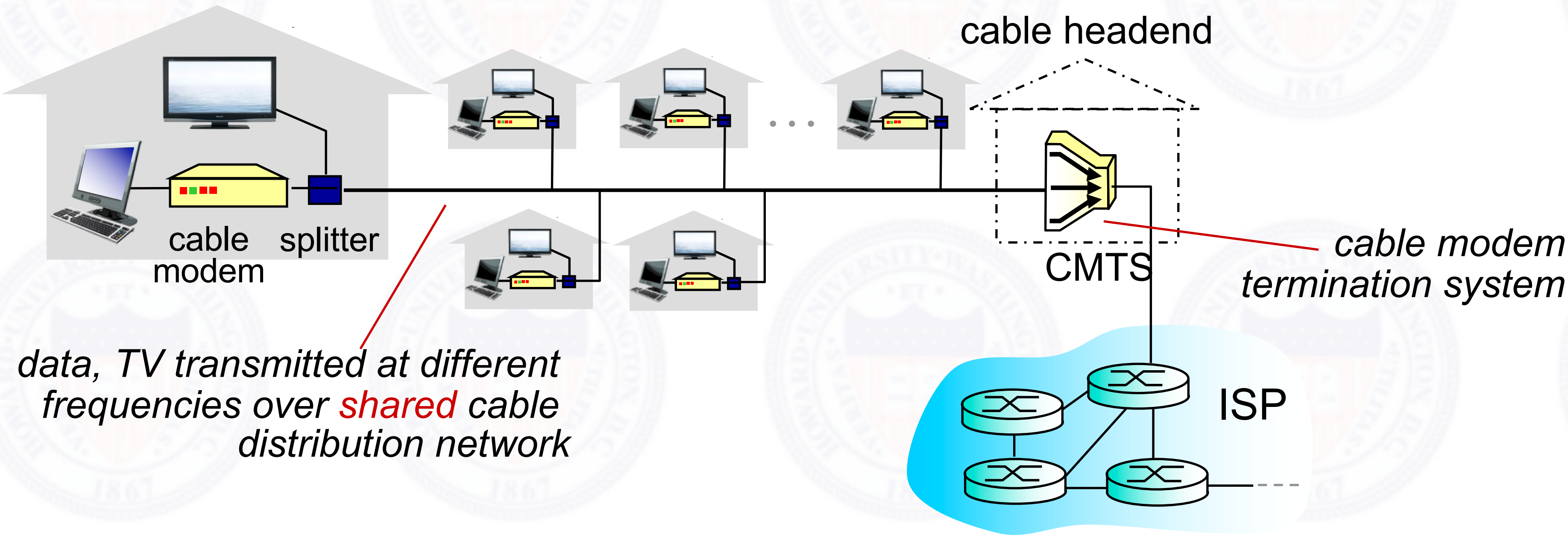
- Use existing telephone line to central office DSLAM
  - Data over DSL phone line goes to Internet
  - Voice over DSL phone line goes to telephone net
- < 2.5 Mbps upstream transmission rate (typically < 1 Mbps)
- < 24 Mbps downstream transmission rate (typically < 10 Mbps)

Access Net: Cable Network



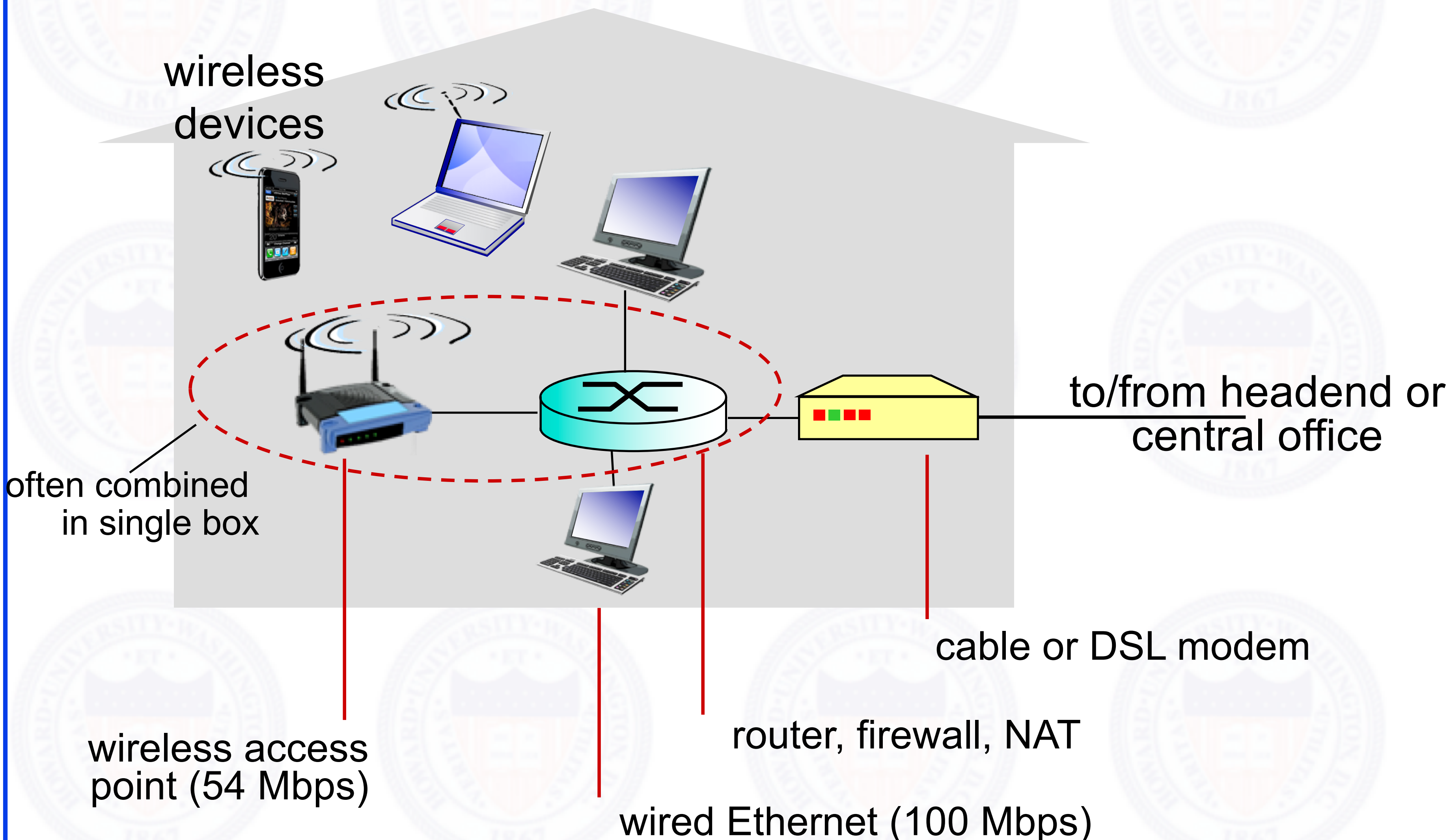
frequency division multiplexing: different channels transmitted in different frequency bands

Access Net: Cable Network

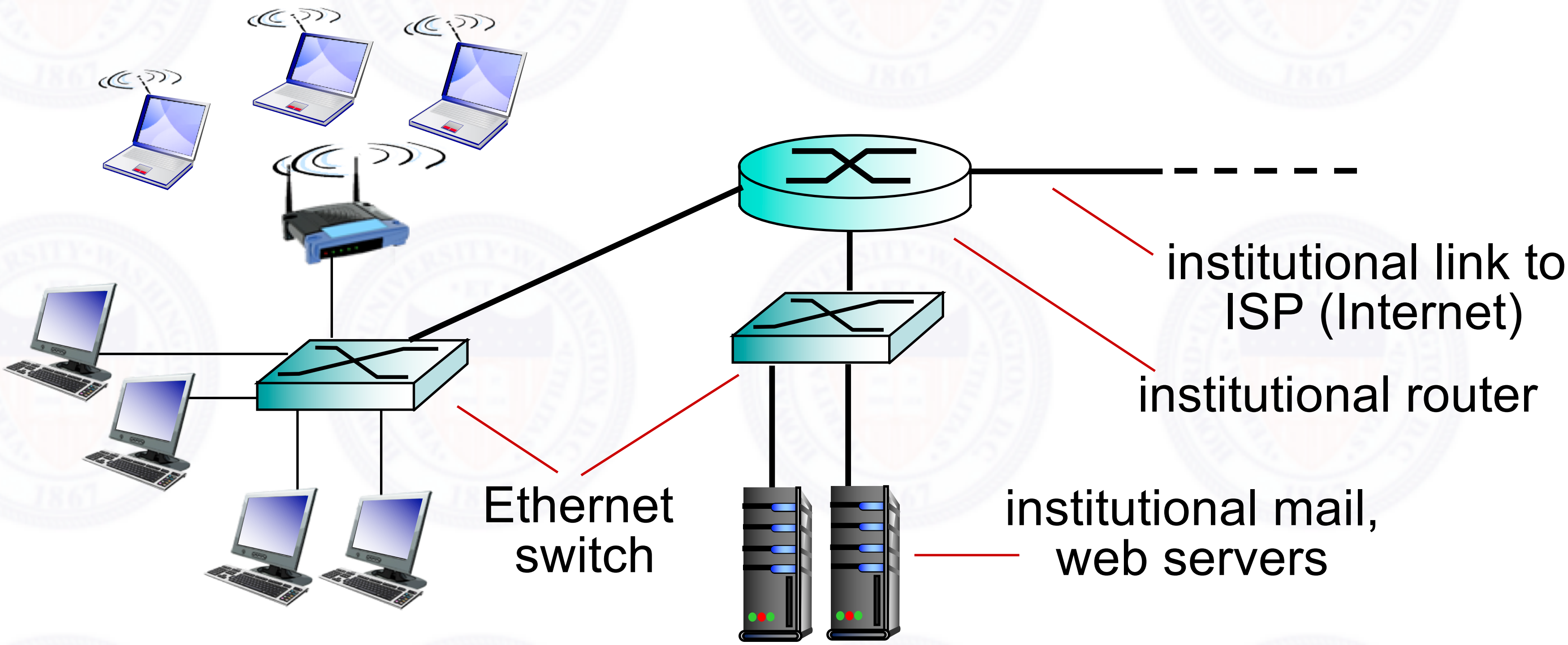


- HFC: hybrid fiber coax
  - Asymmetric: up to 30Mbps downstream transmission rate, 2 Mbps upstream transmission rate
- Network of cable, fiber attaches homes to ISP router
  - Homes share access network to cable headend
  - Unlike DSL, which has dedicated access to central office

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"

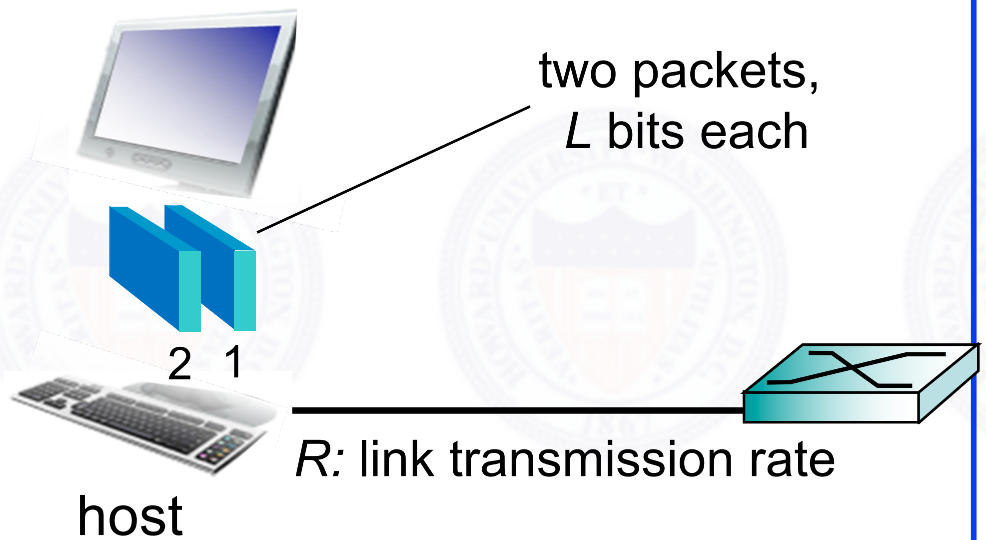
- Wireless LANs:
  - Within building (100 ft)
  - 802.11b/g (WiFi): 11, 54 Mbps transmission rate

- Wide-area wireless access
  - Brovided by telco (cellular) operator, 10's km
  - Between 1 and 10 Mbps
  - 3G, 4G: LTE

Host: Sends *Packets* of Data

Host sending function:

- Takes application message
- Breaks into smaller chunks, known as *packets*, of length *L* bits
- Transmits packet into access network at *transmission rate R*
  - link transmission rate, aka link *capacity, aka link bandwidth*



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

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
  - Category 5e: Gigabit 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)
  - e.g. 3G: ~ 1 Mbps
- Satellite
  - Kbps to 45Mbps channel (or multiple smaller channels)
  - 270 msec end-end delay
  - Geosynchronous versus low altitude

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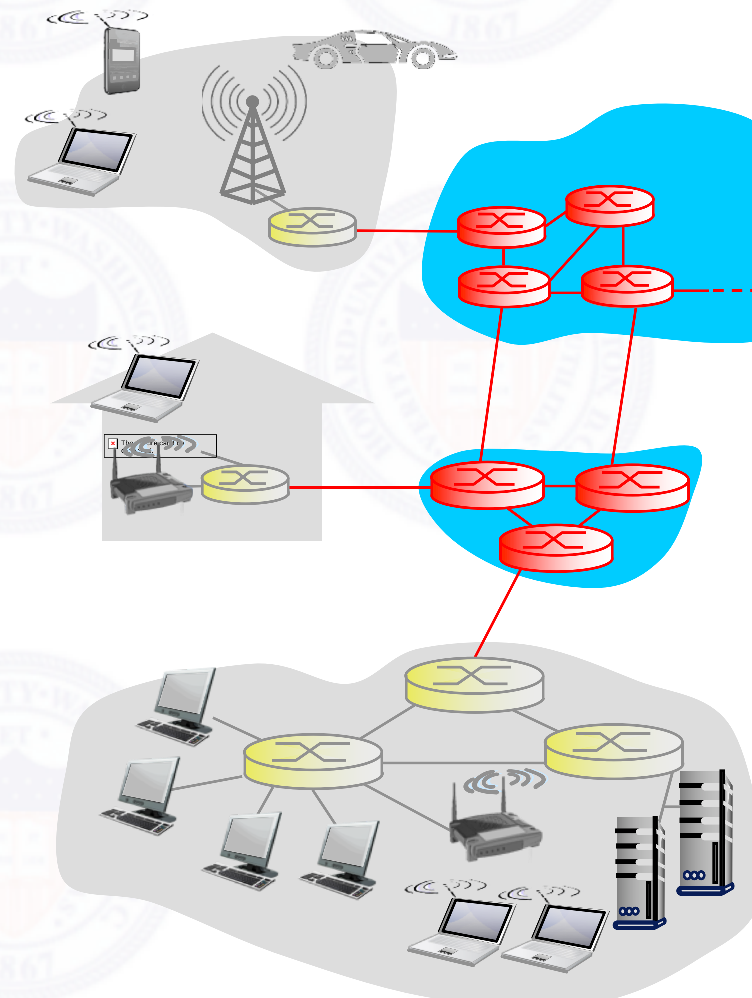
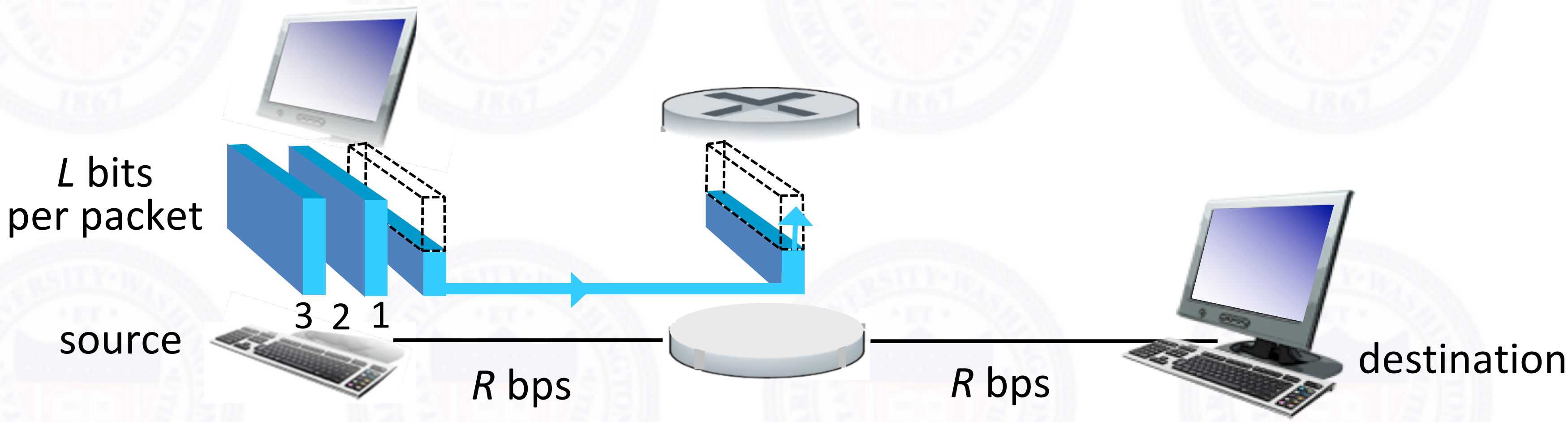
The Network Core

