

Computer Networks

Chapter 1 Introduction

Adapted from Book Slides: “Computer Networking: A Top-Down Approach”

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Chapter 1: introduction

Chapter goal:

- Get “feel,” “big picture,” introduction to terminology
 - more depth, detail *later* in course
- Approach:
 - Use Internet as example

Overview/roadmap:

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

Chapter 1: roadmap

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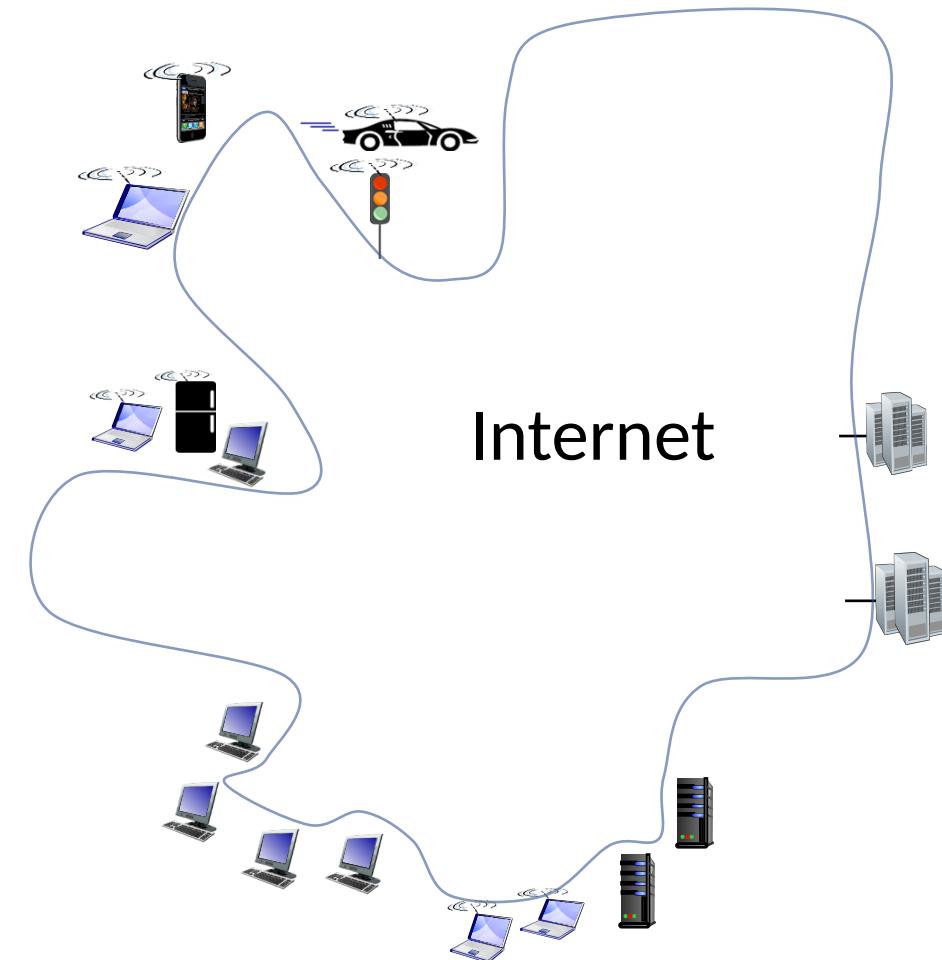
The Internet: a “nuts and bolts” view

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Billions of connected computing *devices*:

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



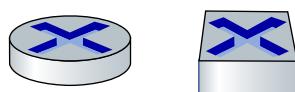
Internet

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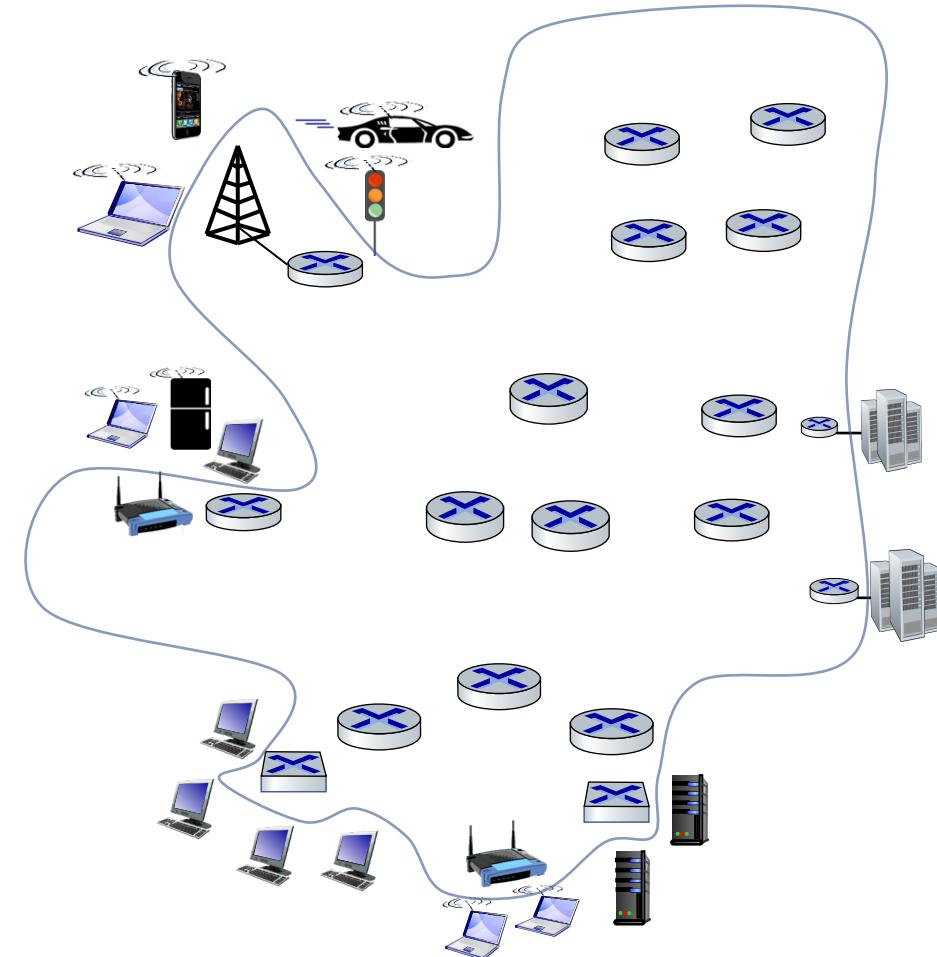
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Packet switches: forward packets (chunks of data)

- routers, switches

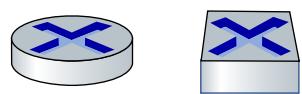


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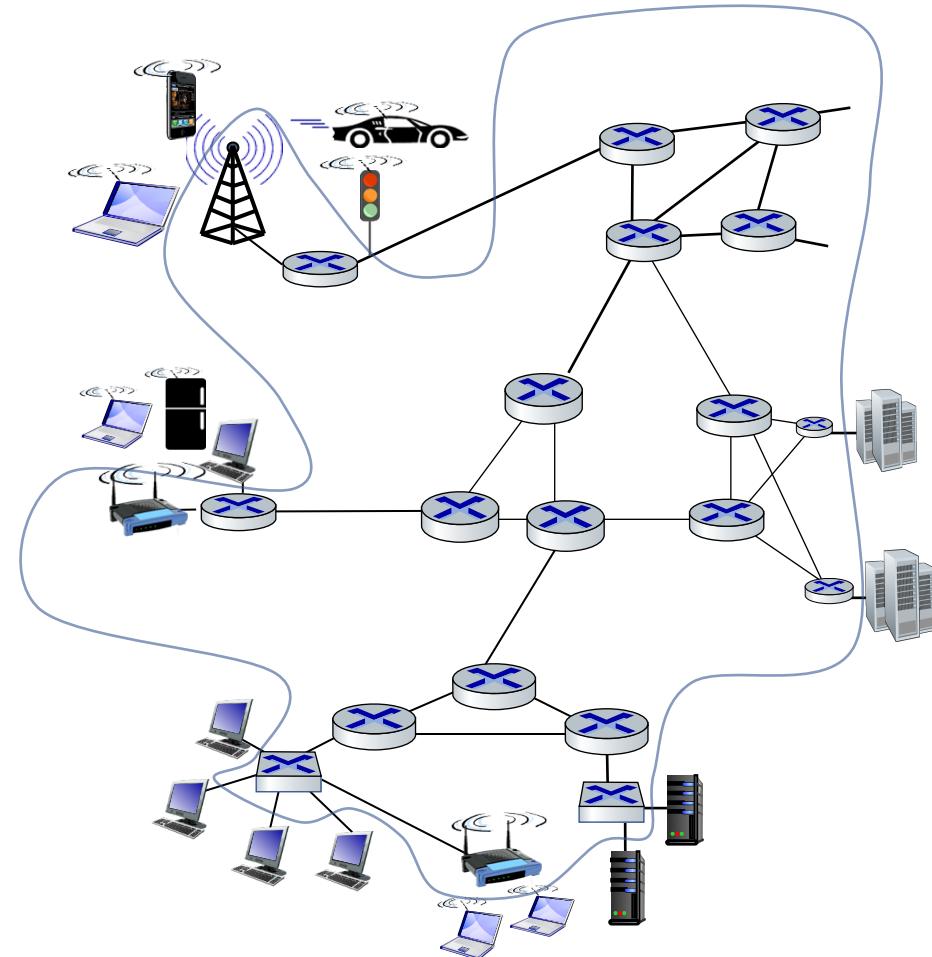
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Communication links

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



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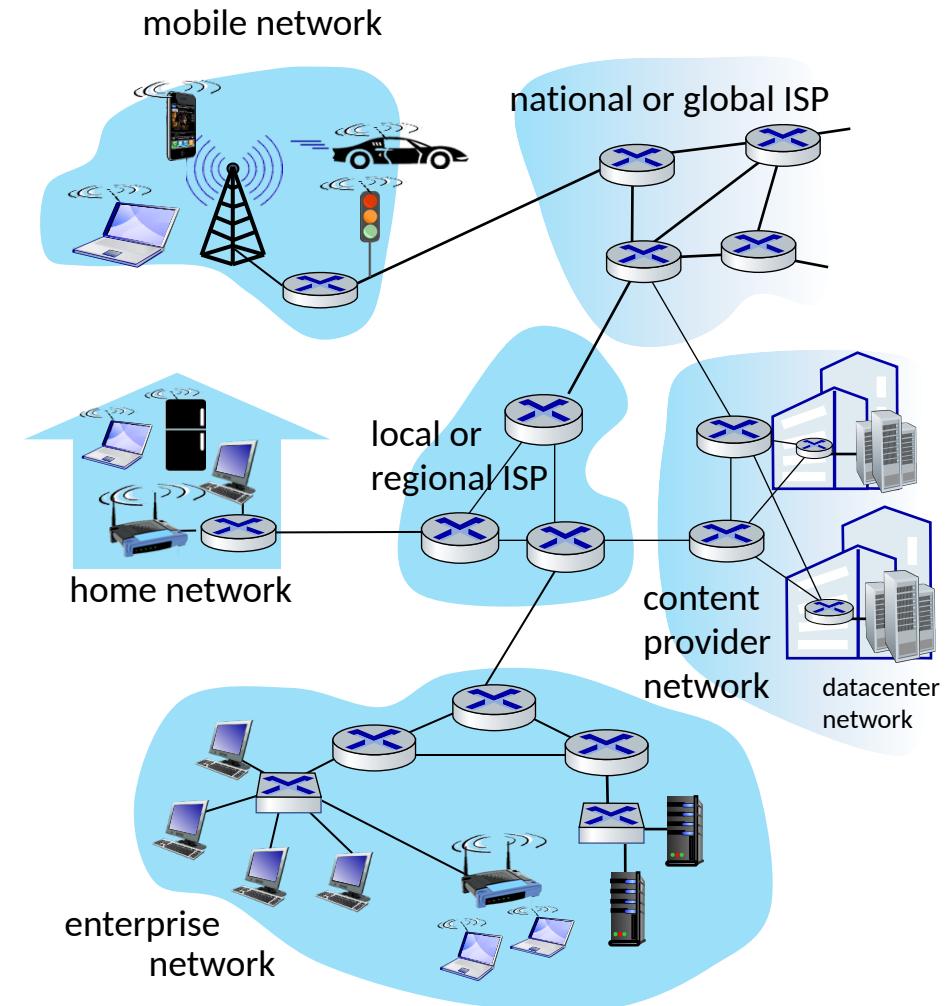
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Networks

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



“Fun” Internet-connected devices

“Fun” Internet-connected devices



Internet phones



Gaming devices



Slingbox: remote
control cable TV

“Fun” Internet-connected devices



Amazon Echo



IP picture frame



Internet
refrigerator

Security Camera



Internet phones



Slingbox: remote
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Gaming devices



sensorized,
bed
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Tweet-a-watt:
monitor energy use

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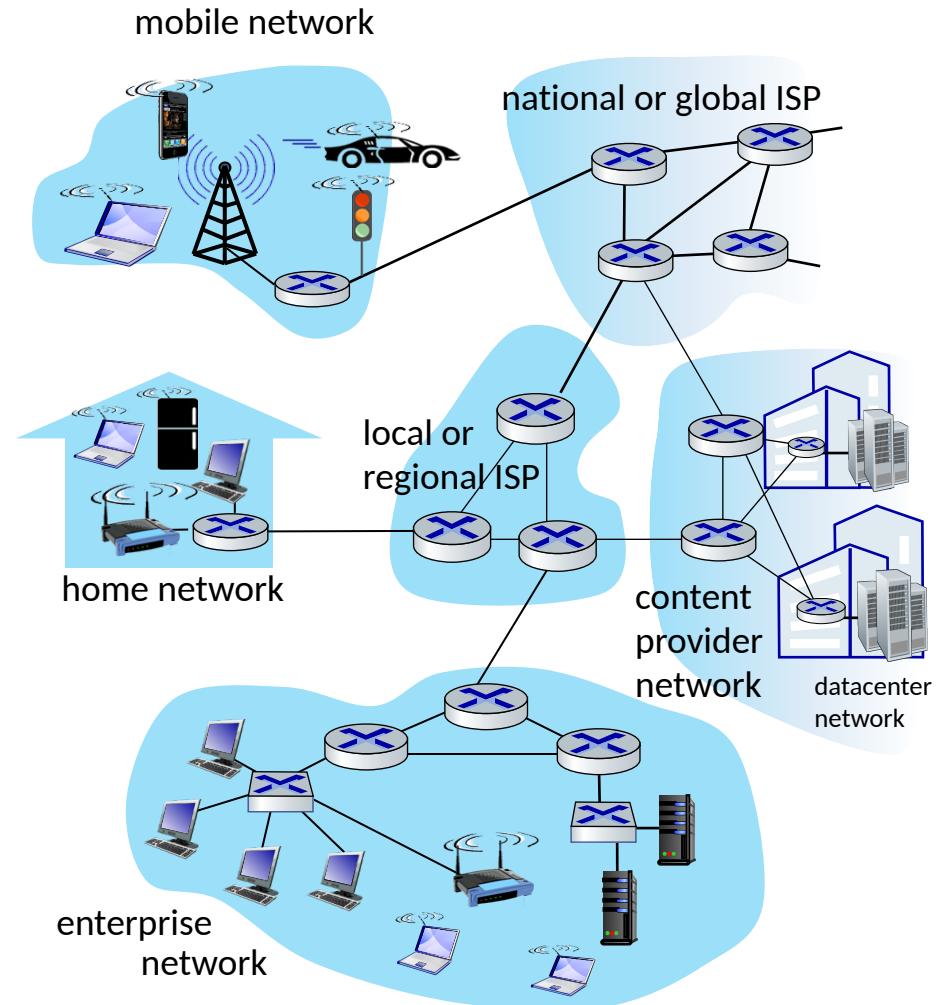


scooters

Others?

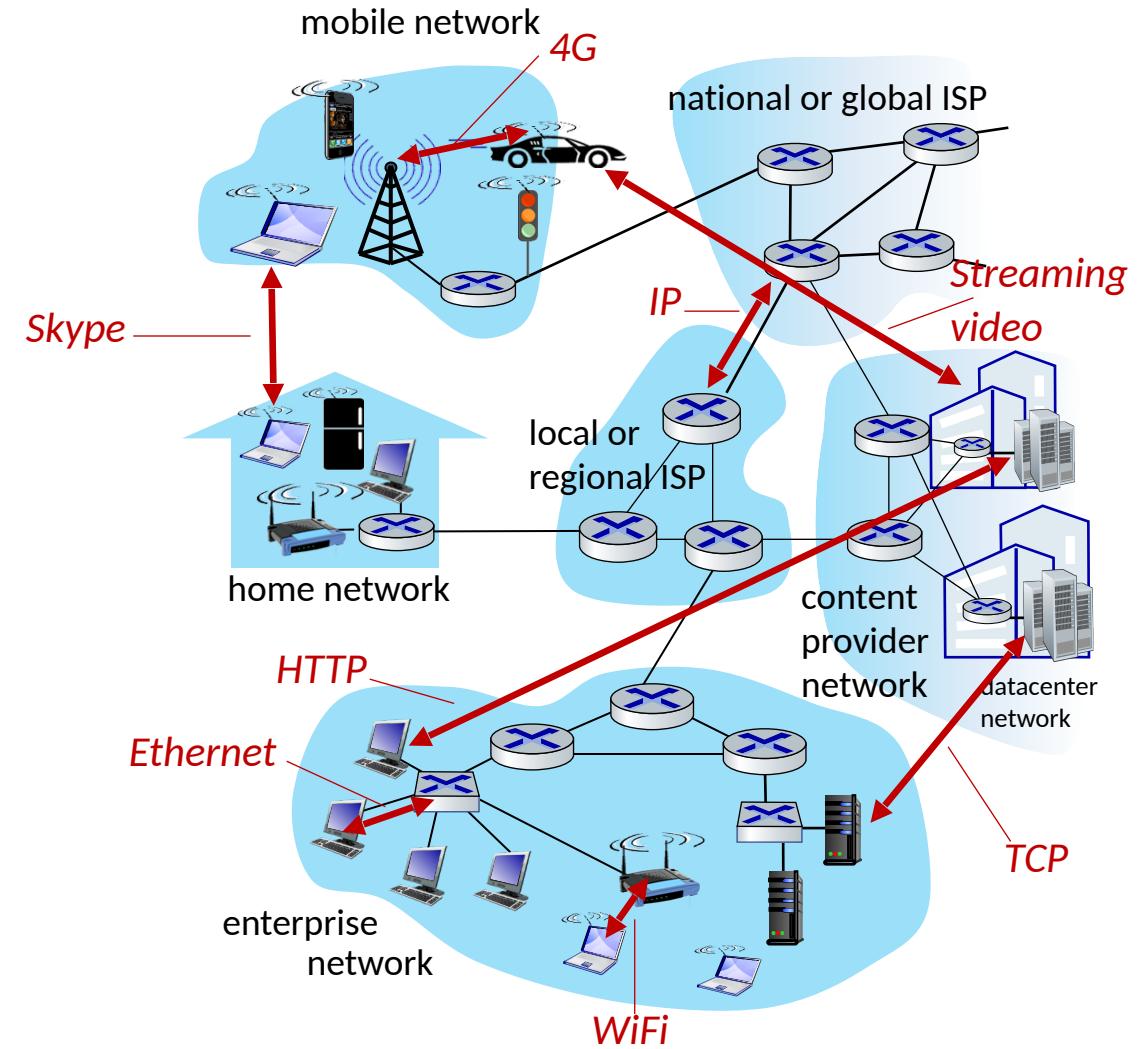
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- *Internet: “network of networks”*
 - Interconnected ISPs



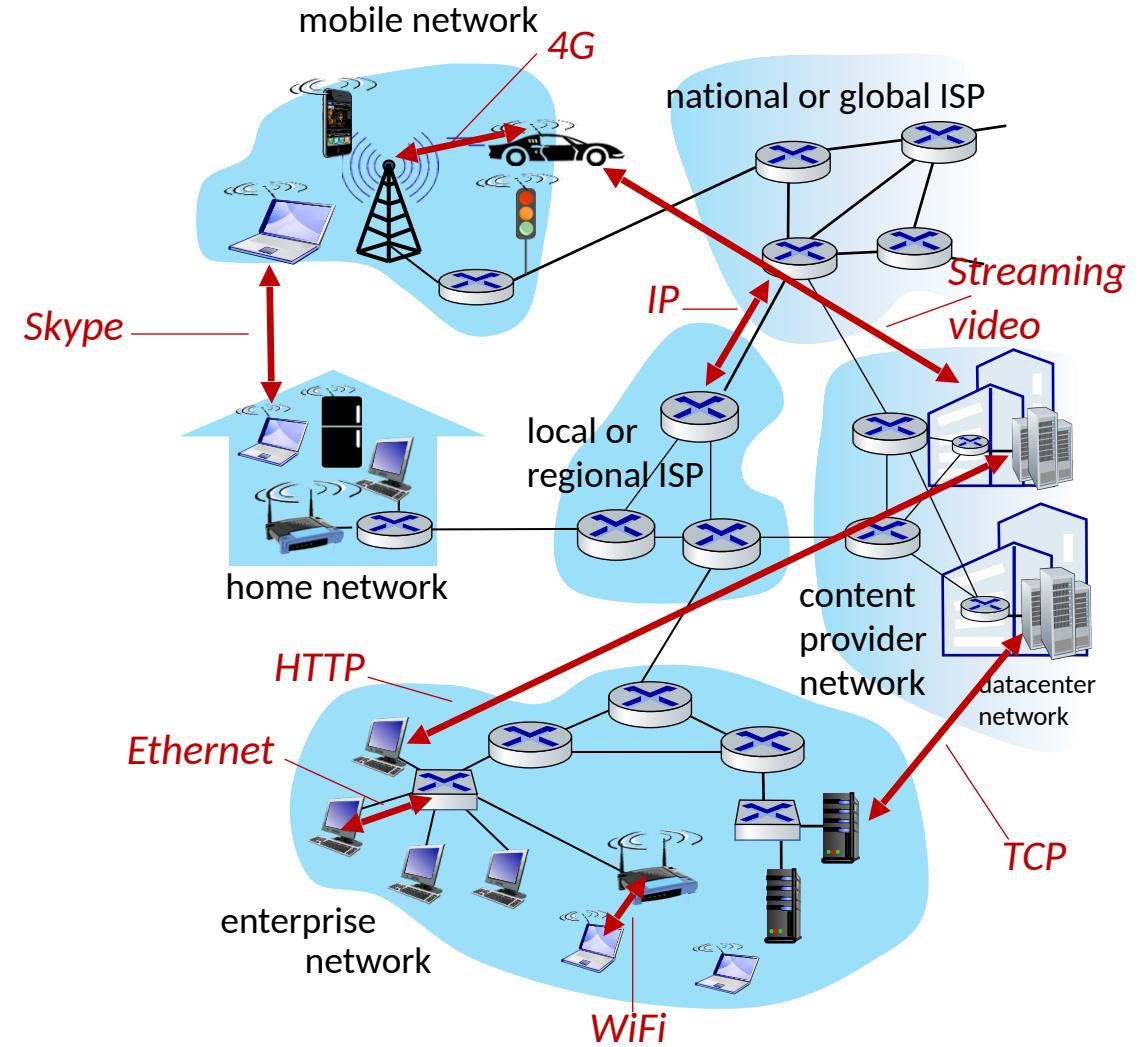
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- *Internet: “network of networks”*
 - Interconnected ISPs
- *protocols are everywhere*
 - control sending, receiving of messages
 - e.g., HTTP (Web), streaming video, Skype, TCP, IP, WiFi, 4G, Ethernet



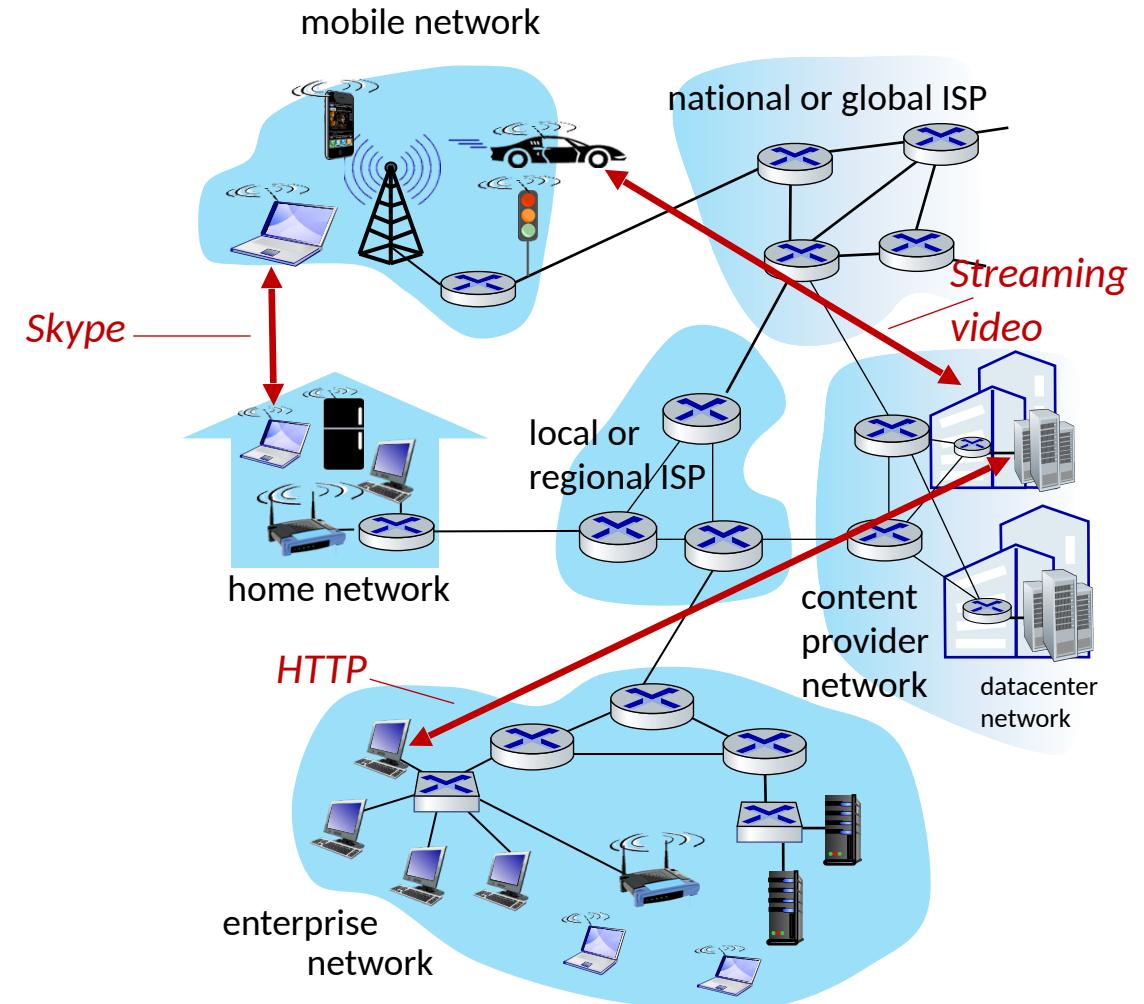
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- *Internet standards*
 - RFC: Request for Comments
 - IETF: Internet Engineering Task Force



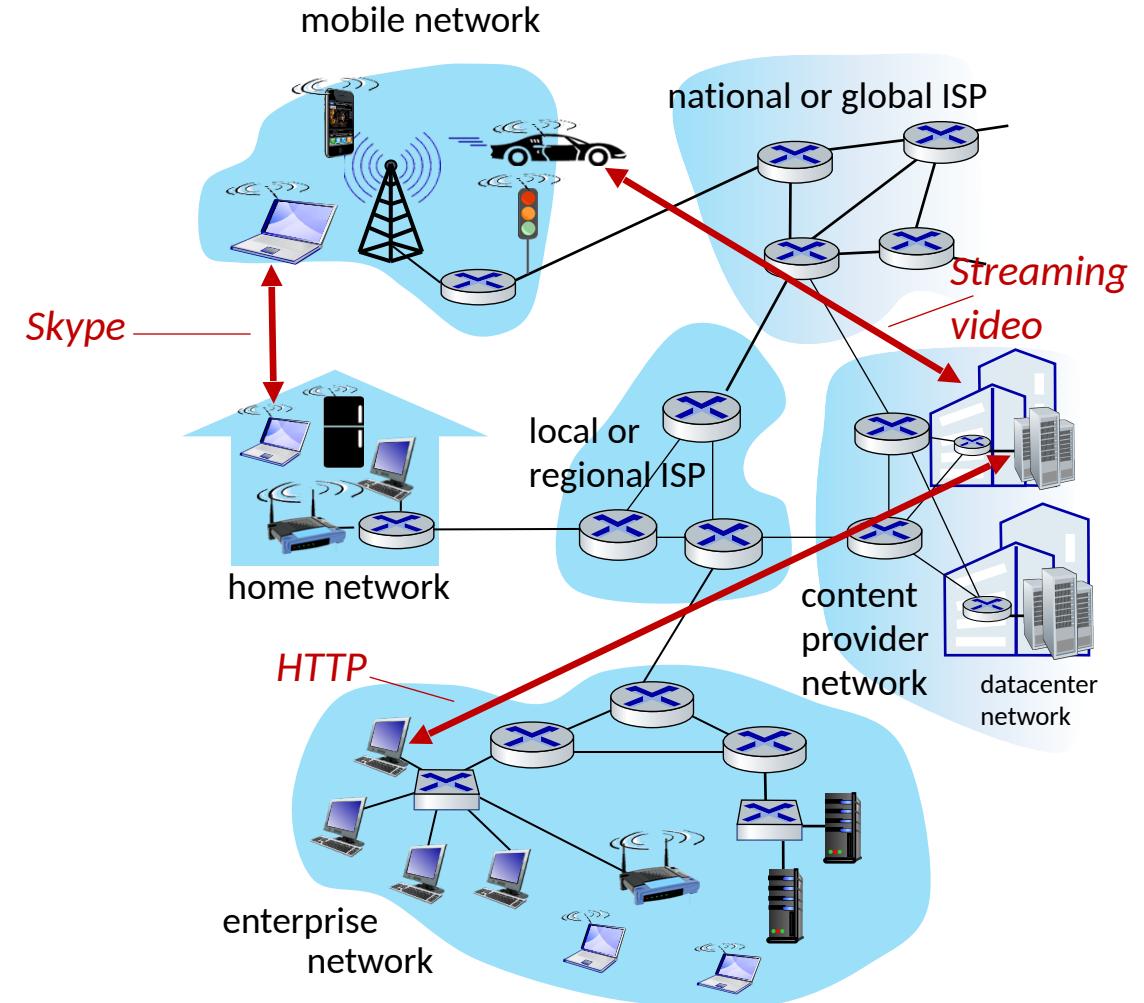
The Internet: a “services” view

- *Infrastructure* that provides services to applications:
 - Web, streaming video, multimedia teleconferencing, email, games, e-commerce, social media, interconnected appliances, ...



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- *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



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Human protocols:

- “what’s the time?”
- “I have a question”
- introductions

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Network protocols:

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

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

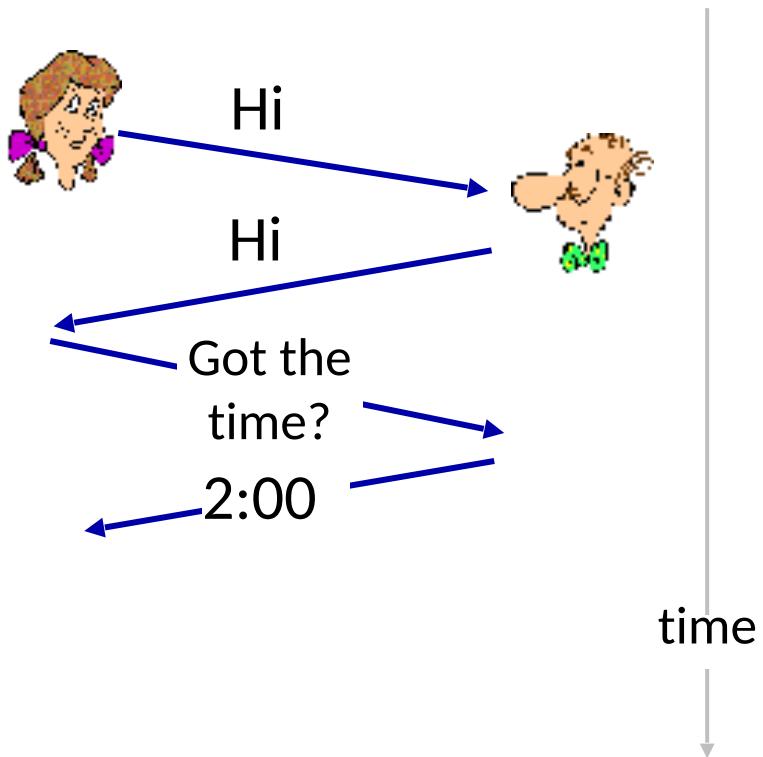
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A human protocol and a computer network protocol:



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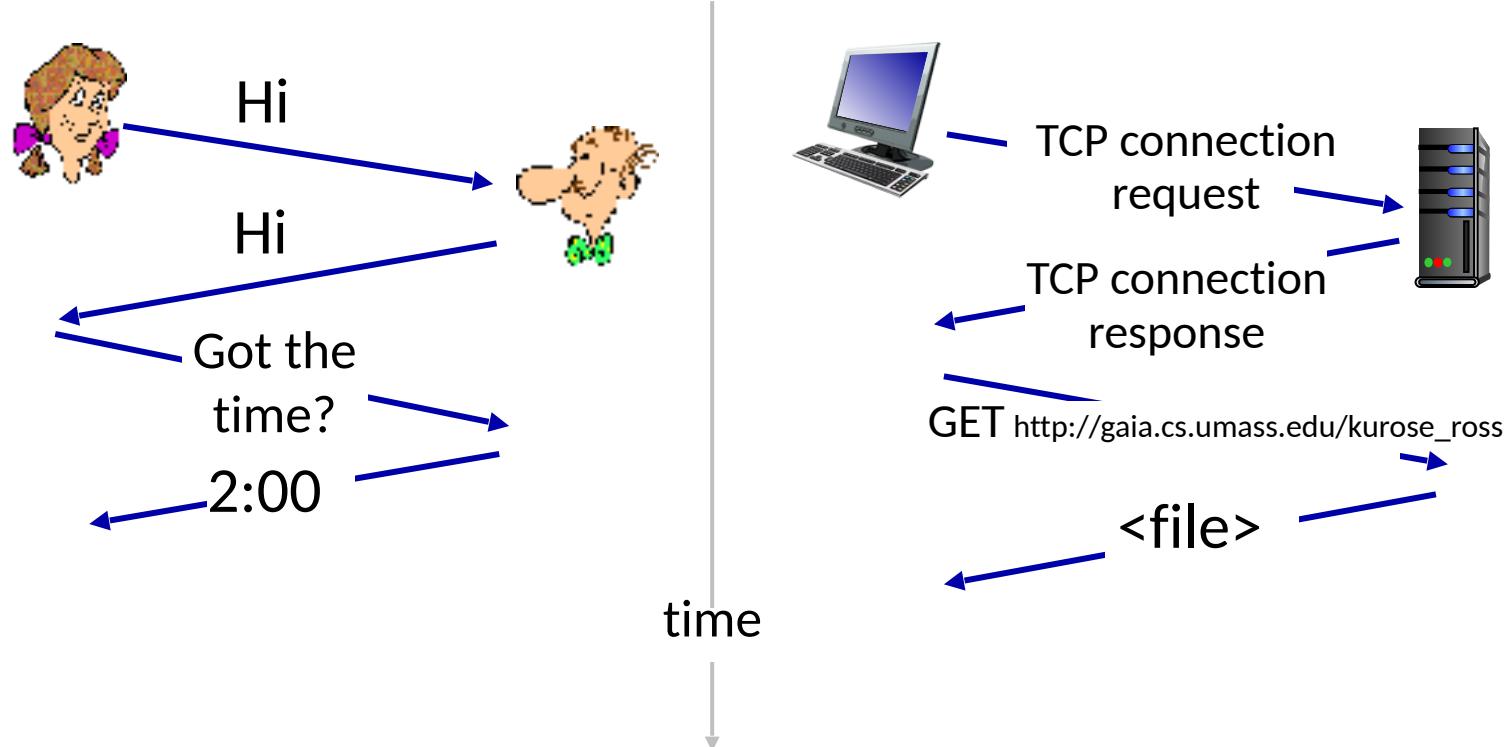
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Q: other human protocols?

