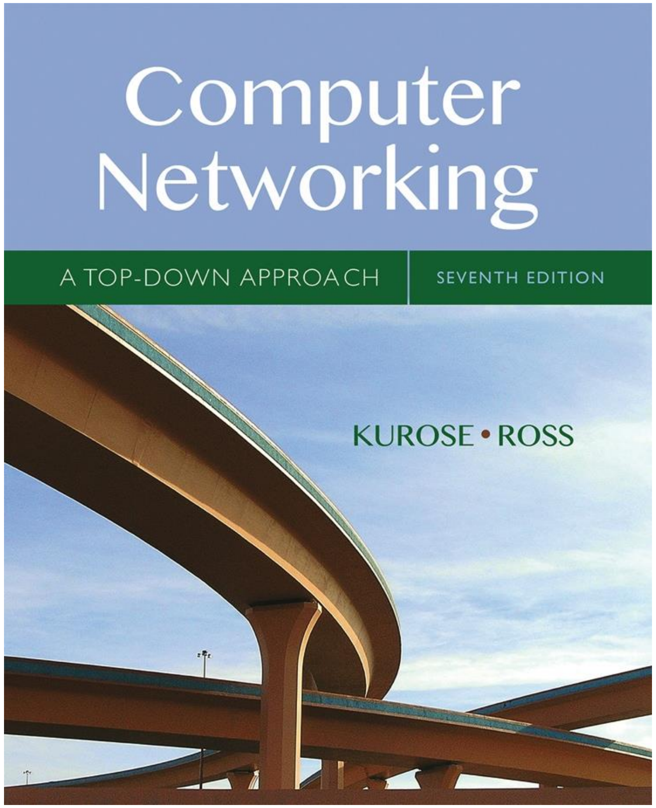
Chapter 1 Introduction



Computer Networking: A Top Down Approach

7th edition
Jim Kurose, Keith Ross
Pearson/Addison Wesley
April 2016

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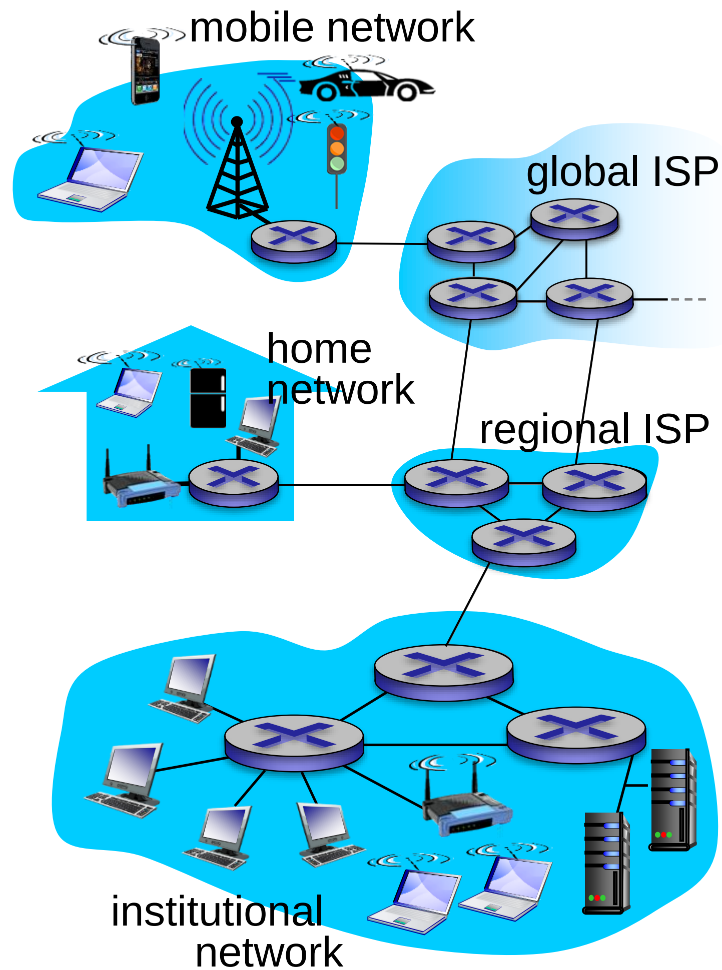
Thanks and enjoy! JFK/KWR

What is the Internet?

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

- billions of connected computing devices:
  - *hosts* = *end systems*
  - running *network apps*
- *communication links*
  - fiber, copper, radio, satellite
  - transmission rate: *bandwidth*
- *packet switches:* forward packets (chunks of data)
  - *routers* and *switches*



“Fun” Internet-connected devices

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

Web-enabled toaster +
weather forecaster

Tweet-a-watt:
monitor energy use

Internet
refrigerator

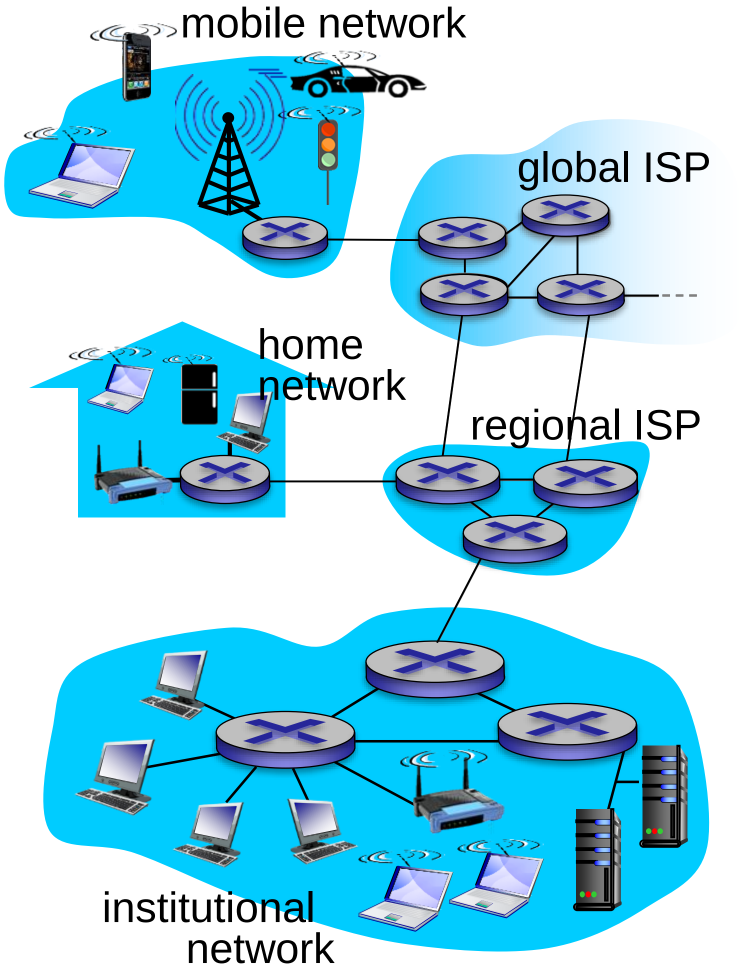
Slingbox: watch,
control cable TV remotely

sensorized,
bed
mattress

Internet phones

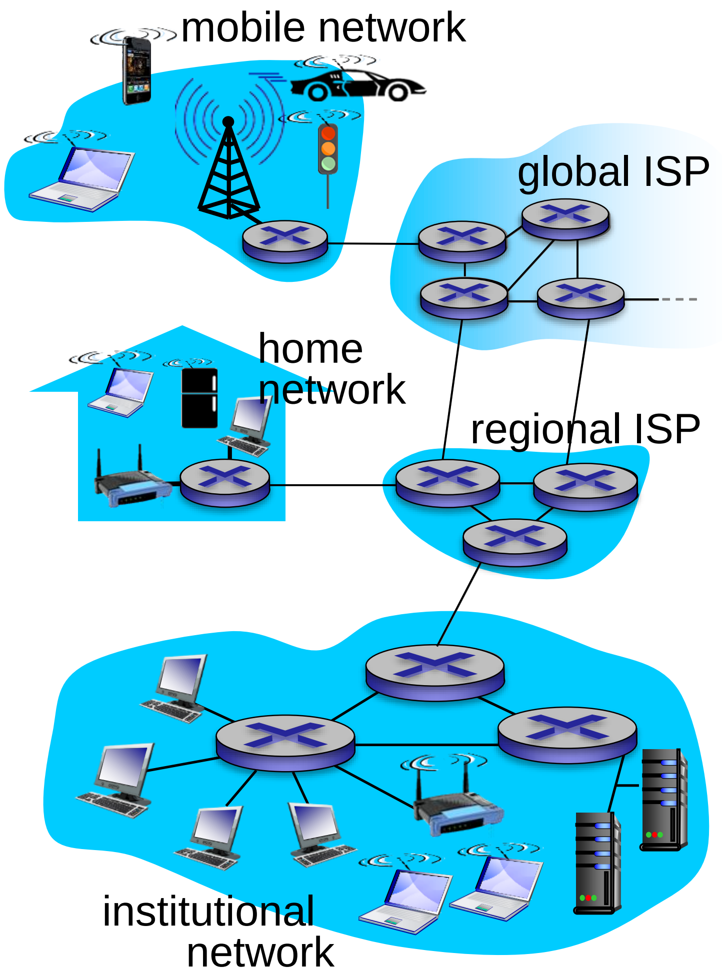
What's the Internet: "nuts and bolts" view

- *Internet:* "network of networks"
  - Interconnected ISPs
- *protocols* control sending, receiving of messages
  - e.g., TCP, IP, HTTP, Skype, 802.11
- *Internet standards*
  - RFC: Request for comments
  - IETF: Internet Engineering Task Force



What's the Internet: a service view

- *infrastructure that provides services to applications:*
  - Web, VoIP, email, games, e-commerce, social nets, …
- *provides programming interface to apps*
  - hooks that allow apps to "connect" to Internet
  - provides service options, analogous to postal service



What's a protocol?

human protocols:

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

… specific messages sent

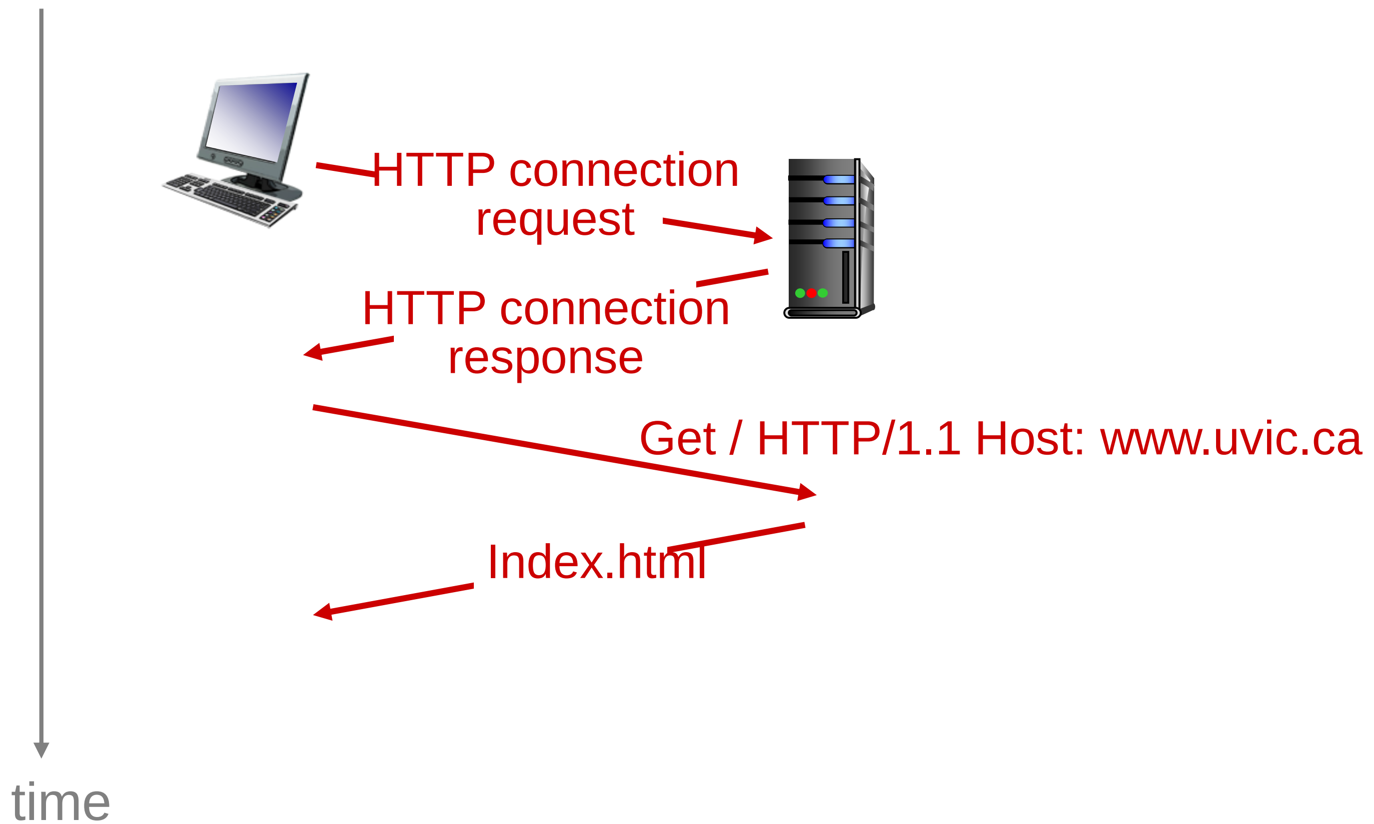
… specific actions taken when messages received, or other events

network protocols:

- machines rather than humans
- all communication activity in Internet governed by protocols

protocols define format, order of messages sent and received among network entities, and actions taken on message transmission, receipt

