Basics of Computer Networks & Internet

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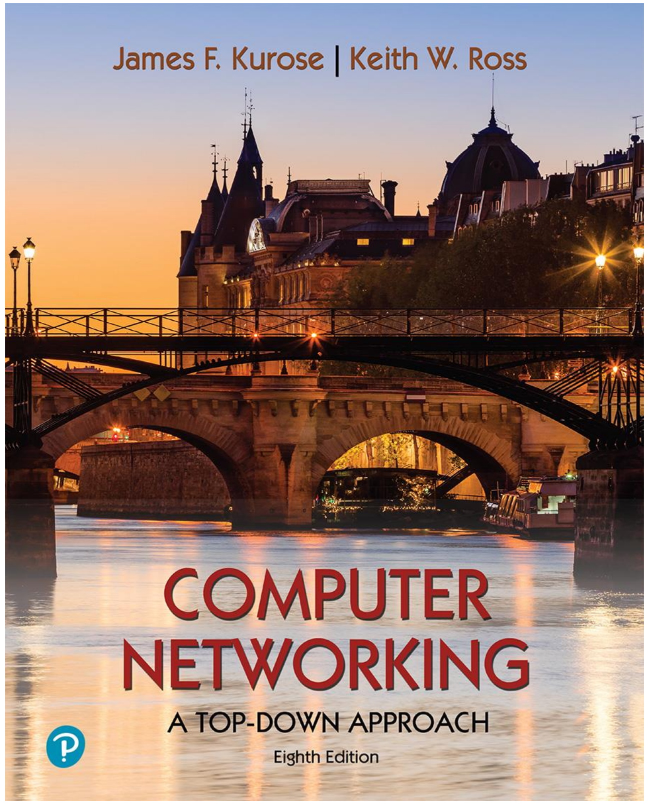


Computer Networking: A Top-Down Approach
8th edition
Jim Kurose, Keith Ross
Pearson, 2020

Outline

- What is a computer network?
- What *is* the Internet?
- What *is* a protocol?
- Network edge: hosts, access network, physical media
- Network core: packet/circuit switching, internet structure
- Network Performance: loss, delay, throughput, etc
- Protocol layers, architecture, service models

Computer Networks

- What is a computer network?
- Other types of networks?
- How is a computer network different from other types of networks?

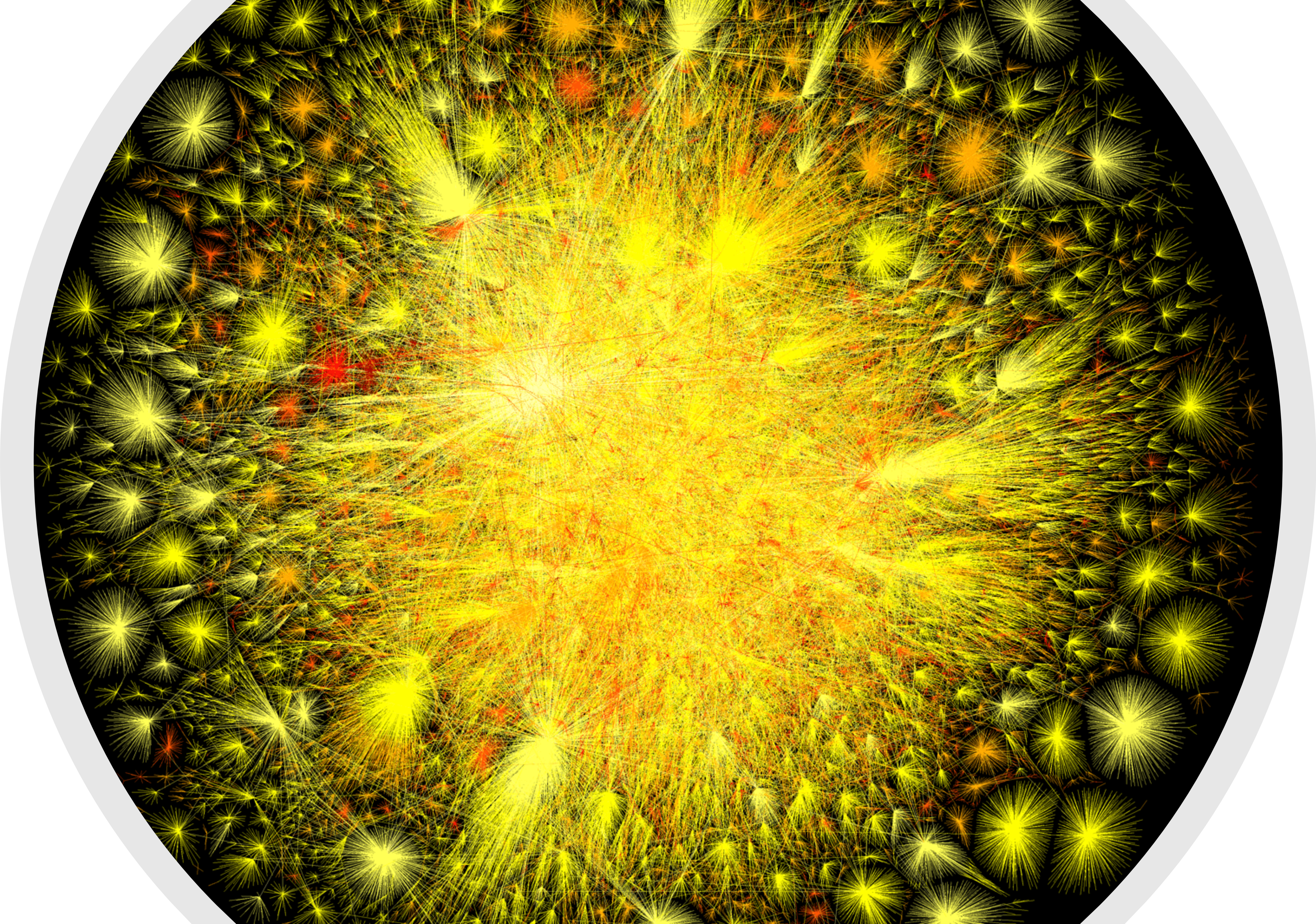
Computer Network Types

LOCAL AREA NETWORK: ETHERNET

WIRELESS LAN (WLAN): WI-FI

WIDE AREA NETWORK (WAN): 4G/5G, INTERNET

PERSONAL AREA NETWORK (PAN): BLUETOOTH

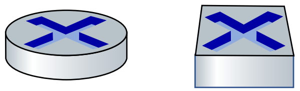


THE INTERNET☺

The Internet: a "nuts and bolts" view

Billions of connected computing *devices*:

- *hosts = end systems*
- running *network apps* at Internet's "edge"



Packet switches: forward packets (chunks of data)

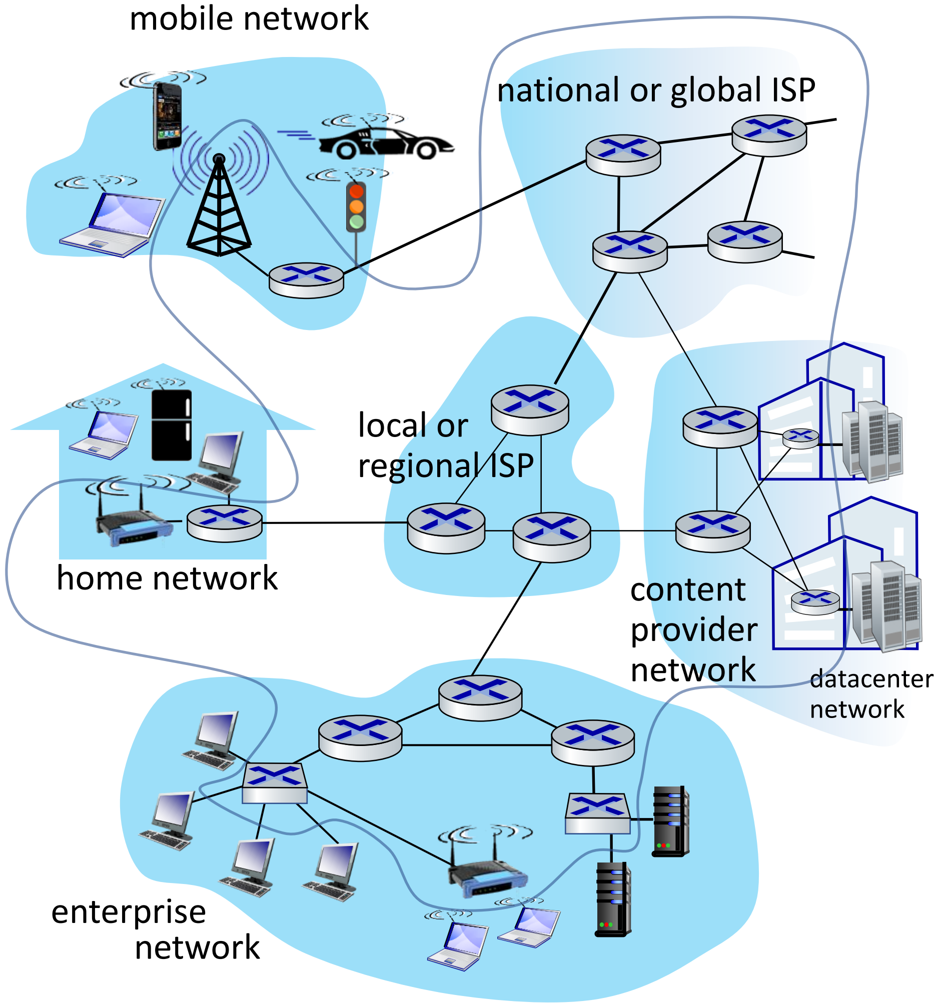
- *routers, switches*

Communication links

- fiber, copper, radio, satellite
- transmission rate: *bandwidth*

Networks

- collection of devices, routers, links: managed by an organization



“Fun” Internet-connected devices

Amazon Echo

Internet refrigerator

IP picture frame

Pacemaker & Monitor

Tweet-a-watt: monitor energy use

bikes

Web-enabled toaster + weather forecaster

cars

scooters

Security Camera

Slingbox: remote control cable TV

AR devices

Fitbit

Internet phones

Gaming devices

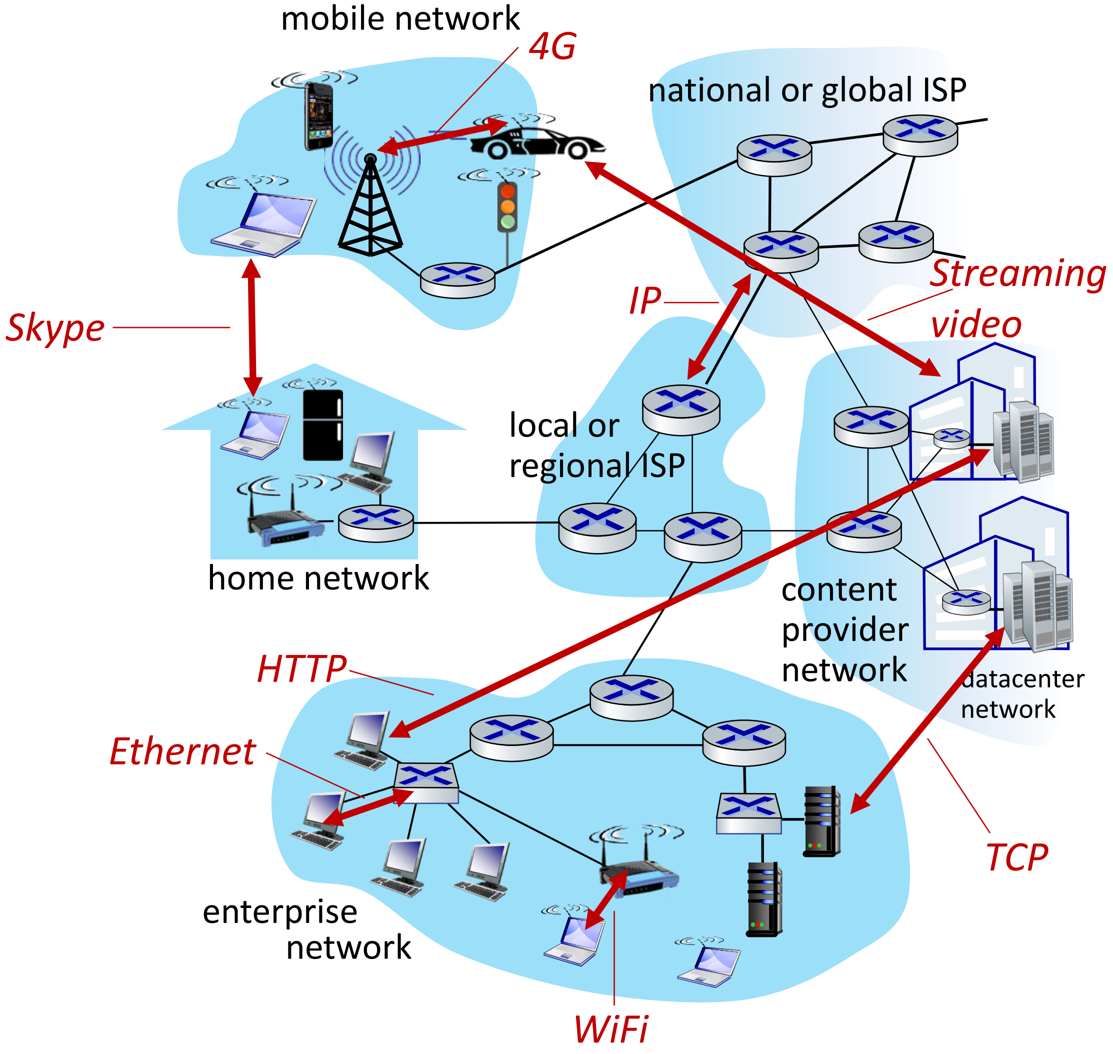
sensorized, bed mattress

diapers

Others?

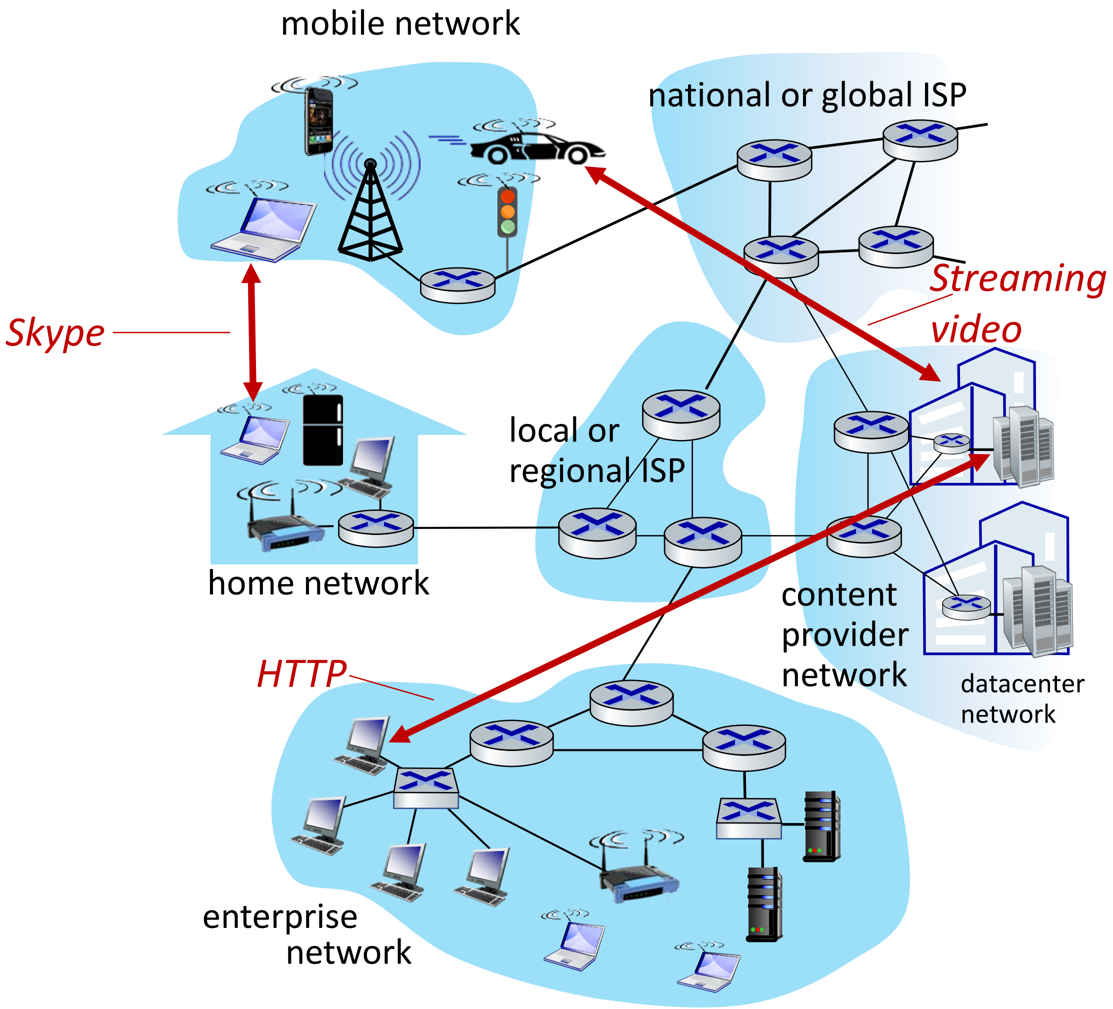
The Internet: a "nuts and bolts" view

- *Internet: "network of networks"*
  - Interconnected ISPs
- *protocols* are *everywhere*
  - control sending, receiving of messages
  - e.g., HTTP (Web), Streaming video, Skype, TCP, IP, WiFi, 4/5G, Ethernet
- *Internet standards*
  - RFC: Request for Comments
  - IETF: Internet Engineering Task Force



The Internet: a "services" view

- *Infrastructure* that provides services to applications:
  - Web, streaming video, multimedia teleconferencing, email, games, e-commerce, social media, inter-connected appliances, …
- provides *programming interface* to distributed applications:
  - "hooks" allowing sending/receiving apps to "connect" to, use Internet transport service
  - provides service options, analogous to postal service



What's a protocol?

Human protocols:

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

Rules for:

… specific messages sent

… specific actions taken when message received, or other events

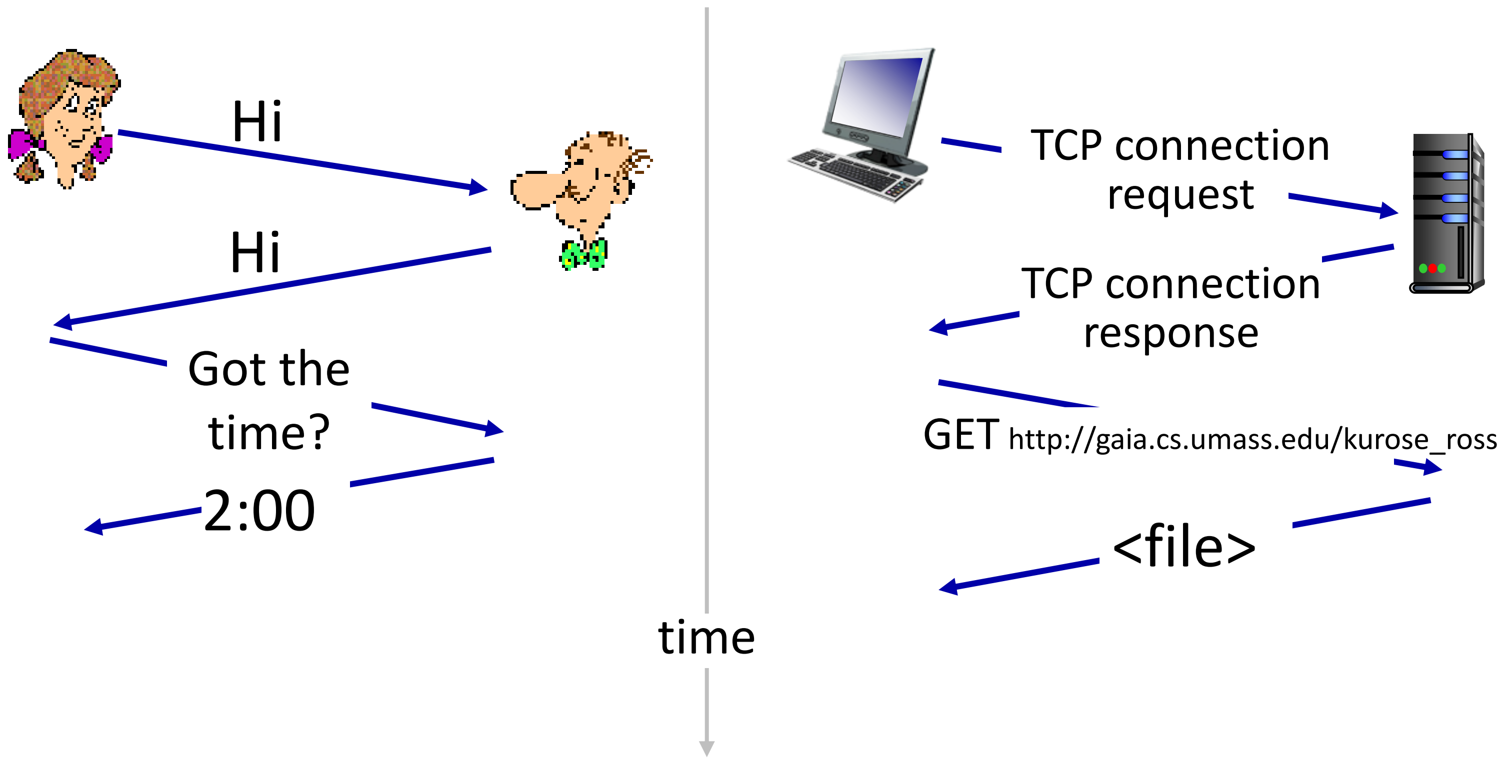
Network protocols:

- computers (devices) rather than humans
- all communication activity in Internet governed by protocols

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

What's a protocol?

A human protocol and a computer network protocol:



Q: other human protocols?

Network Communication Protocols

- TCP (transmission control protocol)
- UDP (user data protocol)
- IP (internet protocol)
- HTTP (hypertext transfer protocol)
- SMTP (simple mail transfer protocol)
- FTP (file transfer protocol)
- 802.3 (Ethernet) Protocol
- 802.11 (Wi-Fi) Protocol

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- Network core: packet/circuit switching, internet structure
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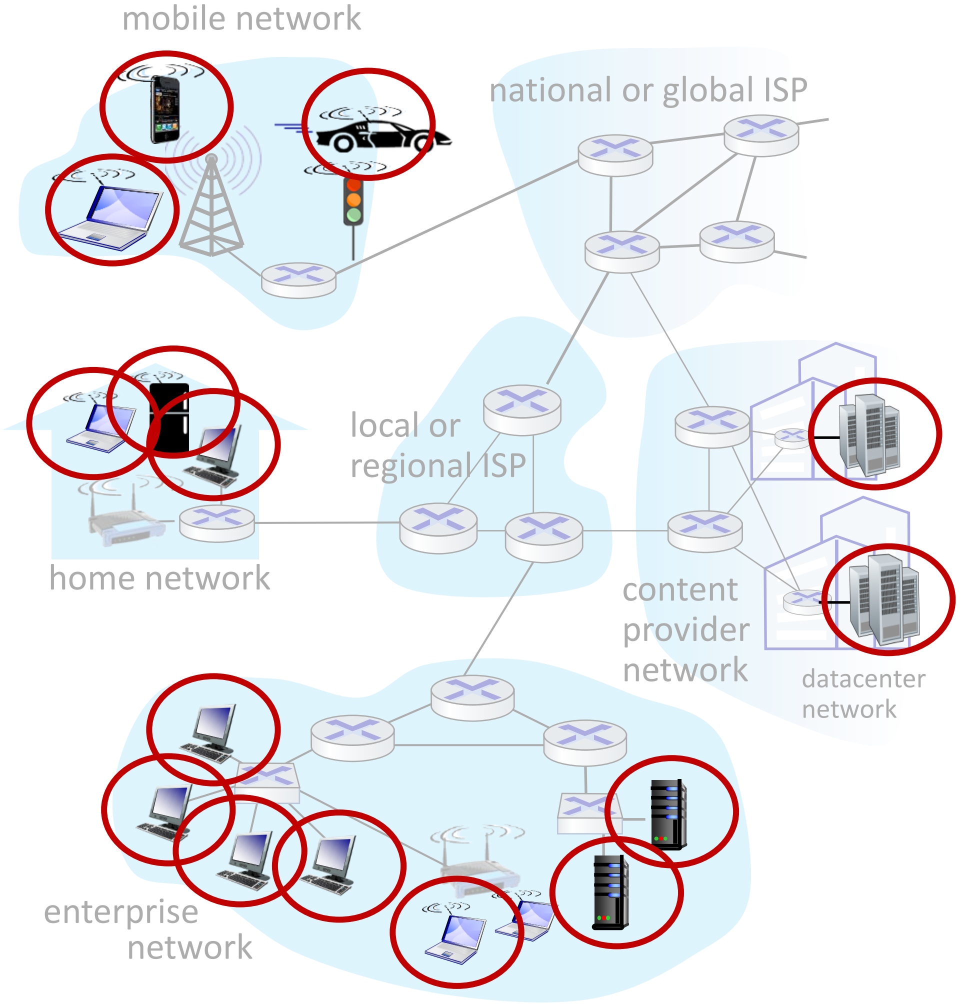
A closer look at Internet structure

Network edge:

