

Computer Networking

Introduction to Computer Systems
22nd Lecture, Dec. 8, 2025

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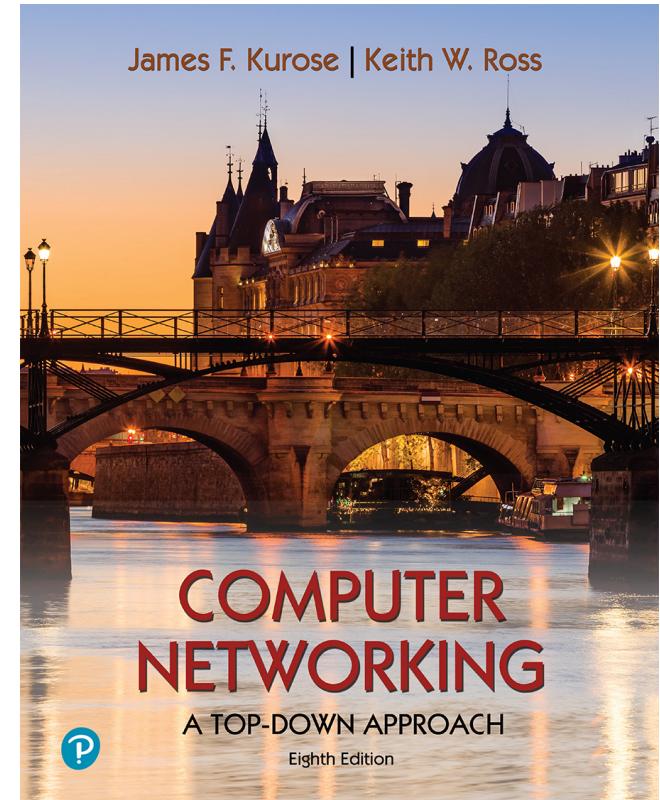
Class 3: Lu Junlin

参考书，非考试范围

Computer Networking: A Top-Down Approach

8th edition

Jim Kurose, Keith Ross
Pearson, 2020



Today

- What is the Internet? What is a protocol?
- Network edge: hosts, access network, physical media
- Network Security
- Protocol layers, service models
- Wireless and Mobile Networks

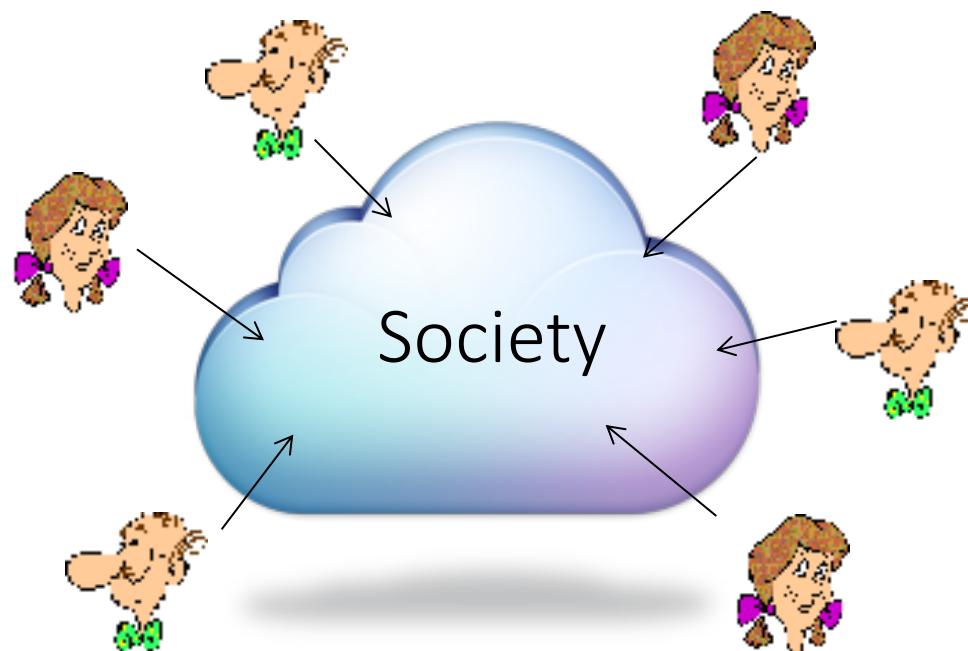


What's included in the Internet

■ What's included in a society?

1. People, entities → [internet components](#)
2. Services → [internet services](#)
3. Laws and rules (define the behaviors of the above two parts)

→ [protocols, standards](#)



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)

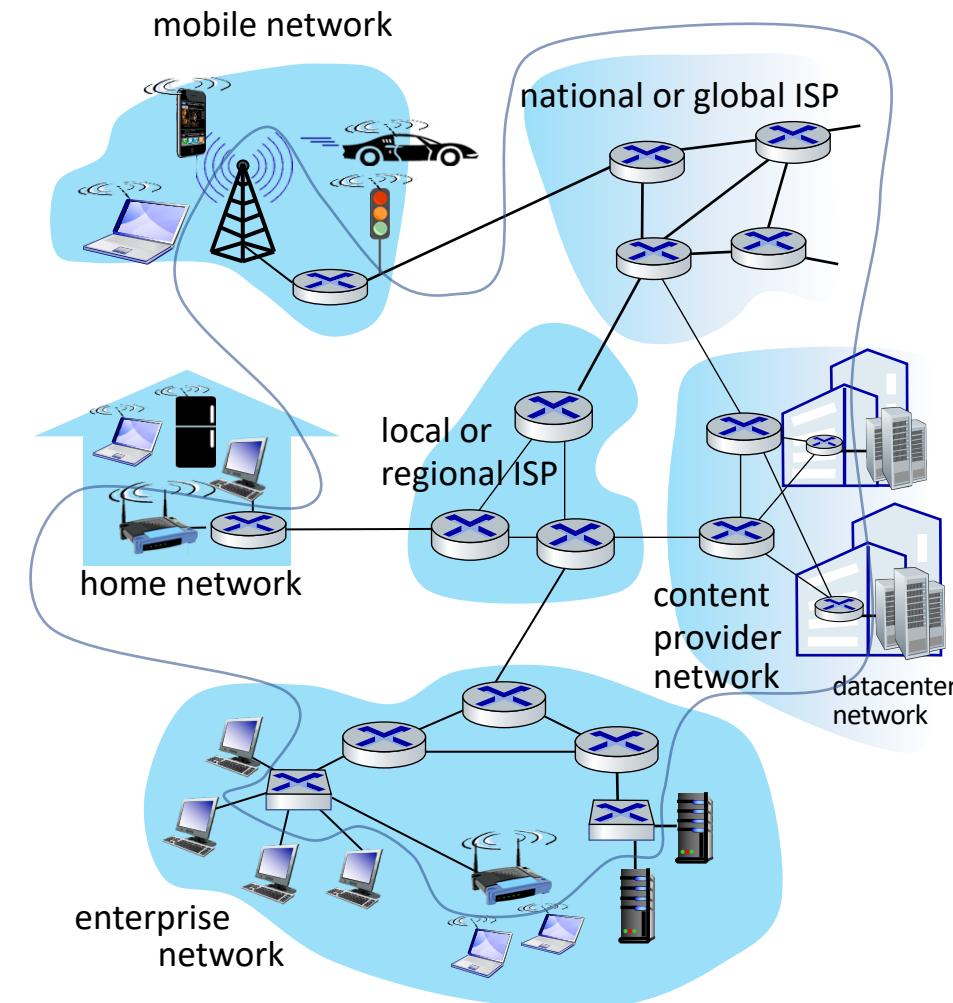
- routers, switches

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



Security Camera



Internet phones



IP picture frame



Slingbox: remote control cable TV



Gaming devices



Pacemaker & Monitor



Web-enabled toaster + weather forecaster



sensorized, bed mattress



AR devices



Fitbit



diapers

Tweet-a-watt:
monitor energy use

bikes



cars

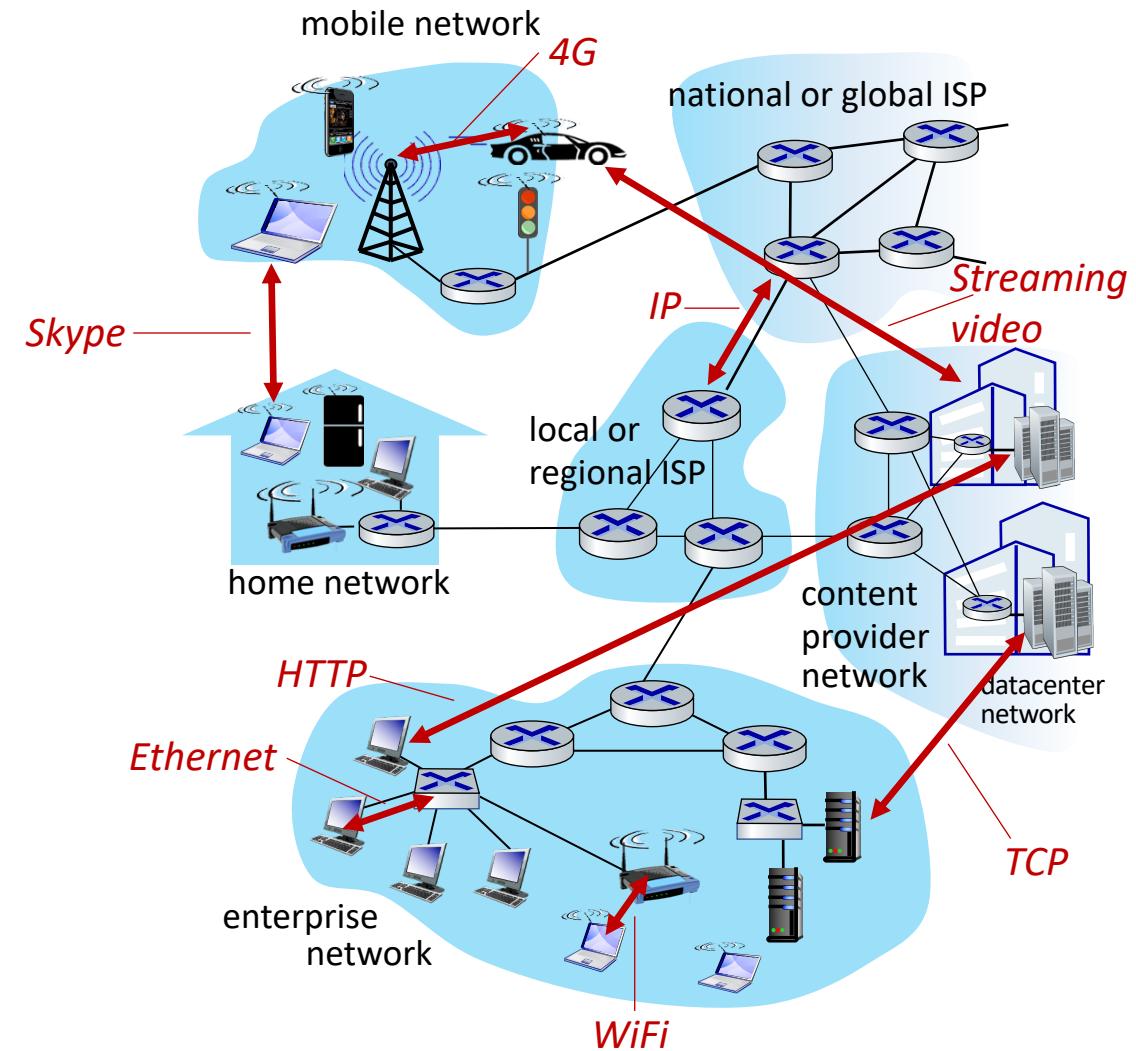


scooters

Others?

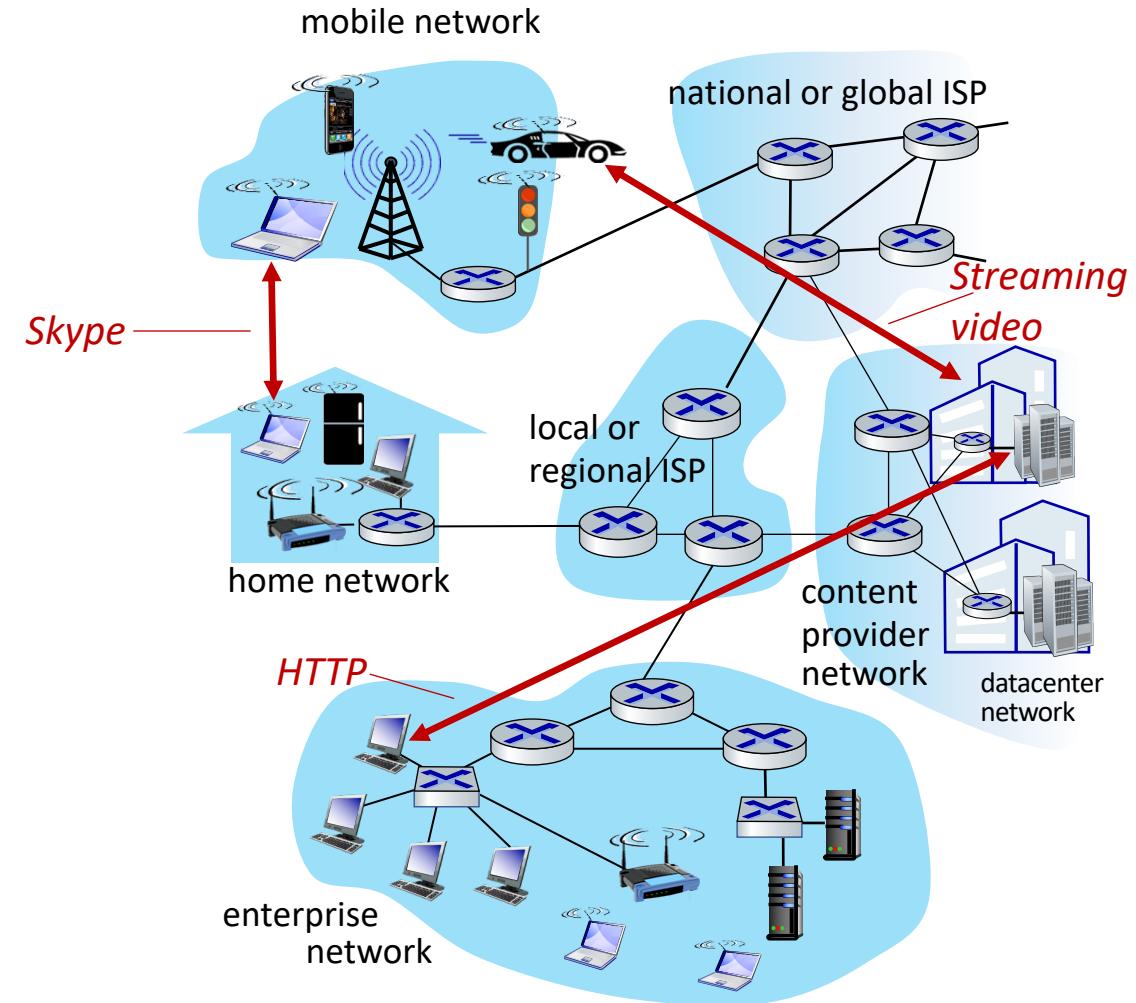
The Internet: a “nuts and bolts” view

- *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, interconnected 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

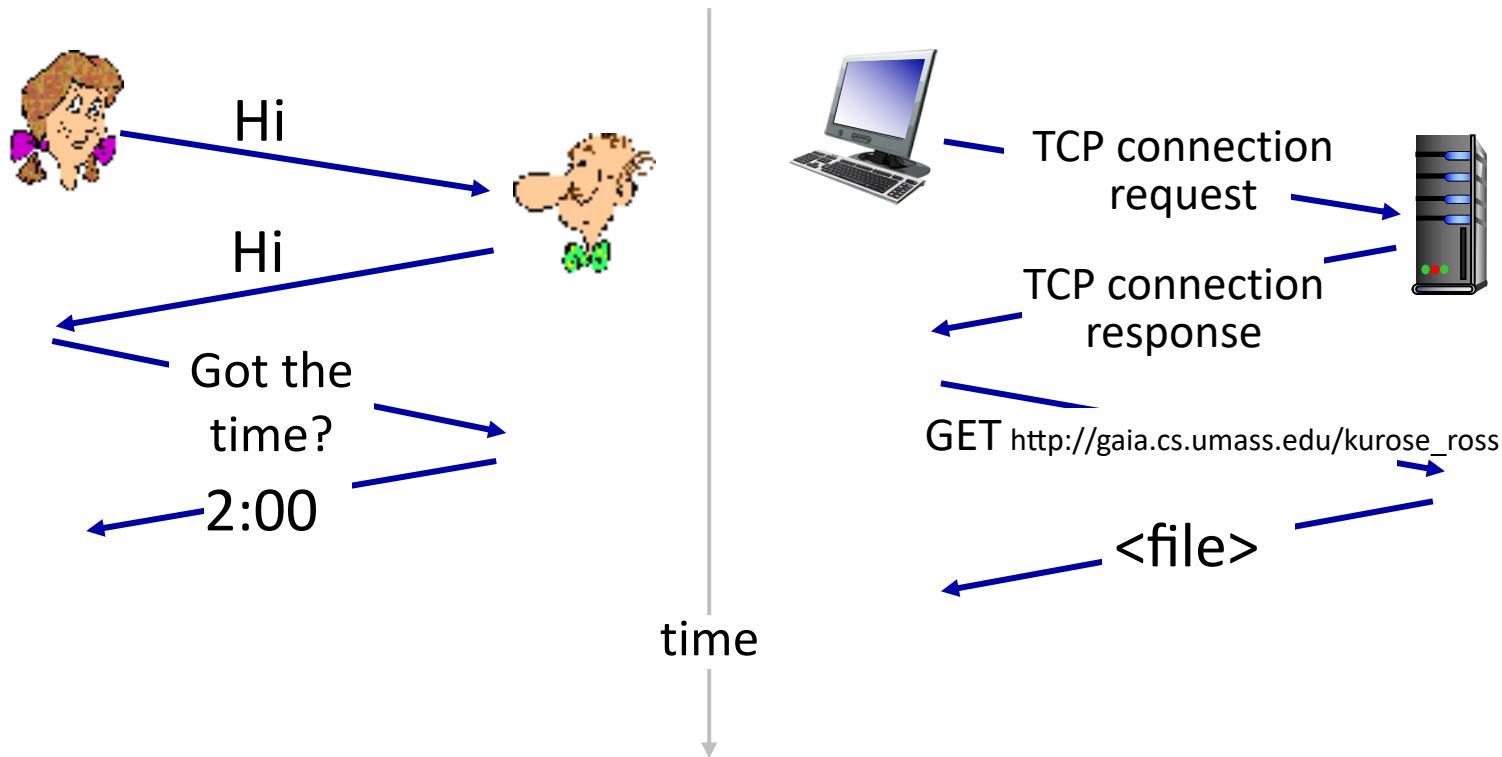
Network protocols:

- 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?