What's a protocol?



```
MacBook-Pro-Retina-Mantis:~ mcheng$ telnet info.cern.ch 80
Trying 188.184.64.53...
Connected to webafs624.cern.ch.
Escape character is '^]'.
GET / HTTP/1.1
Host: info.cern.ch

HTTP/1.1 200 OK
Date: Tue, 15 Aug 2017 03:21:54 GMT
Server: Apache
Last-Modified: Wed, 05 Feb 2014 16:00:31 GMT
ETag: "40521bd2-286-4f1aadb3105c0"
Accept-Ranges: bytes
Content-Length: 646
Connection: close
Content-Type: text/html

<html><head></head><body><header>
<title>http://info.cern.ch</title>
</header>

<h1>http://info.cern.ch - home of the first website</h1>
```

connection request

connection response

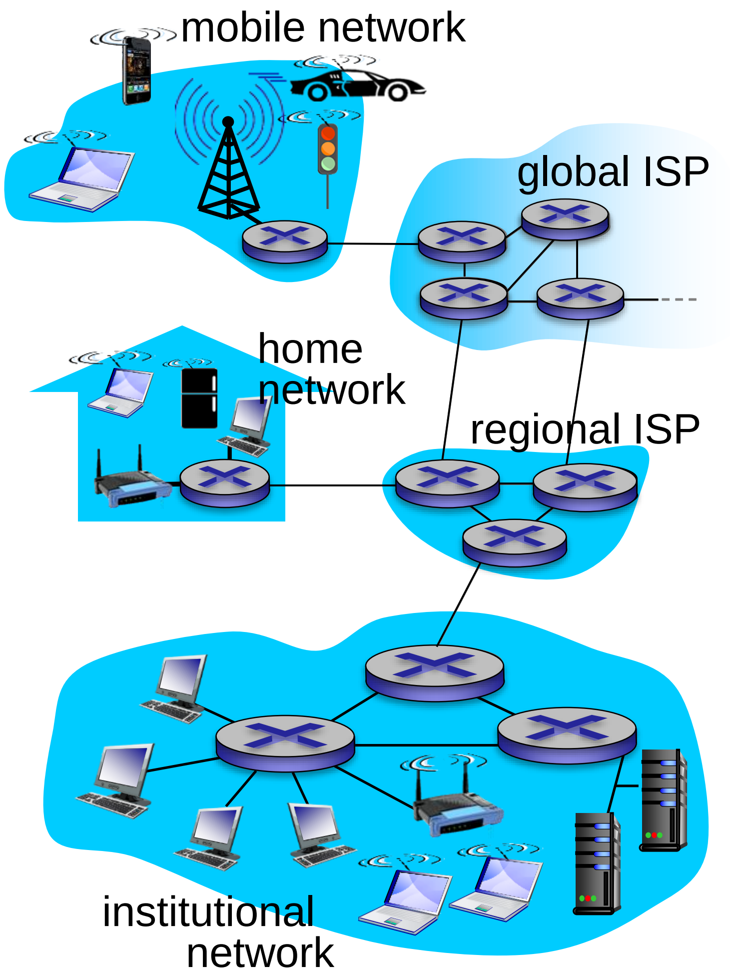
HTTP request

HTTP response

Network Technologies and Structures

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



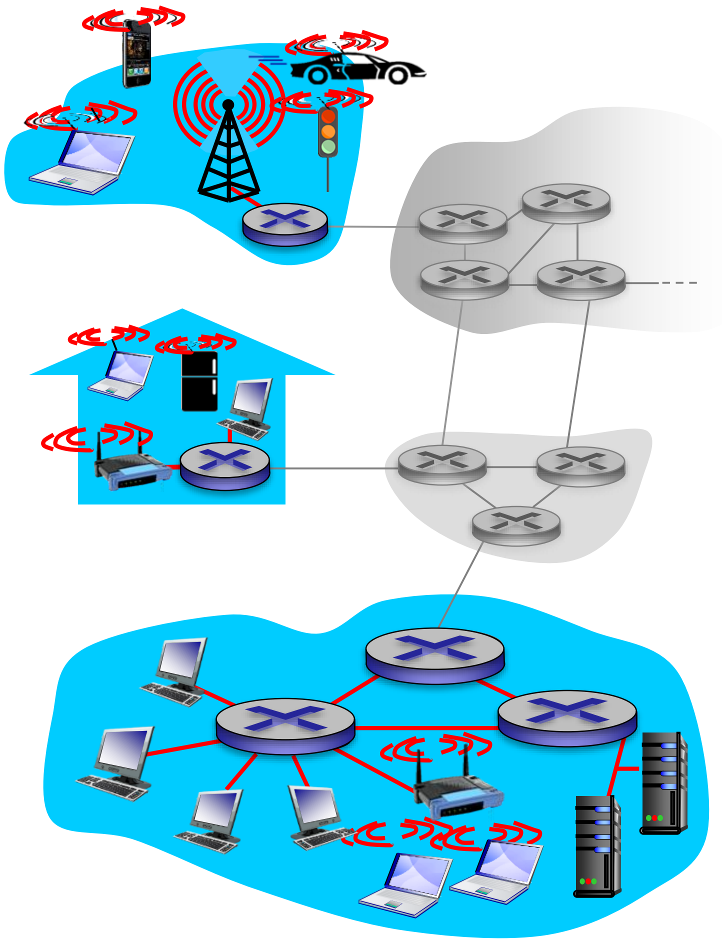
Access networks and physical media

Q: How to connect end systems to edge routers?

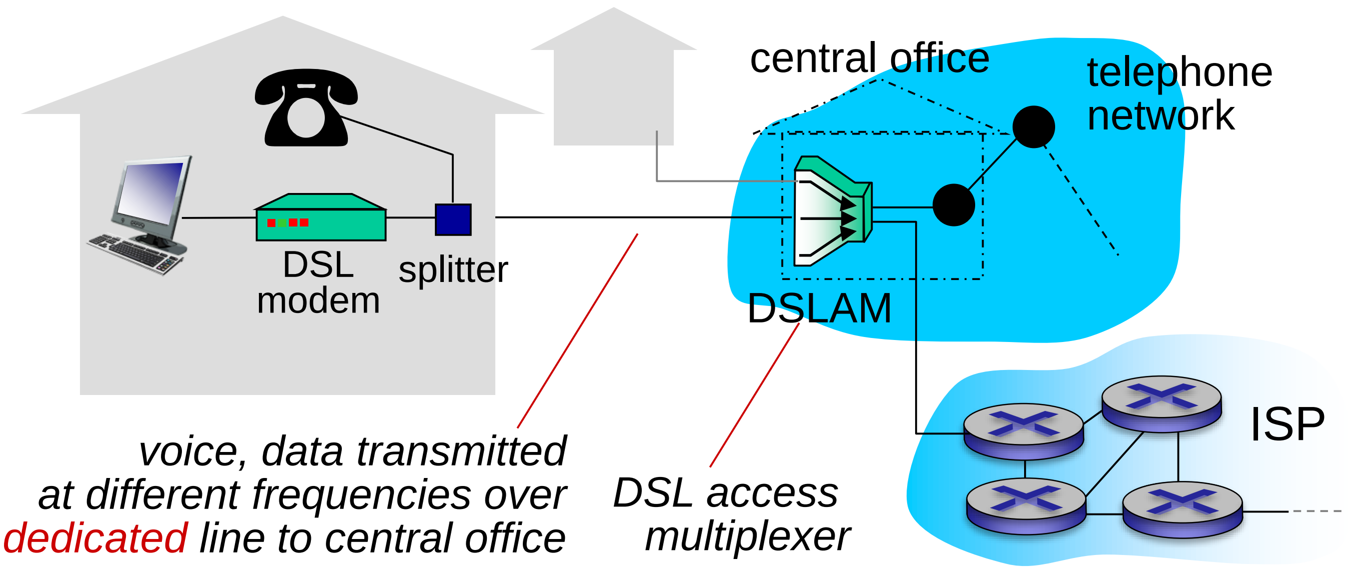
- residential access nets
- institutional access networks (school, company)
- mobile access networks

keep in mind:

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

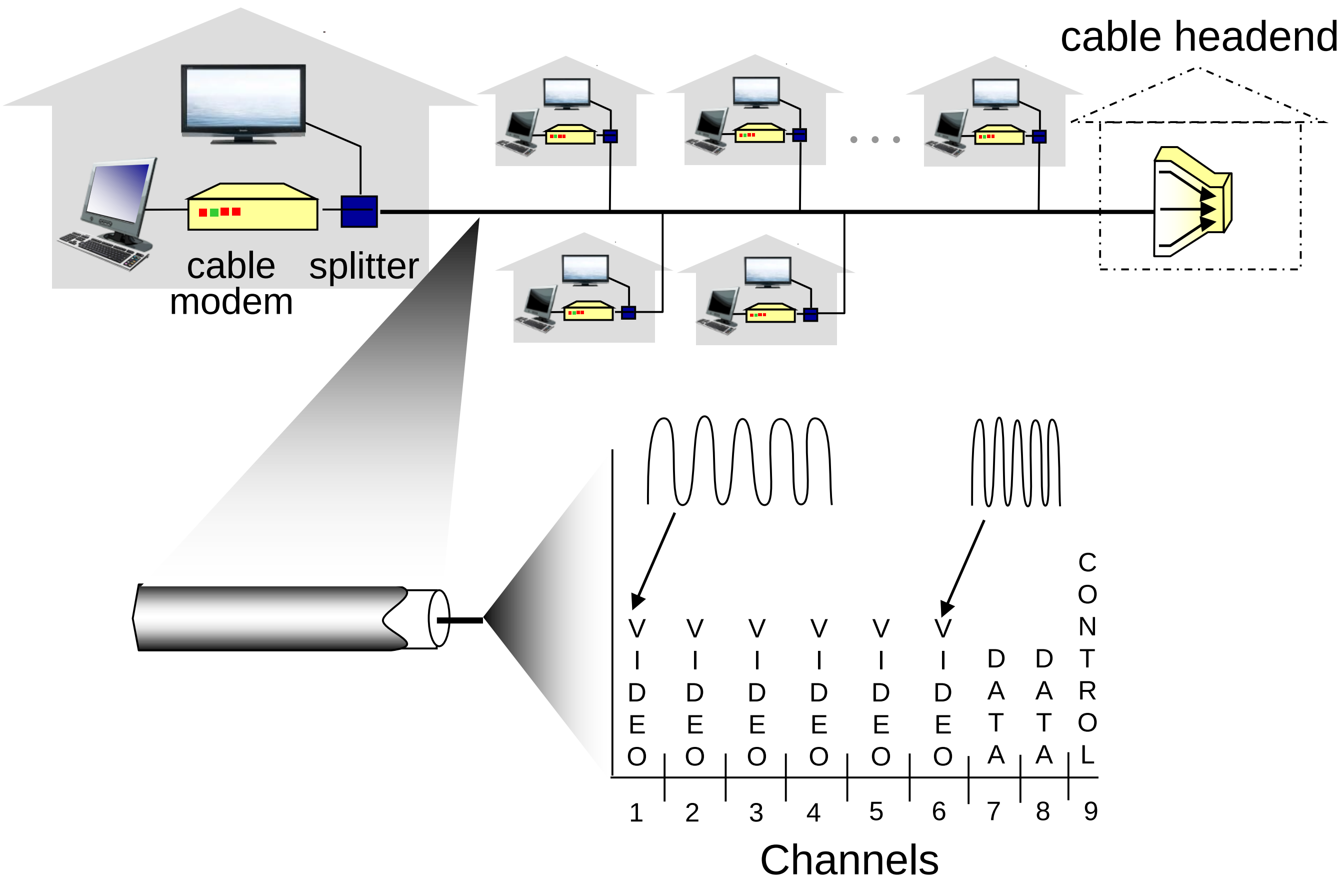


Access network: digital subscriber line (DSL)



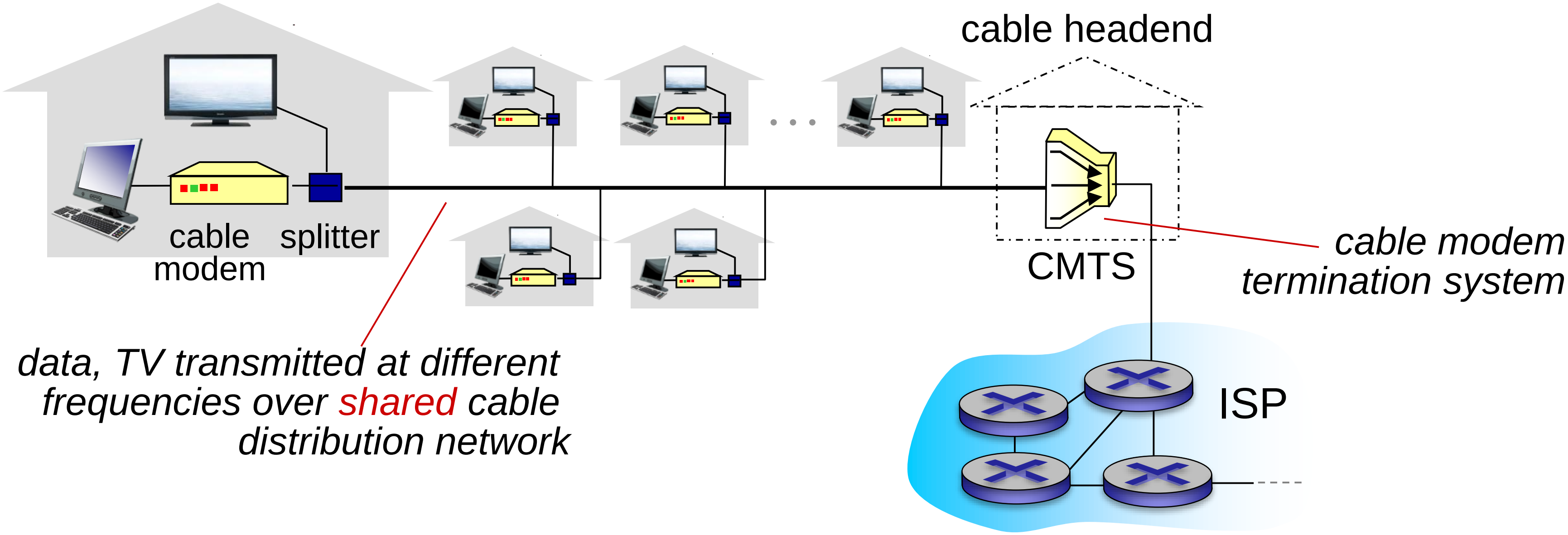
- use *existing* telephone line to central office DSLAM
  - data over DSL phone line goes to Internet
  - voice over DSL phone line goes to telephone net
- < 2.5 Mbps upstream transmission rate (typically < 1 Mbps)
- < 24 Mbps downstream transmission rate (typically < 10 Mbps)

Access network: cable network



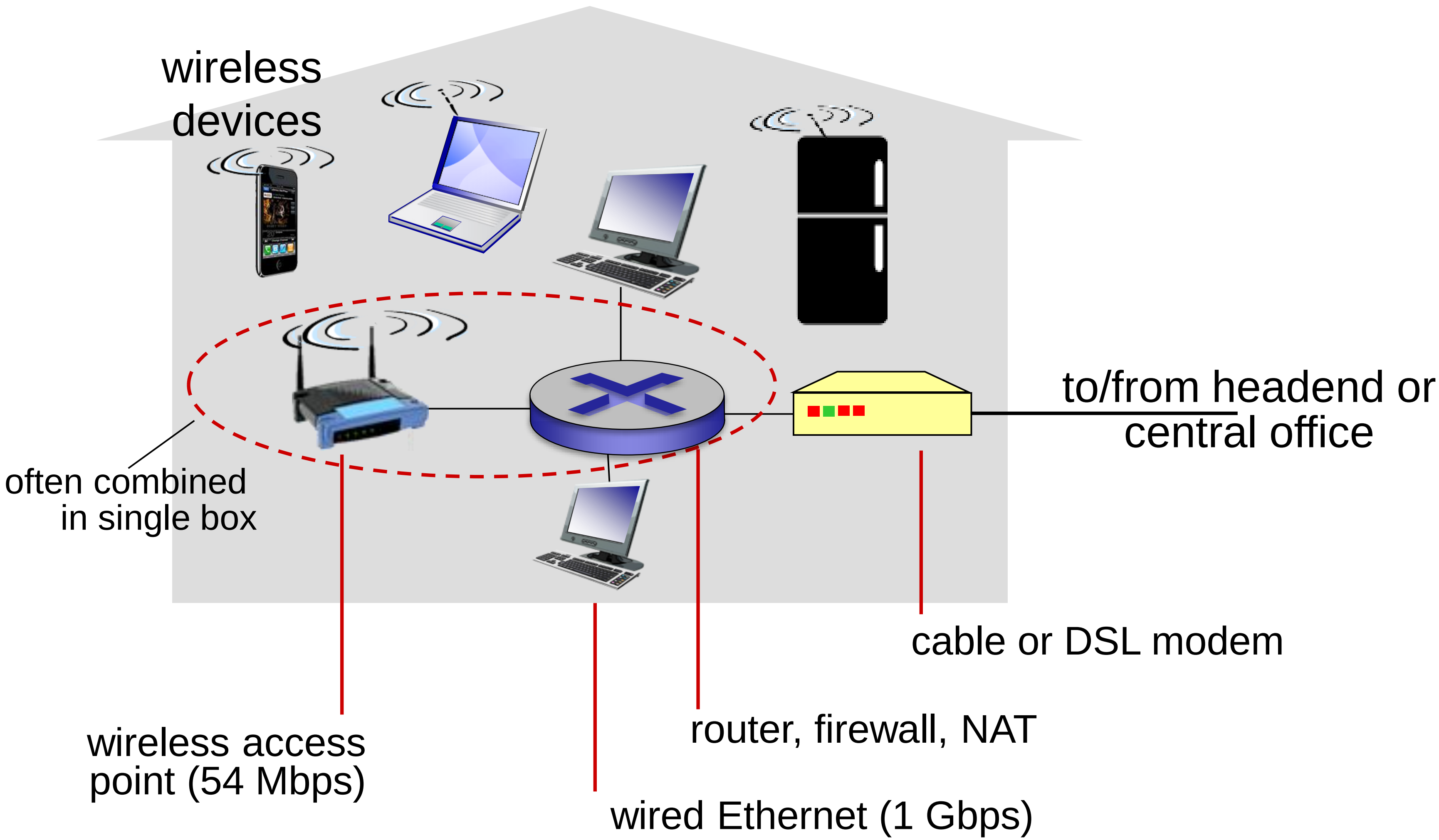
frequency division multiplexing: different channels transmitted in different frequency bands