- hosts: clients and servers
- servers often in data centers



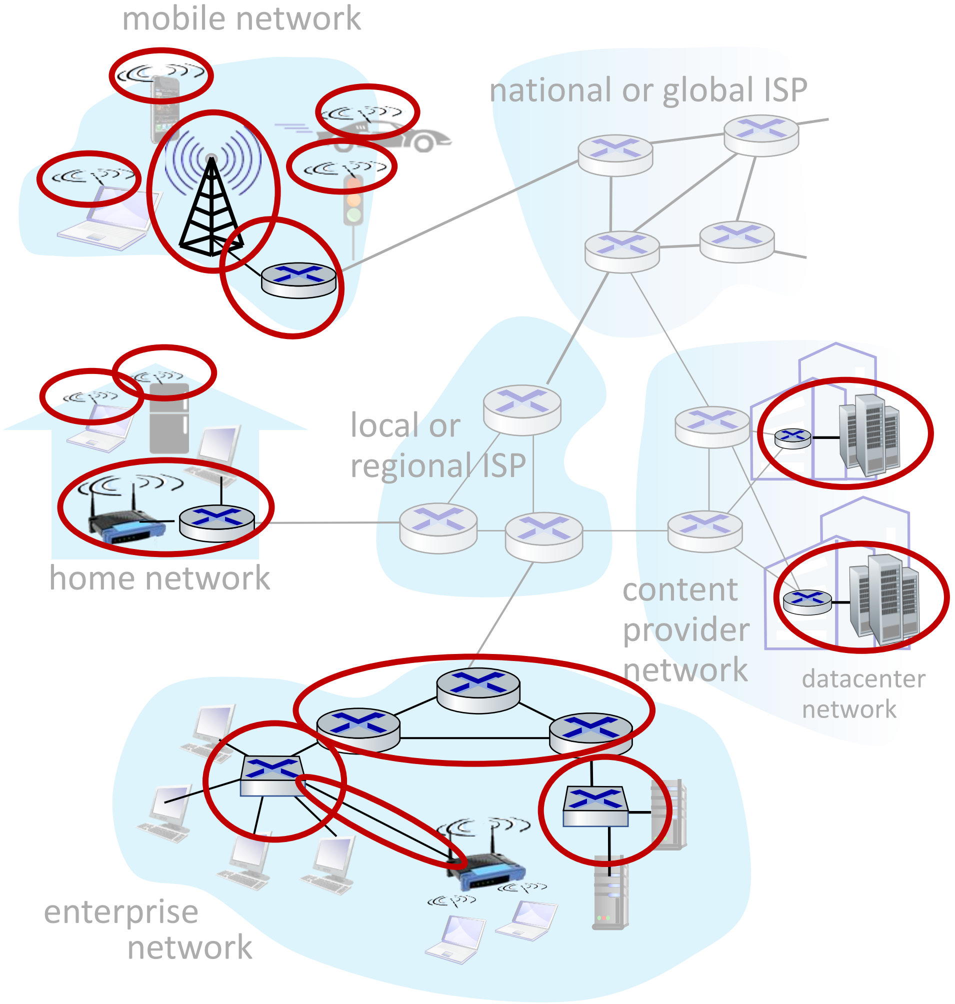
A closer look at Internet structure

Network edge:

- hosts: clients and servers
- servers often in data centers

Access networks, physical media:

- wired, wireless communication links



A closer look at Internet structure

Network edge:

- hosts: clients and servers
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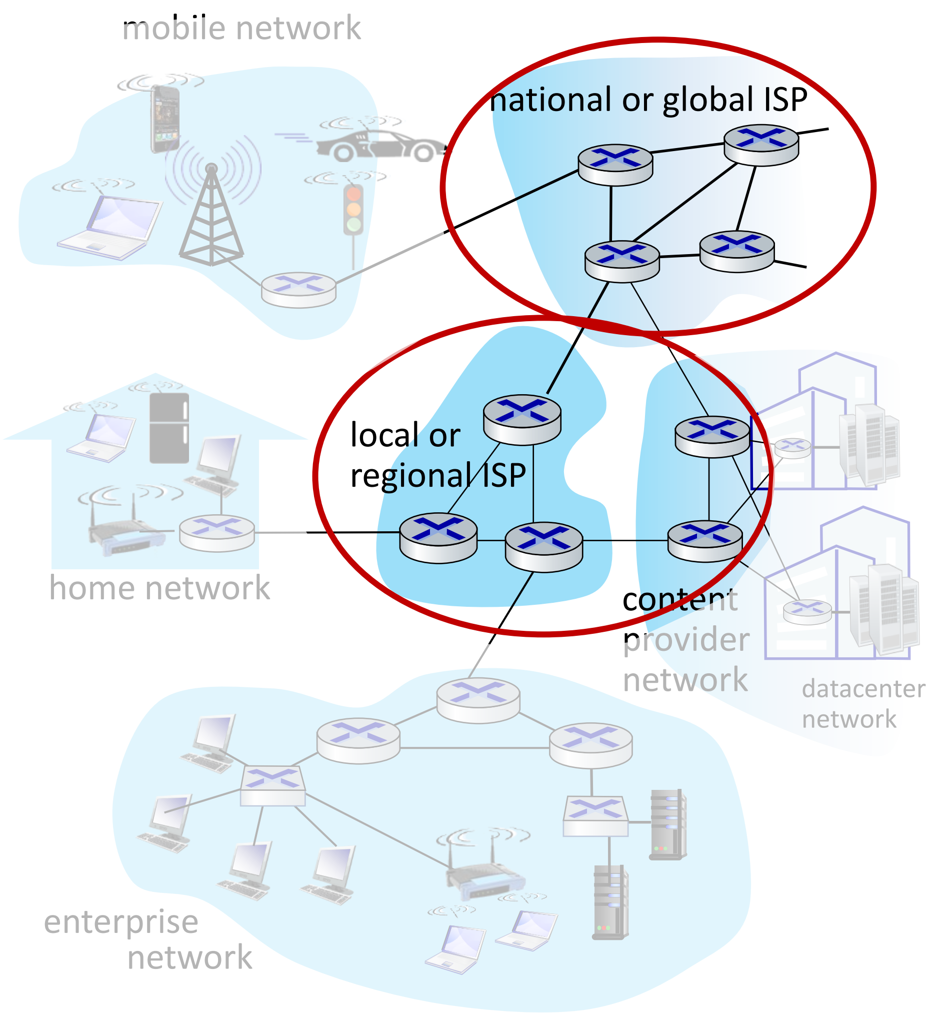
Access networks, physical media:

- wired, wireless communication links

Network core:

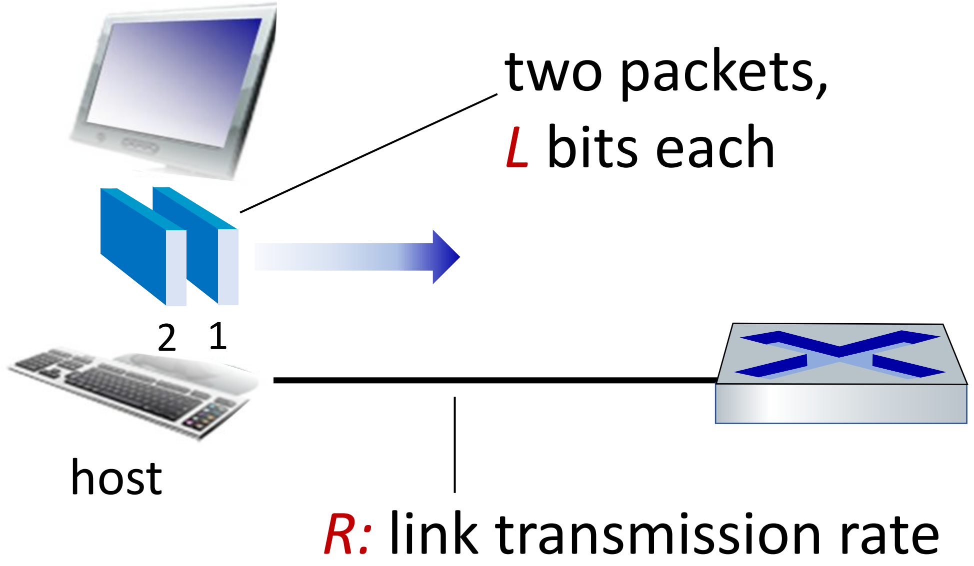
- interconnected routers
- network of networks



Host: sends *packets* of data

host sending function:

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



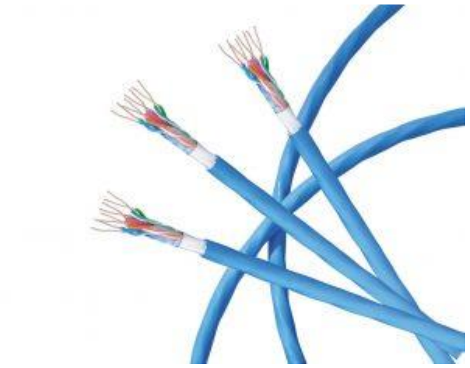
packet transmission delay = time needed to transmit *L*-bit packet into link = $\frac{L \text{ (bits)}}{R \text{ (bits/sec)}}$

Links: physical media

- bits: propagate between transmitter/receiver pairs using electromagnetic waves or light pulses
- physical link/media: what lies between transmitter & receiver
- guided media:
  - signals propagate in solid media: copper, fiber, coax
- unguided media:
  - signals propagate freely, e.g., radio channels

Twisted pair (TP)

- two insulated copper wires
  - Category 5: 100 Mbps, 1 Gbps Ethernet
  - Category 6: 10Gbps Ethernet



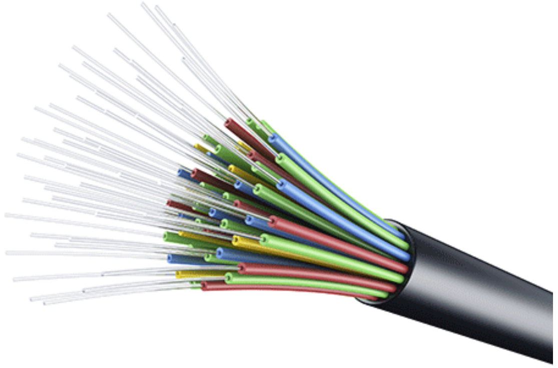
Links: physical media

Coaxial cable:

- two concentric copper conductors
- bidirectional
- broadband:
  - multiple frequency channels on cable
  - 100's Mbps per channel

Fiber optic cable:

- glass fiber carrying light pulses, each pulse a 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



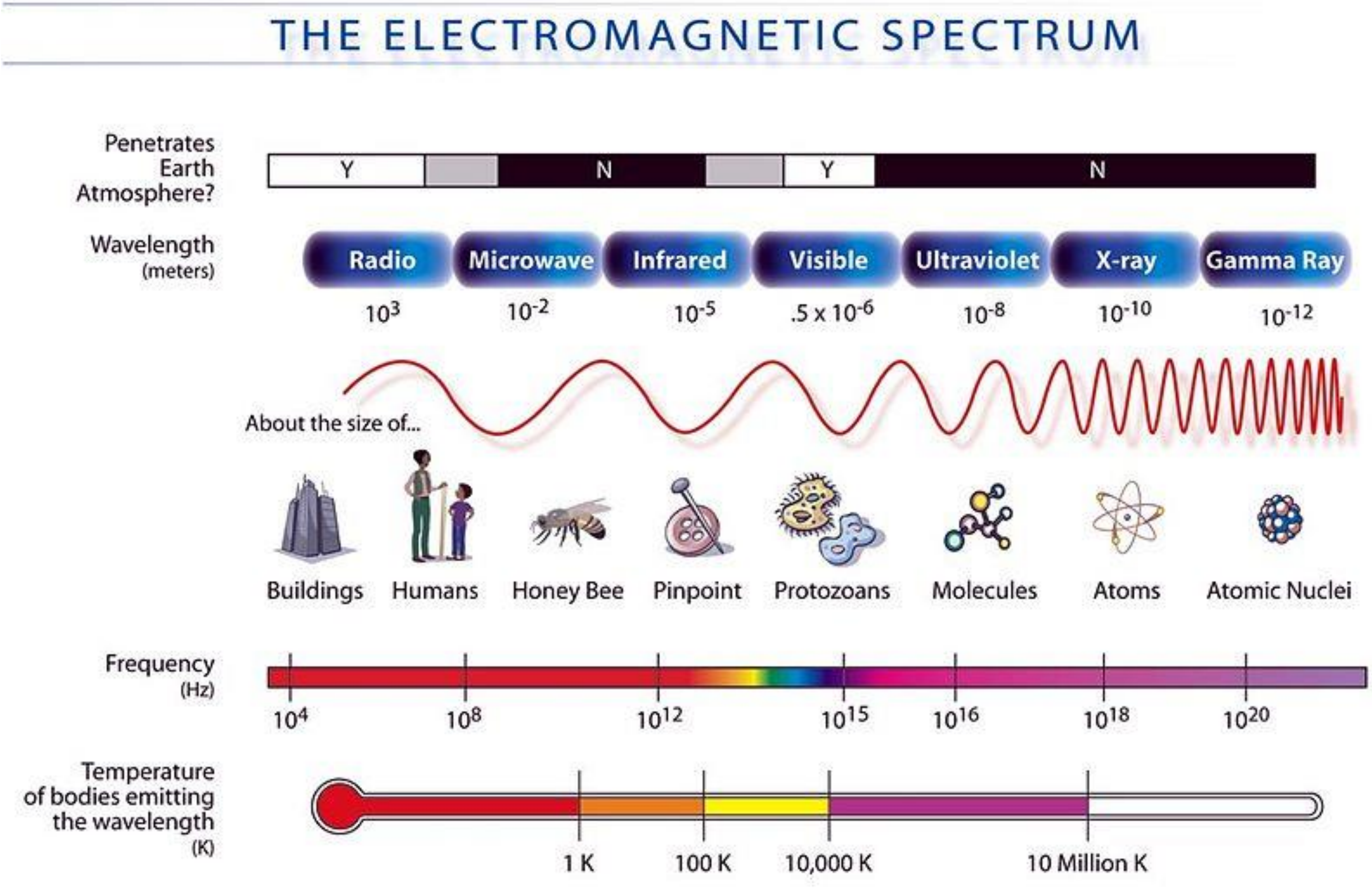
Links: physical media

Wireless radio

- signal carried in various "bands" in electromagnetic spectrum
- no physical "wire"
- broadcast, "half-duplex" (sender to receiver)
- propagation environment effects:
  - reflection
  - obstruction by objects
  - Interference/noise

Radio link types:

- Wireless LAN (WiFi)
  - 10-100's Mbps; 10's of meters
- wide-area (e.g., 4G/5G cellular)
  - 10's Mbps (4G) over ~10 Km
- Bluetooth: cable replacement
  - short distances, limited rates
- terrestrial microwave
  - point-to-point; 45 Mbps channels
- satellite
  - up to < 100 Mbps (Starlink) downlink
  - 270 msec end-end delay (geostationary)


THE ELECTROMAGNETIC SPECTRUM
Penetrates Earth Atmosphere?
Y
N
Y
N
Wavelength (meters)
Radio
Microwave
Infrared
Visible
Ultraviolet
X-ray
Gamma Ray
10^{3}
10^{-2}
10^{-5}
$.5 \times 10^{-6}$
10^{-8}
10^{-10}
10^{-12}
About the size of...
Buildings
Humans
Honey Bee
Pinpoint
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^{4}
10^{8}
10^{12}
10^{15}
10^{16}
10^{18}
10^{20}
Temperature of bodies emitting the wavelength (K)
1 K
100 K
10,000 K
10 Million K

Source:NASA

Radio waves

- One type of EM waves
- 30 Hz to 300 GHz
- 1-30 GHz also called as Microwaves
- 30-300 GHz also called as Millimeter waves
  - Unused, abundant, main candidate spectrum for 5G operations

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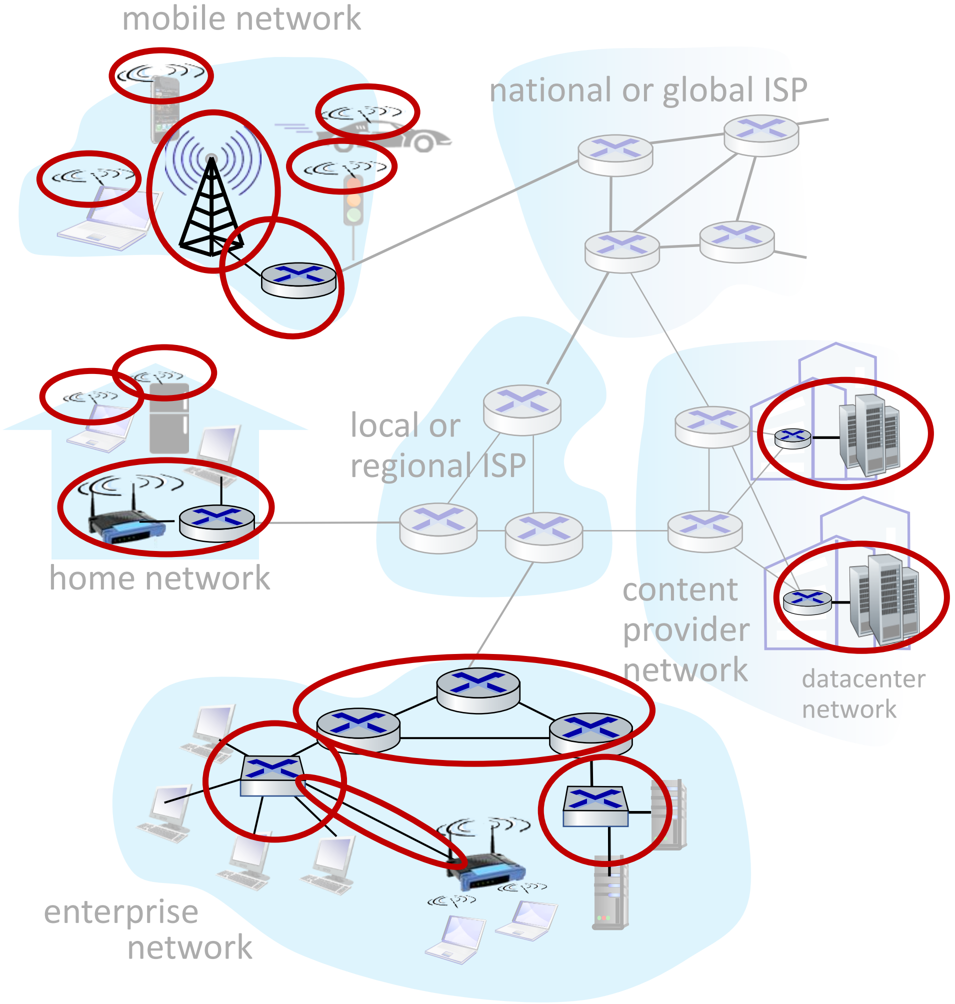
http://www.astrosurf.com/luxorion/qsl-propa.htm

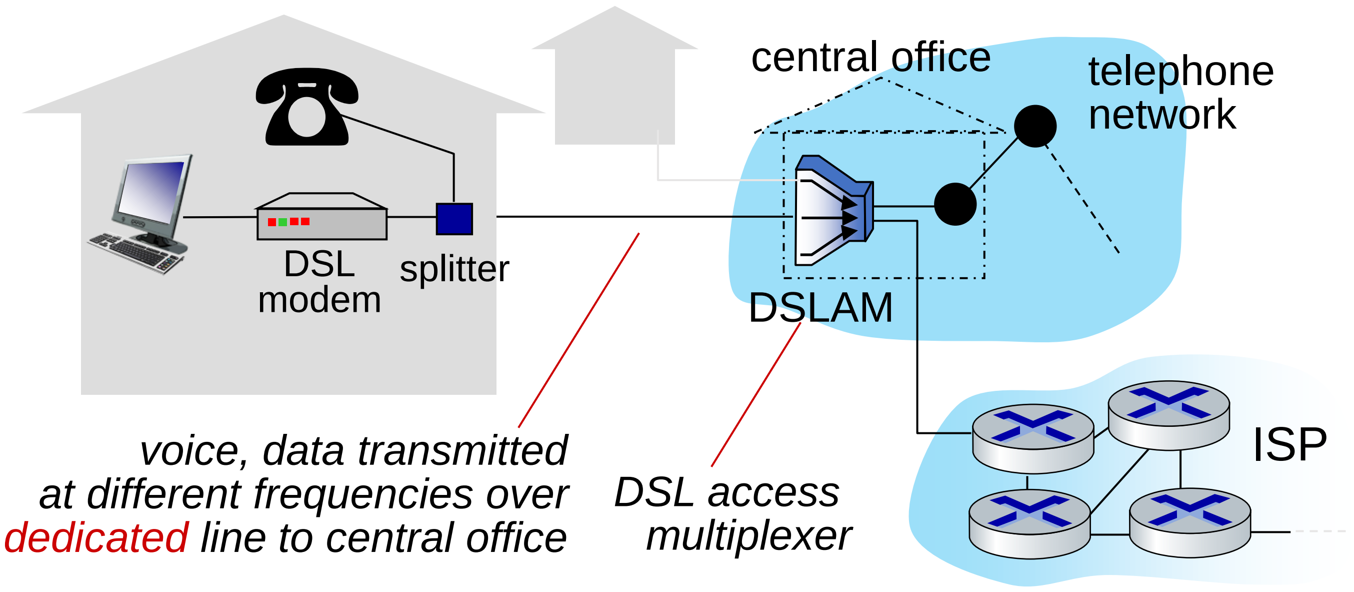
Access networks and physical media

Q: How to connect end systems to edge router?

- residential access networks
- enterprise access networks (school, company)
- wireless access networks (WiFi, 4G/5G)

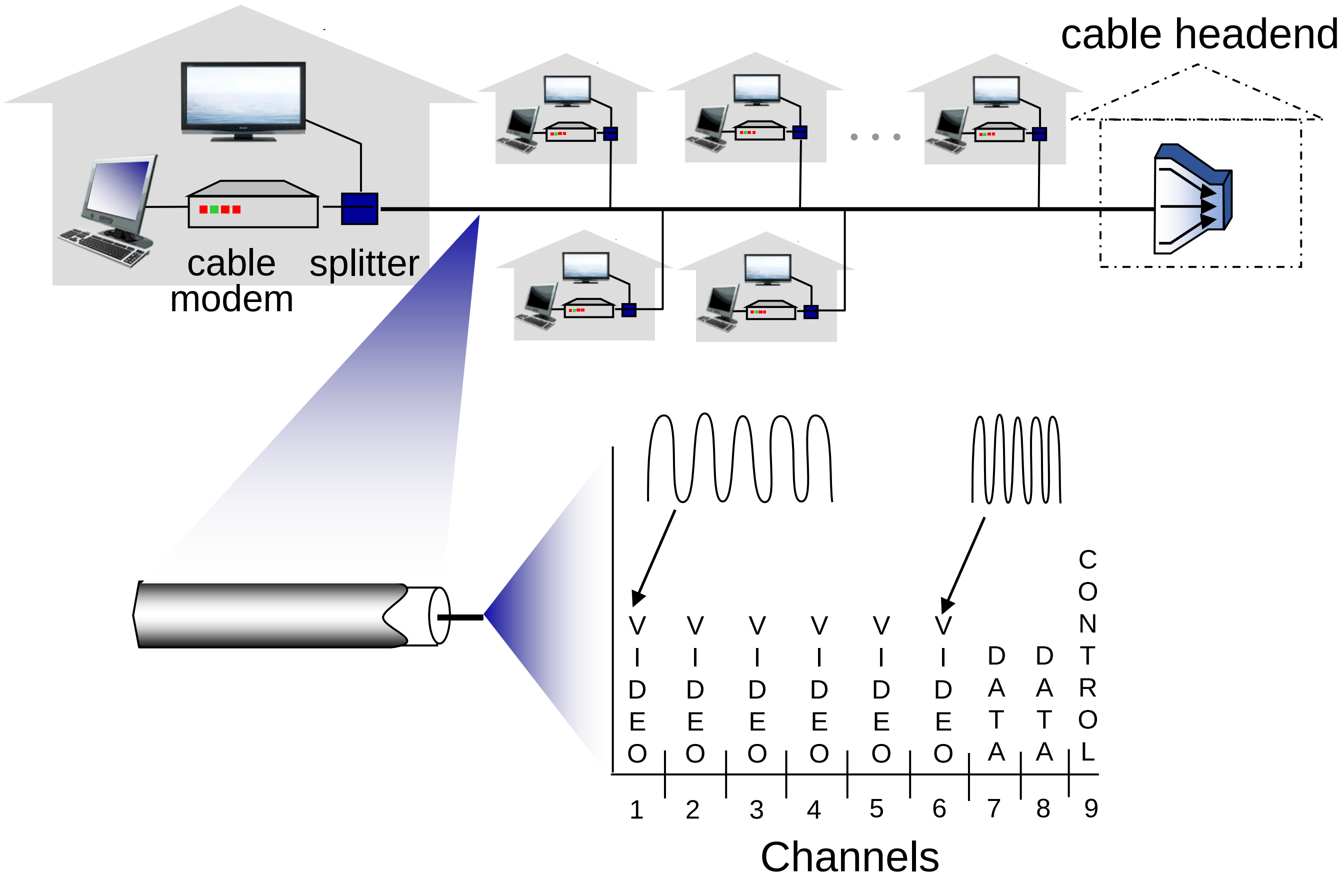


Access networks: digital subscriber line (DSL)



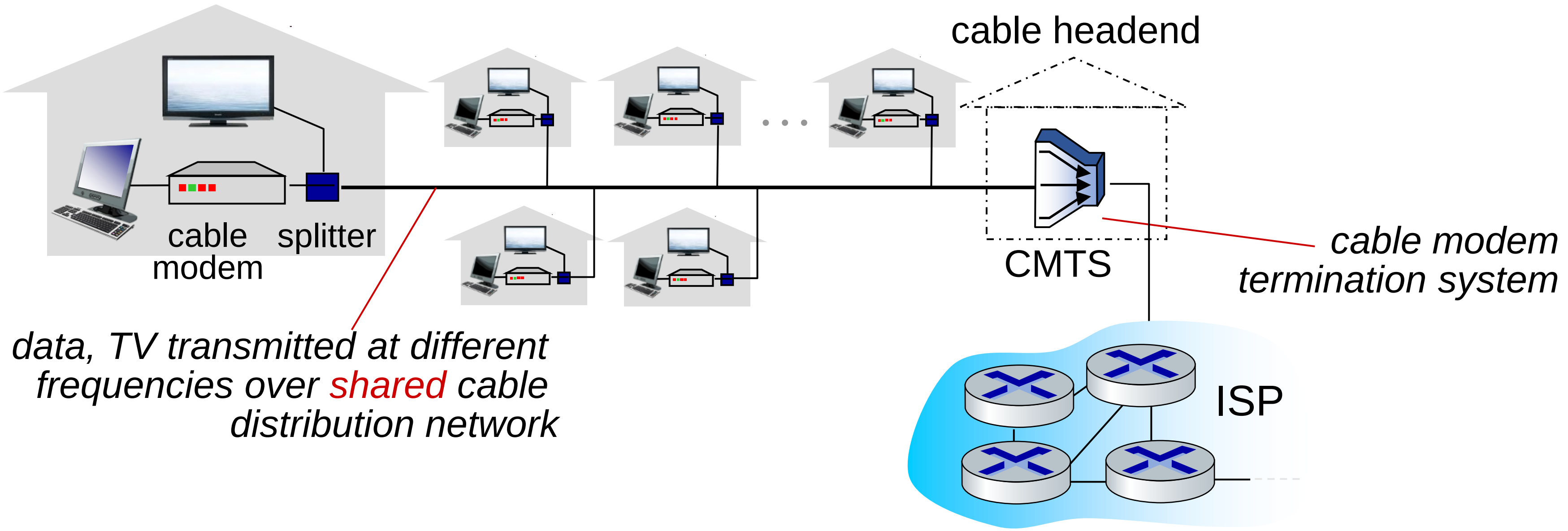
- use *existing* telephone line to central office DSLAM
  - data over DSL phone line goes to Internet
  - voice over DSL phone line goes to telephone net
- 24-52 Mbps dedicated downstream transmission rate
- 3.5-16 Mbps dedicated upstream transmission rate