- 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

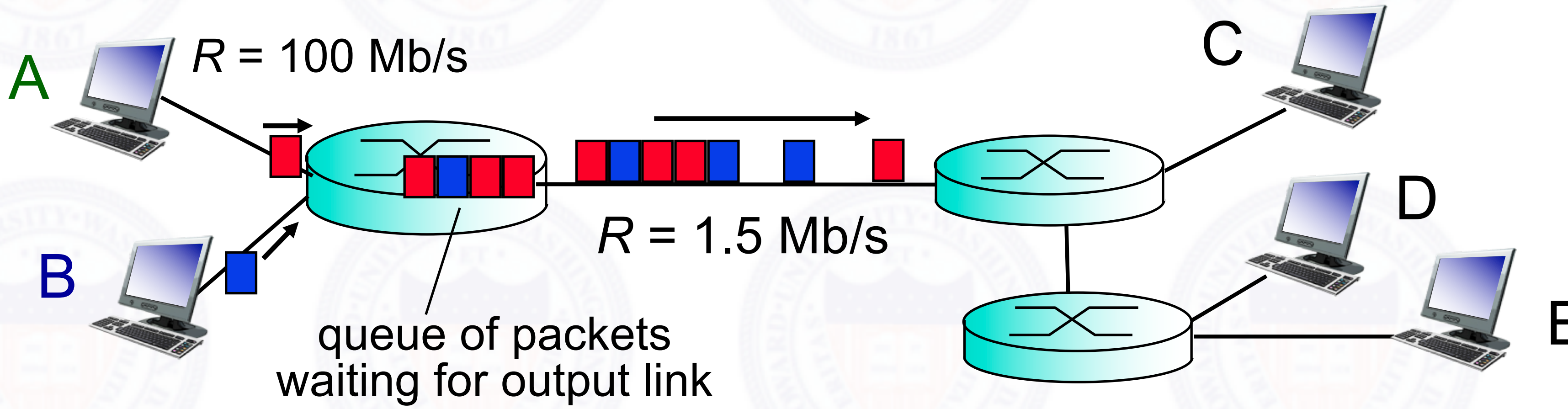
one-hop numerical example:

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

- end-end delay = $2L/R$ (assuming zero propagation delay)

more on delay shortly …

Packet Switching: Queueing Delay, Loss



Queuing and loss:

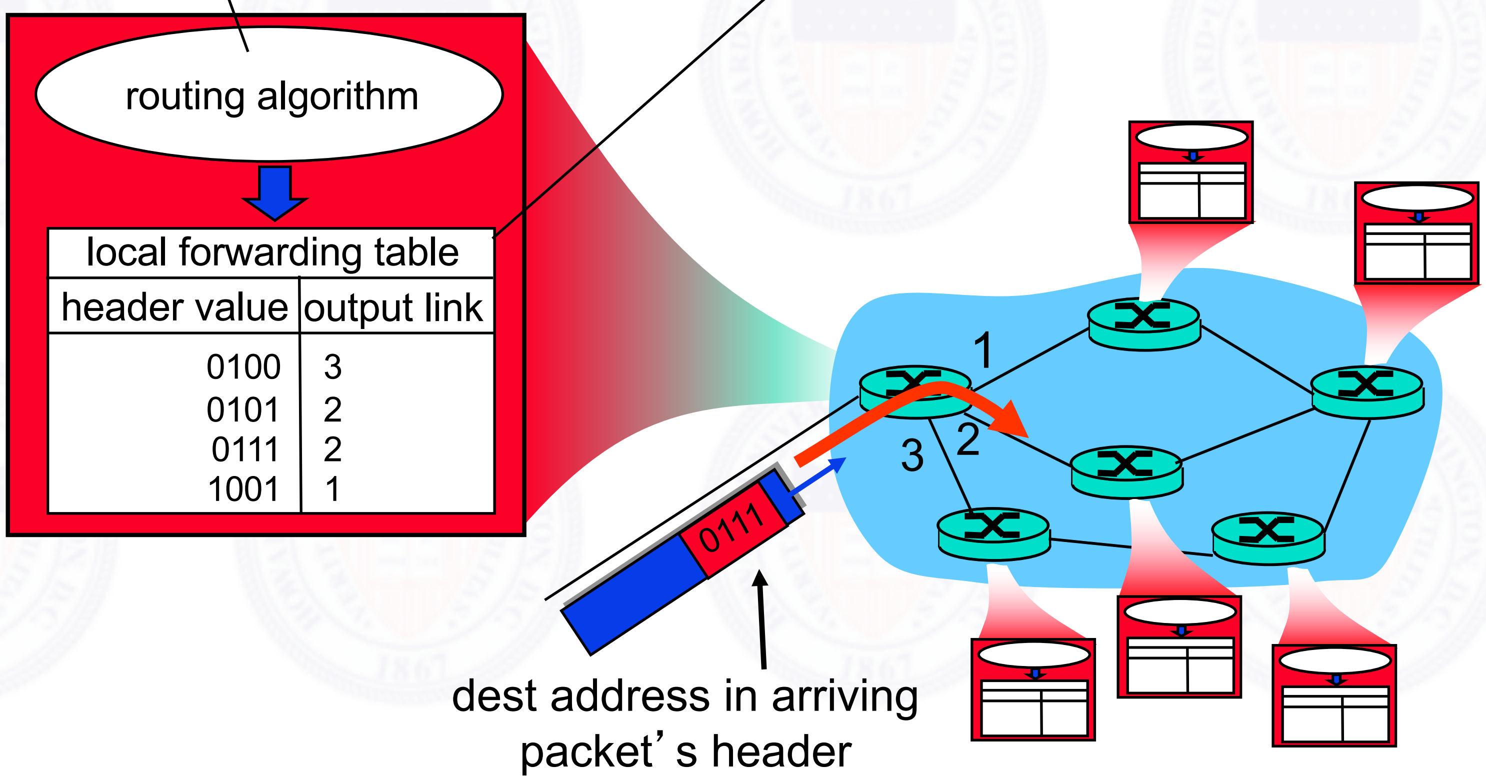
- If arrival rate (in bits) to link exceeds transmission rate of link for a period of time:
  - Packets will queue, wait to be transmitted on link
  - Packets can be dropped (lost) if memory (buffer) fills up

Two Key Network-Core Functions

Routing: determines source-destination route taken by packets

- Routing algorithms

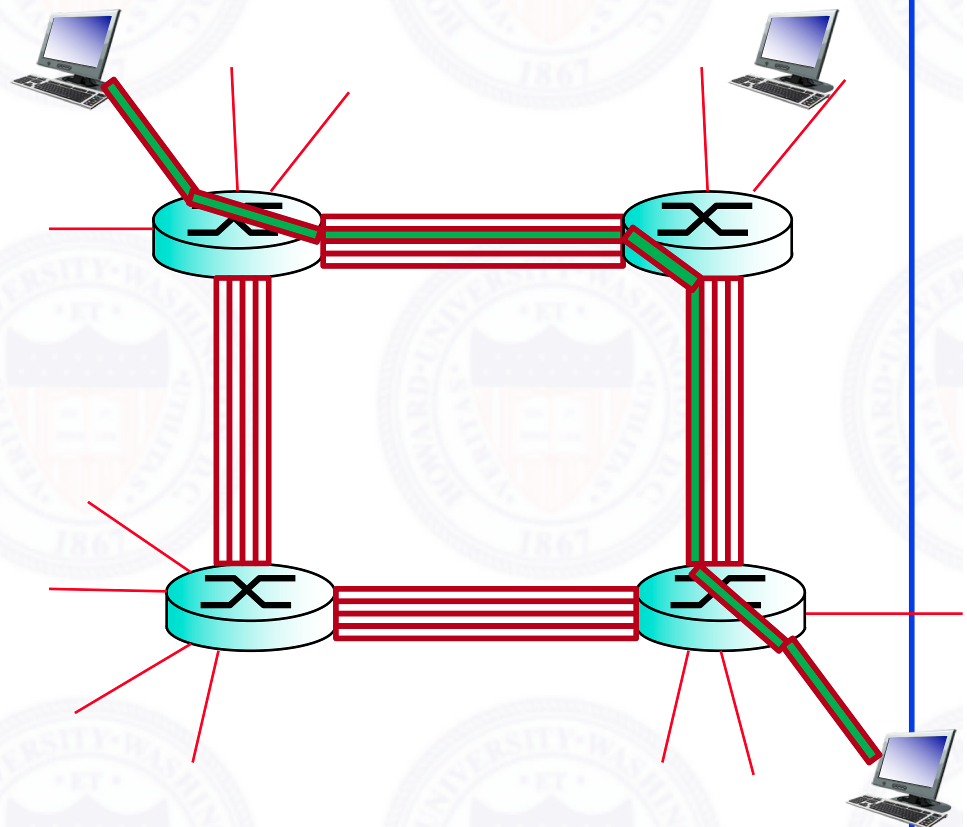
Forwarding: move packets from router's input to appropriate router output



Alternative Core: Circuit Switching

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

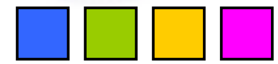
- In diagram, each link has four circuits.
  - Call gets 2nd circuit in top link and 1st circuit in right link.
- Dedicated resources: no sharing
  - Circuit-like (guaranteed) performance
- Circuit segment idle if not used by call *(no sharing)*
- Commonly used in traditional telephone networks



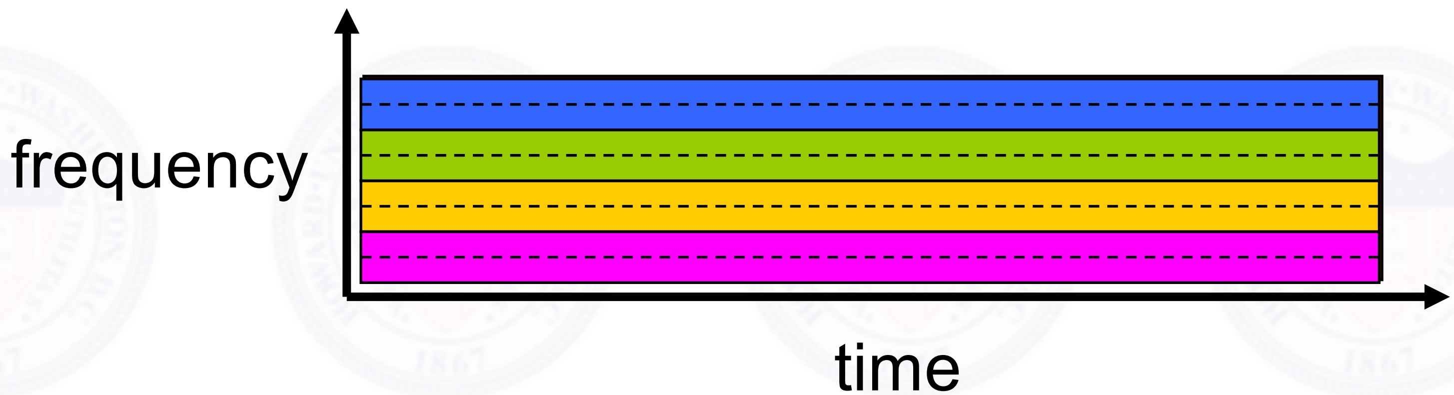
Circuit Switching: FDM and TDM

Example:

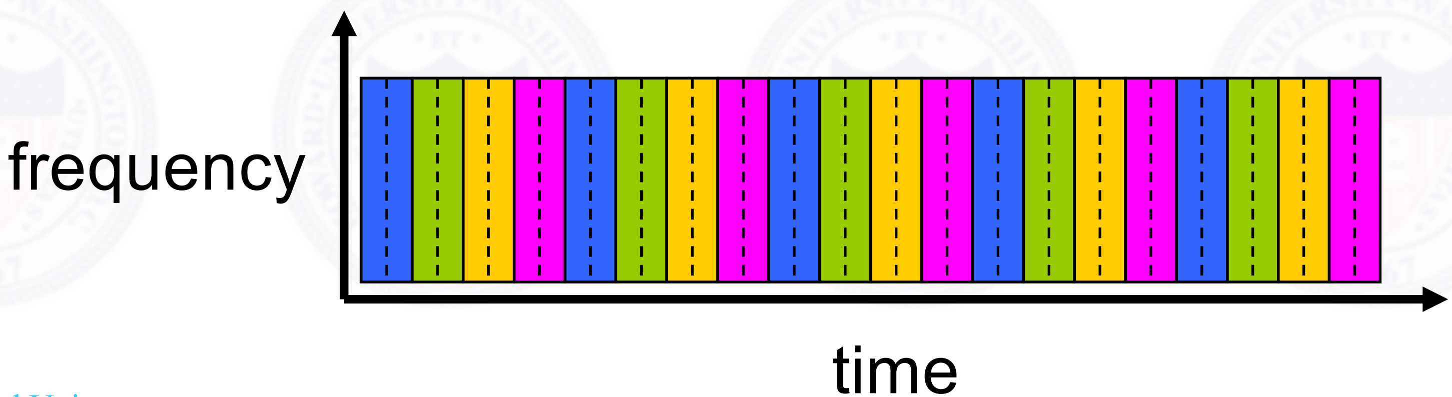
4 users



FDM



TDM



Numerical example

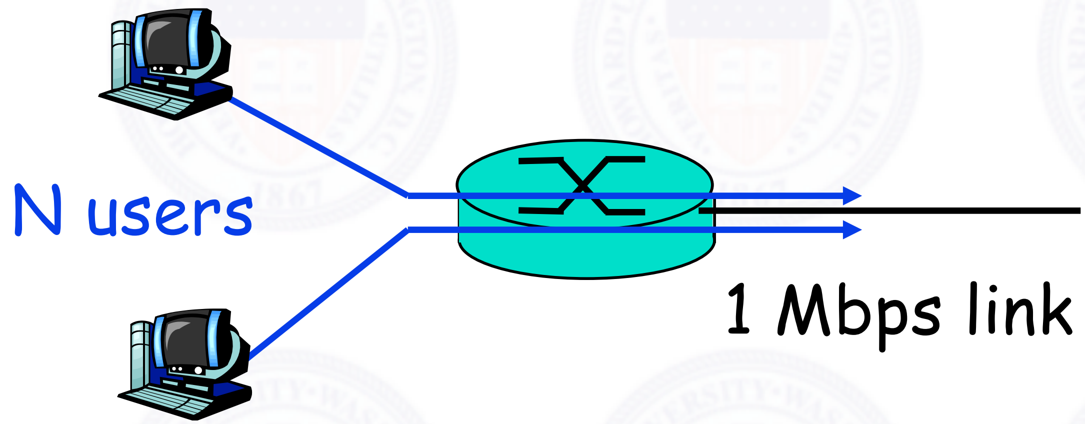
- How long does it take to send a file of 640,000 bits from host A to host B over a circuit-switched network?
  - All links on the path from A to B are 1.536 Mbps
  - Each link uses TDM with 24 slots/sec
  - 500 msec to establish end-to-end circuit

Packet Switching vs. 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

… with some risks



Q: How did we get value 0.0004?
Q: What happens if > 35 users ?