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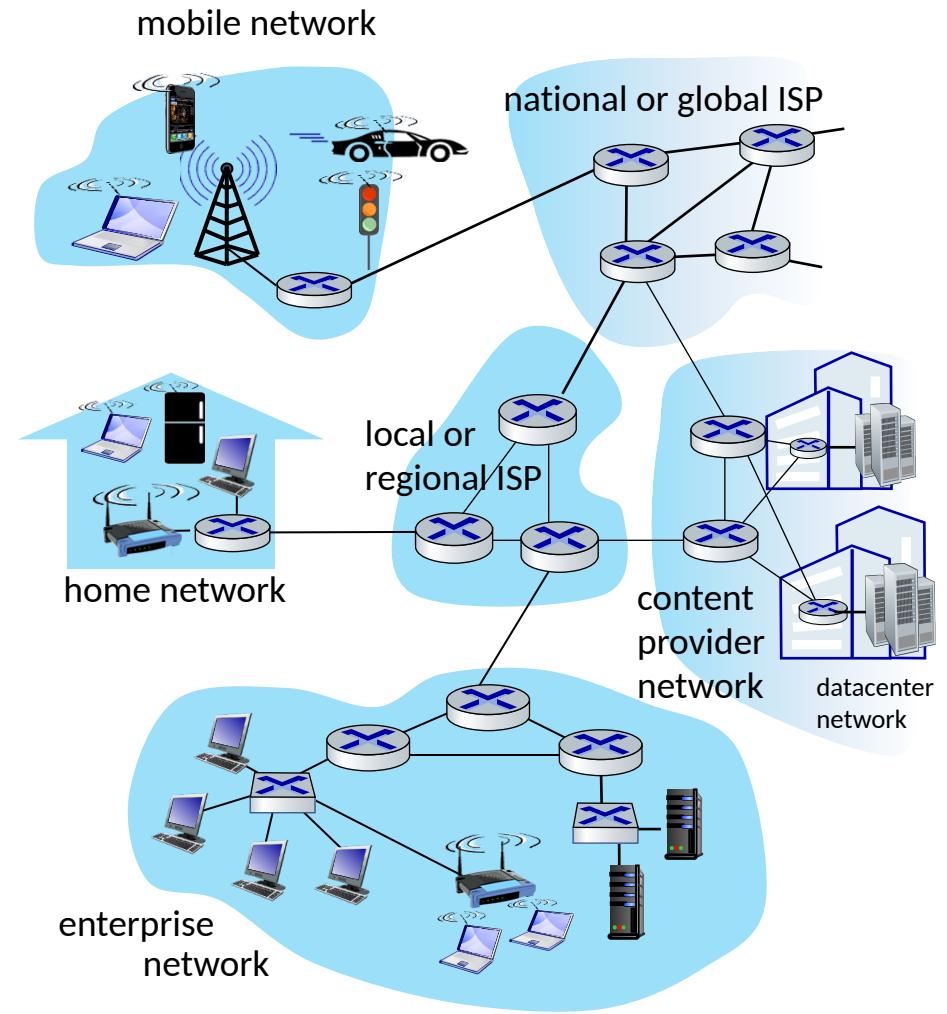


Q: other human protocols?

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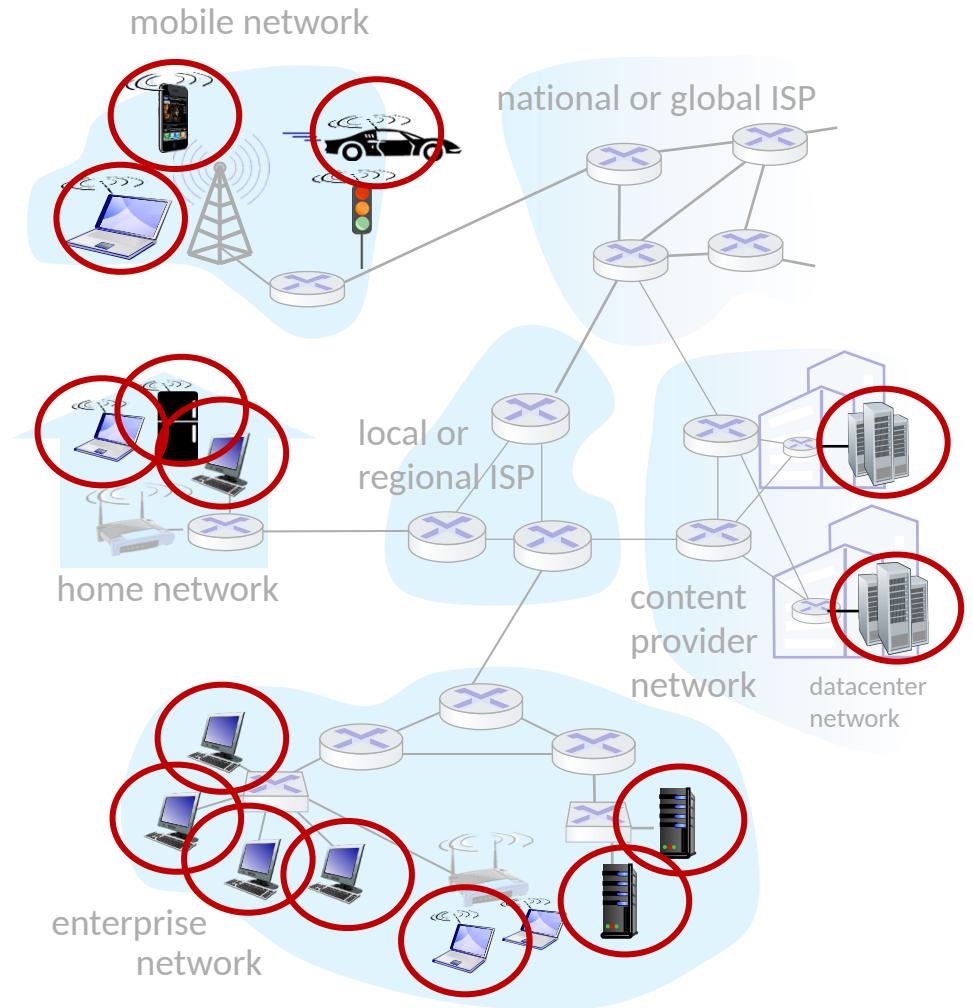
A closer look at Internet structure



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Network edge:

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



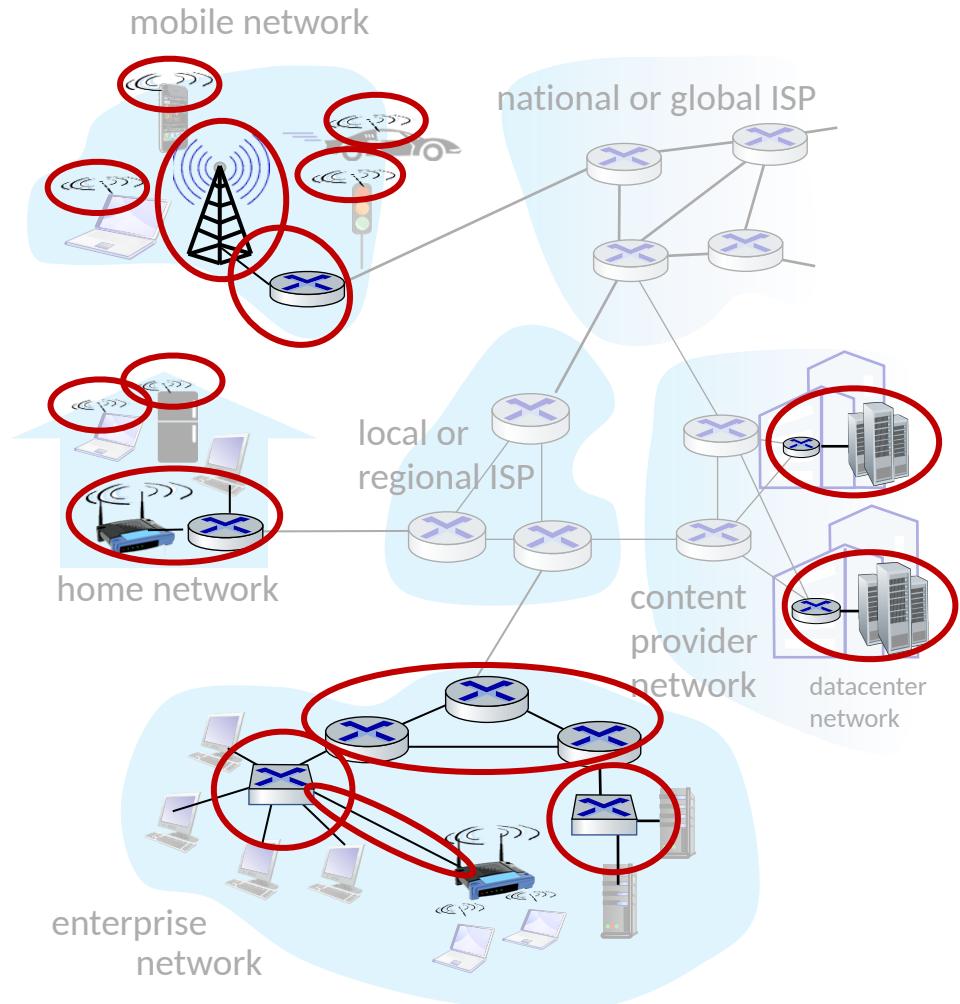
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Access networks, physical media:

- wired, wireless communication links



A closer look at Internet structure

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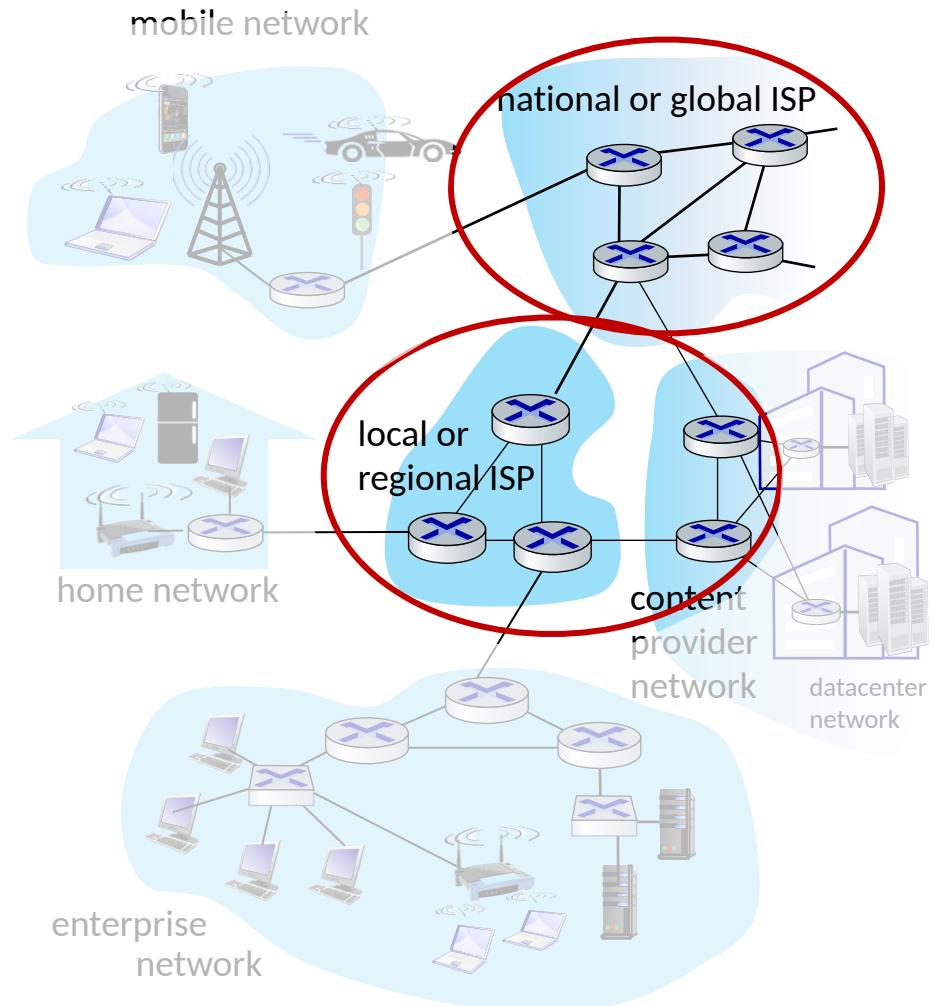
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Network core:

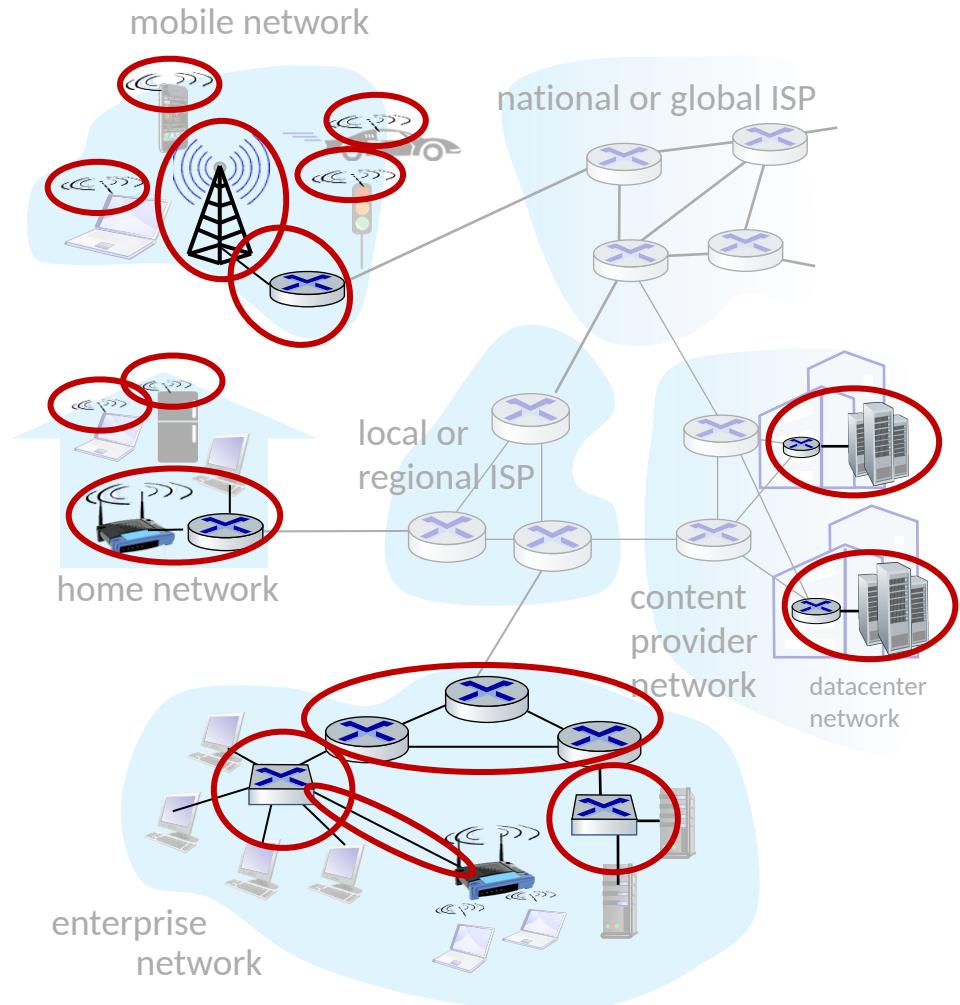
- interconnected routers
- network of networks



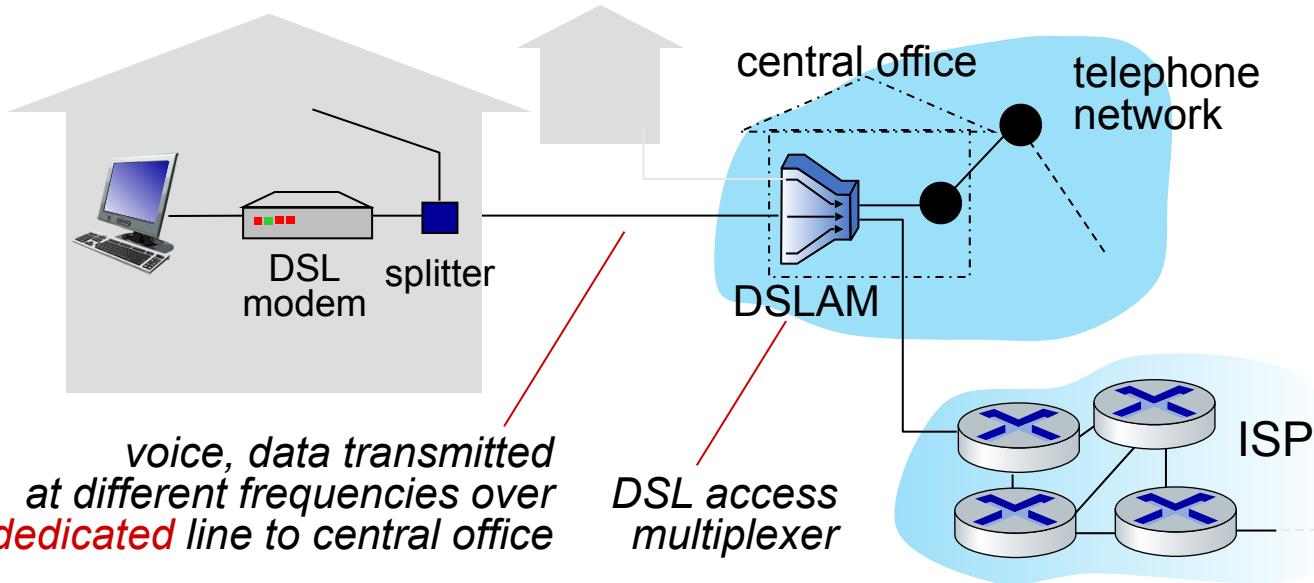
Access networks and physical media

Q: How to connect end systems to edge router?

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

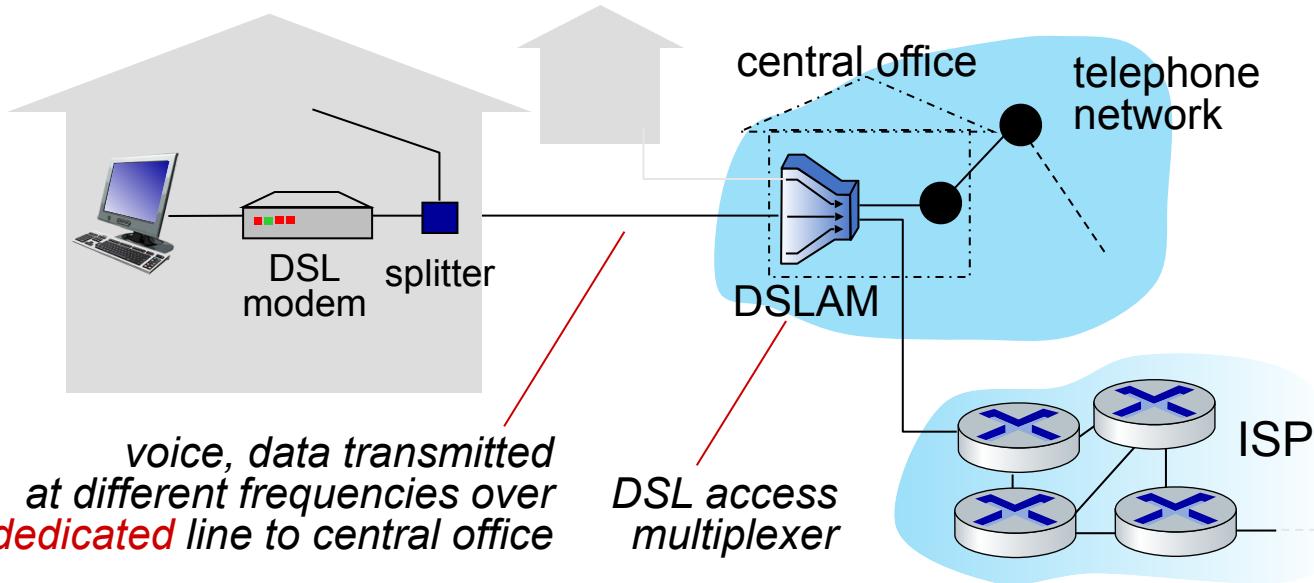


Access networks: digital subscriber line (DSL)



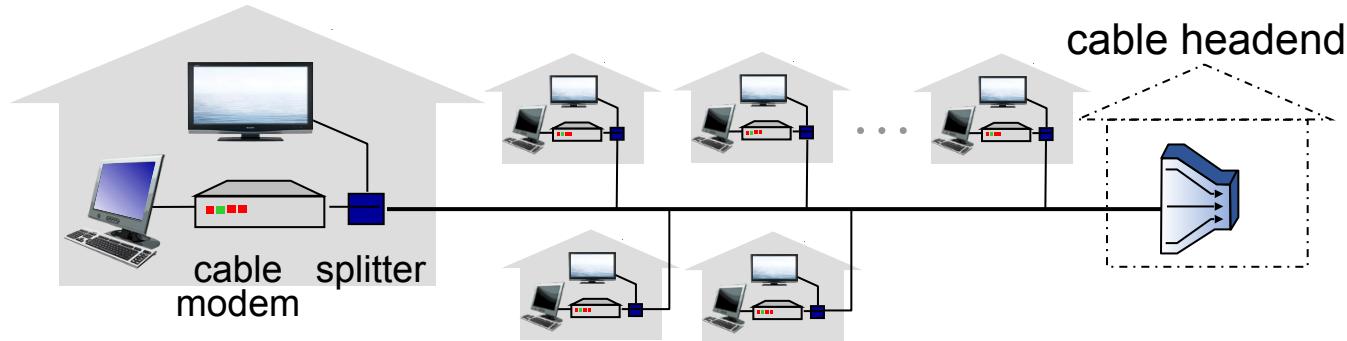
- use *existing* telephone line to central office DSLAM
 - data over DSL phone line goes to Internet
 - voice over DSL phone line goes to telephone net

Access networks: digital subscriber line (DSL)

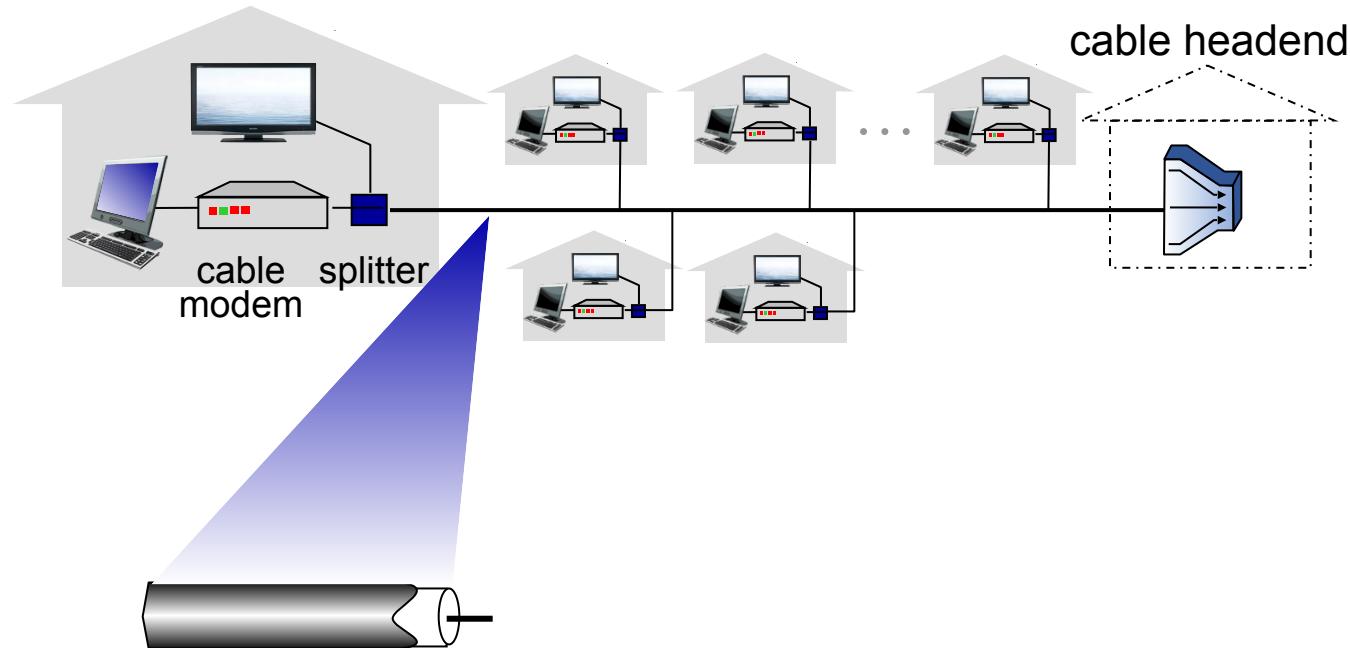


- use *existing* telephone line to central office DSLAM
 - data over DSL phone line goes to Internet
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- 24-52 Mbps dedicated downstream transmission rate
- 3.5-16 Mbps dedicated upstream transmission rate

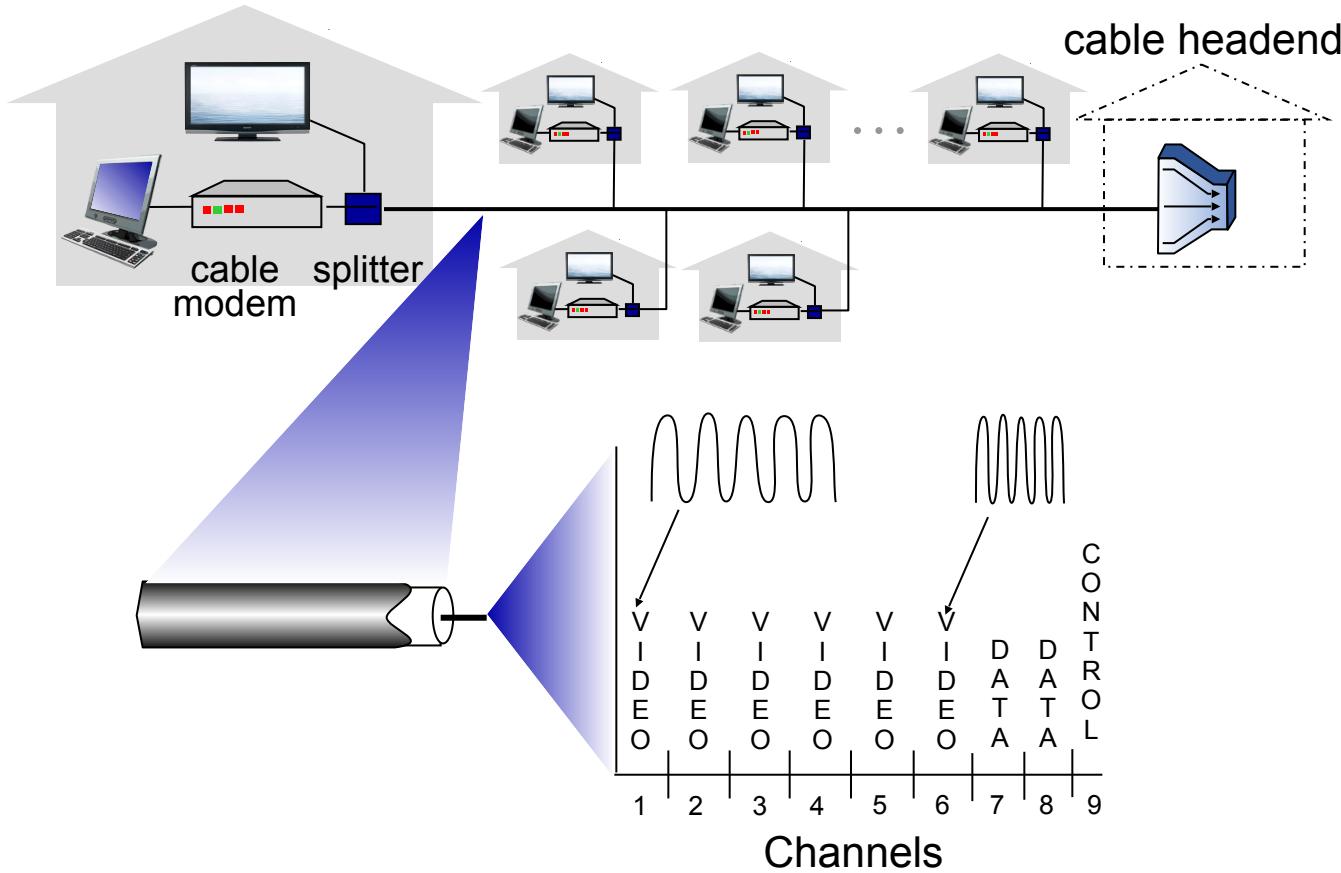
Access networks: cable-based access



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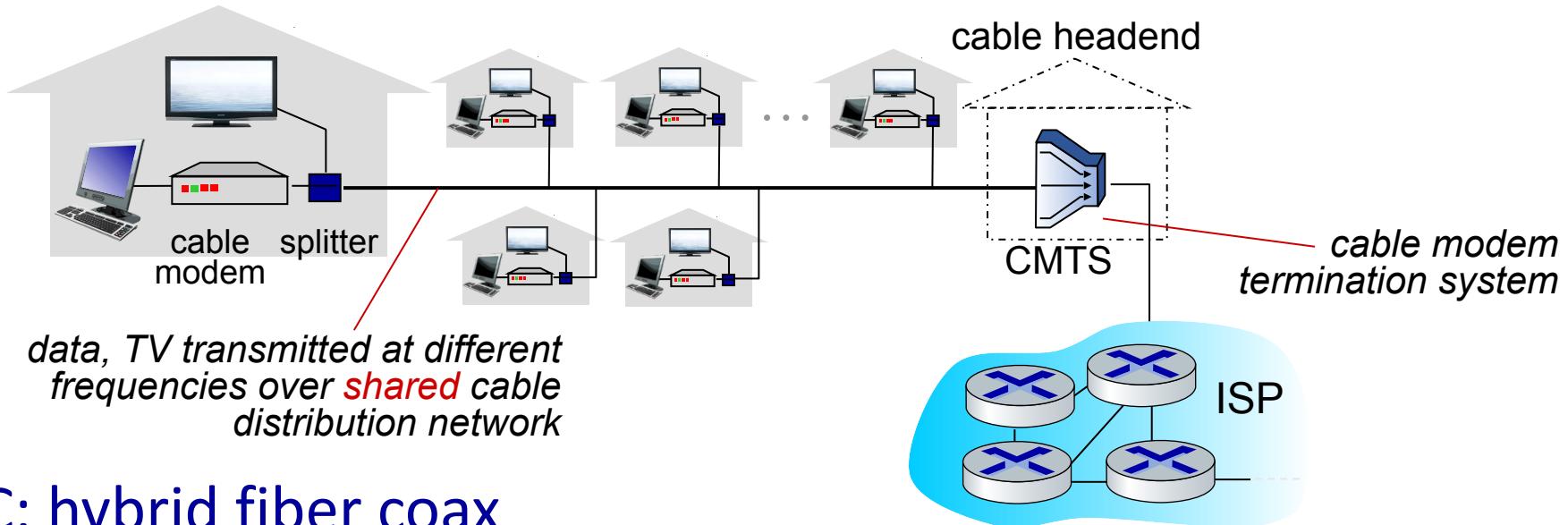


Access networks: cable-based access



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

Access networks: cable-based access



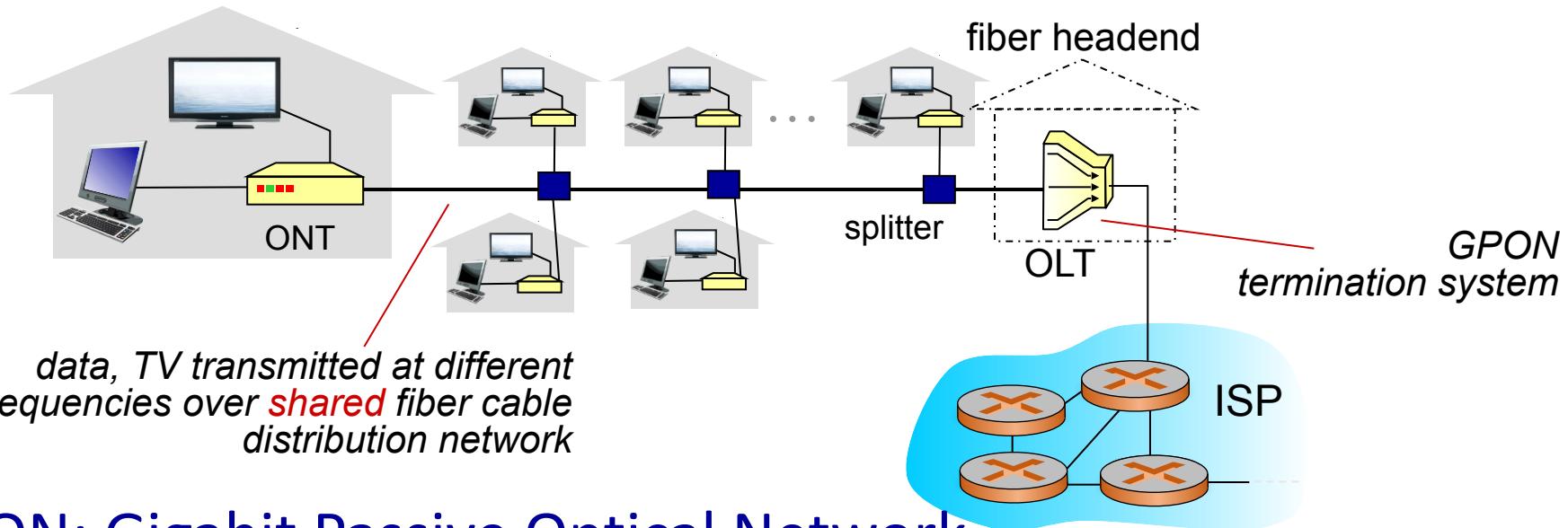
- HFC: hybrid fiber coax

- Asymmetric
- EuroDOCSIS 3.0: 50Mbps downstream/27Mbps upstream per channel
- EuroDOCSIS 3.1: >1.5Gbps downstream/>0.8Gbps upstream per channel