Access networks: cable-based access



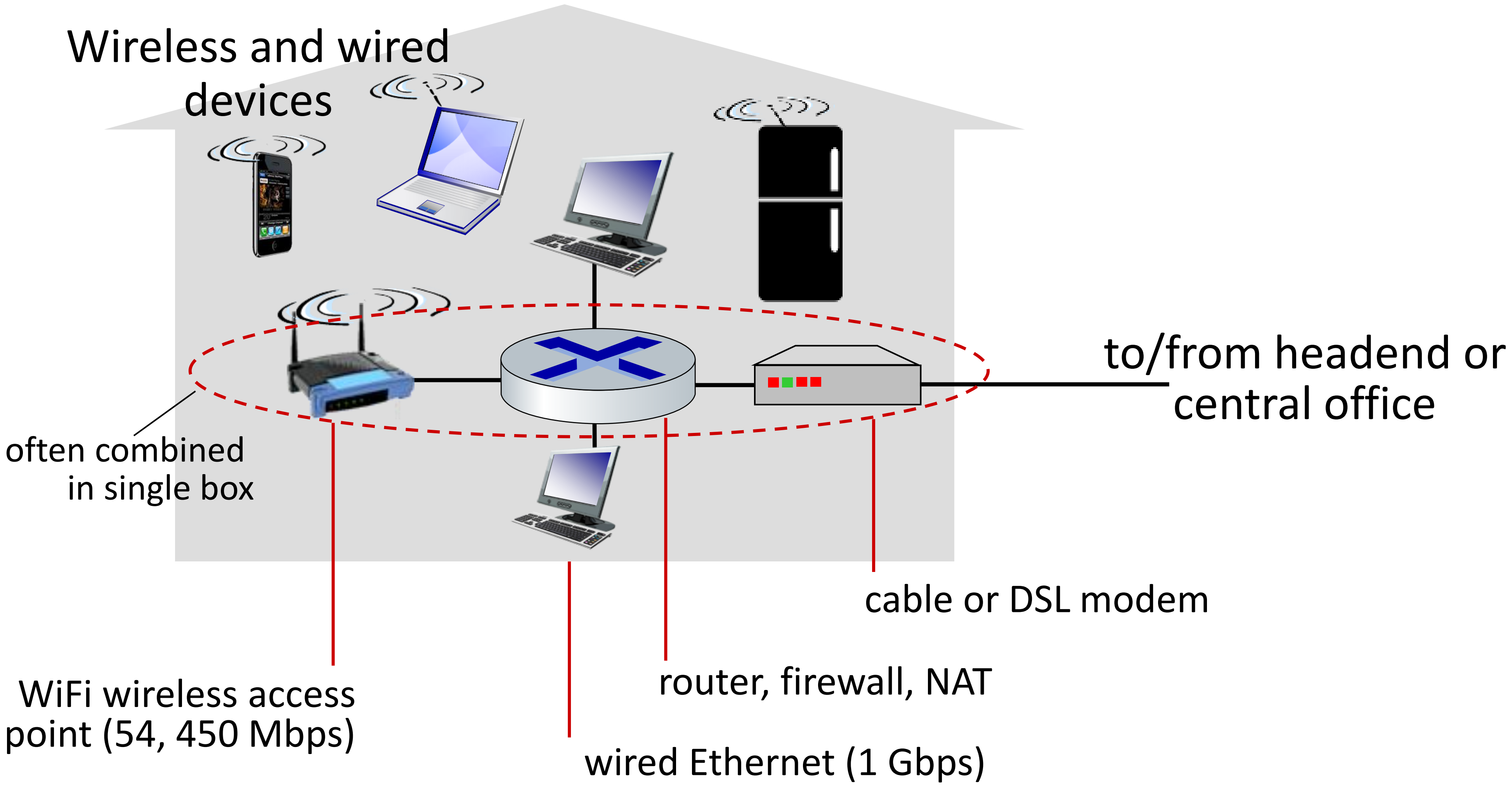
frequency division multiplexing (FDM): different TV channels & data transmitted in different frequency bands on the shared coaxial cable

Access networks: cable-based access

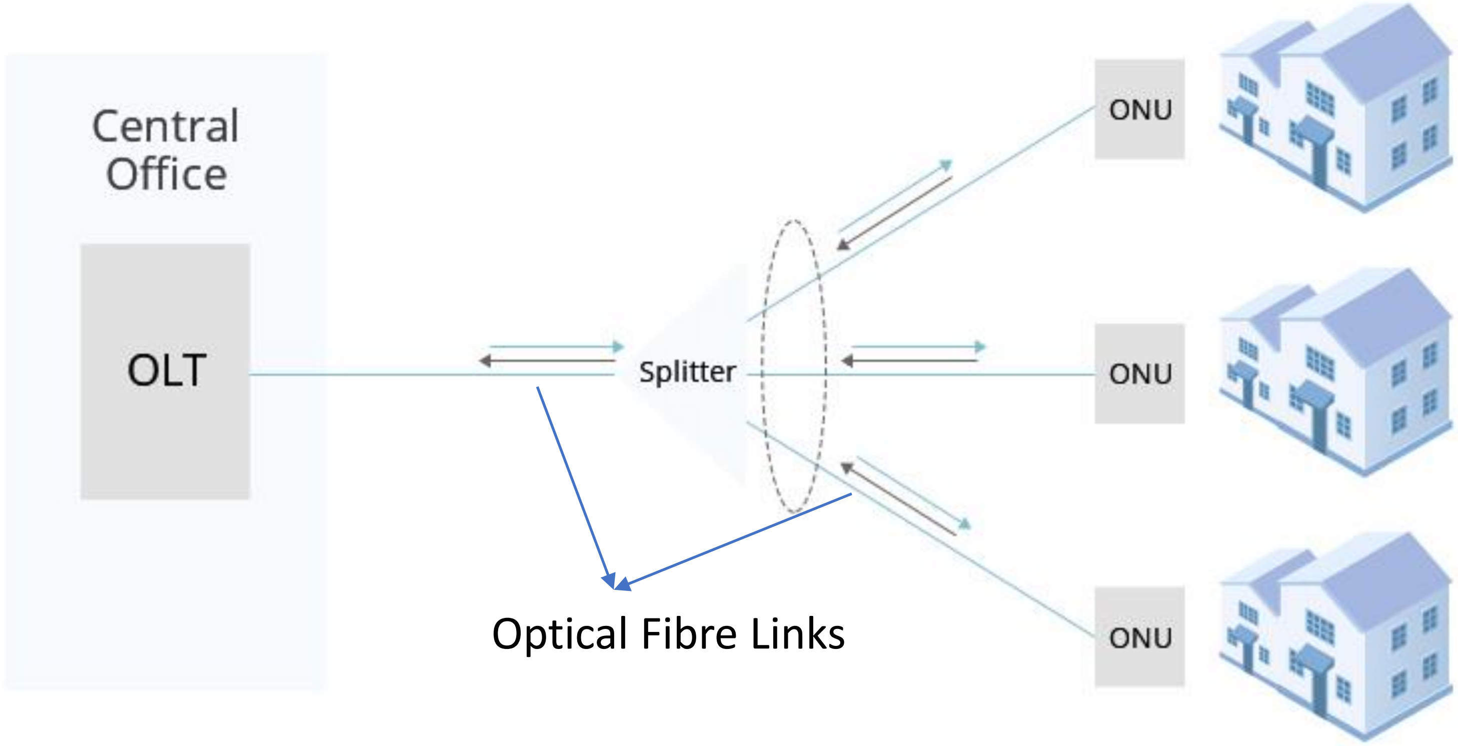


- HFC: hybrid fiber coax
  - asymmetric: up to 40 Mbps – 1.2 Gbps downstream transmission rate, 30-100 Mbps upstream transmission rate
- network of cable, fiber attaches homes to ISP router
  - homes *share access network* to cable headend

Access networks in homes: Wi-Fi/Ethernet



Access networks in homes: FTTH

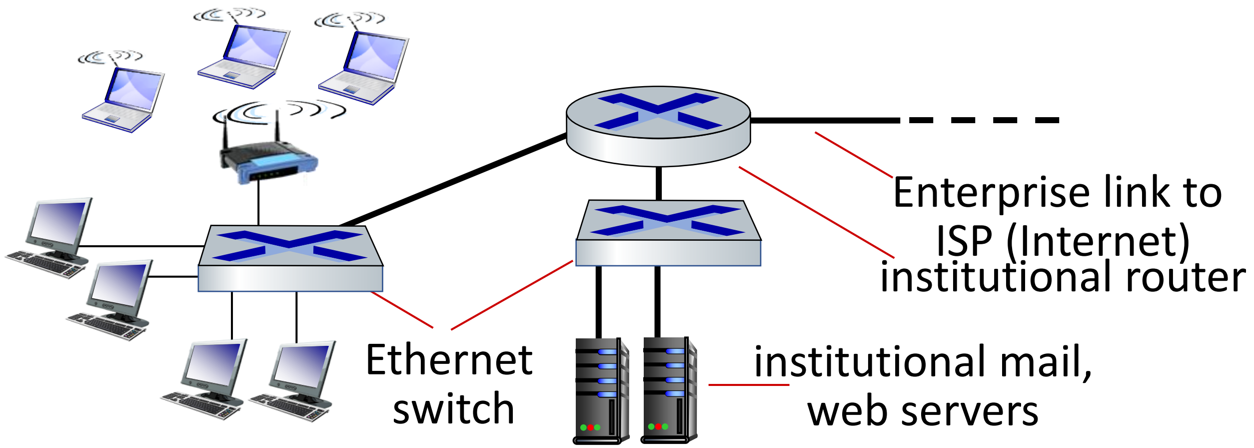


FTTH: Fibre To The Home
OLT: Optical Line Terminal
ONU (ONT): Optical Network Unit/Terminal


Jio Fiber
Wireless-G
Ethernet
Power
DMZ
WLAN 1 2 3 4 Internet
Wireless-G
Broadband Router


WPS
RESET
Team-BHP.com

Access networks in enterprises



- companies, universities, etc.
- mix of wired, wireless link technologies, connecting a mix of switches and routers (we'll cover differences shortly)
  - Ethernet: wired access at 100Mbps, 1Gbps, 10Gbps
  - WiFi: wireless access points at 11, 54, 450 Mbps

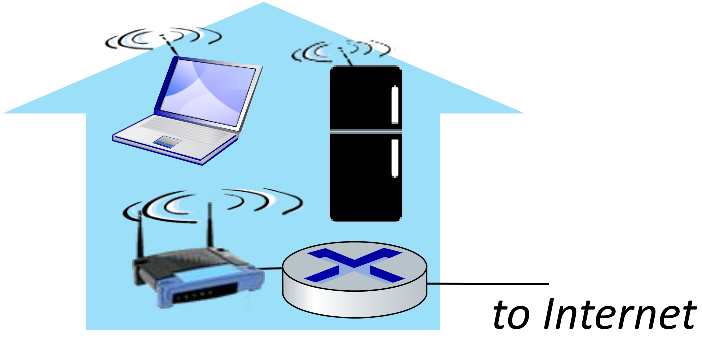
Wireless access networks

Shared *wireless* access network connects end system to router

- via base station aka "access point"

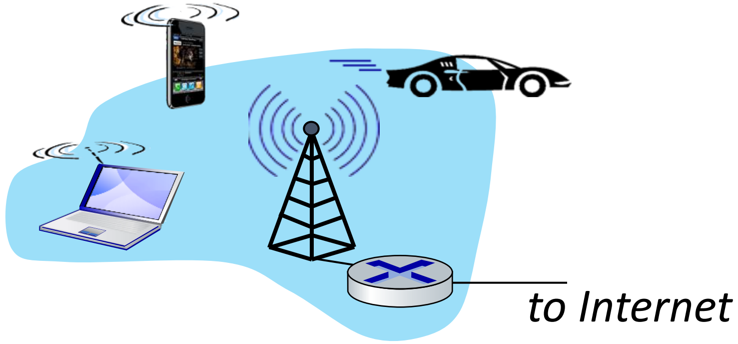
Wireless local area networks (WLANs)

- typically within or around building (~100 ft)
- 802.11b/g/n (WiFi): 11, 54, 450 Mbps transmission rate



Wide-area cellular access networks

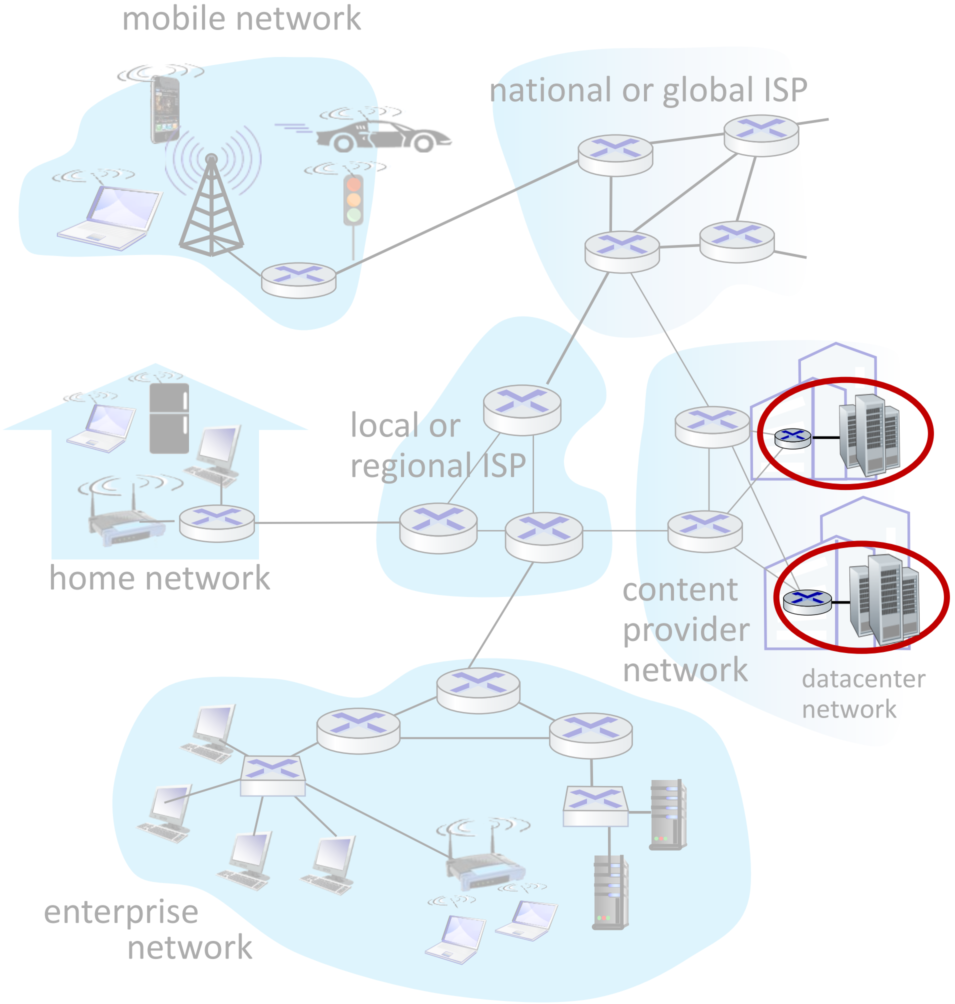
- provided by mobile, cellular network operator (10's km)
- 10's Mbps
- 4G/5G cellular networks



Access networks in data centers

- high-bandwidth links (10s to 100s Gbps) connect hundreds to thousands of servers together, and to Internet

Courtesy: Massachusetts Green High Performance Computing Center (mghpcc.org)



Next Lecture: Outline

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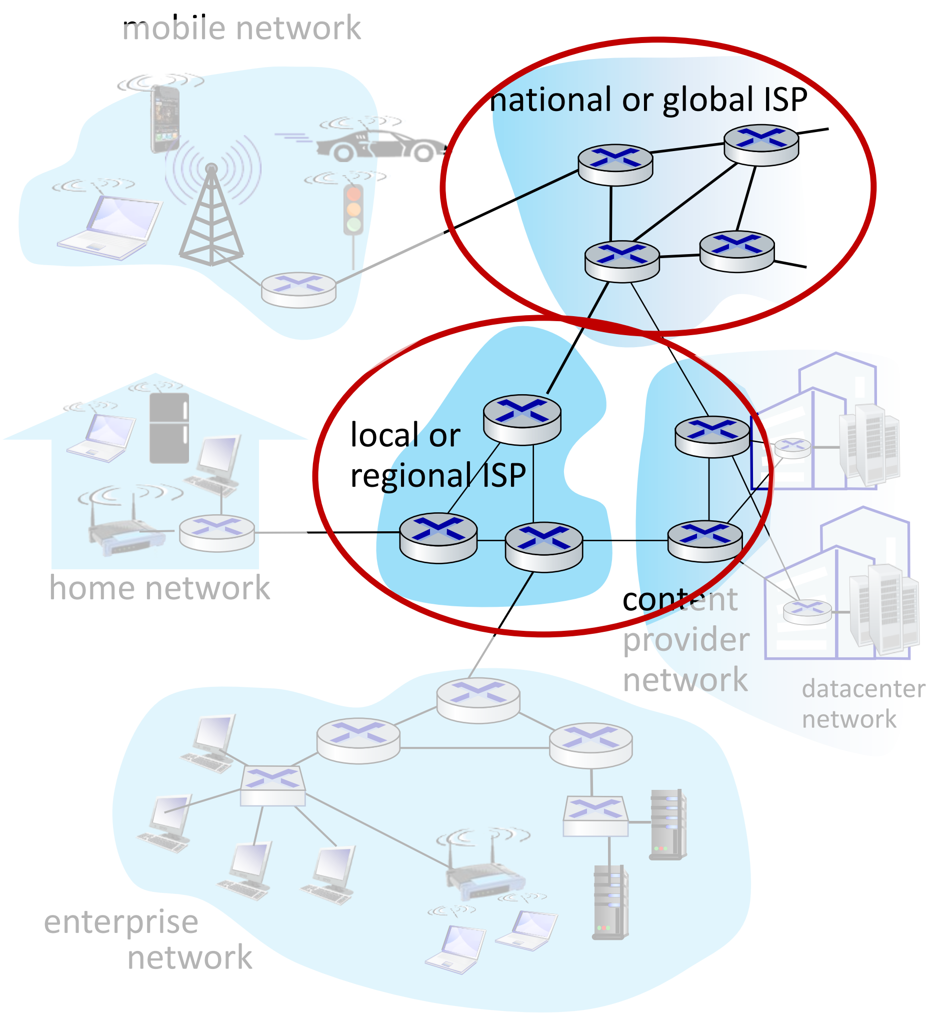
Readings

- Chapter 1.1 & 1.2 of Computer Networking: A Top-Down Approach **by James F. Kurose and Keith W. Ross**, 8th Edition, 2020, Addison Wesley (Pearson Education)
  - https://gaia.cs.umass.edu/kurose_ross/videos/1/
- https://cse.iith.ac.in/academics/plagiarism-policy.html

The network core

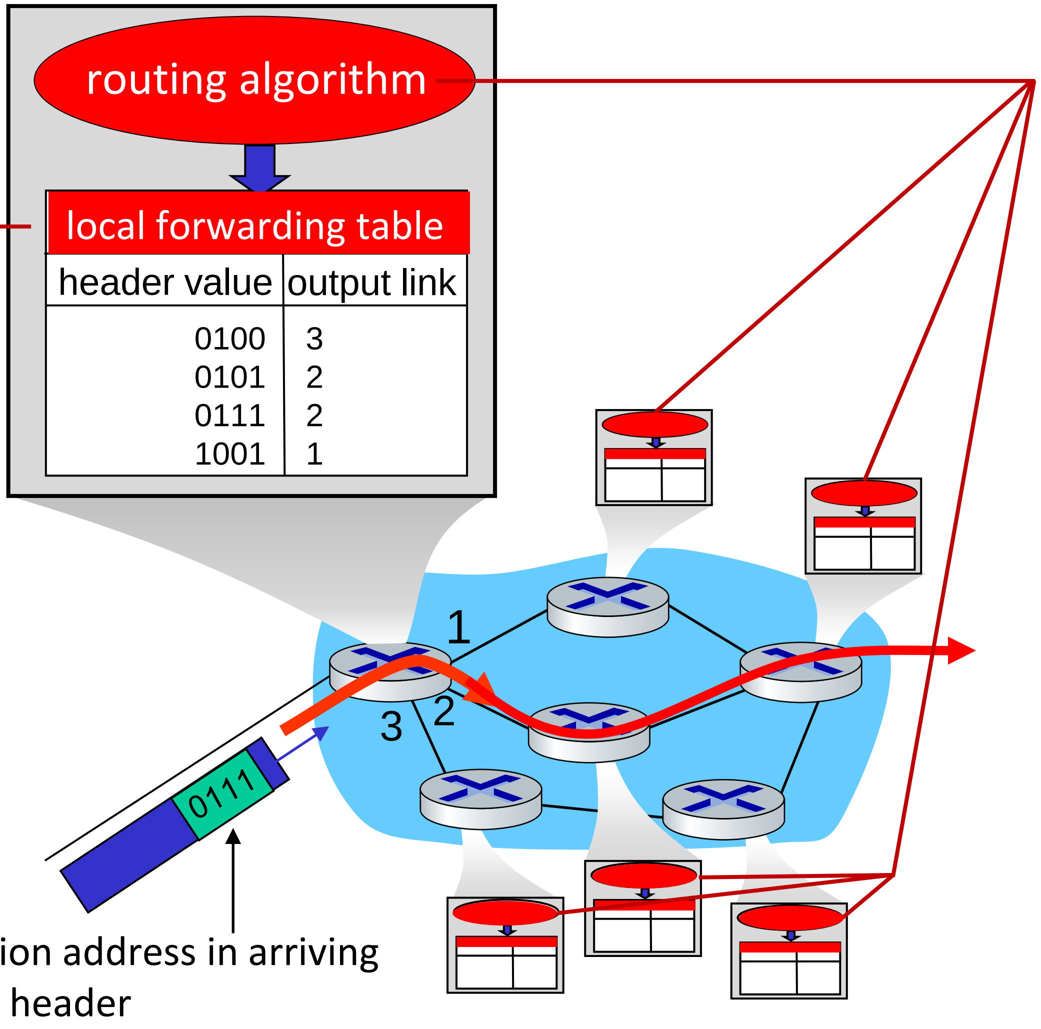
- mesh of interconnected routers
- packet-switching: hosts break application-layer messages into *packets*
  - network forwards packets from one router to the next, across links on path from source to destination



Two key network-core functions

Forwarding:

- aka "switching"
- *local* action: move arriving packets from router's input link to appropriate router output link



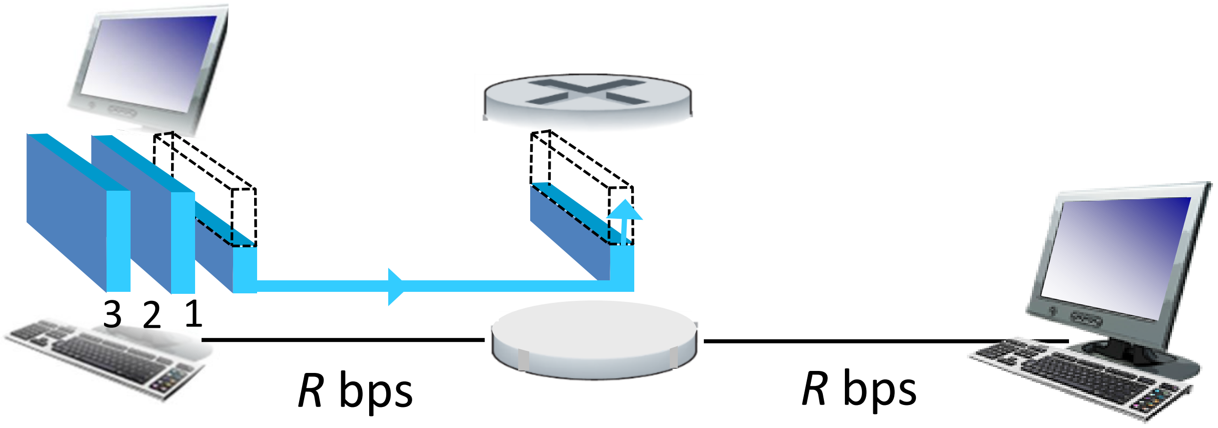
Routing:

- *global* action: determine source-destination paths taken by packets
- routing algorithms


45 h
3,053 miles
48 h
3,309 miles
United States
routing
San Jose
Northampton

forwarding
forwarding
45 h
3,053 miles
48 h
3,309 miles
United States
San Jose
Northampton
Sacramento
Cleveland

Packet-switching: store-and-forward



- packet transmission delay: *L*/*R* seconds
- *store and forward: entire* packet must arrive at router before it can be transmitted on next link
- *propagation delay*: Distance/Speed of light

Total one-hop delay?

Total two-hop delay?