Access network: cable network

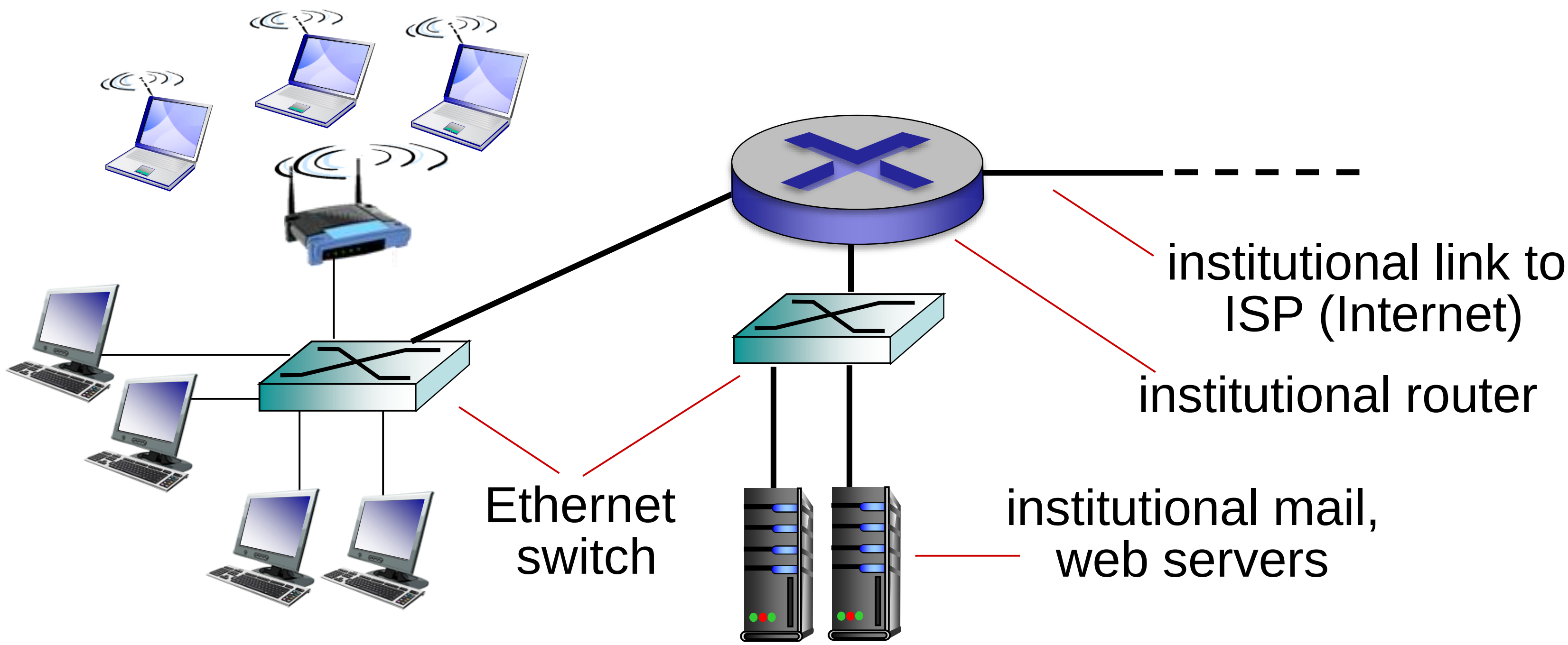


- HFC: hybrid fiber coax
  - asymmetric: up to 30Mbps downstream transmission rate, 2 Mbps upstream transmission rate
- network of cable, fiber attaches homes to ISP router
  - homes *share access network* to cable headend
  - unlike DSL, which has dedicated access to central office

Access network: home network



Enterprise access networks (Ethernet)



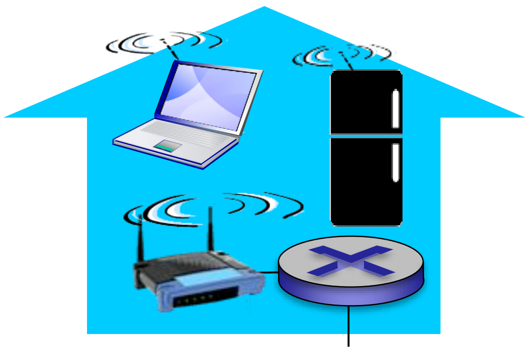
- typically used in companies, universities, etc.
- 10 Mbps, 100Mbps, 1Gbps, 10Gbps transmission rates
- today, end systems typically connect into Ethernet switch

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/n (WiFi): 11, 54, 450 Mbps transmission rate



to Internet

wide-area wireless access

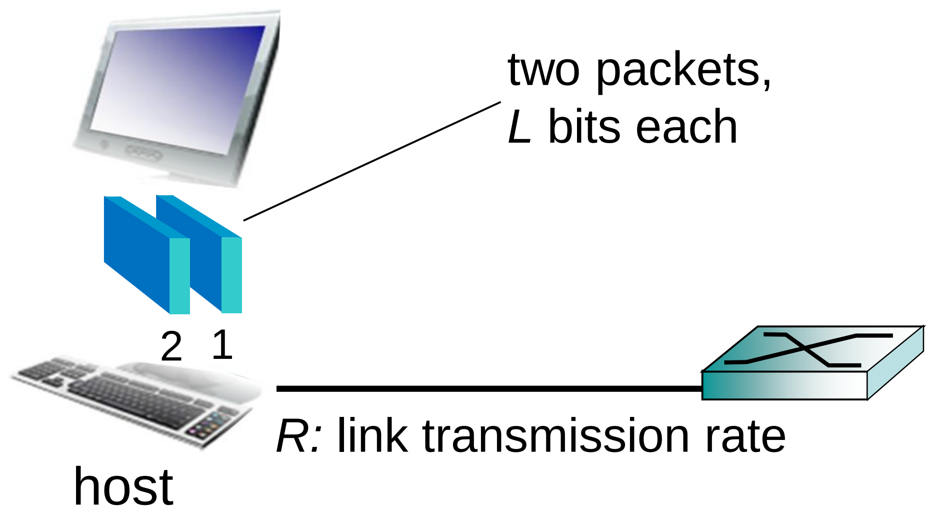
- provided by telco (cellular) operator, 10s km
- between 1 and 10 Mbps
- 3G, 4G: LTE

to Internet

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/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

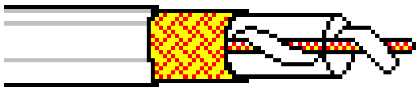
twisted pair (TP)

- two insulated copper wires
  - Category 5: 100 Mbps, 1 Gbps 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 Gbps transmission rate)
- low error rate:
  - repeaters spaced far apart
  - immune to electromagnetic noise

Physical media: radio

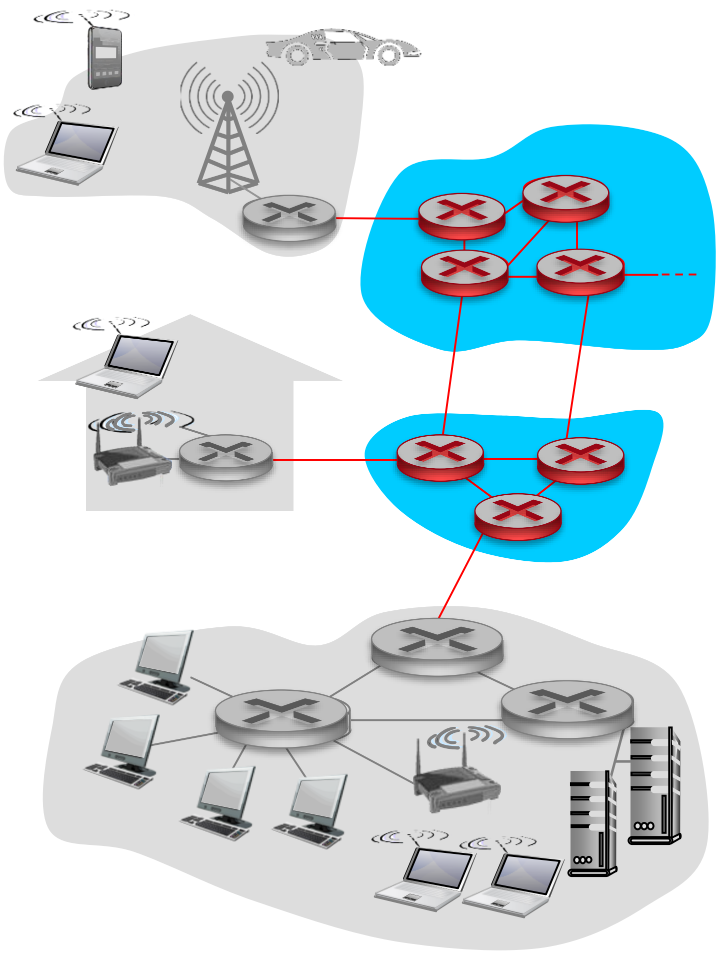
- signal carried in electromagnetic spectrum
- no physical “wire”
- bidirectional
- propagation environment effects:
  - reflection
  - obstruction by objects
  - interference

radio link types:

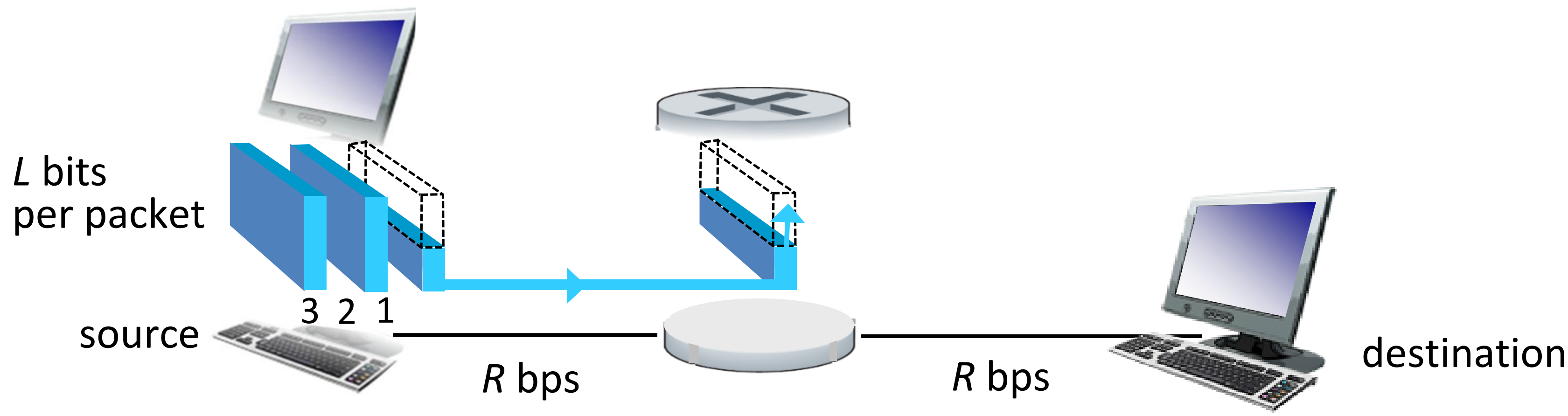
- terrestrial microwave
  - e.g. up to 45 Mbps channels
- LAN (e.g., WiFi)
  - 54 Mbps
- wide-area (e.g., cellular)
  - 4G cellular: ~ 10 Mbps
- satellite
  - Kbps to 45Mbps channel (or multiple smaller channels)
  - 270 msec end-end delay
  - geosynchronous versus low altitude

The network core

- mesh of interconnected routers
- packet-switching: hosts break application-layer messages into *packets*
  - **store and then forward** packets from one router to the next
  - each packet transmitted at **full** link capacity



Packet-switching: store-and-forward



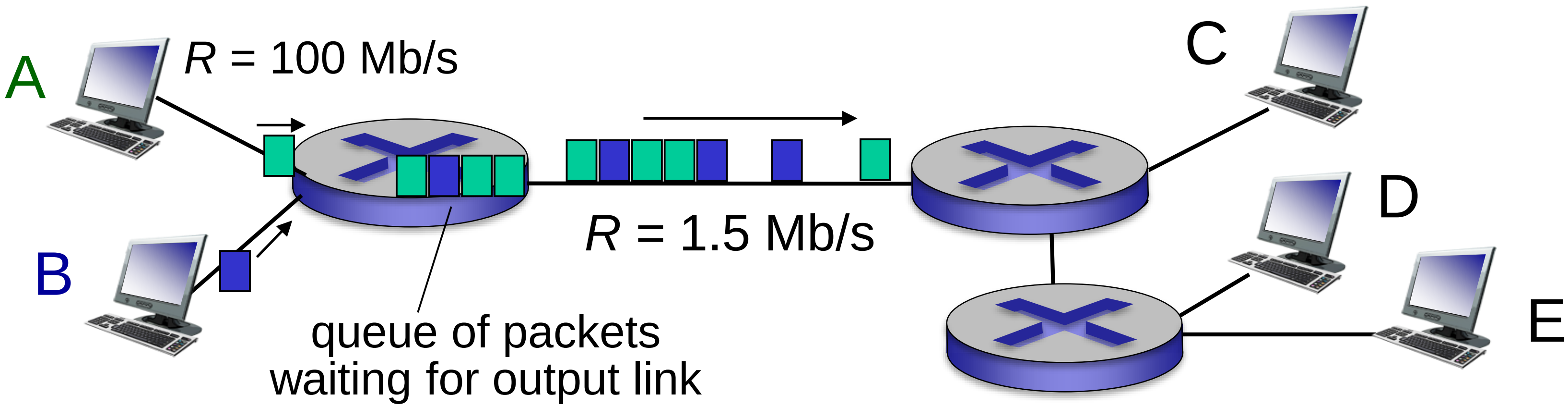
- takes *L*/*R* seconds to transmit (push out) *L*-bit packet into link at *R* bps
- *store and forward:* **entire** packet must arrive at router before it can be transmitted
- end-end delay = 2 (hops) x *L*/*R* (assume **zero** propagation delay)

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:

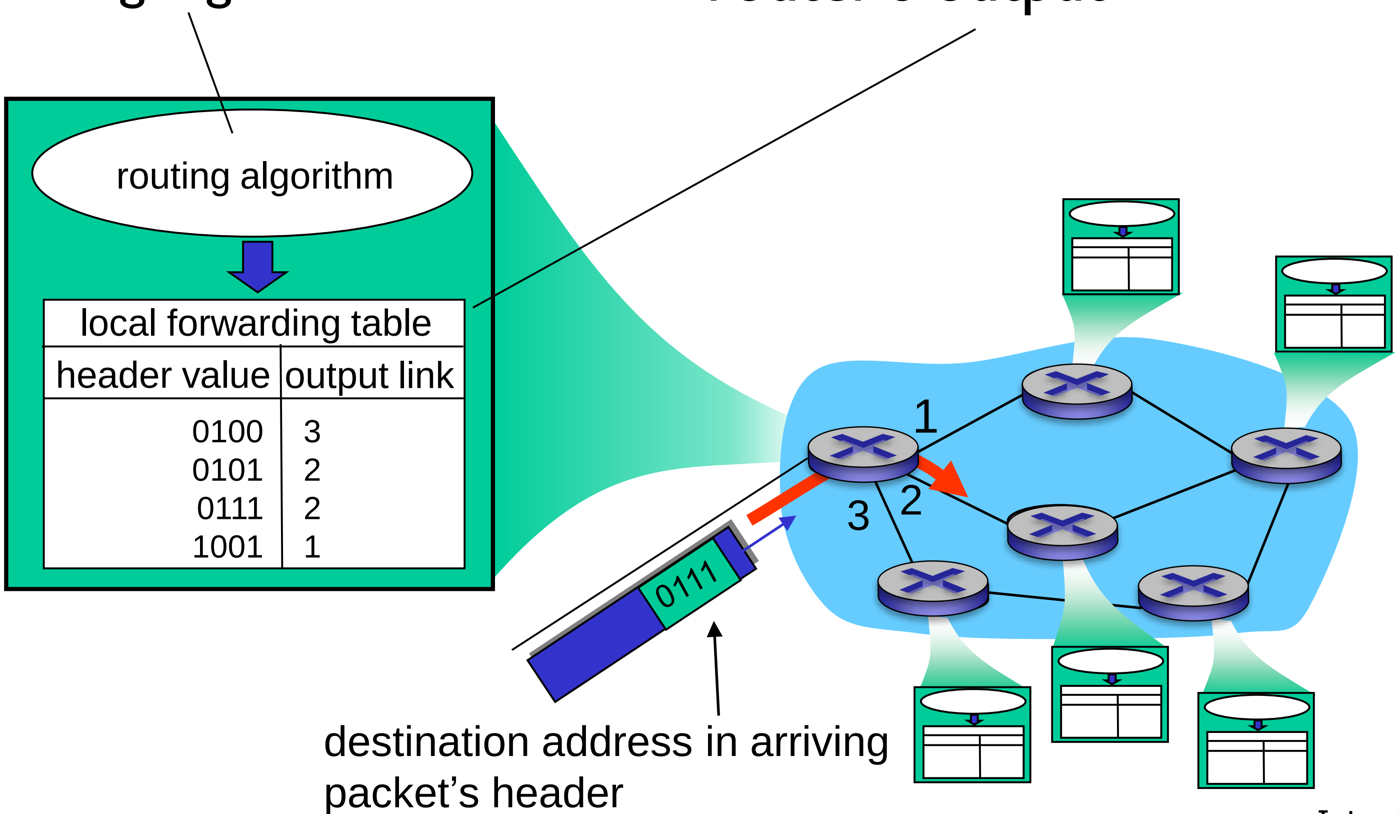
- if aggregated (A and B) **arrival** rate (in bits) exceeds **transmission** rate for a period of time:
  - packets will be **queued**, or
  - packets can be **dropped** if internal buffer is full

Two key network-core functions

routing: determines source-destination route taken by packets

- *routing algorithms*

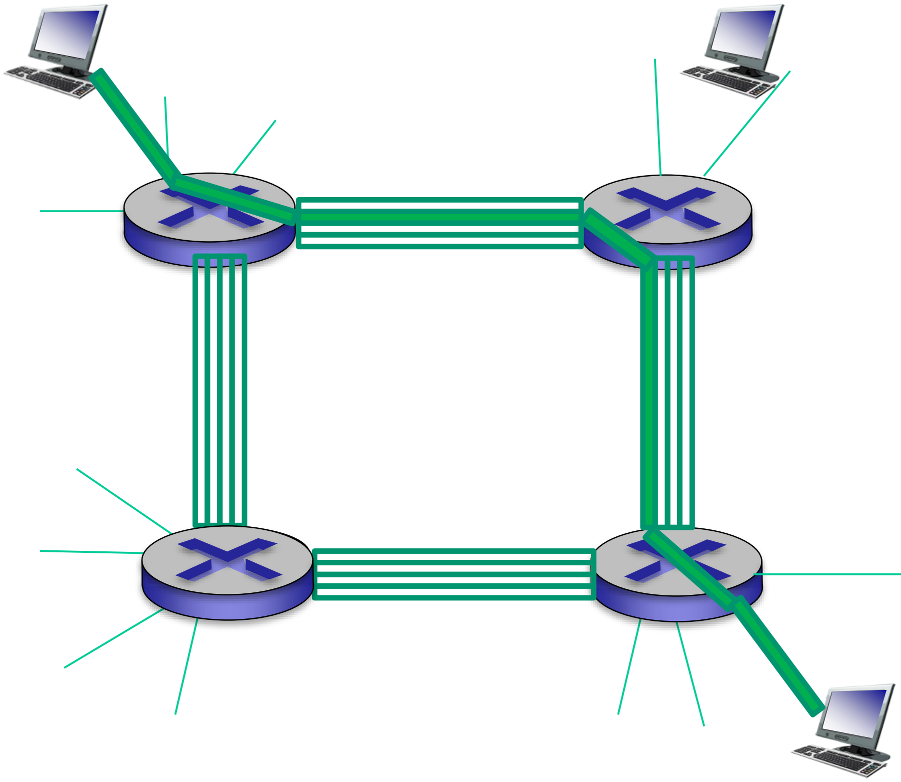
forwarding: move packets from router's input to appropriate router's output



Alternative core: circuit switching

end-end resources reserved for “call” between source & destination:

- in diagram, each link has four circuits.
- dedicated resources:
  - guaranteed performance
  - no sharing, except the dedicated source/dest.
- circuit idle during silence, used in traditional telephone networks

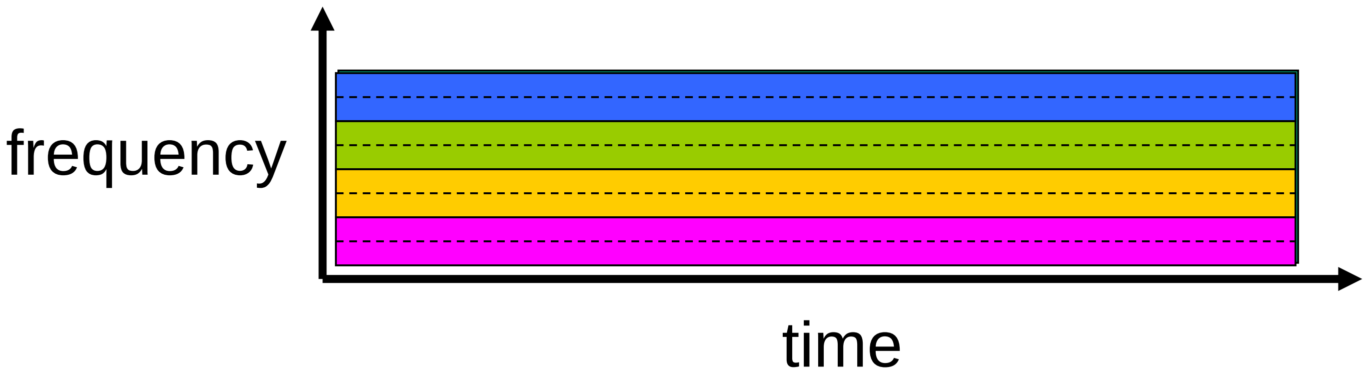


Circuit switching: FDM versus TDM

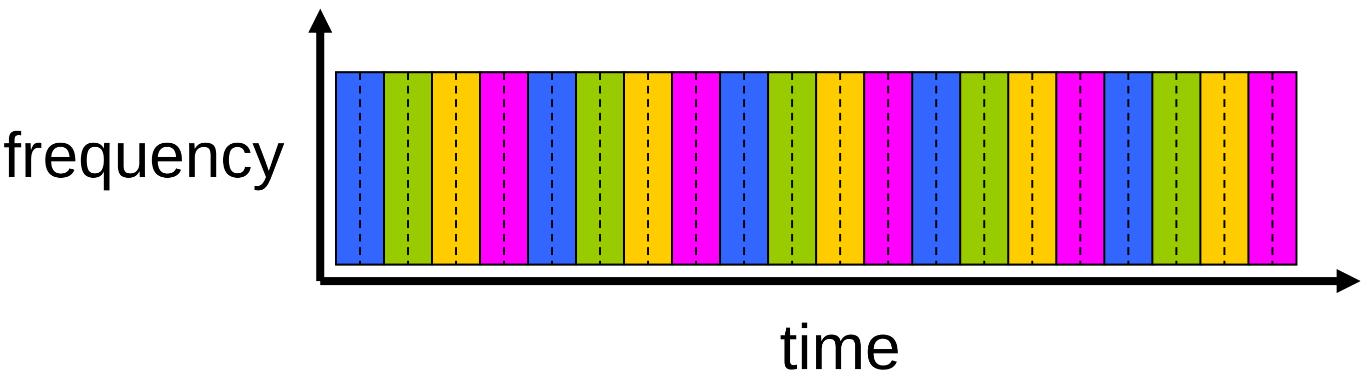
Example:

4 users

FDM



TDM

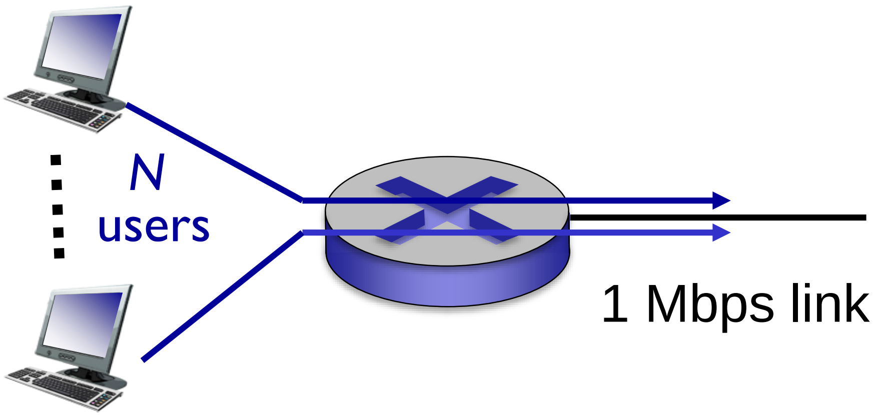


*Note: Each user shares equal amount of bandwidth.

Packet switching versus circuit switching

packet switching allows more concurrent users to use network!

example:
- 1 Mbps link
- each user:
  - 100 kbps (max) when "active"
  - but only active 10% of time



- *circuit-switching:*
  - 10 users (TDM or FDM)
- *packet switching:*
  - with 35 users, probability of more than 10 users are sending/receiving is low

* Check out the online exercises: http://gaia.cs.umass.edu/kurose_ross/interactive/

Packet switching versus circuit switching

Q. is packet switching a “slam dunk winner?”

- great for bursty data
  - resource sharing
  - simpler, no call (or circuit) 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

Internet structure: network of networks

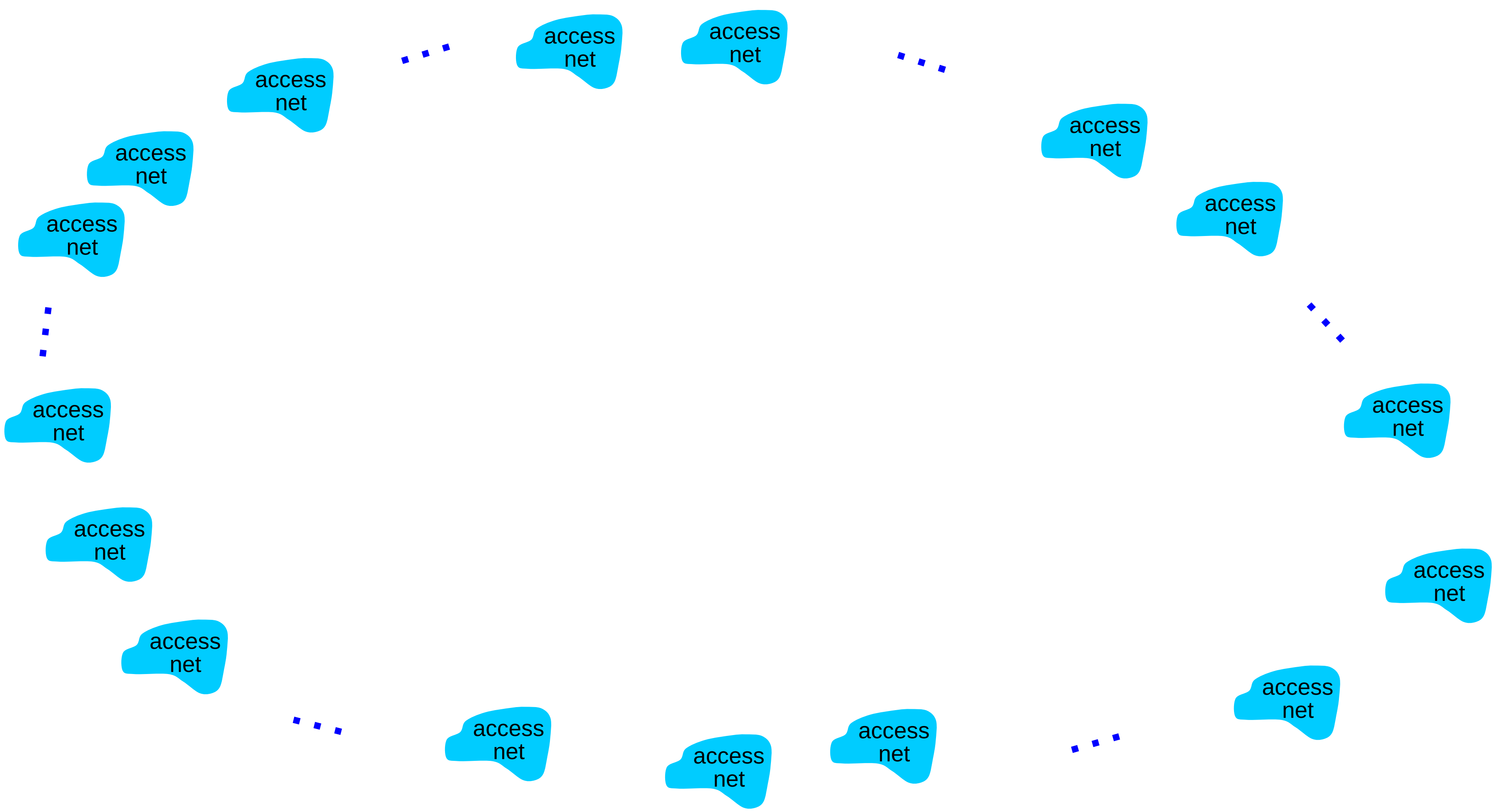
- End systems connect to Internet via access ISPs (Internet Service Providers)

- Access ISPs in turn must be interconnected; so any two hosts can send packets to each other