Today

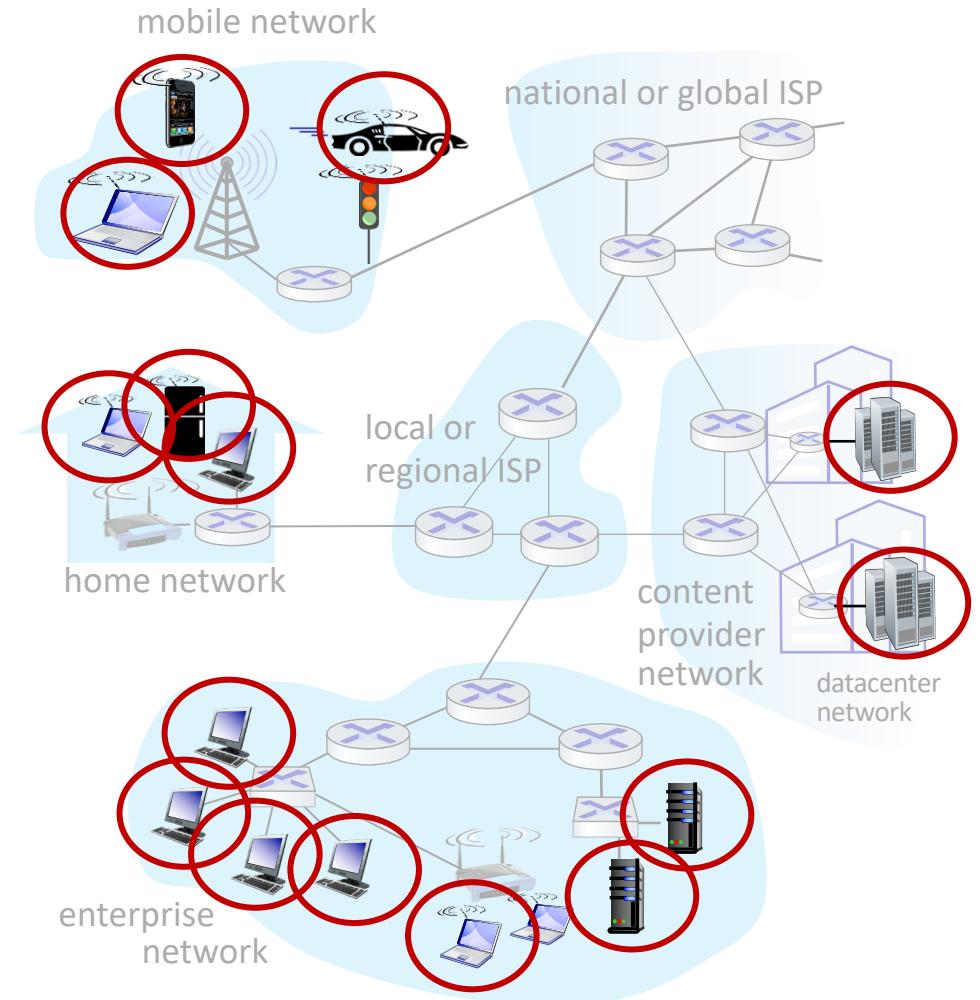
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A closer look at Internet structure

Network edge:

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



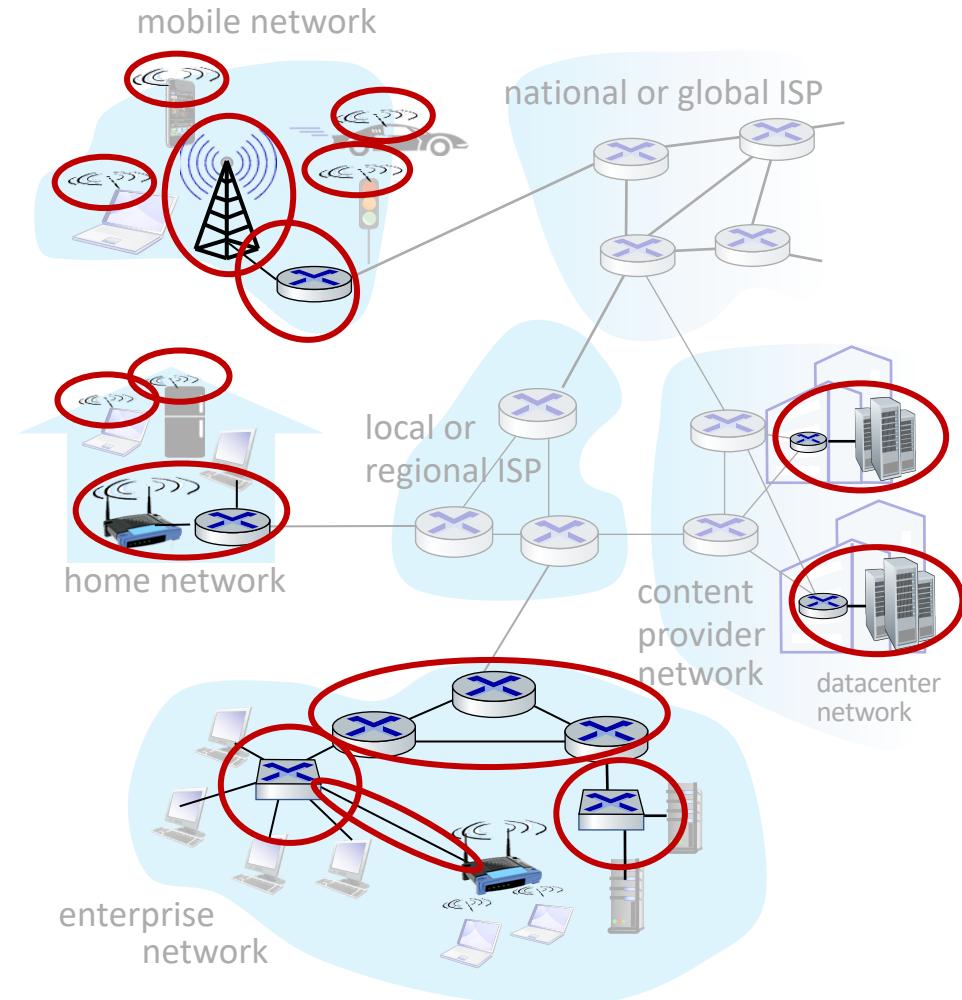
A closer look at Internet structure

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

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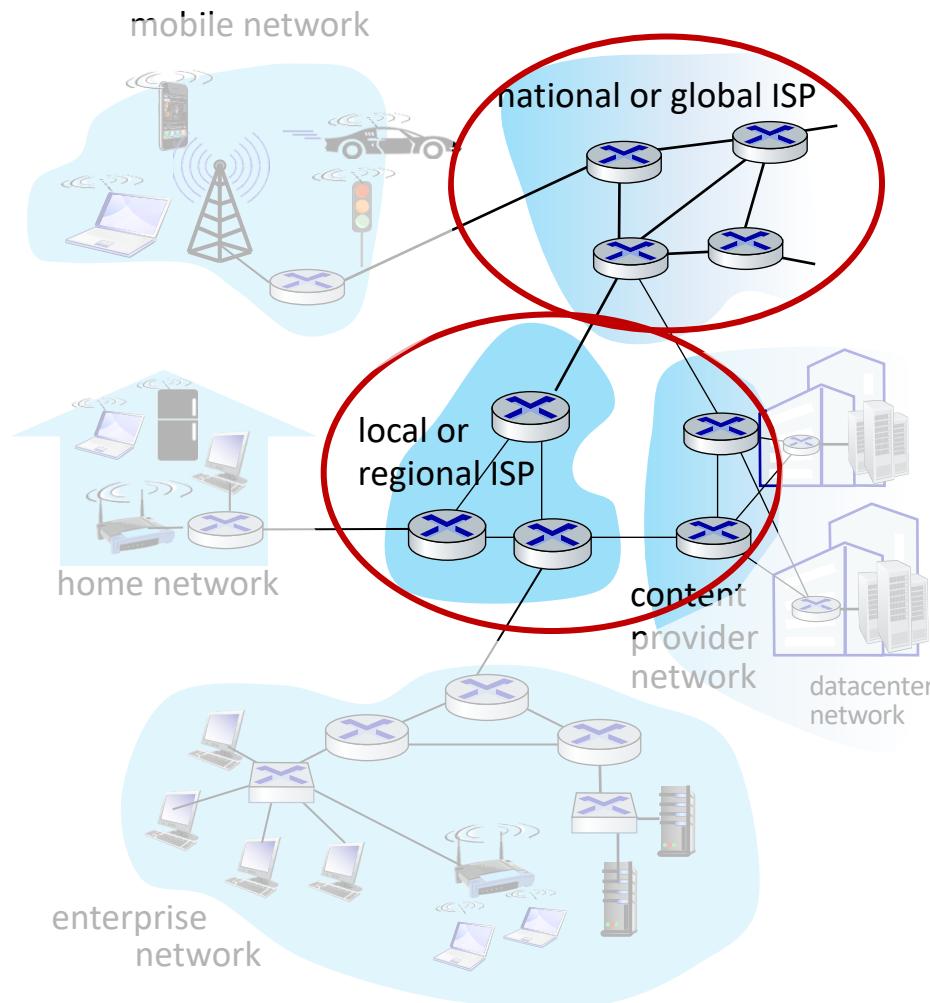
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Access networks, physical media:

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Network core:

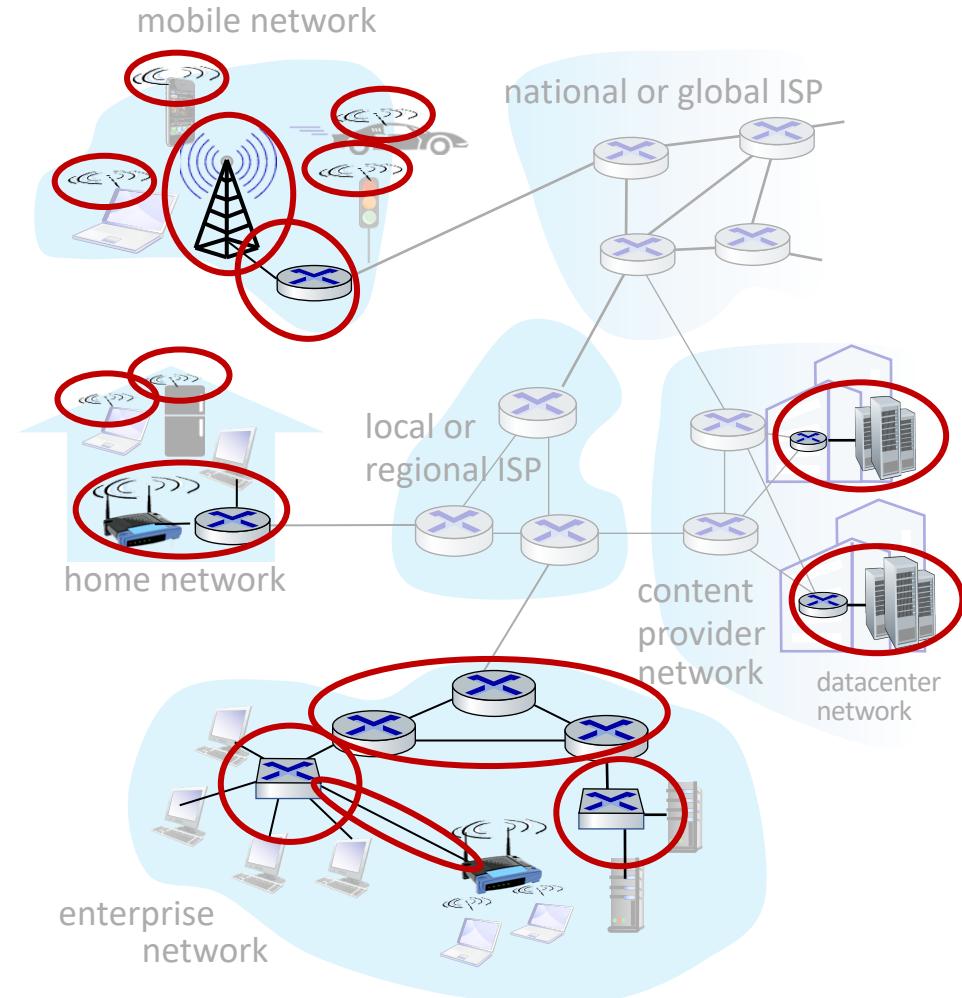
- interconnected routers
- network of networks



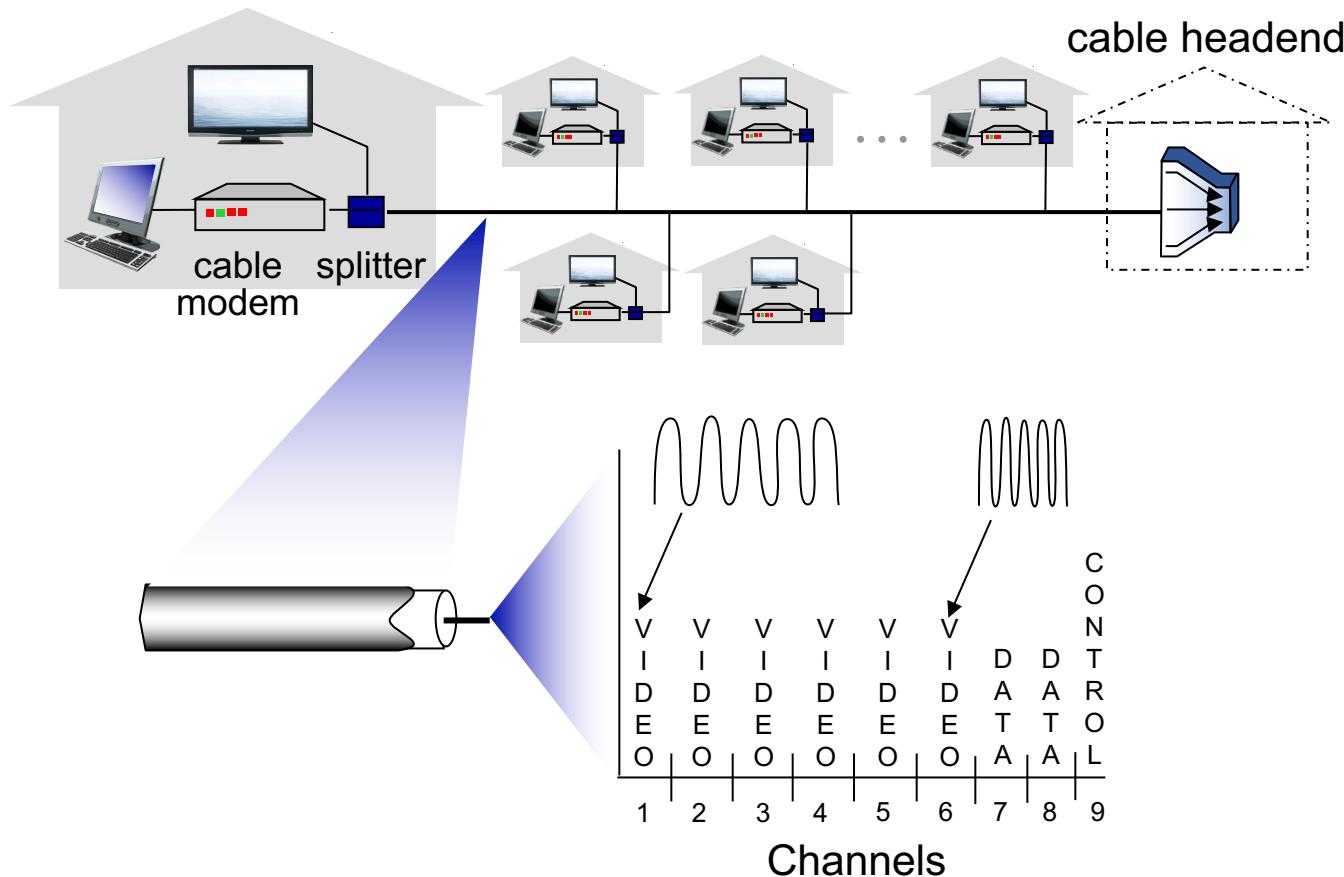
Access networks and physical media

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

- residential access nets
- institutional access networks (school, company)
- mobile access networks (WiFi, 4G/5G)