Packet Switching vs. Circuit Switching

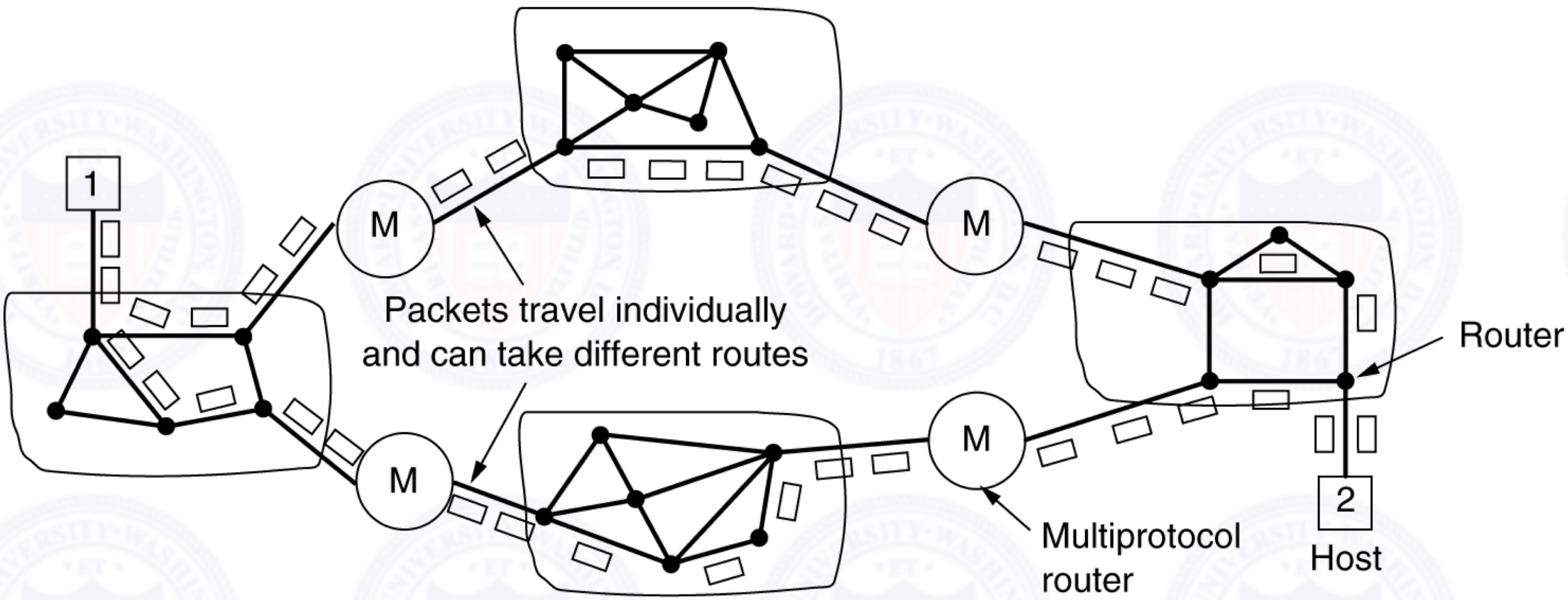
Is packet switching a "slam dunk winner?"

- 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 (Ch. 7)

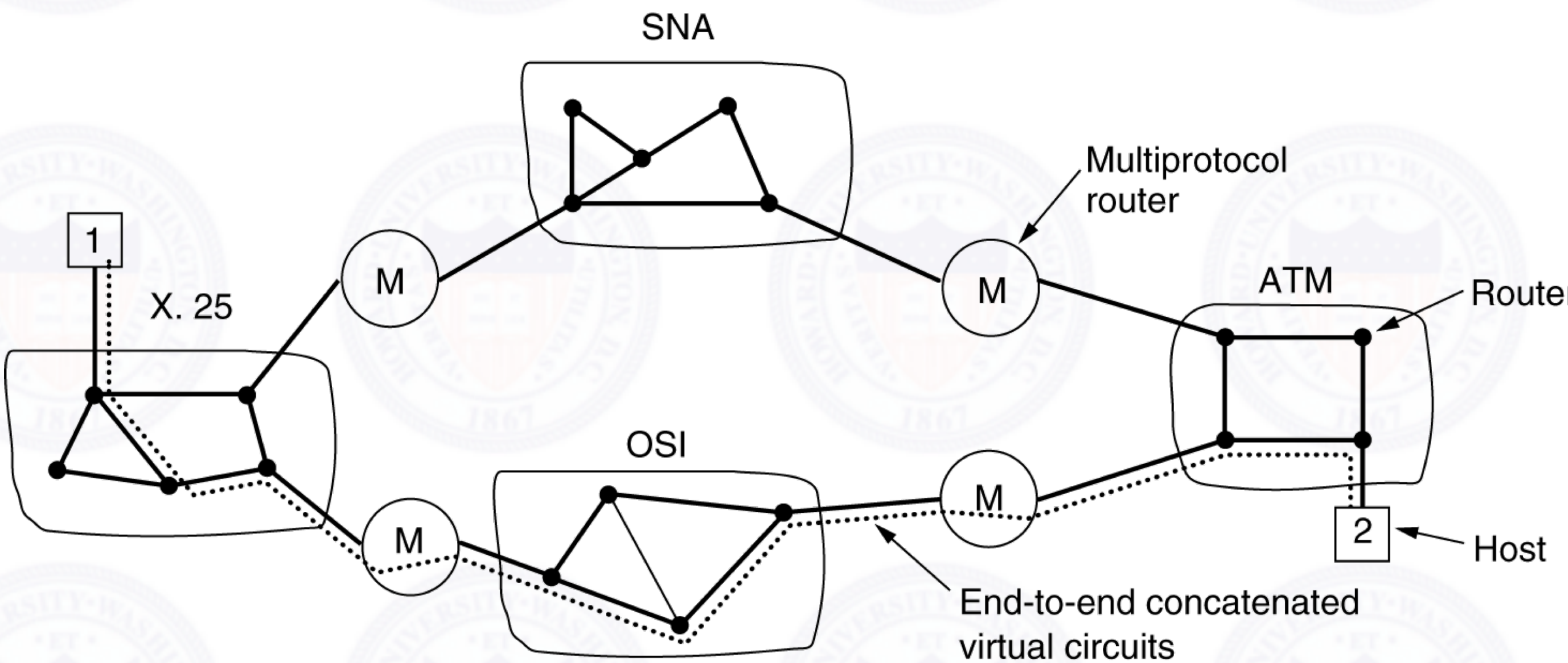
Grafting Circuit Switching on Packet-Switching

- Datagram network – no circuit switching features :
  - *Destination address* in packet determines next hop
  - Routes may change during session
  - Analogy: driving, asking directions
- Virtual circuit network - hybrid:
  - Each packet carries tag (virtual circuit ID), tag determines next hop
  - Fixed path determined at *call setup time*, remains fixed thru call
  - *Routers maintain per-call state*

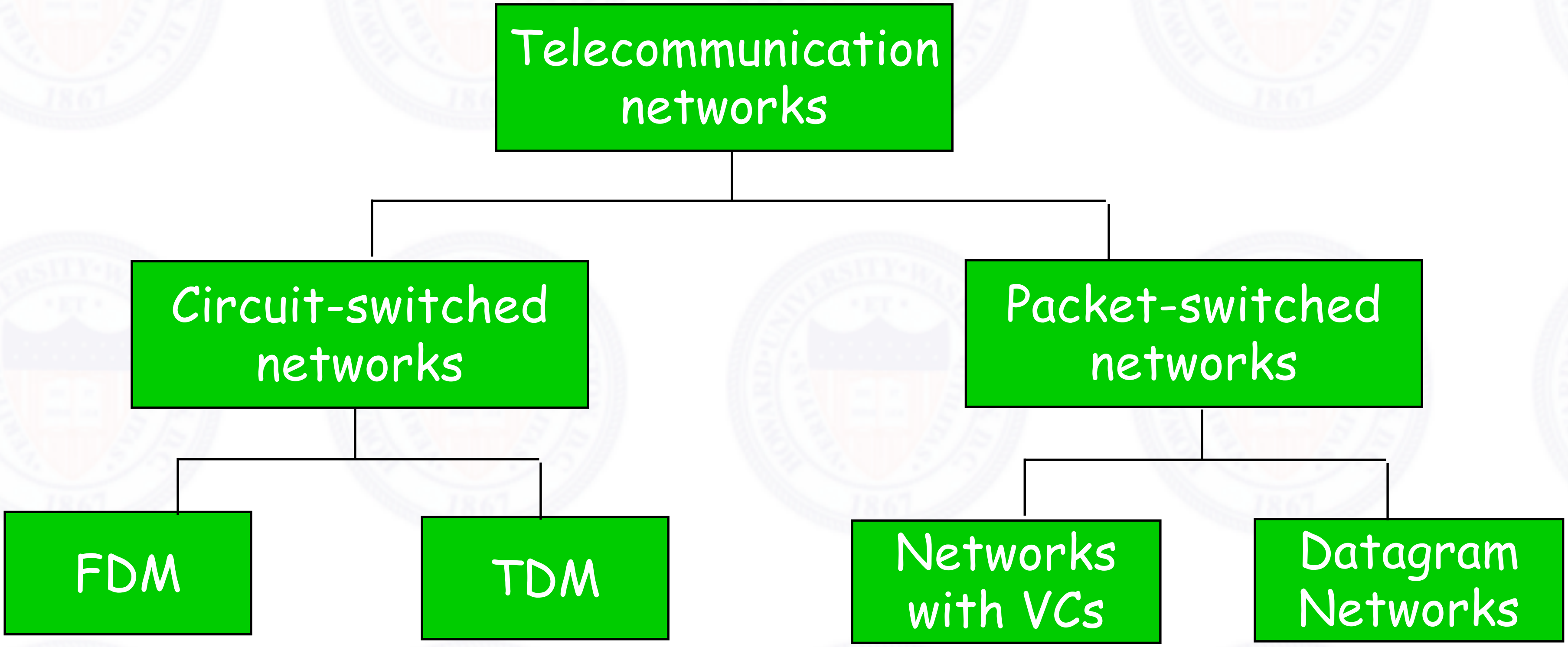
Datagram Network



Virtual Circuit Network



Network Taxonomy



- Can't simply say datagram network is connectionless
- Internet provides both connection-oriented (TCP) and connectionless services (UDP) to apps.

Internet Structure: Network of Networks

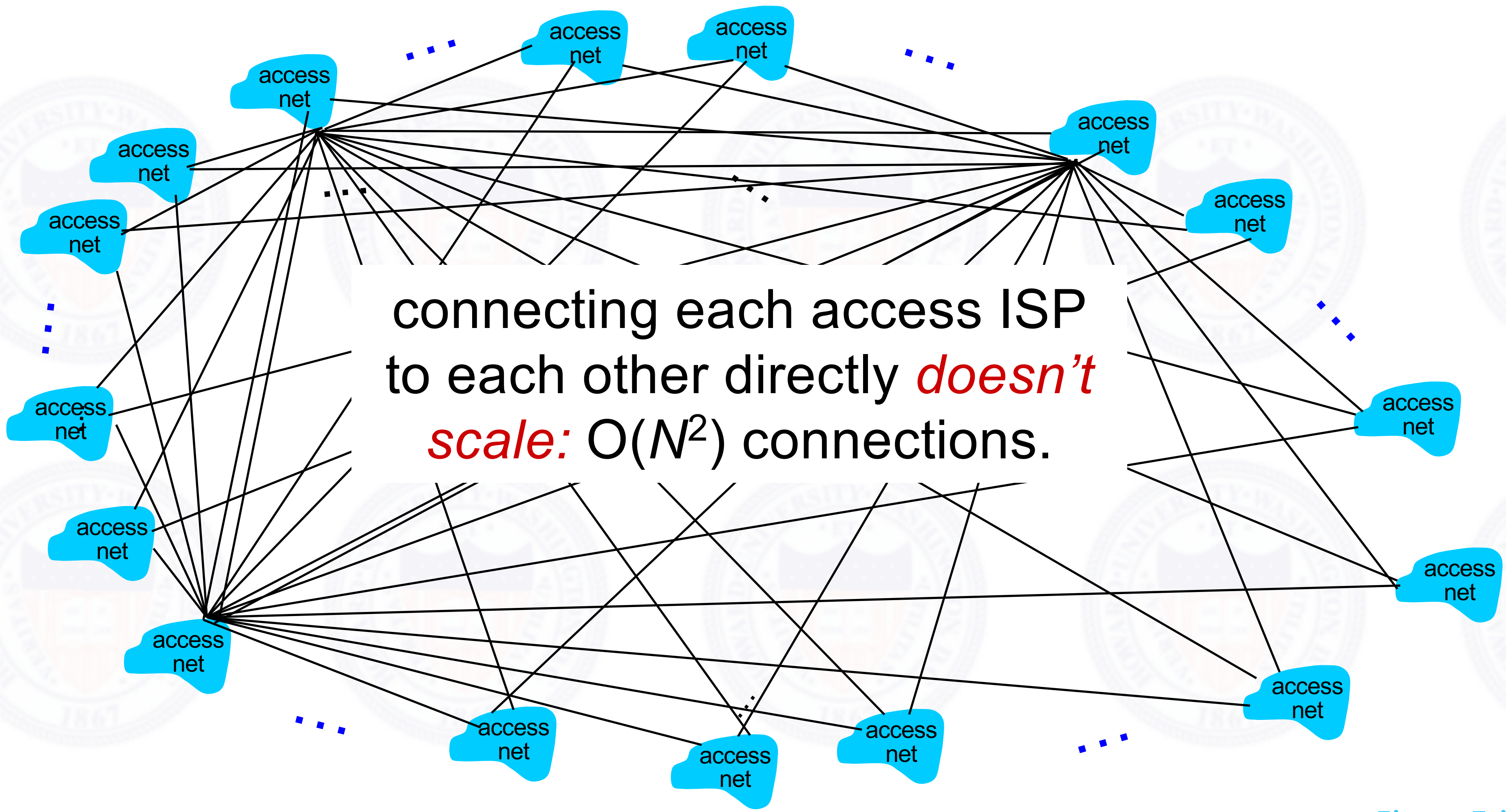
- End systems connect to Internet via access ISPs (Internet Service Providers)
  - Residential, company and university ISPs
- Access ISPs in turn must be interconnected.
  - So that any two hosts can send packets to each other
- Resulting network of networks is very complex
  - Evolution was driven by 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

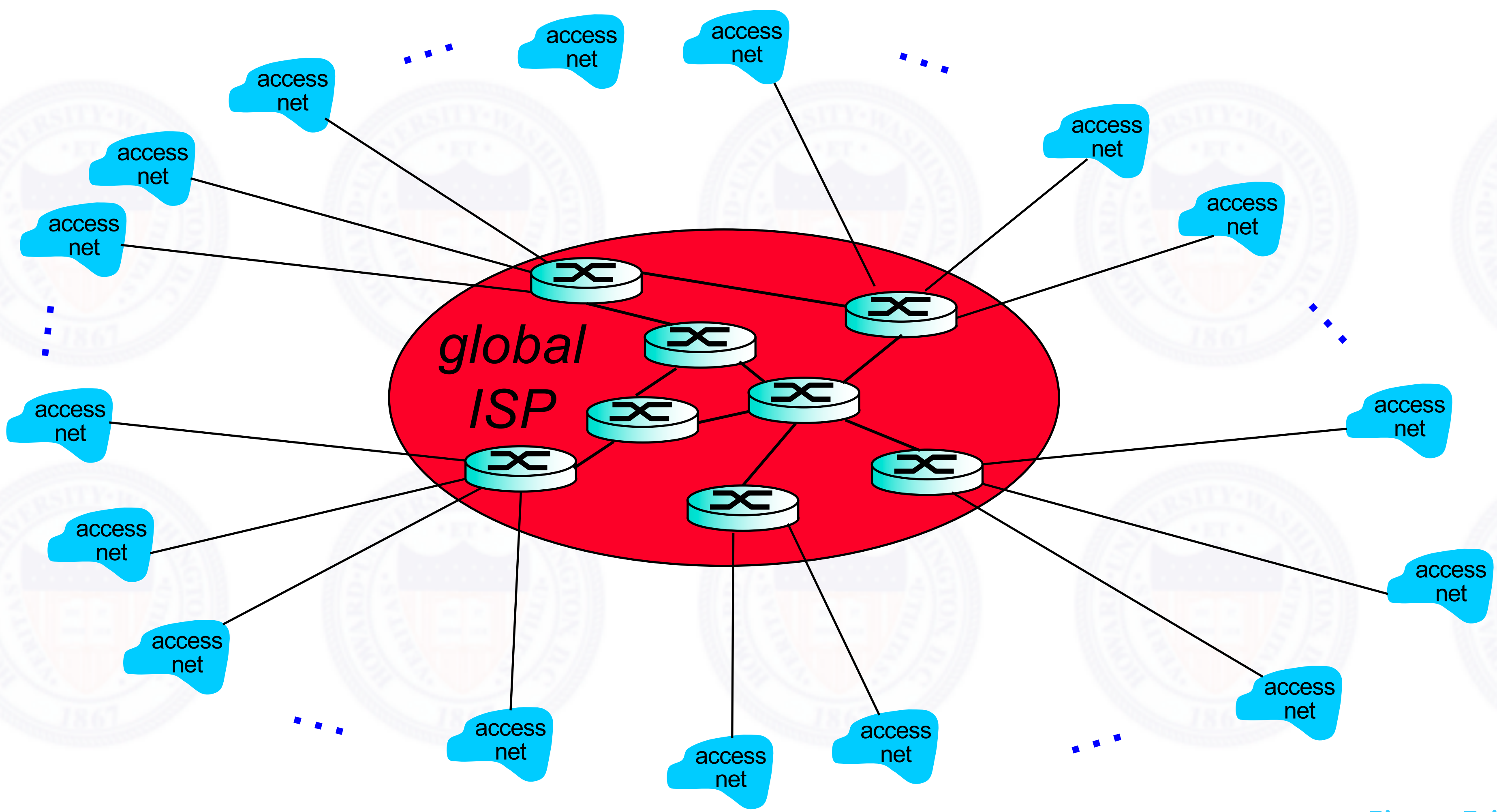
Option: connect each access ISP to every other access ISP?



connecting each access ISP to each other directly *doesn't scale:* $O(N^2)$ connections.