One-hop numerical example:

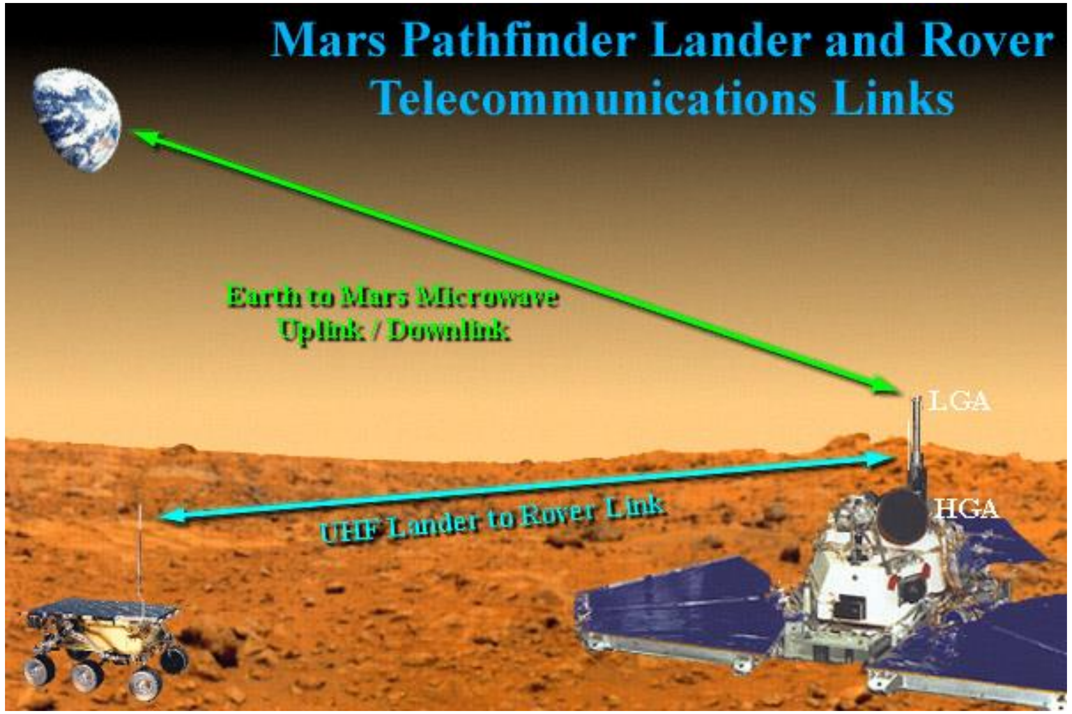
- *L* = 10 Kbits, D = 300 m
- *R* = 100 Mbps, S=$3*10^8$ m/s
- one-hop transmission delay = 100 micro-sec
- One-hop propagation delay = 1 micro-sec

Homework (Q1): delay comparison in packet-switching

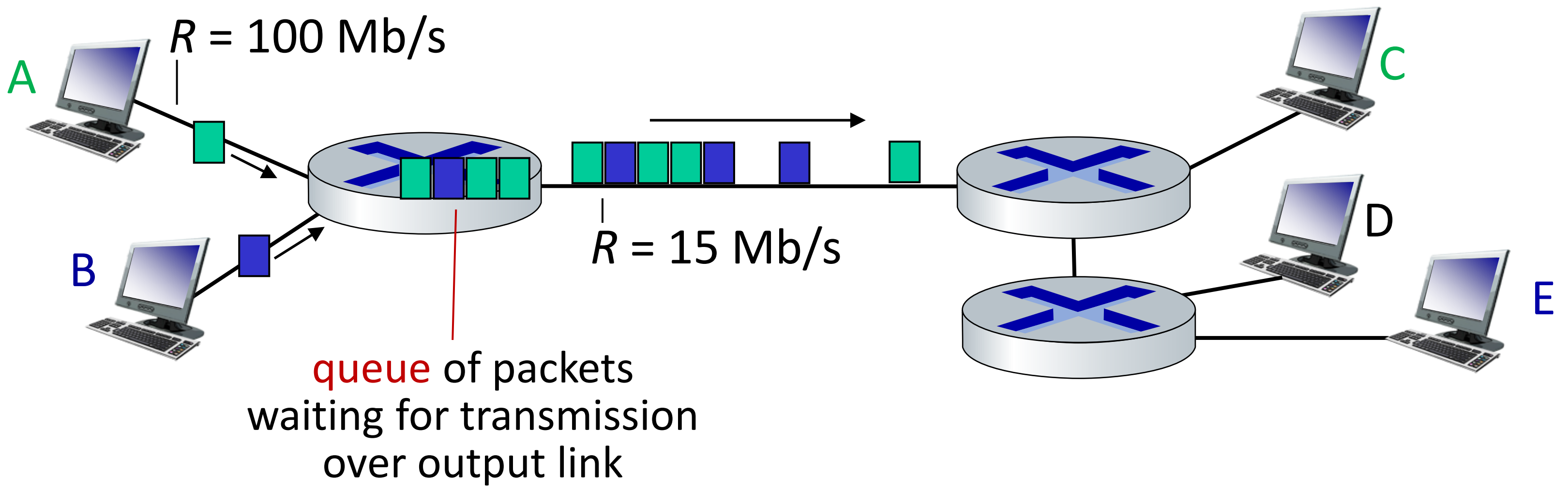
- Packet Size: L bits
- Transmission Rate of links: R bps
- Link length: D meters
- Speed of light: S meters/second
- Total delay incurred in transmitting P packets back-to-back from the source to the destination over N links in case of
  - Store-and-forward switching?
  - Pass-through switching?

Homework (Q2)

- Suppose two hosts, Earth ground station and NASA's Mars Pathfinder, are separated by **250 Million KM** and are connected by a direct point-to-point microwave link of capacity, **R = 1 Mbps**. Suppose the propagation speed of light over the link is **2.5 * 10^8 m/s**. Consider sending a packet of **1MB** from Pathfinder to Earth.
  - How long does it take to receive the packet on Earth's ground station?



Packet-switching: queueing

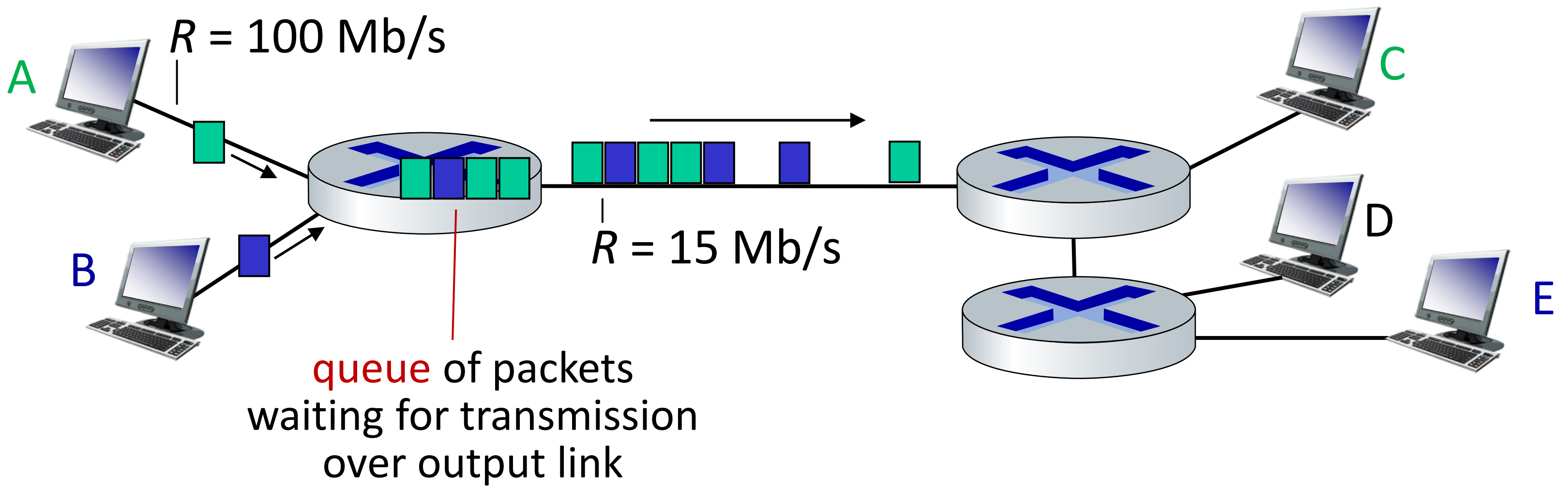


Queueing occurs when work arrives faster than it can be serviced:

Homework

- Task-1: Go through Chapter 1.3 of Computer Networking: A Top-Down Approach **by James F. Kurose and Keith W. Ross**, 8th Edition, 2020, Addison Wesley (Pearson Education)
  - https://gaia.cs.umass.edu/kurose_ross/videos/1/
- Task-2: Do the interactive exercises on circuit-switching at https://gaia.cs.umass.edu/kurose_ross/interactive/circuit_switching.php
- Task-3: Solve Homework problems(Q1 & Q2) in slides 41-42 and post your solutions in Google classroom
- Task-4: Solve Chapter-1 of Kurose and Ross textbook's exercise problems P4, P6 and P7 and post your solutions in Google classroom

Packet-switching: queueing



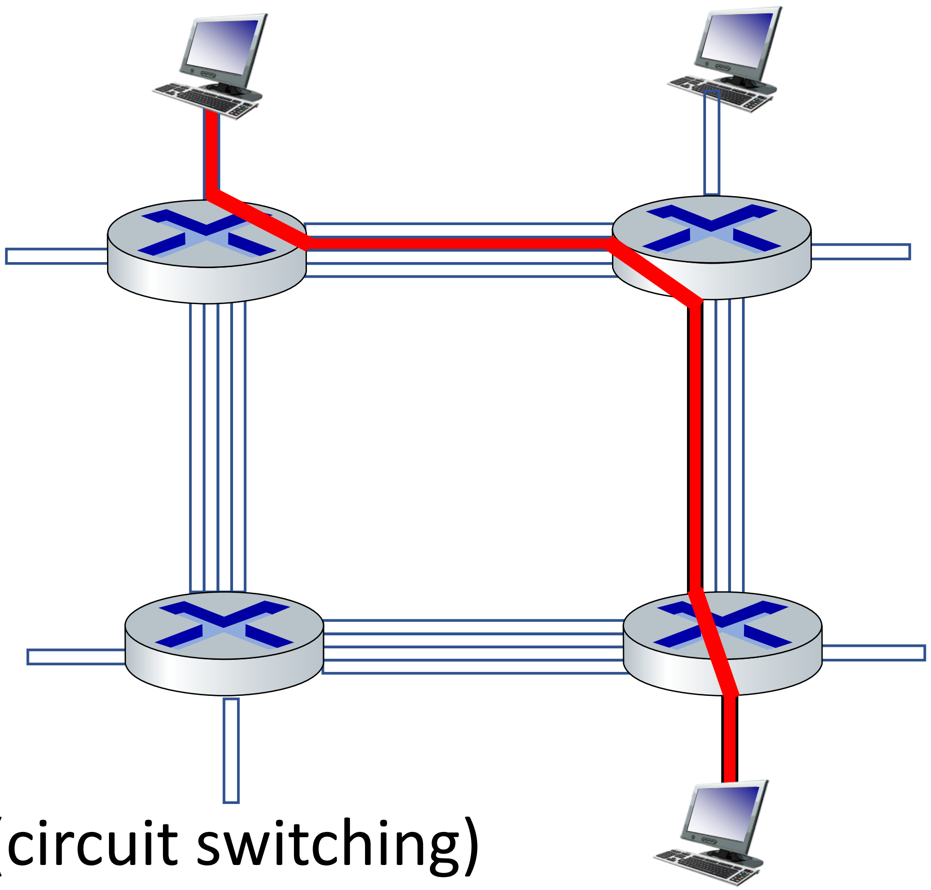
Packet queuing and loss: if arrival rate (in bps) to link exceeds transmission rate (bps) of link for some period of time:

- packets will queue, waiting to be transmitted on output link
- packets can be dropped (lost) if memory (buffer) in router fills up

Alternative to packet switching: circuit switching

end-to-end resources allocated to, reserved for "call" b/w source & dst

- 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



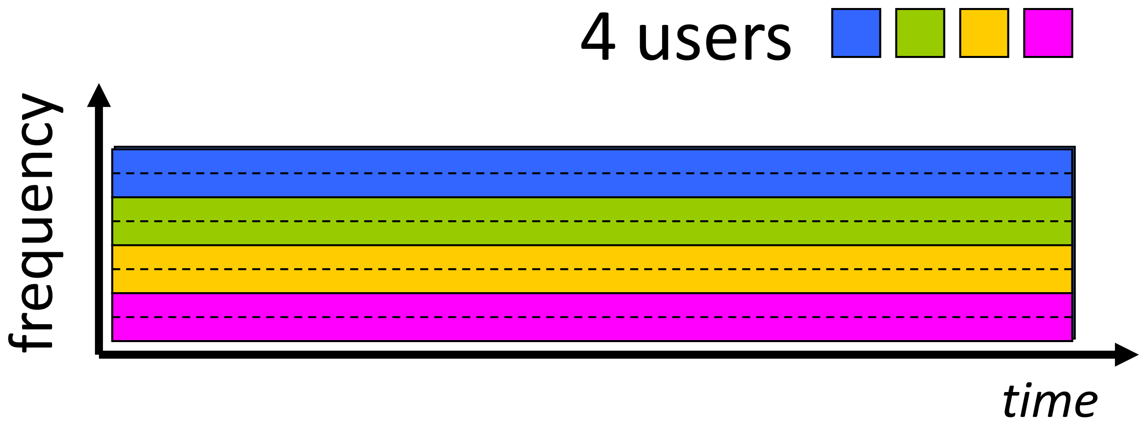
Q: human analogies of reserved resources (circuit switching) versus on-demand allocation (packet switching)?

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

Circuit switching: FDM and TDM

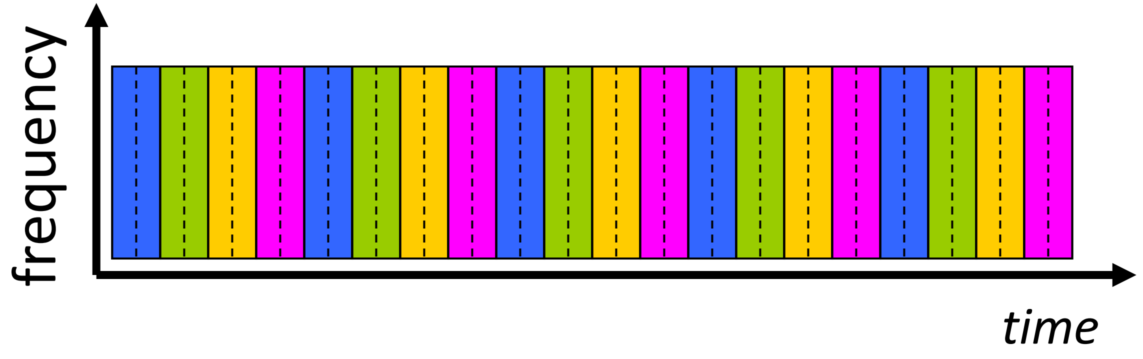
Frequency Division Multiplexing (FDM)

- optical, electromagnetic frequencies divided into (narrow) frequency bands
- each call allocated its own band, can transmit at max rate of that narrow band



Time Division Multiplexing (TDM)

- time divided into slots
- each call allocated periodic slot(s), can transmit at maximum rate of (wider) frequency band (only) during its time slot(s)



Radio waves

- One type of EM waves
- 30 Hz to 300 GHz
- 1-30 GHz also called as Microwaves
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  - Unused, abundant, main candidate spectrum for 5G operations

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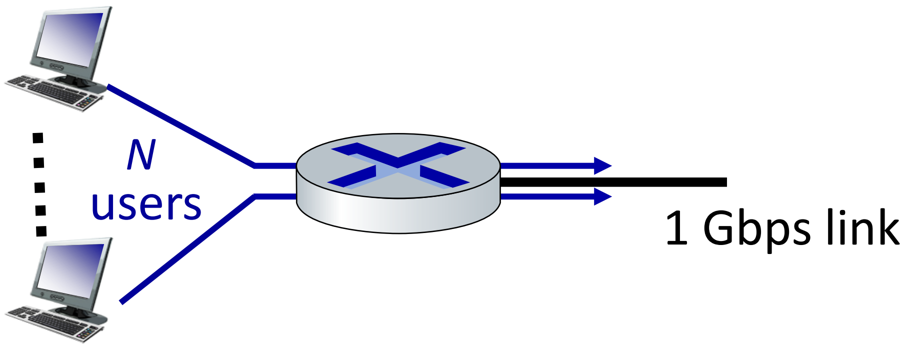
http://www.astrosurf.com/luxorion/qsl-propa.htm

Packet switching versus circuit switching

example:

- 1 Gb/s link
- each user:
  - 100 Mb/s when "active"
  - active 10% of time



Q: how many users can use this network under circuit-switching and packet switching?

- *circuit-switching:* 10 users
- *packet switching:* with 35 users, probability > 10 active at same time is less than .0004 *

Q: how did we get value 0.0004?

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

- Online calculator: https://shiny.rit.albany.edu/stat/binomial/

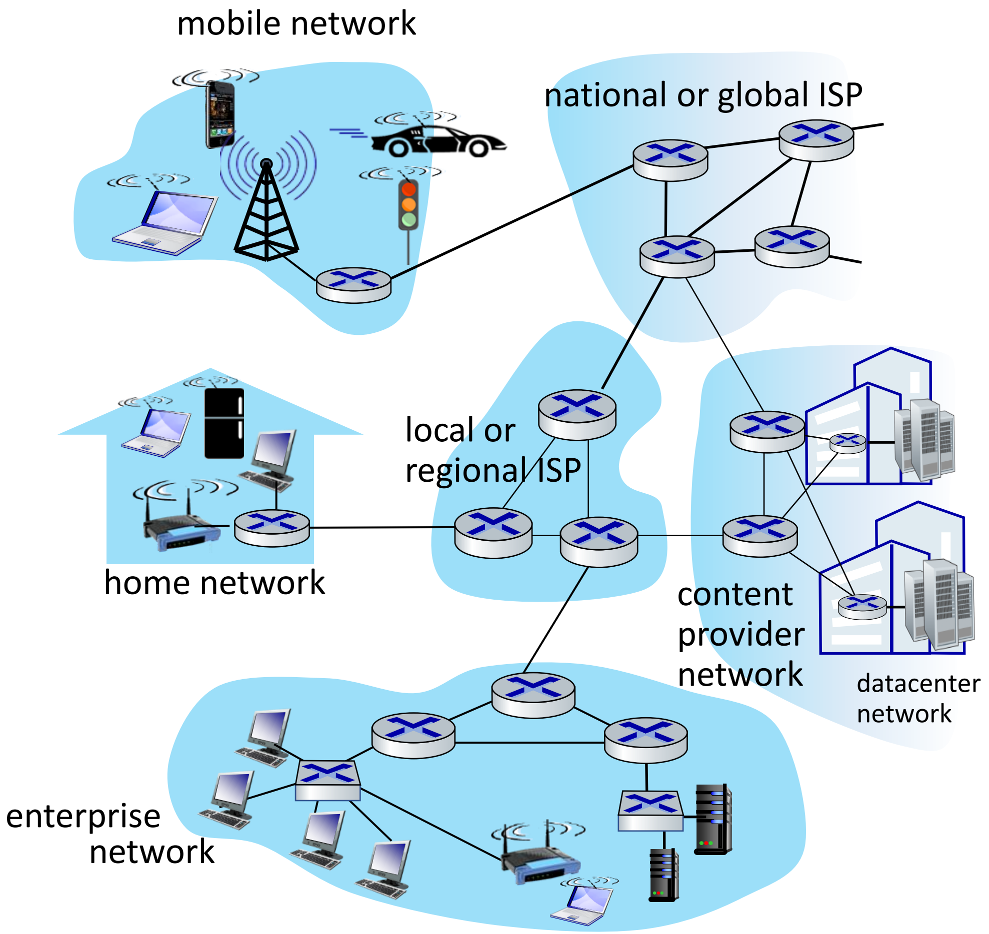
Packet switching versus circuit switching

Is packet switching a "slam dunk winner"?

- great for "bursty" data (which is the case on the Internet) – sometimes has data to send, but at other times not
  - resource sharing
  - simpler, no call setup
- excessive congestion possible: packet delay and loss due to buffer overflow
  - protocols needed for reliable data transfer, congestion control
- *Q:* How to provide circuit-like behavior with packet-switching?
  - "It's complicated."
  - We'll study various techniques that try to make packet switching as "circuit-like" as possible.

Internet structure: a “network of networks”

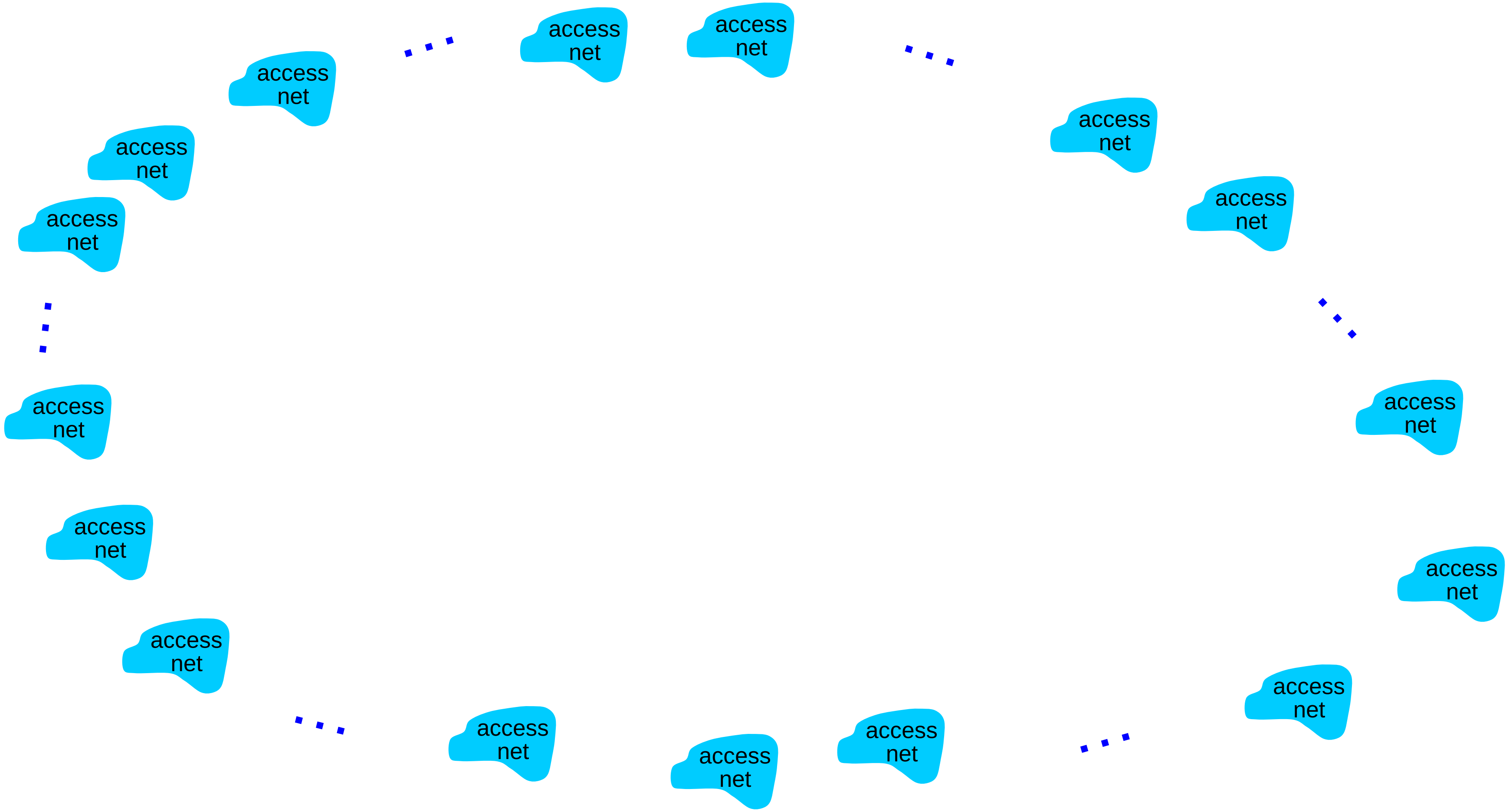
- hosts connect to Internet via access Internet Service Providers (ISPs)
- access ISPs in turn must be interconnected
  - so that *any* two hosts *(anywhere!)* can send packets to each other
- resulting network of networks is very complex
  - evolution driven by economics & national policies



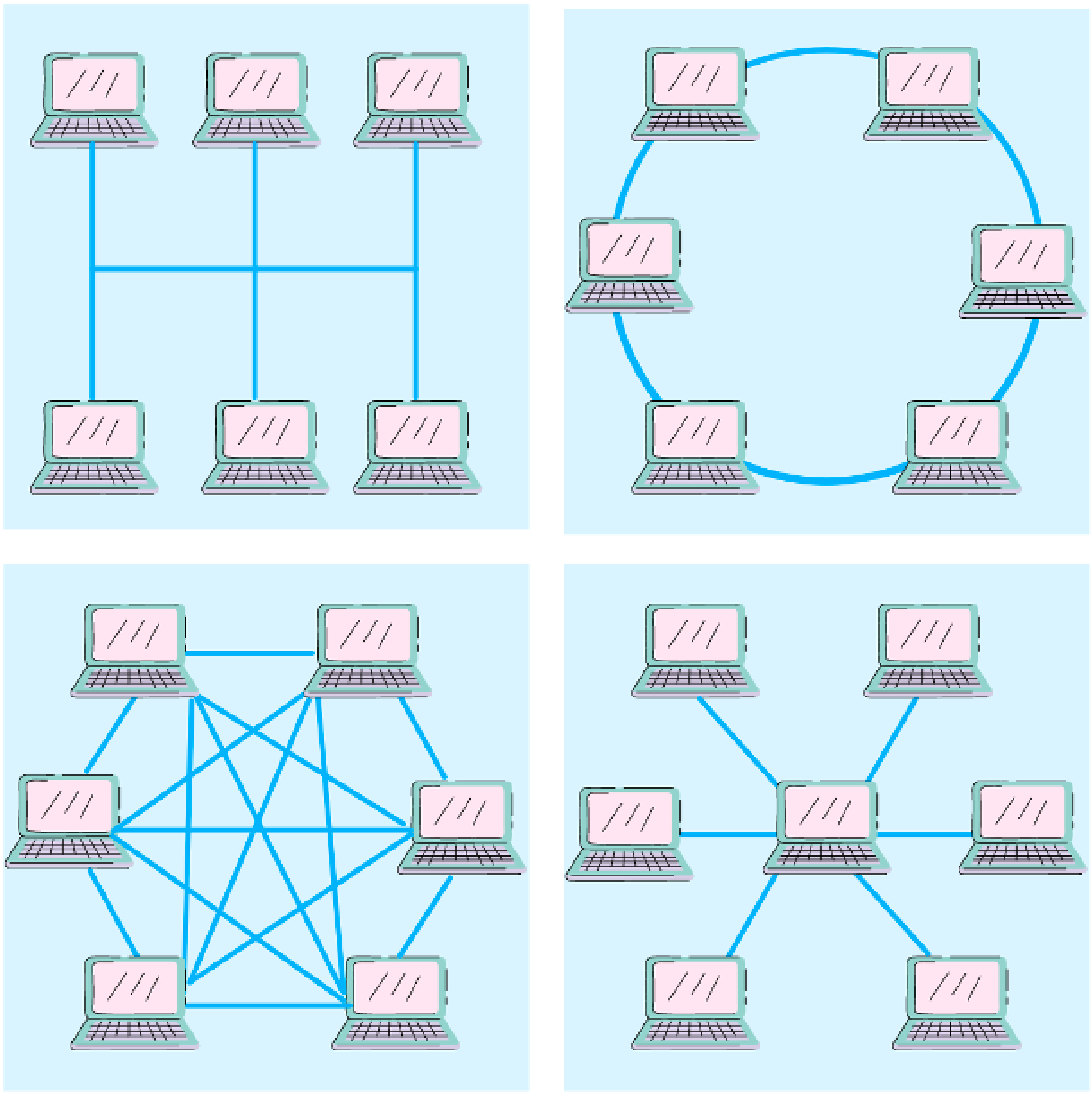
Let’s take a stepwise approach to describe current Internet structure

Internet structure: a "network of networks"