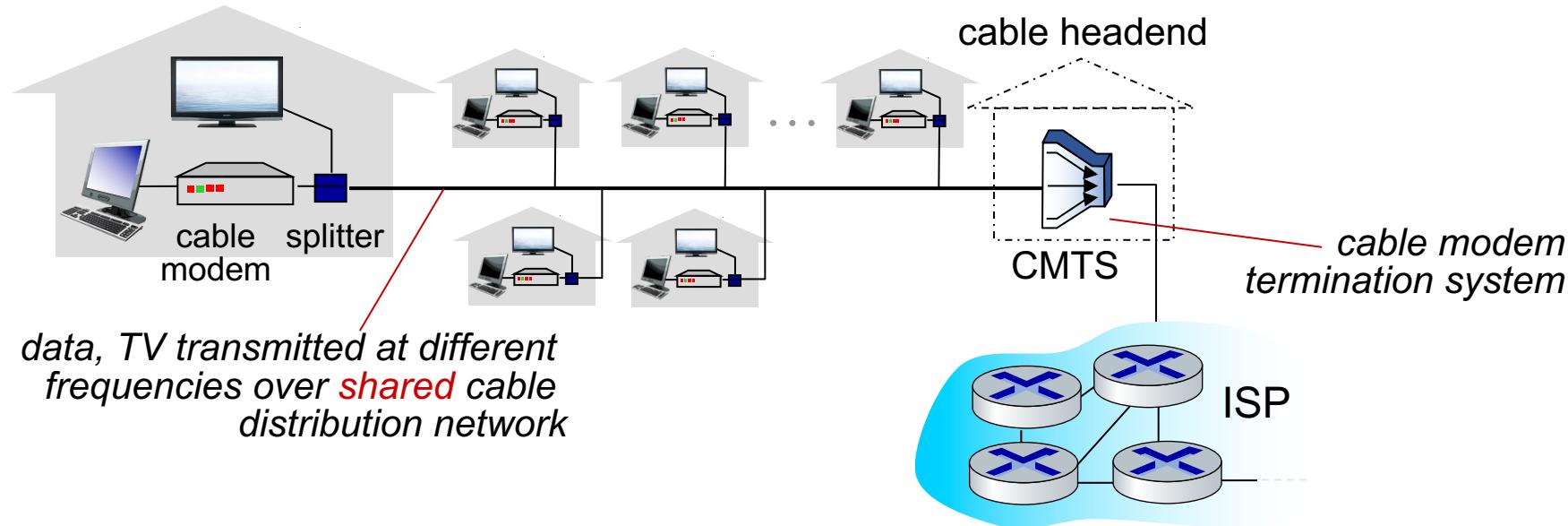


Access networks: cable-based access



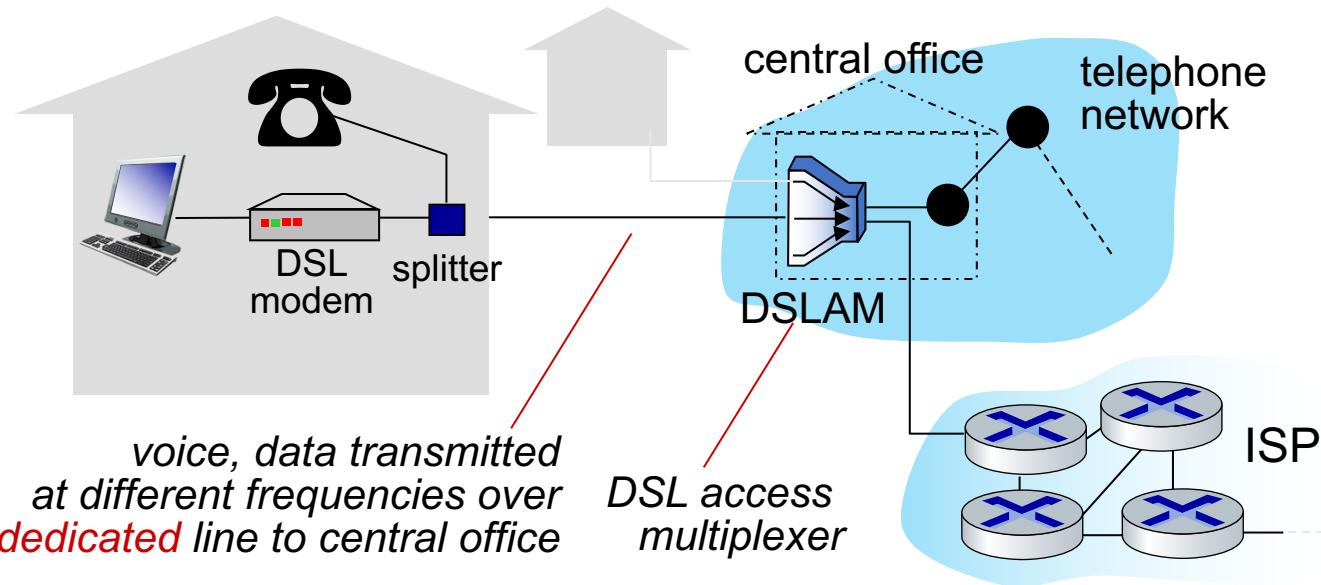
frequency division multiplexing (FDM): different channels transmitted in different frequency bands

Access networks: cable-based access



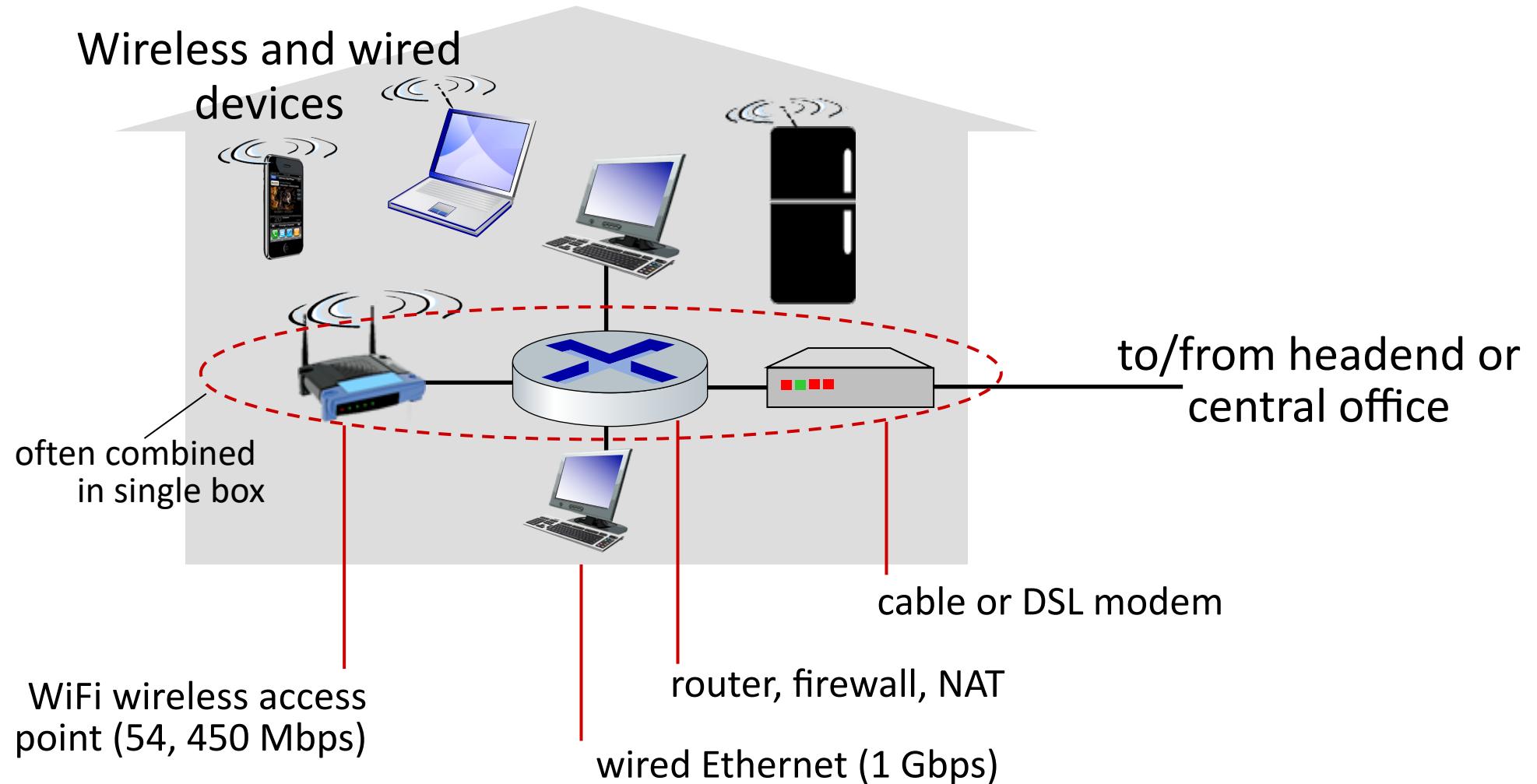
- HFC: hybrid fiber coax
 - asymmetric: up to 40 Mbps – 1.2 Gbps downstream transmission rate, 30-100 Mbps upstream transmission rate
- network of cable, fiber attaches homes to ISP router
 - homes **share access network** to cable headend

Access networks: 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: home networks



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

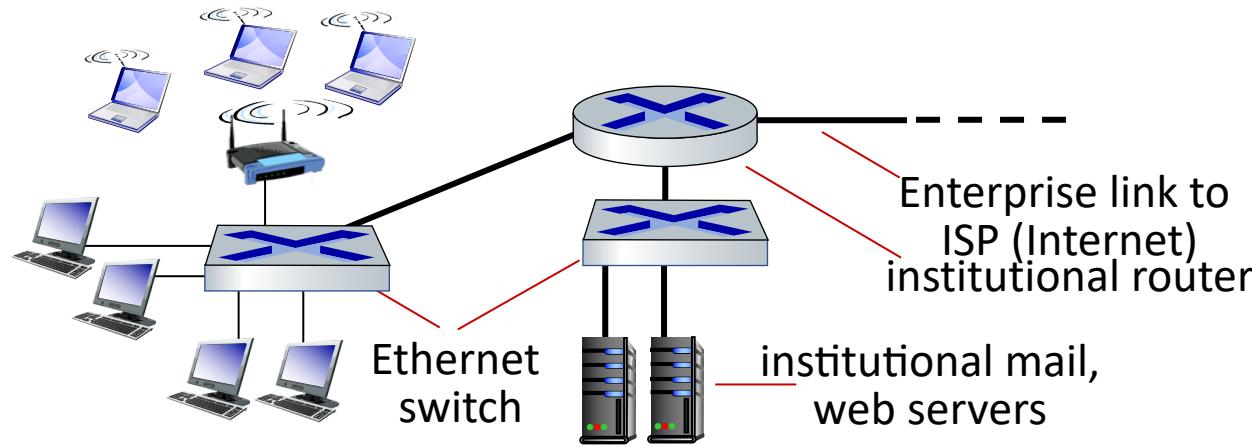


Wide-area cellular access networks

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



Access networks: enterprise networks



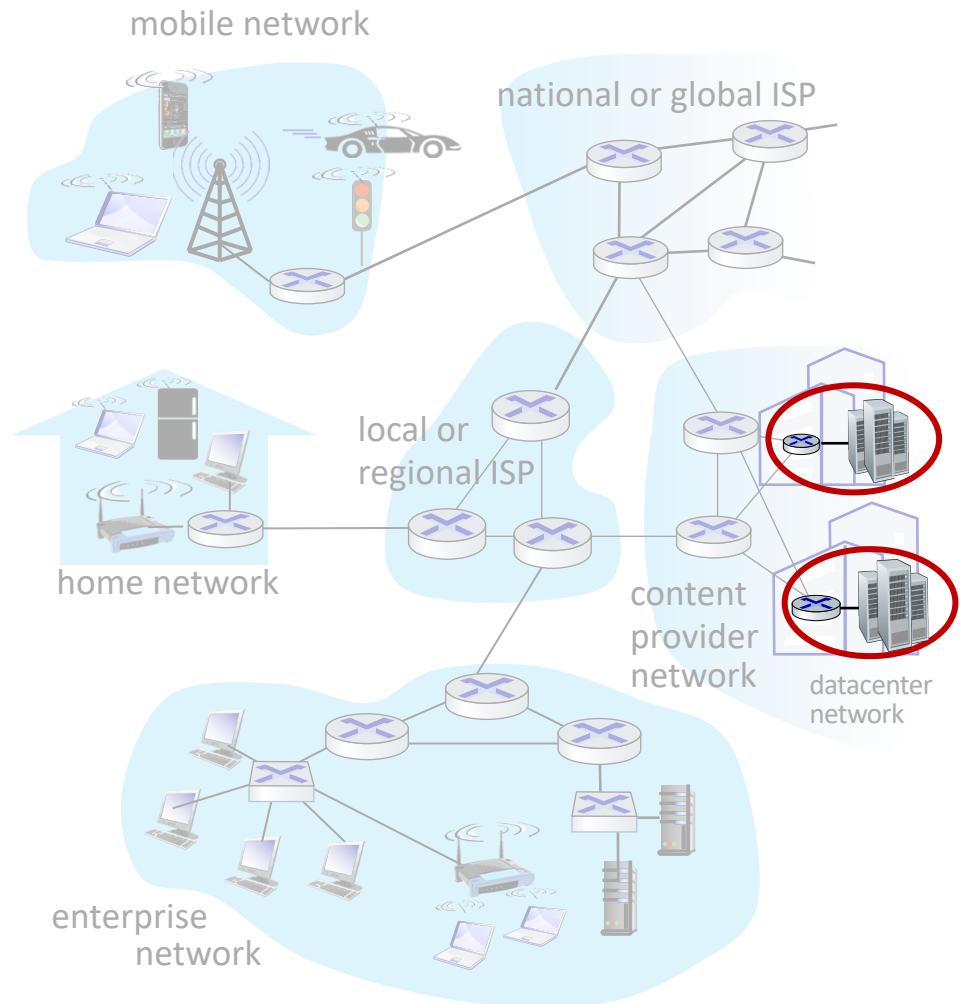
- companies, universities, etc.
- mix of wired, wireless link technologies, connecting a mix of switches and routers (we'll cover differences shortly)
 - Ethernet: wired access at 100Mbps, 1Gbps, 10Gbps
 - WiFi: wireless access points at 11, 54, 450 Mbps

Access networks: data center networks

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



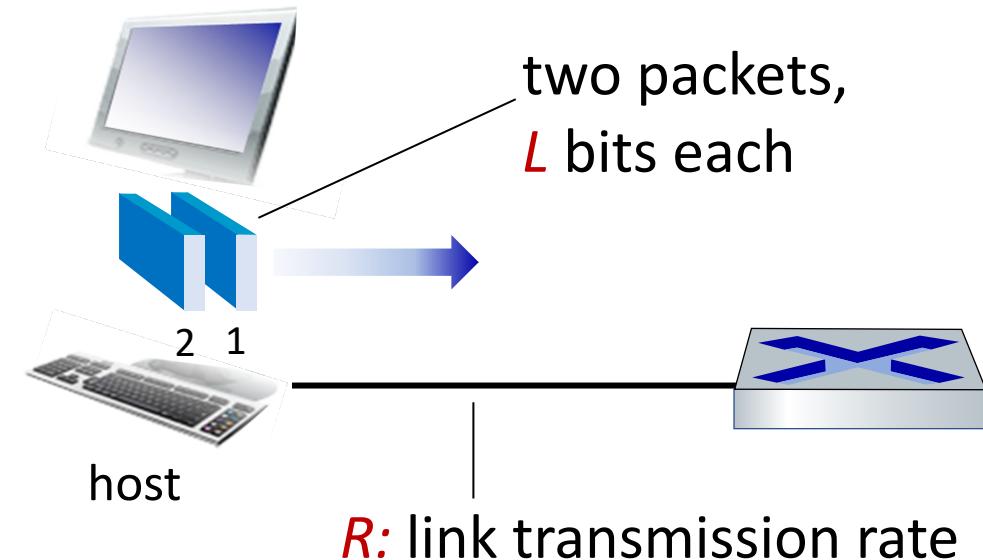
Courtesy: Massachusetts Green High Performance Computing Center (mghpcc.org)



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*



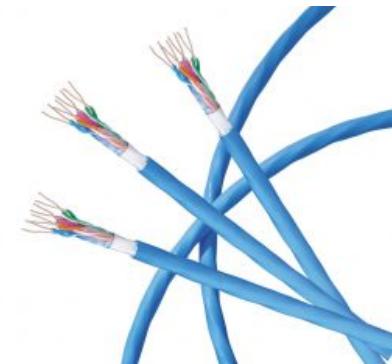
$$\text{packet transmission delay} = \frac{\text{time needed to transmit } L\text{-bit packet into link}}{R \text{ (bits/sec)}} = \frac{L \text{ (bits)}}{R \text{ (bits/sec)}}$$

Links: 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 Ethernet



Links: physical media

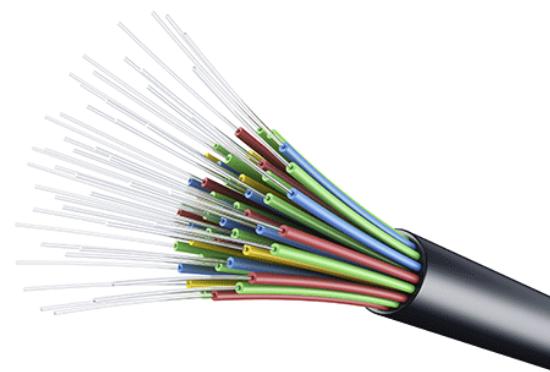
Coaxial cable:

- 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)

Today

- What is the Internet? What is a protocol?
- Network edge: hosts, access network, physical media
- **Network Security**
- Protocol layers, service models
- Wireless and Mobile Networks



Network security

- 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!
- We now need to think about:
 - how bad guys can attack computer networks
 - how we can defend networks against attacks
 - how to design architectures that are immune to attacks

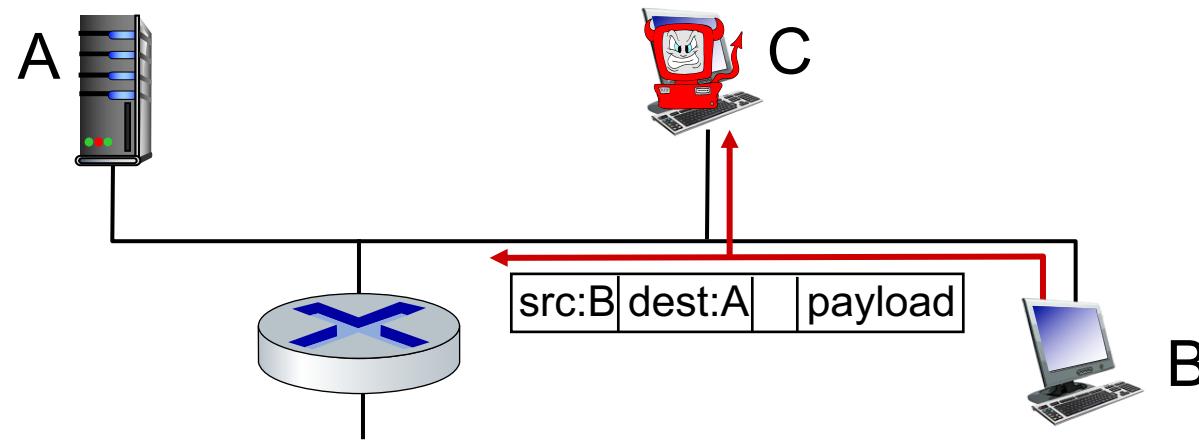
Bad guys can put malware into hosts via Internet

- Malware can get in host from a **virus**, **worm**, or **trojan horse**.
 - 病毒, 蠕虫, 木马
- **Spyware malware** can record keystrokes, web sites visited, upload info to collection site.
- Infected host can be enrolled in a **botnet**, used for spam and DDoS attacks.
- Malware is often **self-replicating**: from an infected host, seeks entry into other hosts

Bad guys: packet interception

packet “sniffing”:

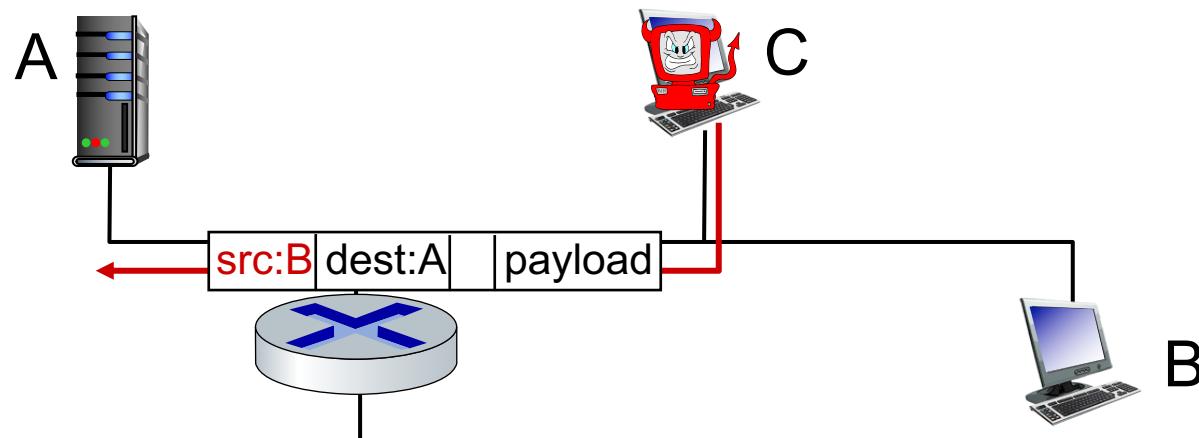
- broadcast media (shared Ethernet, wireless)
- promiscuous network interface reads/records all packets (e.g., including passwords!) passing by



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

Bad guys: fake identity

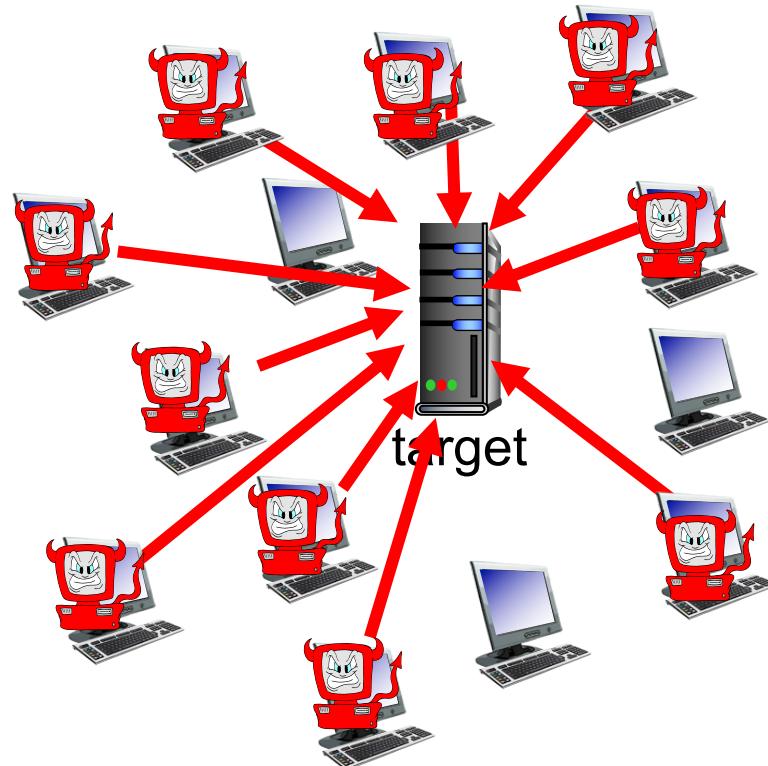
IP spoofing: injection of packet with false source address



Bad guys: denial of service

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



Lines of defense:

- **authentication:** proving you are who you say you are
 - cellular networks provides hardware identity via SIM card; no such hardware assist in traditional Internet
- **confidentiality:** via encryption
- **integrity checks:** digital signatures prevent/detect tampering
- **access restrictions:** password-protected VPNs
- **firewalls:** specialized “middleboxes” in access and core networks:
 - off-by-default: filter incoming packets to restrict senders, receivers, applications
 - detecting/reacting to DOS attacks

Network Security

basic techniques.....

- cryptography (symmetric and public key)
- message integrity
- end-point authentication

.... used in many different security scenarios

- secure email
- secure transport (TLS)
- IP sec
- 802.11, 4G/5G

operational security: firewalls and IDS

What is network security?

confidentiality: only sender, intended receiver should “understand” message contents

- sender encrypts message
- receiver decrypts message

authentication: sender, receiver want to confirm identity of each other

message integrity: sender, receiver want to ensure message not altered (in transit, or afterwards) without detection

access and availability: services must be accessible and available to users

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Protocol “layers” and reference models

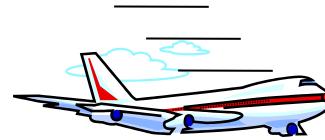
Networks are complex,
with many “pieces”:

- 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)

baggage (check)

gates (load)

runway takeoff

airplane routing

ticket (complain)

baggage (claim)

gates (unload)

runway landing

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

应用层：传什么样数据？干什么事

- *application*: supporting network applications

- HTTP, IMAP, SMTP, DNS

- *transport*: process-process data transfer

- TCP, UDP

传输层：从哪里到哪里？

需要确认吗？可靠传输？

- *network*: routing of datagrams from source to destination

- IP, routing protocols

网络路由层：

途径哪些地方？

- *link*: data transfer between neighboring network elements

- Ethernet, 802.11 (WiFi), PPP

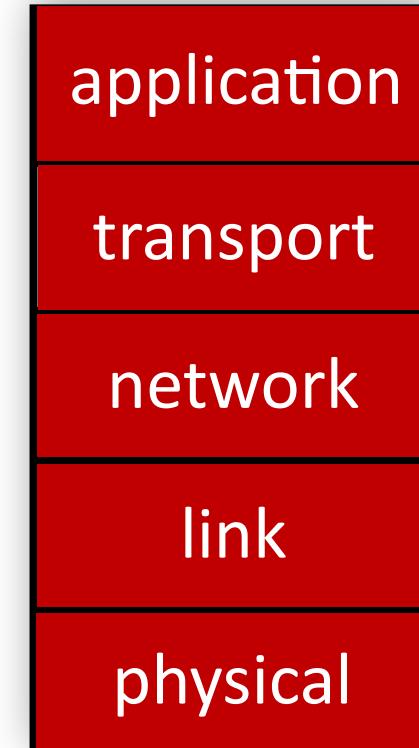
链路访问层：有线or无线链路？

下一站是哪？链路可访问吗？

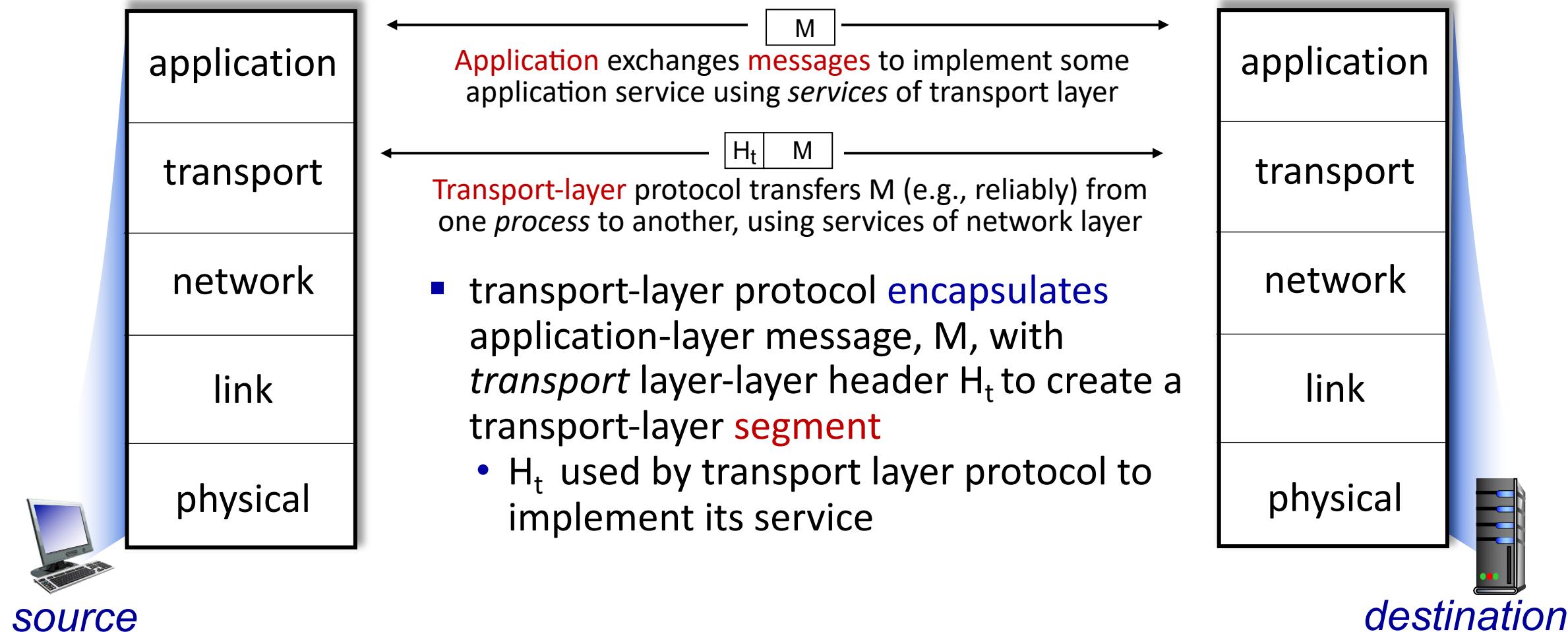
- *physical*: bits “on the wire”