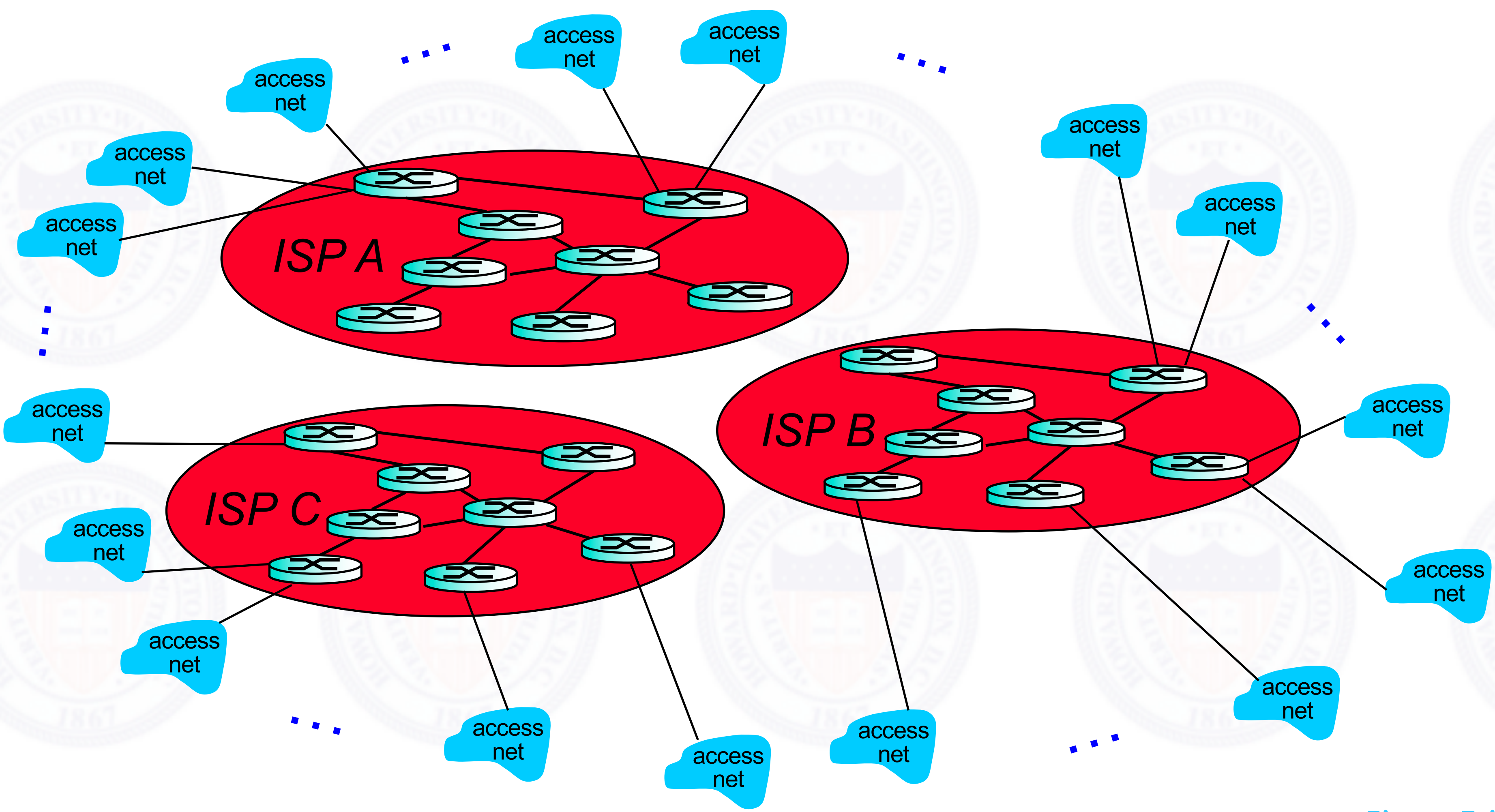
Internet Structure: Network of Networks

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



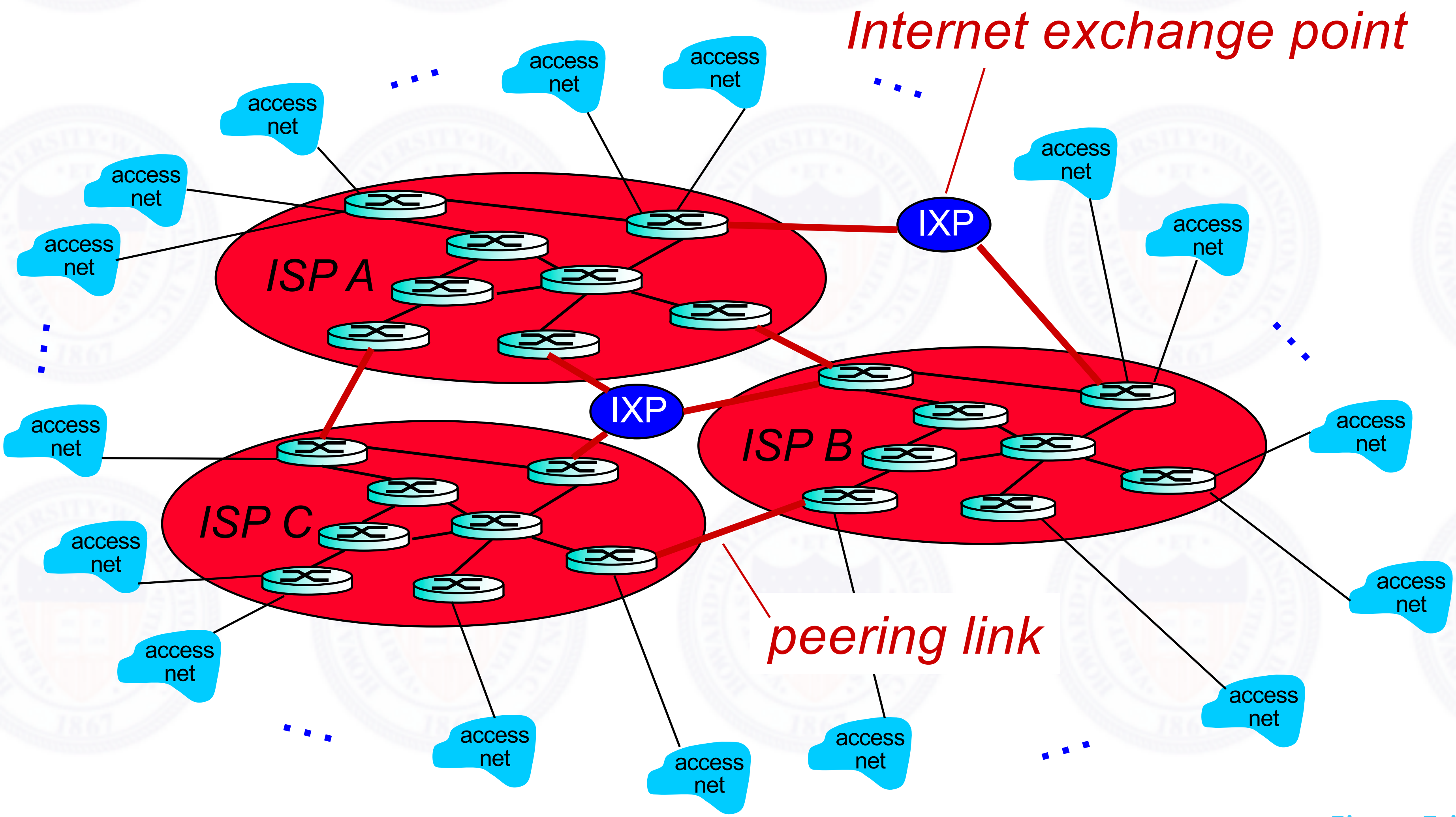
Internet Structure: Network of Networks

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



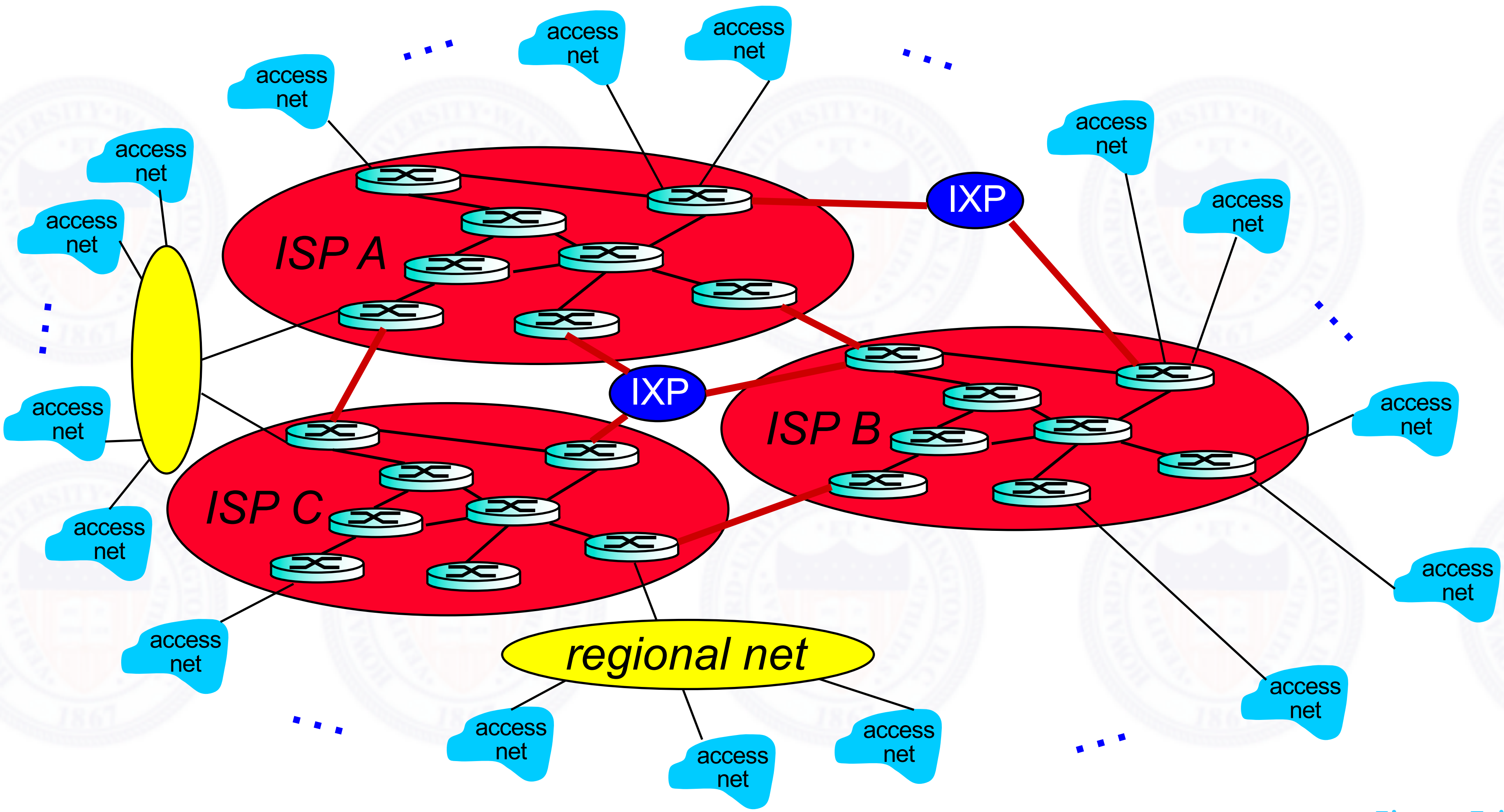
Internet Structure: Network of Networks

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



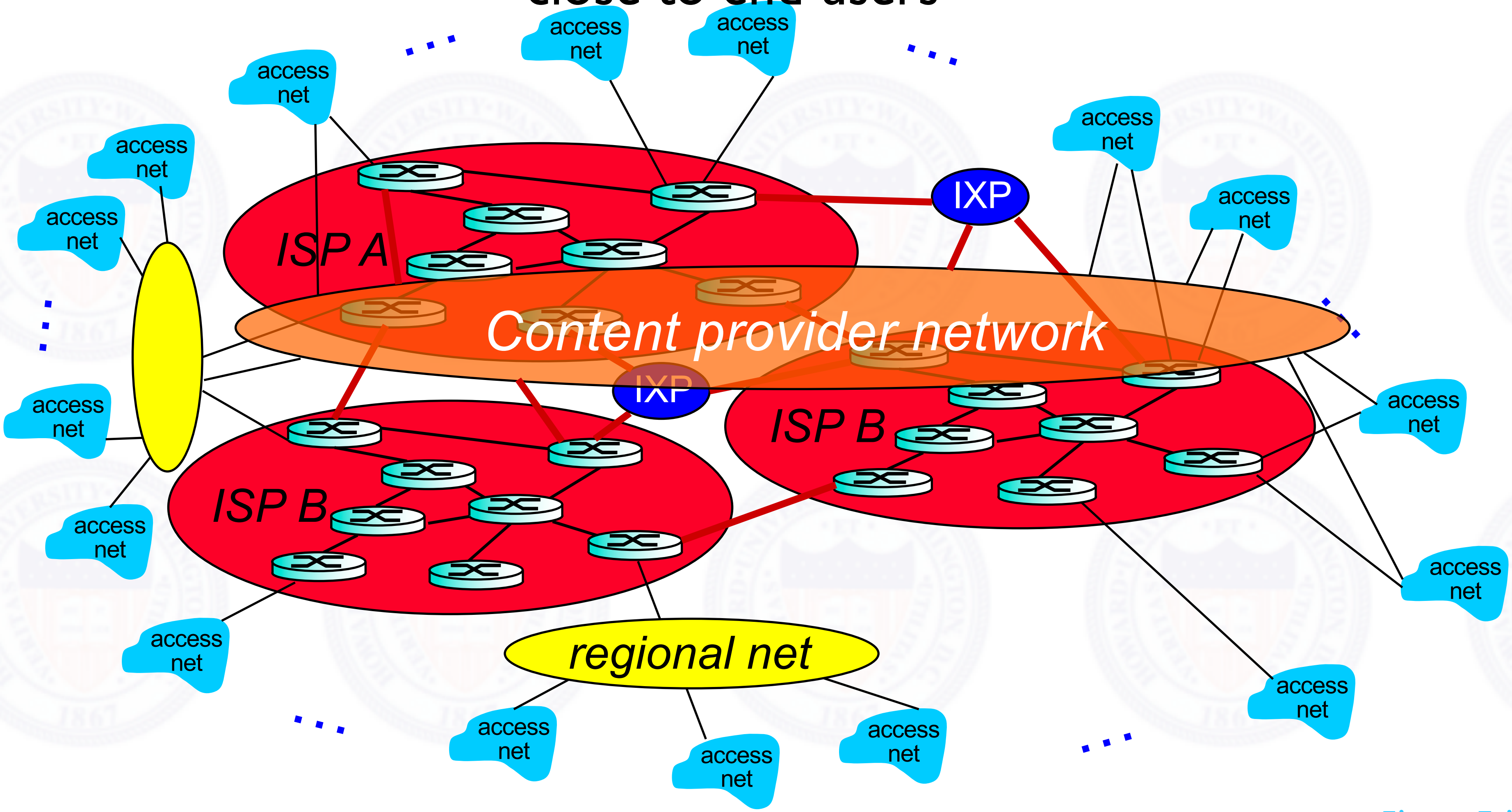
Internet Structure: Network of Networks

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

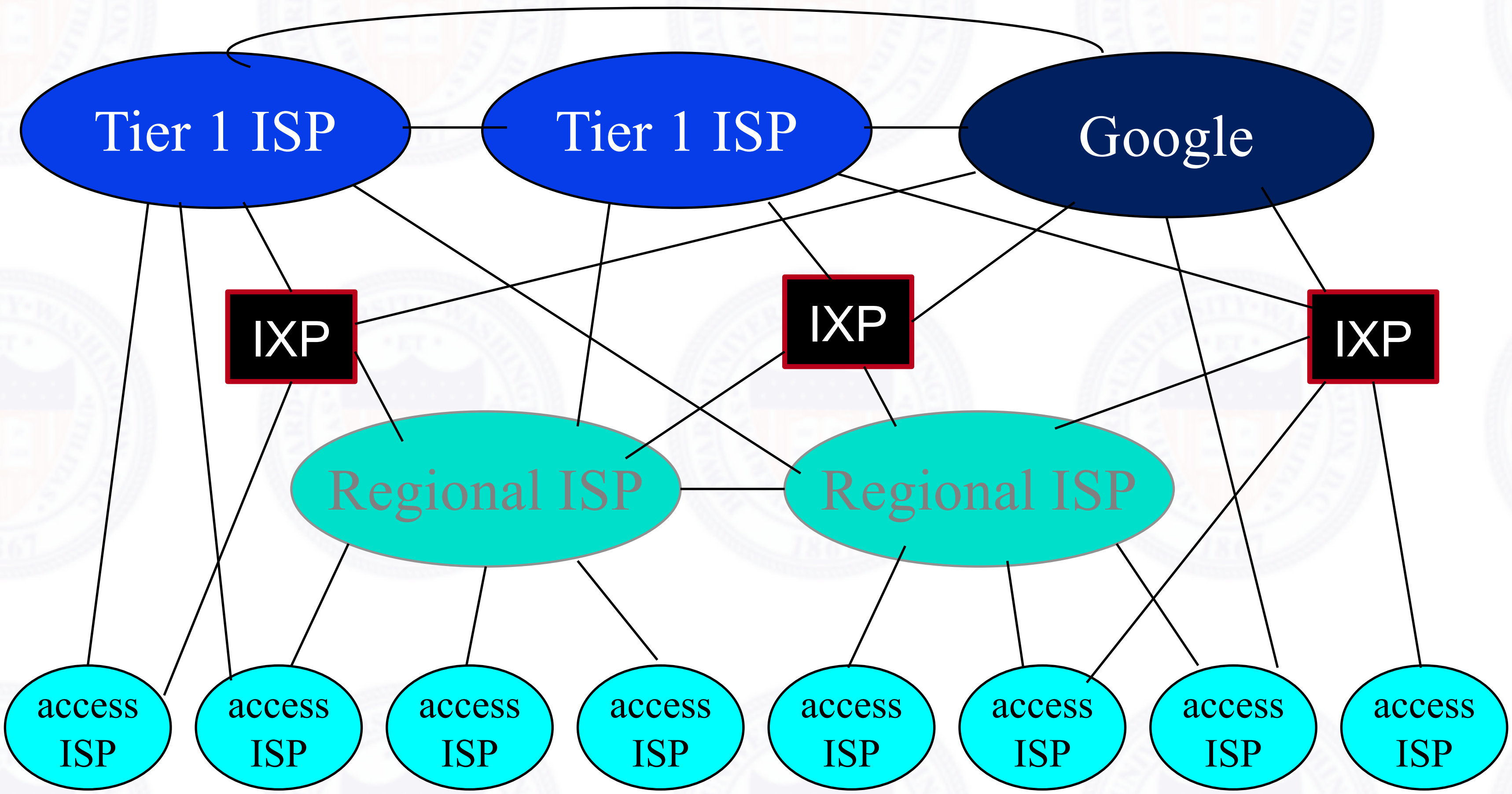


Internet Structure: Network of Networks

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

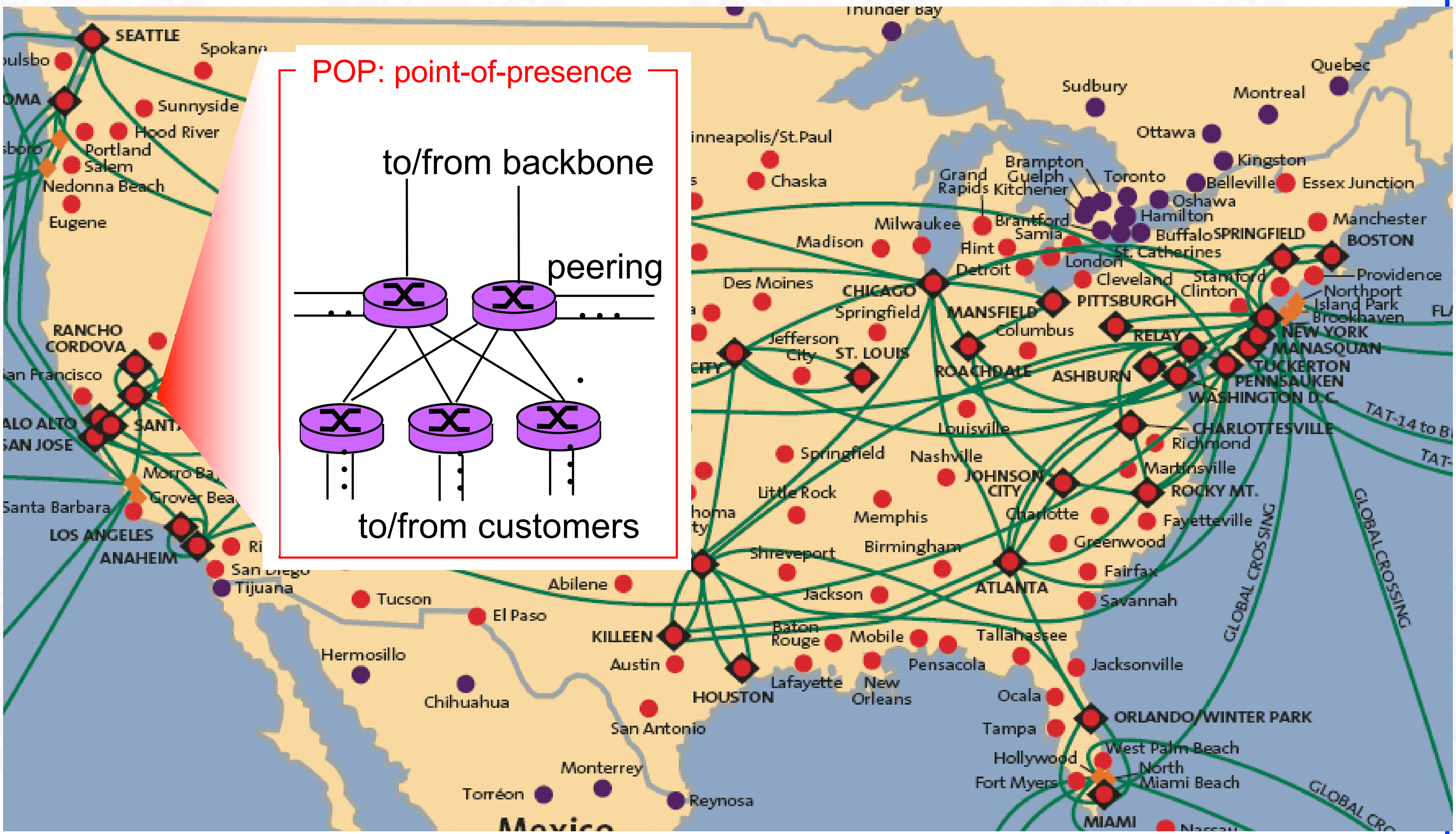


Internet Structure: Network of Networks