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

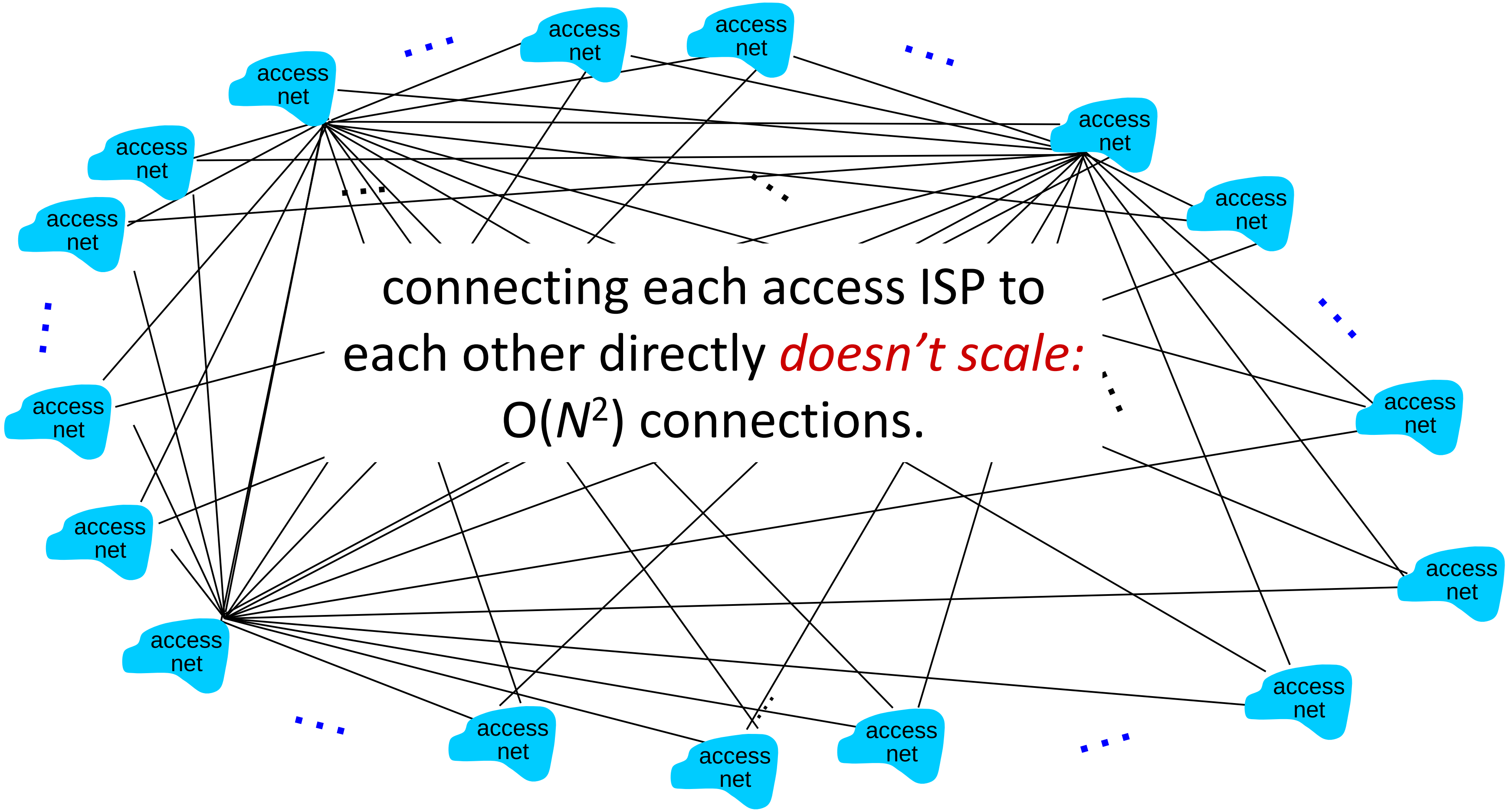


Network Structure: Different Topologies



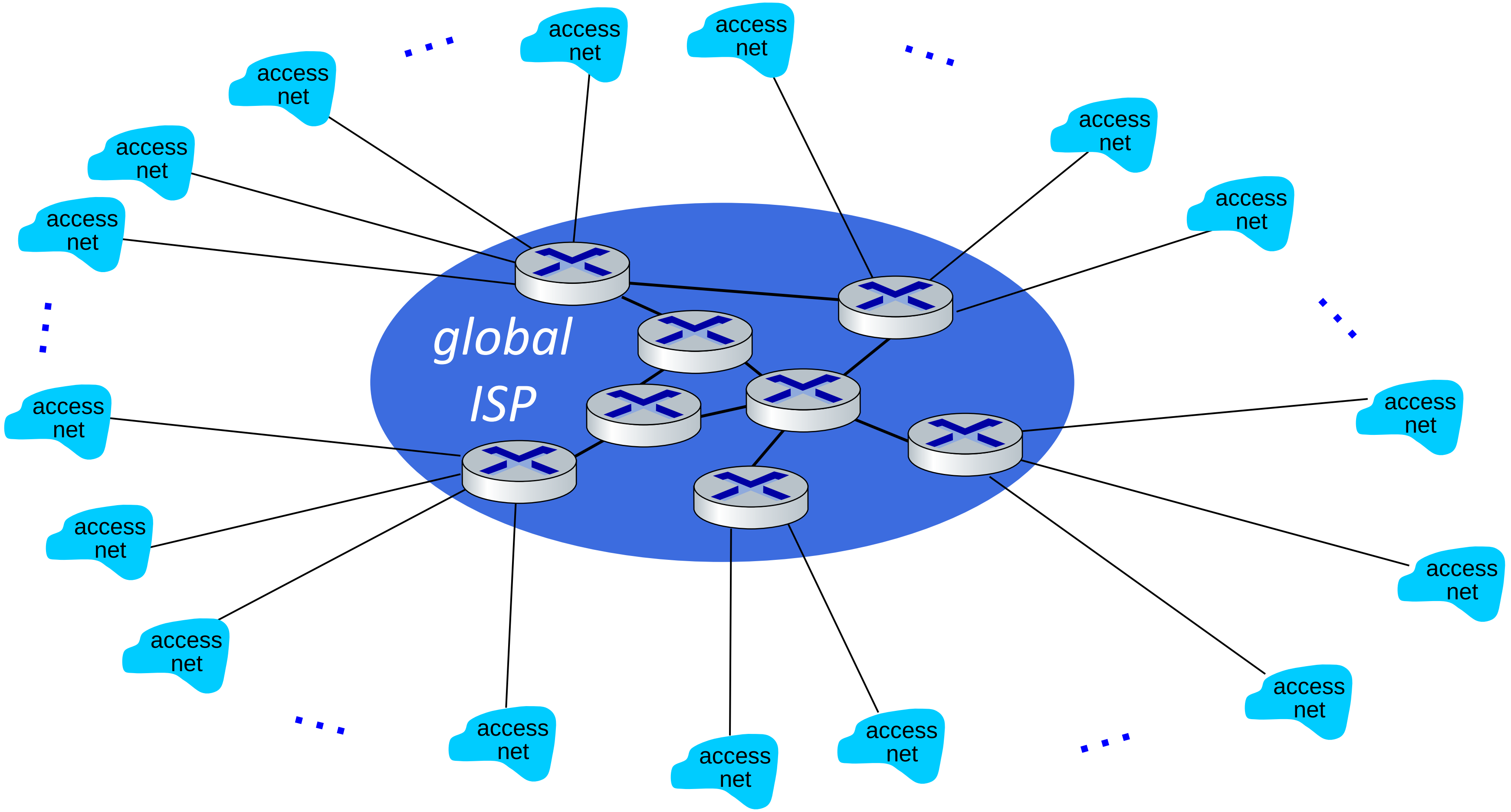
Internet structure: a “network of networks”

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



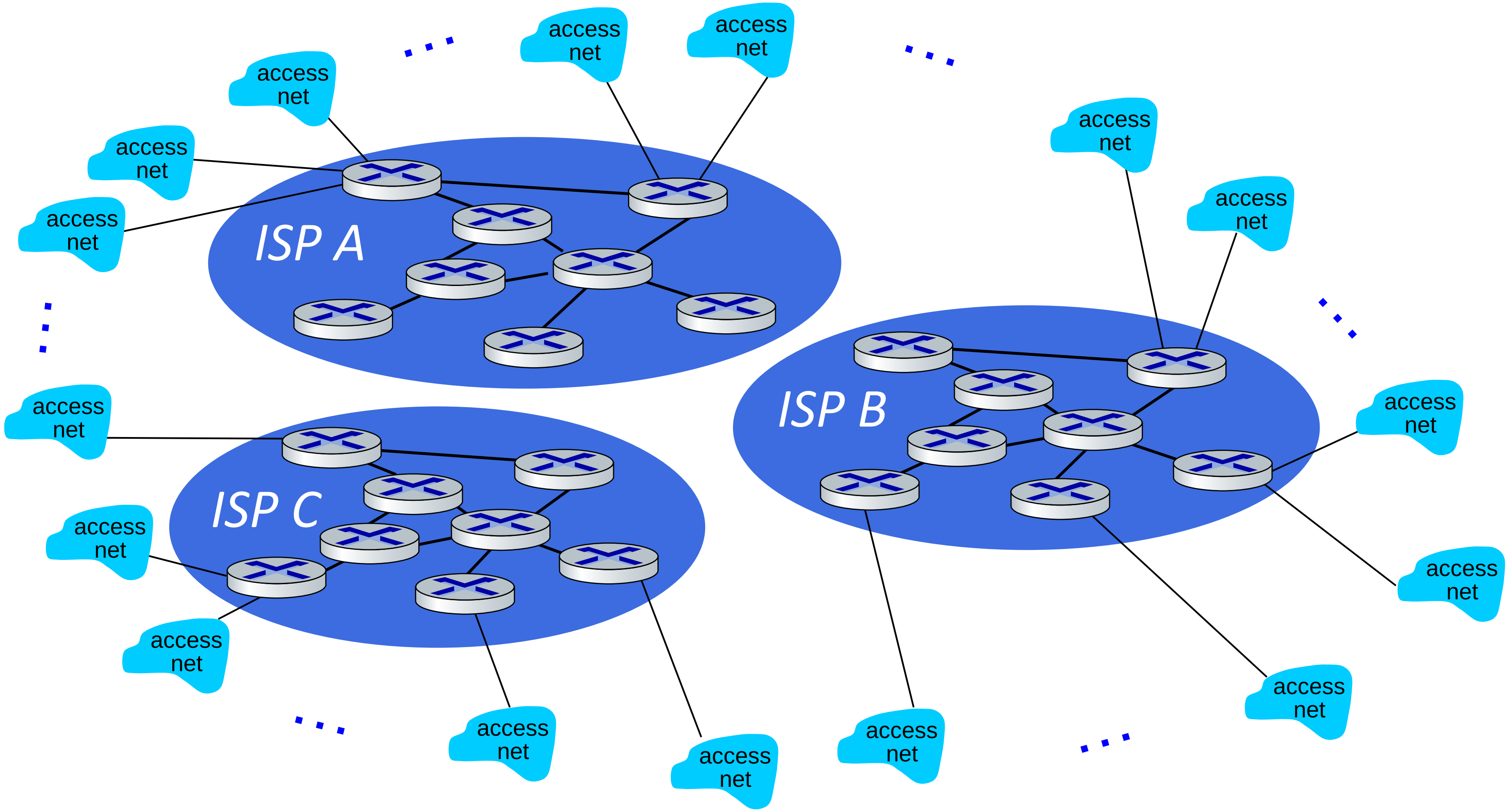
Internet structure: a "network of networks"

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



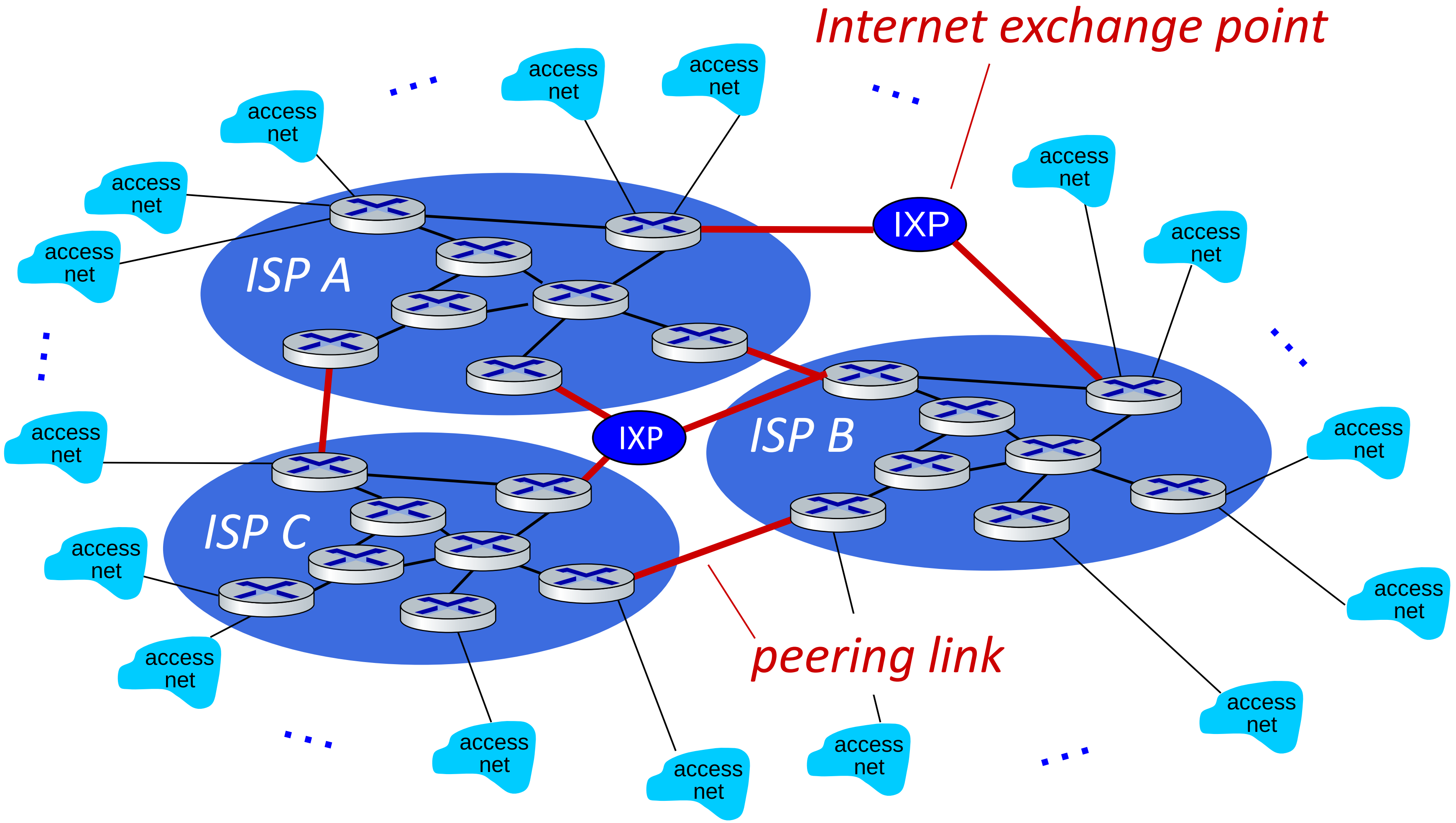
Internet structure: a "network of networks"

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



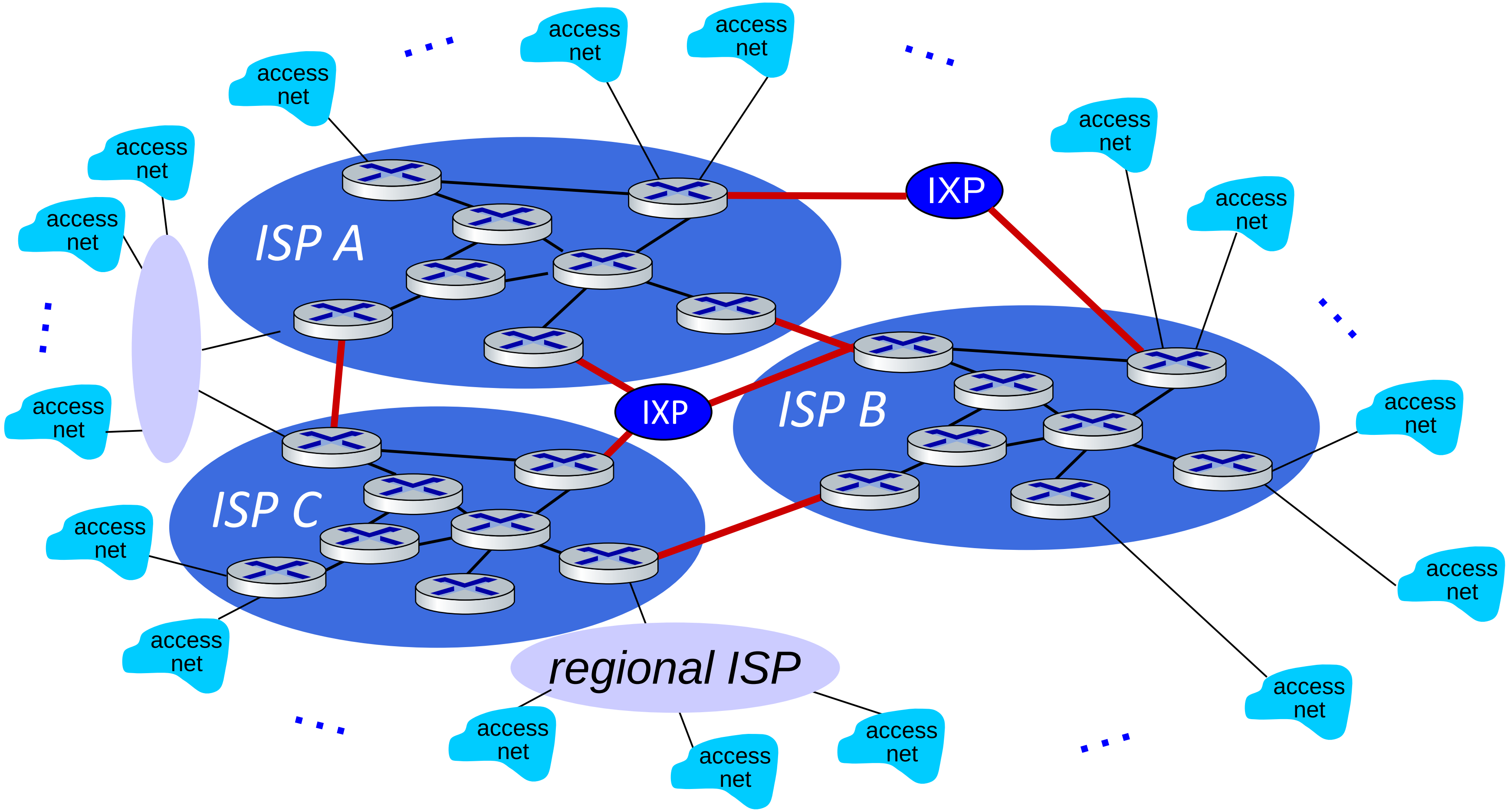
Internet structure: a "network of networks"

But if one global ISP is viable business, there will be competitors …. who will want to be connected



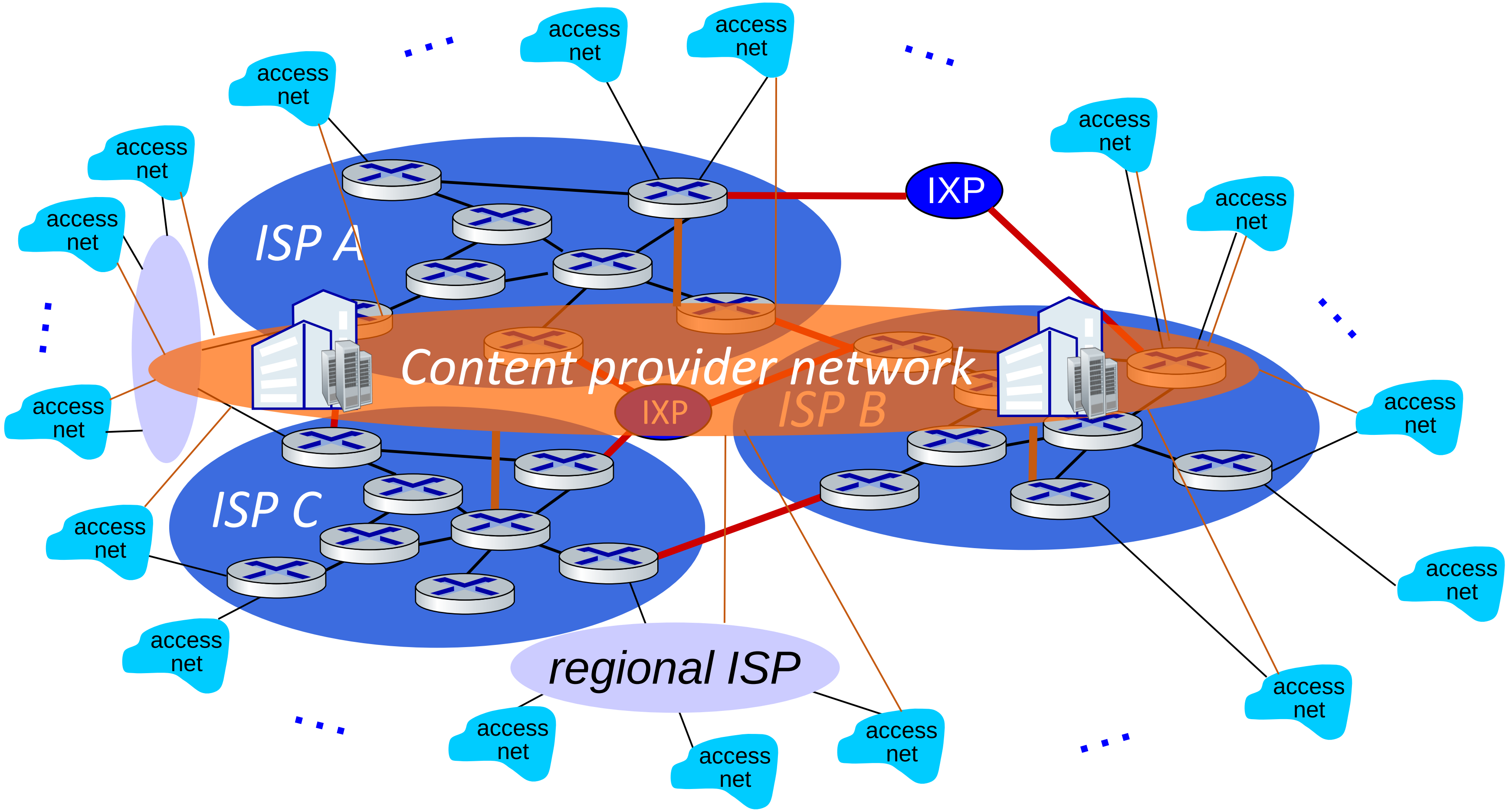
Internet structure: a "network of networks"

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

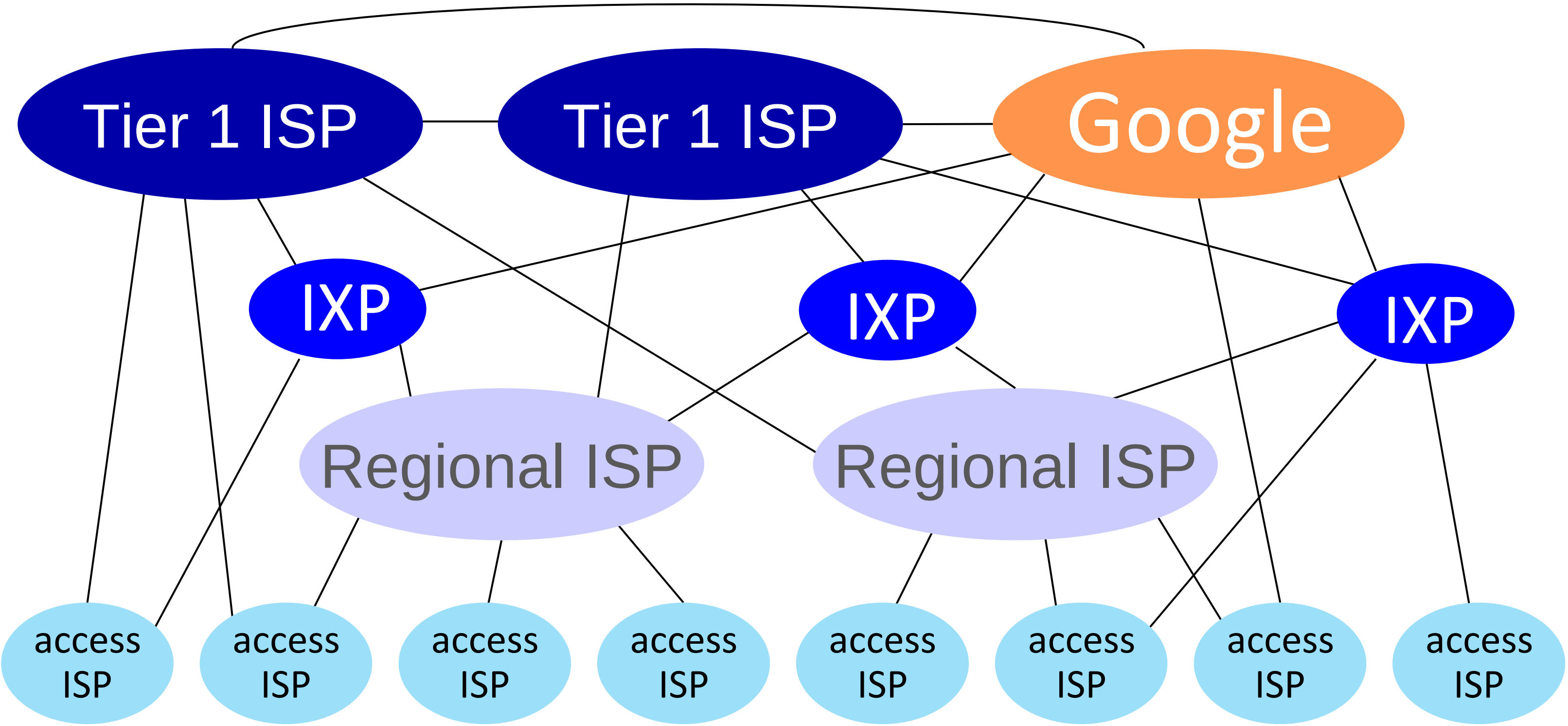


Internet structure: a "network of networks"