物理层：具体怎么传每个 bit 数据？

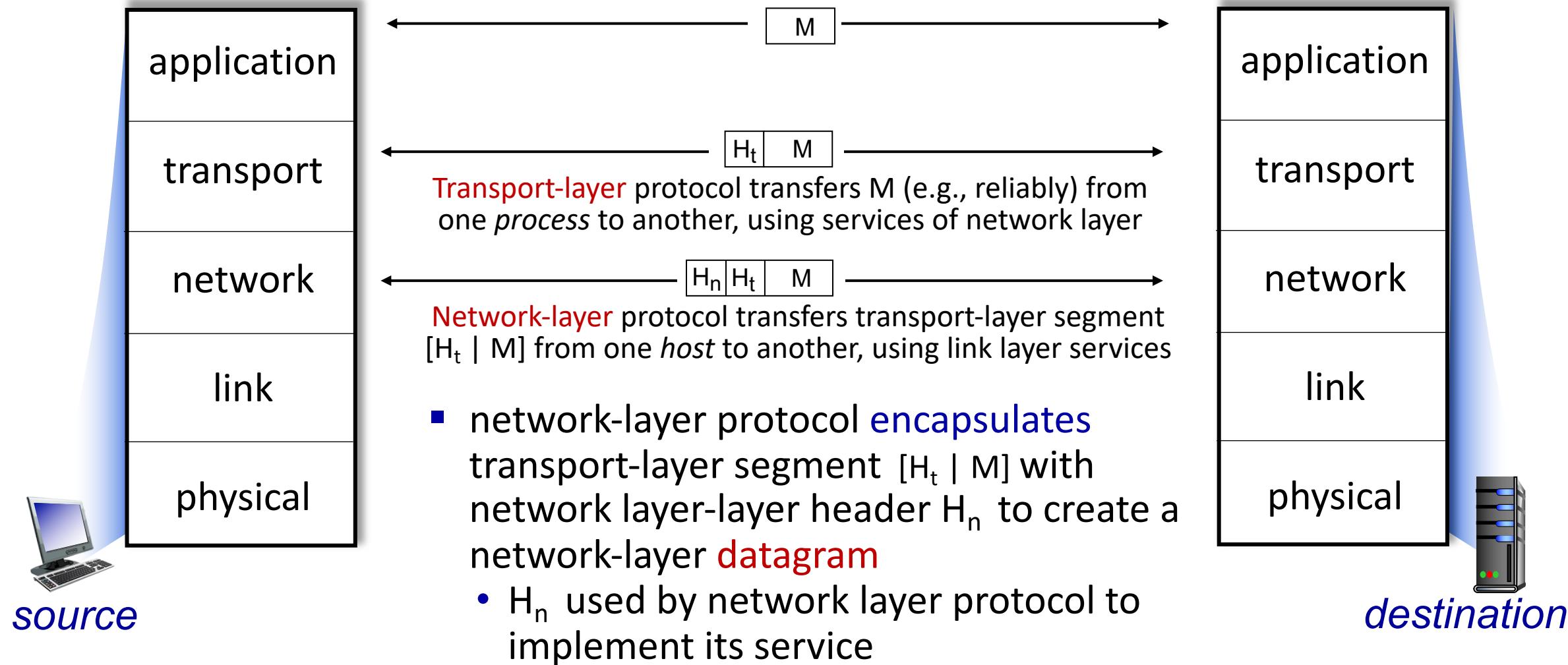
什么调制格式？



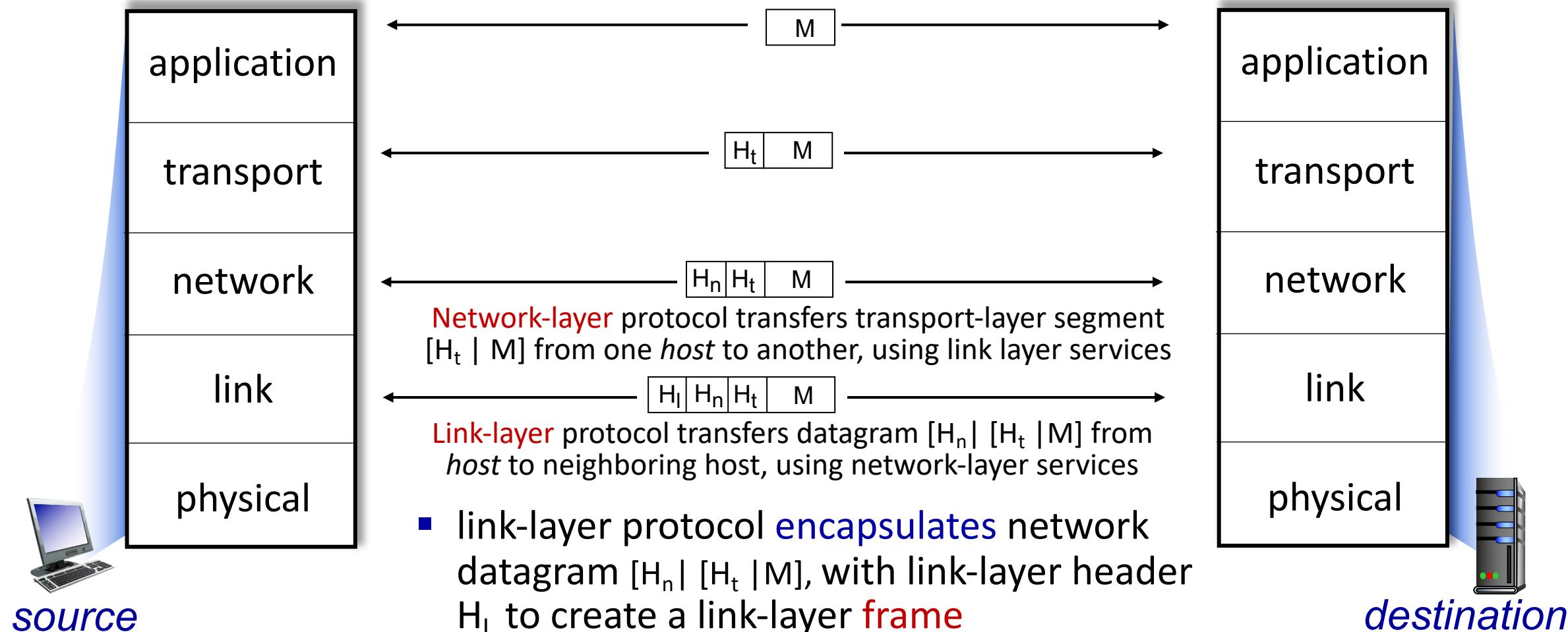
Services, Layering and Encapsulation



Services, Layering and Encapsulation

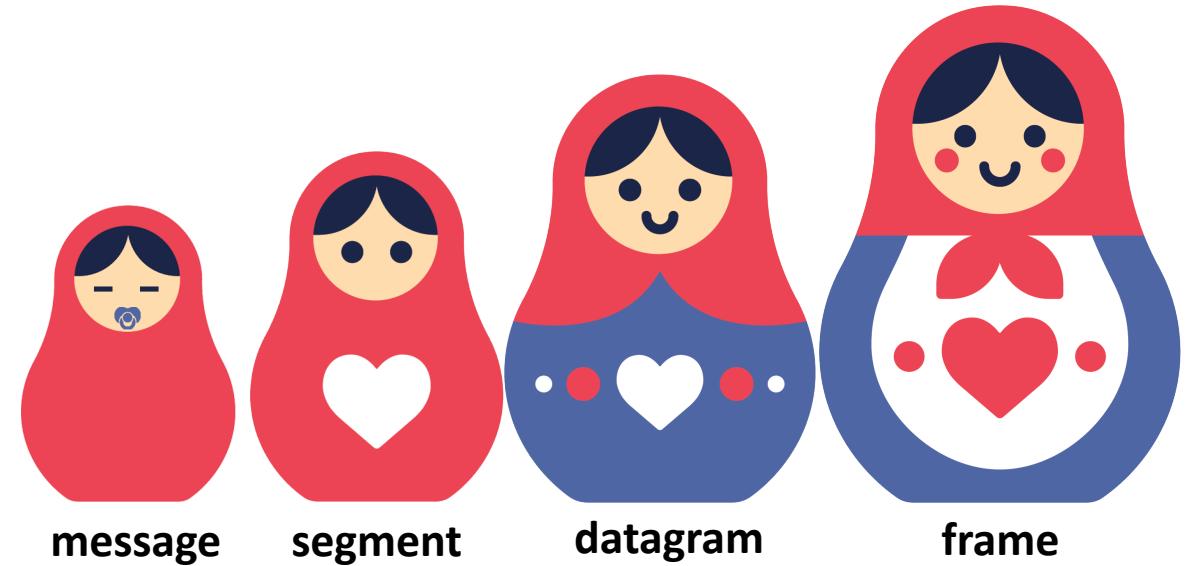


Services, Layering and Encapsulation

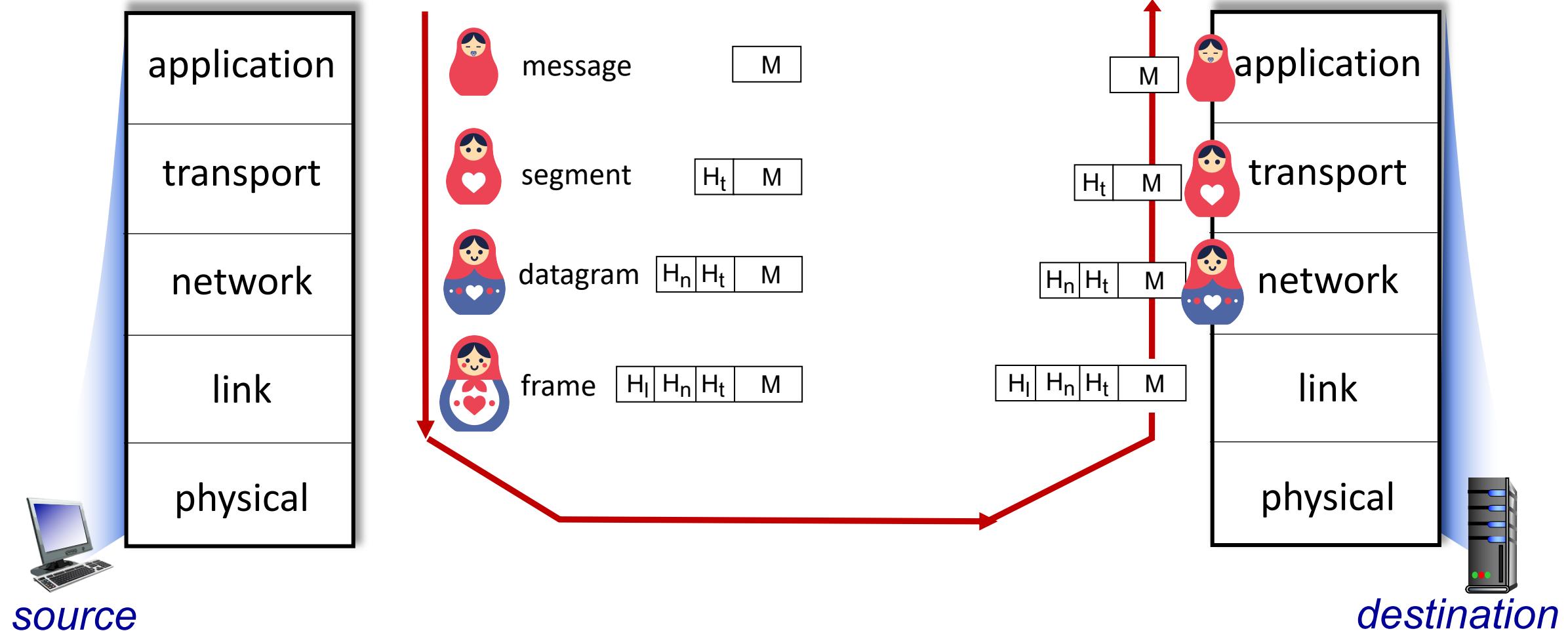


Encapsulation

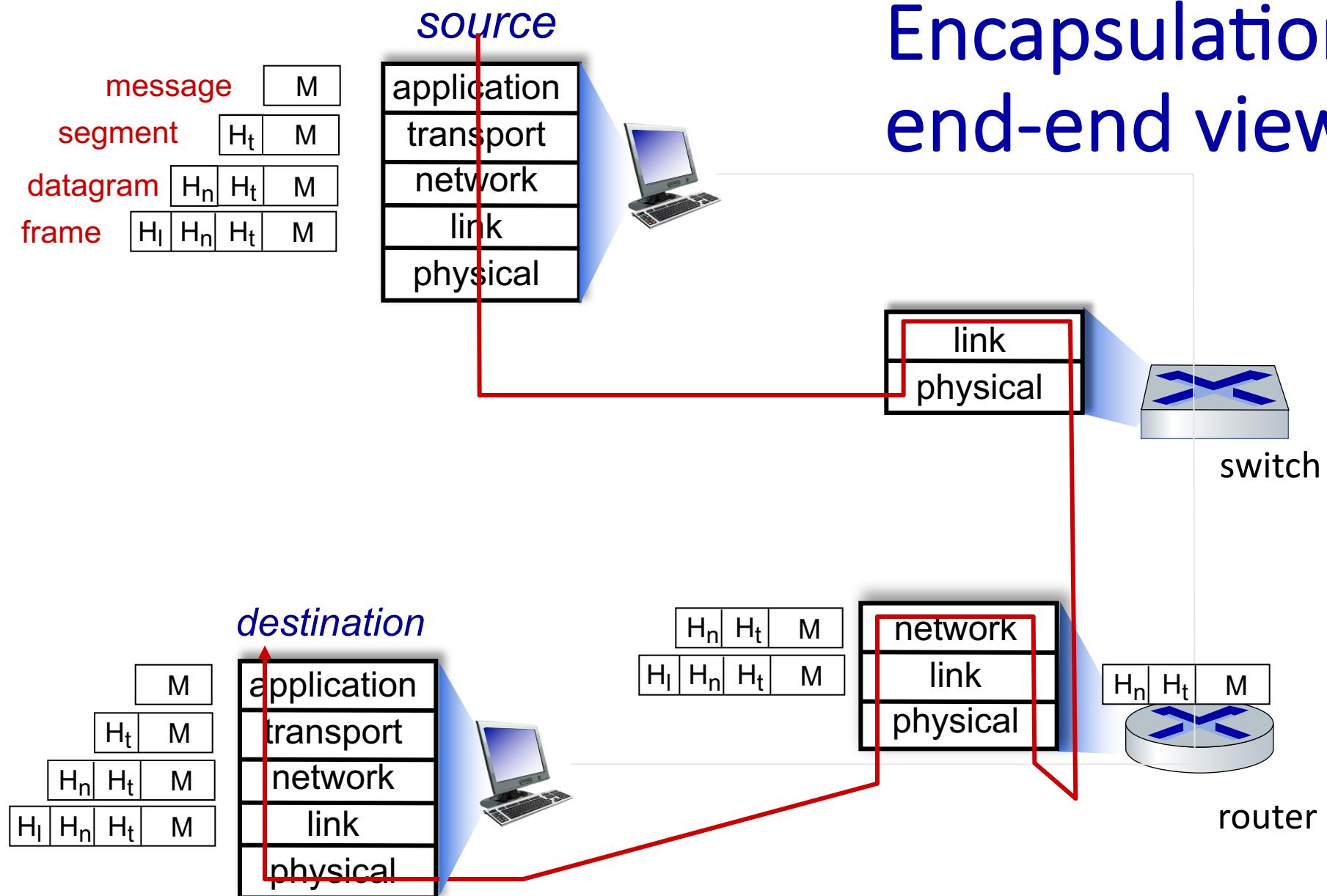
Matryoshka dolls (stacking dolls)



Services, Layering and Encapsulation



Encapsulation: an end-end view



Today

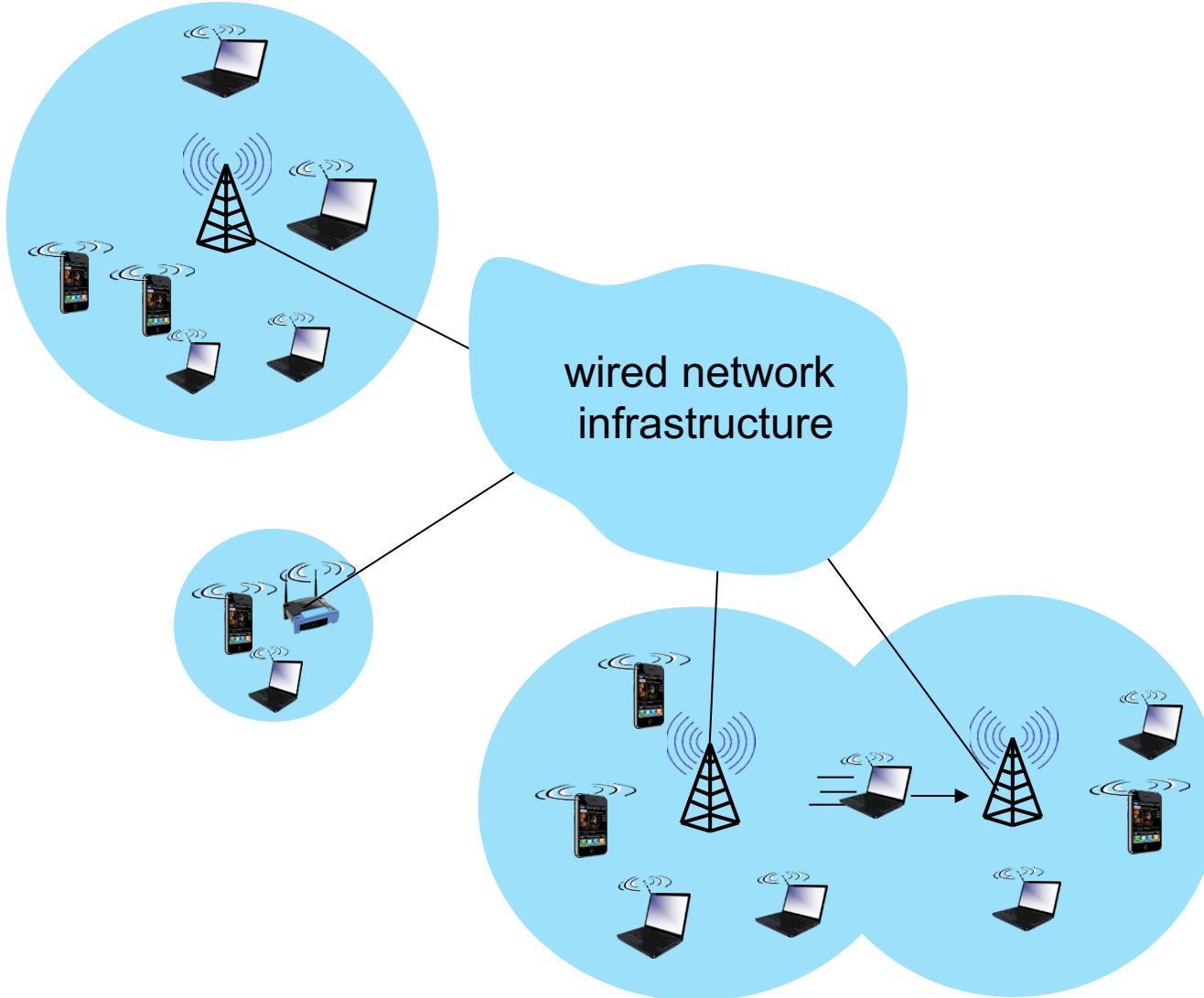
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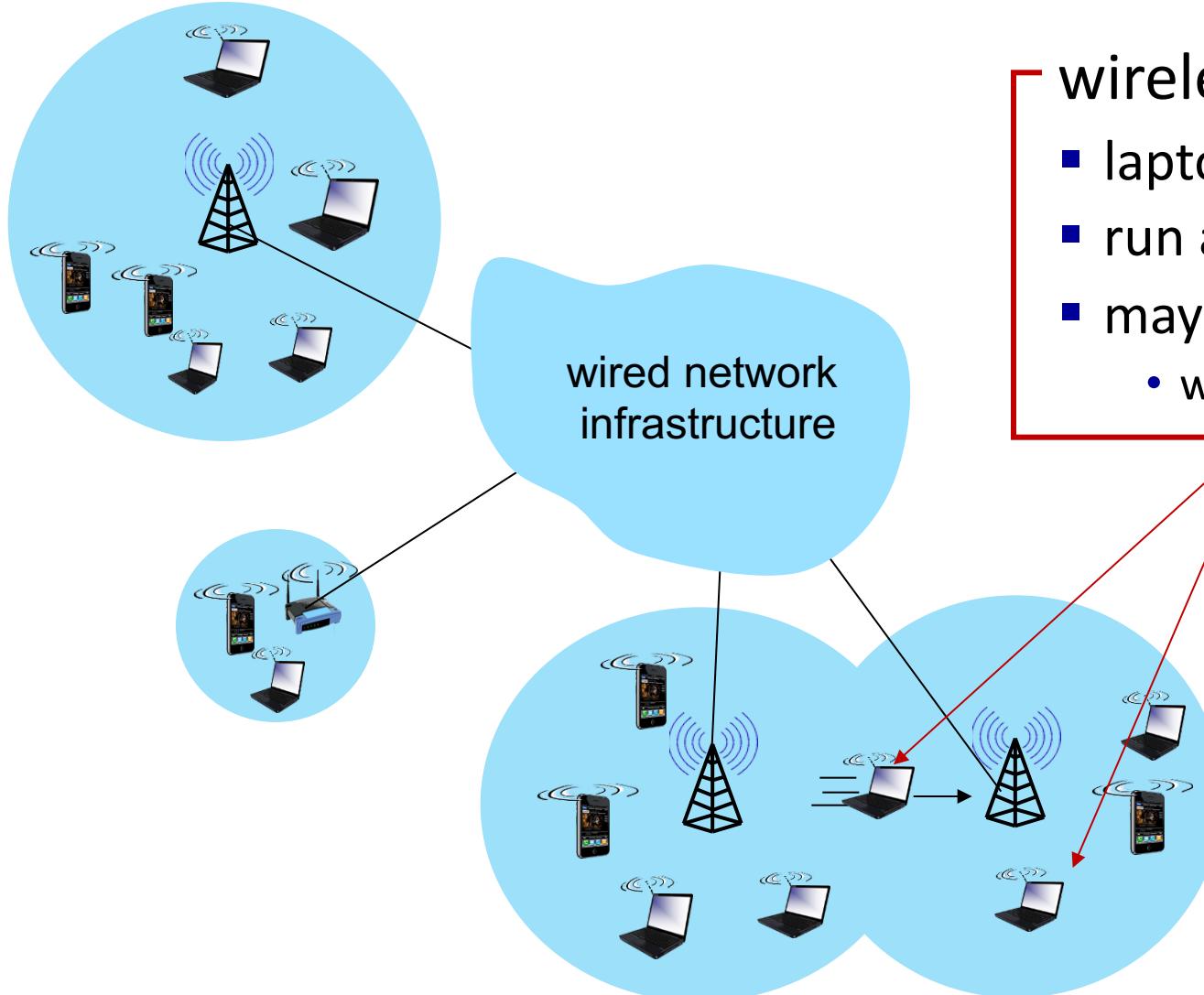
Wireless and Mobile Networks: context

- more wireless (mobile) phone subscribers than fixed (wired) phone subscribers (10-to-1 in 2019)!
- more mobile-broadband-connected devices than fixed-broadband-connected devices (5-1 in 2019)!
 - 4G/5G cellular networks now embracing Internet protocol stack, including SDN
- two important (but different) challenges
 - **wireless**: communication over wireless link
 - **mobility**: handling the mobile user who changes point of attachment to network