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

Tier-1 ISP: e.g., Sprint



Chapter 1: Roadmap

1.1 What *is* the Internet?

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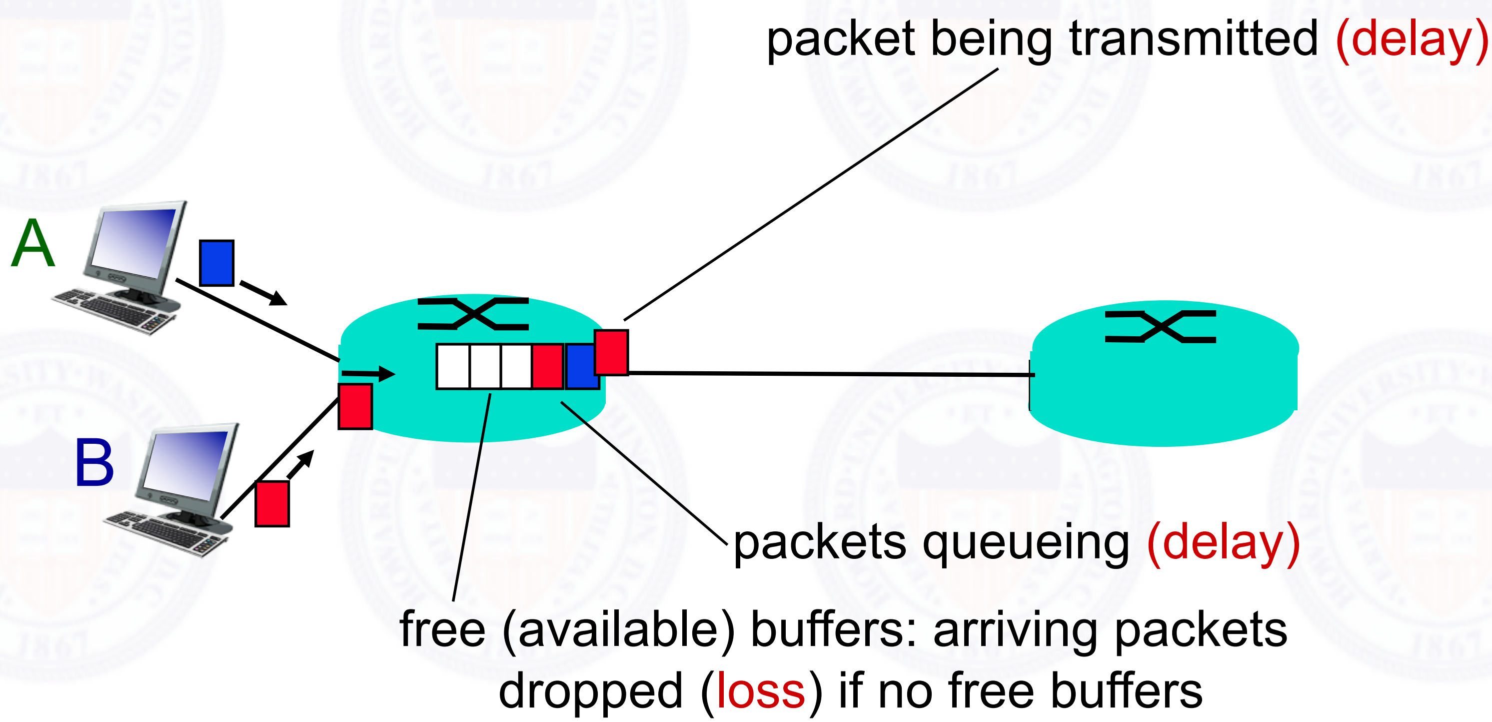
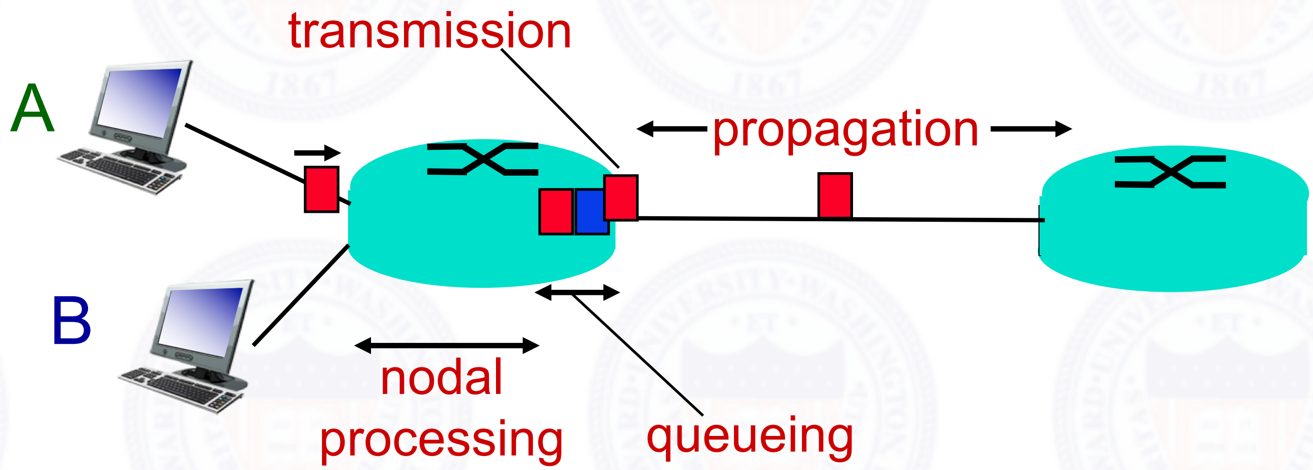
How does delay occur?

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



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

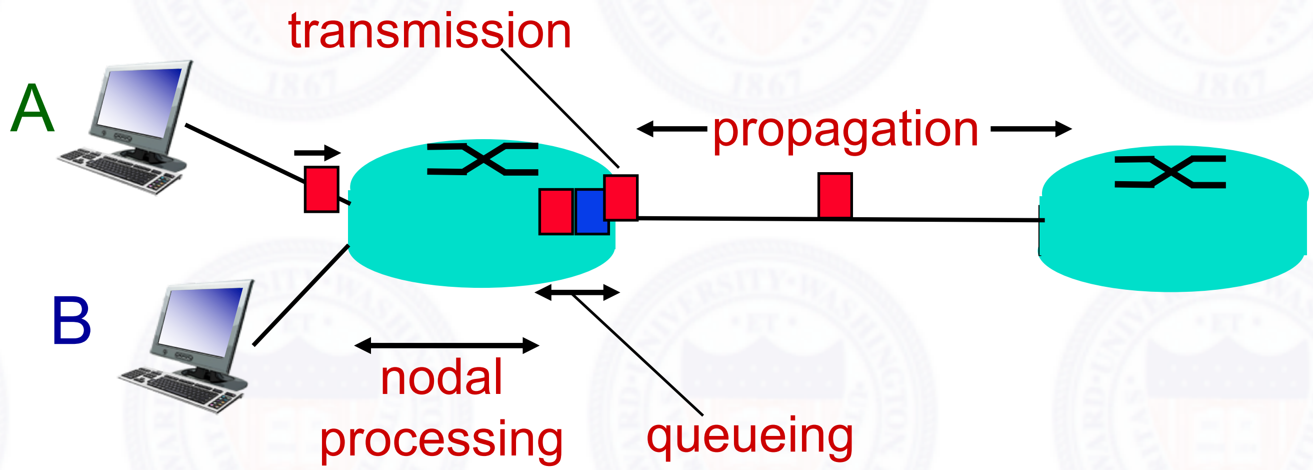
d_{proc}: nodal processing

- 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



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

d_{trans}: transmission delay:

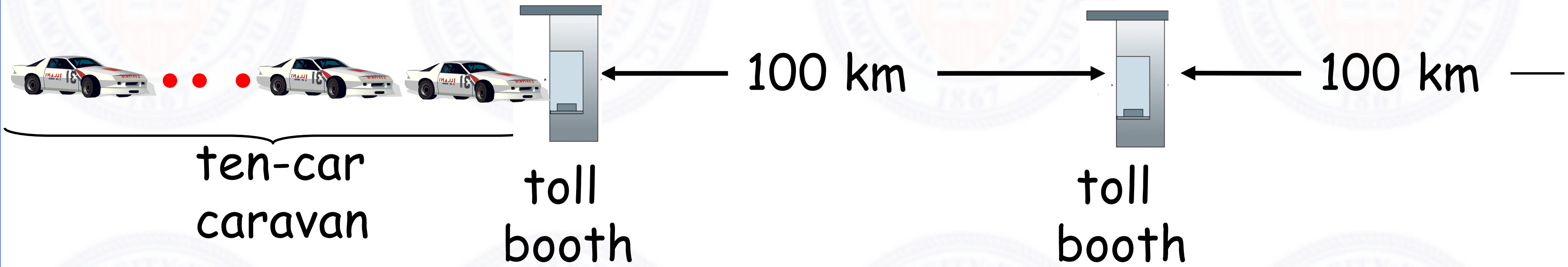
- L: packet length (bits)
- R: link bandwidth (bps)
- d_{trans} = L/R

d_{prop}: propagation delay:

- d: length of physical link
- s: propagation speed in medium (~2x10^8 m/sec)
- d_{prop} = d/s

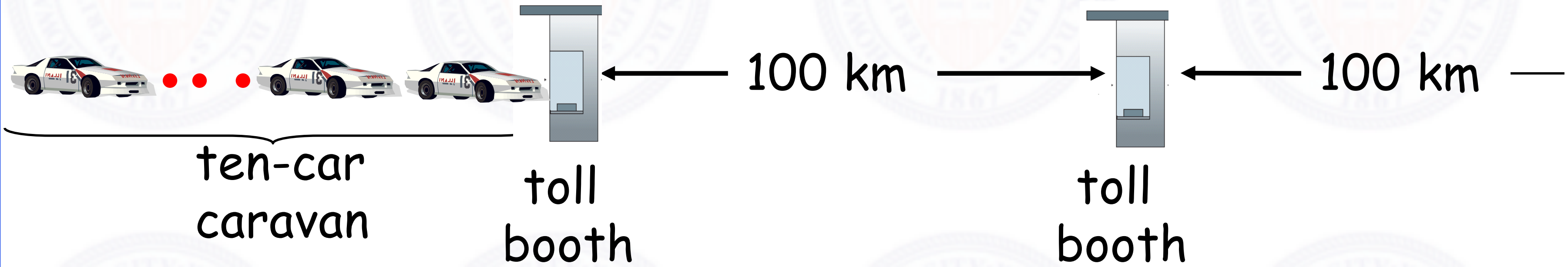
d_{trans} and d_{prop} *very* different

Caravan Analogy



- Cars "propagate" at 100 km/hr
- Toll booth takes 12 sec to service a car (transmission rate)
- Car~bit; caravan ~ packet
- Q: How long until the whole 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)

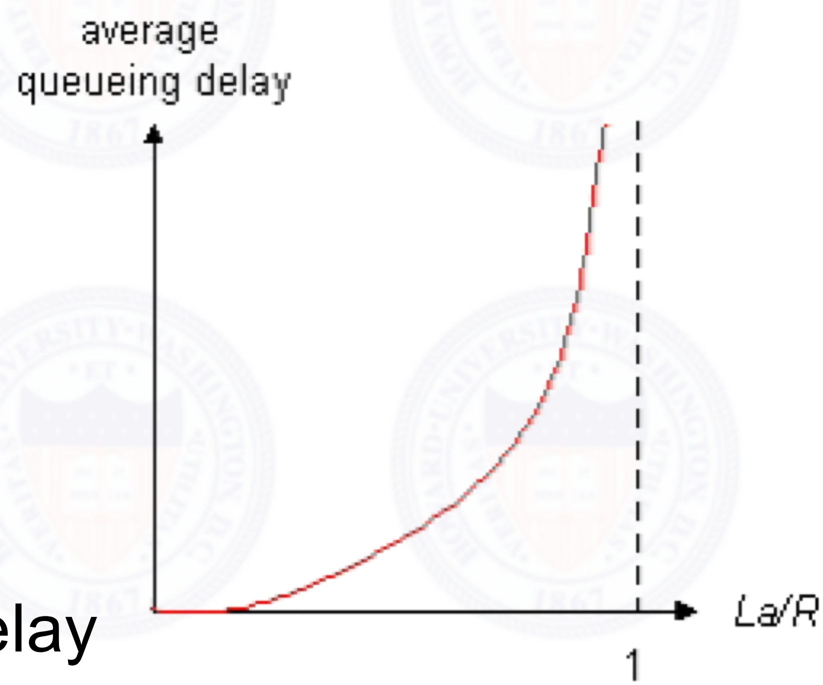


- Cars now "propagate" at 1000 km/hr
- Toll booth now takes 1 min to service a car
- Q: Will cars arrive to 2nd booth before all cars serviced at 1st booth?
- Yes! After 7 min, 1st car at 2nd booth and 3 cars still at 1st booth.
- 1st bit of packet can arrive at 2nd router before packet is fully transmitted at 1st router!

Queueing Delay (Revisited)

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

traffic intensity = La/R



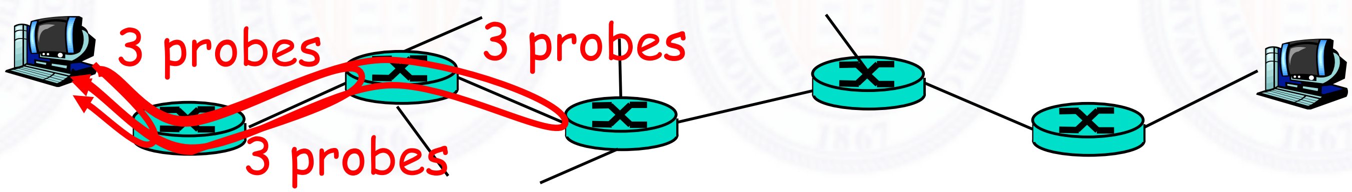
- La/R ~ 0: average queueing delay small
- La/R → 1: average queueing delay become large
- La/R > 1: more "work" arriving than can be serviced, average delay infinite!


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-to-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.
- Command
  - *nix: traceroute, Windows: tracert



"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

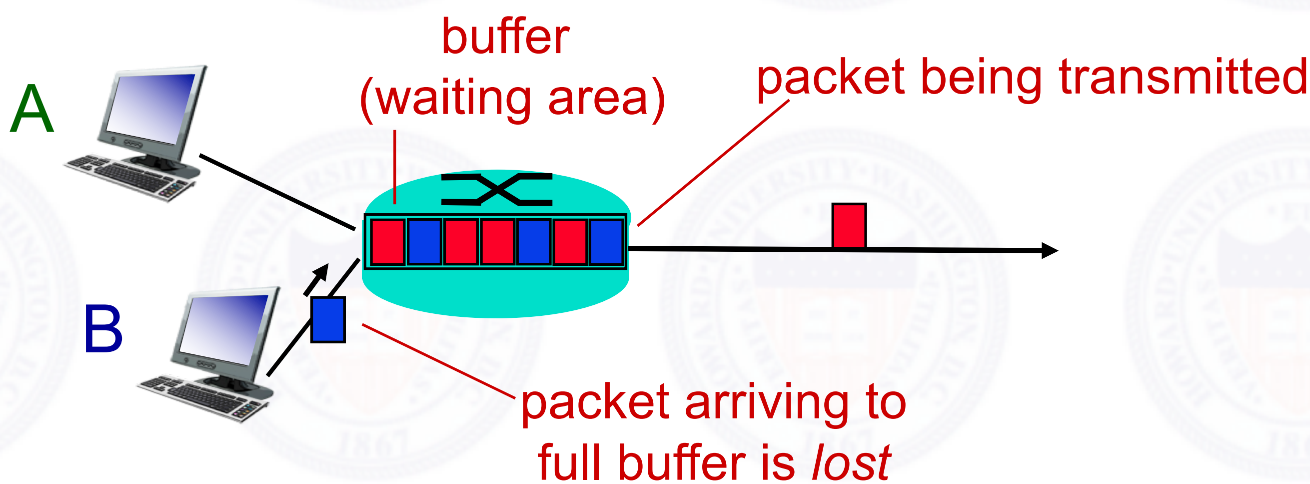
trans-oceanic link

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

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

Packet loss

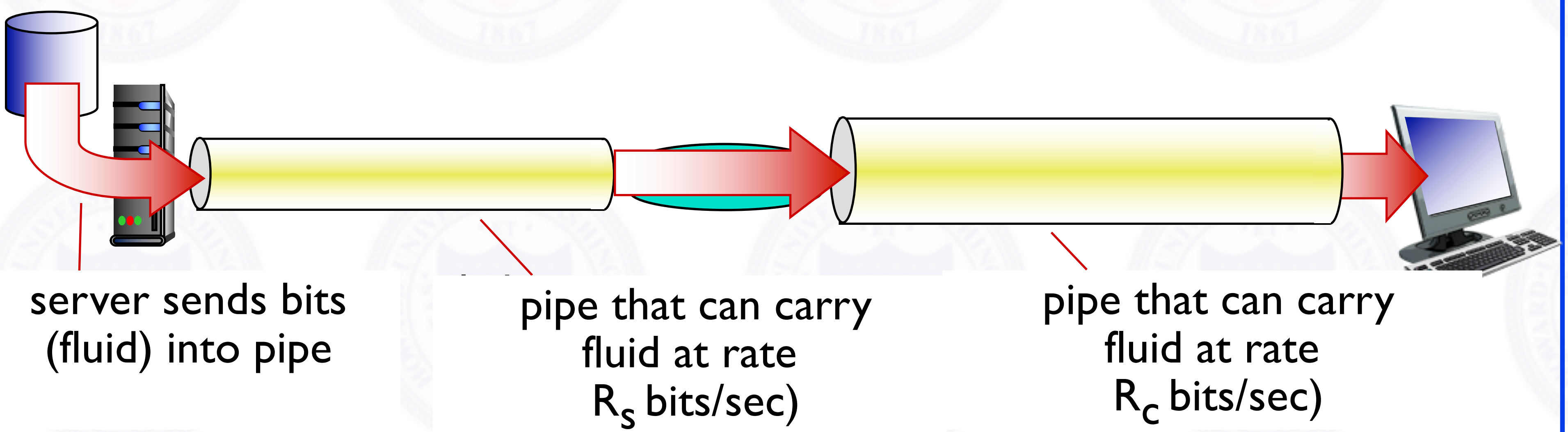
- Loss due to buffer overflow
  - Queue (aka buffer) preceding link in buffer has finite capacity
  - Packet arriving to full queue dropped (aka lost)
- Loss due to corruption (rare on wired networks)
- Lost packet may be retransmitted by previous node, by source end system, or not at all



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

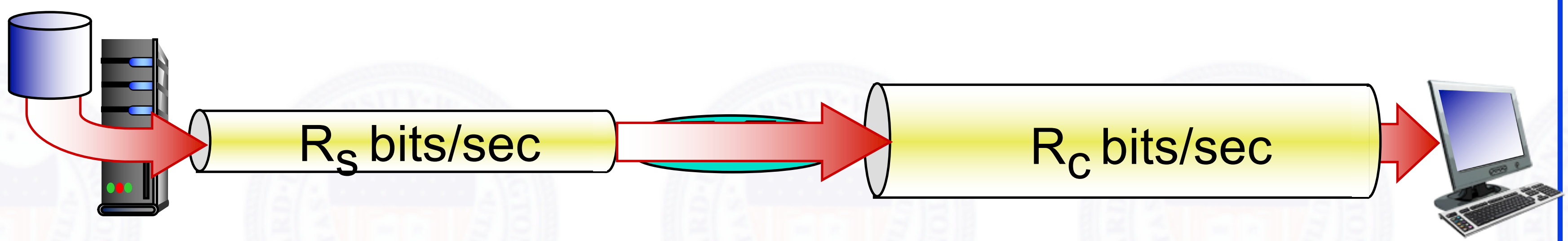
Throughput

- *Throughput:* rate (bits/time unit) at which bits transferred between sender/receiver
  - Usually means the average over a long period of time

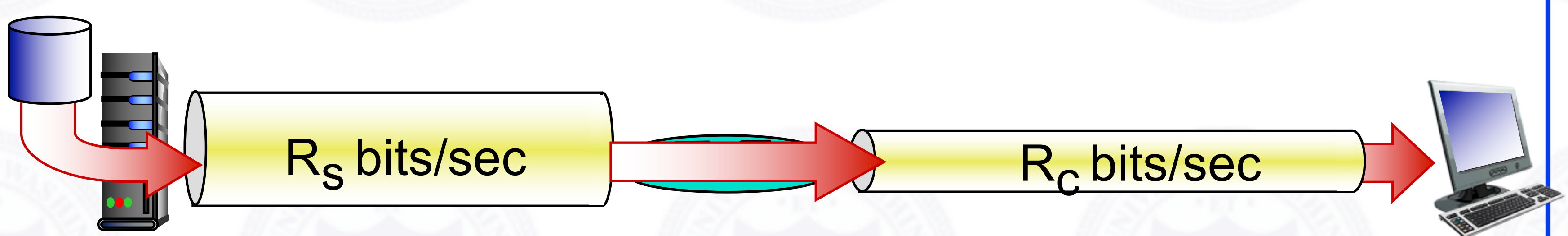


Throughput (more)

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



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

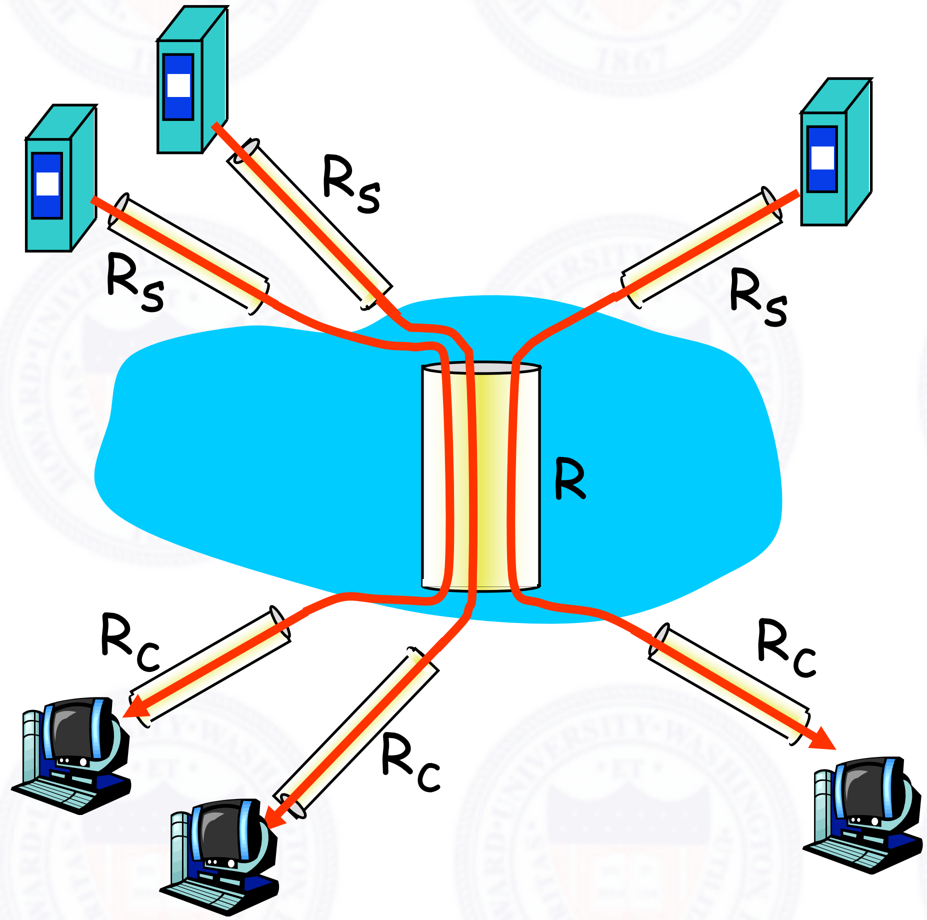


bottleneck link

link on end-end path that constrains end-end throughput

Throughput: Internet Scenario

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



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

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Protocol “Layers“

Networks are complex!