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

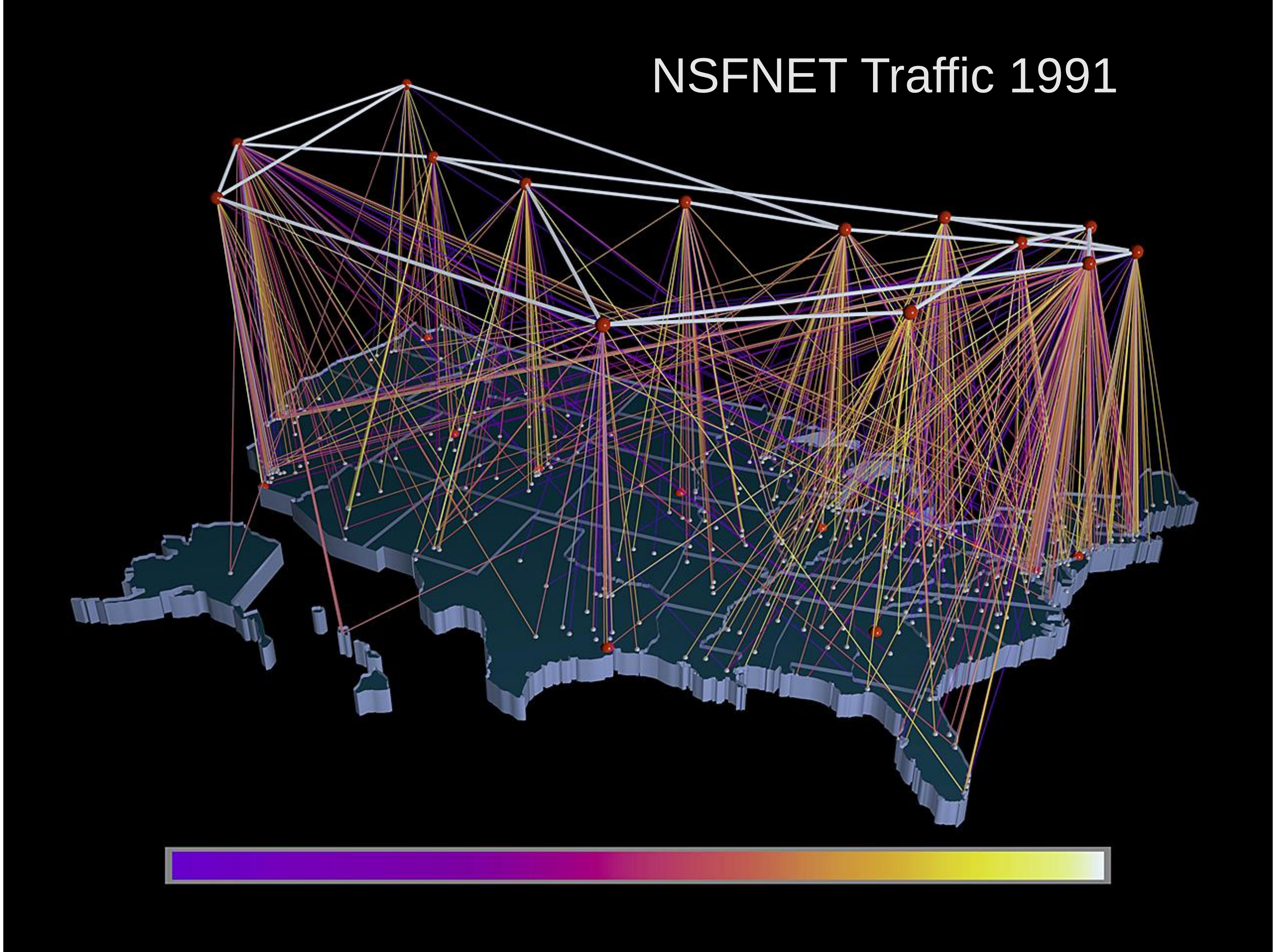


Internet structure: a "network of networks"



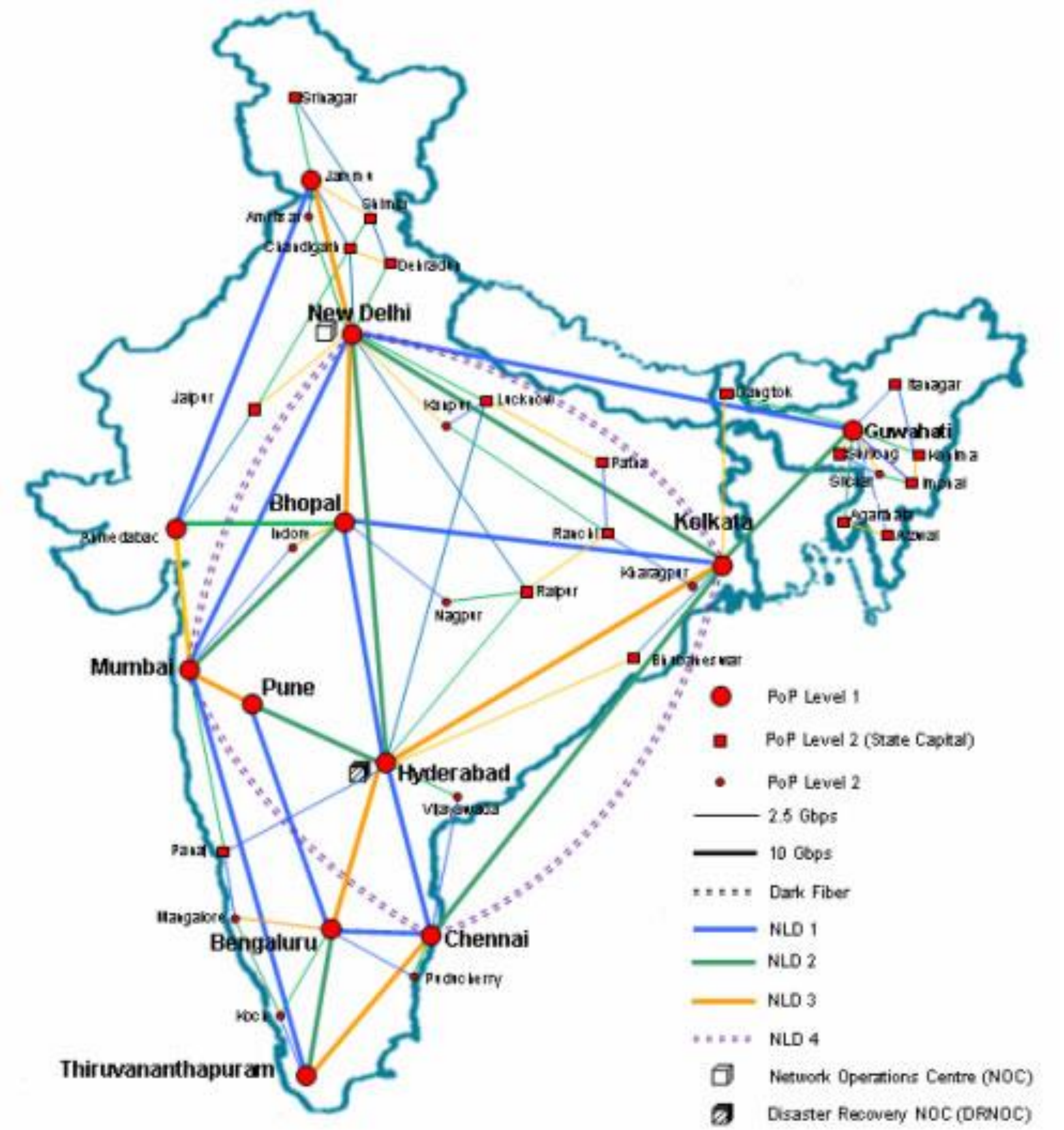
At "center": small # of well-connected large networks

- "tier-1" commercial ISPs (e.g., Level 3, Sprint, AT&T, NTT), national & international coverage
- content provider networks (e.g., Google, Facebook): private network that connects its data centers to Internet, often bypassing tier-1, regional ISPs



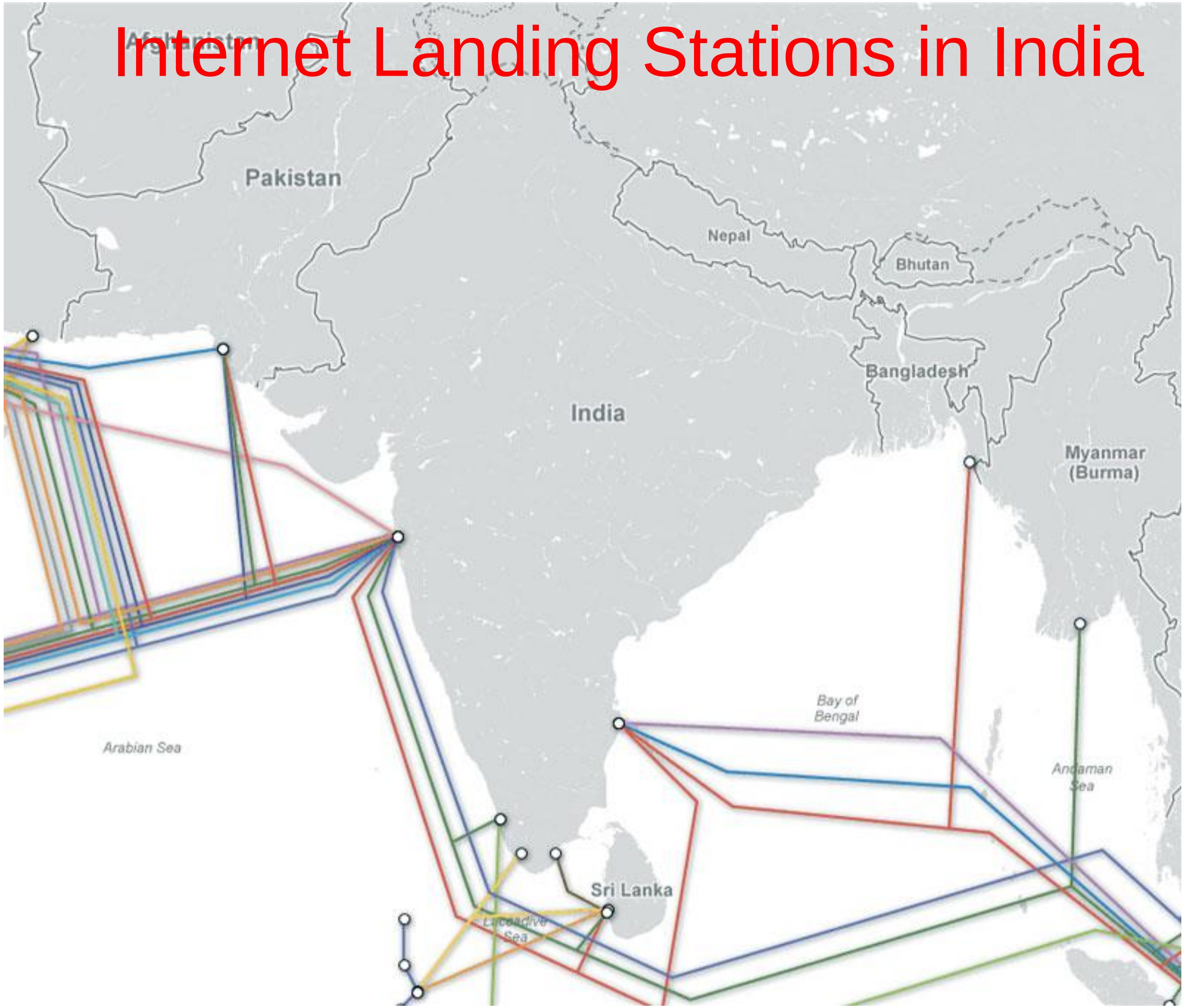
https://avl.ncsa.illinois.edu/project-archive/visualizing-the-early-internet

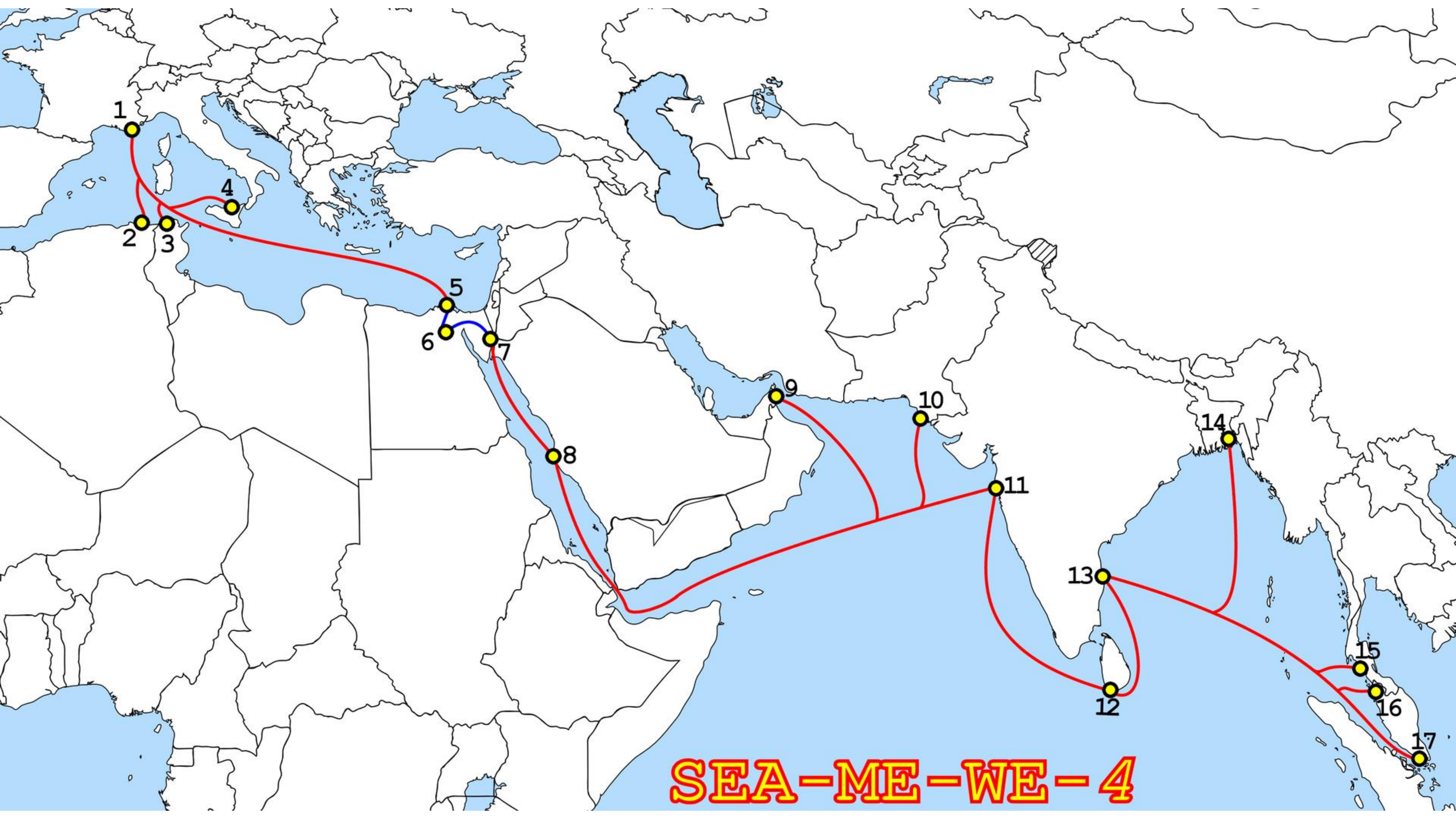
National Knowledge Network



https://nkn.gov.in/en/design-and-architecture-lt-en/detailed-design-lt-en

Internet Landing Stations in India

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SEA-ME-WE-4

Readings

- Go through Chapter 1.3 of Computer Networking: A Top-Down Approach **by James F. Kurose and Keith W. Ross**, 8th Edition, 2020, Addison Wesley (Pearson Education)
  - https://gaia.cs.umass.edu/kurose_ross/videos/1/
- https://www.cloudflare.com/learning/cdn/glossary/internet-exchange-point-ixp/
- https://www.indiatimes.com/technology/news/submarine-cable-network-india-internet-link-world-537327.html
- https://en.wikipedia.org/wiki/Cable_landing_point
- https://www.submarinenetworks.com/stations/asia/india

Homework

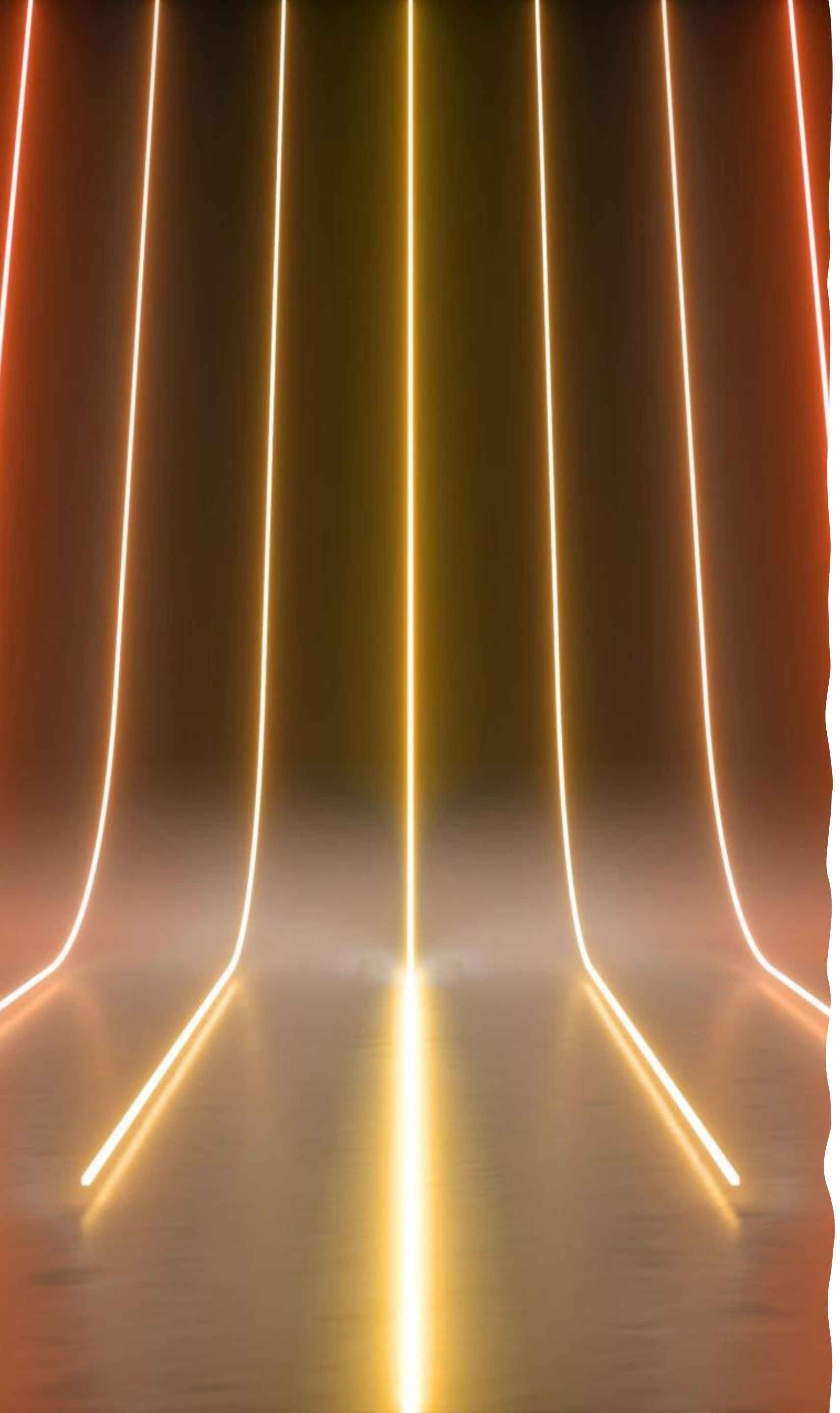
- Task-1: Do the interactive exercises on circuit-switching vs pkt-switching

https://gaia.cs.umass.edu/kurose_ross/interactive/ps_versus_cs.php

- Task-2: Solve Chapter-1 of Kurose and Ross textbook's exercise problems P8 and P9 and post your solutions in Google classroom
  - https://shiny.rit.albany.edu/stat/binomial/
  - https://www.danielsoper.com/statcalc/calculator.aspx?id=71

Outline

- What is a computer network?
- What *is* the Internet?
- What *is* a protocol?
- Network edge: hosts, access network, physical media
- Network core: packet/circuit switching, internet structure
- Network Performance: loss, delay, throughput, etc
- Protocol layers, service models



Apps on the Internet

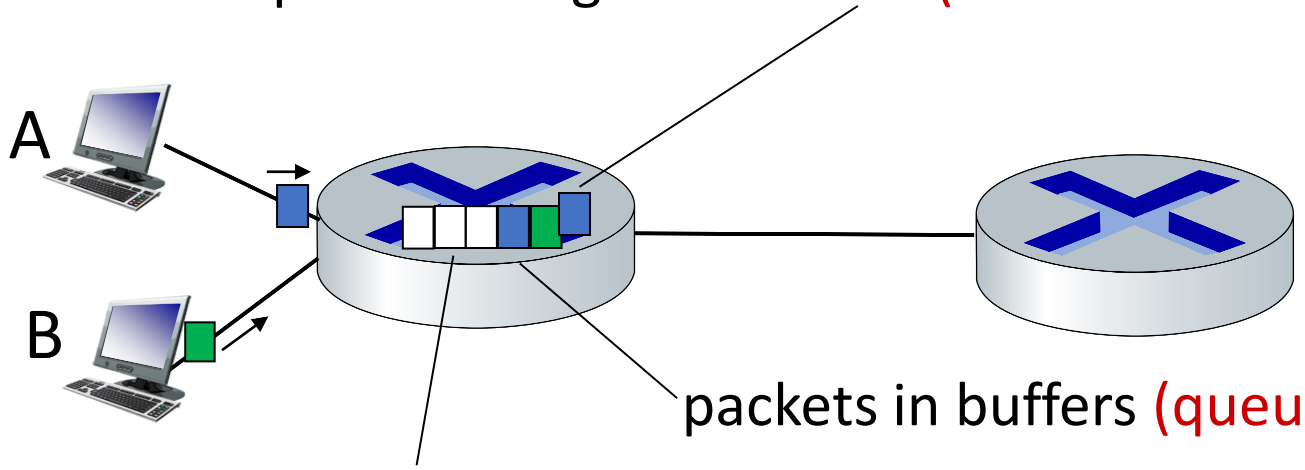
- World Wide Web (WWW)
- E-Mail
- Peer-to-Peer File Sharing
- Streaming stored video
- Instant Messaging
- Voice over IP
- Real-time video conferencing
- Online games
- Social media
- Cloud Computing
- ??

Service requirements: common apps

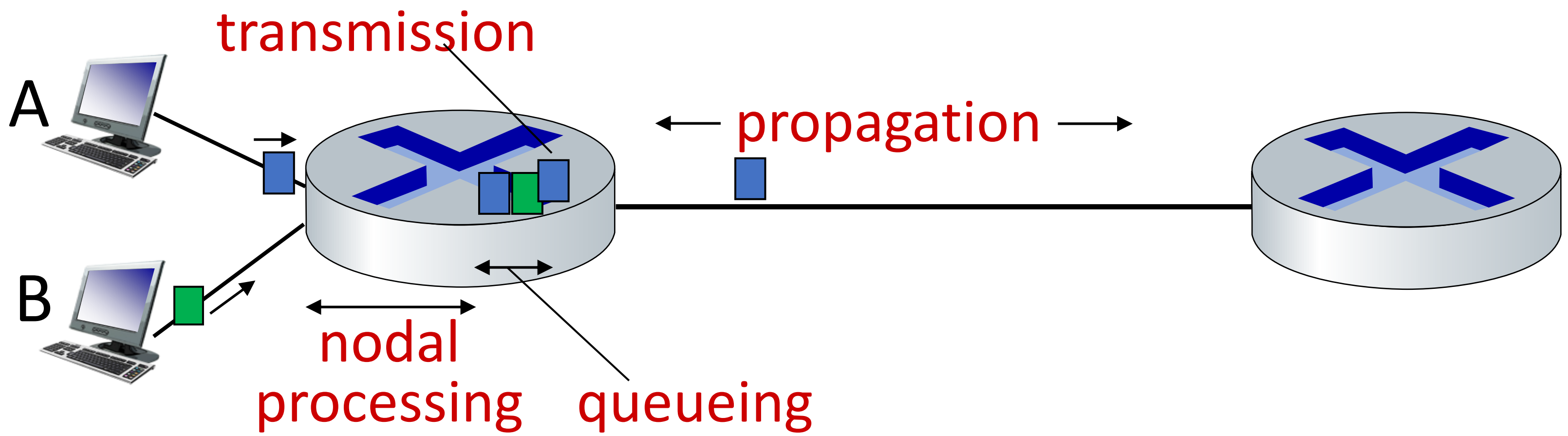
application	data loss	throughput	time sensitive?
file transfer/download	no loss	elastic	no
e-mail	no loss	elastic	no
Web documents	no loss	elastic	no
real-time audio/video	loss-tolerant	audio: 5Kbps-1Mbps video:10Kbps-5Mbps	yes, 10's msec
streaming audio/video	loss-tolerant	same as above	yes, few secs
interactive games	loss-tolerant	Kbps+	yes, 10's msec
text messaging	no loss	elastic	yes and no

How do packet delay and loss occur?