Elements of a wireless network



Elements of a wireless network

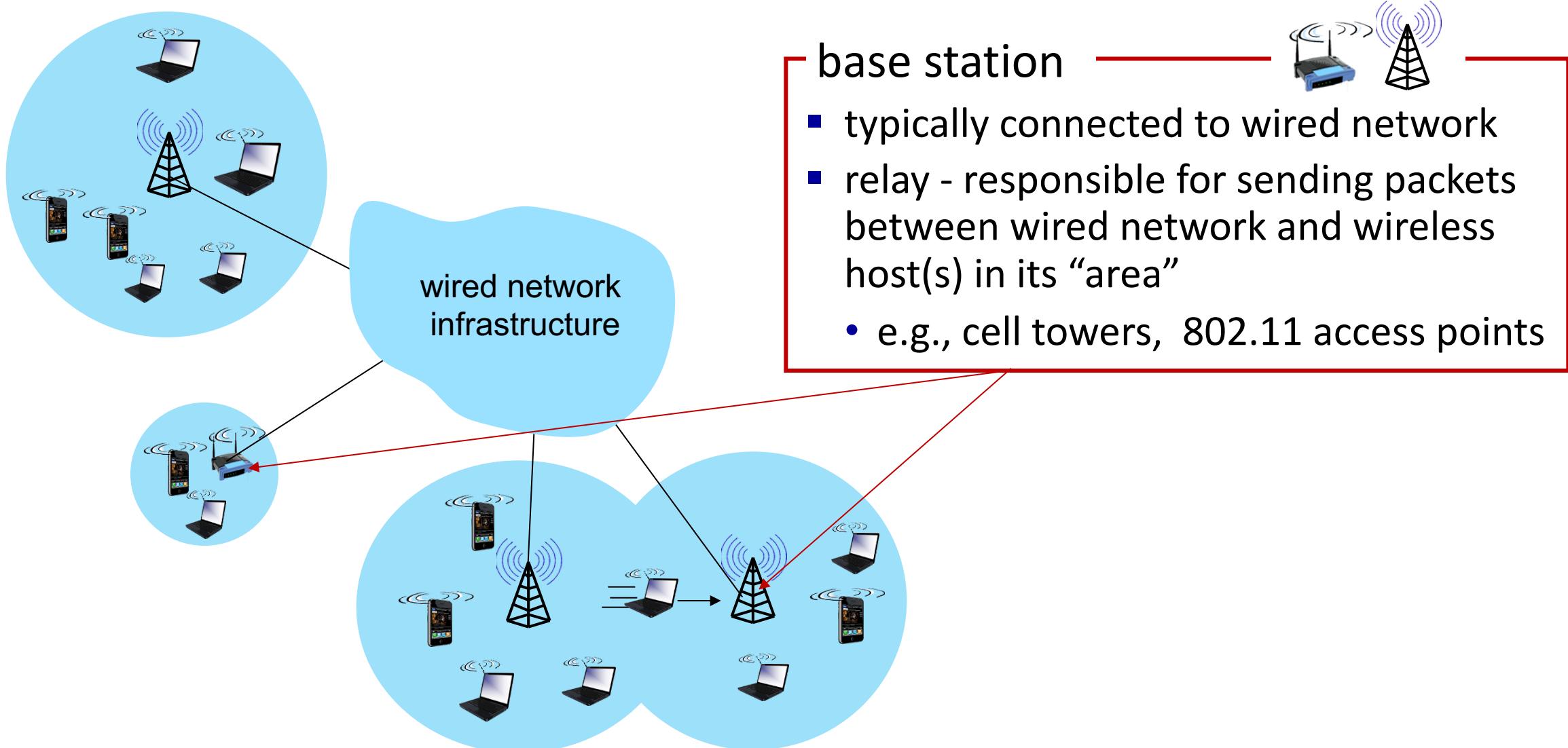


wireless hosts

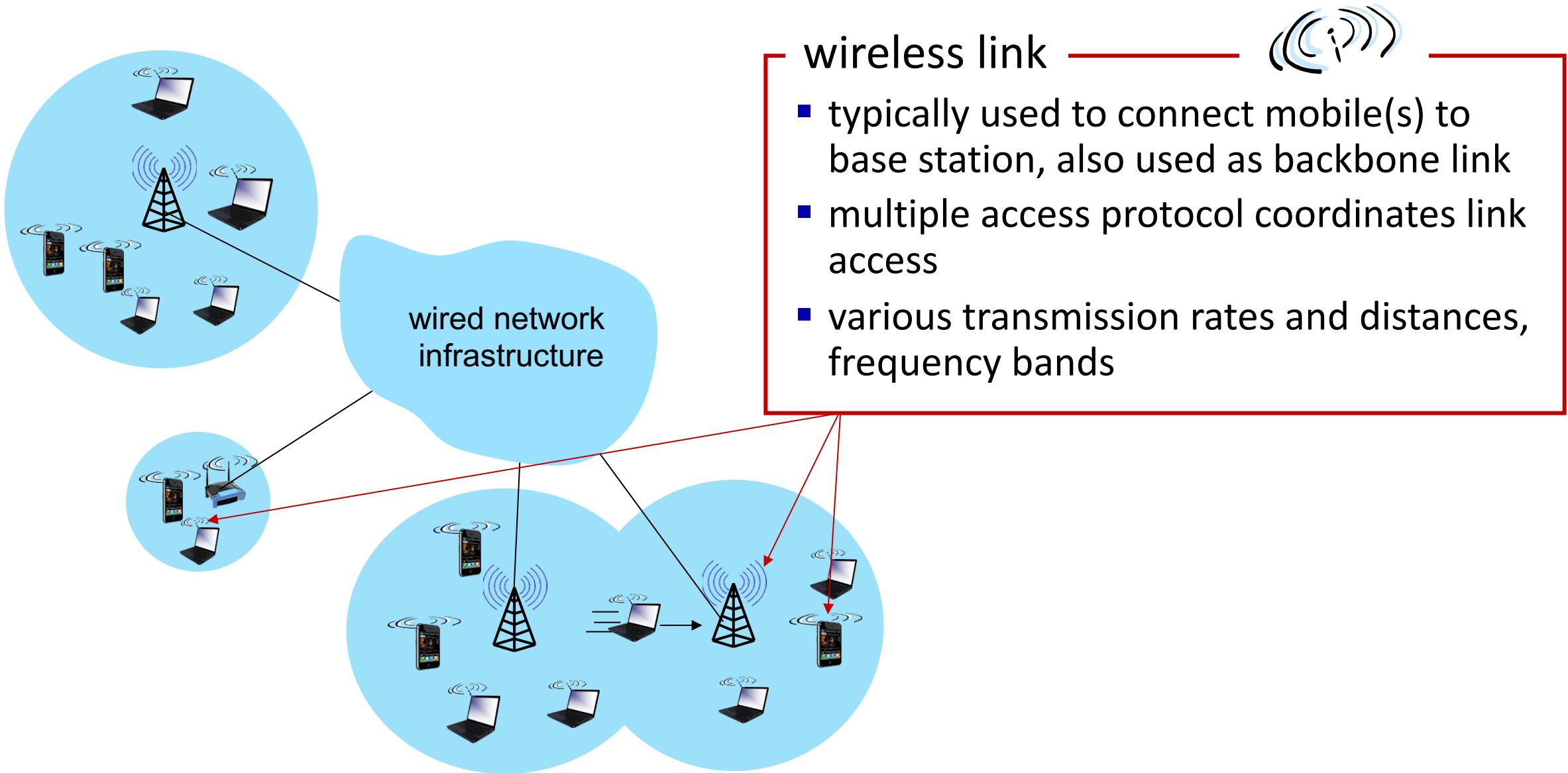
- laptop, smartphone, IoT
- run applications
- may be stationary (non-mobile) or mobile
 - wireless does *not* always mean mobility!



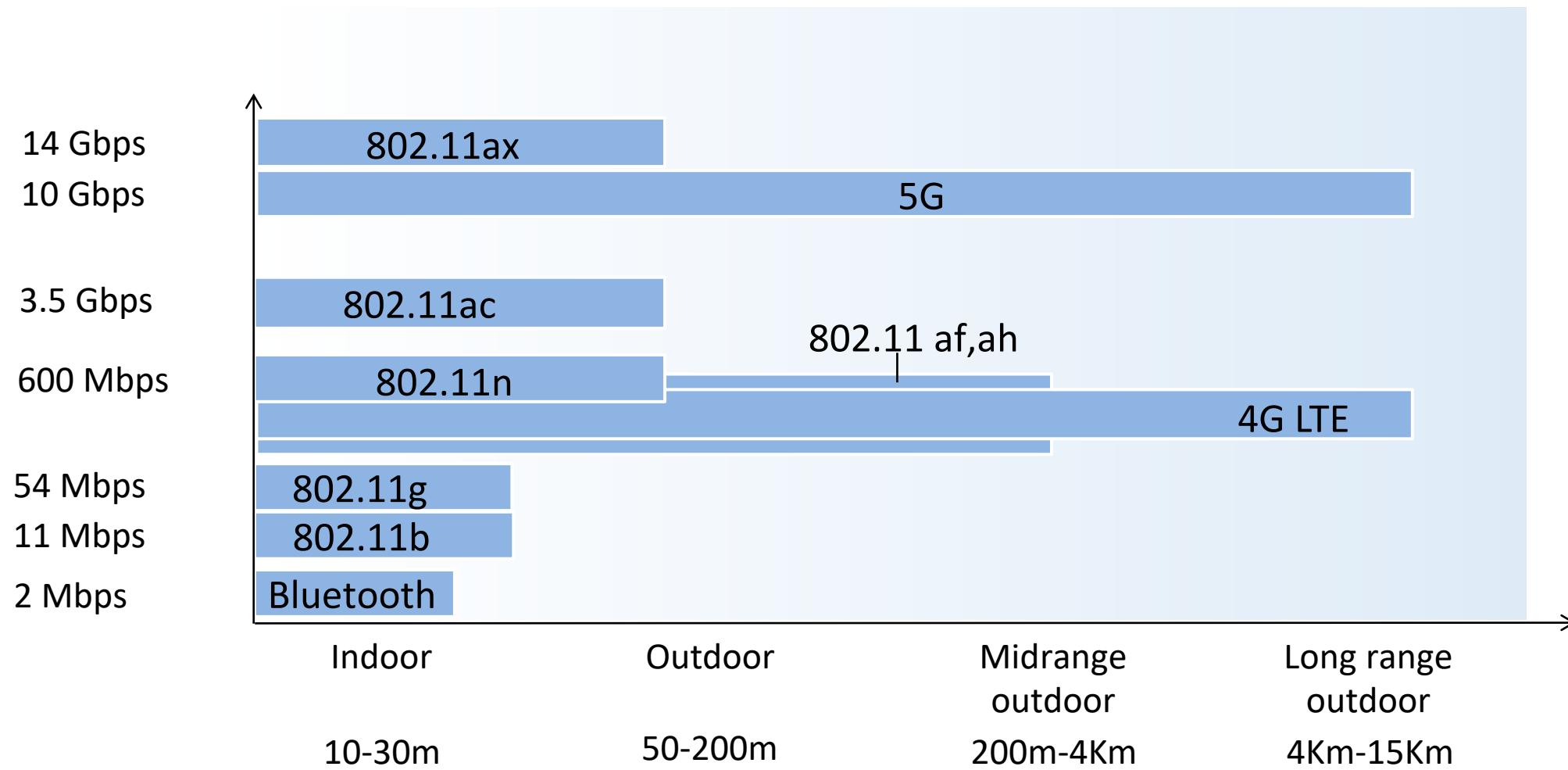
Elements of a wireless network



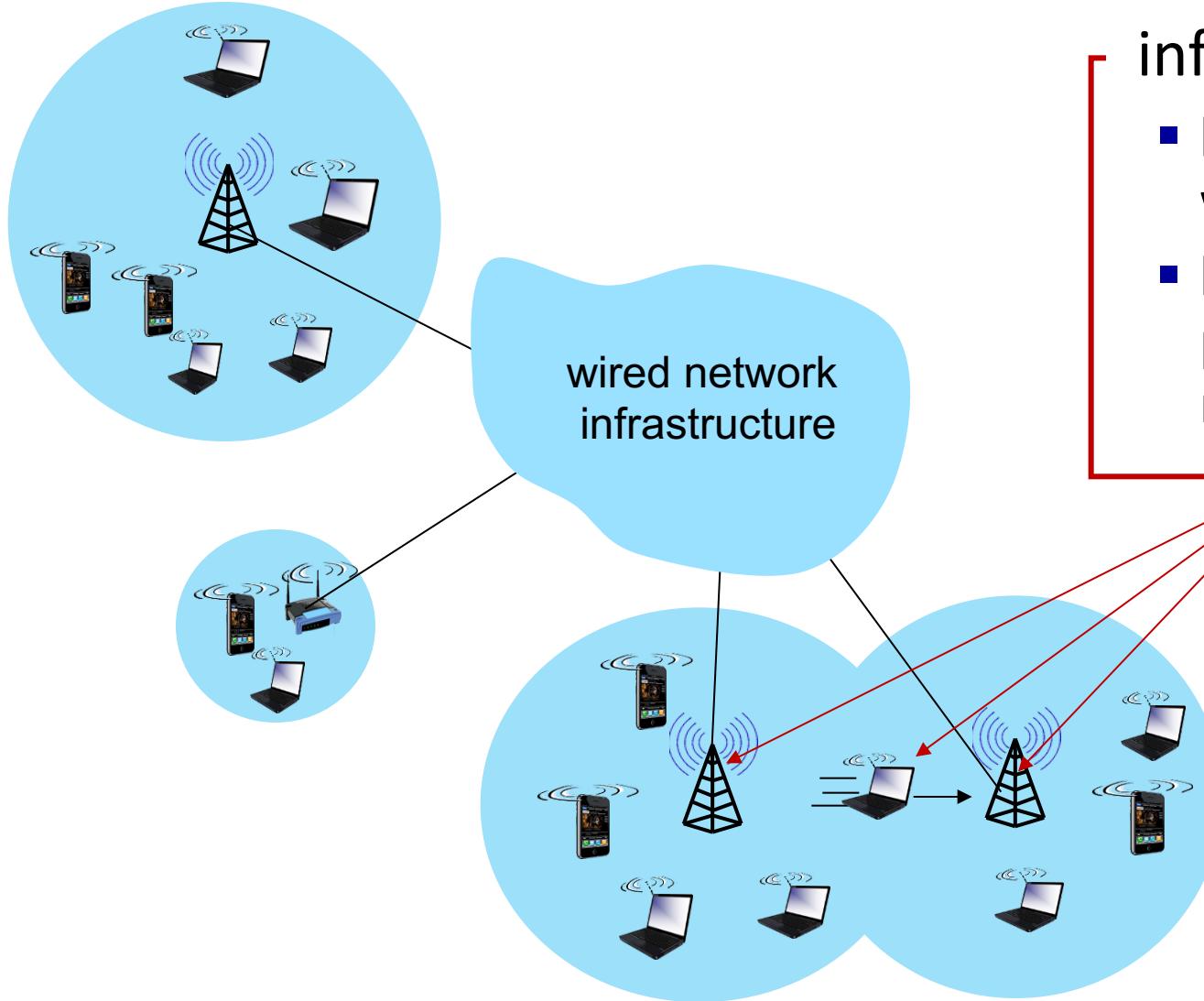
Elements of a wireless network



Characteristics of selected wireless links



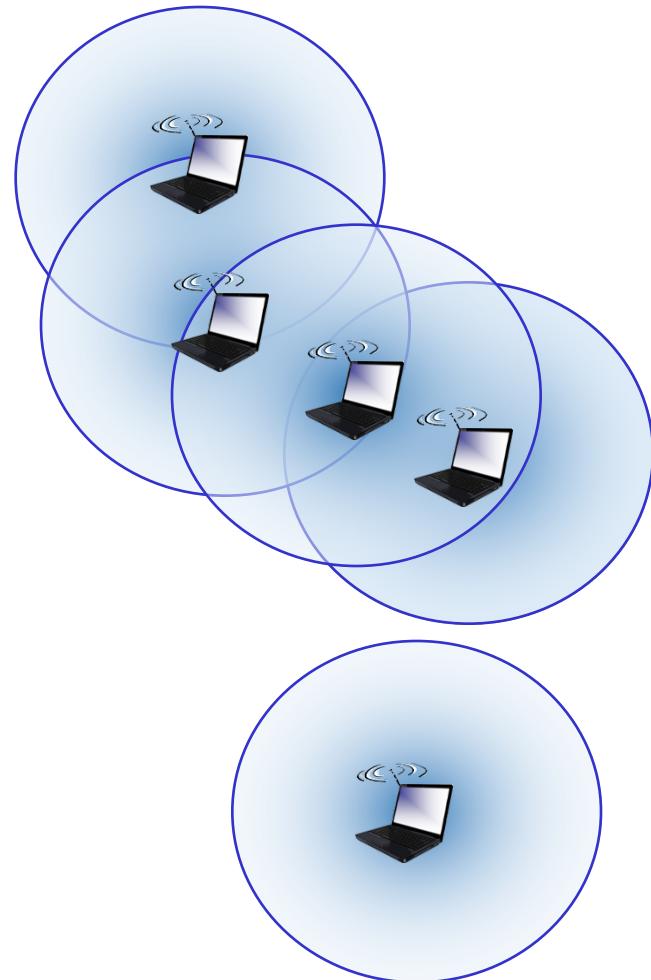
Elements of a wireless network



infrastructure mode

- base station connects mobiles into wired network
- handoff: mobile changes base station providing connection into wired network

Elements of a wireless network



ad hoc mode

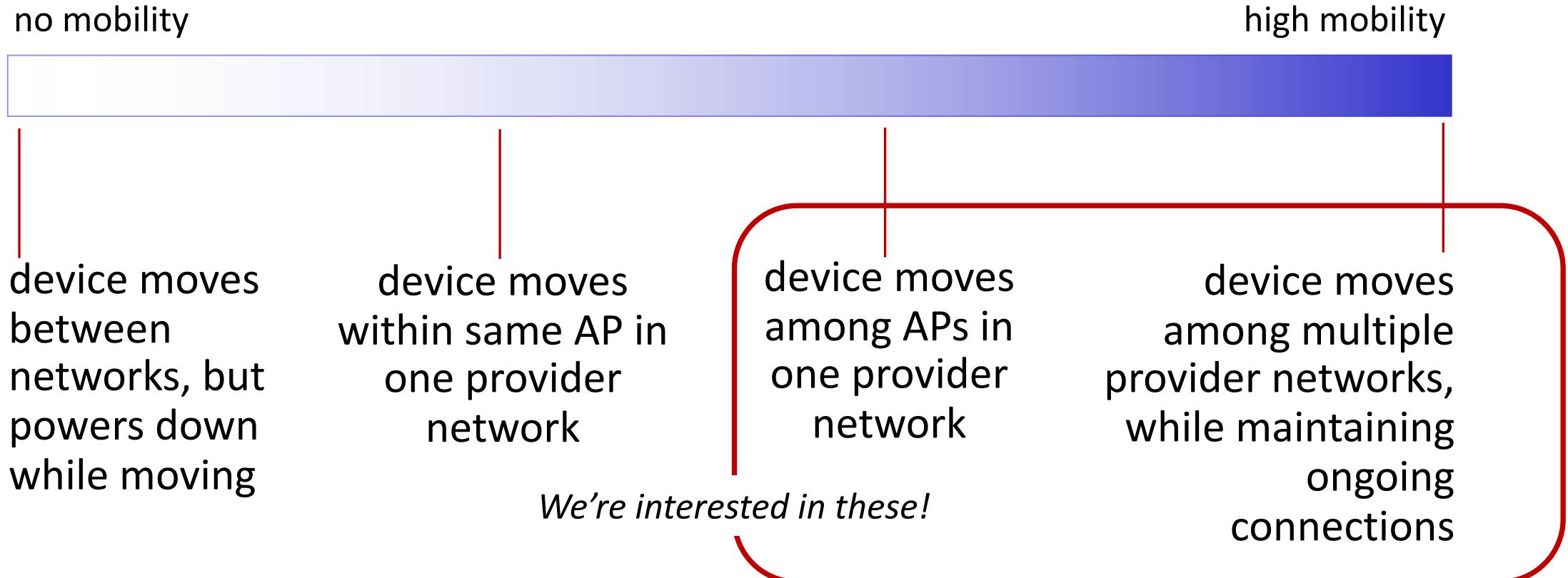
- no base stations
- nodes can only transmit to other nodes within link coverage
- nodes organize themselves into a network: route among themselves

Wireless network taxonomy

	single hop	multiple hops
infrastructure (e.g., APs)	host connects to base station (WiFi, cellular) which connects to larger Internet	host may have to relay through several wireless nodes to connect to larger Internet: <i>mesh net</i>
<i>no infrastructure</i>	no base station, no connection to larger Internet (Bluetooth, ad hoc nets)	no base station, no connection to larger Internet. May have to relay to reach other a given wireless node MANET, VANET

What is mobility?