- Many “pieces“:
  - Hosts
  - Routers
  - Links of various media
  - Applications
  - Protocols
  - Hardware, software

Question:

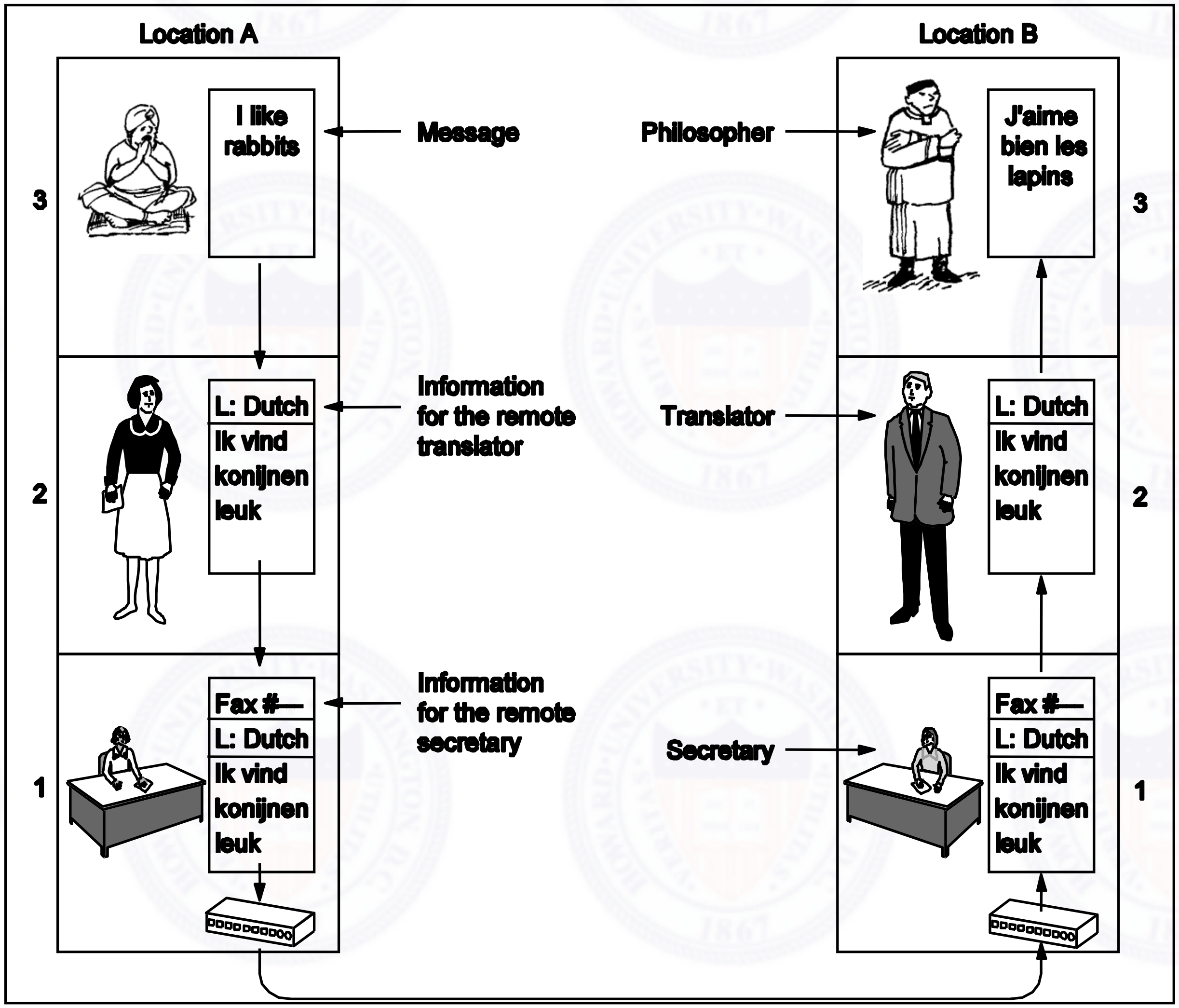
Is there any hope of *organizing* structure of network?

… or at least our discussion of networks?

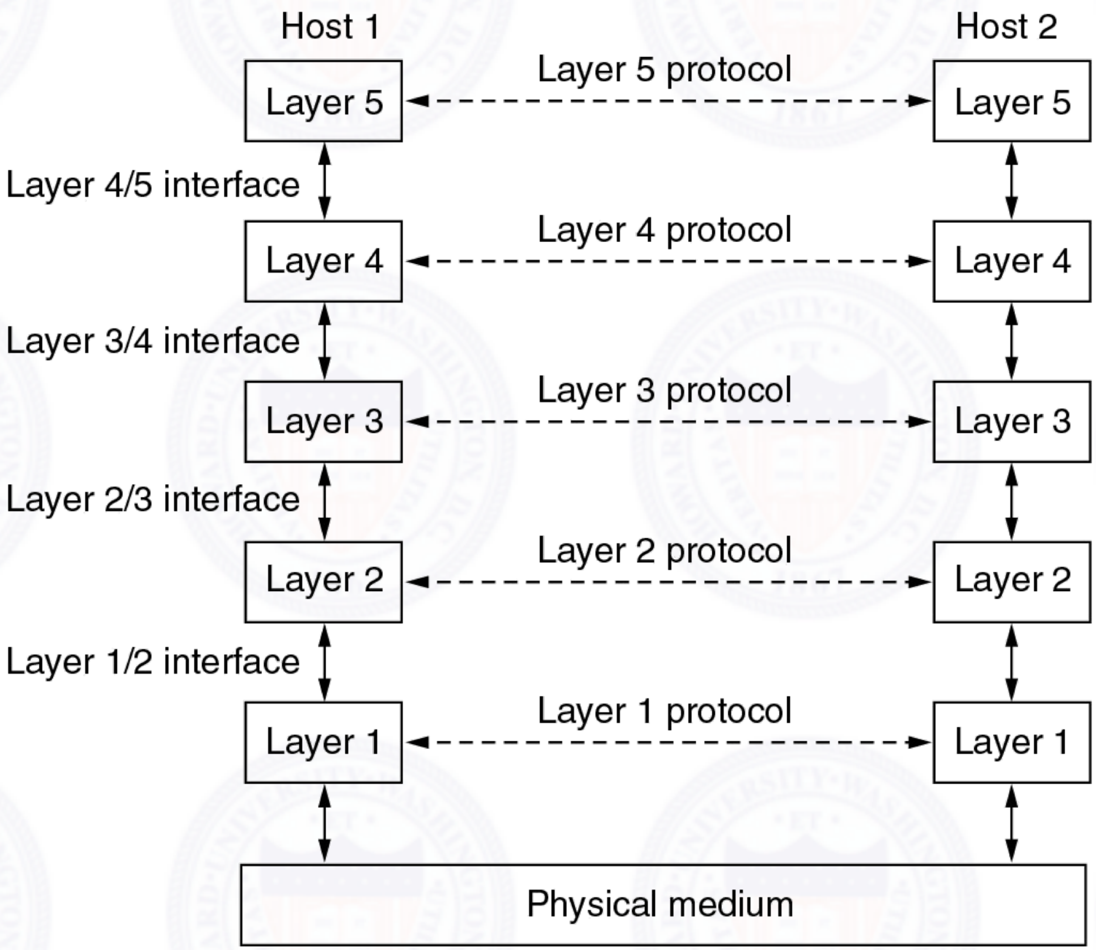
Layering

- Layers: each layer implements a service
  - Via its own internal-layer actions
  - Relying on services provided by layer below
  - More (logically) complex tasks are done at upper levels
    - Lowest layer only takes care of signal transmission
    - Highest layer sends semantically complicated messages over multiple hops from (Internet) edge to edge
- The combination of the stack (of multiple layers) does the complete job

Layering of The Philosopher-Translator-Secretary Architecture

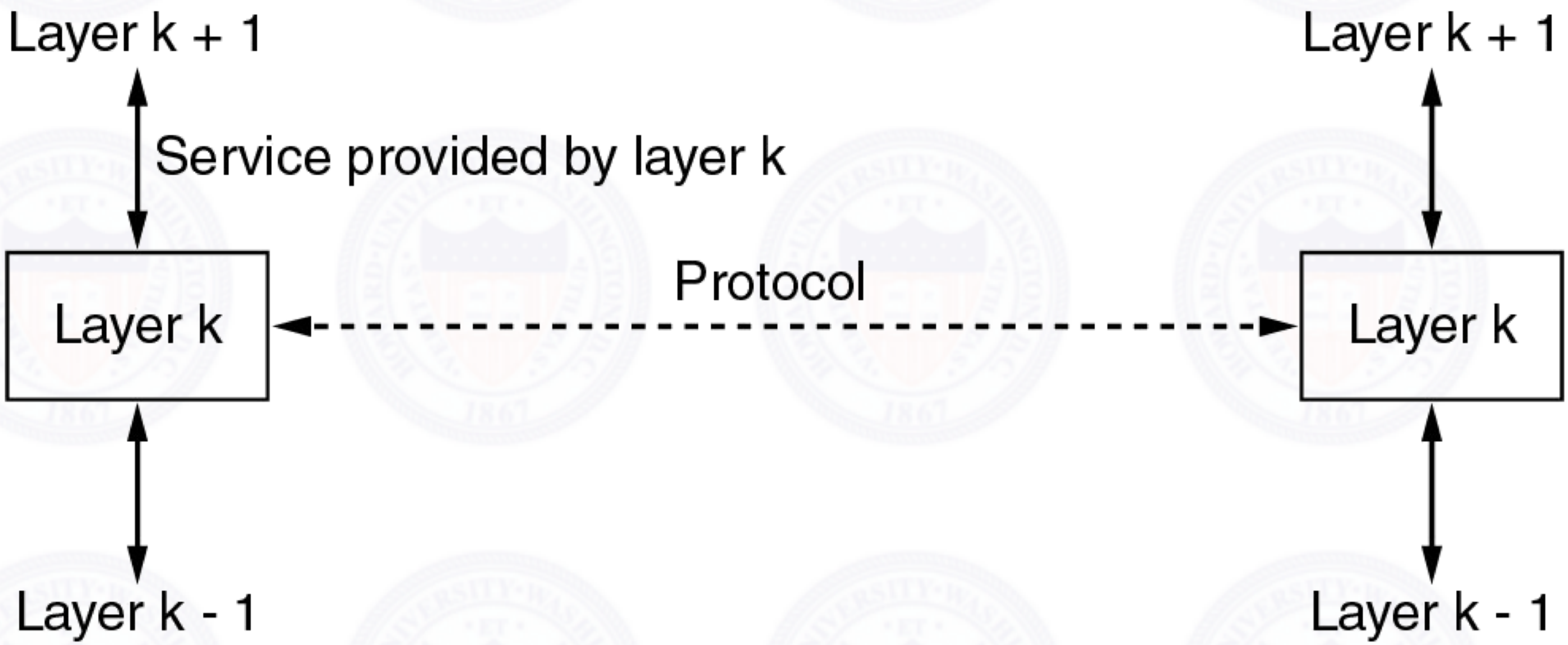


Network Software Protocol Hierarchies



Layers, protocols, and interfaces.

Services to Protocols Relationship

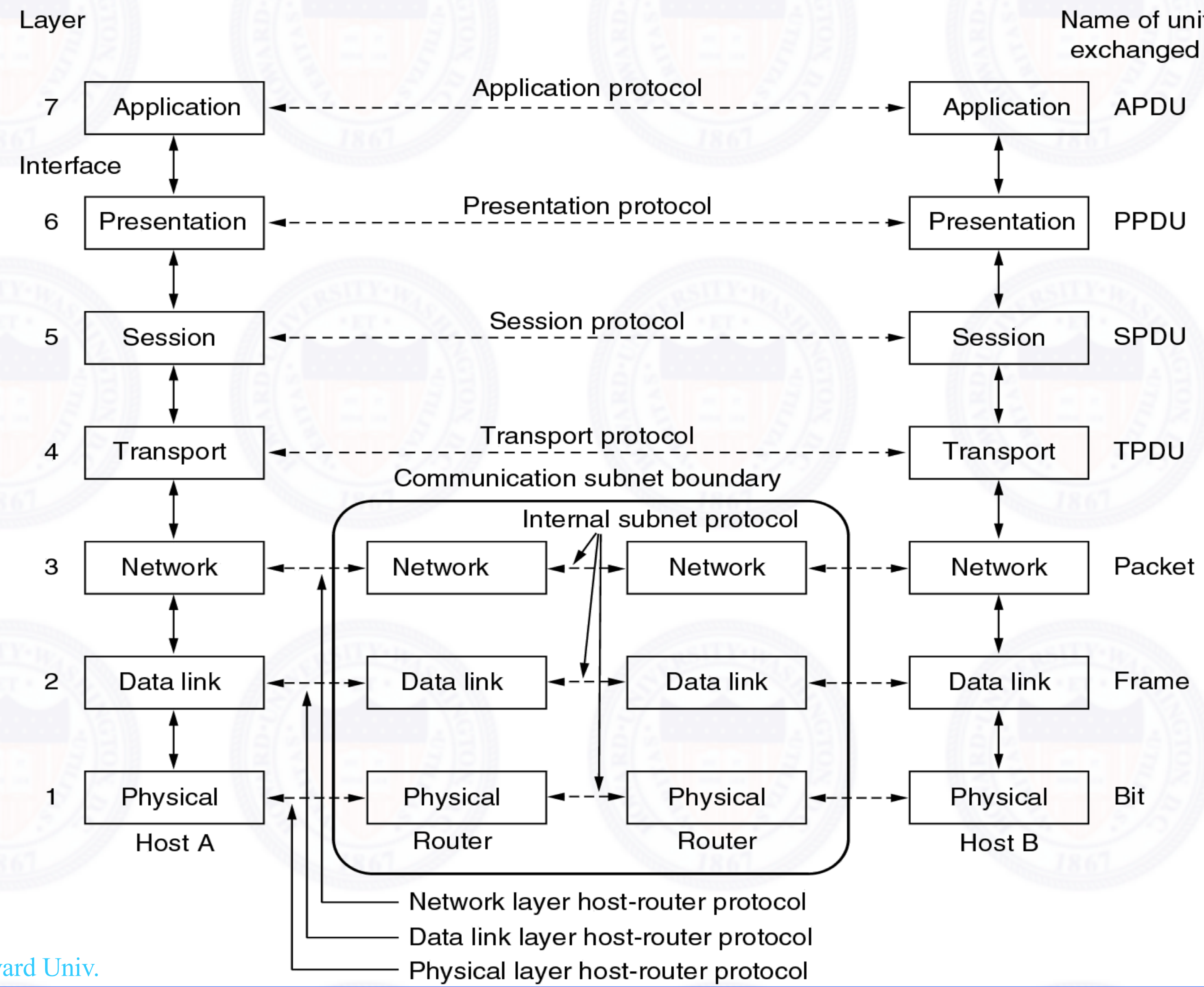


Why Layering?

Dealing with complex systems:

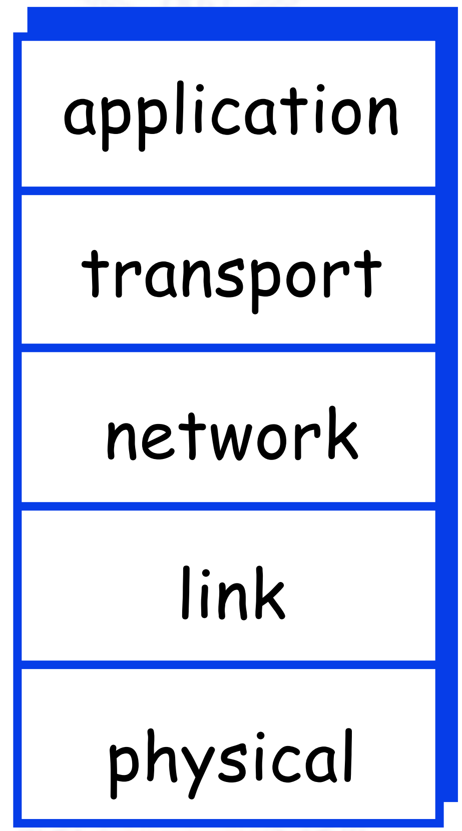
- Explicit structure allows identification, relationship of complex system's pieces
  - Layered reference model for discussion
- Modularization eases maintenance, updating of system
  - change of implementation of layer's service transparent to rest of system
  - e.g., change in translator doesn't affect rest of system
- Layering considered harmful?