- network of cable, fiber attaches homes to ISP router

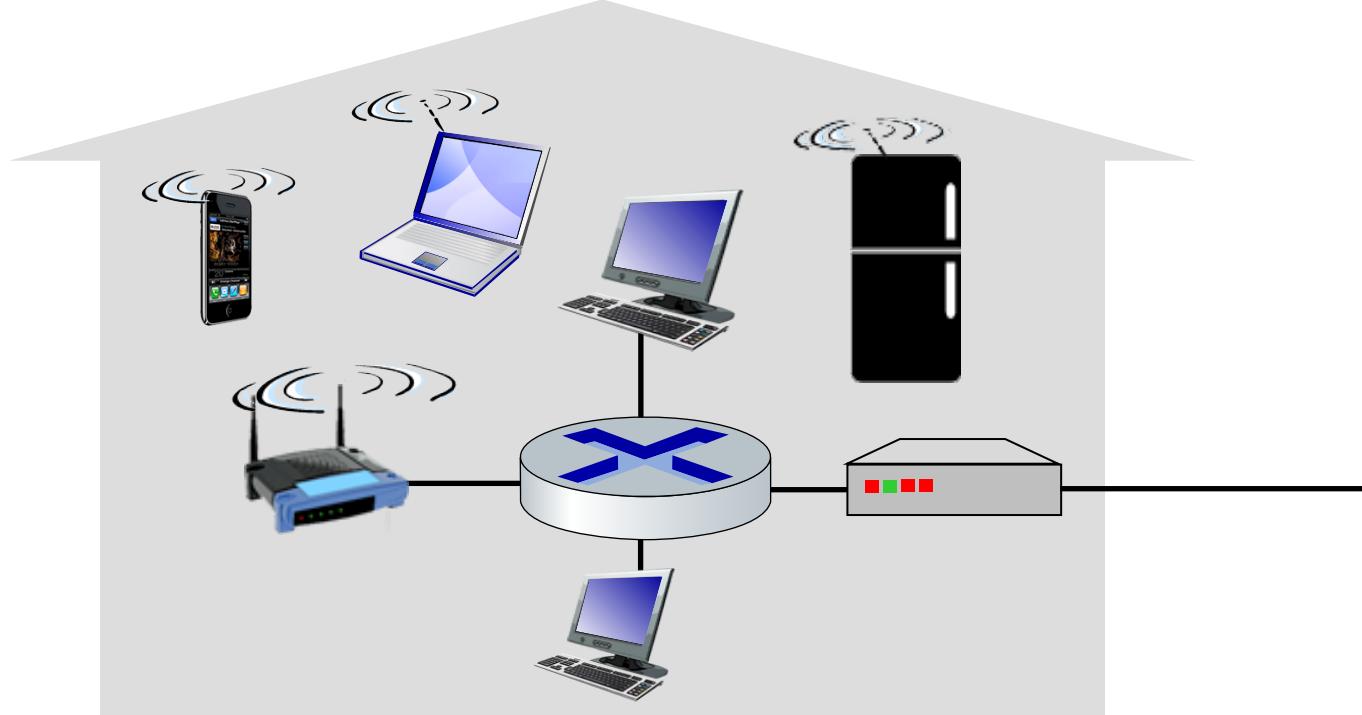
- homes **share access network** to cable headend
- unlike DSL, which has dedicated access to central office

Access networks: fiber (PON)

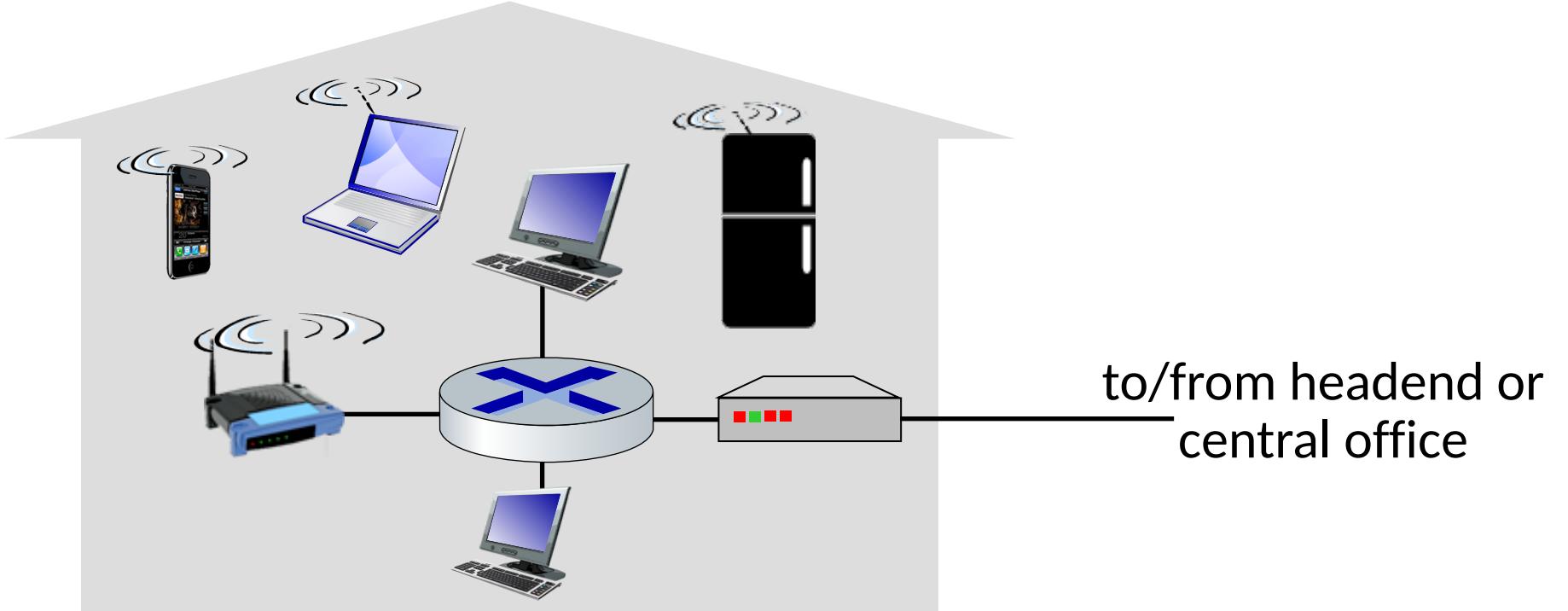


- **GPON: Gigabit Passive Optical Network**
 - Asymmetric: up to 2.488 Gbps downstream transmission rate, 1.244 Gbps upstream transmission rate
- **network of fiber attaches homes to ISP router**
 - homes **share access network** to fiber headend (most common)
 - Each ONT (Optical Network Terminal) gets its timeslot in order to send data upstream to Optical Line Termination)

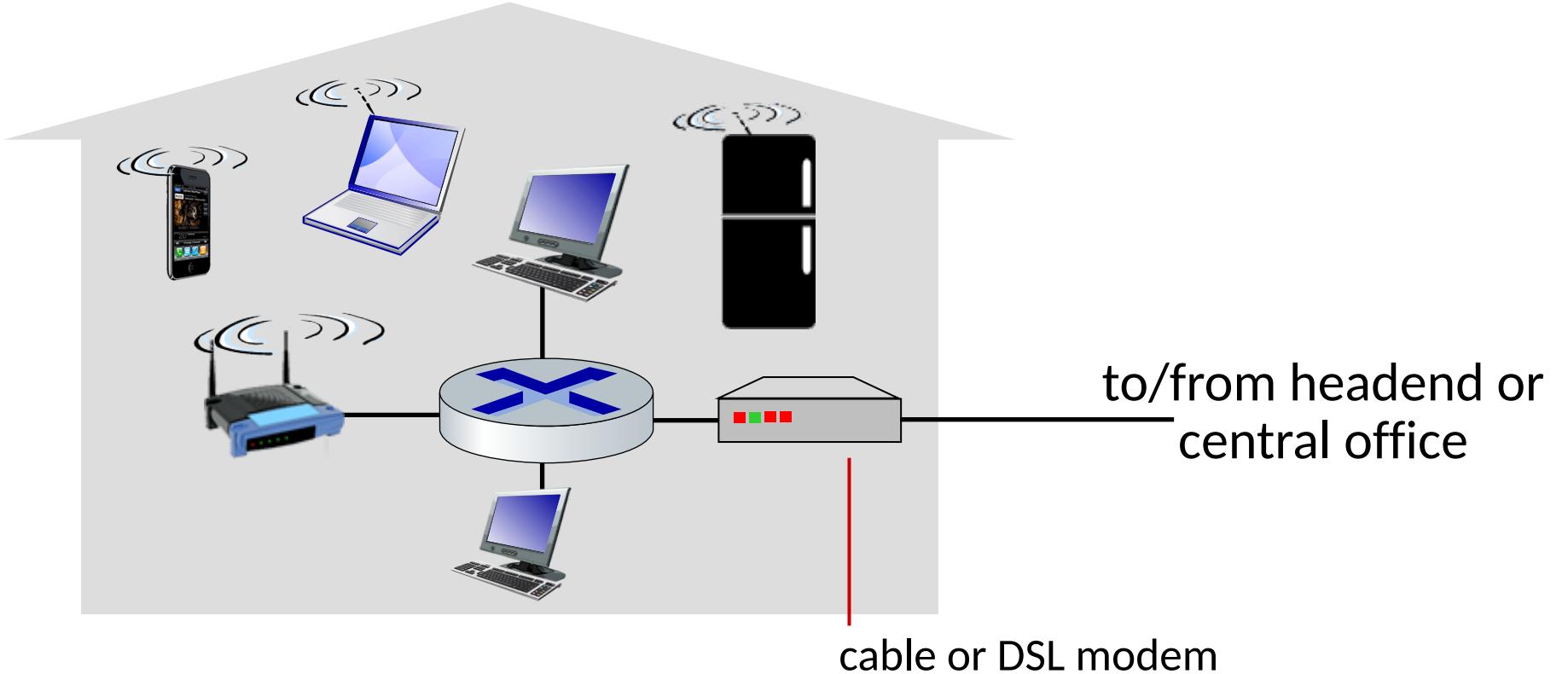
Access networks: home networks



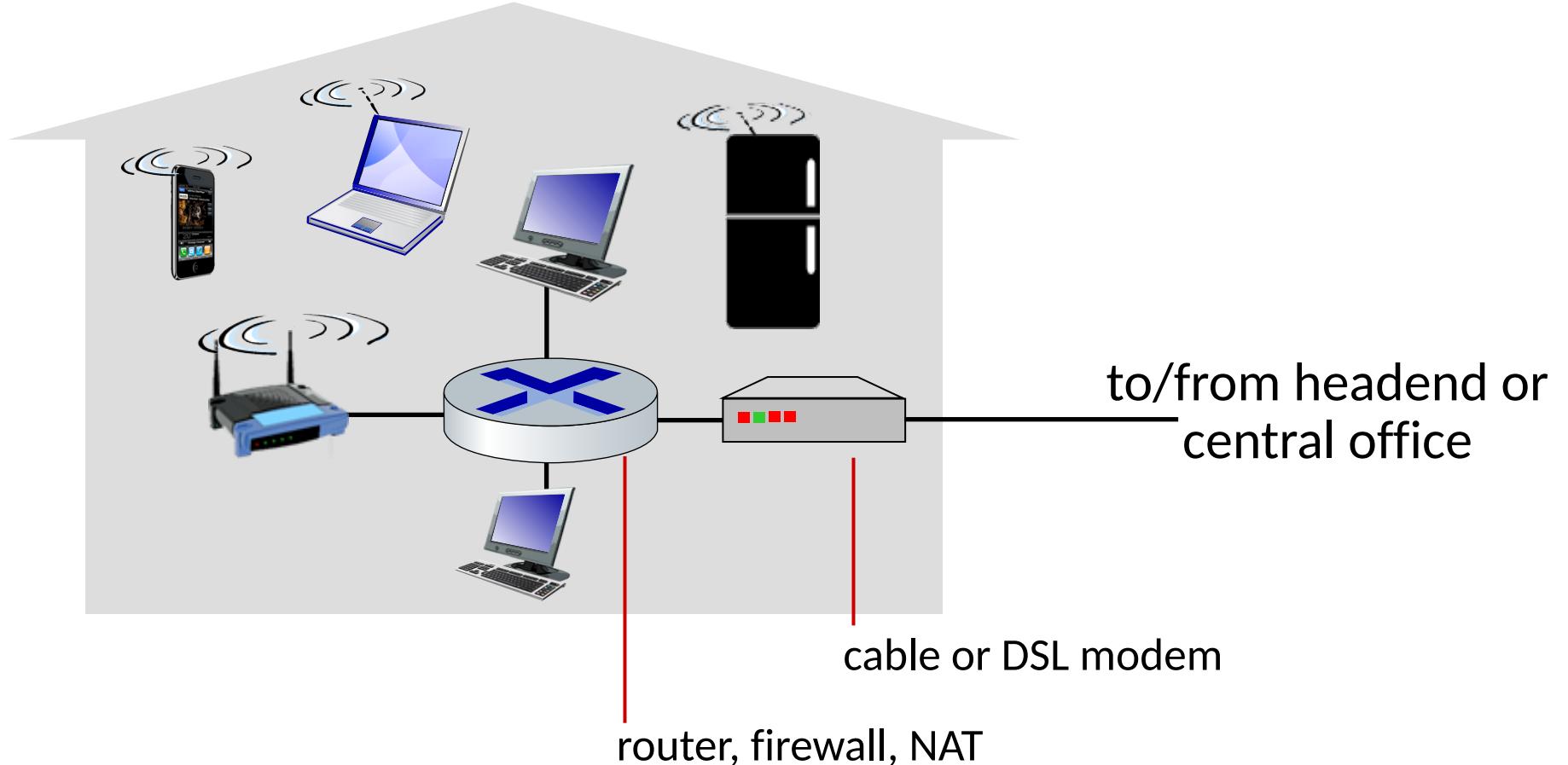
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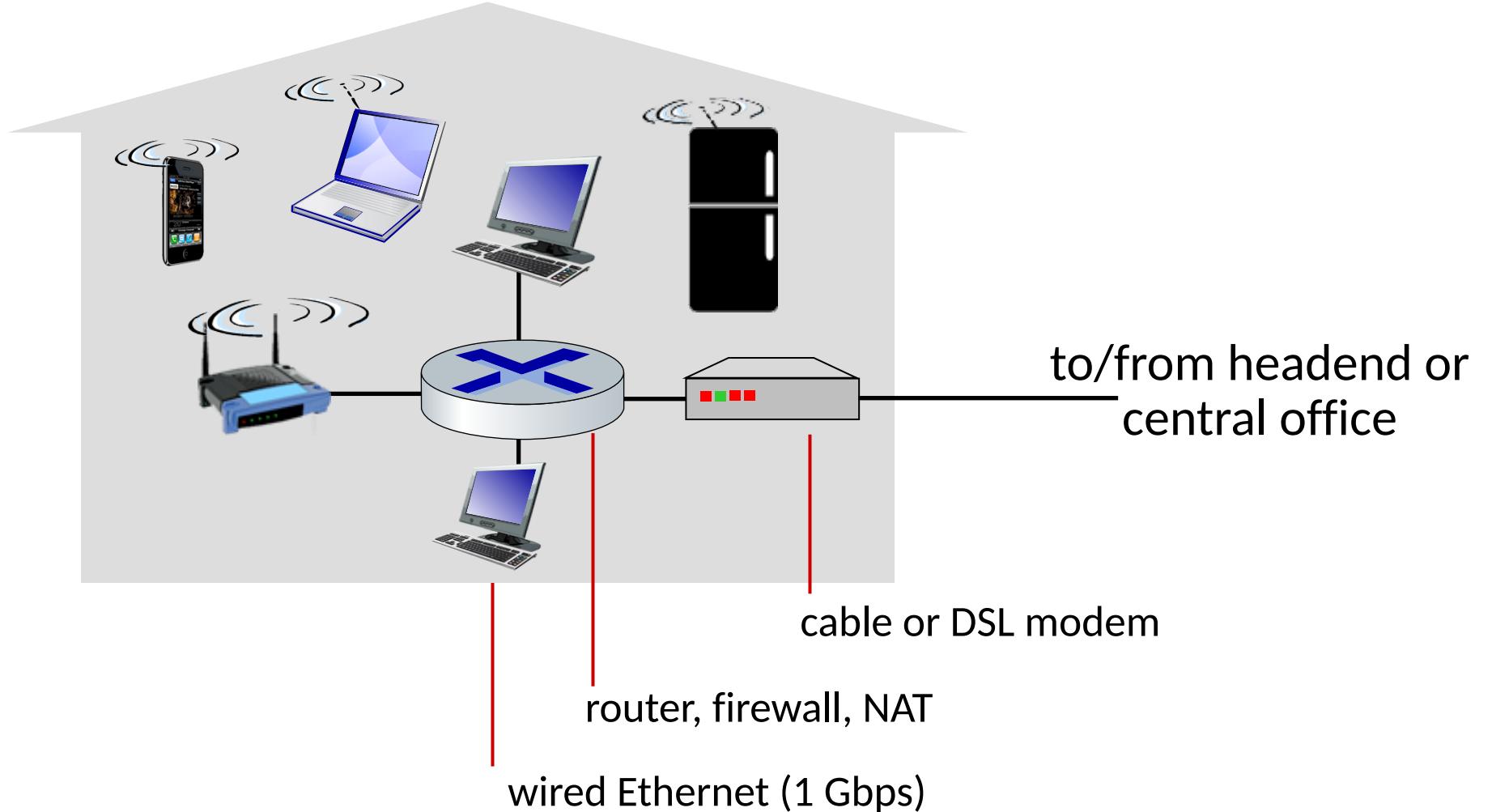
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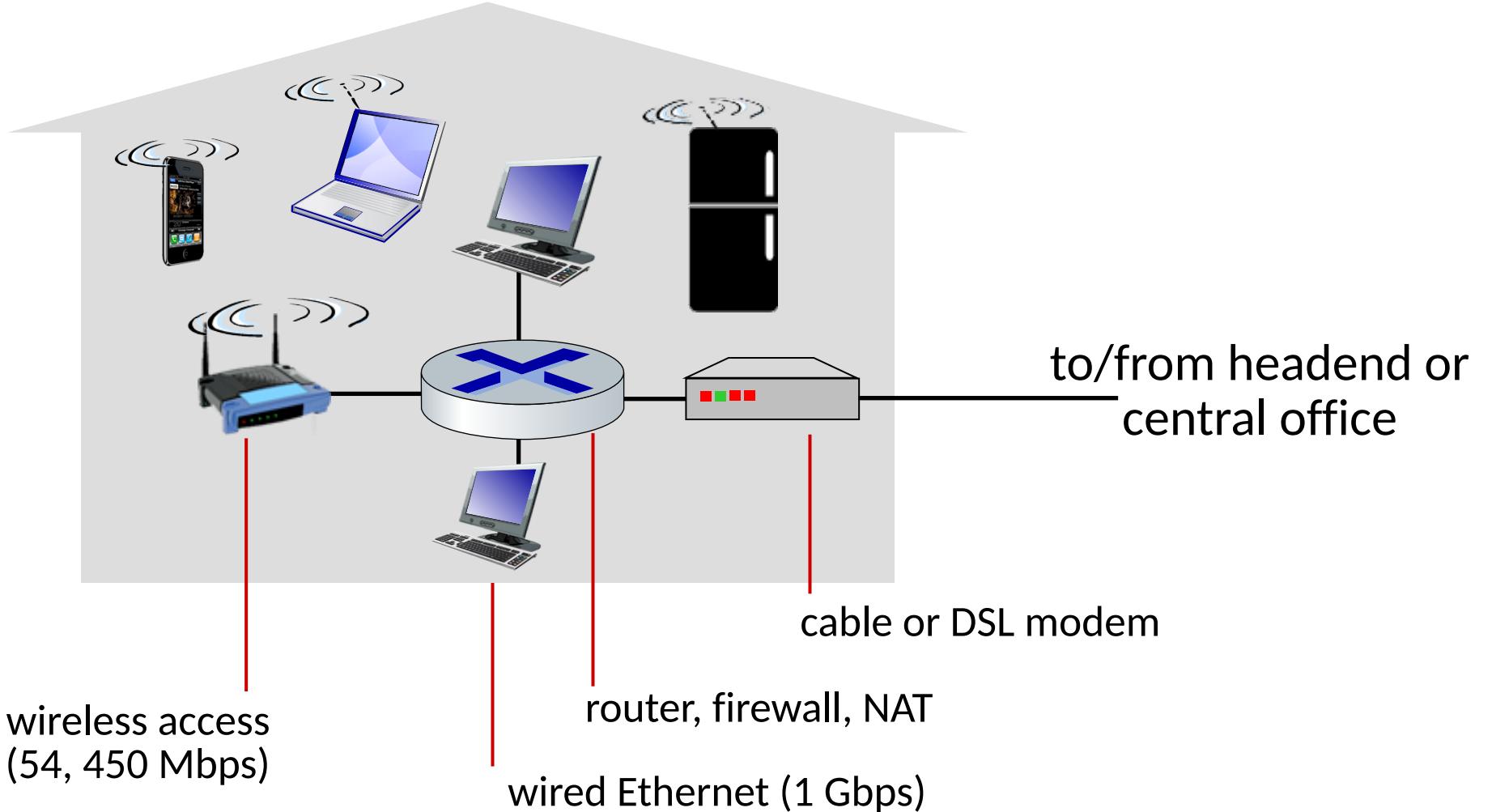
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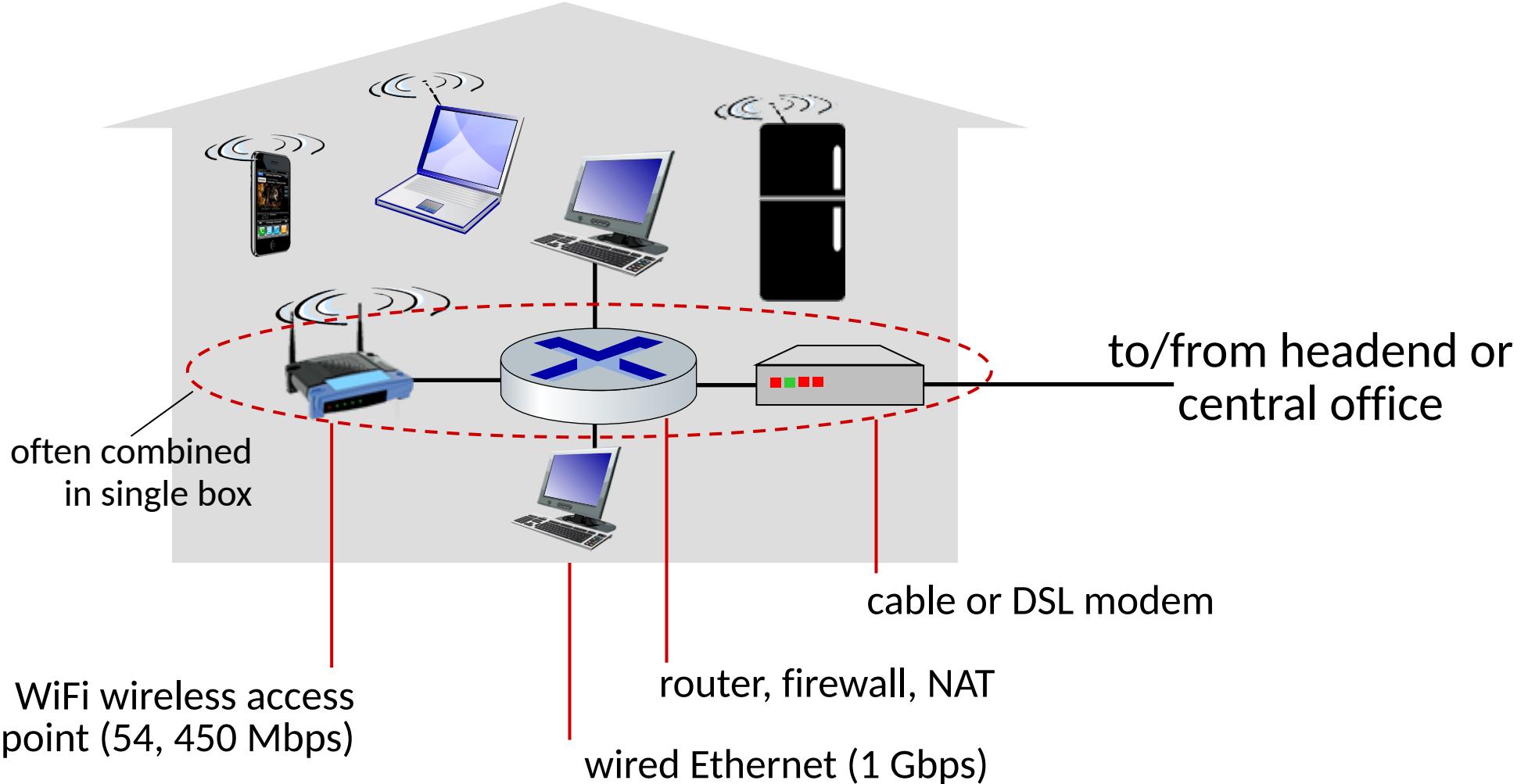
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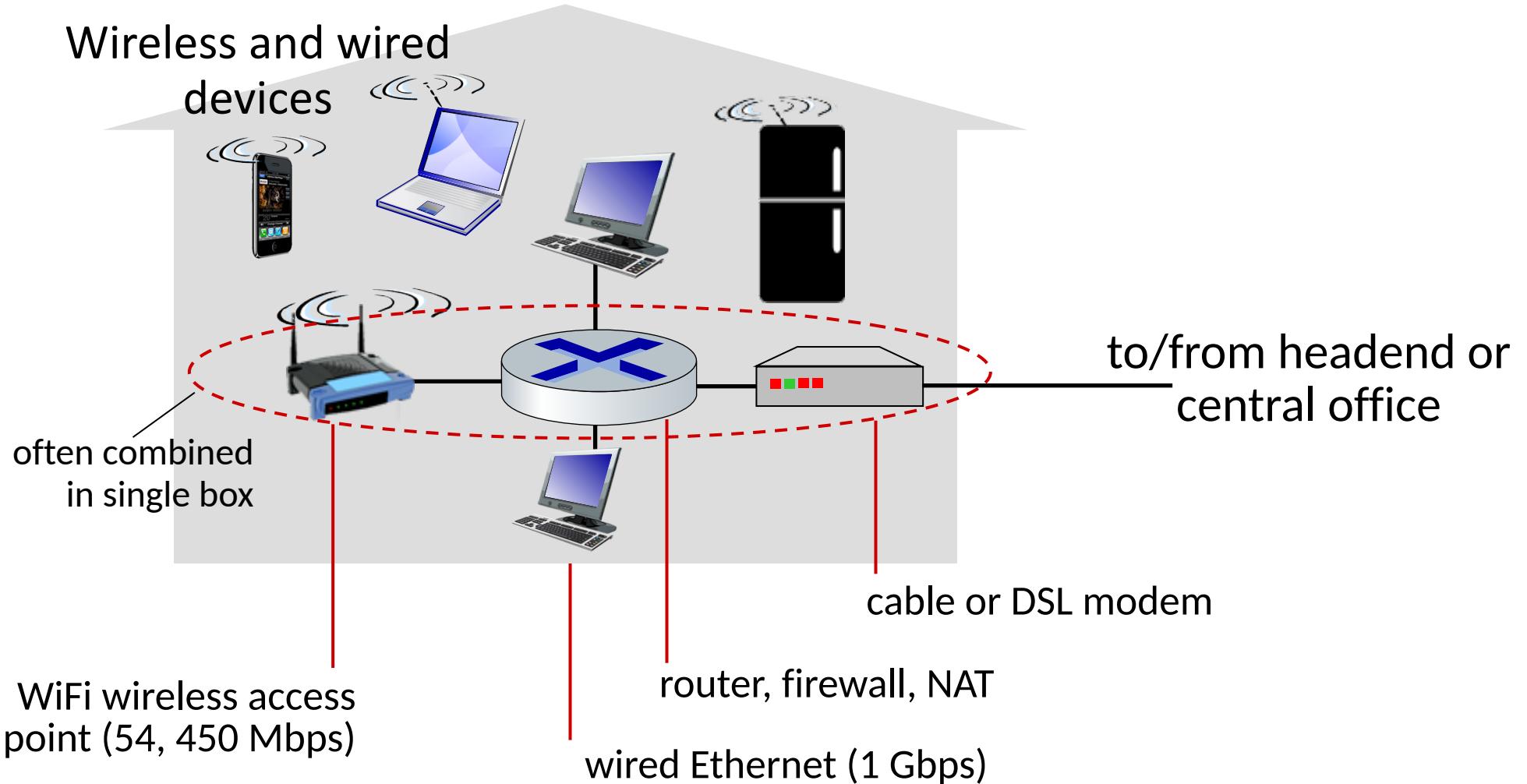
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Wireless access networks

Shared *wireless* access network connects end system to router

- via base station aka “access point”

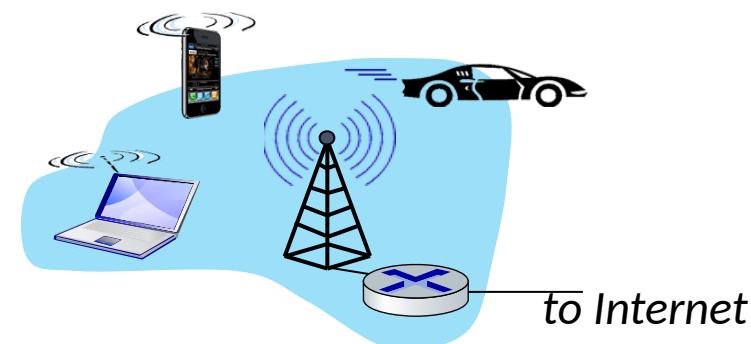
Wireless local area networks (WLANs)

- typically within or around building (~100 m)
- 802.11b/g/n/ac/ax (WiFi): 11, 54, 450, 600 Mbps or more (6.77Gbps) transmission rate

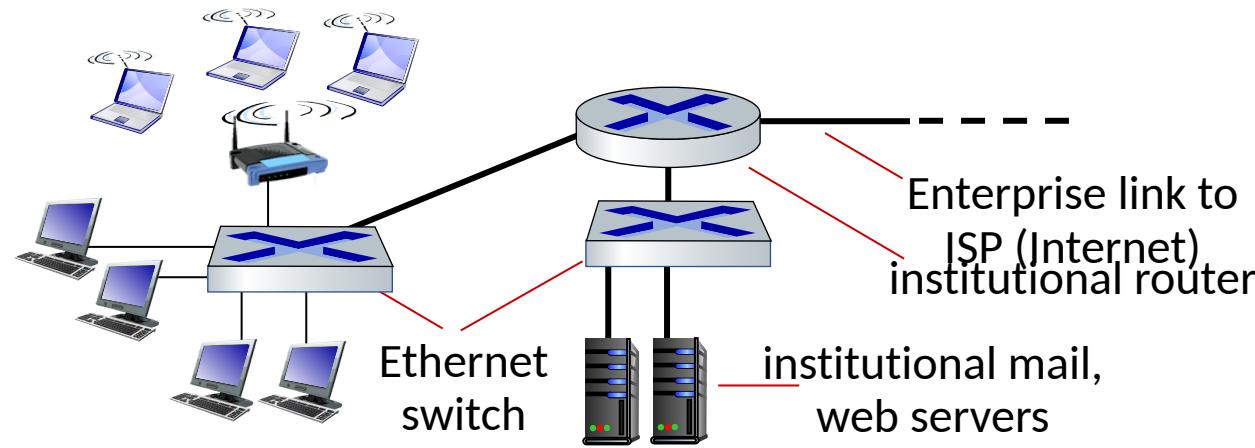


Wide-area cellular access networks

- provided by mobile, cellular network operator (10's km)
- Between 1 Mbps and 1 Gbps
- 3G, 4G (LTE) and 5G



Access networks: enterprise networks



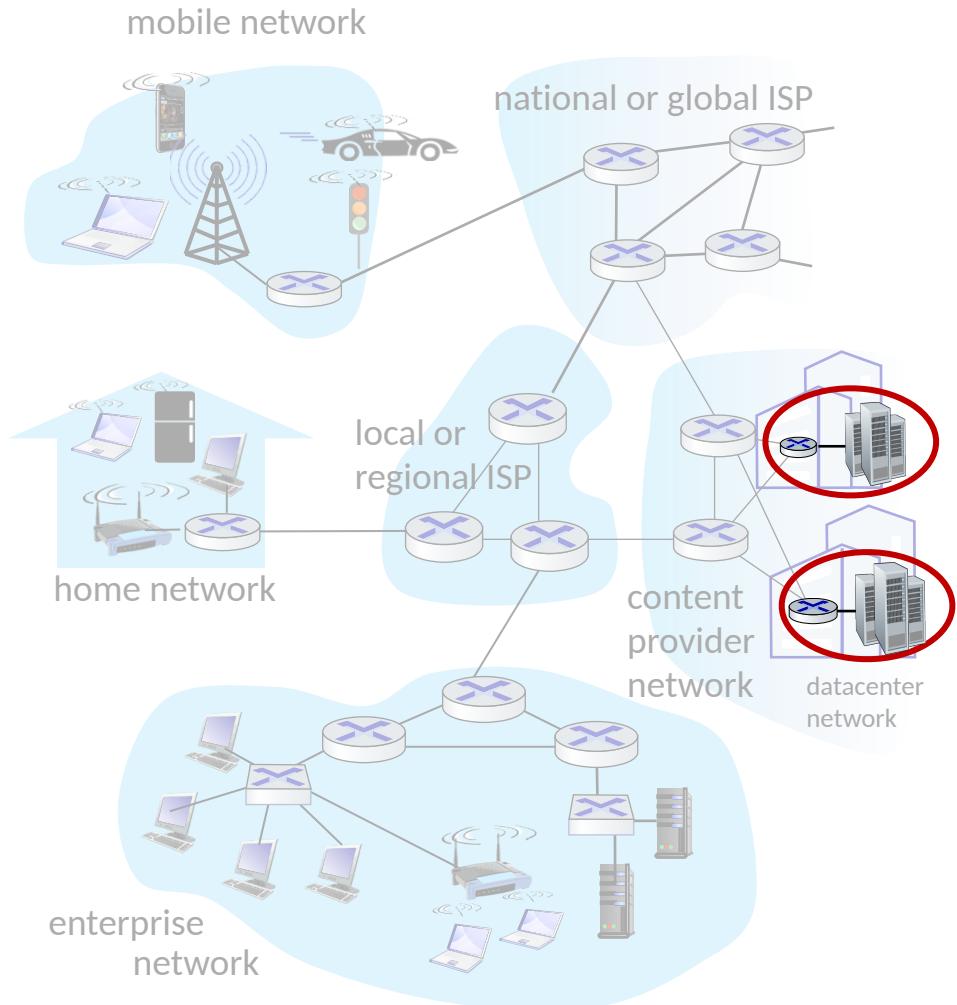
- companies, universities, etc.
- mix of wired, wireless link technologies, connecting a mix of switches and routers (we'll cover differences shortly)
 - Ethernet: wired access at 100Mbps, 1Gbps, 10Gbps
 - WiFi: wireless access points at 11, 54, 450 Mbps

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)



Links: physical media

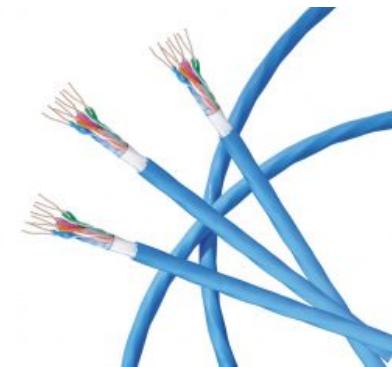
- **bit**: propagates between transmitter/receiver pairs
- **physical link**: what lies between transmitter & receiver
- **guided media**:
 - signals propagate in solid media: copper, fiber, coax
- **unguided media**:
 - signals propagate freely, e.g., radio