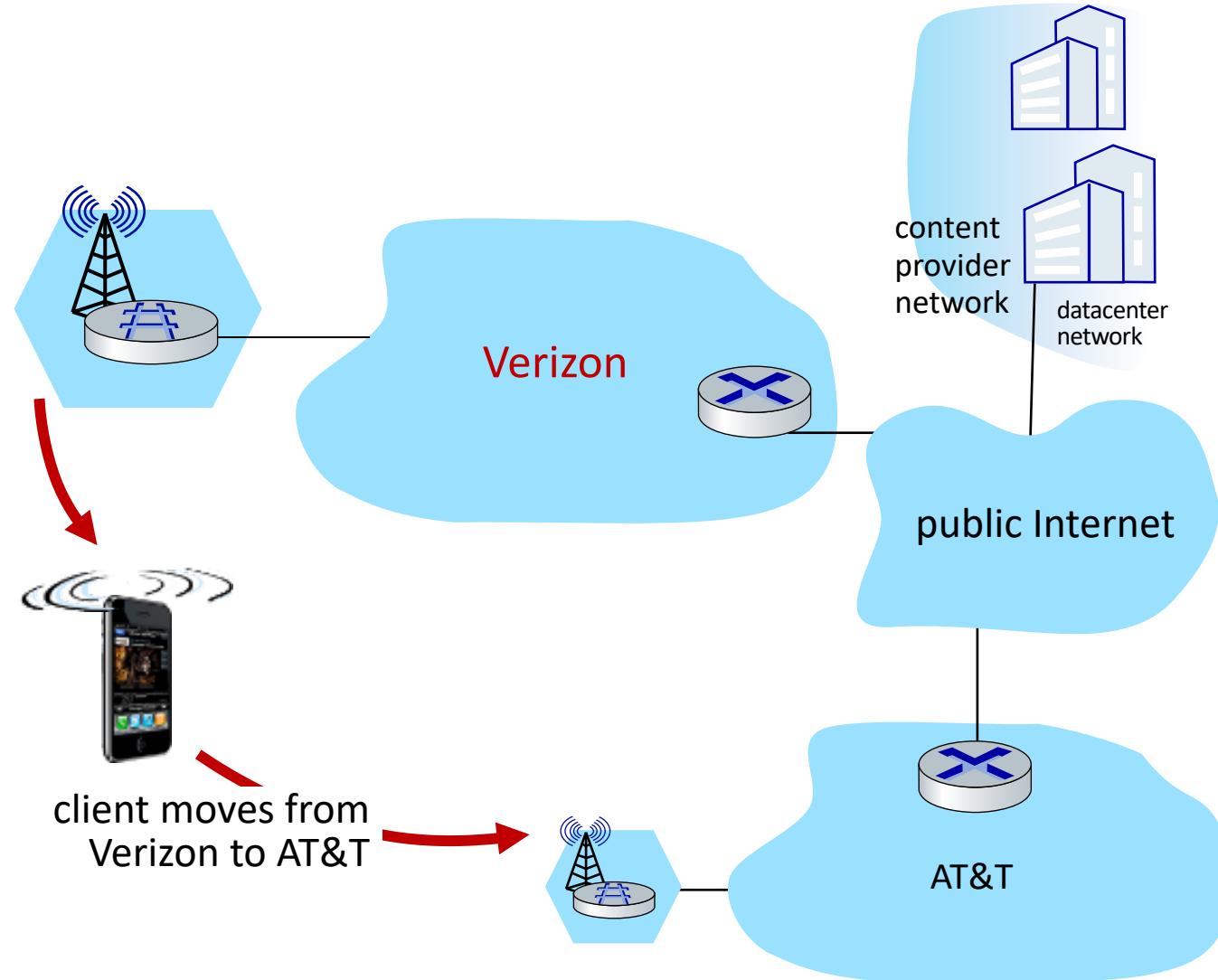
- spectrum of mobility, from the **network** perspective:



Mobility challenge:

If a device moves from one network another:

- How will the “network” know to forward packets to the *new* network?



Wireless, mobility: impact on higher layer protocols

- logically, impact *should* be minimal ...
 - best effort service model remains unchanged
 - TCP and UDP can (and do) run over wireless, mobile
- ... but performance-wise:
 - packet loss/delay due to bit-errors (discarded packets, delays for link-layer retransmissions), and handover loss
 - TCP interprets loss as congestion, will decrease congestion window unnecessarily
 - delay impairments for real-time traffic
 - bandwidth a scarce resource for wireless links

Summary

We've covered a "ton" of material!

- What is the Internet? What is a protocol?
- Network edge: hosts, access network, physical media
- Network Security
- Protocol layers, service models
- Wireless and Mobile Networks



You now have:

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

Additional Slides

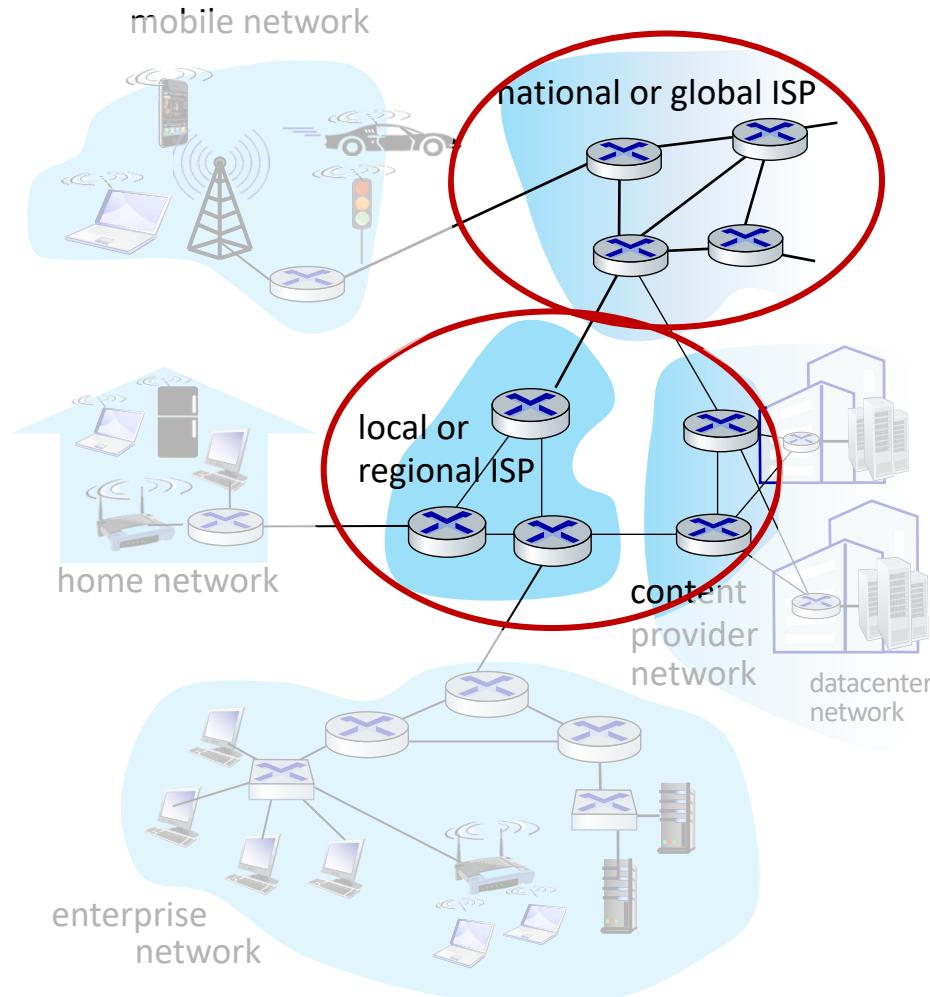
Additional Slides

- Network core: packet/circuit switching, internet structure
- Performance: loss, delay, throughput
- Internet history



The network core

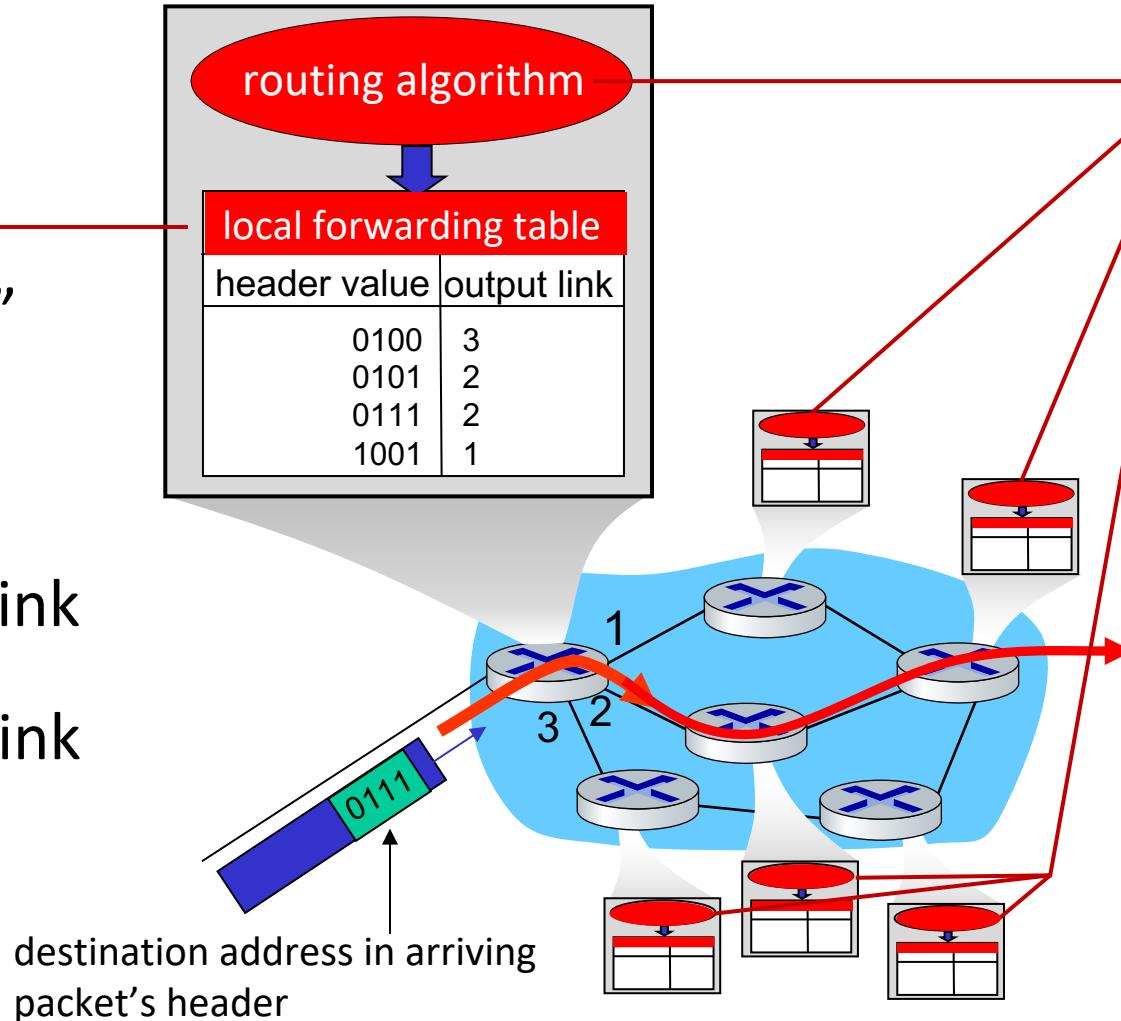
- mesh of interconnected routers
- ***the fundamental question:*** how is data transferred through net? Two ways
 - **circuit switching:** dedicated circuit per call:
telephone net
 - **packet-switching:** data sent thru net in discrete
“chunks”
- **packet-switching:** hosts break application-layer messages 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:

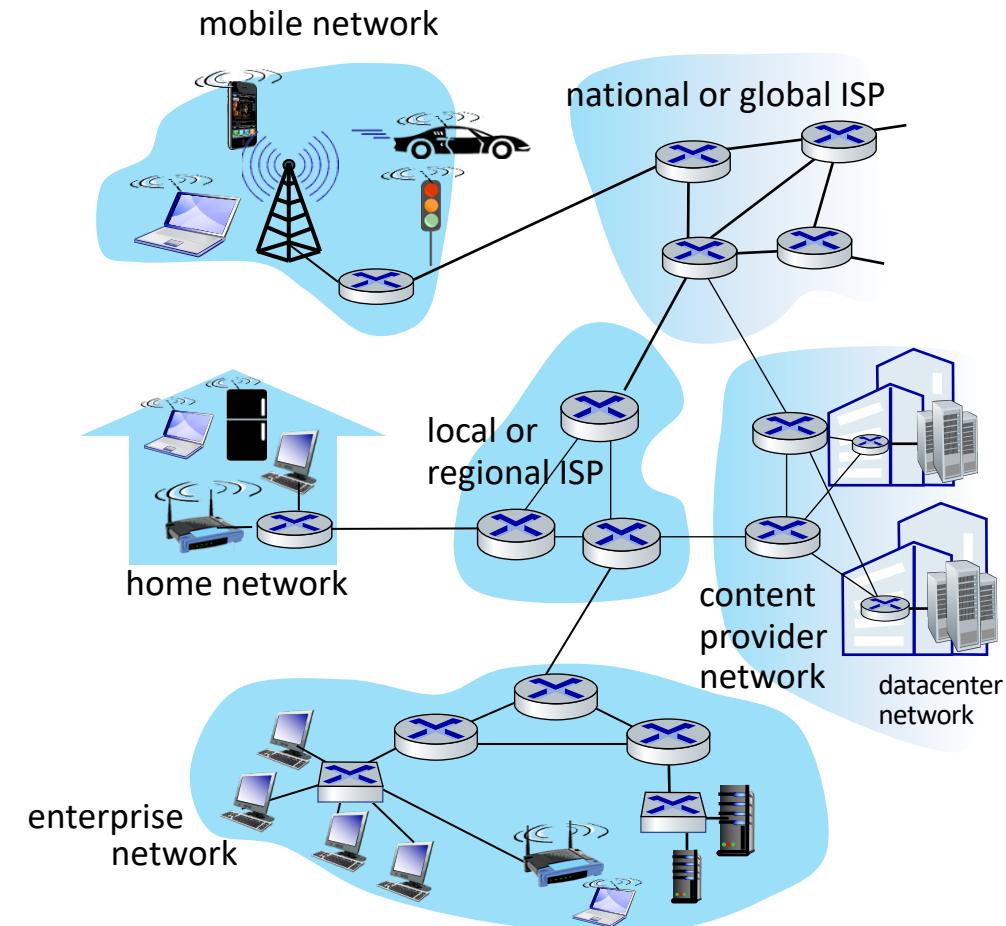
- *global* action: determine source-destination paths taken by packets
- routing algorithms



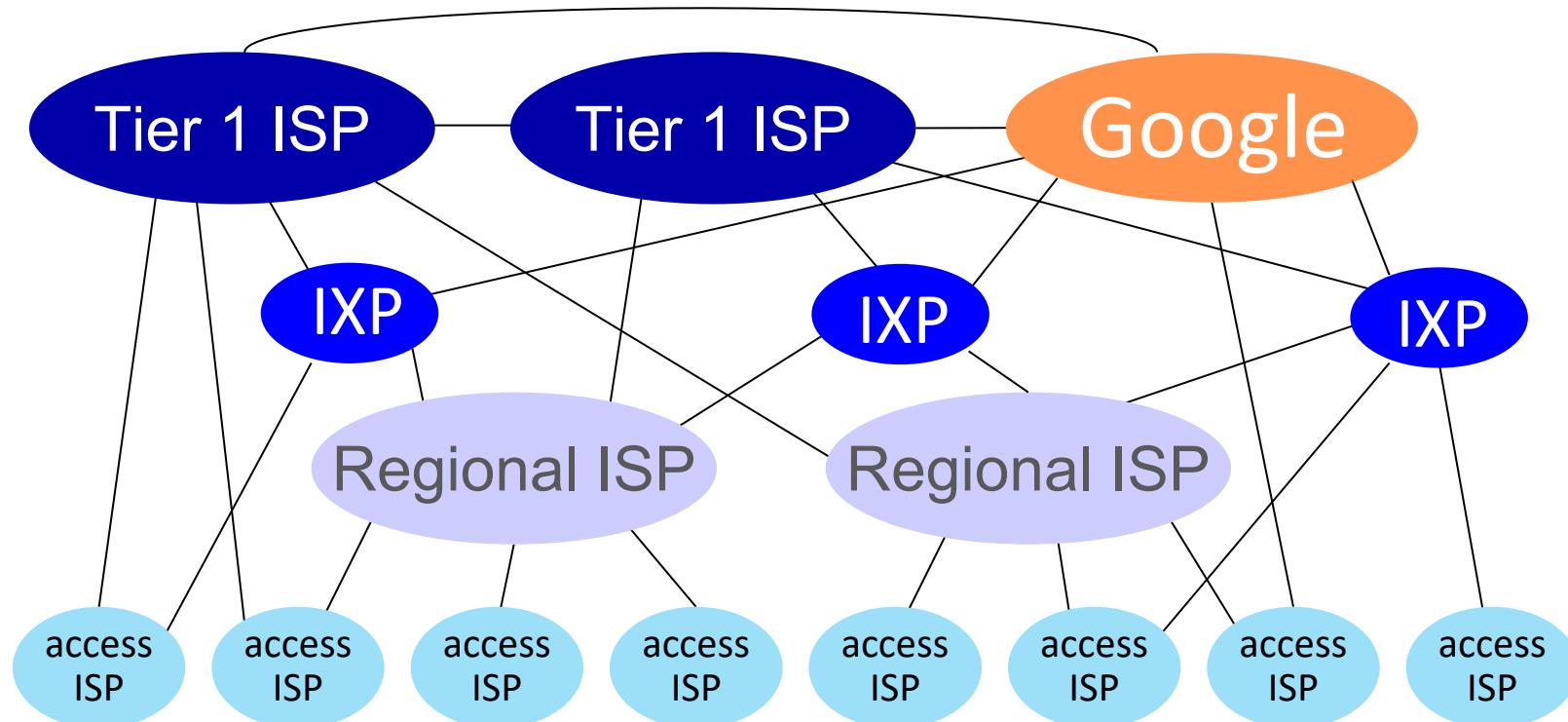


Internet structure: a “network of networks”

- 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**



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

Additional Slides

- Network core: packet /circuit switching, internet structure
- Performance: loss, delay, throughput
- Internet history



Why we need metrics?