- packets *queue* in router buffers, waiting for turn for transmission
  - queue length grows when arrival rate to link (temporarily) exceeds output link capacity
- packet *loss* occurs when memory to hold queued packets fills up



Packet delay: four sources



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

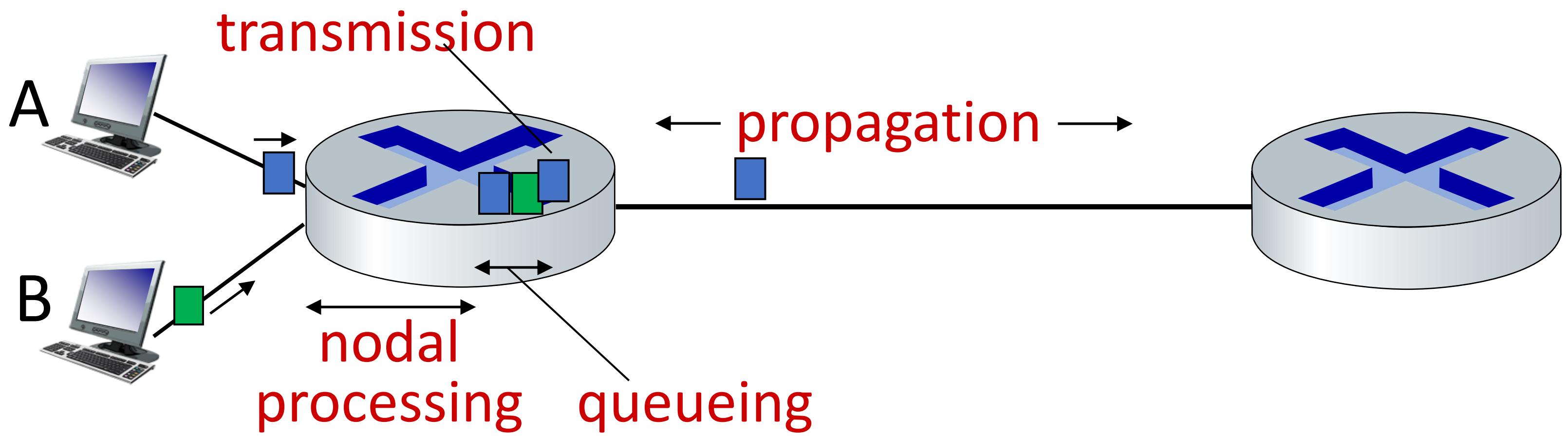
d_{proc}: nodal processing

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

d_{queue}: queueing delay

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

Packet delay: four sources



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

d_{trans}: transmission delay:

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

d_{prop}: propagation delay:

- d: length of physical link
- s: propagation speed (~2×10^8 m/sec)
- $d_{prop} = d/s$

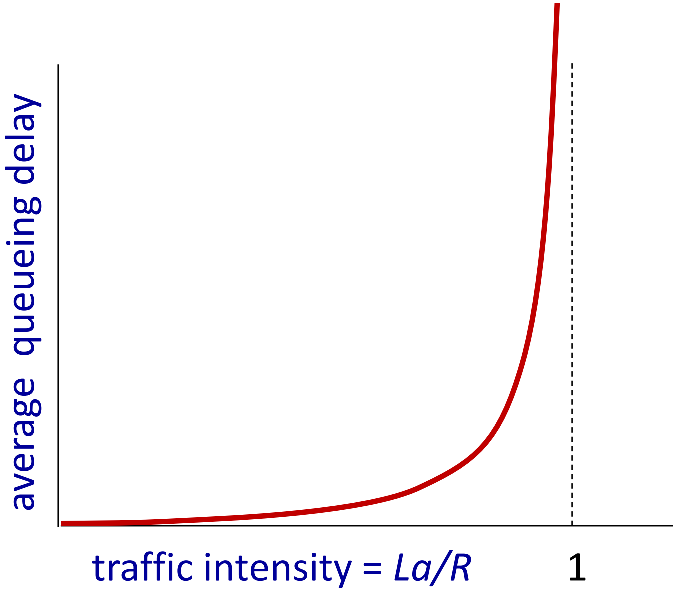
d_{trans} and d_{prop}
very different

Packet queueing delay (revisited)

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

$$\frac{L \cdot a}{R} : \frac{\text{arrival rate of bits}}{\text{service rate of bits}}$$

"traffic intensity"



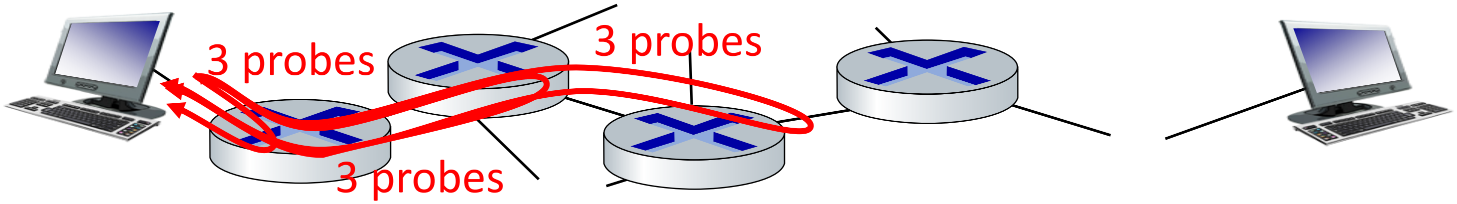
- *La/R* ~ 0: avg. queueing delay small
- *La/R* -> 1: avg. queueing delay large
- *La/R* > 1: more "work" arriving than that can be serviced - average delay infinite, when we have infinite buffer!

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 (with time-to-live field value of *i*)
  - router *i* will return packets to sender
  - sender measures time interval between transmission and reply



Real Internet delays and routes

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

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

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

3 delay measurements
to border1-rt-fa5-1-0.gw.umass.edu

trans-oceanic link

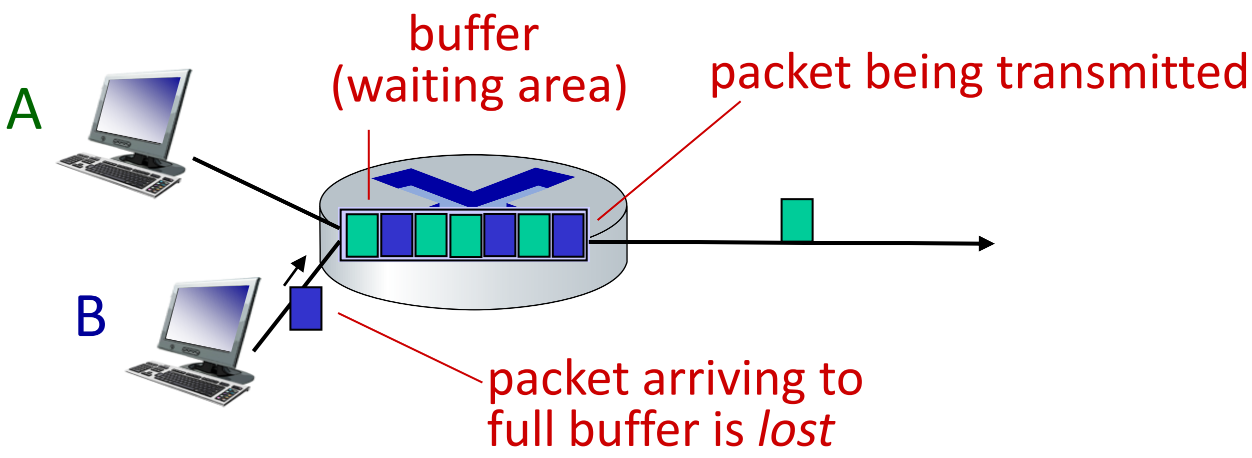
looks like delays *decrease*! Why?

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

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

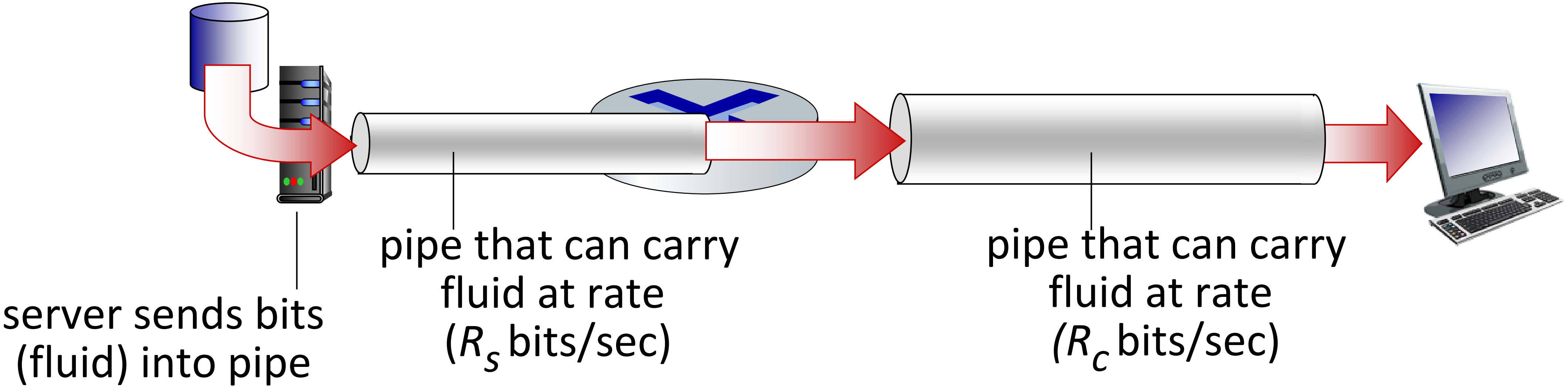
Packet loss

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



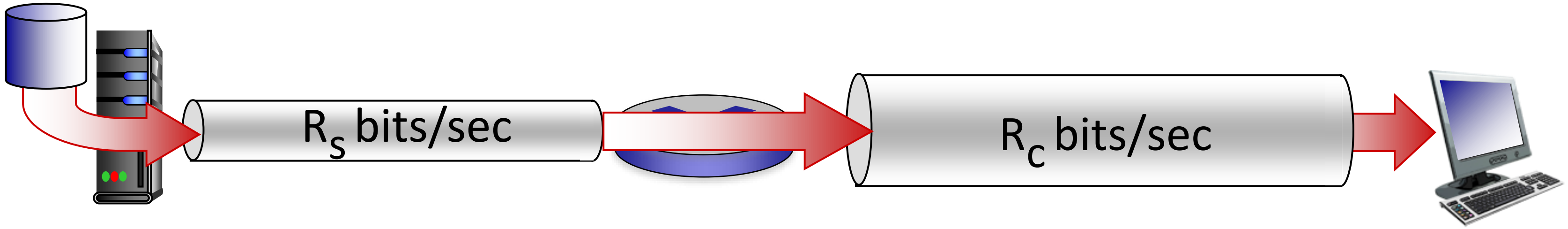
Throughput

- *throughput:* rate (bits/time unit) at which bits are being sent from sender to receiver
  - *instantaneous:* rate at given point in time
  - *average:* rate over longer period of time

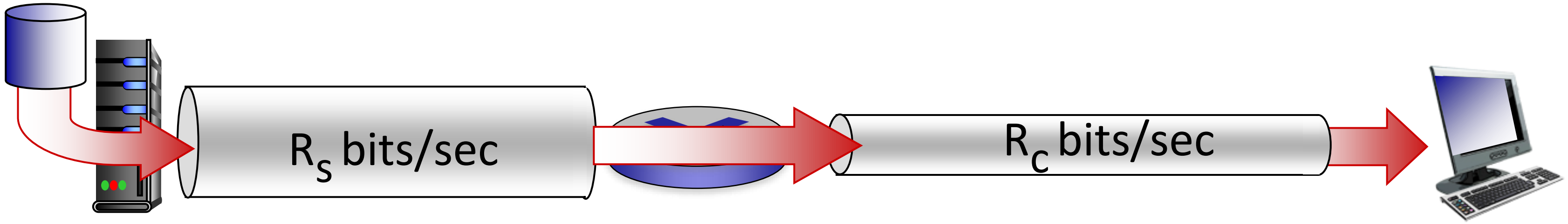


Throughput

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



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

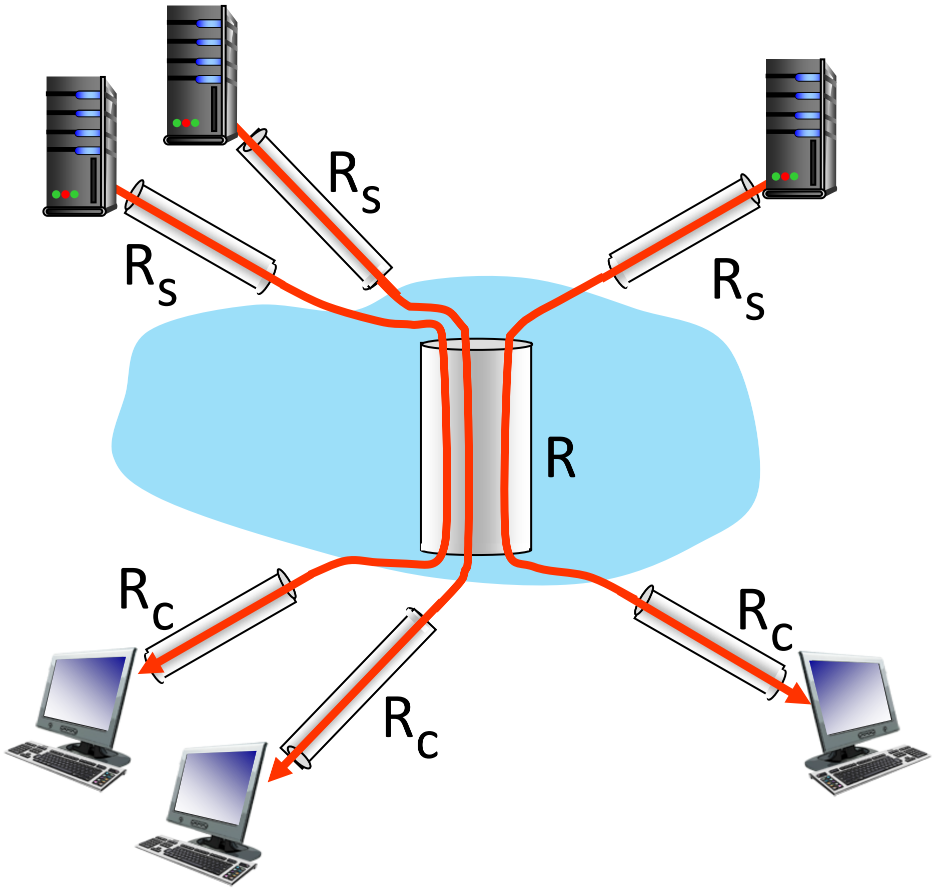


Note: Here, except transmission delay, other delays are ignored

bottleneck link

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

Throughput: network scenario



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

- per-connection end-to-end throughput: $min(R_c,R_s,R/10)$
- in practice: R_c or R_s is often bottleneck

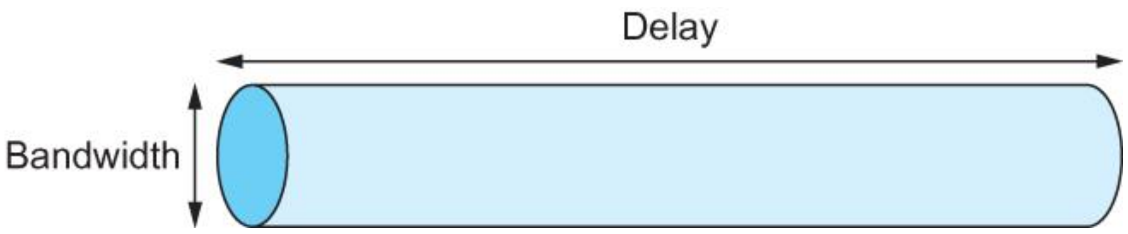
* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/

Delay X Bandwidth

- We think of the link between a pair of nodes as a hollow pipe
- Latency (delay): length of the pipe
- Bandwidth (aka Transmission Rate): width of the pipe
- Delay of 50 ms and bandwidth of 45 Mbps

$\Rightarrow$ 50 x 10^{-3} seconds x 45 x 10^{6} bits/second

$\Rightarrow$ 2.25 x 10^{6} bits = 280 KB data.



Network/link as a pipe

Delay X Bandwidth

- It tells how many bits the sender must transmit before the first bit arrives at the receiver if the sender wants to keep the pipe full
- Takes another one-way latency to receive a response (acknowledgement) from the receiver
- If the sender does not fill the pipe—send a whole delay × bandwidth product's worth of data before it stops to wait for a signal—the sender will not fully utilize the network

Example delay × bandwidth products

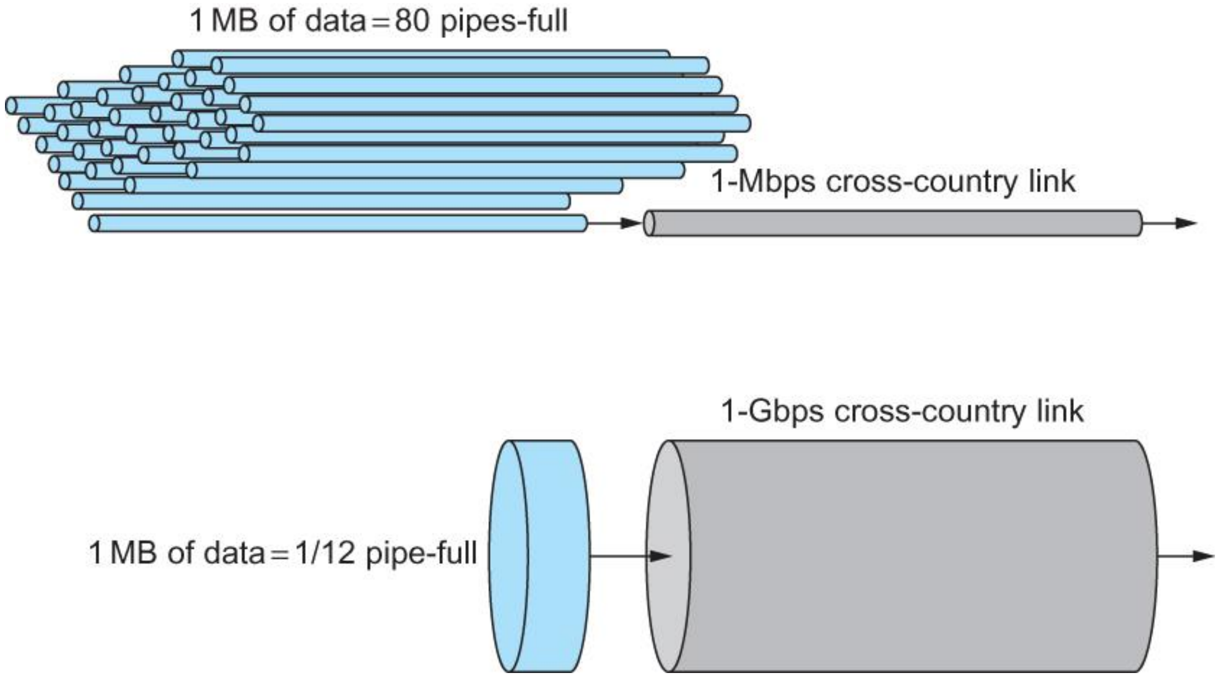
Link Type	Bandwidth	One-Way Distance	RTT	RTT x Bandwidth
Wireless LAN	54 Mbps	50 m	0.33 μs	18 bits
Satellite	1 Gbps	35,000 km	230 ms	230 Mb
Cross-country fiber	10 Gbps	4,000 km	40 ms	400 Mb

Delay X Bandwidth

- Relative importance of bandwidth and latency depends on application
  - For large file transfer, bandwidth (aka transmission rate) is critical
  - For small messages (HTTP, NFS, etc.), latency (prop. delay) is critical
  - Variance in latency (jitter) can also affect some applications (*e.g.*, audio/video conferencing)

- Infinite bandwidth
  - Prop. delay dominates
  - Throughput = TransferSize / TransferTime
  - TransferTime = Prop. delay + TransferSize / Bandwidth

Relationship between bandwidth and latency



RTT=100 ms;

A 1-MB file would fill the 1-Mbps link 80 times,

but only fill the 1-Gbps link 1/12 of one time

Readings

- Go through Chapter 1.4 of Computer Networking: A Top-Down Approach **by James F. Kurose and Keith W. Ross**, 8^{th} Edition, 2020, Addison Wesley (Pearson Education)
  - https://gaia.cs.umass.edu/kurose_ross/videos/1/

- https://book.systemsapproach.org/foundation/performance.html

- Traceroute:
  - https://www.net.princeton.edu/traceroute.html
  - https://traceroute-online.com/

Homework & Tutorial

- Task-1: Do the interactive exercises on Chapter 1
  - https://gaia.cs.umass.edu/kurose_ross/interactive/index.php

- Task-2: Solve Chapter-1 of Kurose and Ross textbook's exercise problems P12, P16 and P18.

- Tutorial on August 16th

Outline

- What is a computer network?
- What *is* the Internet?
- What *is* a protocol?
- Network edge: hosts, access network, physical media
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- Protocol layers, service models

Protocol "layers" and reference models

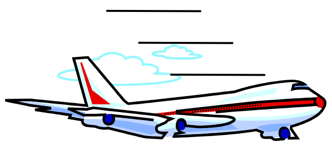
Networks are complex, with many "pieces":

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

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

- and/or our *discussion* of networks?

Example: organization of air travel



end-to-end transfer of person plus baggage

ticket (purchase)	ticket (complain)
baggage (check)	baggage (claim)
gates (load)	gates (unload)
runway takeoff	runway landing
airplane routing	airplane routing

airplane routing

How would you *define/discuss* the *system* of airline travel?

- a series of steps, involving many services

Example: organization of air travel

layers: each layer implements a service

- via its own internal-layer actions
- relying on services provided by layer below

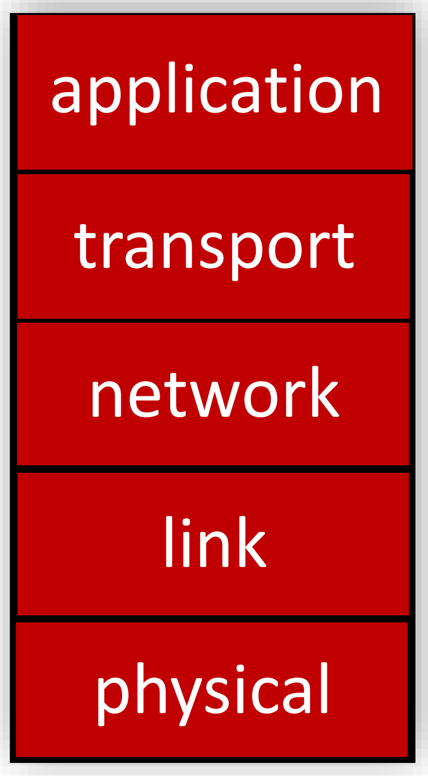
Why layering?

Approach to designing/discussing complex systems:

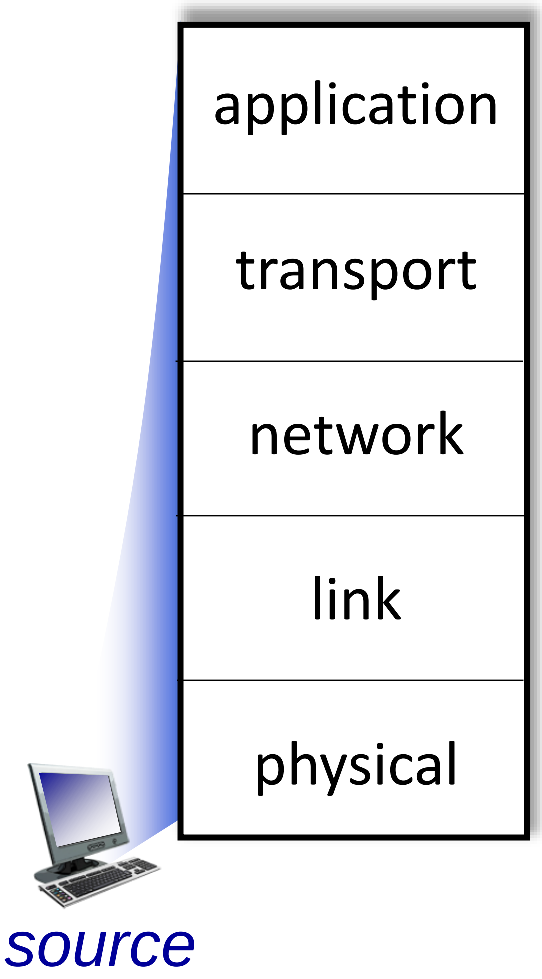
- explicit structure allows identification, relationship of system’s pieces
  - layered *reference model* for discussion
- modularization eases maintenance, updating of system
  - change in layer's service *implementation*: transparent to rest of system
  - e.g., change in gate procedure doesn’t affect rest of system

Layered Internet protocol stack

- *application:* supporting network applications
  - HTTP, IMAP, SMTP, DNS
- *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”



Services, Layering and Encapsulation



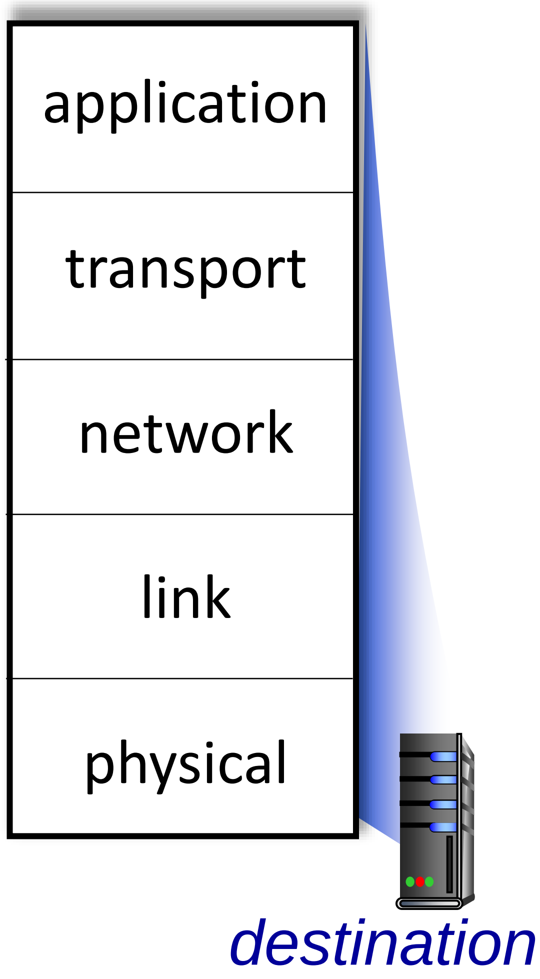
M

Application exchanges messages to implement some application service using *services* of transport layer

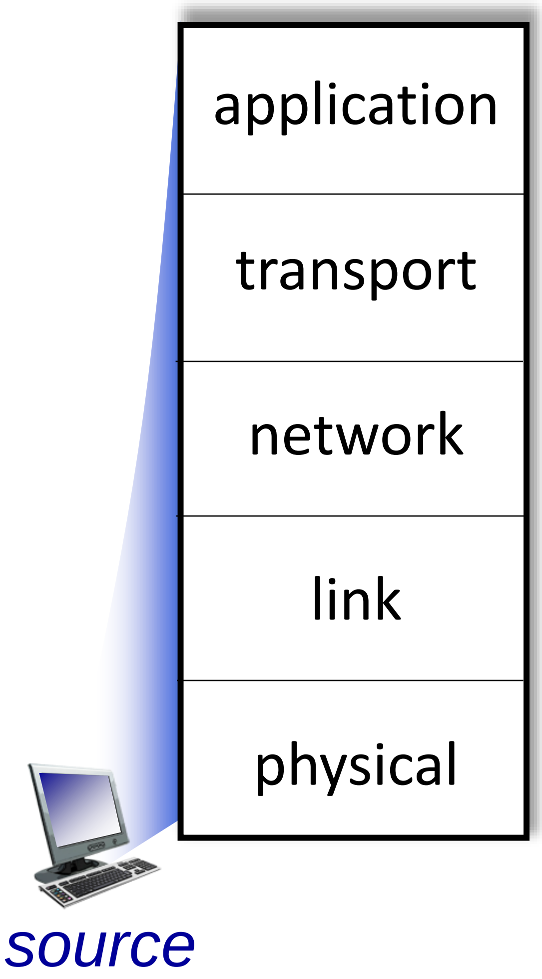
H_t M

Transport-layer protocol transfers M (e.g., reliably) from one *process* to another, using services of network layer

- transport-layer protocol encapsulates application-layer message, M, with *transport* layer-layer header H_t to create a transport-layer segment
  - H_t used by transport layer protocol to implement its service