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Twisted pair (TP)

- two insulated copper wires
 - Category 5: 100 Mbps, 1 Gbps Ethernet
 - Category 6: 10Gbps
 - Category 8: 40Gbps



Links: physical media

Coaxial cable:

- two concentric copper conductors
- bidirectional
- broadband:
 - multiple frequency channels on cable
 - HFC



Links: physical media

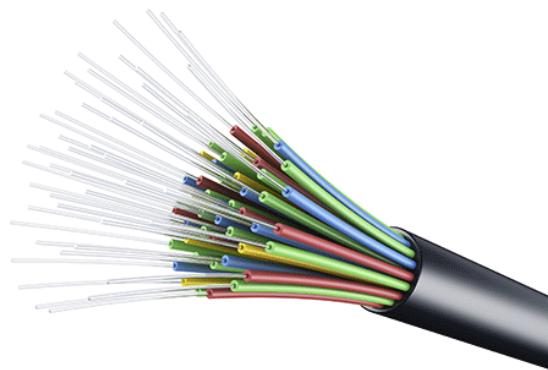
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Fiber optic cable:

- 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

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 - short distances, limited rates

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- terrestrial microwave
 - point-to-point; 45 Mbps channels

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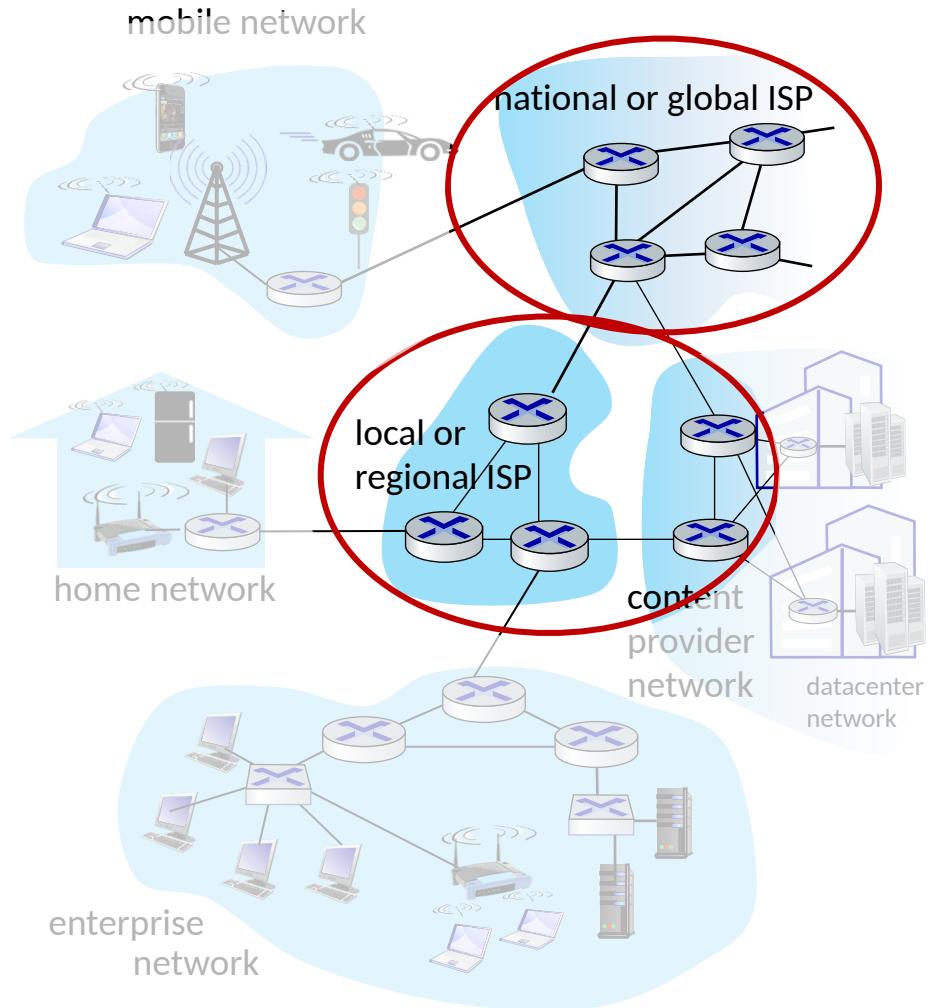
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- satellite
 - up to 45 Mbps per channel
 - 270 msec end-end delay
 - geosynchronous versus low altitude

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- Performance:
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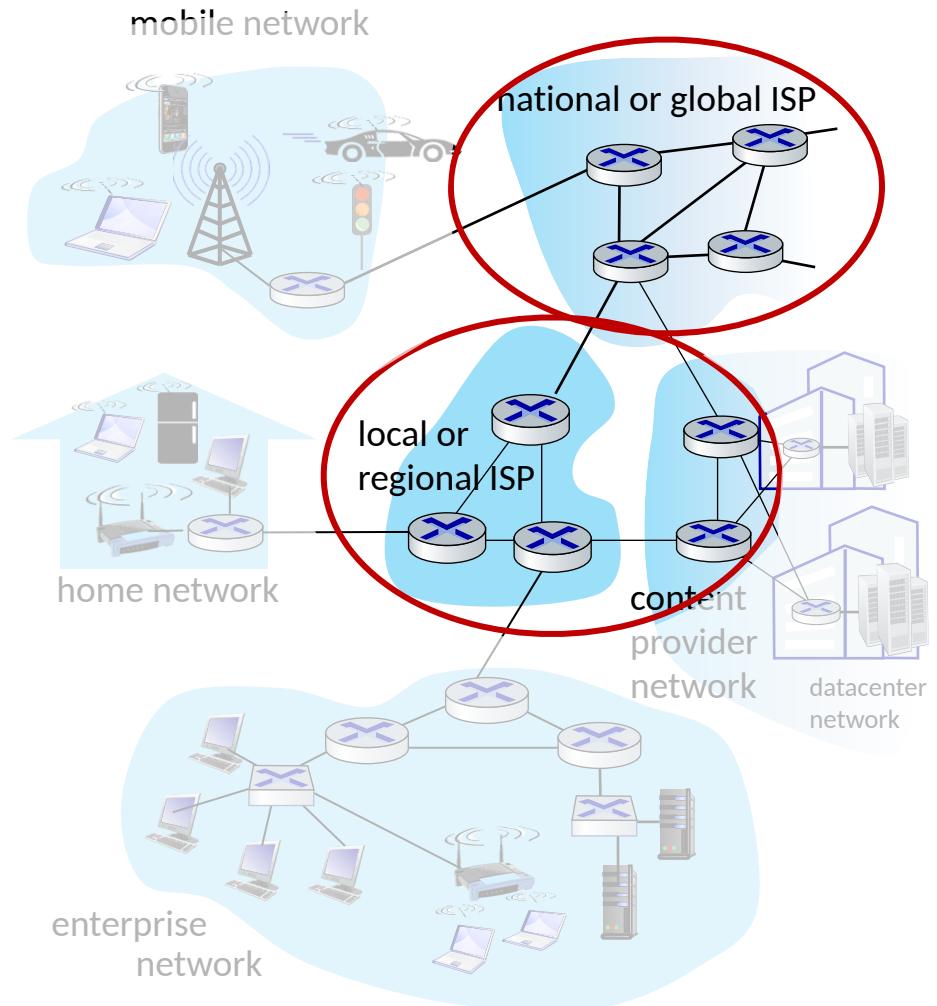
The network core

- mesh of interconnected routers



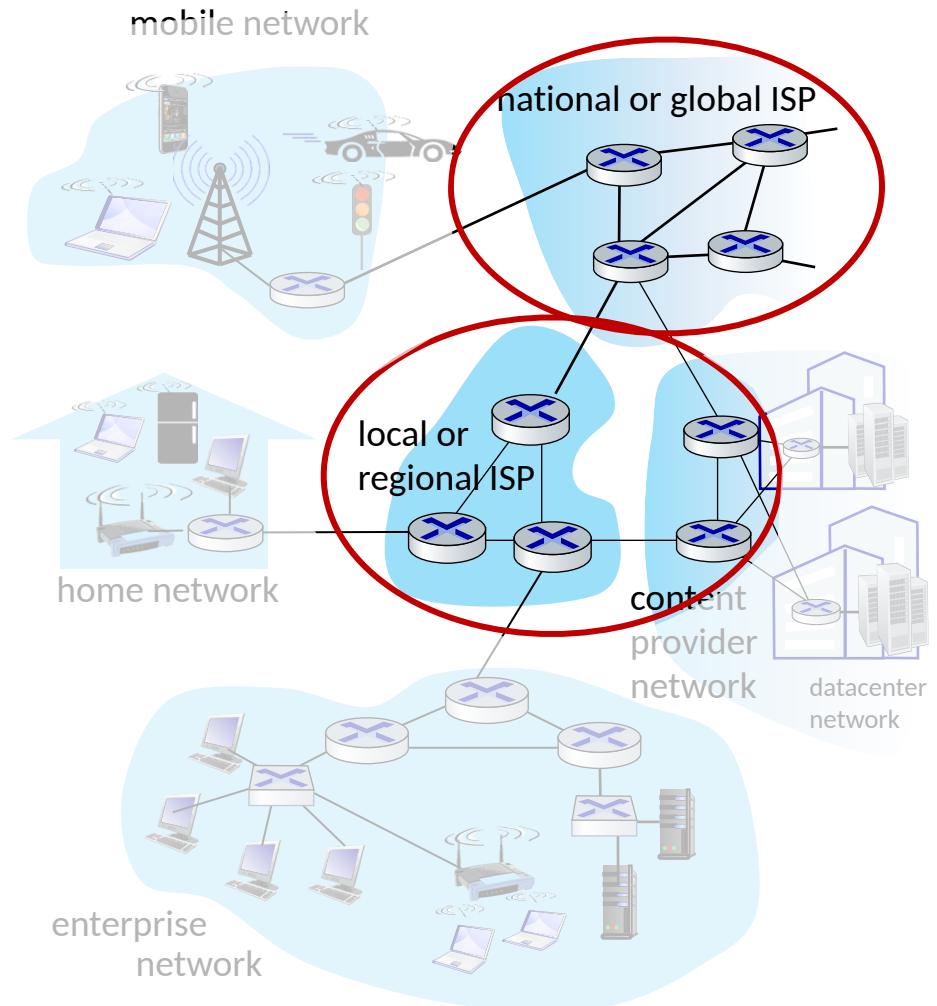
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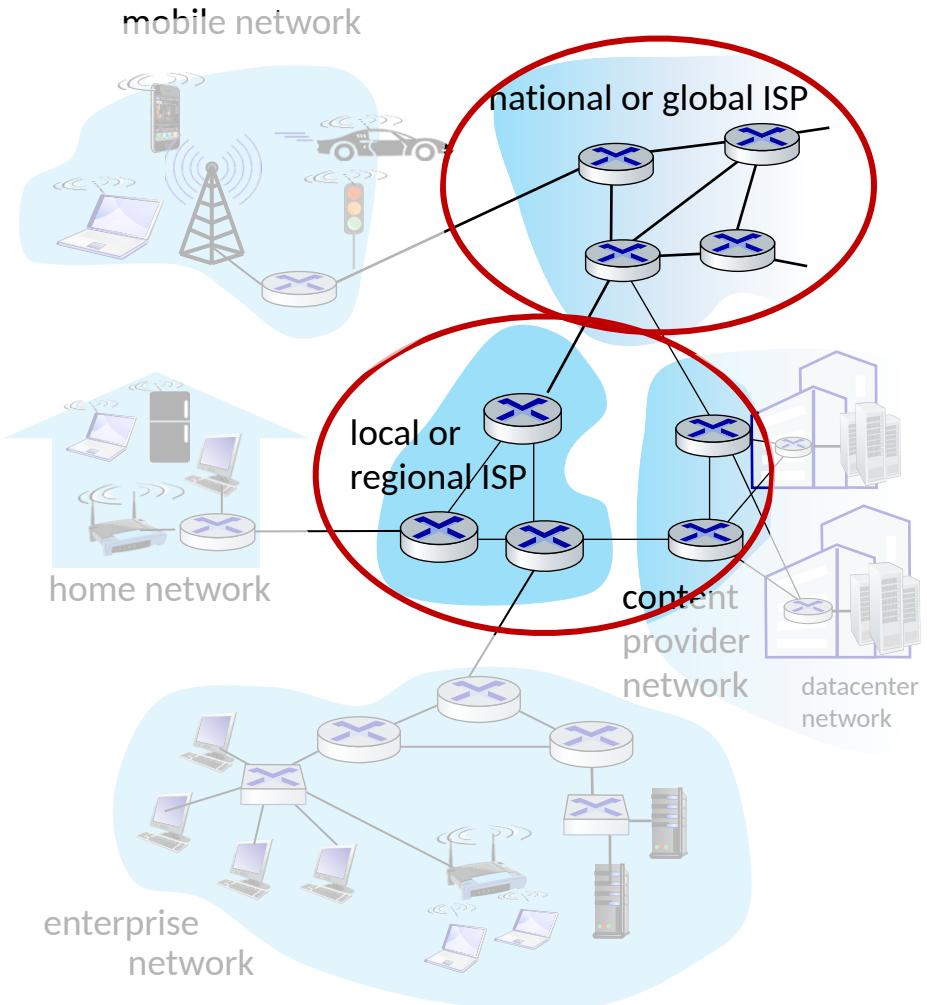
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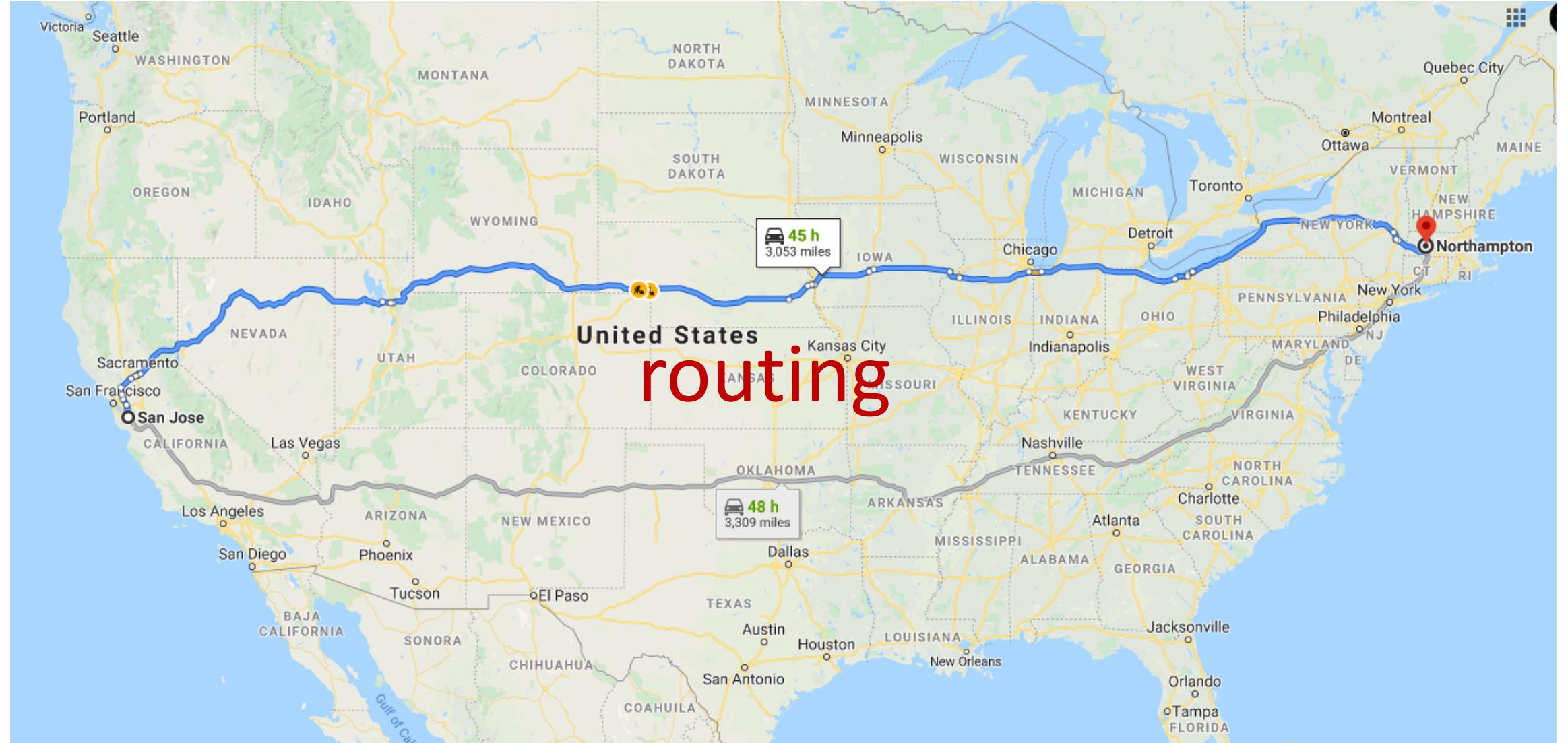
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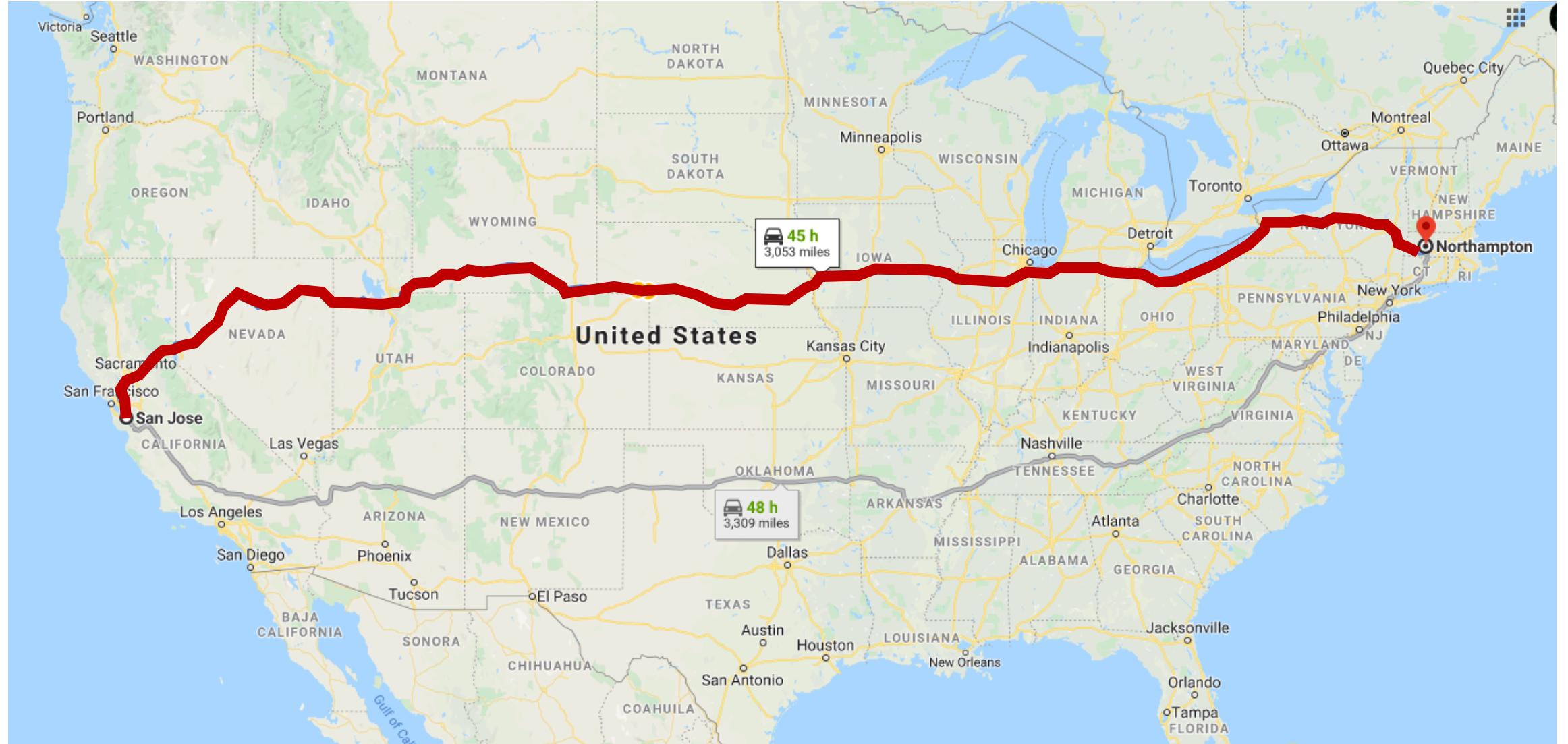
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 - each packet transmitted at full link capacity









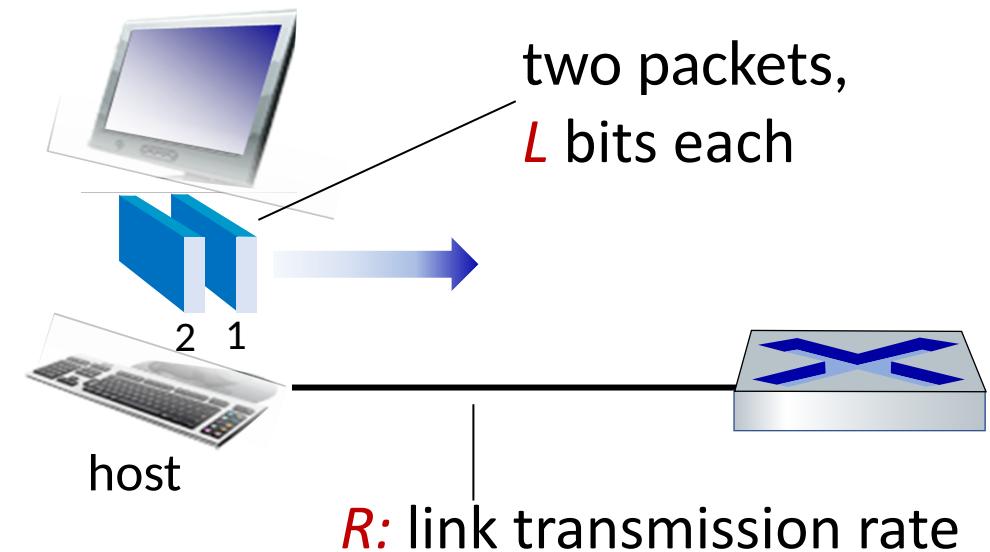






Host: sends packets of data

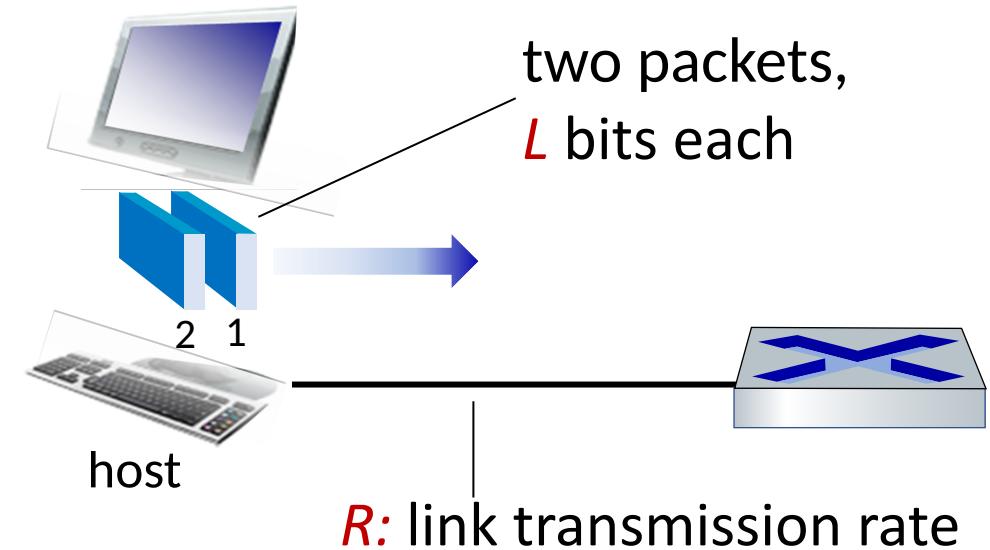
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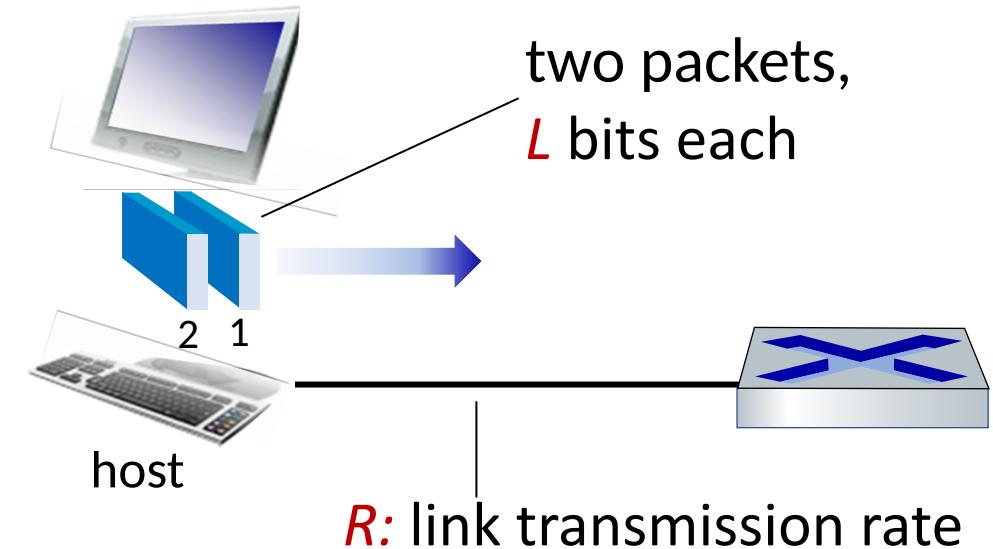
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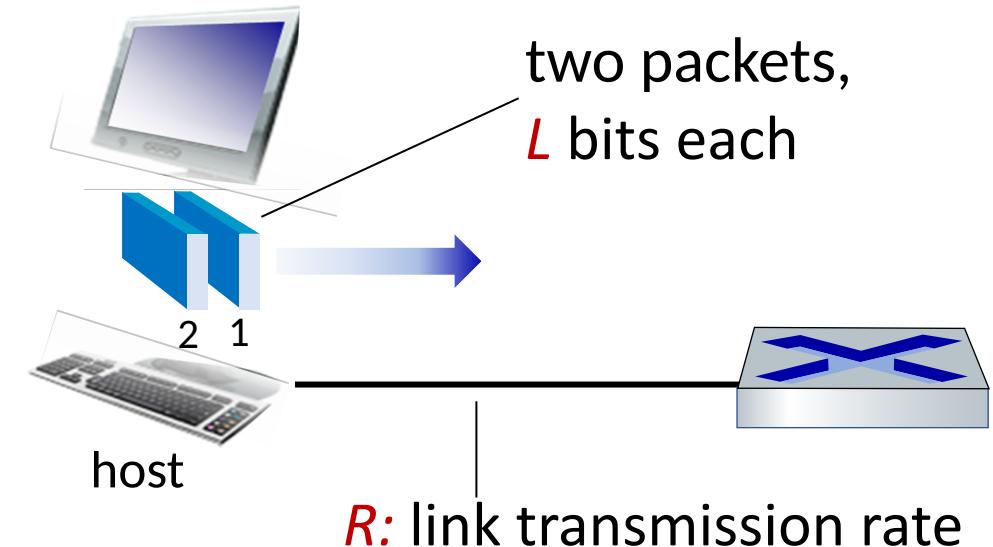
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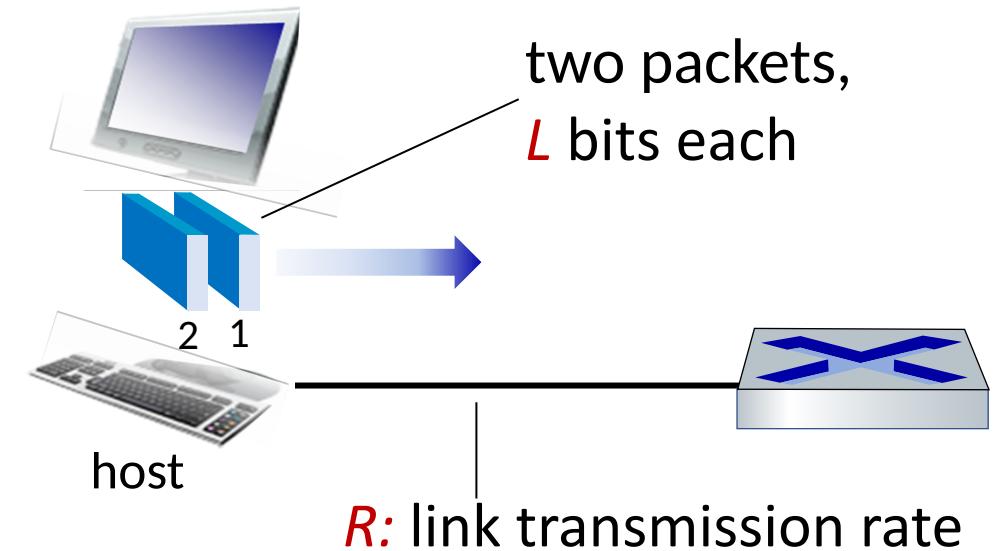
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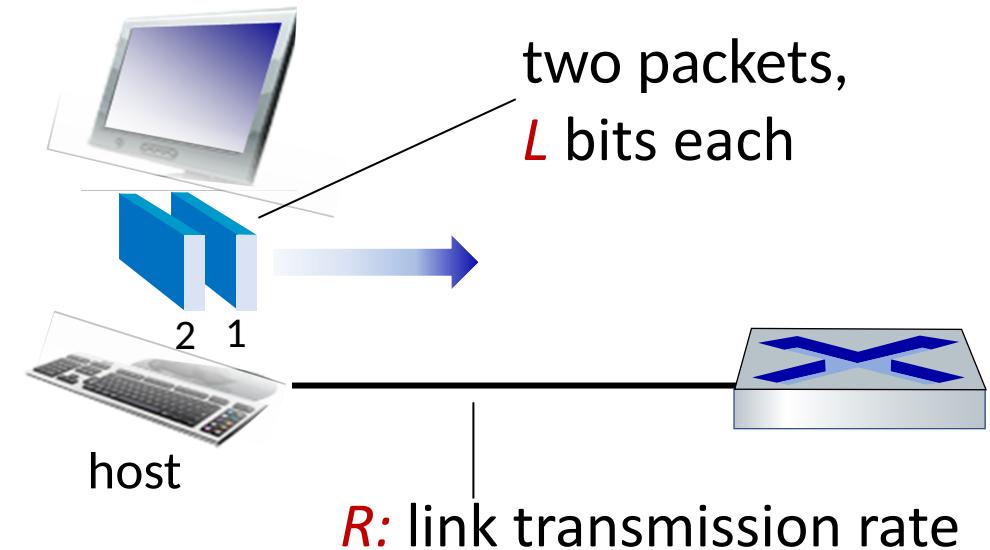
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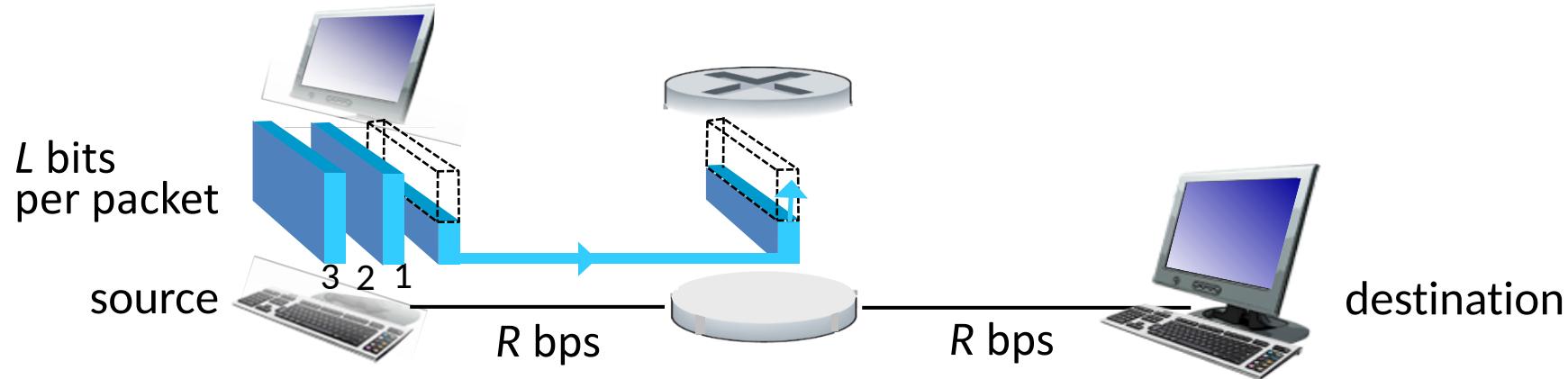
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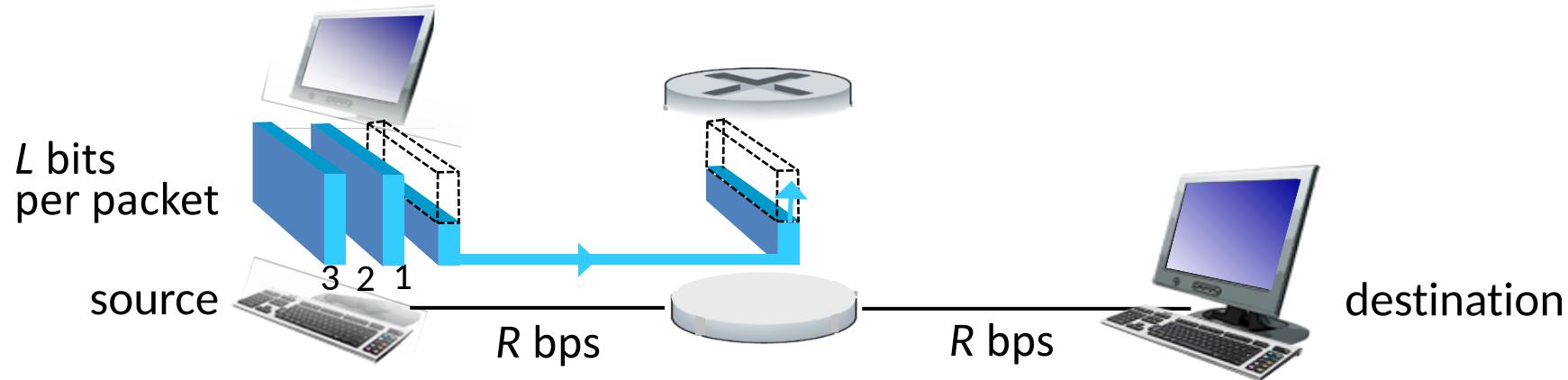
$$\text{packet transmission delay} = \frac{\text{time needed to transmit } L\text{-bit packet into link}}{R \text{ (bits/sec)}} = \frac{L \text{ (bits)}}{R \text{ (bits/sec)}}$$

Packet-switching: store-and-forward



- **packet transmission delay:** takes L/R seconds to transmit (push out) L -bit packet into link at R bps