- To evaluate the performance of a system

- Transportation system

- Cross-road traffic jam
 - Delay, accident, vehicle traffic

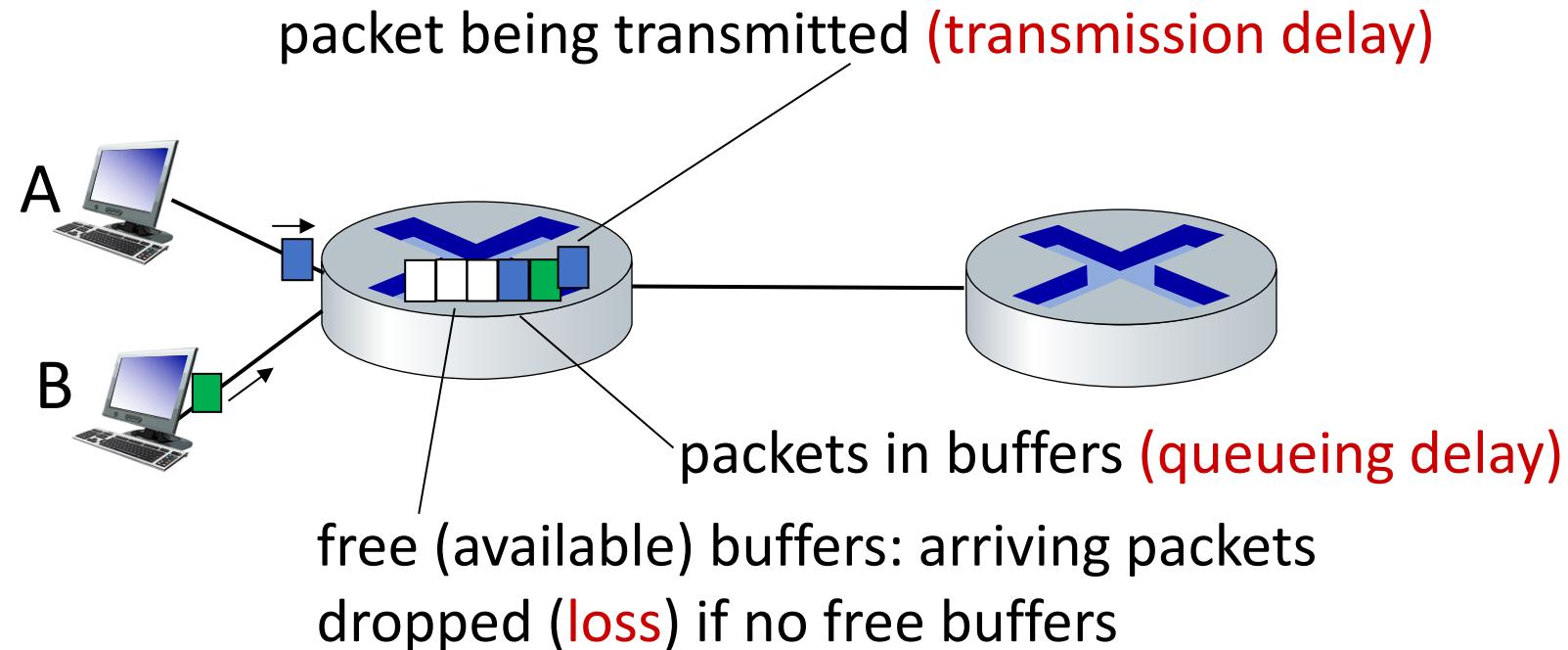


- Internet

- Congestion
 - Delay, loss, throughput

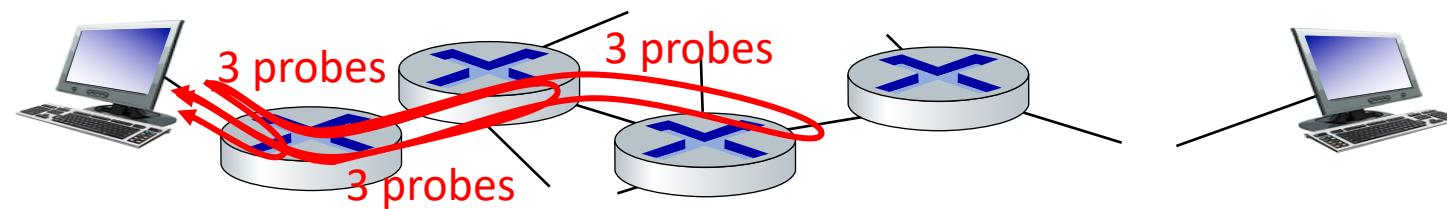
How do packet delay and loss occur?

- 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



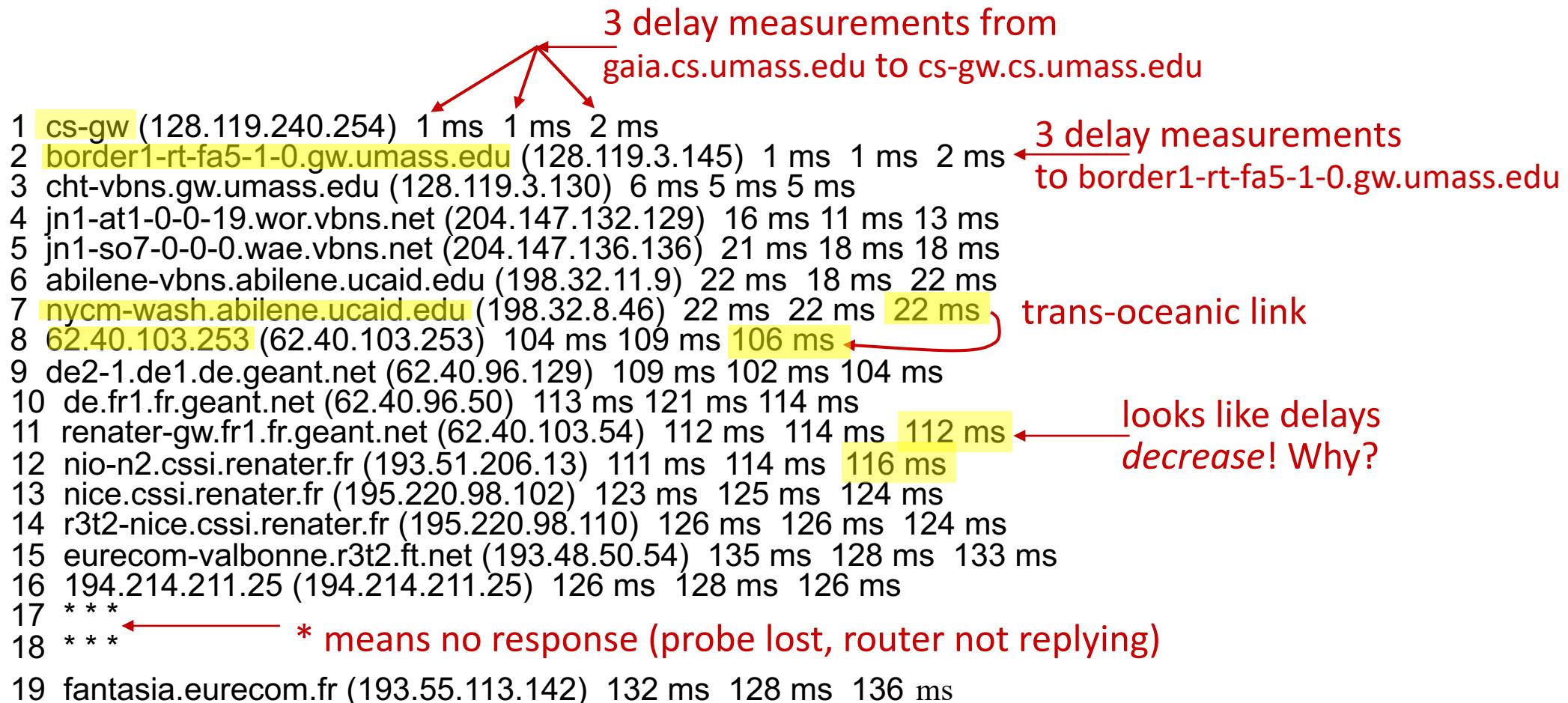
“Real” Internet delays and routes

- 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

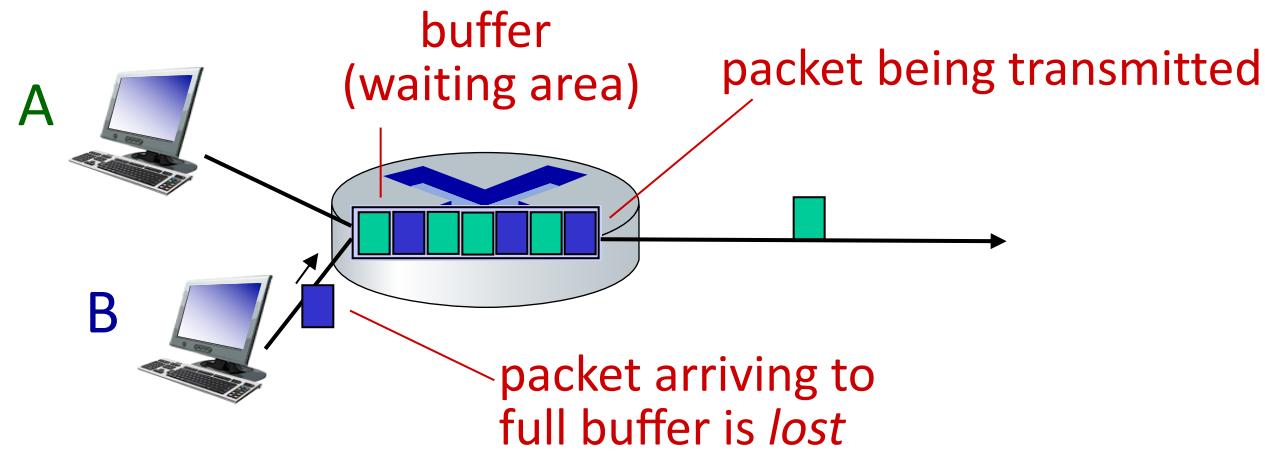
traceroute: gaia.cs.umass.edu to www.eurecom.fr



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

Packet loss

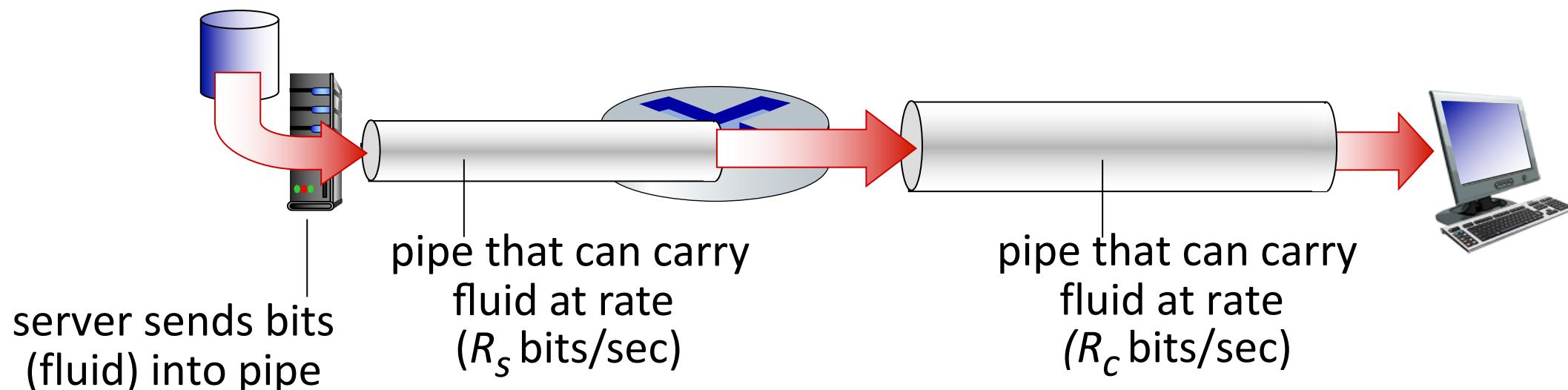
- queue (aka buffer) preceding link in buffer has finite capacity
- packet arriving to full queue dropped (aka lost)
- lost packet may be retransmitted by previous node, by source end system, or not at all



* Check out the Java applet for an interactive animation (on publisher's website) of queuing and loss

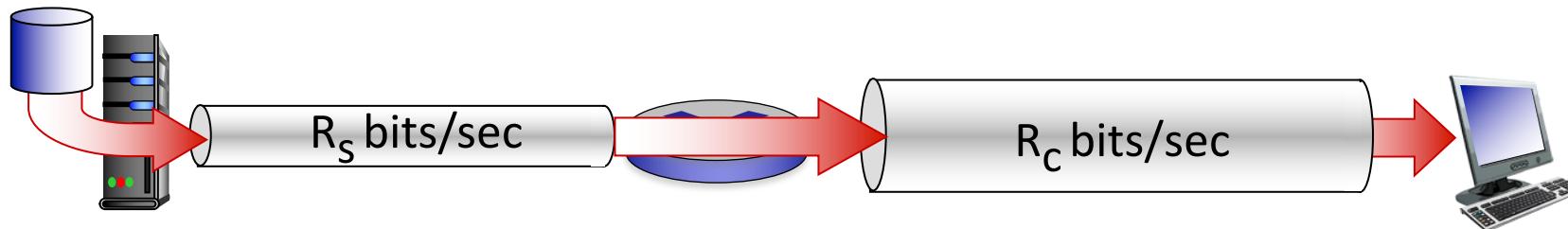
Throughput

- **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

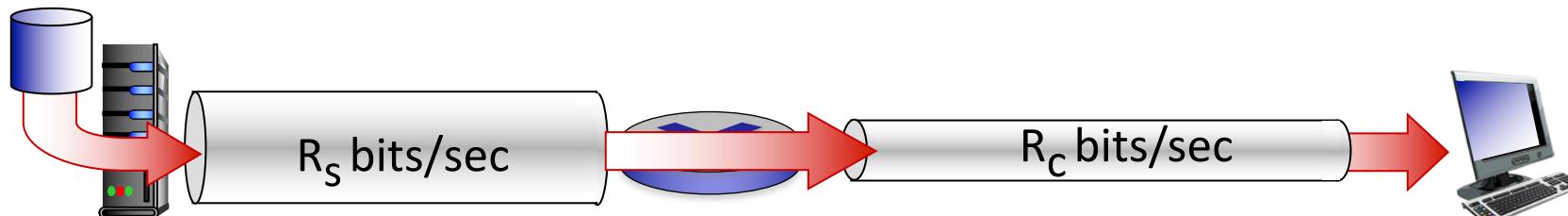


Throughput

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



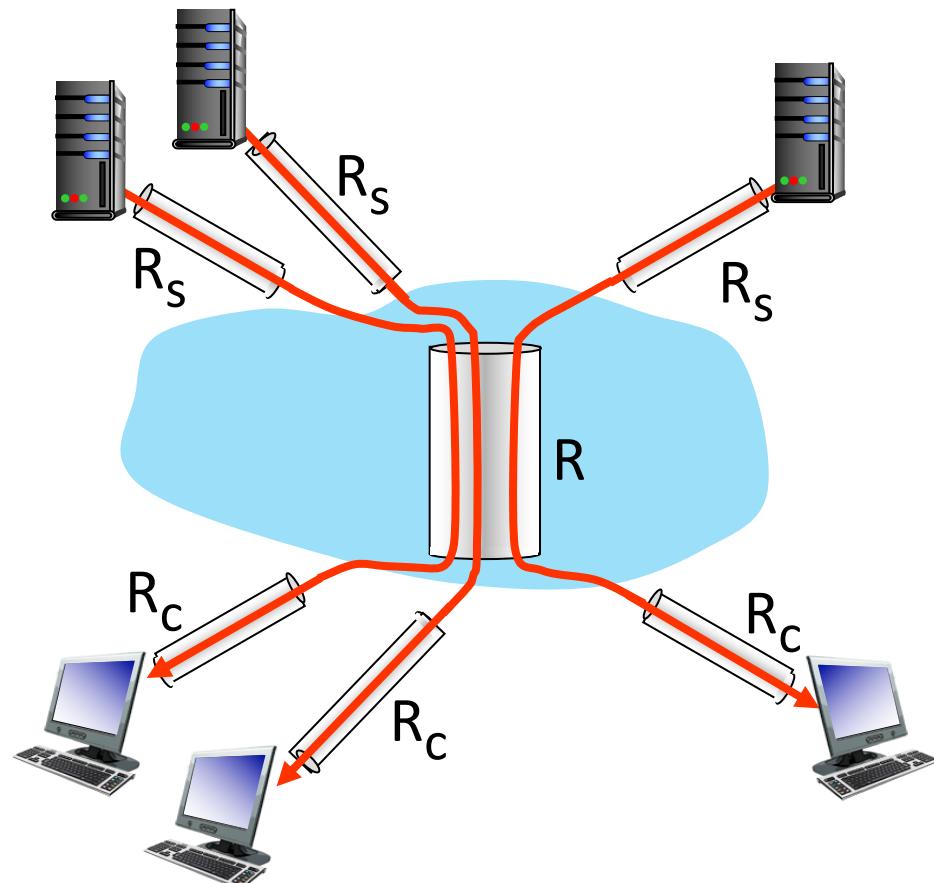
$R_s > R_c$ What is average end-end throughput?



bottleneck link

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

Throughput: network scenario



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

- per-connection end-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/

Additional Slides

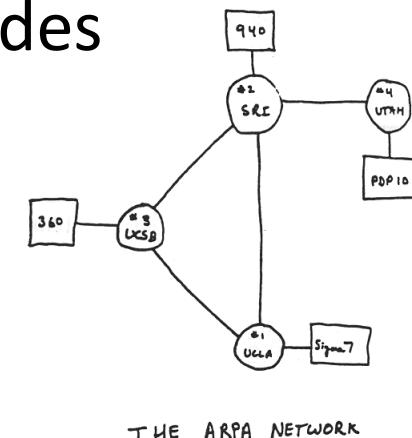
- Network core: packet /circuit switching, internet structure
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- Internet history



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



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

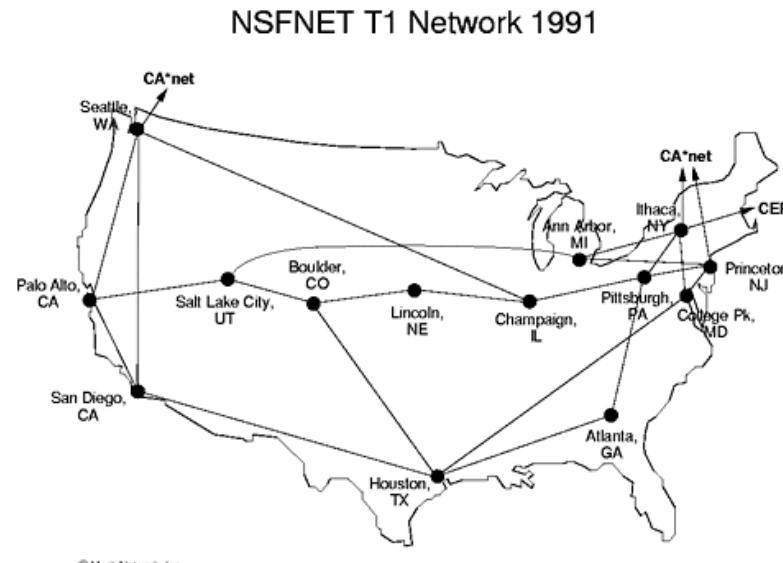
Cerf and Kahn's internetworking principles:

- 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



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)