- Resulting network of networks is very complex

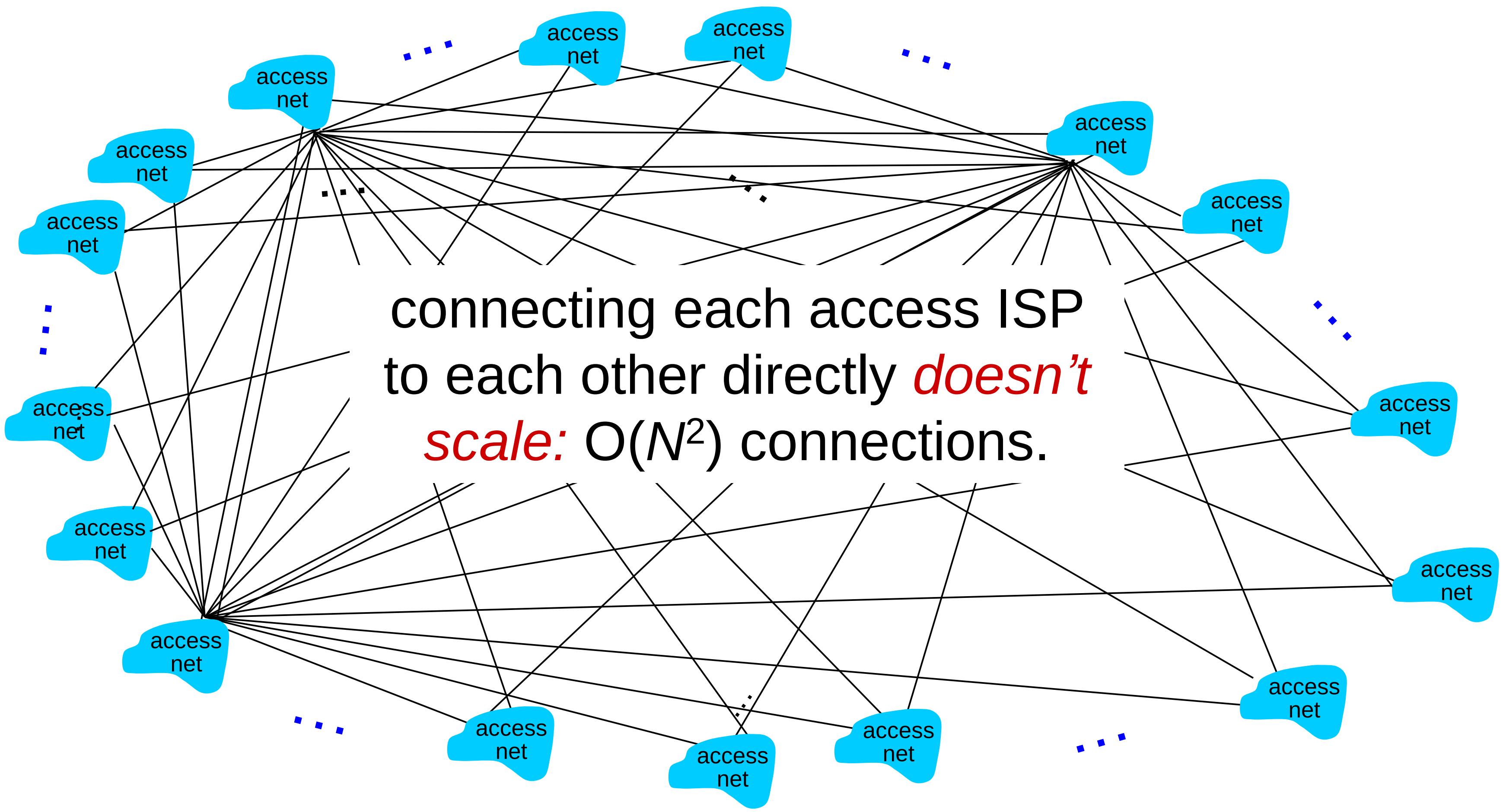
Internet structure: network of networks

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



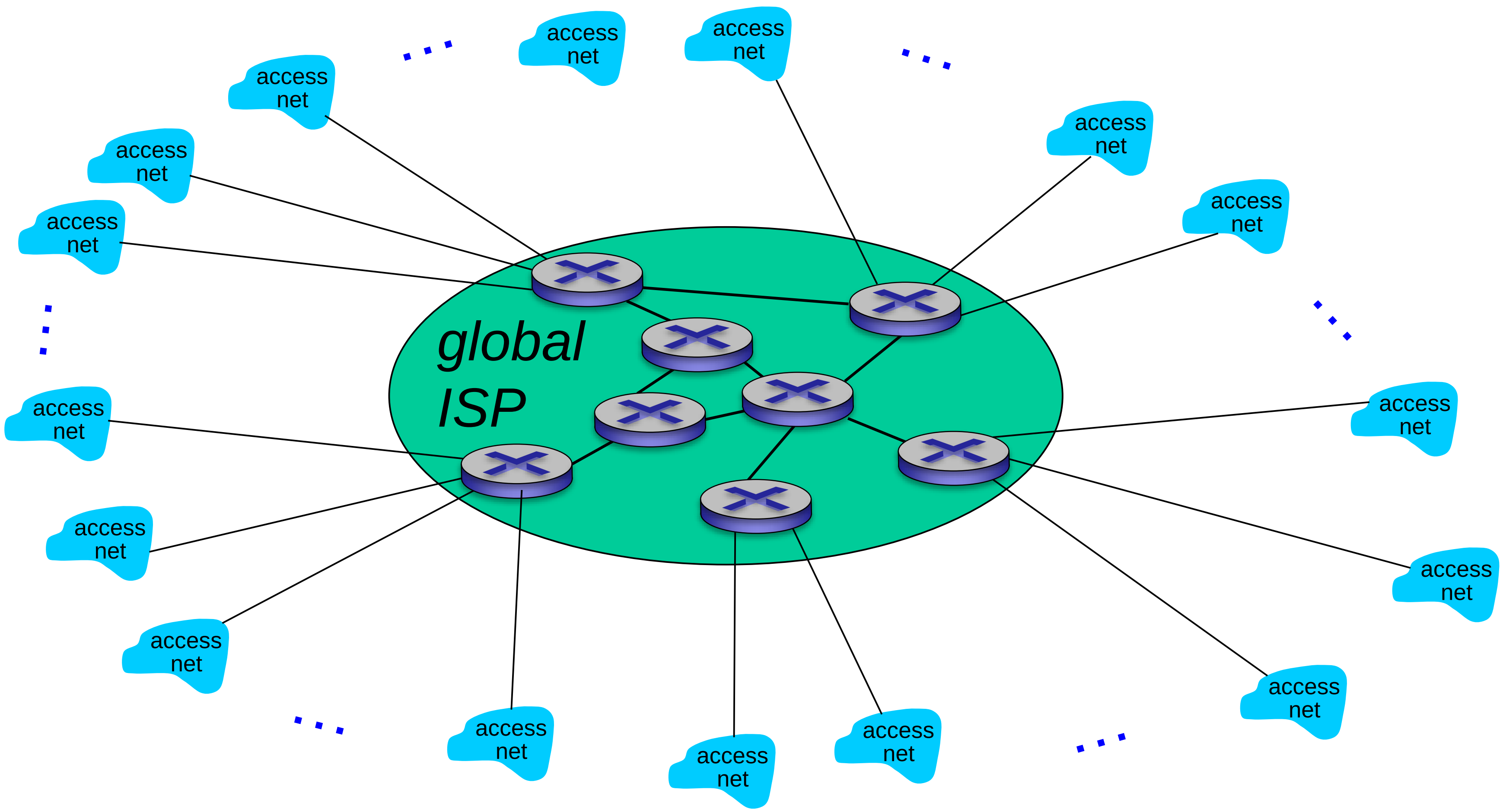
Internet structure: network of networks

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



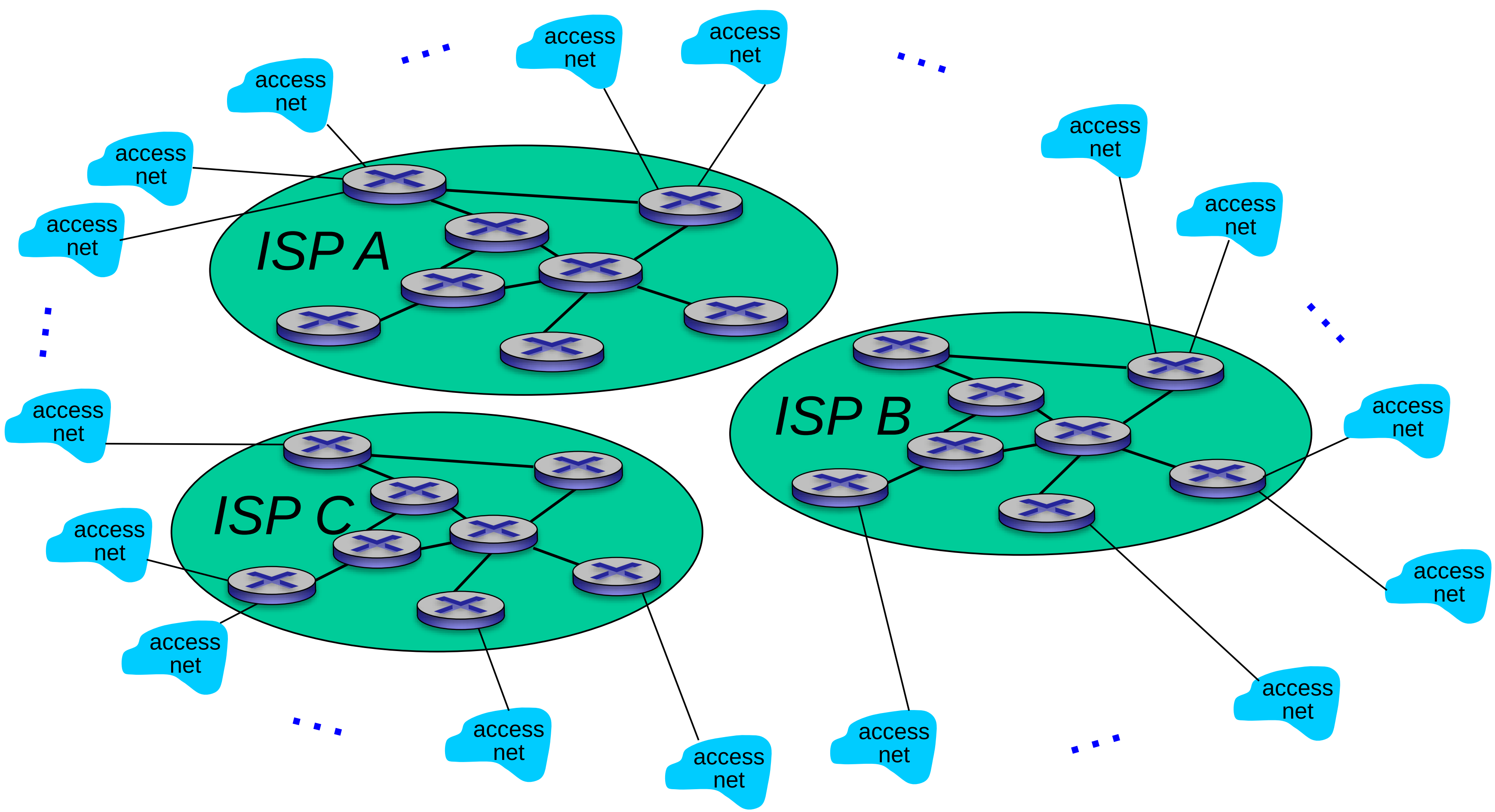
Internet structure: network of networks

Option: connect each access ISP to one global transit ISP?



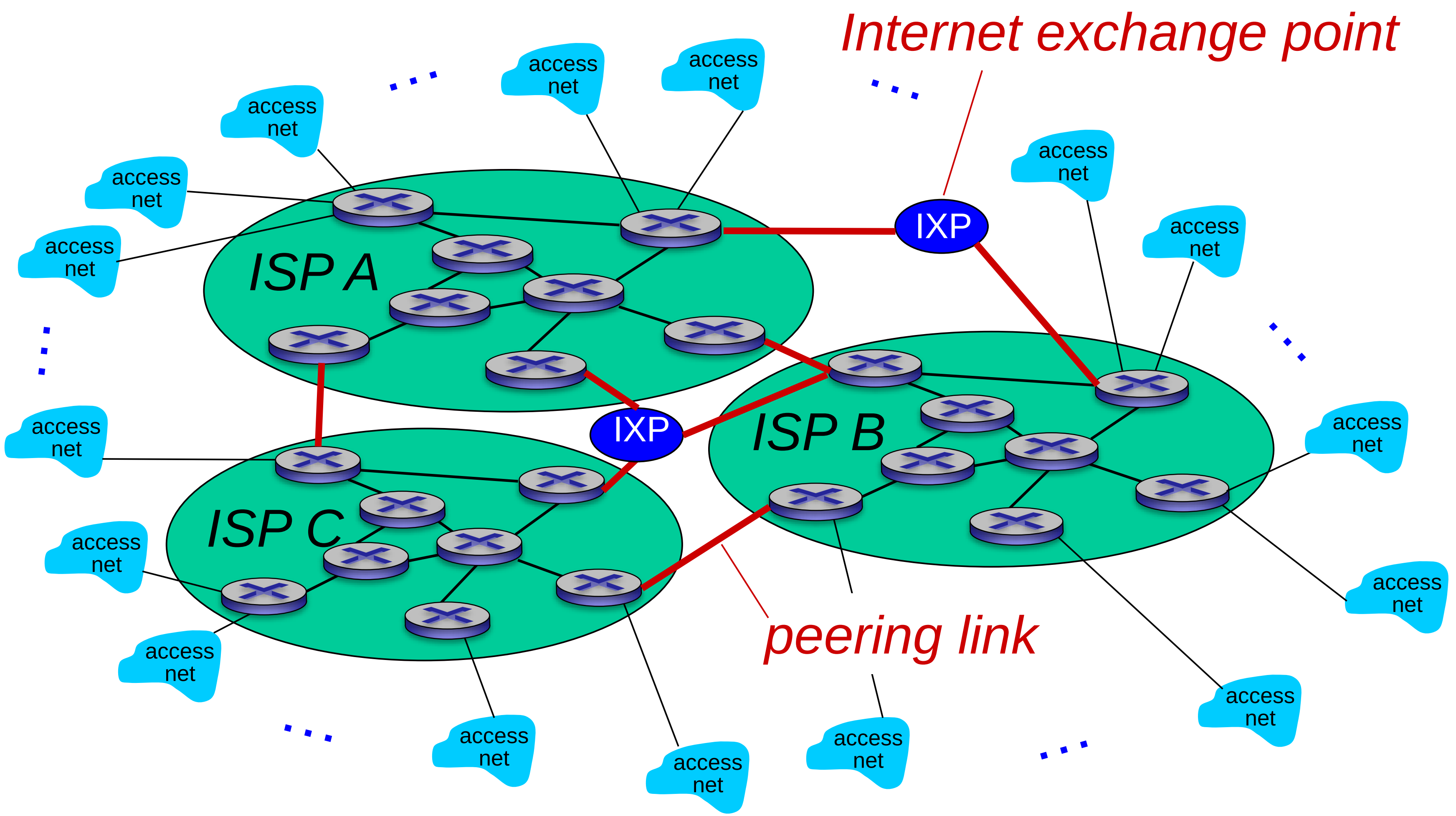
Internet structure: network of networks

Option: Or multiple global ISPs.