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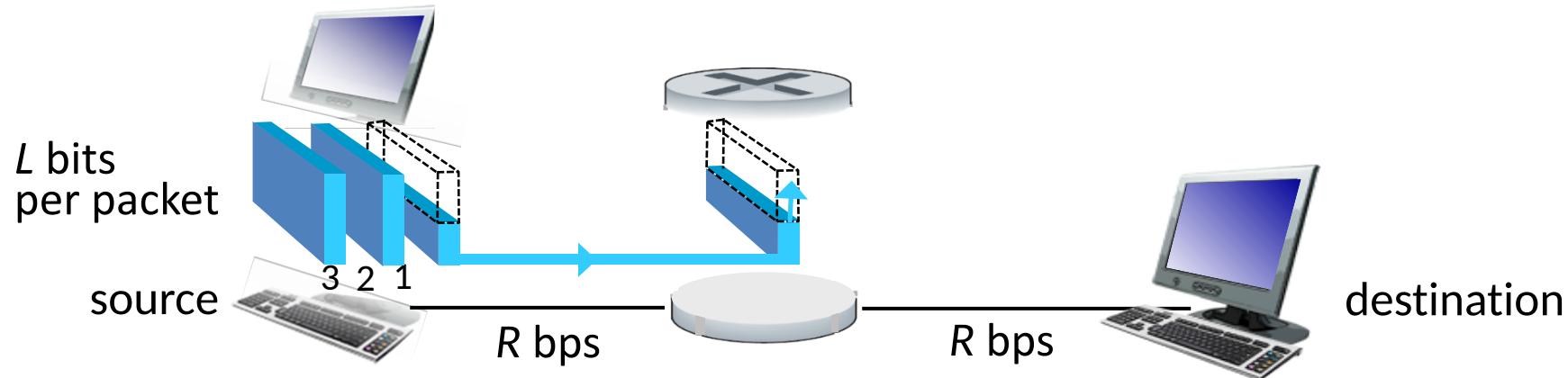


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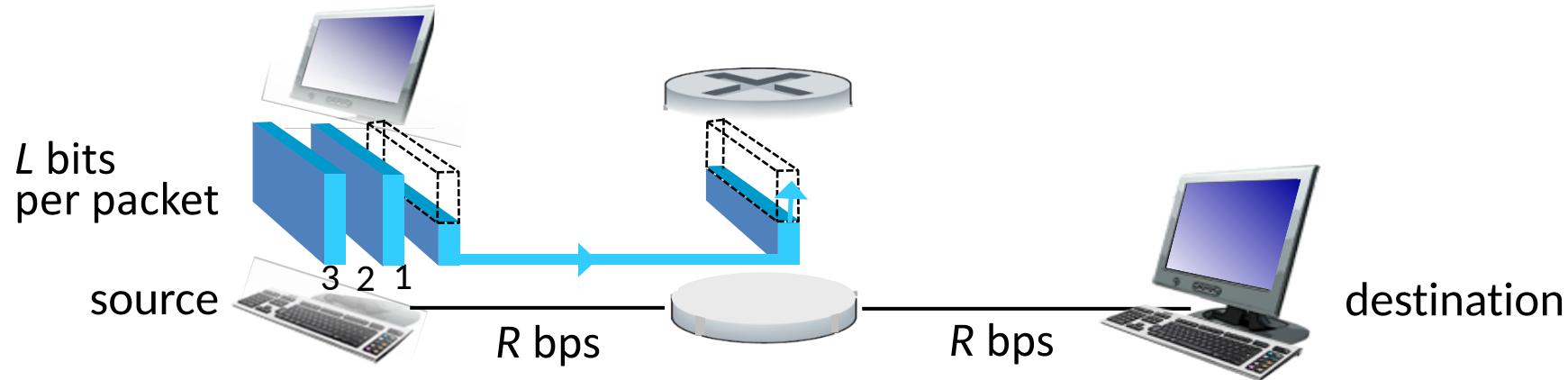


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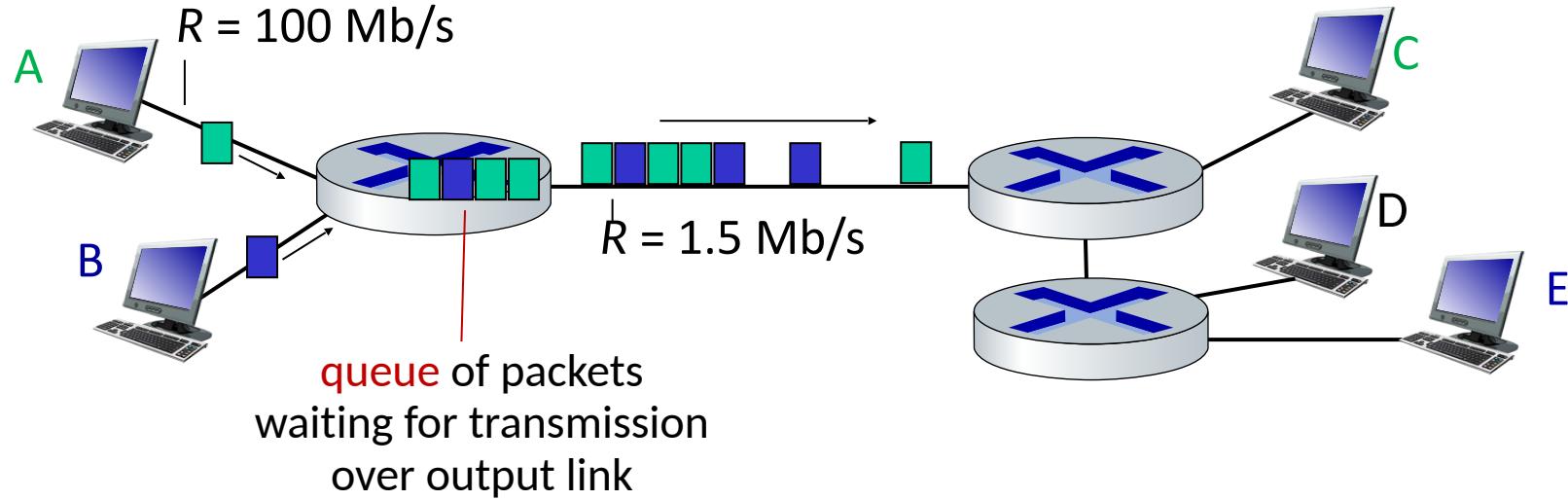


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- **end-to-end delay** (in this picture): $2L/R$ (assuming zero propagation delay)

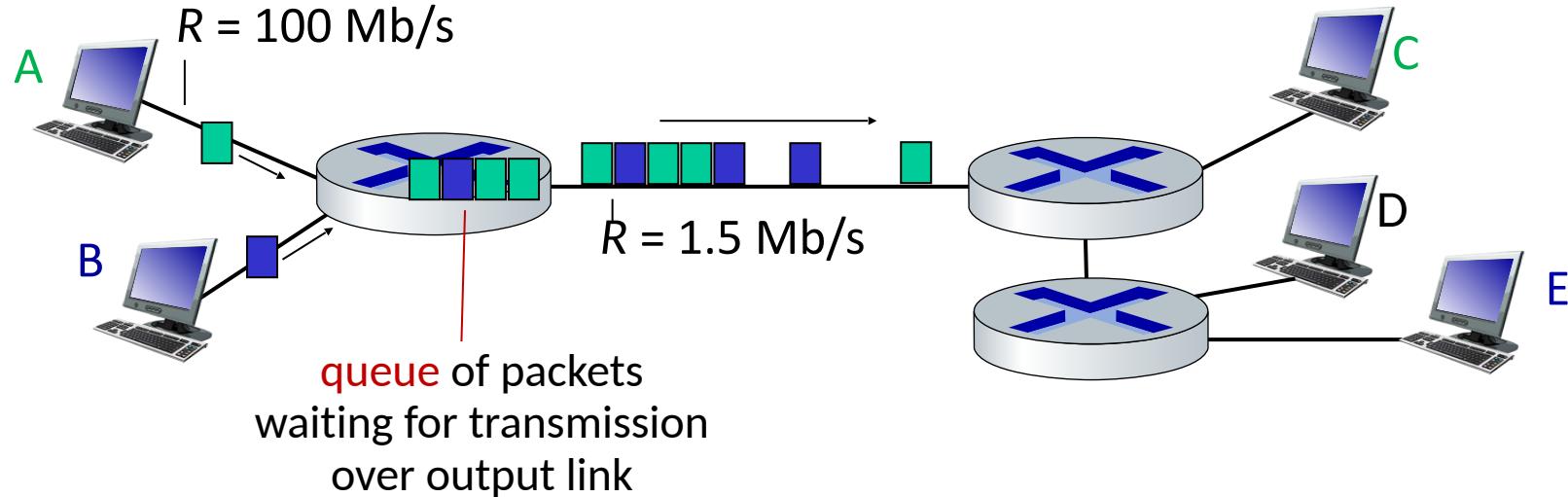
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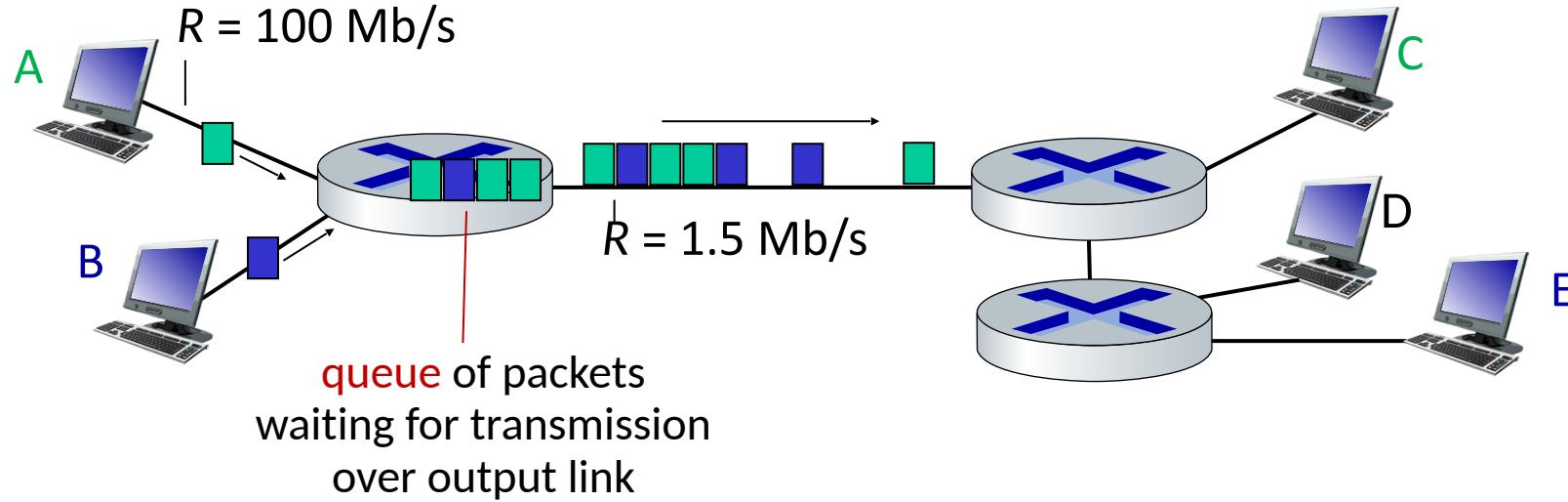
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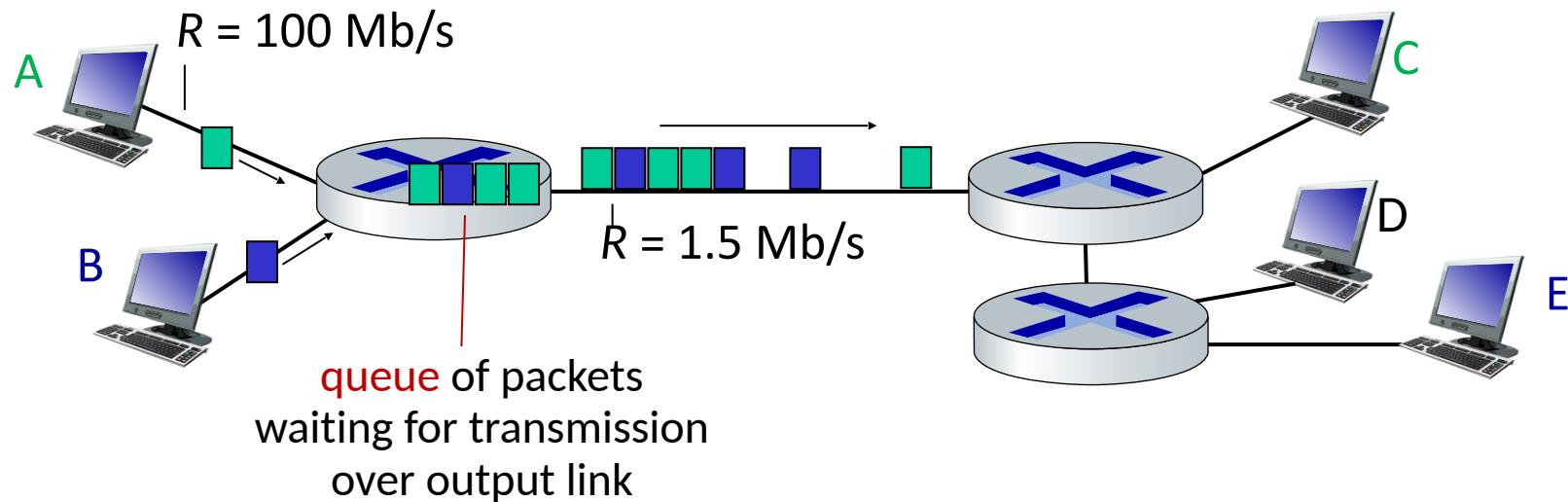
Queueing occurs when work arrives faster than it can be serviced:



Packet-switching: queueing



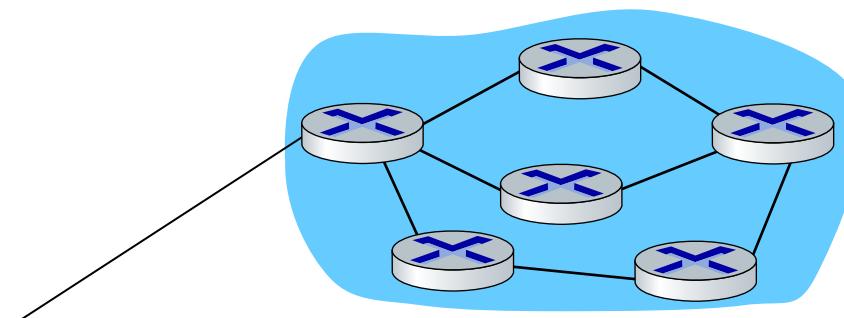
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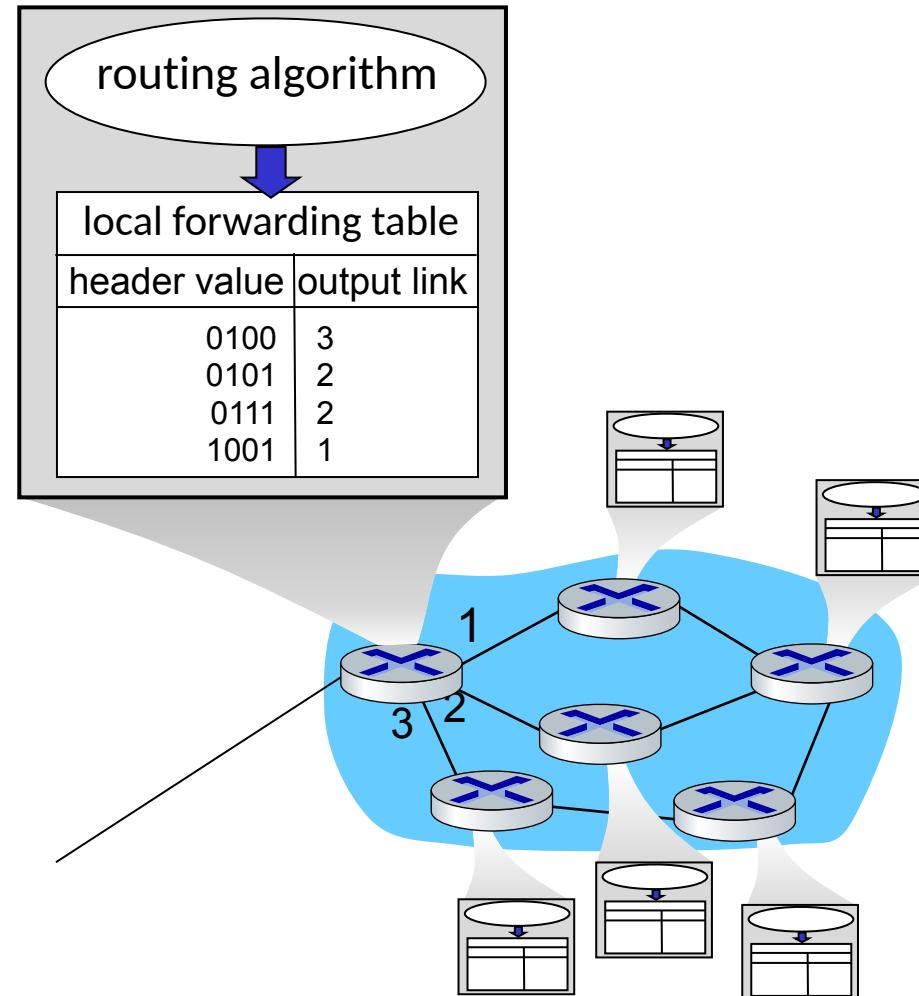
Packet queuing and loss: if arrival rate (in bps) to link exceeds transmission rate (bps) of link for some period of time:

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

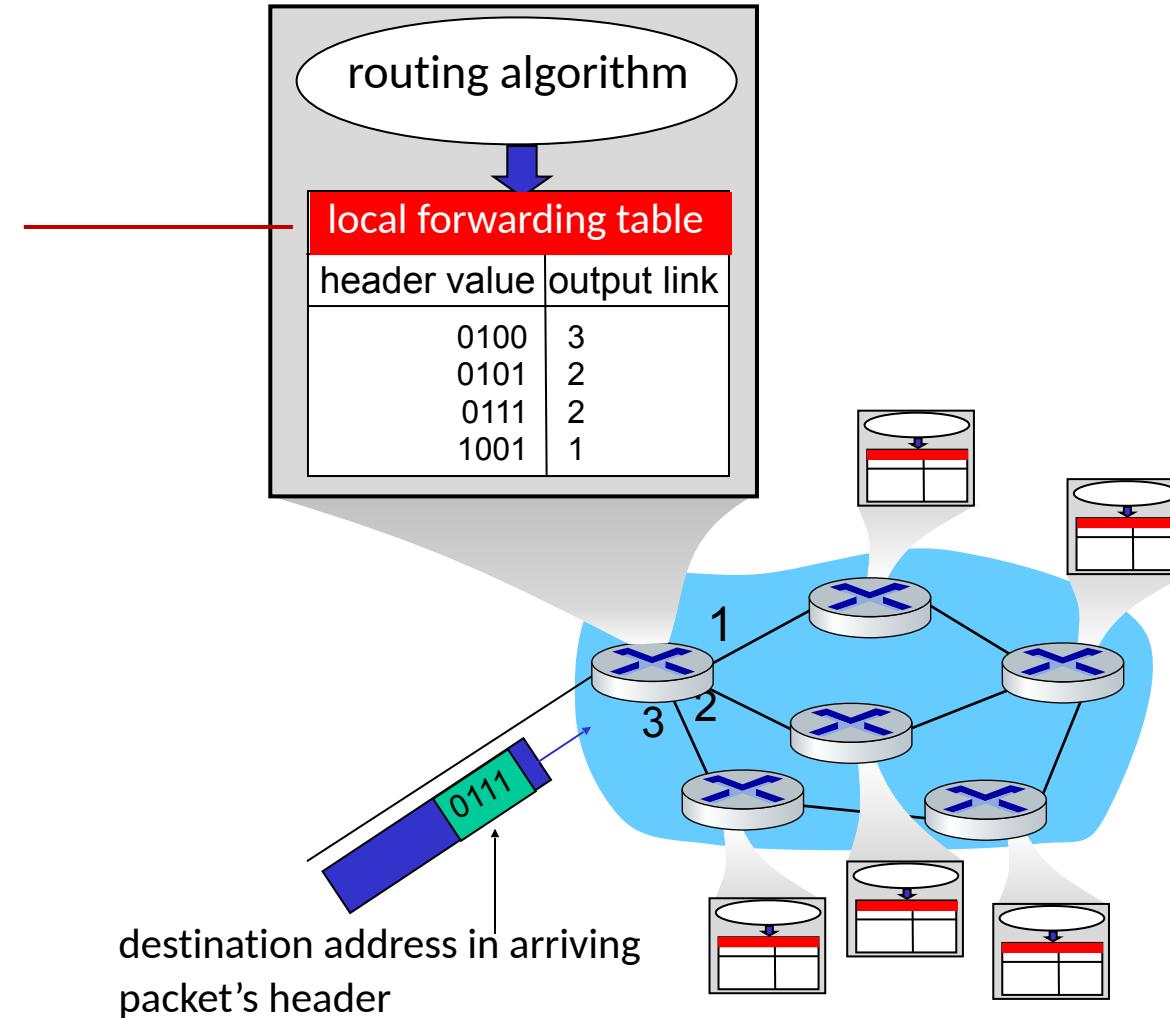
Two key network-core functions



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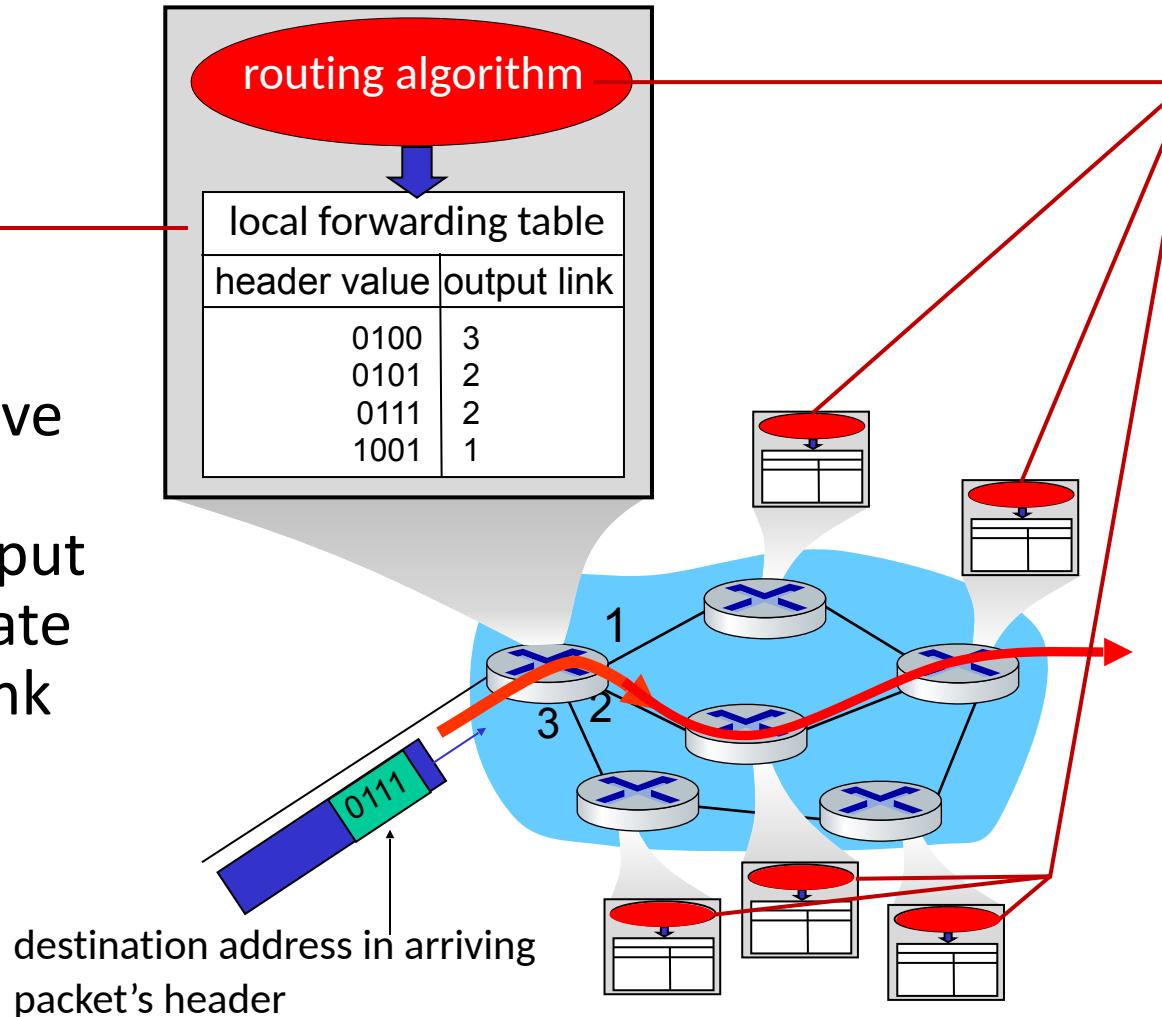
Two key network-core functions



Two key network-core functions

Forwarding:

- aka “switching”
- *local* action: move arriving packets from router’s input link to appropriate router output link

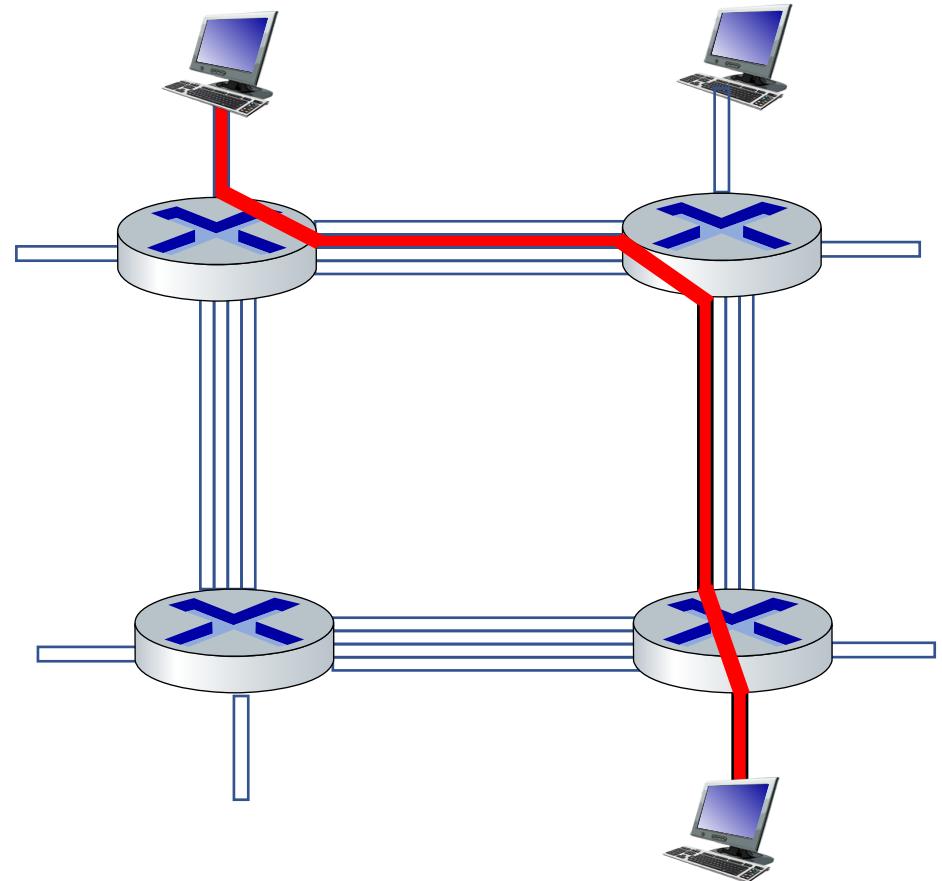


Routing:

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

Alternative to packet switching: circuit switching

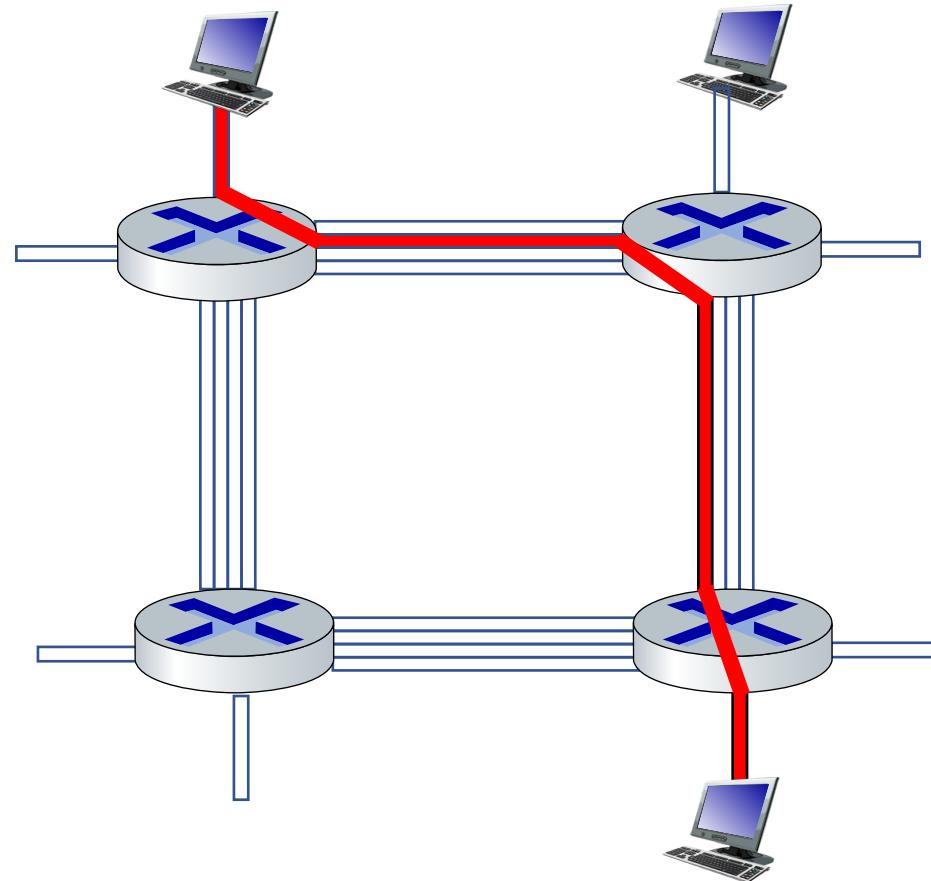
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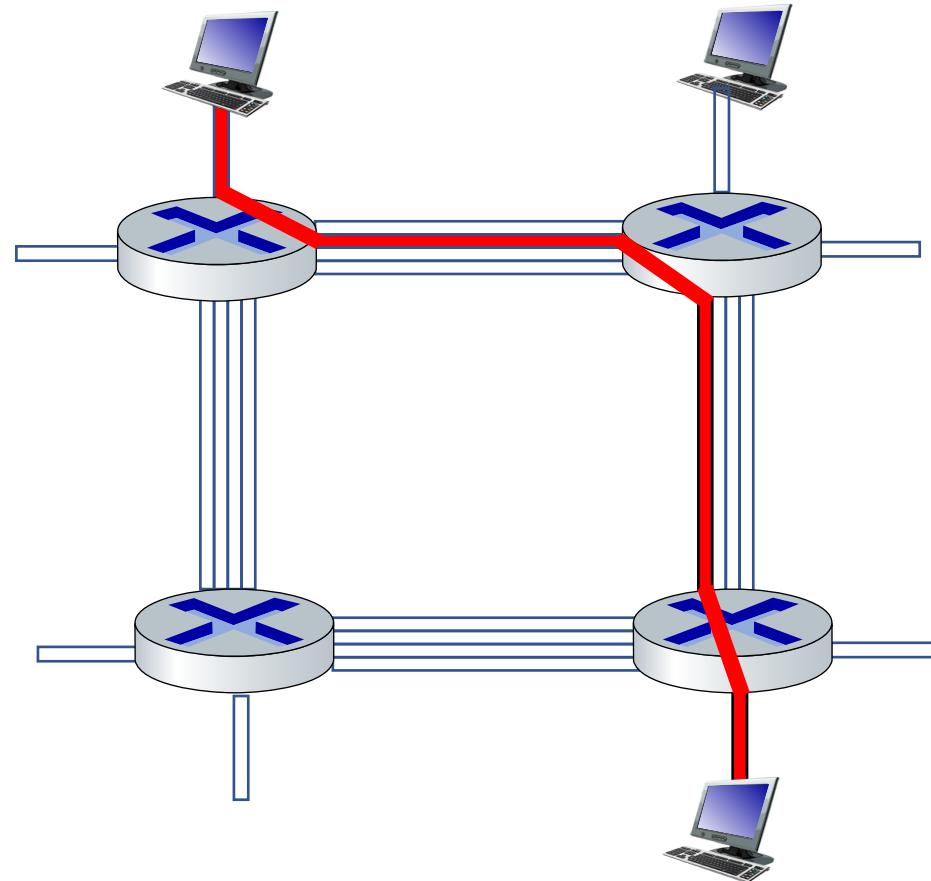
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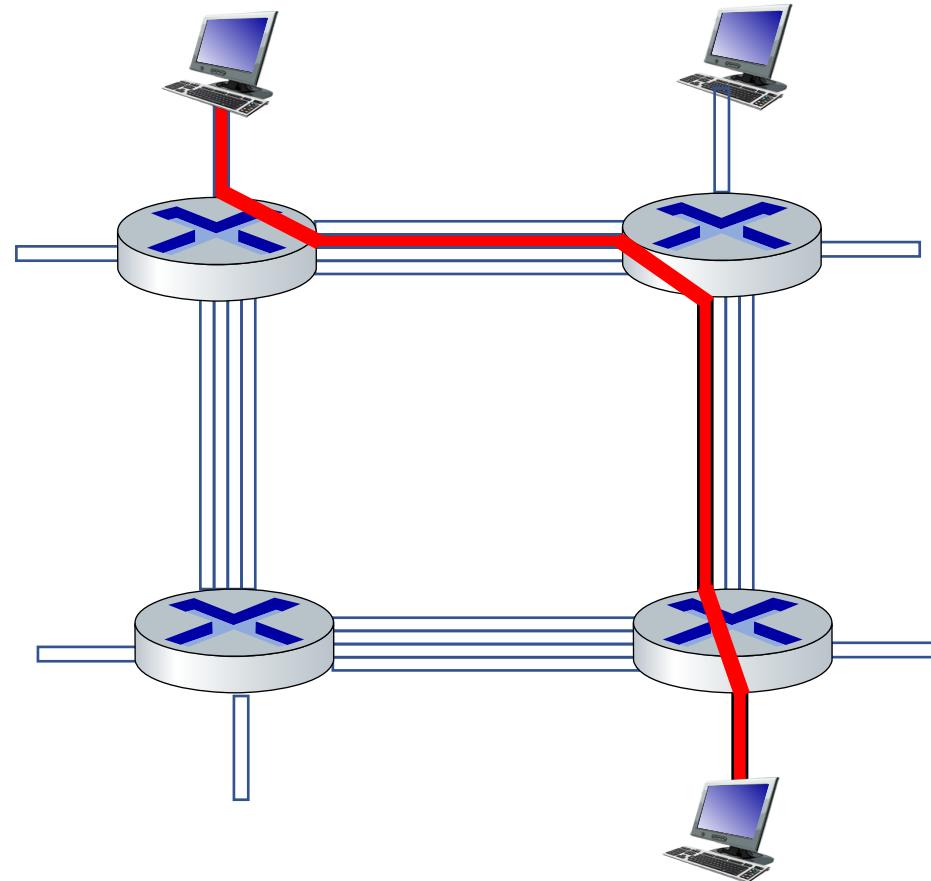
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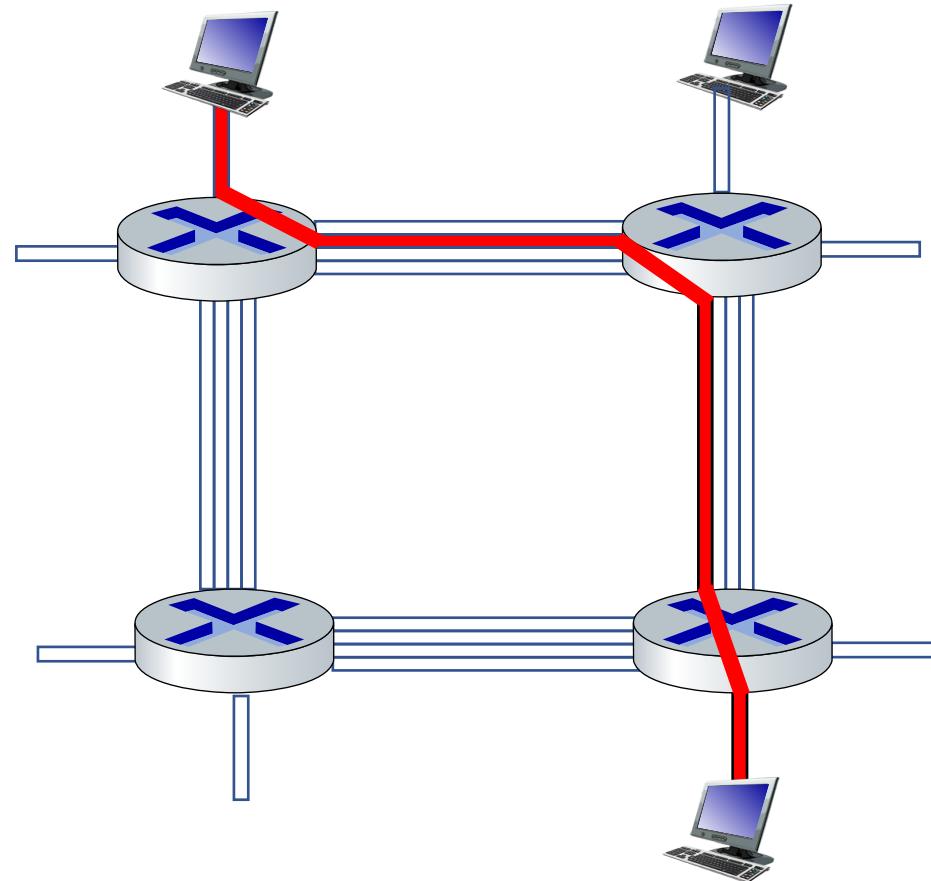
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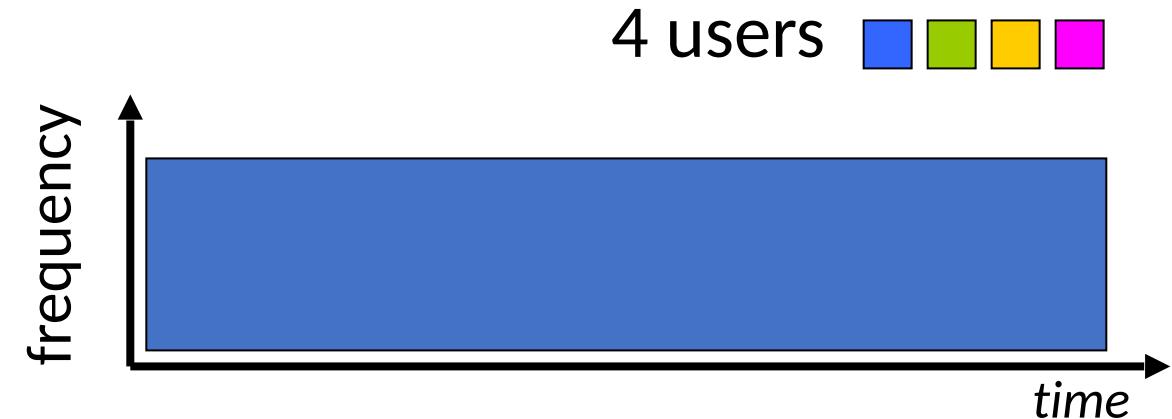
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- commonly used in traditional telephone networks