Services, Layering and Encapsulation



M

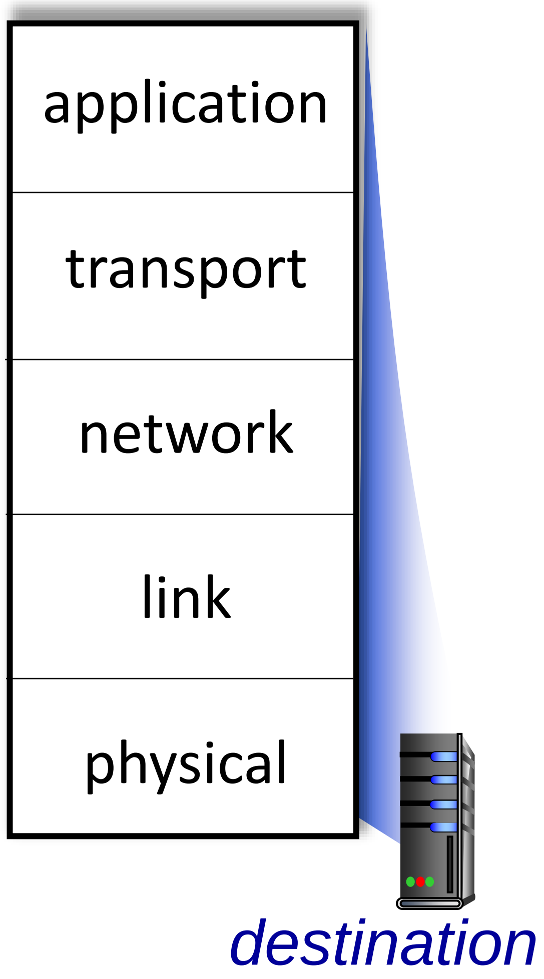
H_t | M

Transport-layer protocol transfers M (e.g., reliably) from one *process* to another, using services of network layer

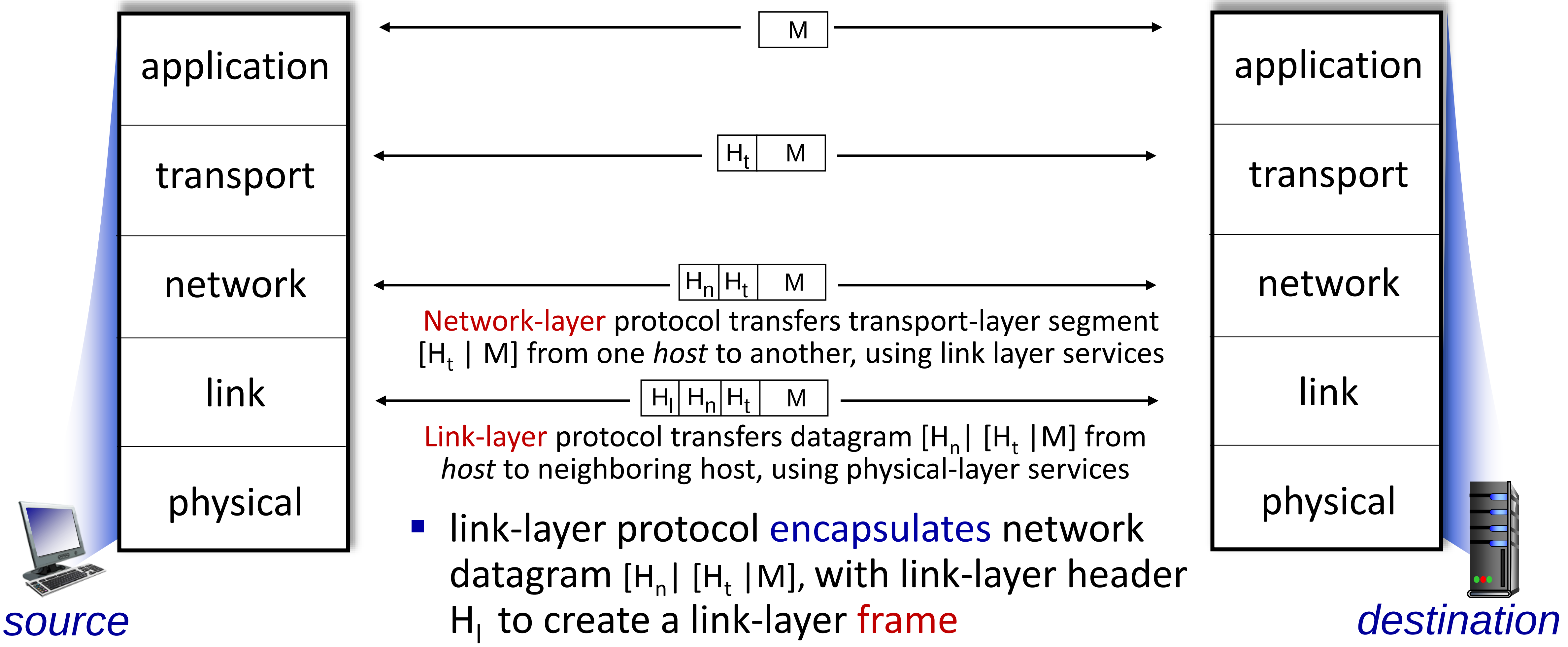
H_n | H_t | M

Network-layer protocol transfers transport-layer segment [H_t | M] from one *host* to another, using link layer services

- network-layer protocol encapsulates transport-layer segment [H_t | M] with network layer-layer header H_n to create a network-layer datagram
  - H_n used by network layer protocol to implement its service



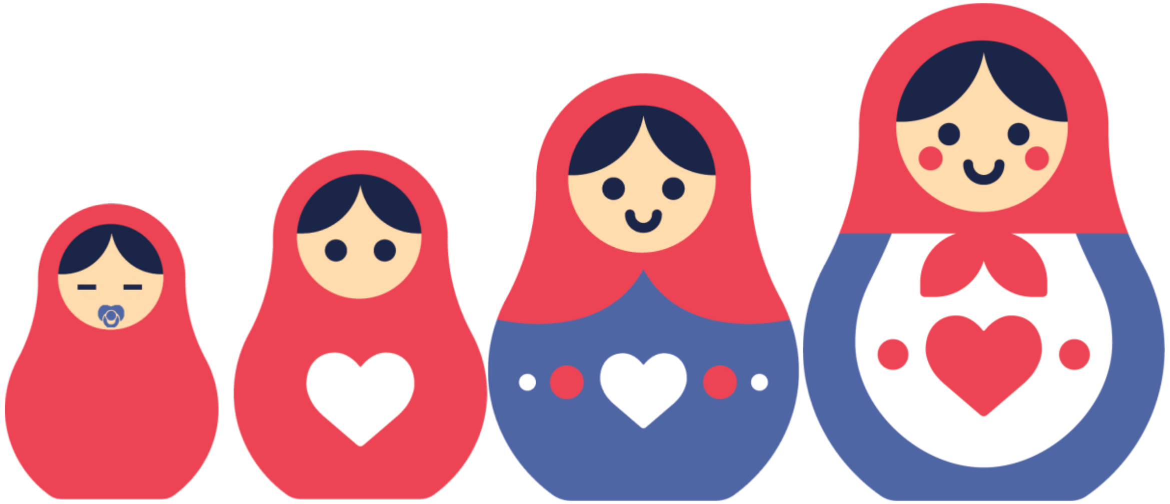
Services, Layering and Encapsulation



- link-layer protocol encapsulates network datagram [H_n| [H_t |M], with link-layer header H_l to create a link-layer frame

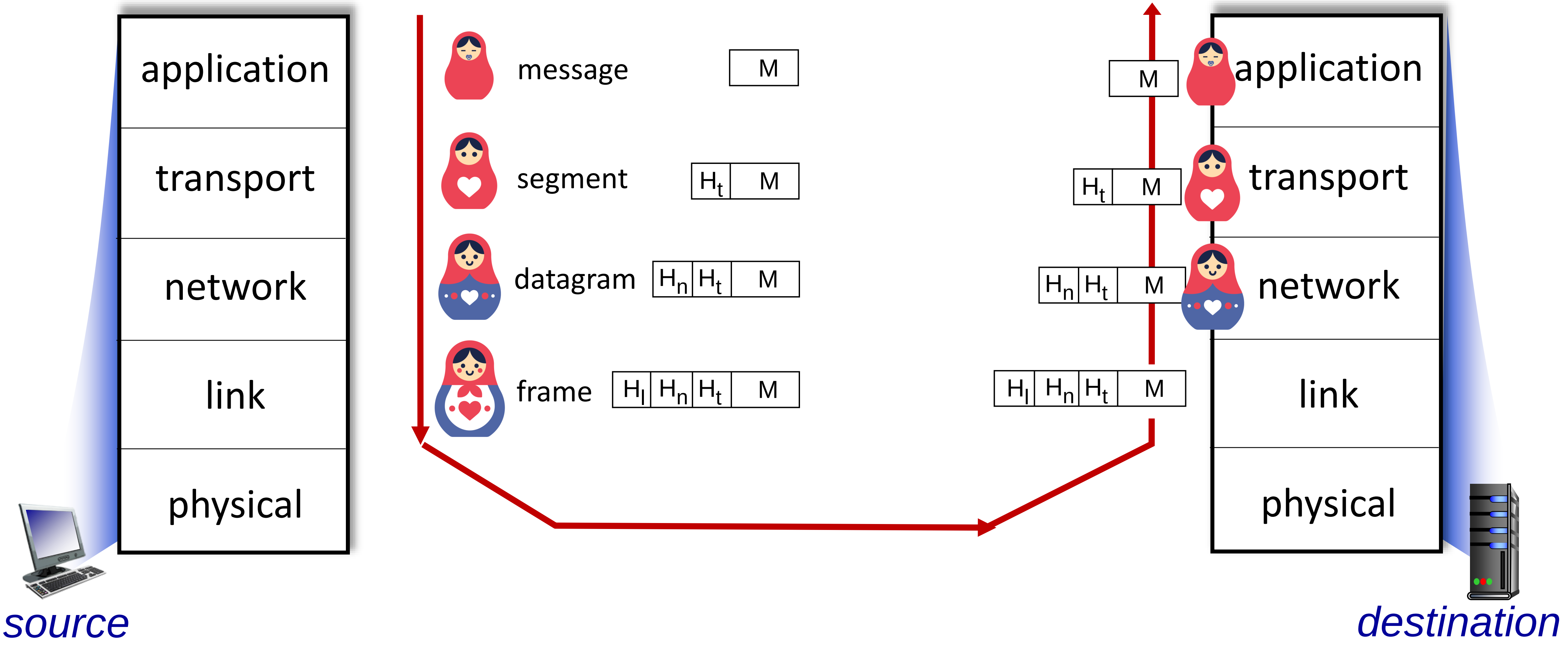
Encapsulation

Matryoshka dolls (stacking dolls)

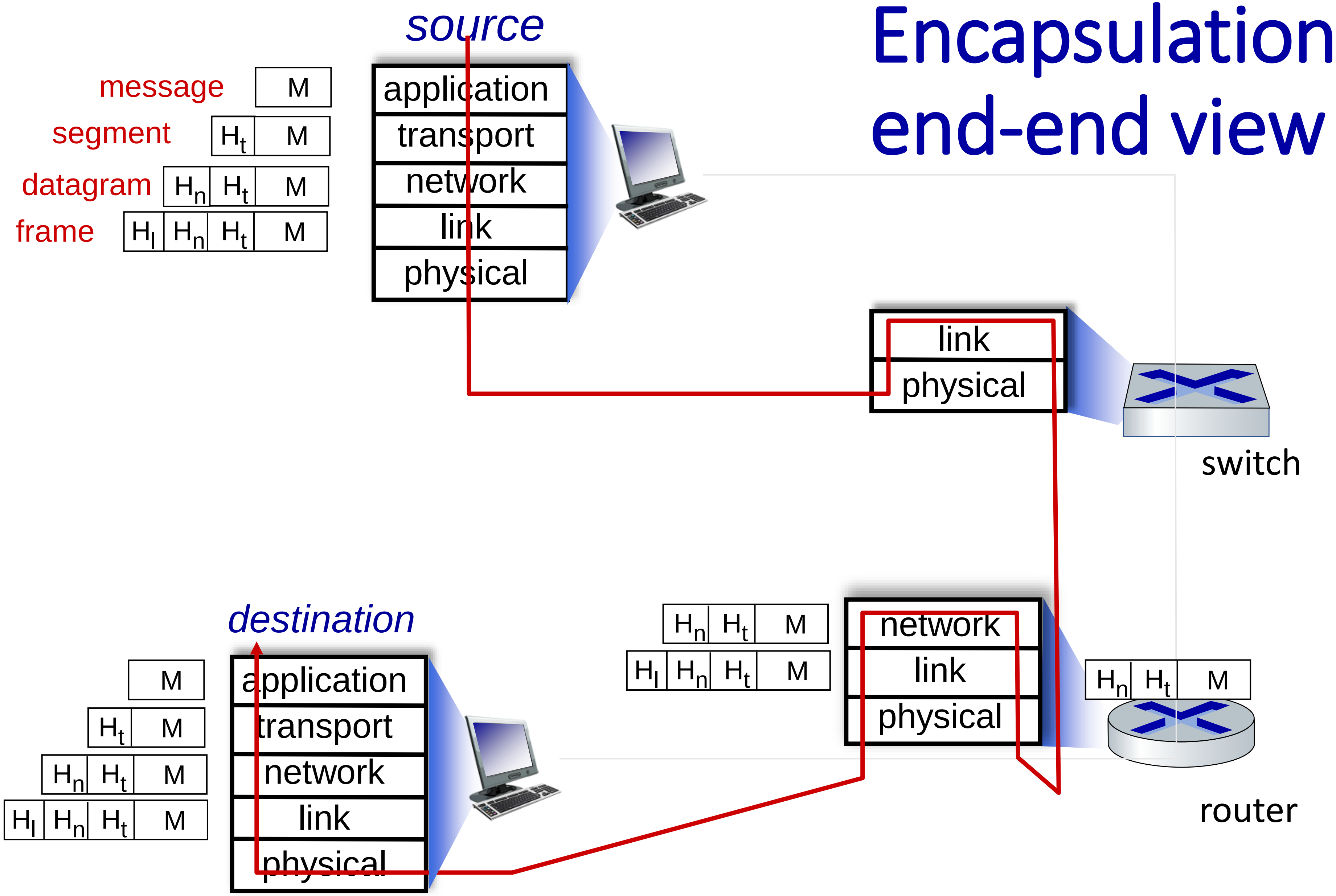


Credit: https://dribbble.com/shots/7182188-Babushka-Boi

Services, Layering and Encapsulation



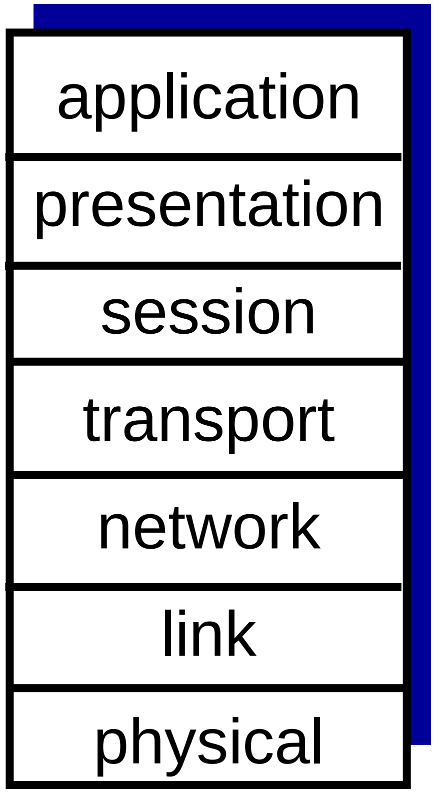
Encapsulation: an end-end view



ISO/OSI reference model

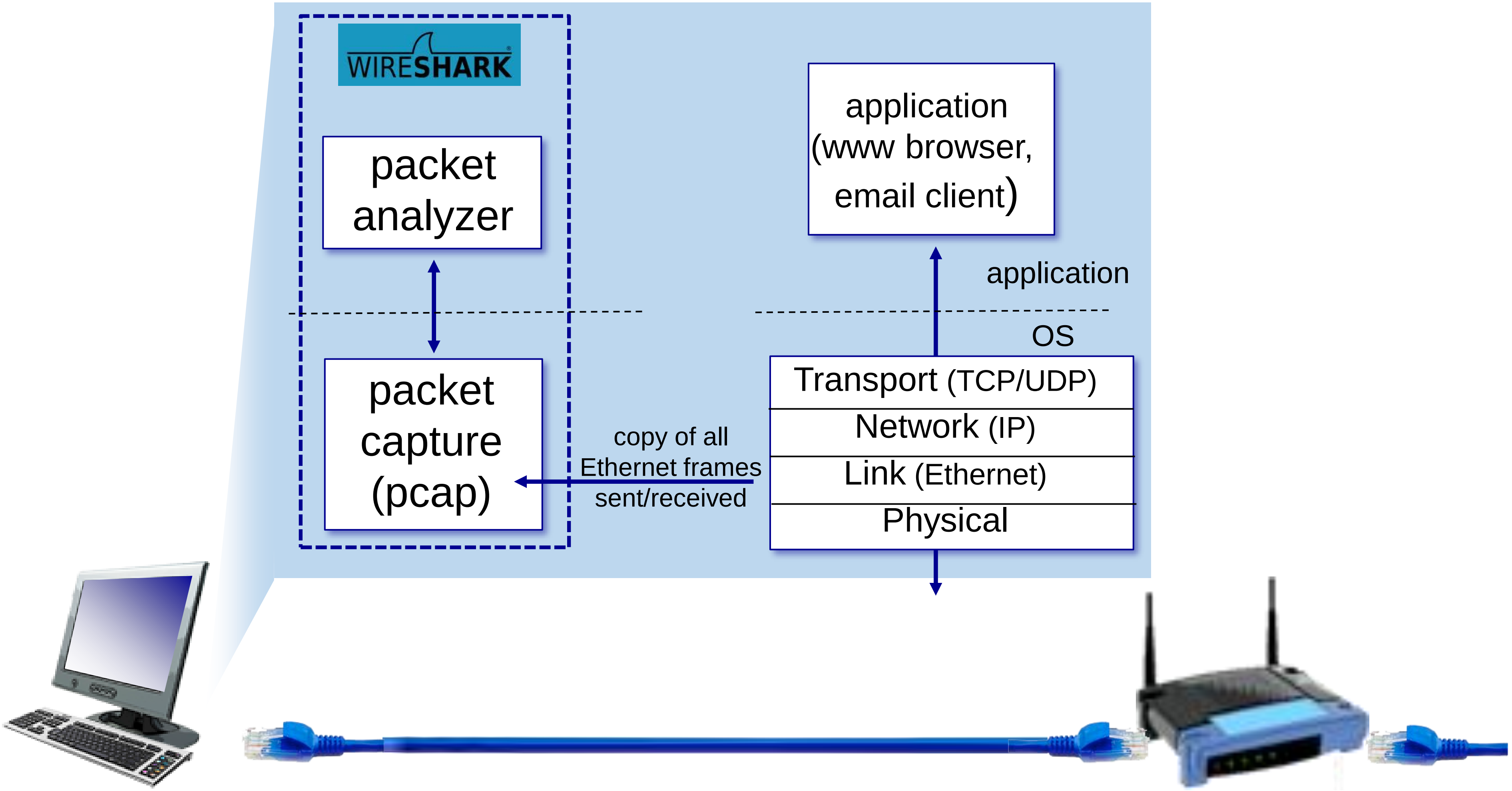
Two layers not found in Internet protocol stack!

- *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?



The seven layer OSI/ISO reference model

Wireshark

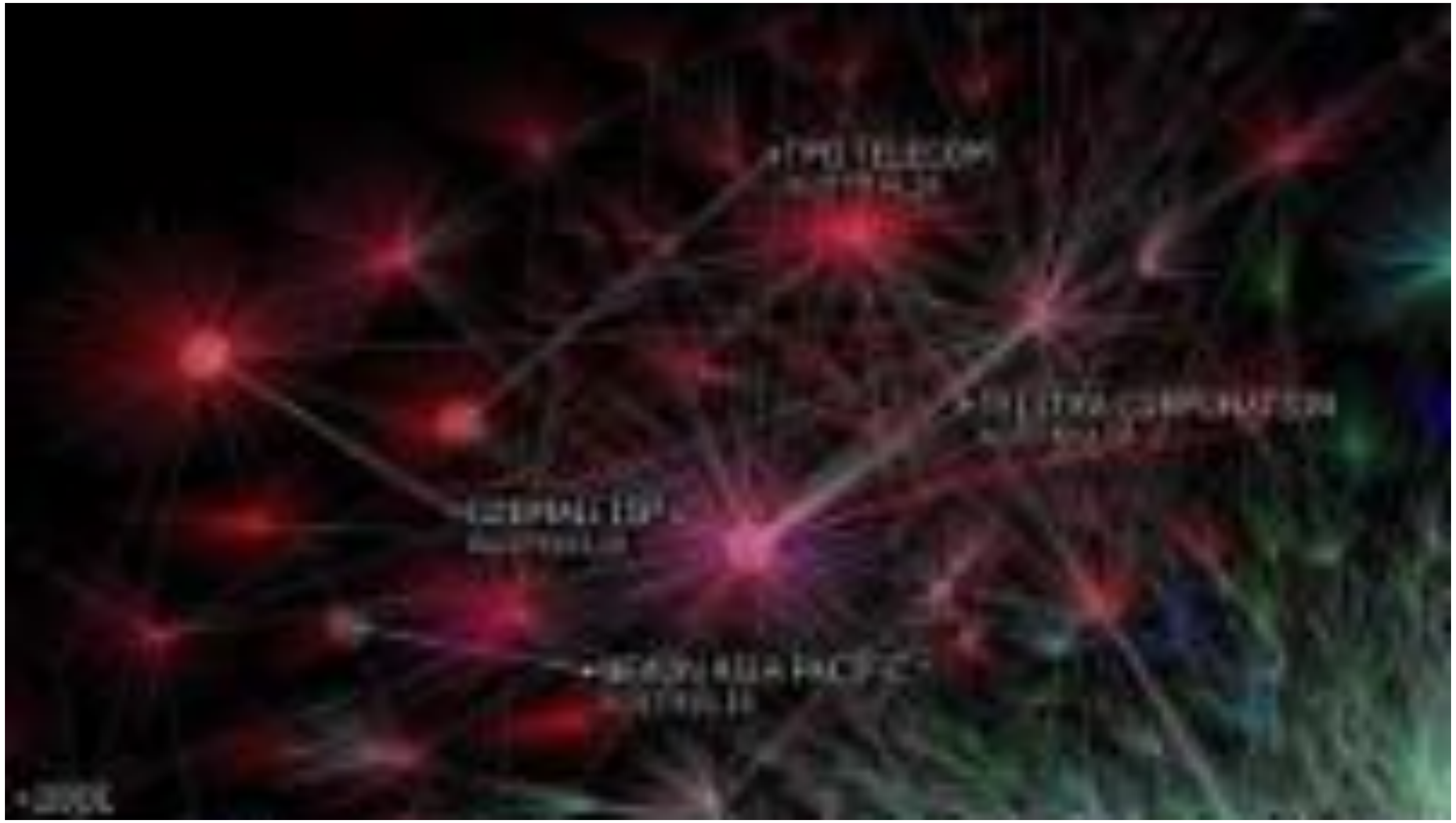


packet analyzer
packet capture (pcap)
copy of all Ethernet frames sent/received
application (www browser, email client)
application
OS
Transport (TCP/UDP)
Network (IP)
Link (Ethernet)
Physical

Wireshark Assignment

- Capture traceroute traffic using wireshark and answer the following:
  - What is the typical gap (delay) between probe packets?
  - What is contained in probe responses?
  - Which protocol has TTL field and comment on how the values of this field varied across probes and responses?
  - How long it took to get the output of traceroute session?

The Internet: 1997 - 2021



https://www.opte.org/the-internet

Key Principles of the Internet

Minimalism, autonomy	Decentralized control	Net neutrality
Packet switching	Best-effort service model	Stateless routing

Summary

We’ve covered a “ton” of material!

- Internet overview
- what’s a protocol?
- network edge, access network, core
  - packet-switching versus circuit-switching
  - Internet structure
- performance: loss, delay, throughput
- layering, service models

You now have:

- context, overview, vocabulary, “feel” of networking
- more depth, detail, *and fun* to follow*!*

References

- https://education.nationalgeographic.org/resource/internet-101
- https://edu.gcfglobal.org/en/internetbasics/what-is-the-internet/1/
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- https://www.vox.com/2014/6/16/18076282/the-internet
- Wireshark tutorial: https://blog.packet-foo.com/2018/08/wireshark-column-setup-deepdive/
- Wireshark Tutorial for BEGINNERS // Where to start with Wireshark

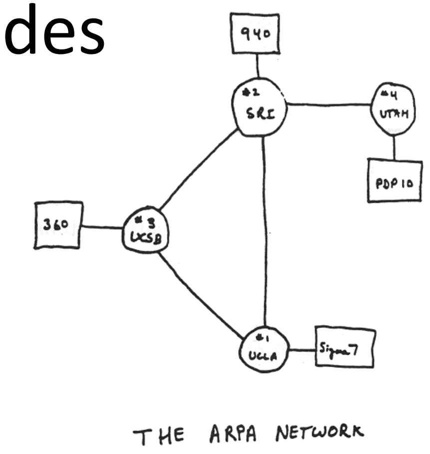
Additional slides

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



Internet history

1972-1980: Internetworking, new and proprietary networks

- 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
- 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 routing
- decentralized control

define today's Internet architecture

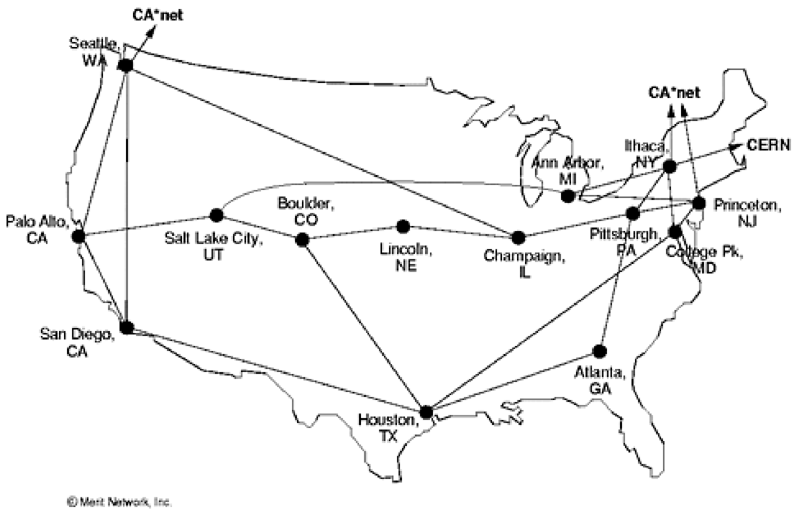
Internet history

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

NSFNET T1 Network 1991



Internet history

1990, 2000s: commercialization, the Web, new applications

- early 1990s: 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 1990s: commercialization of the Web

late 1990s – 2000s:

- 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: scale, SDN, mobility, cloud

- aggressive deployment of broadband home access (10-100's Mbps)
- 2008: software-defined networking (SDN)
- increasing ubiquity of high-speed wireless access: 4G/5G, WiFi
- service providers (Google, FB, Microsoft) create their own networks
  - bypass commercial Internet to connect "close" to end user, providing "instantaneous" access to social media, search, video content, …
- enterprises run their services in "cloud" (e.g., Amazon Web Services, Microsoft Azure)
- rise of smartphones: more mobile than fixed devices on Internet (2017)
- ~15B devices attached to Internet (2023, statista.com)