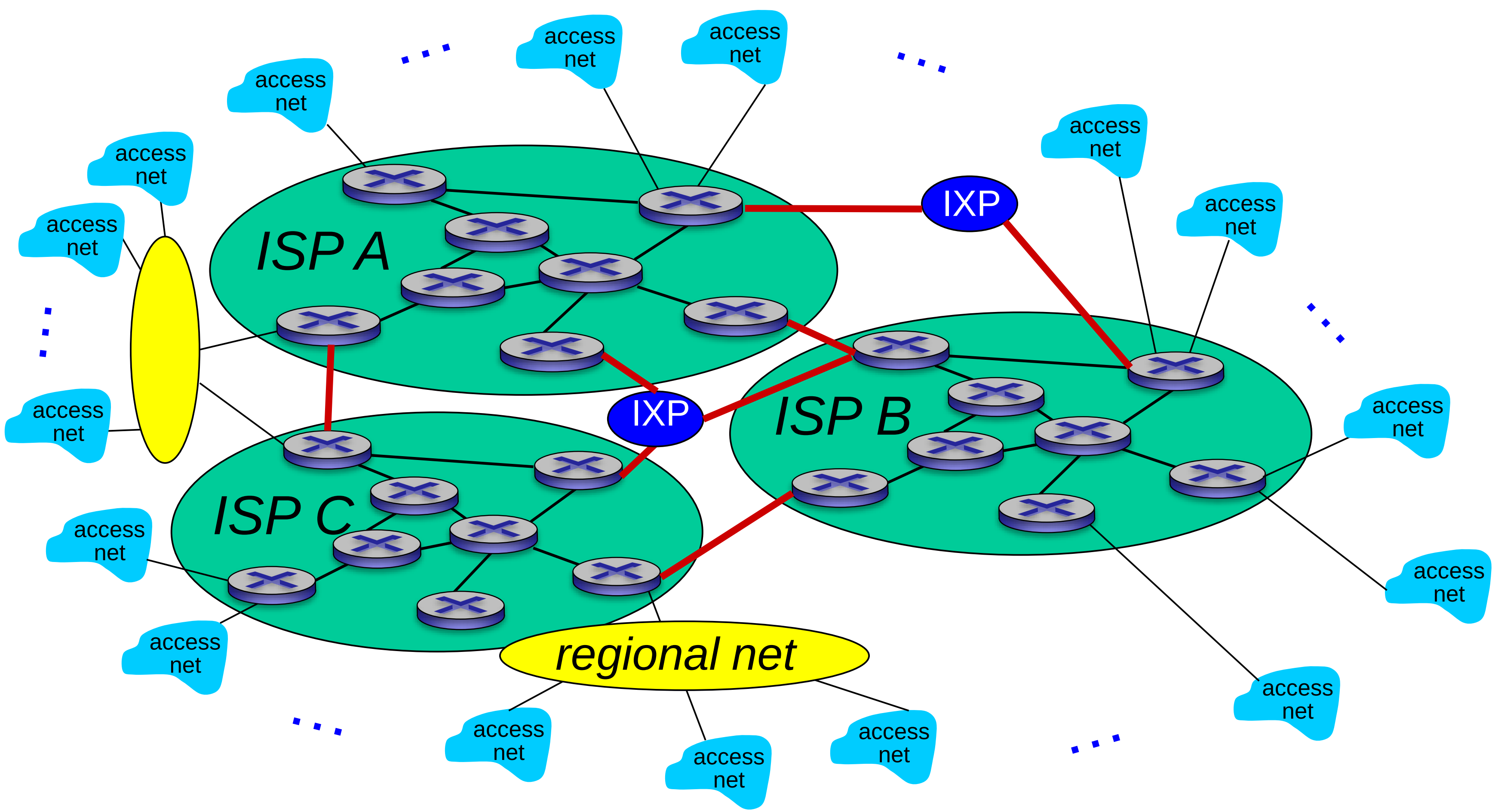
Internet structure: network of networks

Option: if one global ISP is a viable business, they must be interconnected.



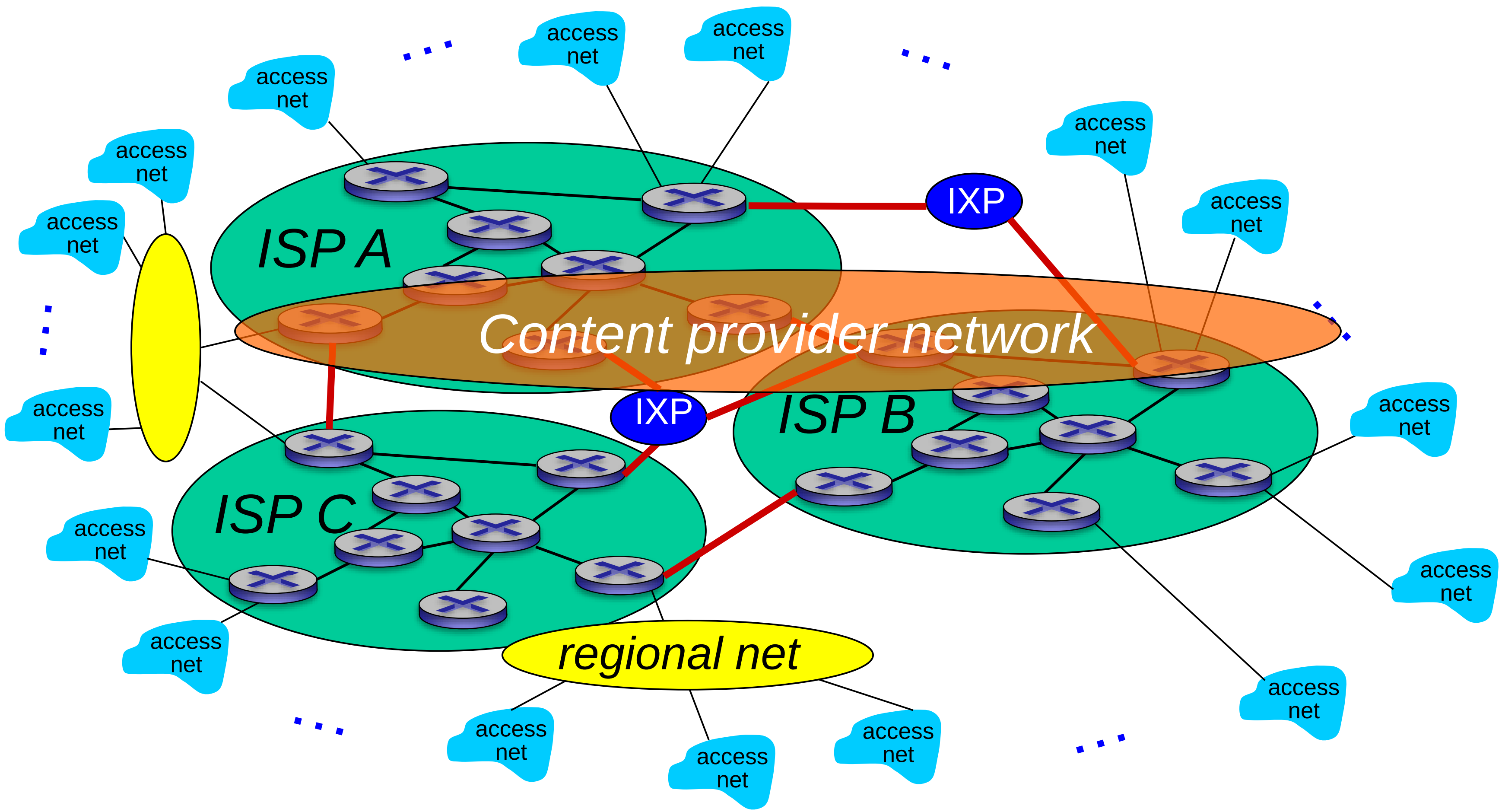
Internet structure: network of networks

Option: regional networks may arise to connect access nets to ISPs

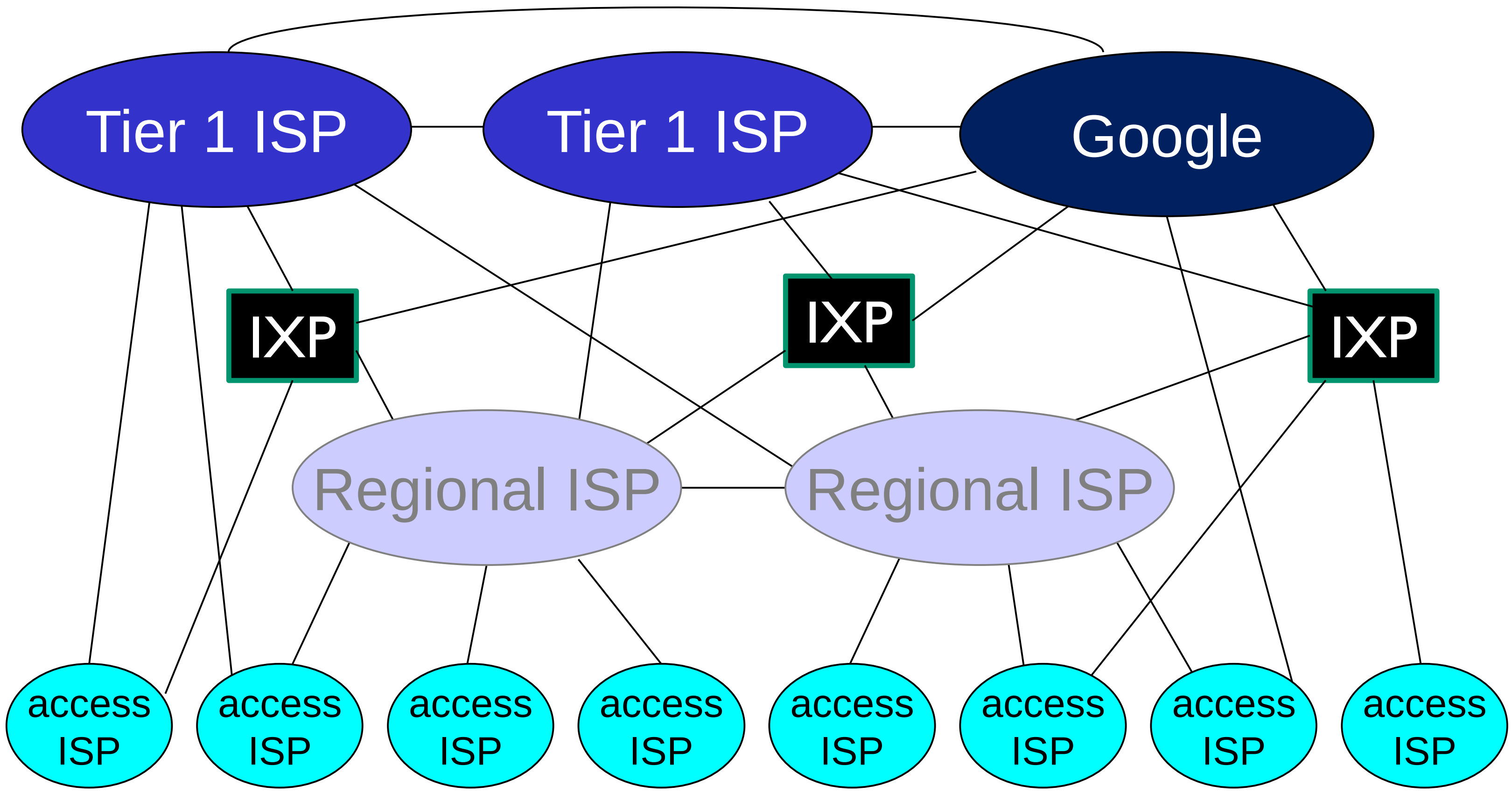


Internet structure: network of networks

… 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, national & international coverage
  - content provider network, private network that connects it data centers to Internet, often bypassing tier-1, regional ISPs

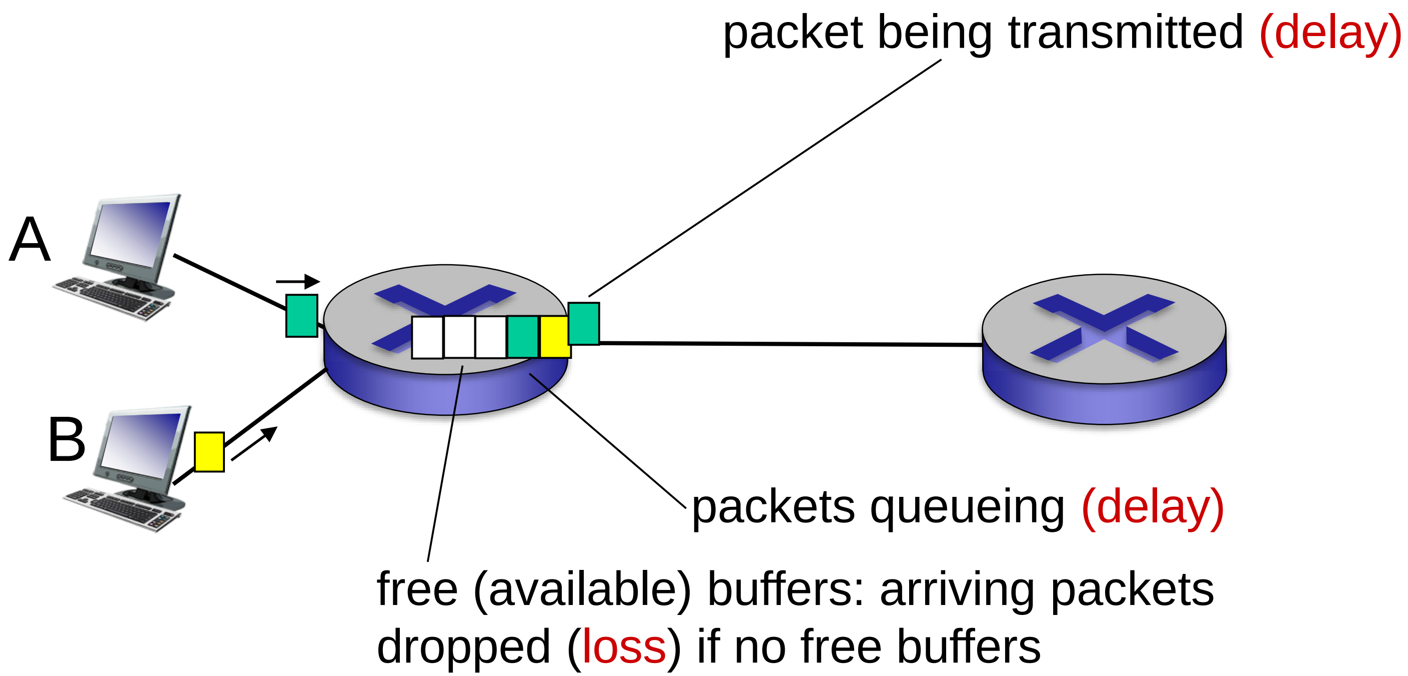
[Google BGP Mistake brought down Japan Internet Access]

Loss, Delays and Throughput

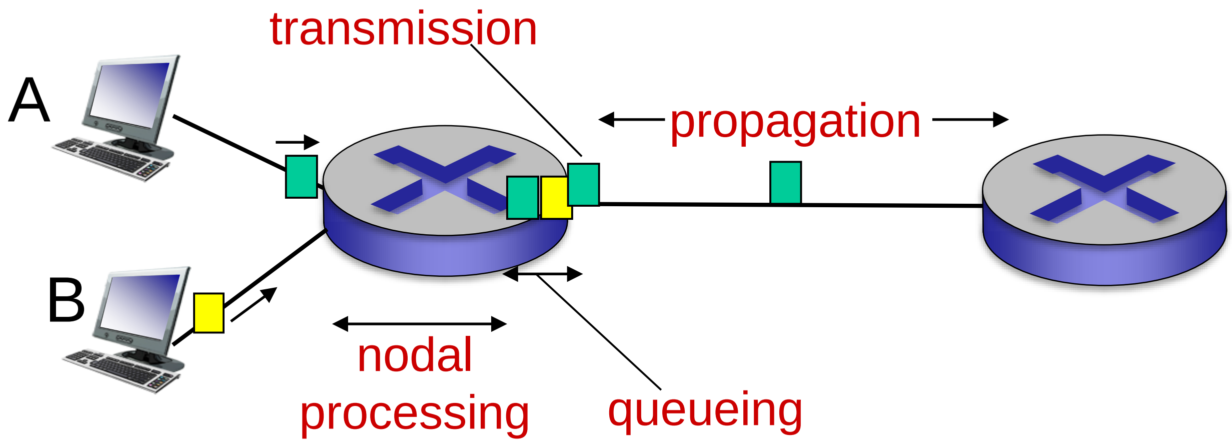
How do loss and delay occur?