Circuit switching: FDM and TDM

Frequency Division Multiplexing (FDM)

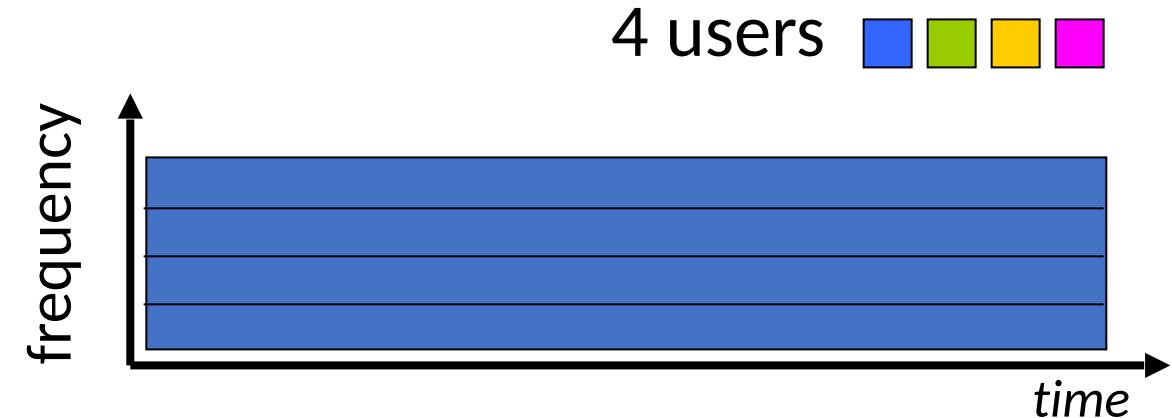
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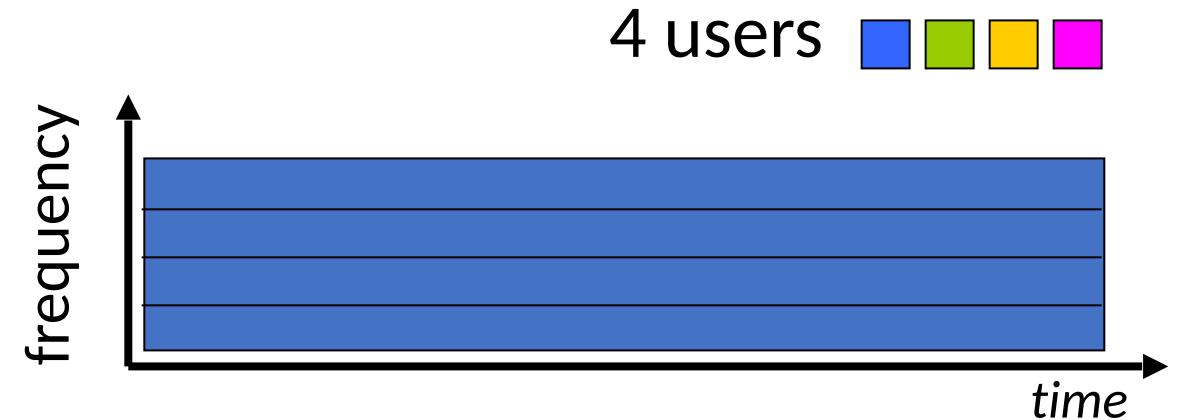
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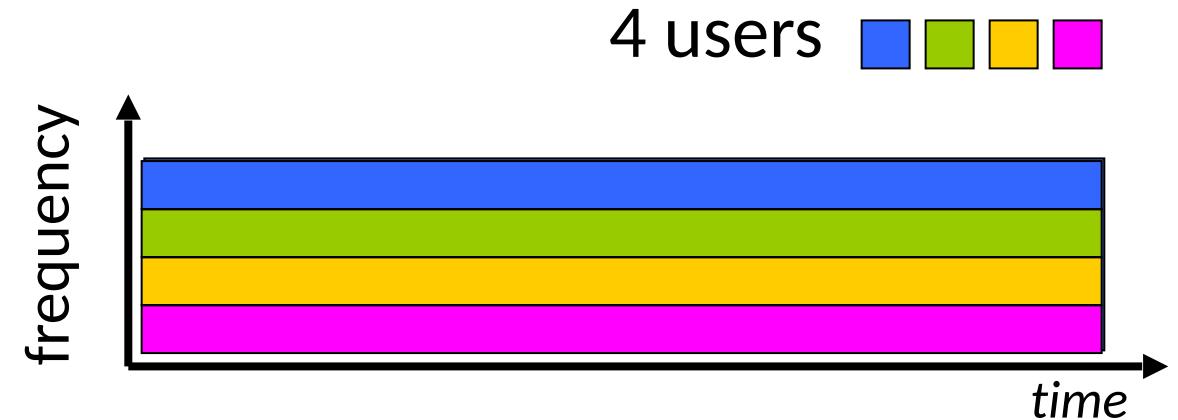
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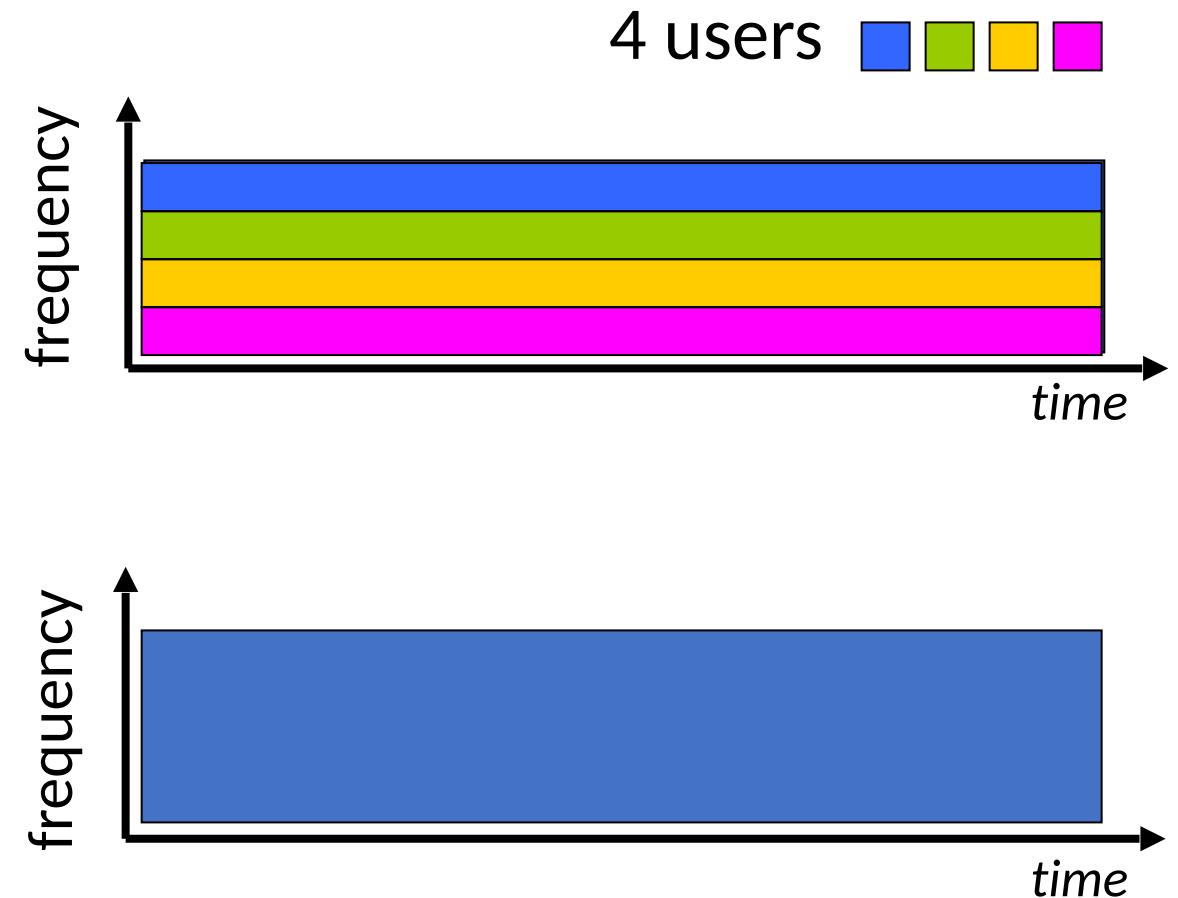
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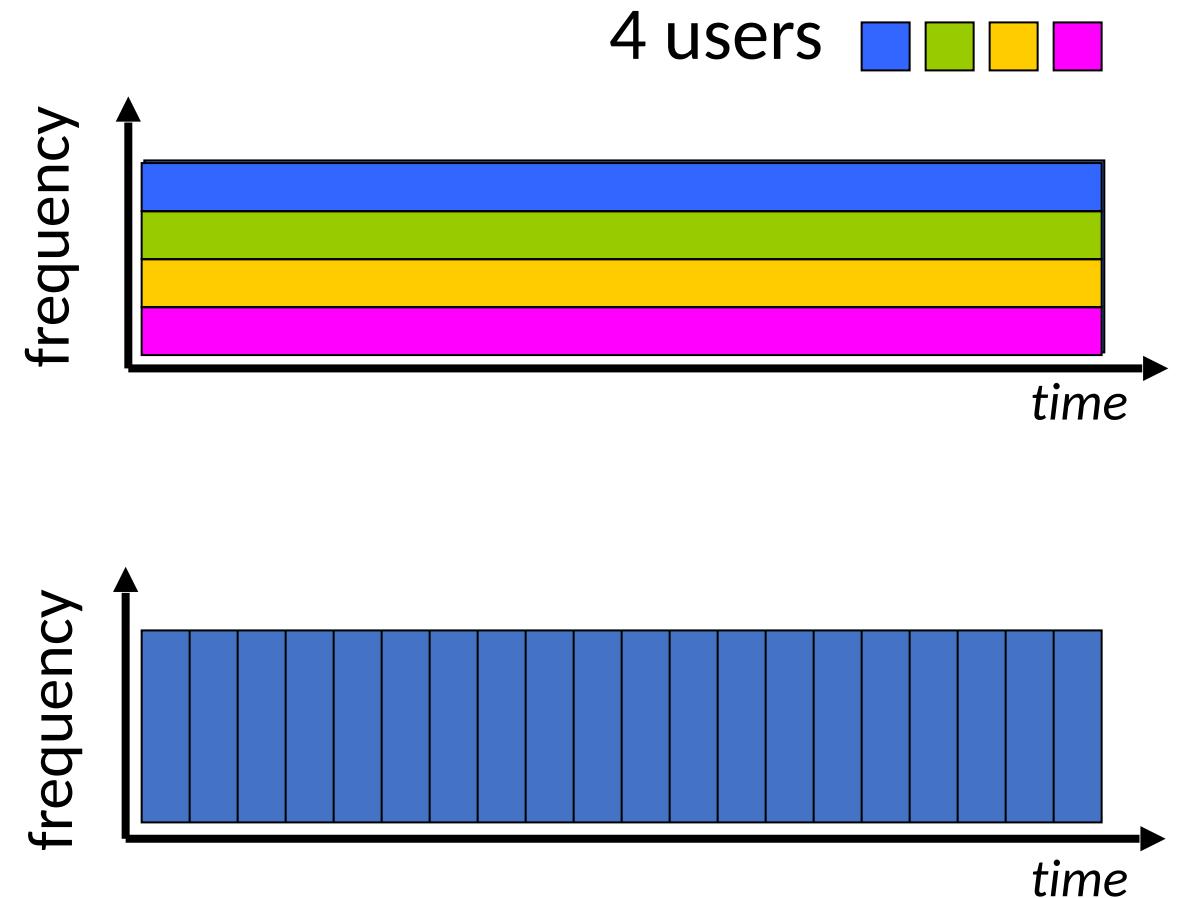
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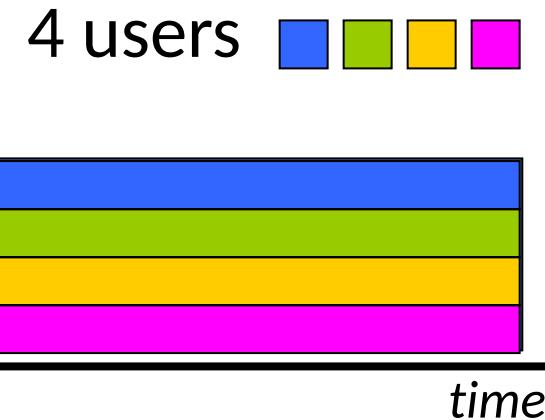
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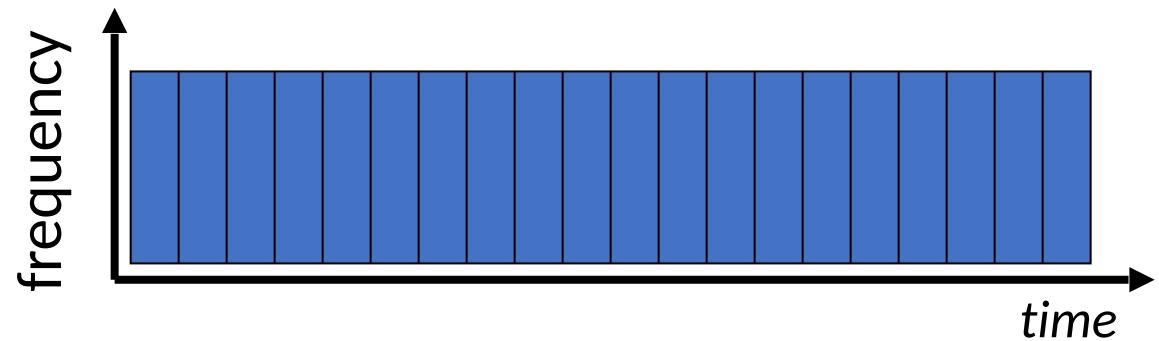
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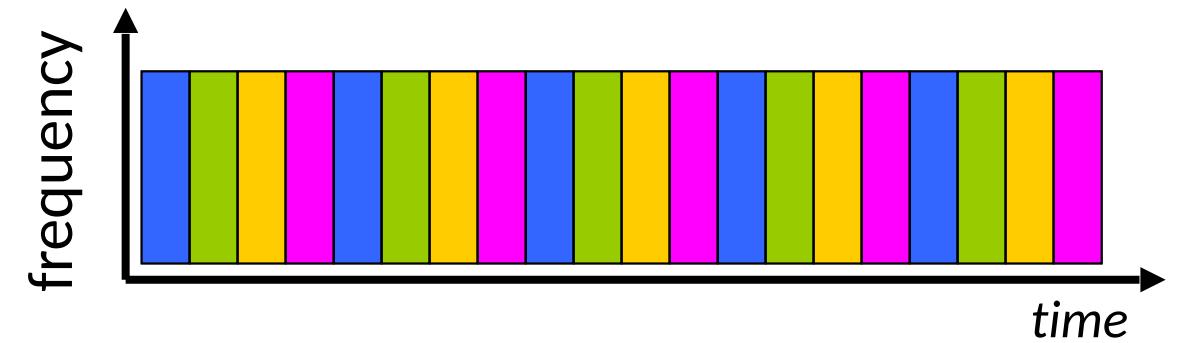
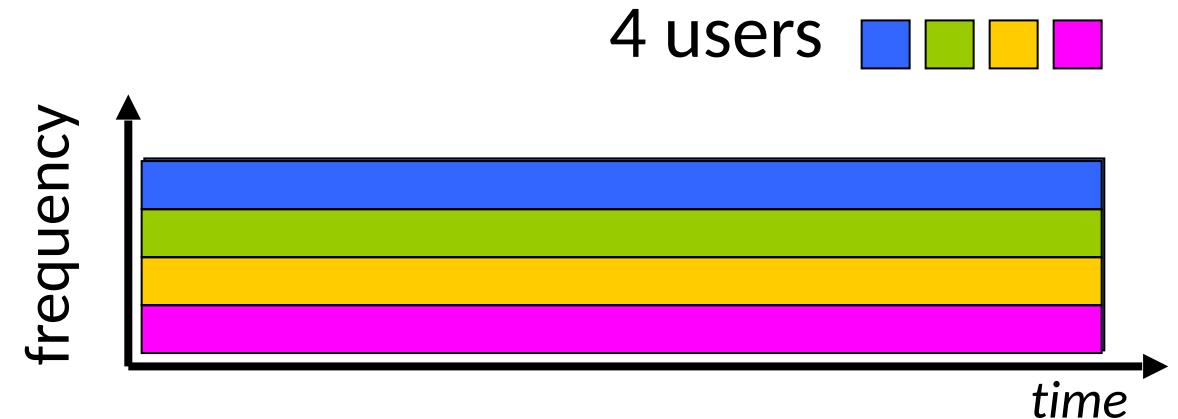
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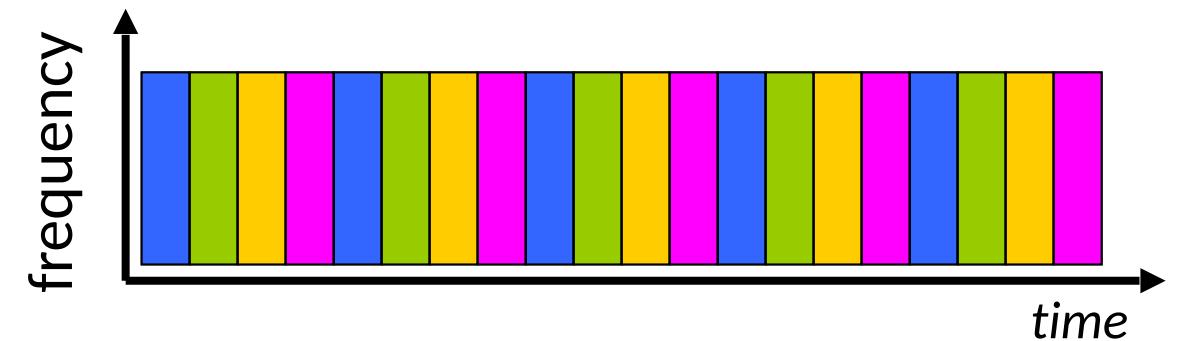
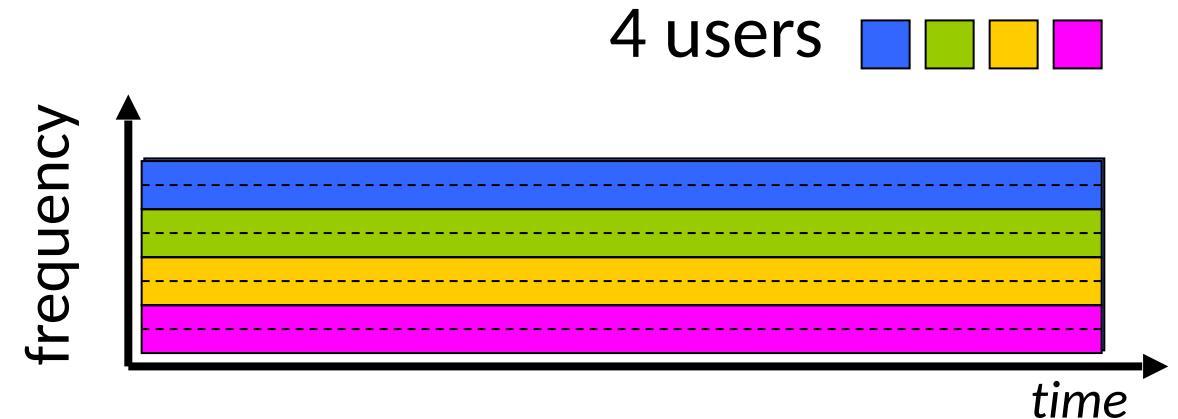
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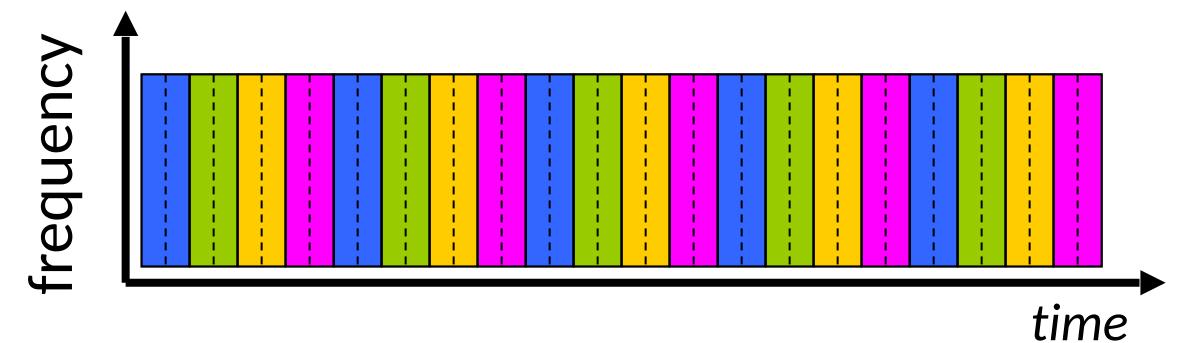
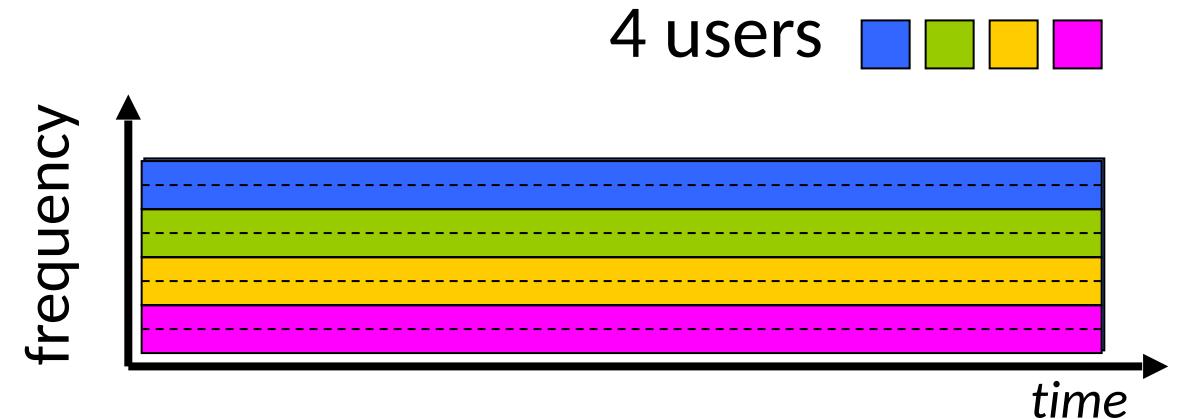
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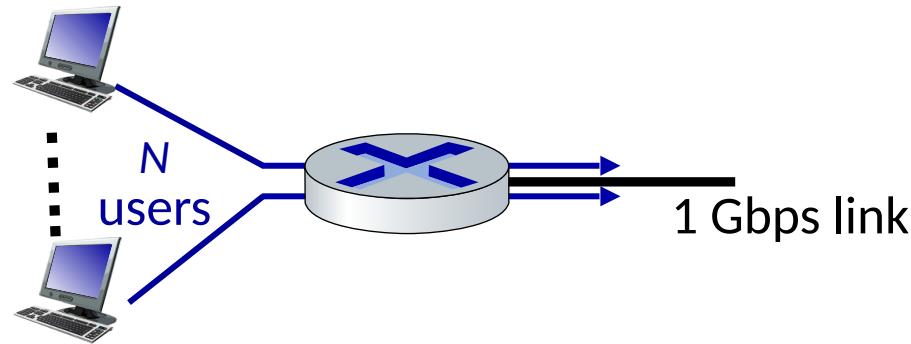
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Packet switching versus circuit switching

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- each user:
 - 100 Mb/s when “active”
 - active 10% of time

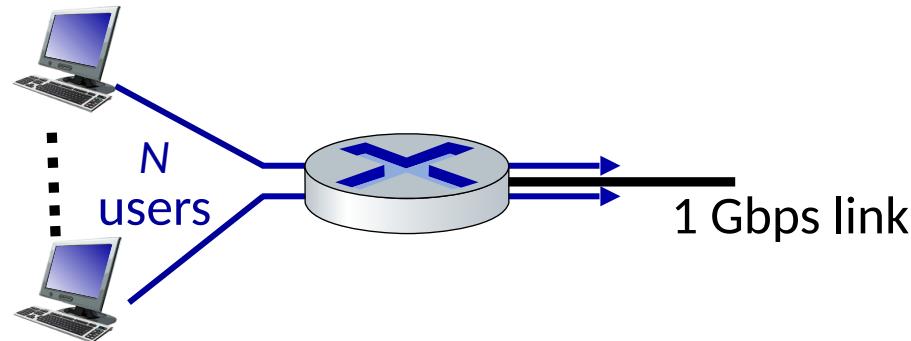


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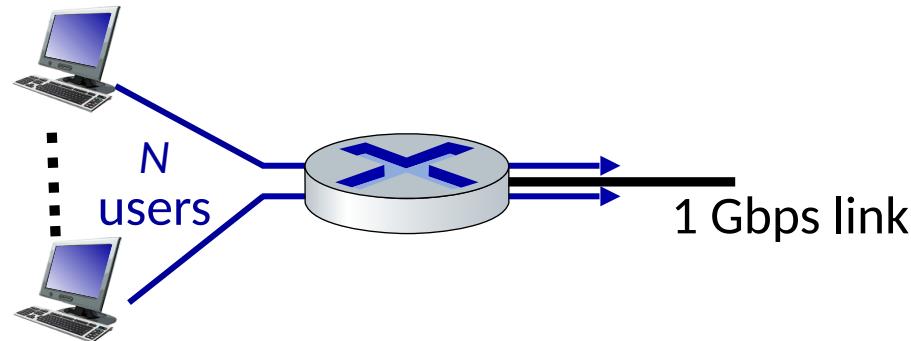
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■ *circuit-switching:* 10 users

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

Q: how did we get value 0.0004?

Q: what happens if > 35 users?

Packet switching versus circuit switching

Is packet switching a “slam dunk winner”?

Packet switching versus circuit switching

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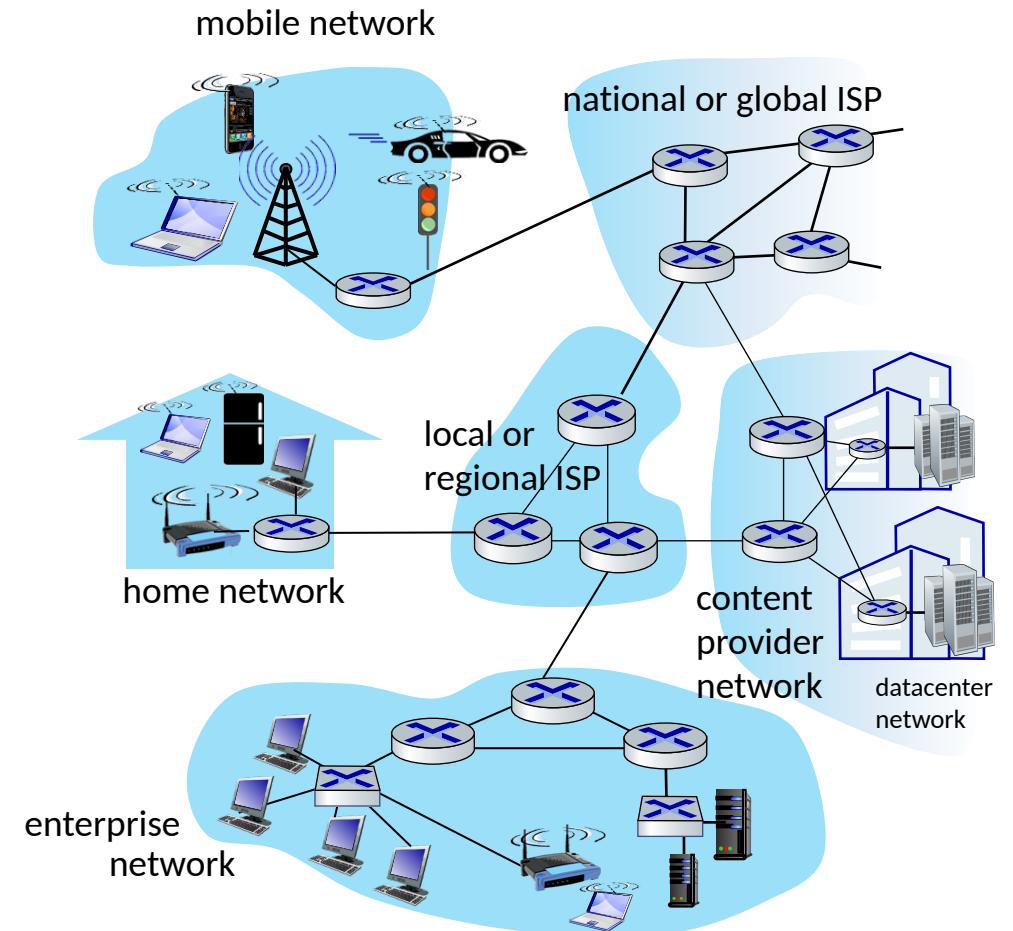
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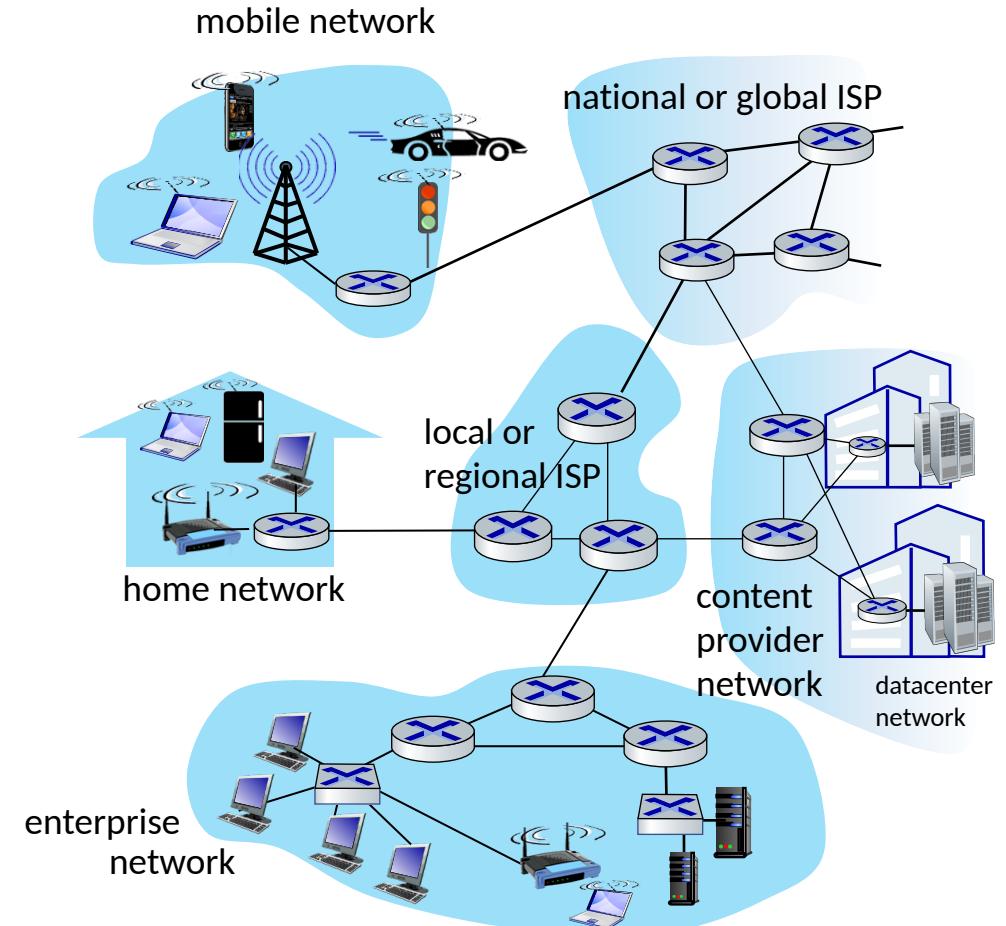
Q: human analogies of reserved resources (circuit switching) versus on-demand allocation (packet switching)?