The OSI Reference Model



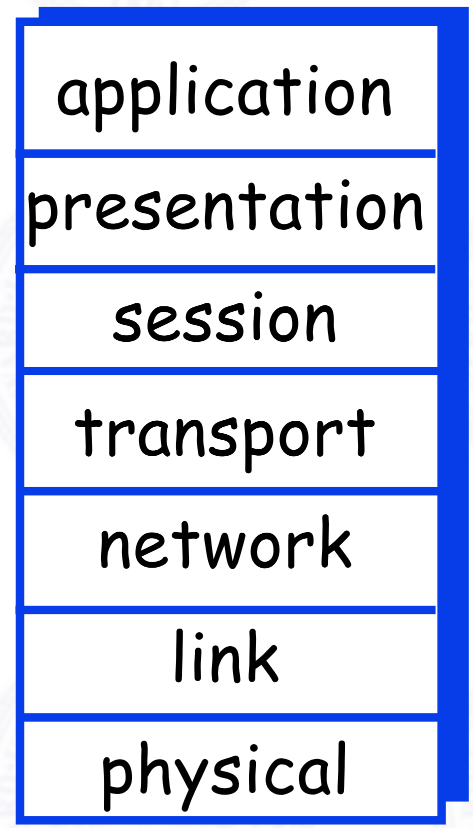
Internet Protocol Stack

- Application: supporting network applications (aware of app. semantics)
  - FTP, SMTP, HTTP, SSH
- Transport: process-process data transfer (rate ctrl, reliability)
  - TCP, UDP
- Network: routing of datagrams from source to destination over multi. hops
  - IP, routing protocols
- Link: data transfer between neighboring network elements (MAC, framing …)
  - PPP, Ethernet
- Physical: bits "on the wire"

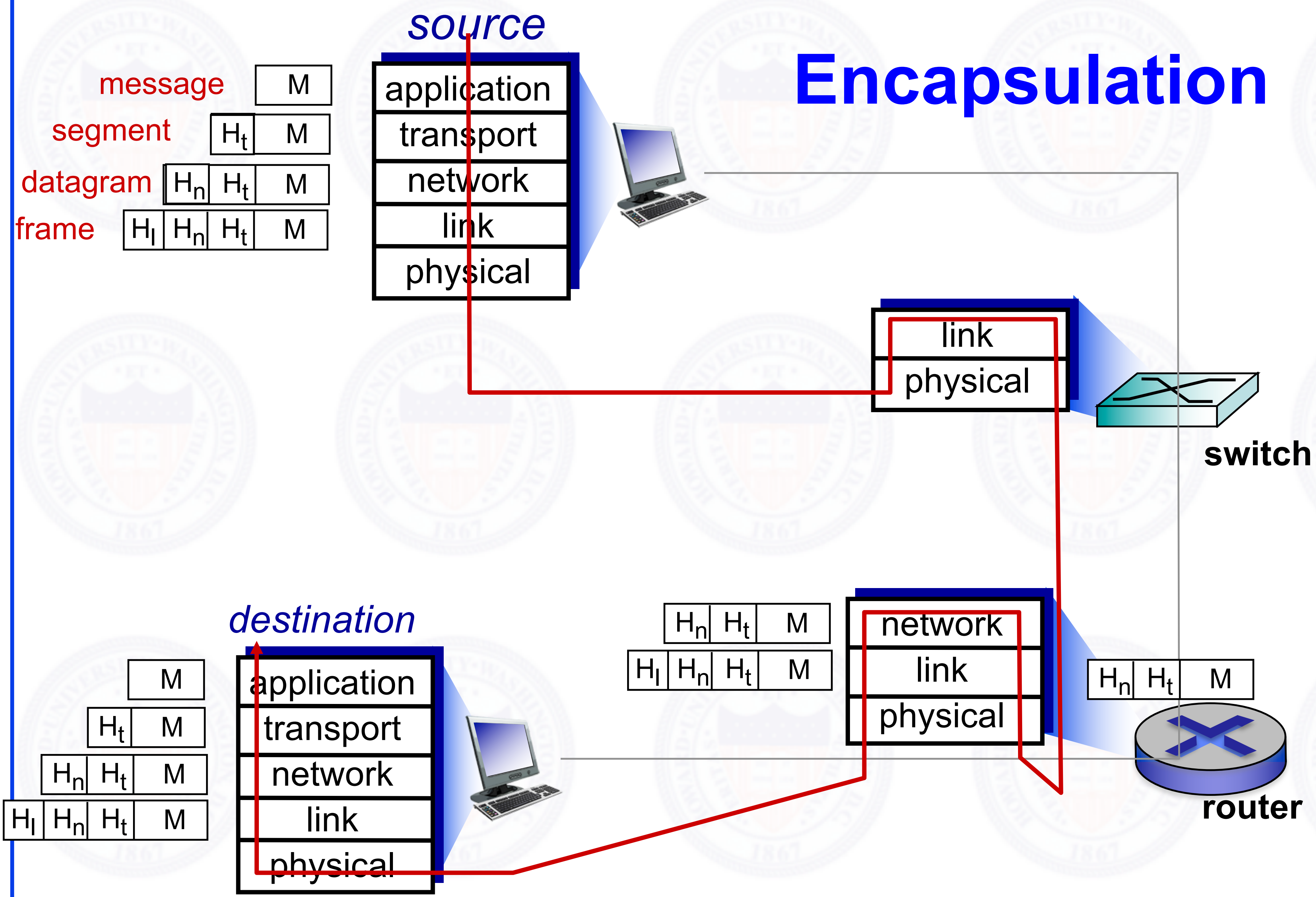


ISO/OSI reference model

- 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



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Network Security

- The field of network security is about:
  - How bad guys can attack computer networks
  - How we can defend networks against attacks
  - How to design architectures that are immune to attacks
- Internet not originally designed with (much) security in mind
  - *Original vision:* "a group of mutually trusting users attached to a transparent network" ☺
  - Internet protocol designers playing "catch-up"
  - Security considerations in all layers!

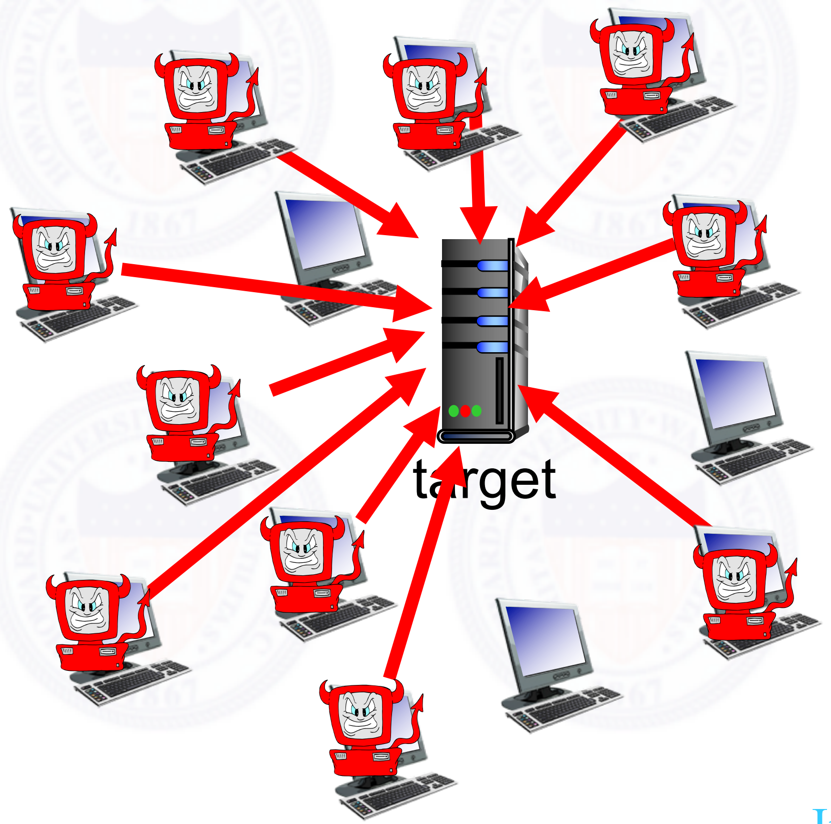
Bad guys: put malware into hosts via Internet

- Malware can get in host from:
  - *Virus:* self-replicating infection by receiving/executing object (e.g., e-mail attachment)
  - *Worm:* self-replicating infection by passively receiving object that gets itself executed
- Spyware malware can record keystrokes, web sites visited, upload info to collection site
- Infected host can be enrolled in botnet, used for spam, DDoS attacks

Bad guys: attack server, network infrastructure

Denial of Service (DoS): attackers make resources (server, bandwidth) unavailable to legitimate traffic by overwhelming resource with bogus traffic

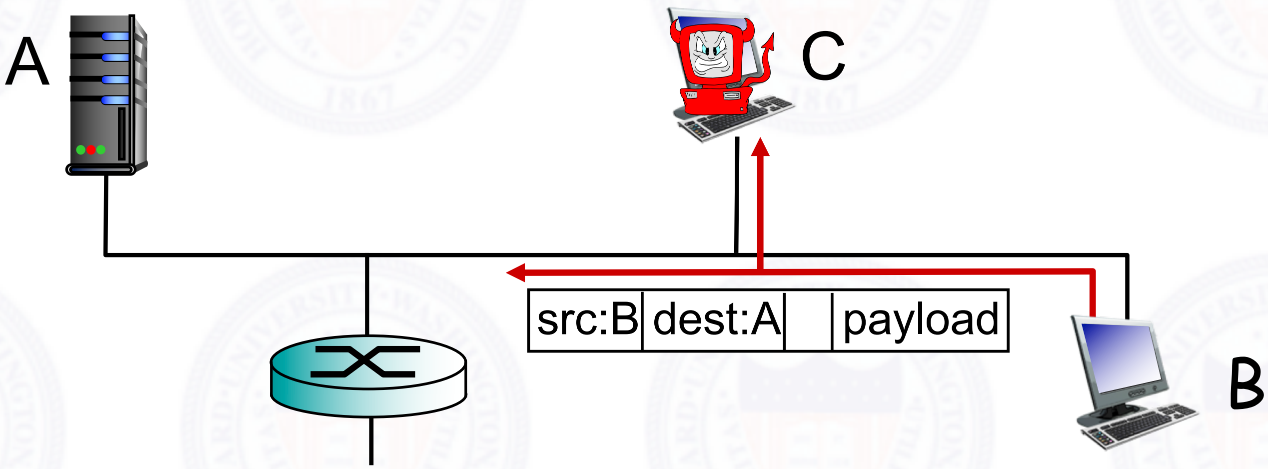
1. select target
2. break into hosts around the network (see botnet)
3. send packets to target from compromised hosts



Bad guys: sniff packets

Packet "sniffing":

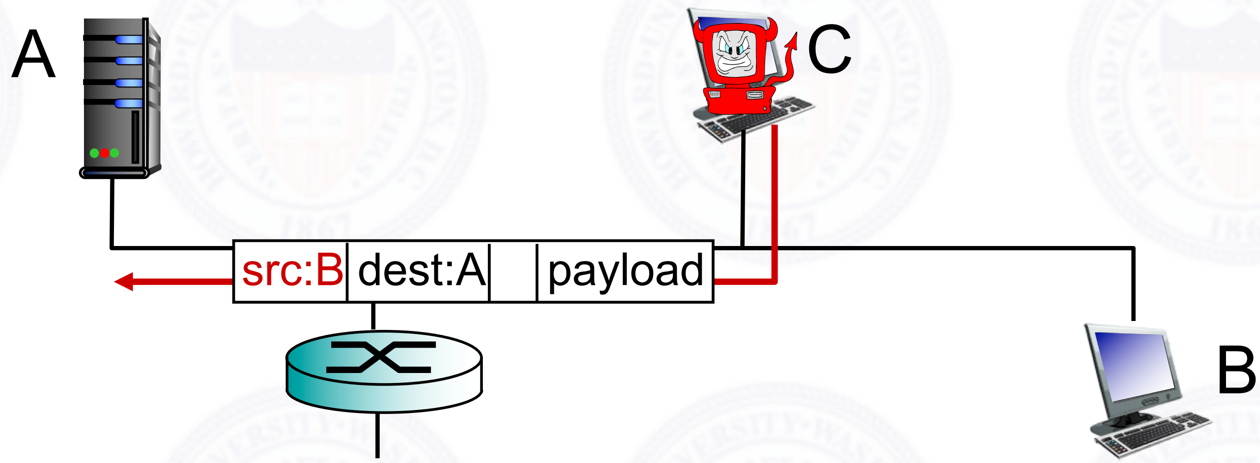
- Broadcast media (shared ethernet, wireless)
- Promiscuous network interface reads/records all packets (e.g., including passwords!) passing by



- Wireshark software used for end-of-chapter labs is a (free) packet-sniffer

Bad guys: use fake addresses

IP spoofing: send packet with false source address



… *lots more on security (throughout, Chapter 8)*

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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

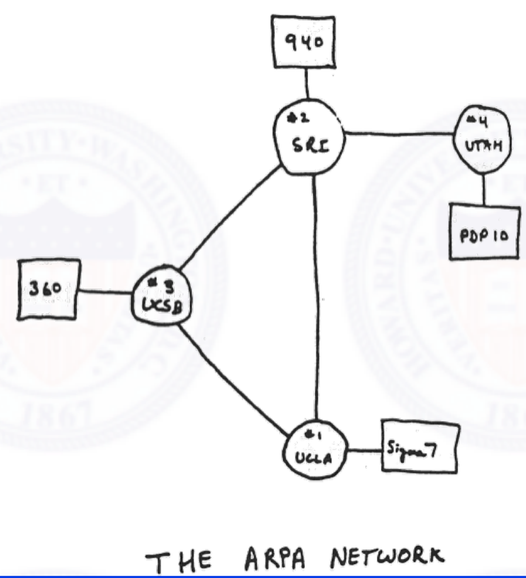
1.7 Protocol layers, service models

1.8 History

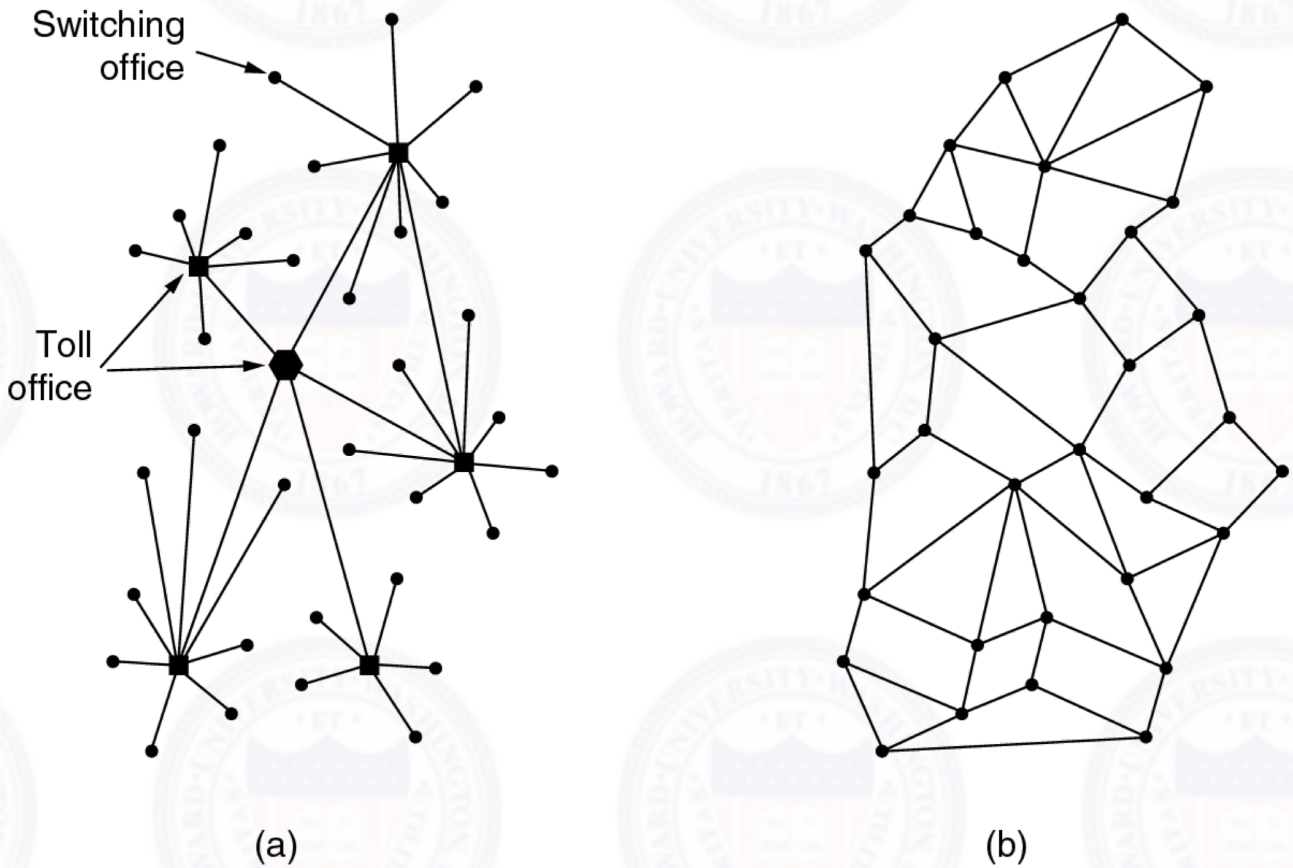
Internet History

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 demonstration
  - NCP (Network Control Protocol) first host-host protocol
  - first e-mail program
  - ARPAnet has 15 nodes



The ARPANET



(a) Structure of the telephone system.
(b) Baran's proposed distributed switching system.

Internet History

1972-1980: Internetworking, new and proprietary nets

- 1970: ALOHAnet satellite network in Hawaii
- 1974: Vinton Gray Cerf and Bob 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, email, etc.
- E-commerce, universities, enterprises running their services in "cloud" (eg, Amazon EC2)

Introduction: Summary

Covered a "ton" of material!

- Internet overview
- What's a protocol?
- Network edge, core, access network
  - Packet-switching versus circuit-switching
  - Internet structure
- Performance: loss, delay, throughput
- Layering, service models
- Security
- History

You now have:

- Context, overview, "feel" of networking
- More depth, detail *to follow!*