packets *queue* in router buffers

- Input packet arrival rate may temporarily exceed output link transmission rate
- packets queue, wait for turn



Four sources of packet delay



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

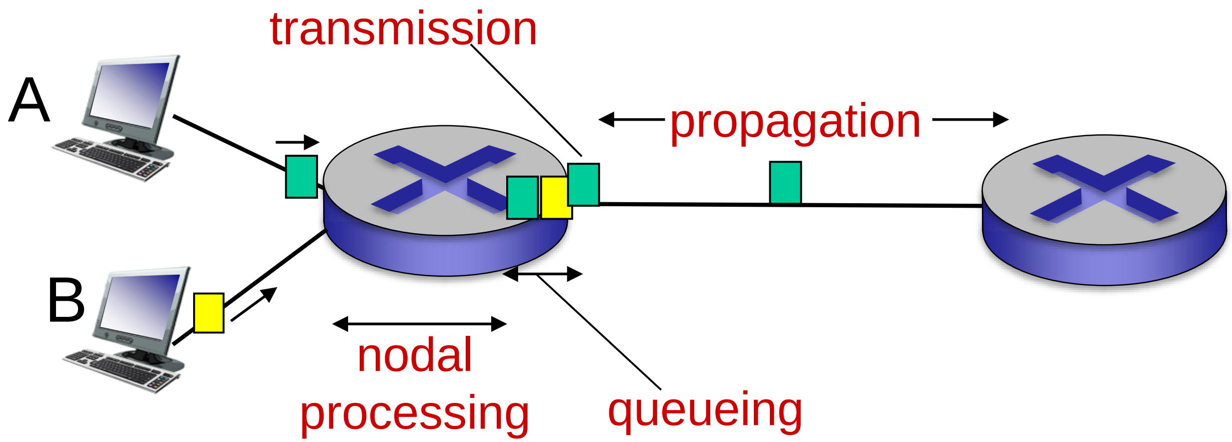
d_{proc}: nodal processing

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

d_{queue}: queueing delay

- time waiting (buffer sizes) at output link
- depends on congestion of routers downstream

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

d_{prop}: propagation delay:

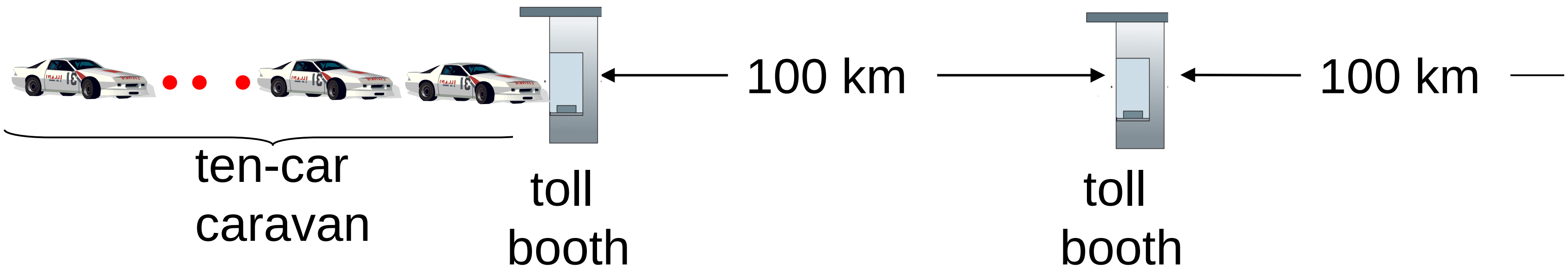
- d: length of physical link
- s: propagation speed (~2x10^8 m/sec)
- $d_{prop} = d/s$

* Check out the Java applet for on trans vs. prop delay http://gaia.cs.umass.edu/kurose_ross/interactive/

Bandwidth-delay product

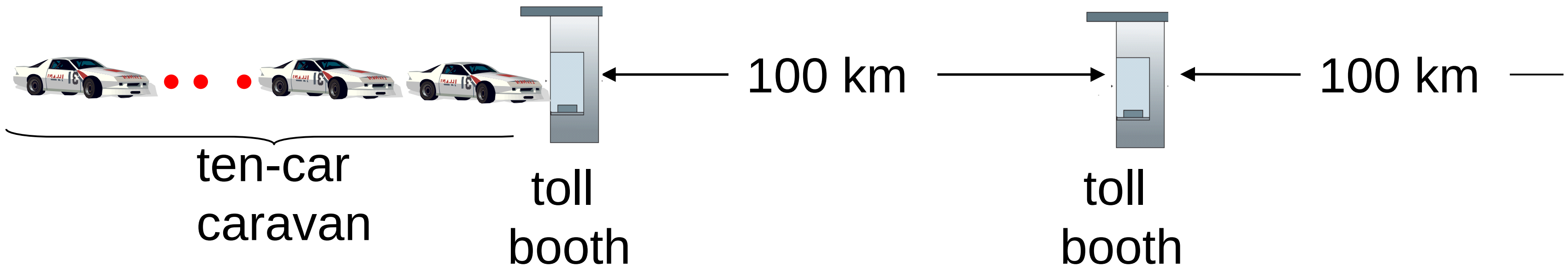
- Suppose two hosts A and B, separated by d=10,000 Km (10^7m), connected by a link R=1 Mbps (10^6 bits/sec). Propagation speed s=2.5*10^8 m/sec.
- What is d_{prop}?
- What is $R * d_{prop}$? (called bandwith-delay product)
- What is the unit of bandwidth-delay product?
- What is the meaning of this product?
- What is the "width" of a "bit" for this link?
- Derive a general expression of this "width" using d, R and s.

Caravan analogy



- cars propagate at 100 km/hr
- toll booth takes 12 sec to service car (processing and transmission time)
- car ~ bit; caravan ~ packet
- *Q:* How long until caravan is lined up before 2nd toll booth?
- time to service entire caravan through toll booth onto highway = 12*10 = 120 sec (2 min)
- time for last car to propagate from 1st to 2nd toll both: 100km/(100km/hr)= 1 hr (60 min)
- *A:* 62 minutes

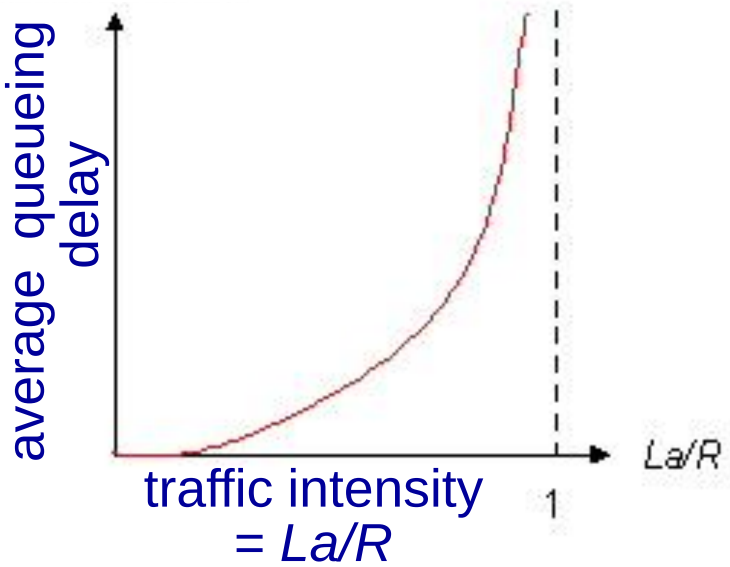
Caravan analogy (more)



- suppose cars now "propagate" at 1000 km/hr
- and suppose toll booth now takes one min to service a car (thus 10 min to service entire caravan, 6 min to propagate each car)
- *Q:* Will cars arrive to 2nd booth before all cars serviced at first booth?
  - *A: Yes!* after 7 min, first car arrives at 2nd booth; 7 cars have been serviced and are in transit, and 3 cars still remain at 1st booth

Queueing delay (revisited)

- *R*: link bandwidth (bps)
- *L*: packet length (bits)
- a: average packet arrival rate
- d_{queue}: *average* queueing delay



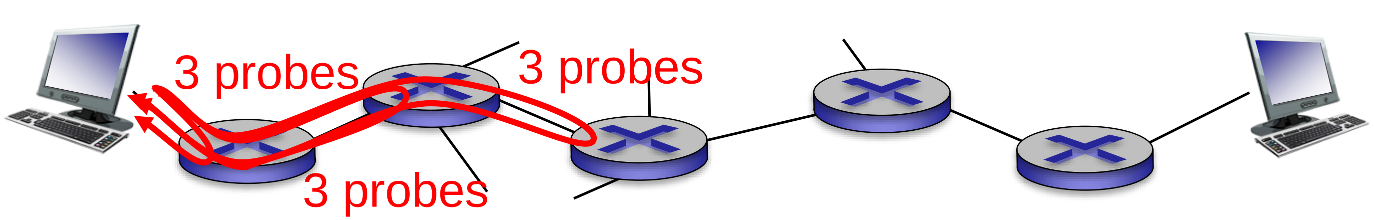
- *L*a is the aggregated arrival bit rate*
- *L*a/R* is small; d_{queue} is small
- *L*a/R* approaches 1; d_{queue} is large
- *L*a/R* exceeds 1; d_{queue} approaches infinite!

La/R ~ 0

La/R -> 1

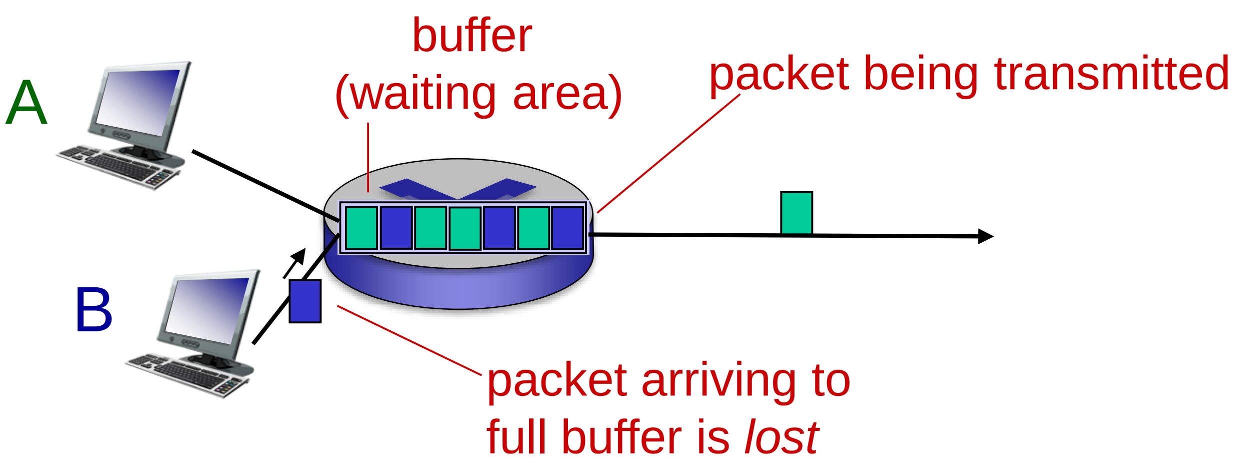
"Real" Internet delays and routes

- what do "real" Internet delay & loss look like?
- **`traceroute (tracert)`** 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.



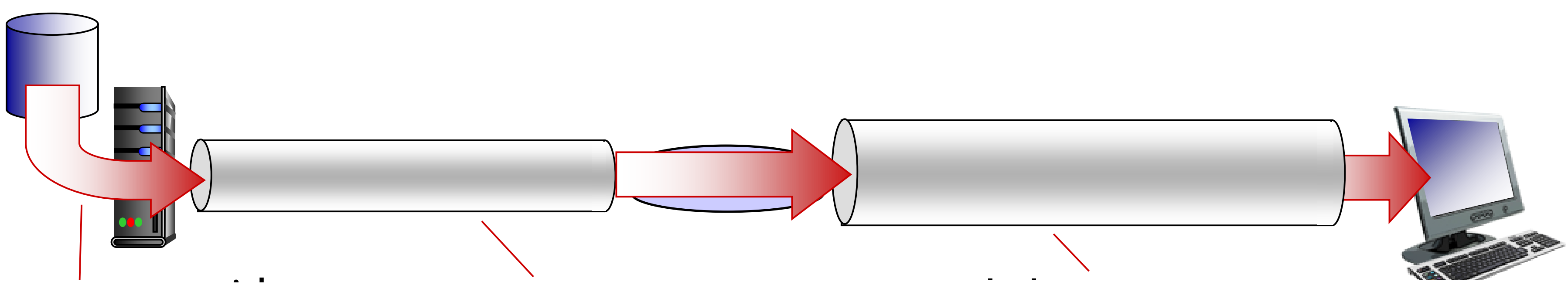
Packet loss

- queue has finite capacity
- packets arrive to a full queue dropped (lost)
- lost packet may or may not be retransmitted by previous node



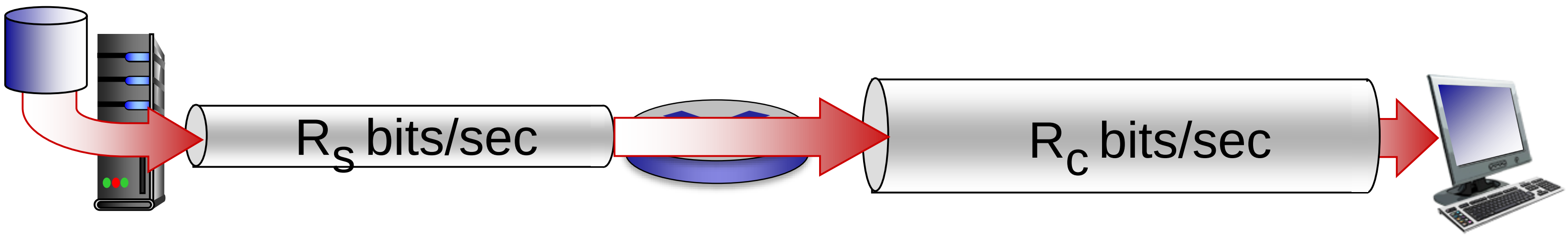
Throughput

- *throughput:* rate (bits/sec) at which bits transferred between sender/receiver
  - *instantaneous:* rate at given point in time
  - *average:* rate over longer period of time

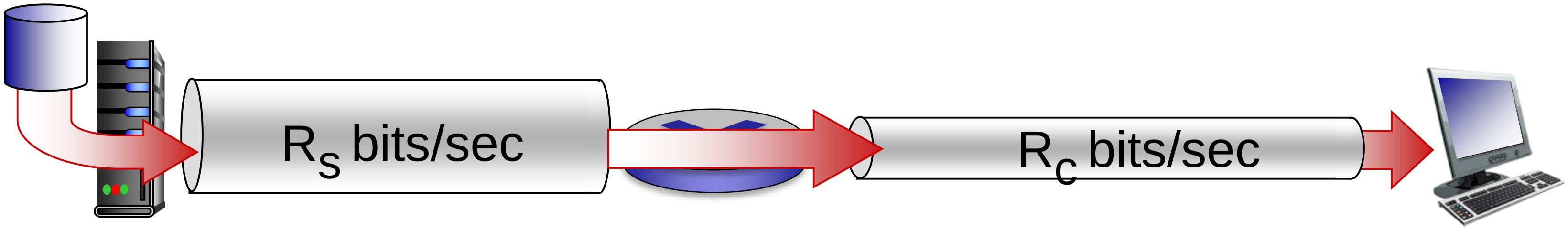


Throughput (more)