Internet structure: a “network of networks”



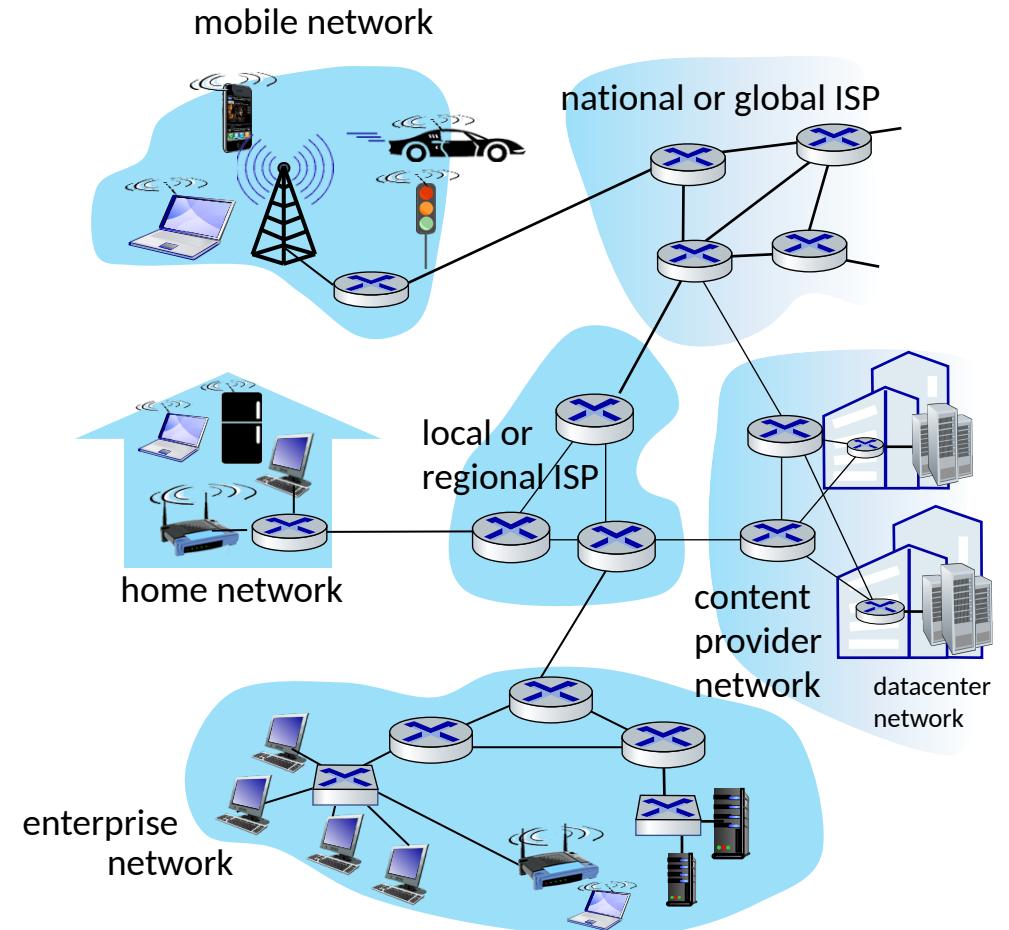
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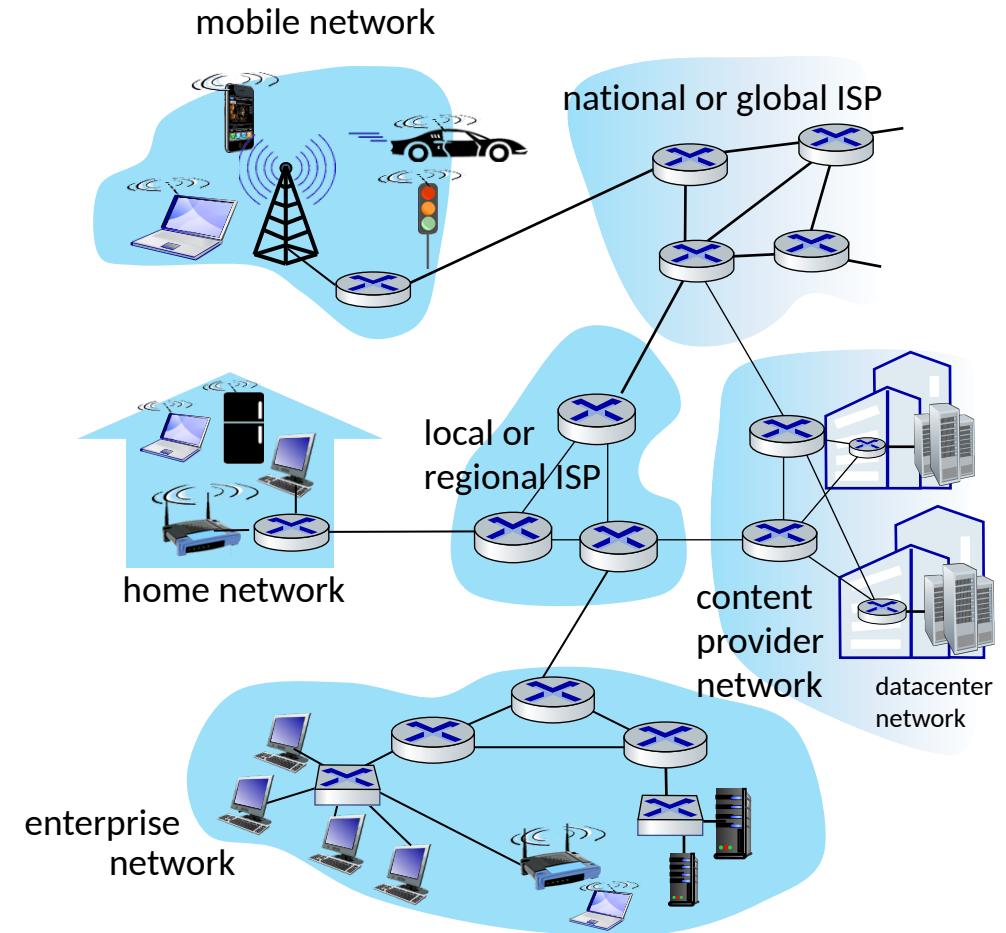
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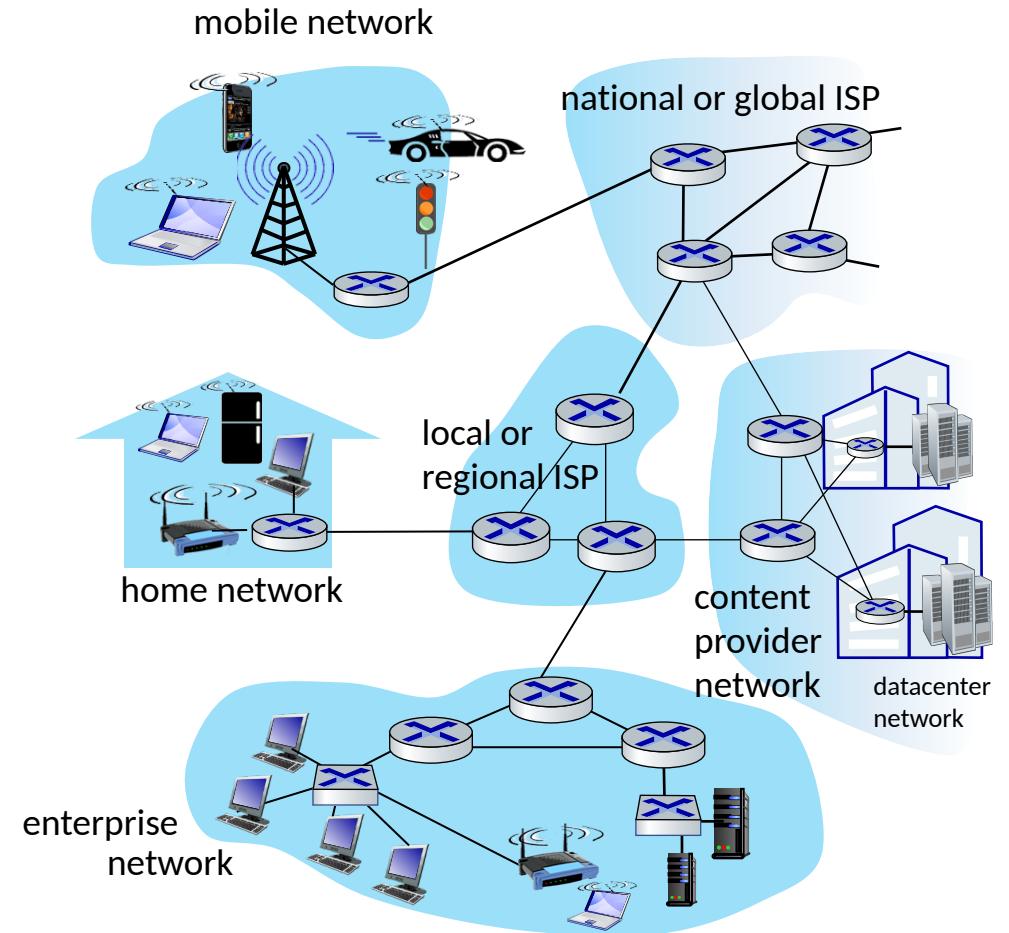
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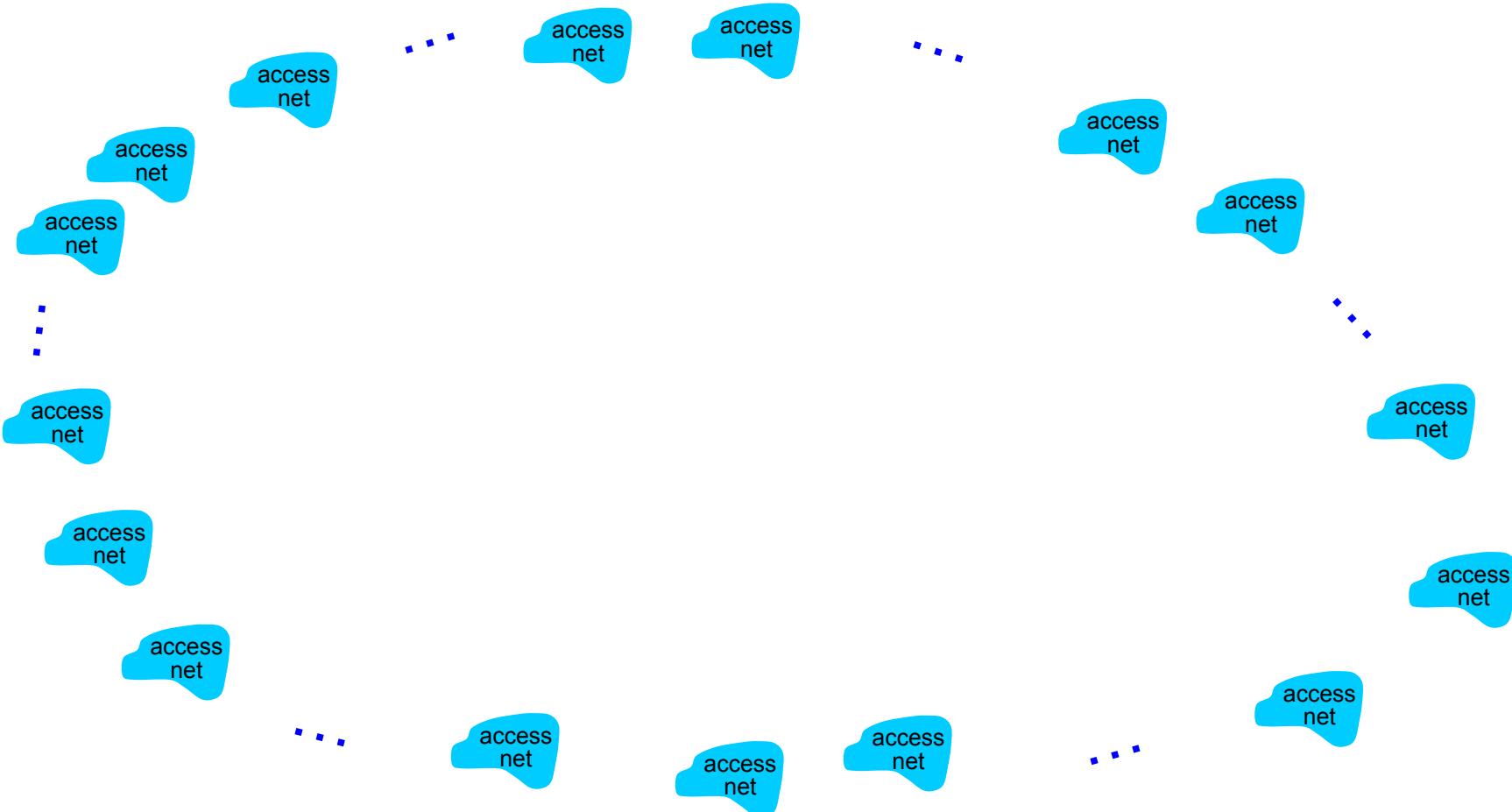
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Let's take a stepwise approach to describe current Internet structure

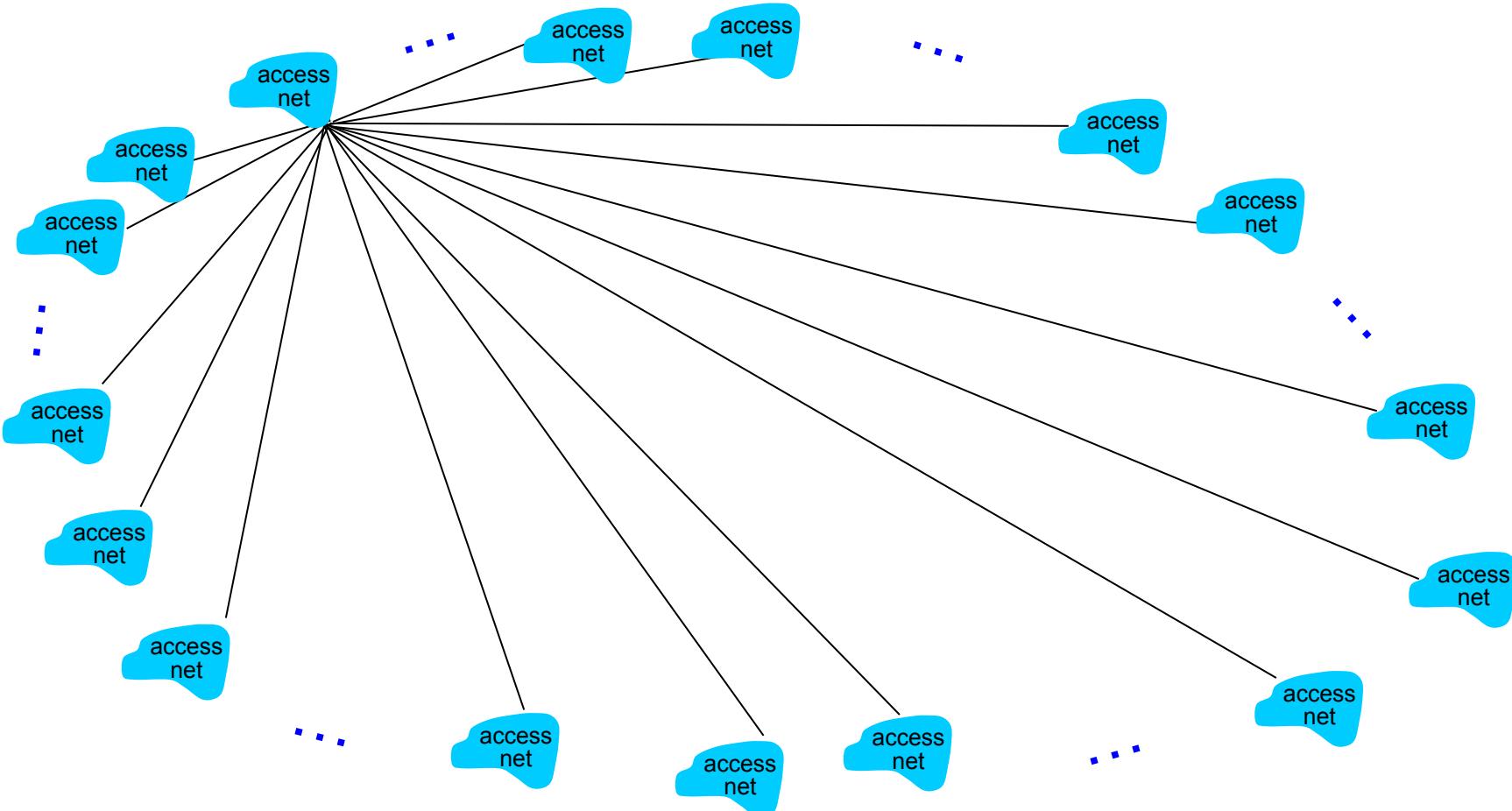
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Question: given *millions* of access ISPs, how to connect them together?



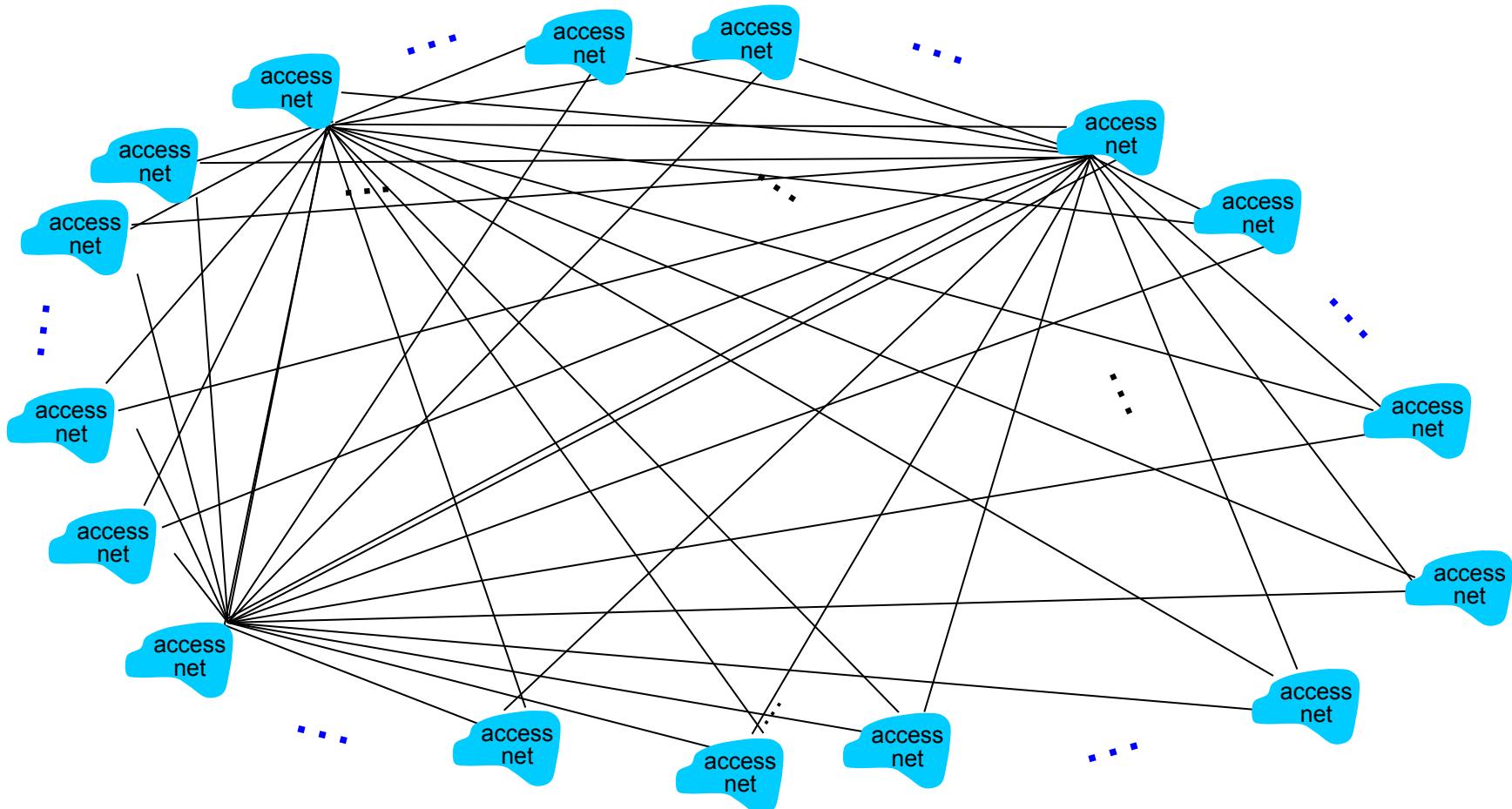
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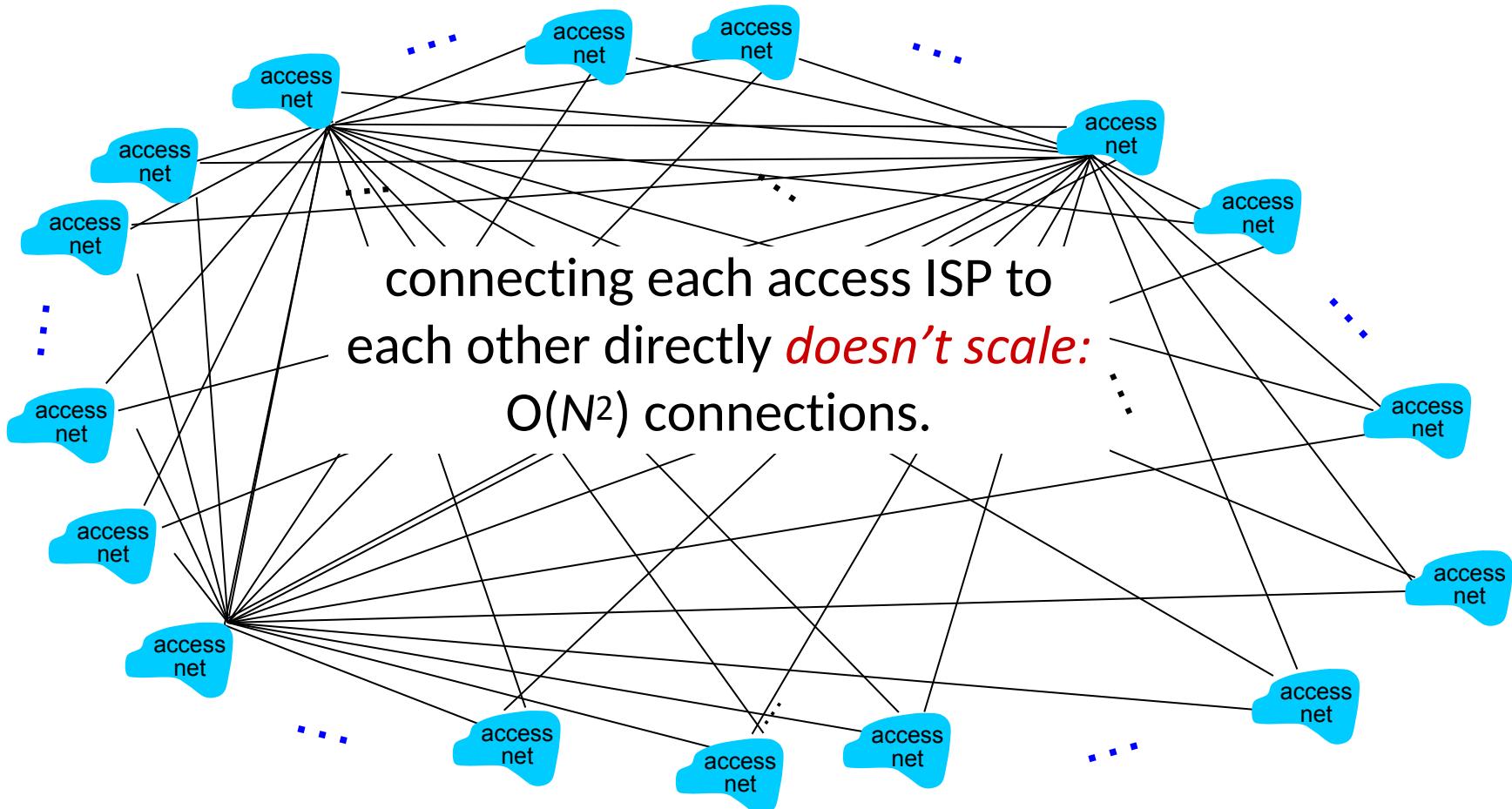
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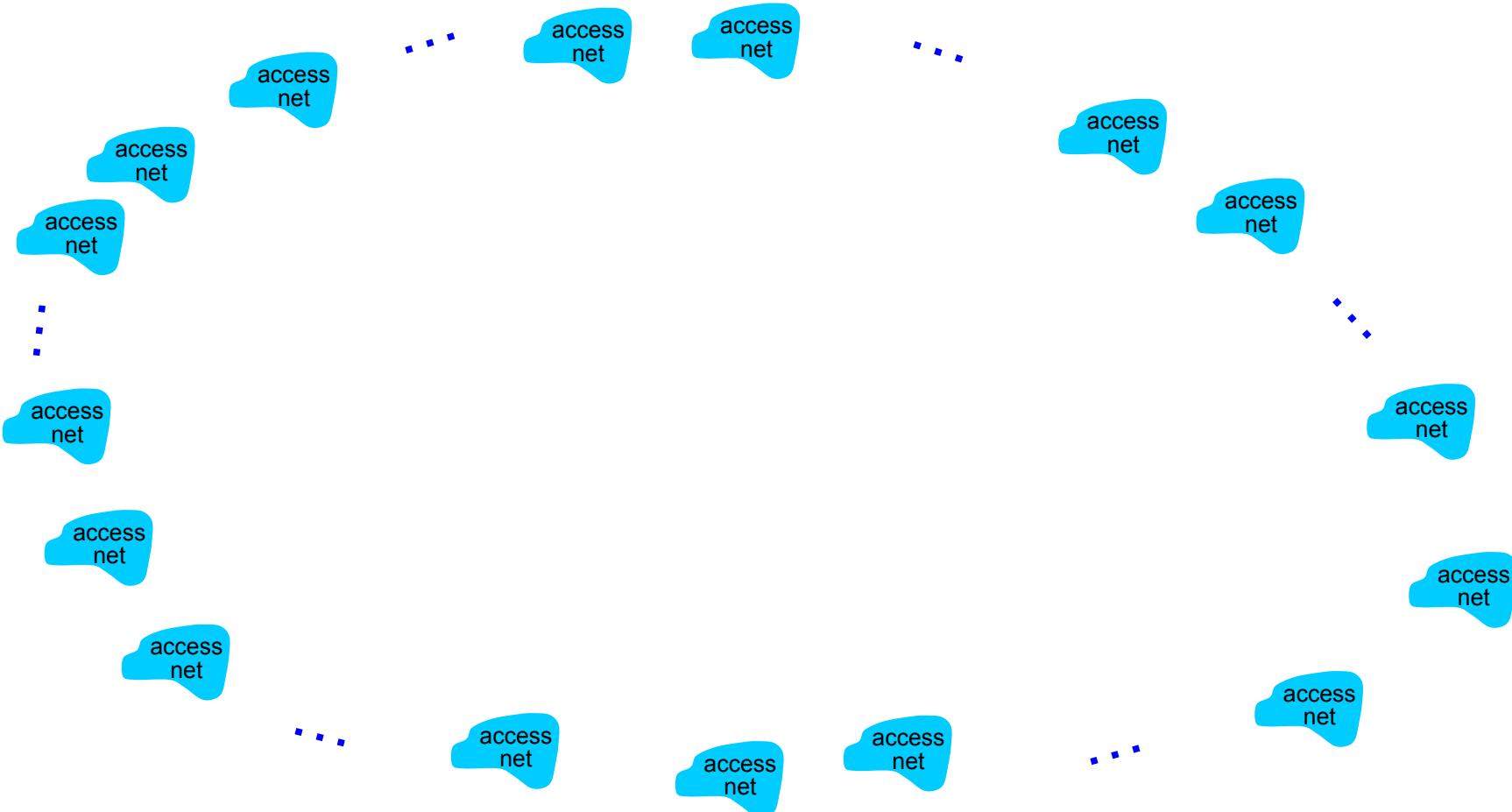
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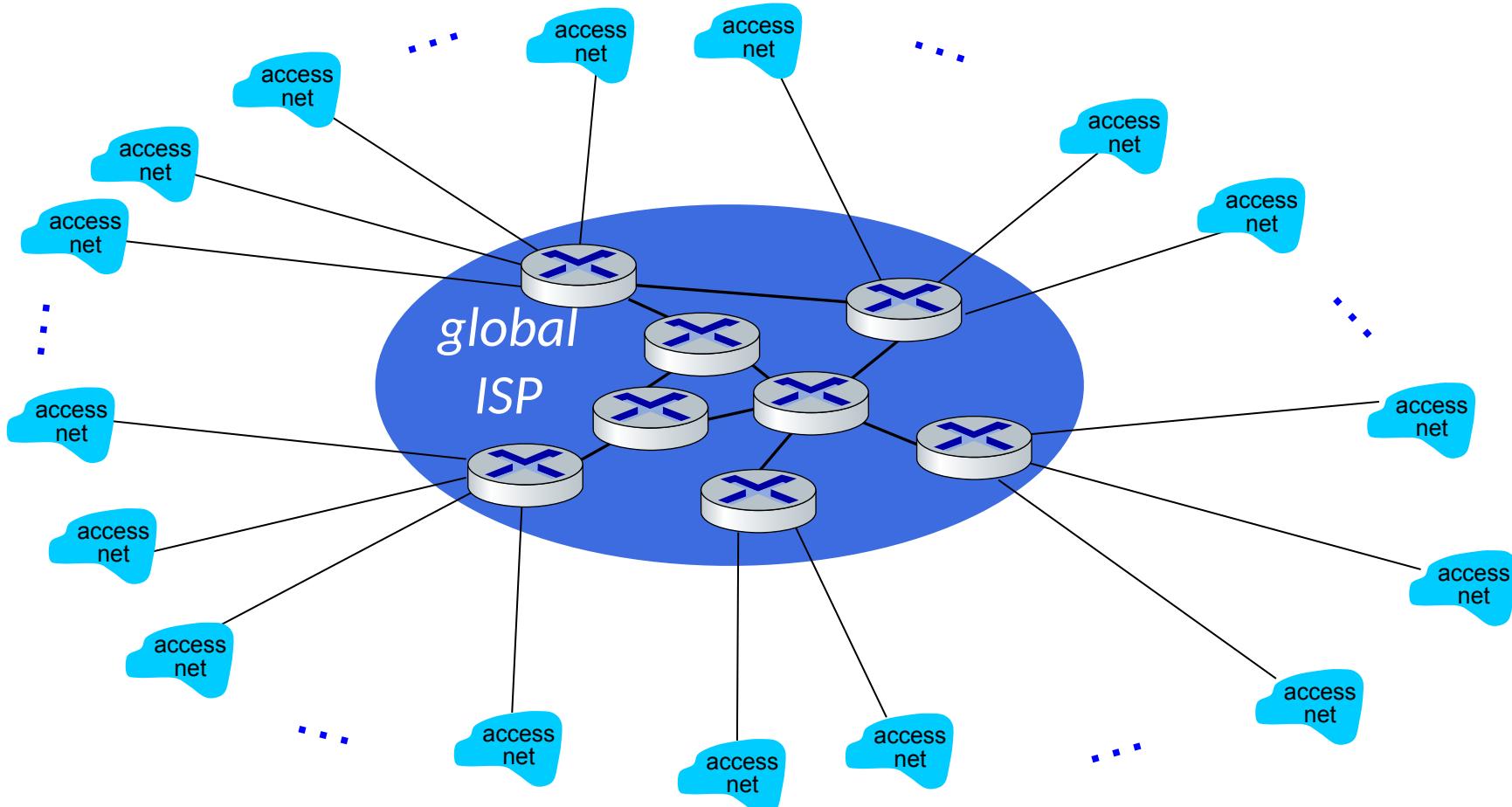
Customer and provider ISPs have economic agreement.