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



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

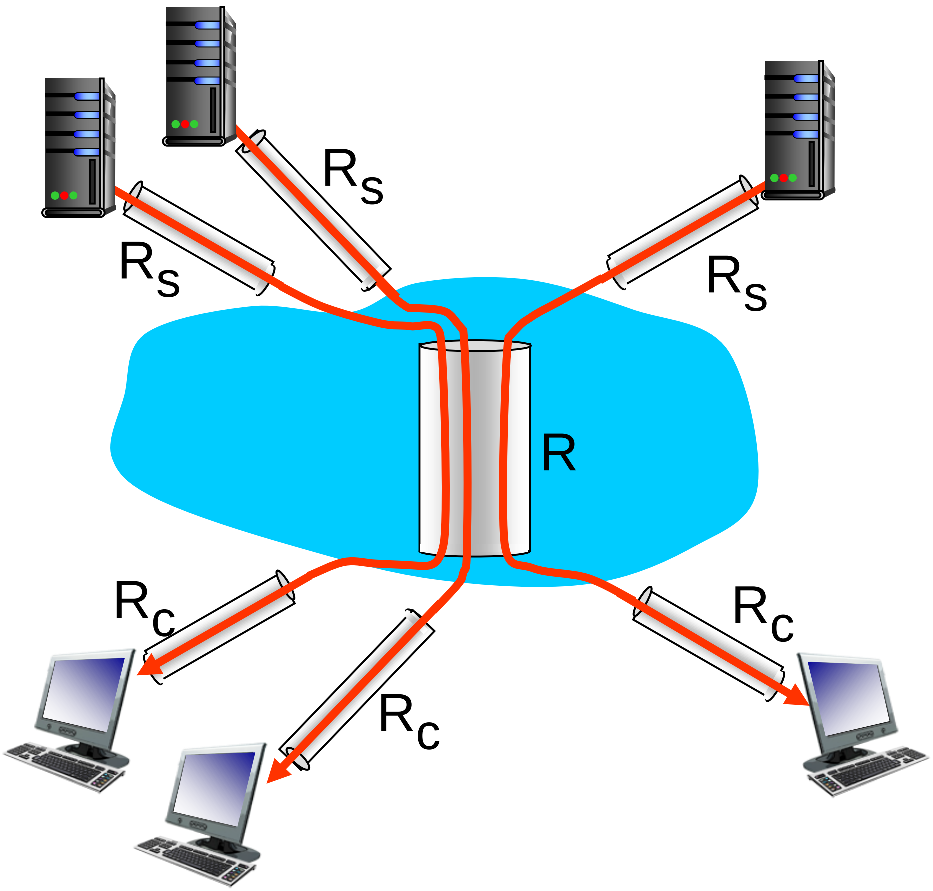


bottleneck link

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

Protocol Layers

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?

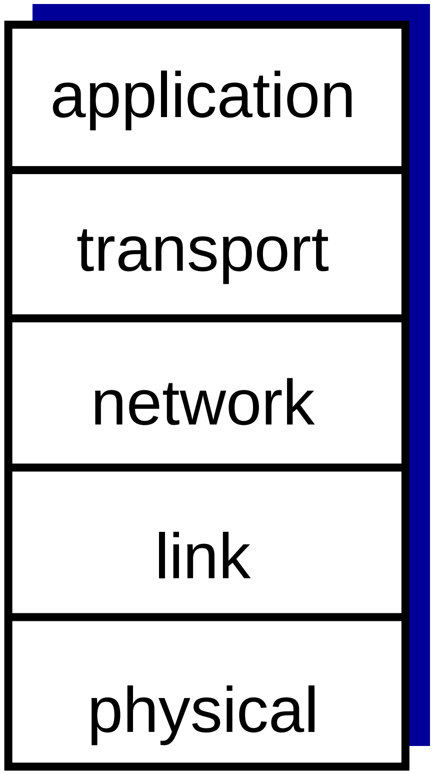
Why layering?

dealing with complex systems:

- explicit structure allows identification of relationship of complex system's design
  - Layered *ISO reference model*
- modularization eases maintenance
  - change of implementation of layer's service transparent to rest of system
- layering considered harmful?
  - redundancy and duplication
  - inefficient

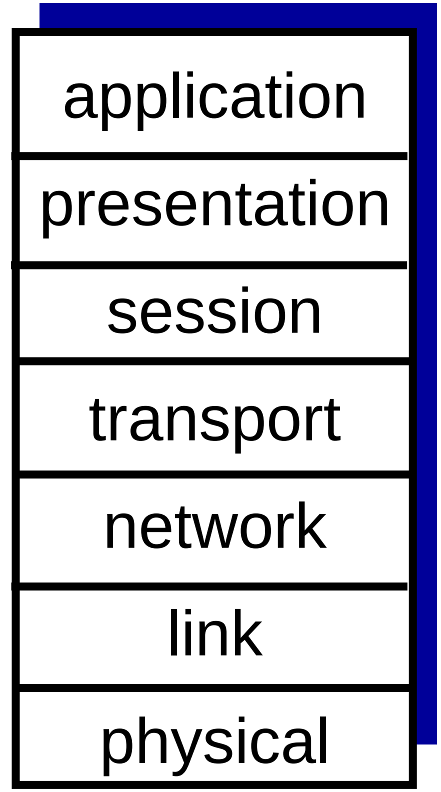
Internet protocol stack

- *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, 802.11 (WiFi), PPP
- *physical:* bits “on the wire”

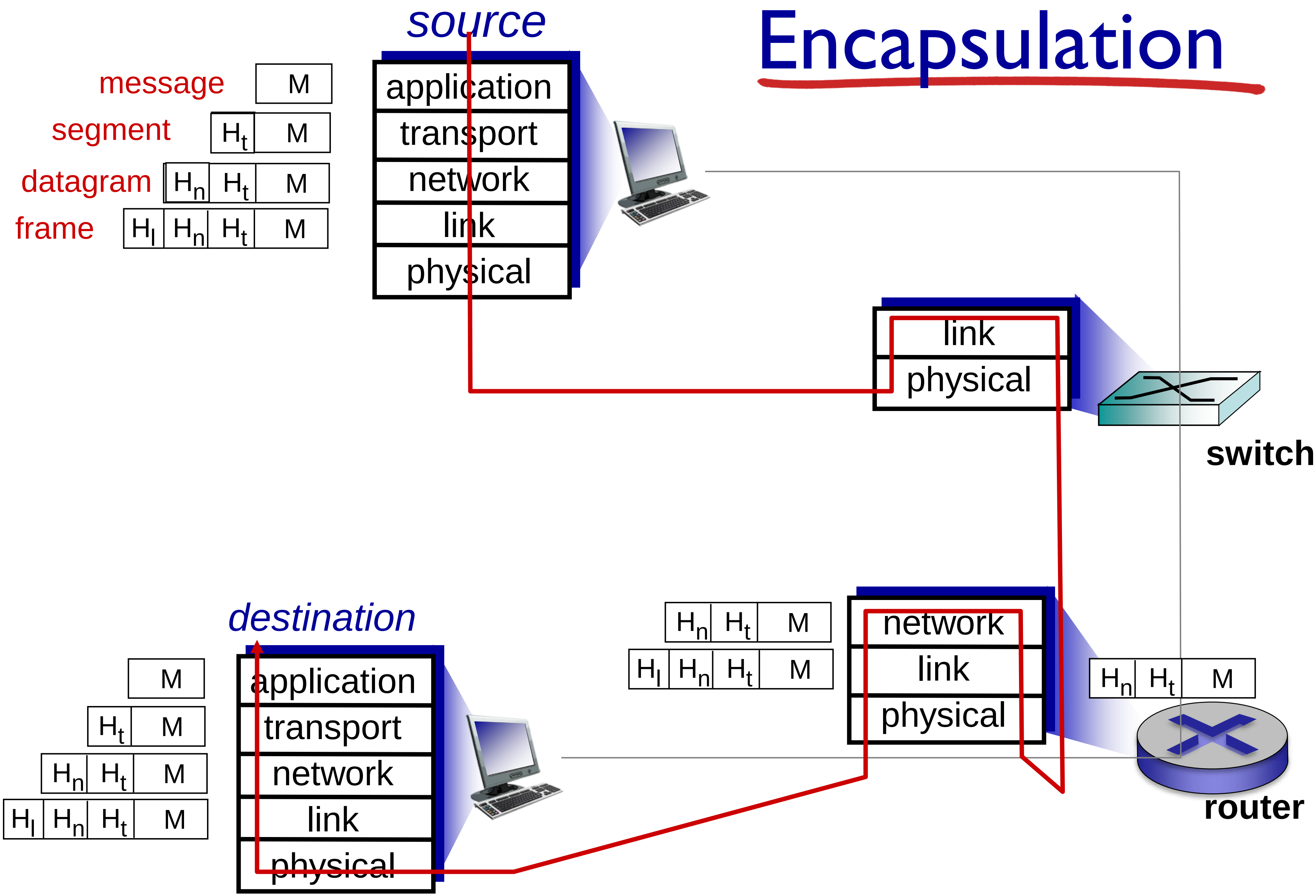


ISO/OSI reference model

- *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



Encapsulation



Network Security

Network security

- field of network security:
  - 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!

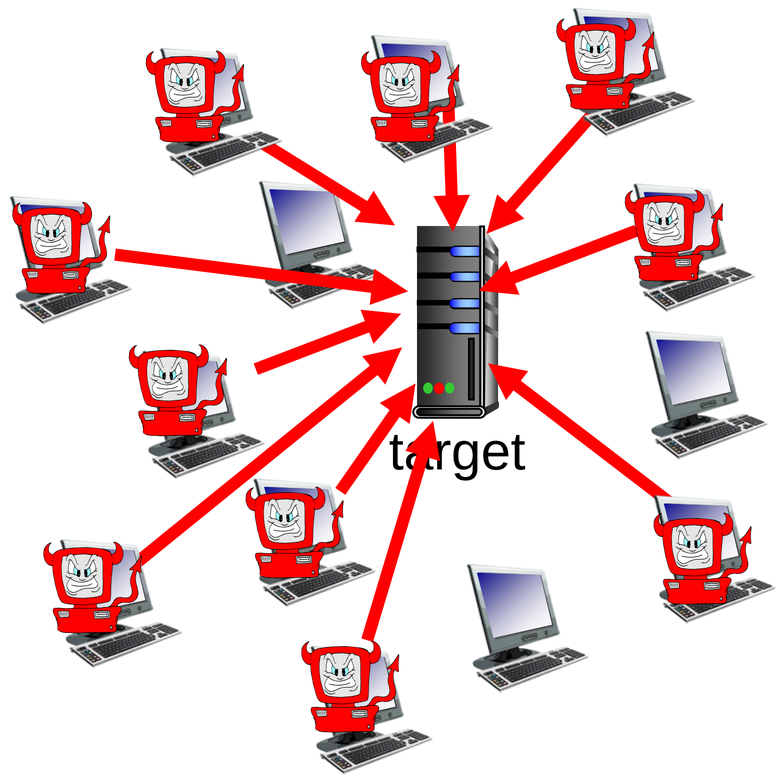
Put malware into hosts via Internet

- 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, or DDoS attacks

Attack server or network infrastructure

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

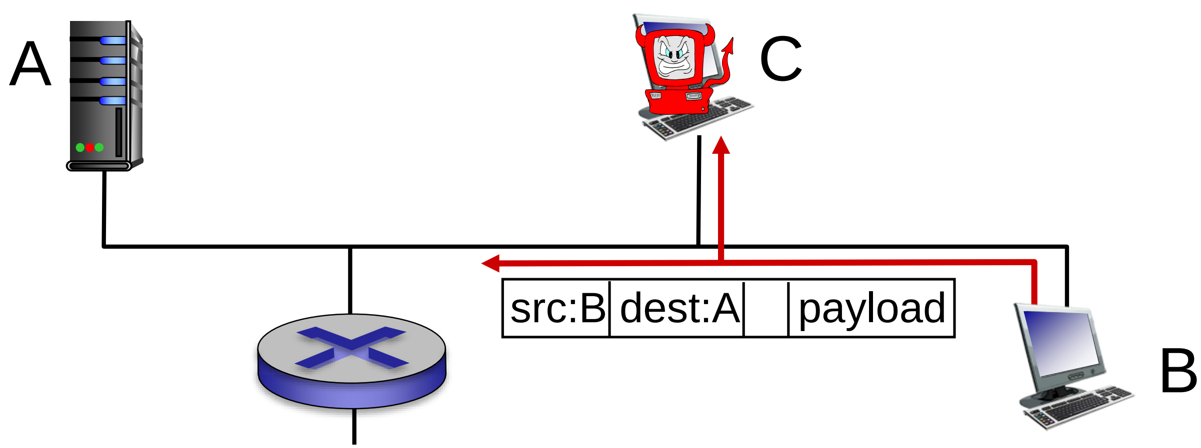
1. select target
2. break into hosts around the network (see botnet)
3. send packets to target from compromised hosts



Bad guys can sniff packets

*Packet "**sniffing**":*

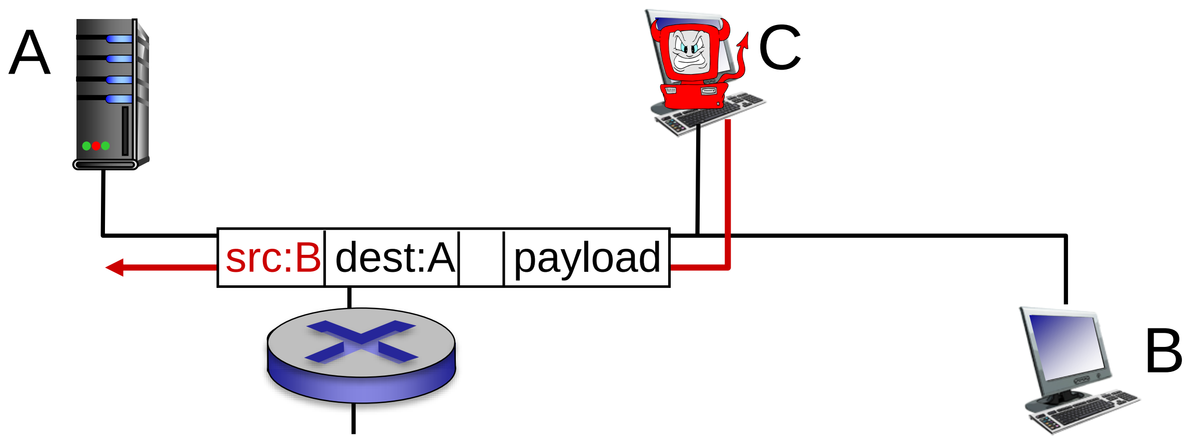
- broadcast media (shared Ethernet, wireless)
- promiscuous network interface reads/records all packets (e.g., including passwords!) passing by



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

Bad guys can use fake addresses

IP spoofing: send packet with false source address



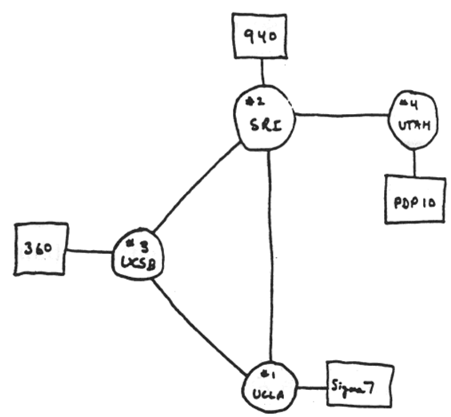
Internet History

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 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

- ~5B devices attached to Internet (2016)
  - smartphones and tablets
- aggressive deployment of broadband access
- increasing ubiquity of high-speed wireless access
- emergence of online social networks:
  - Facebook: ~ one billion users
- service providers (Google, Microsoft) create their own networks
  - bypass Internet, providing "instantaneous" access to search, video content, email, etc.
- e-commerce, universities, enterprises running their services in "**cloud**" (e.g., Amazon EC2)