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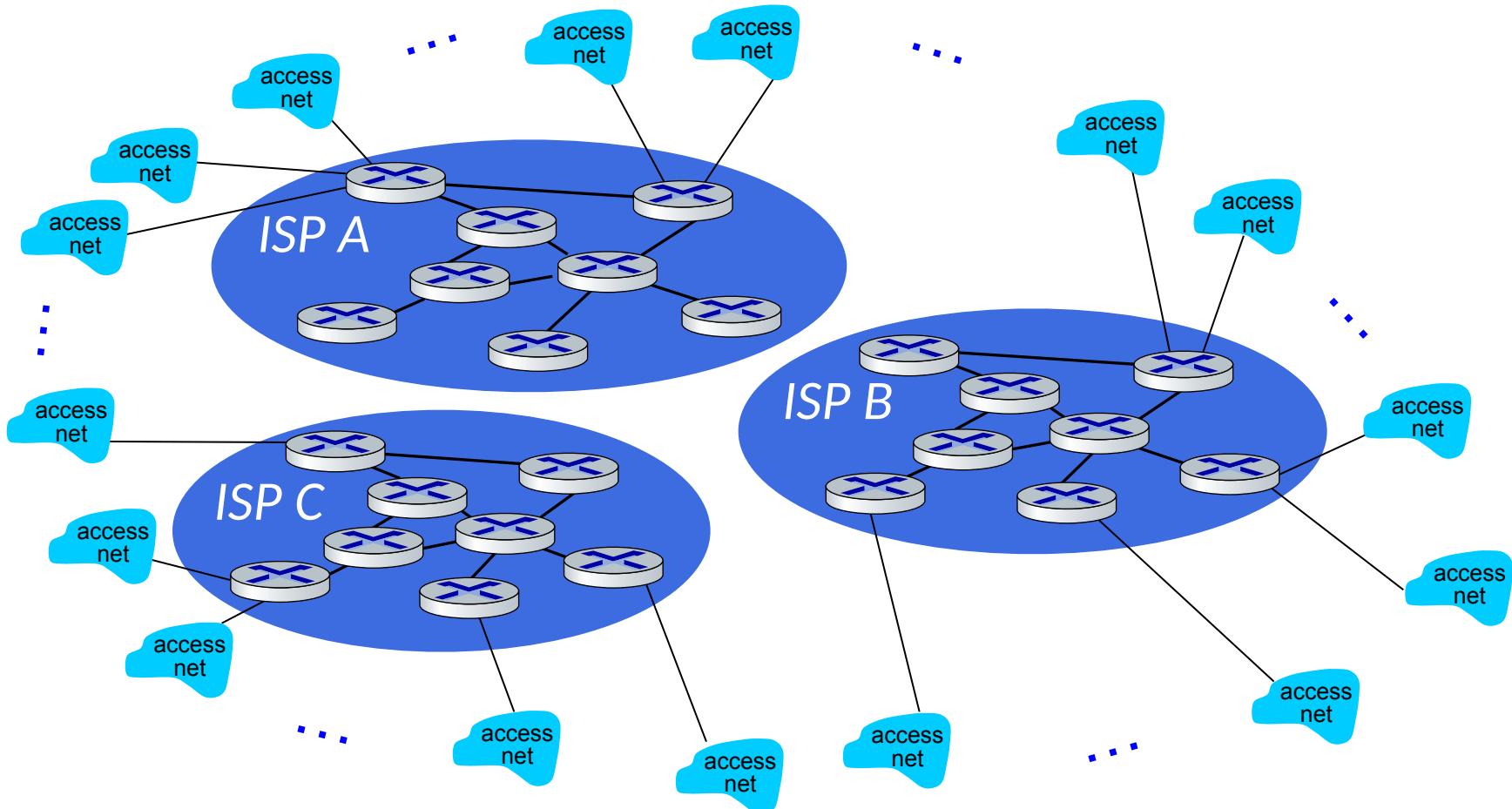
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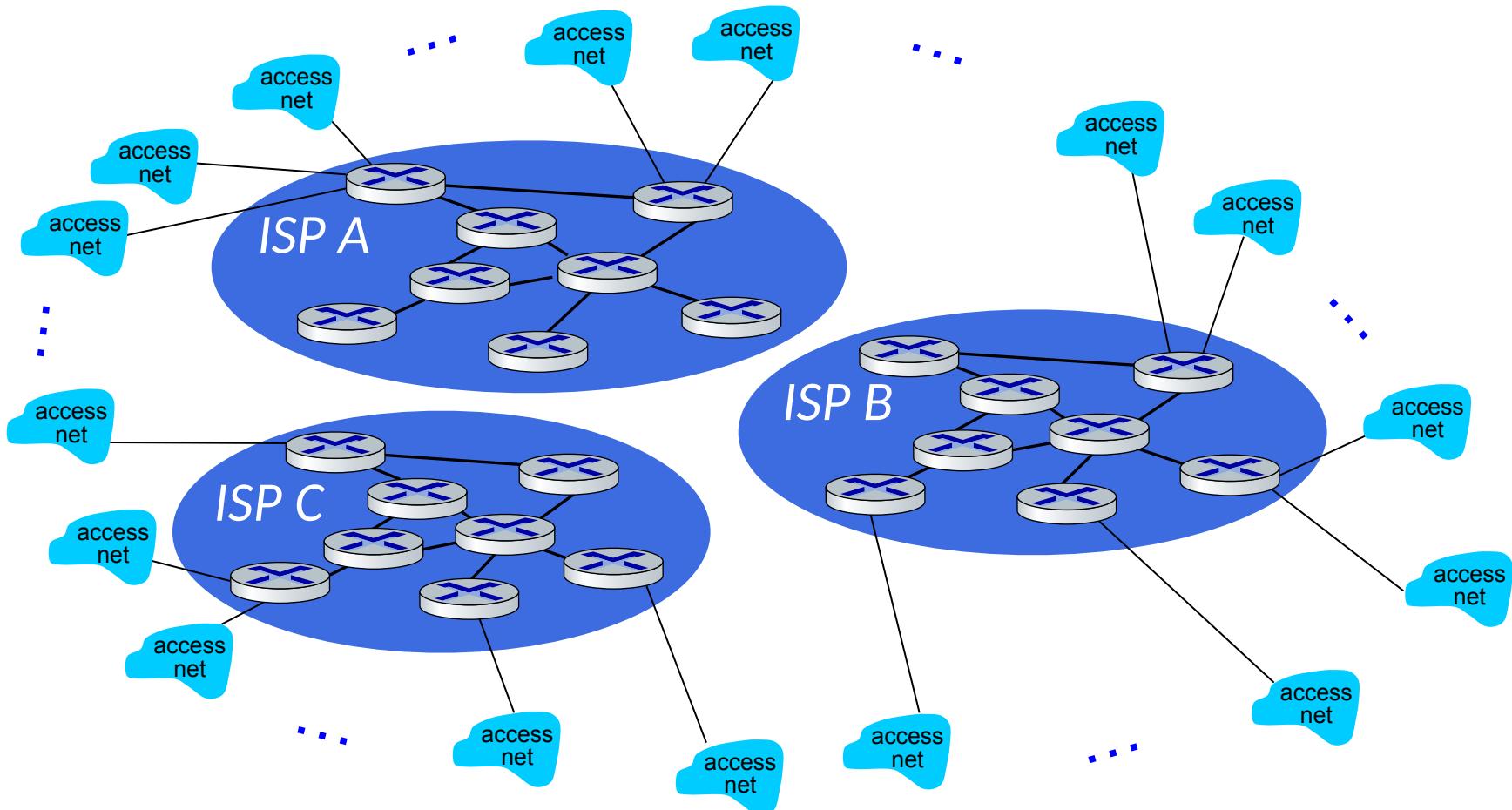
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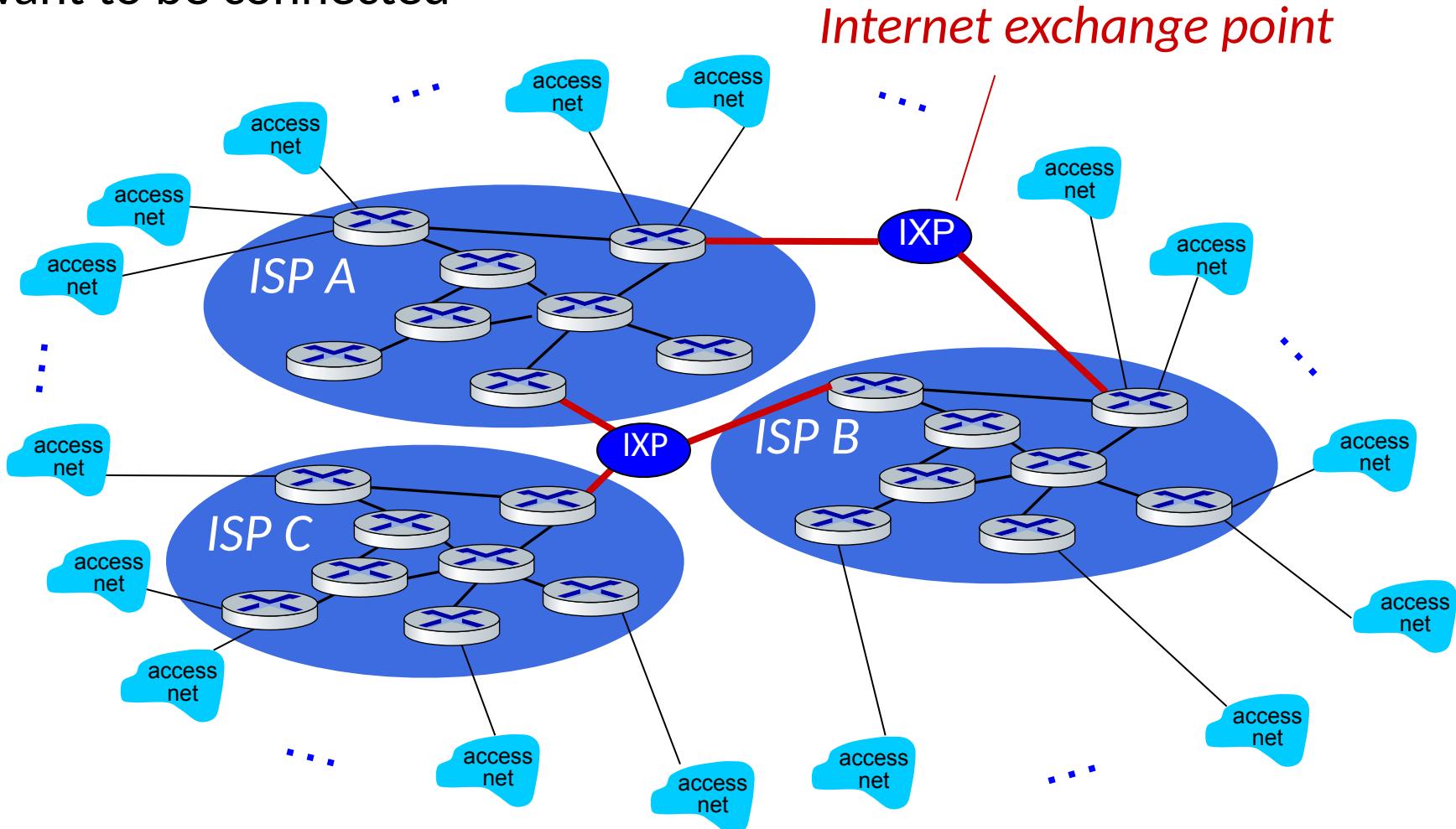
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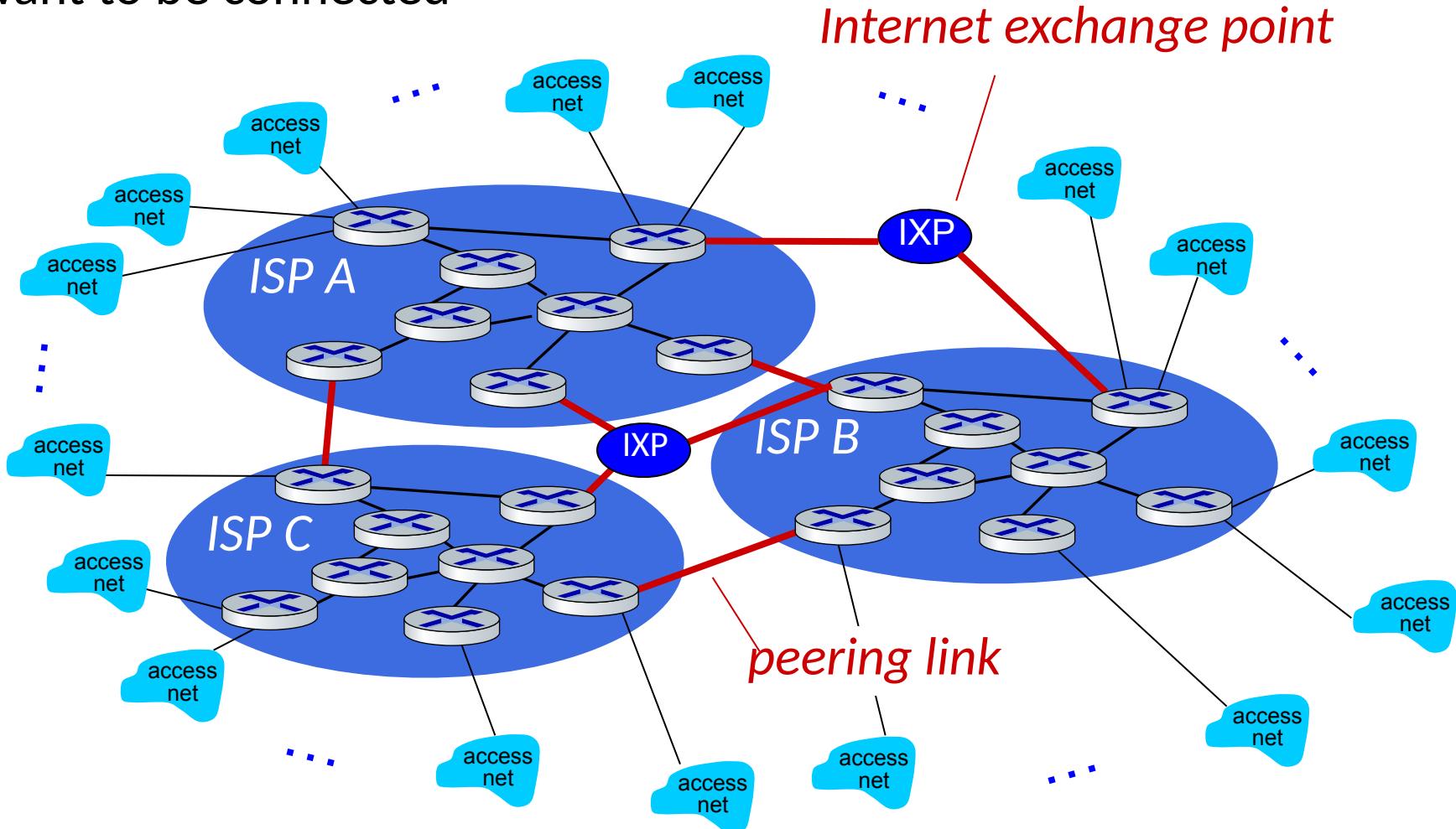
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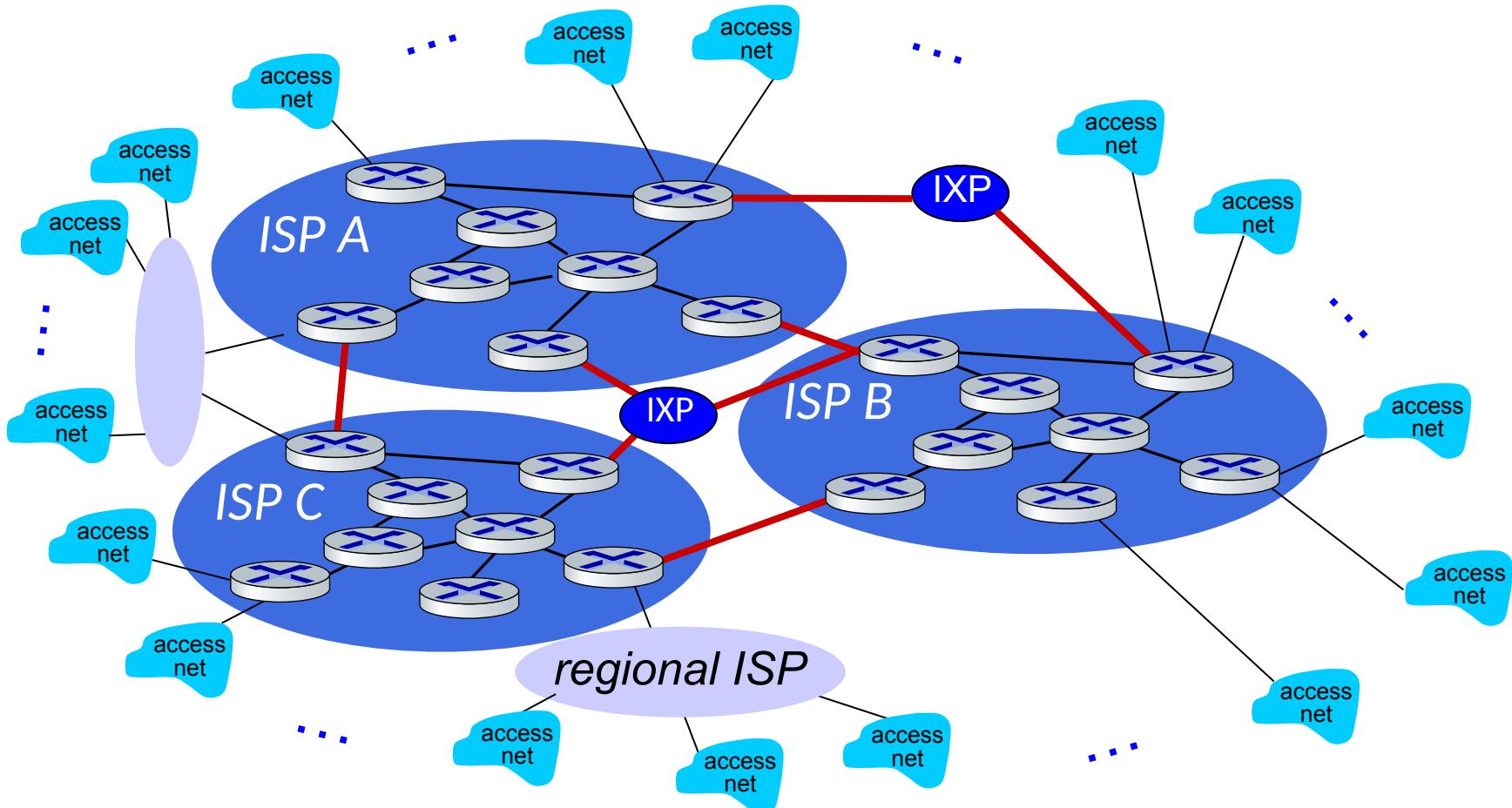
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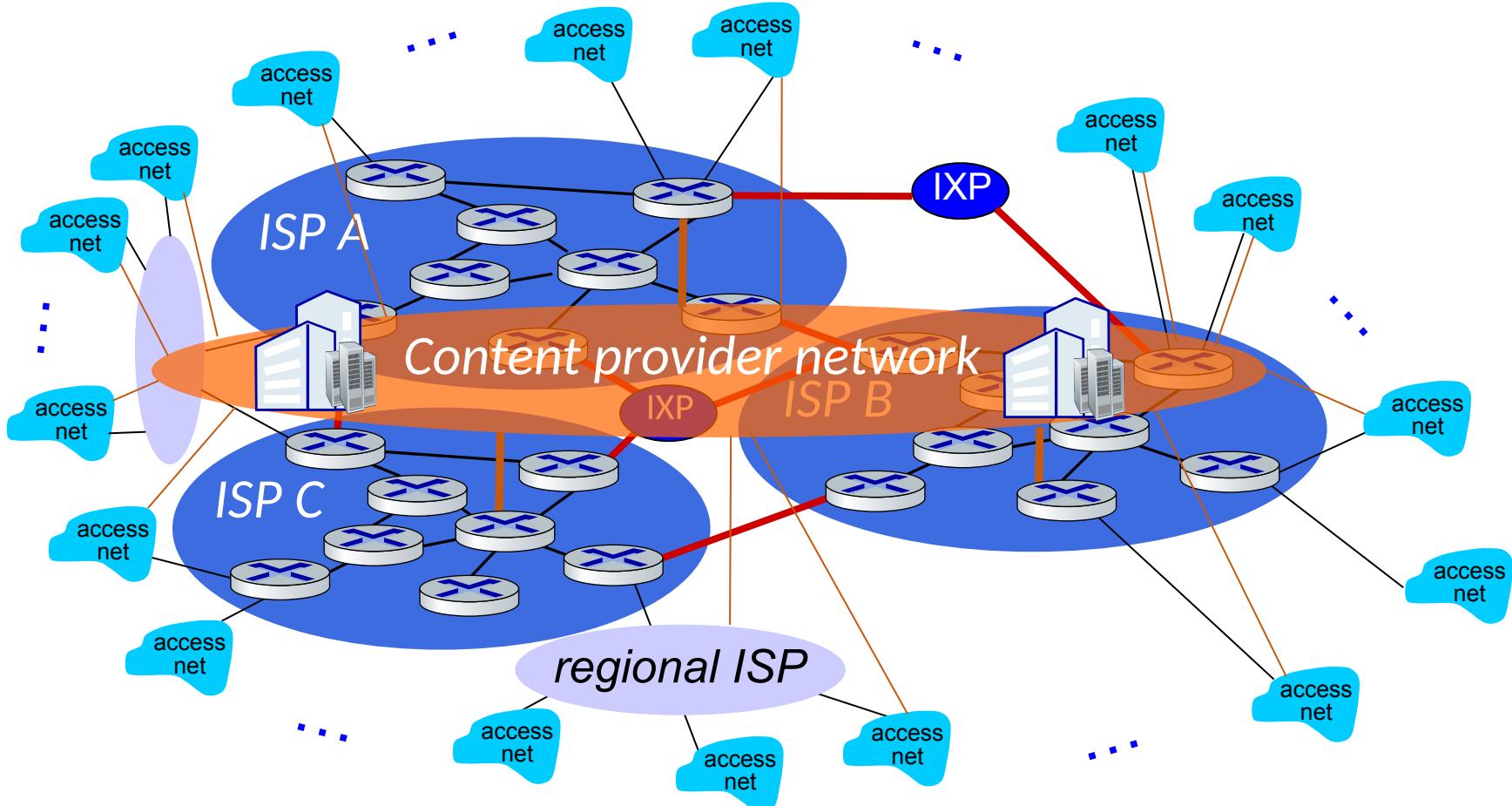
Internet structure: a “network of networks”

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

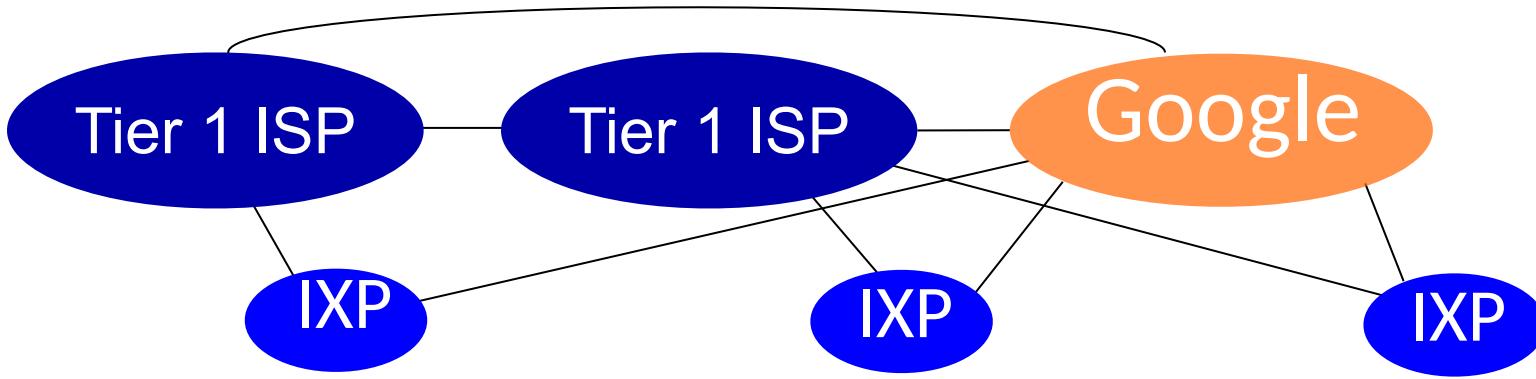


Internet structure: a “network of networks”

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



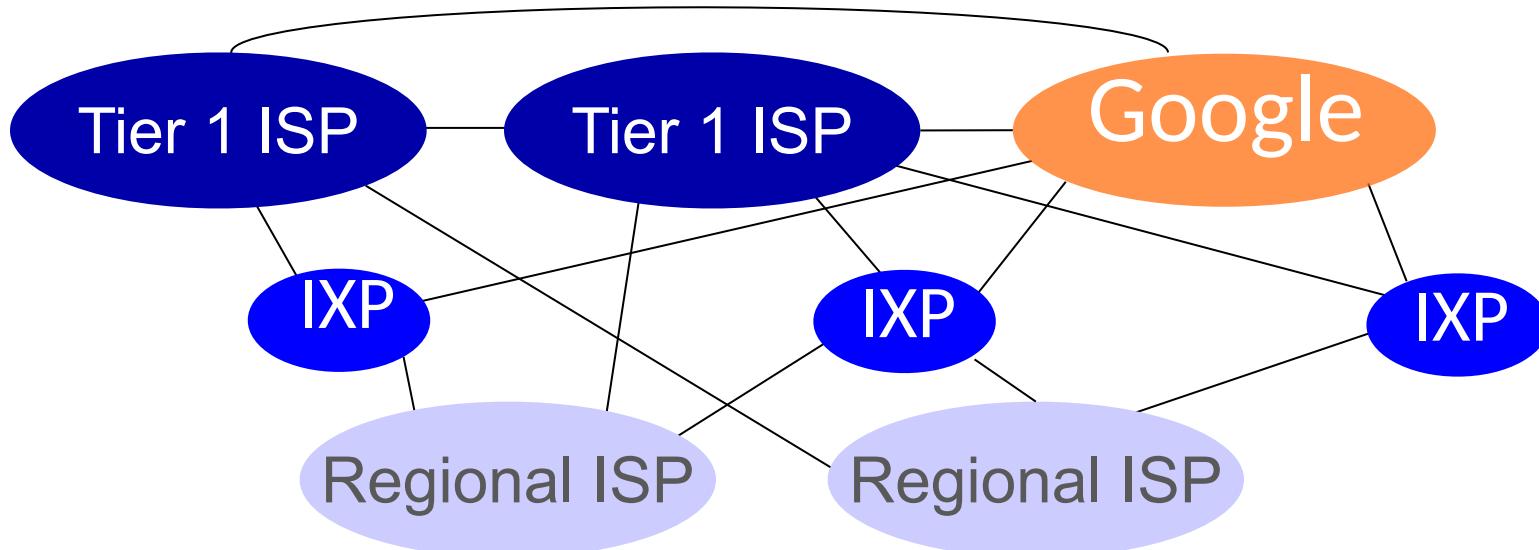
Internet structure: a “network of networks”



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

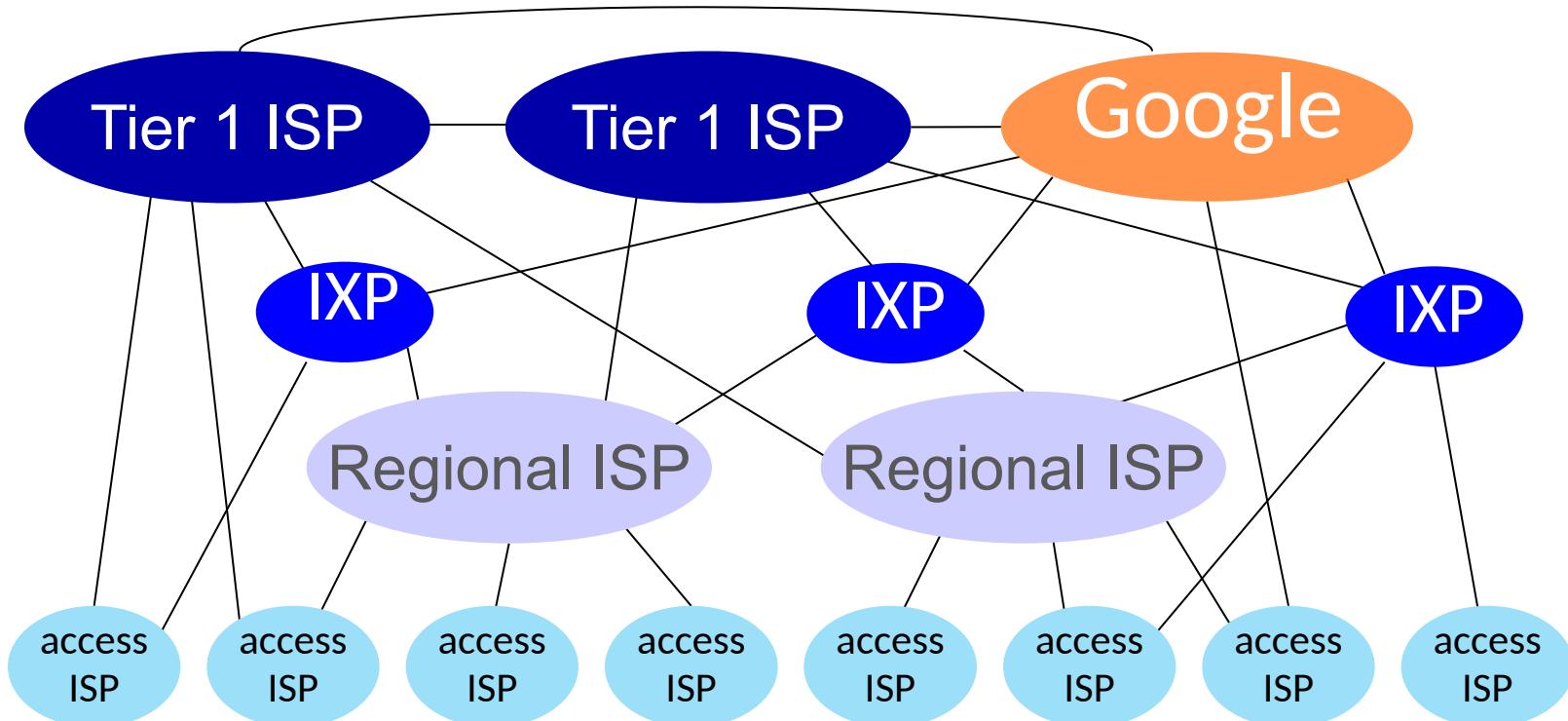
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More about communication networks: where?

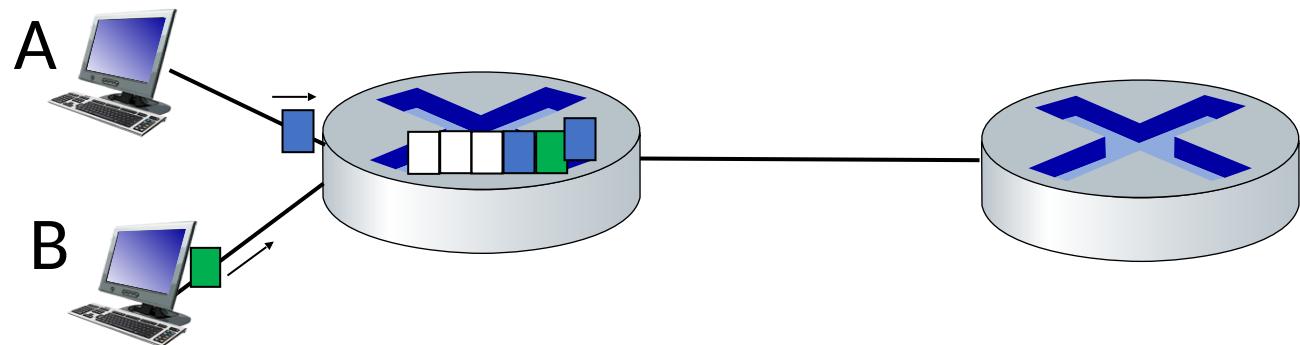
- Internet related routing is presented in [Redes de Internet](#)
- The evolution of Internet and Wireless Networks are presented in [Tecnologias Avançadas de Redes](#)
- Core networks are presented in [Redes de Núcleo](#)
- Content networks are presented in [Redes de Distribuição de Conteúdos](#)
- Quality of service and multimedia related protocols are presented in [Redes e Serviços de Comunicações Multimédia](#)
- Network services are presented in [Integração de Redes e Serviços](#)
- Network design is presented in [Projecto de Redes de Computadores](#)
- Network automation is presented in [Administração Automatizada de Redes](#)
- Security is presented in [Ciber-segurança](#) and [Segurança em Redes](#)
- Internet of Things is presented in [Internet das Coisas](#)
- Mobile Networks are presented in [Redes de Comunicações Móveis](#)

Chapter 1: roadmap

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

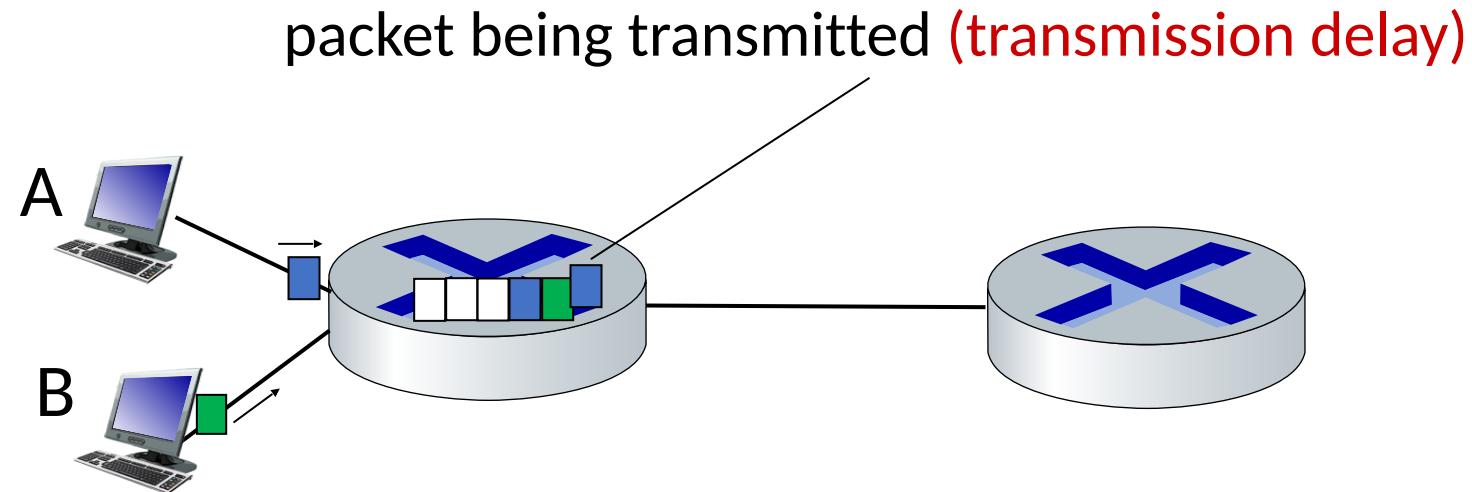
How do packet delay and loss occur?

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- packet *loss* occurs when memory to hold queued packets fills up



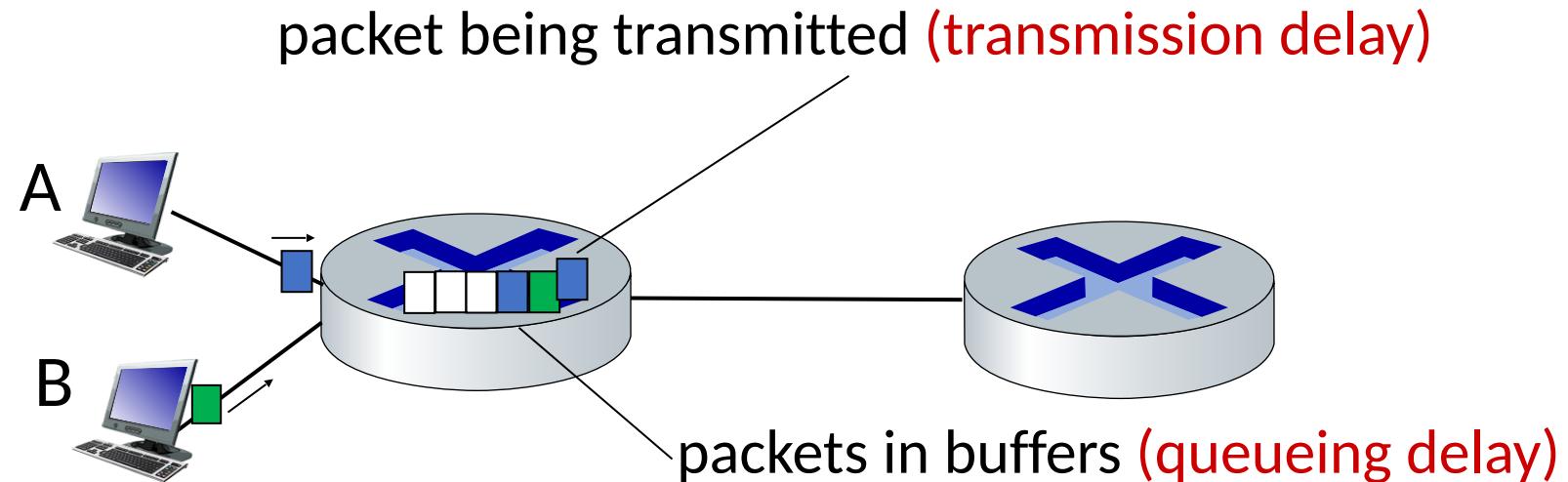
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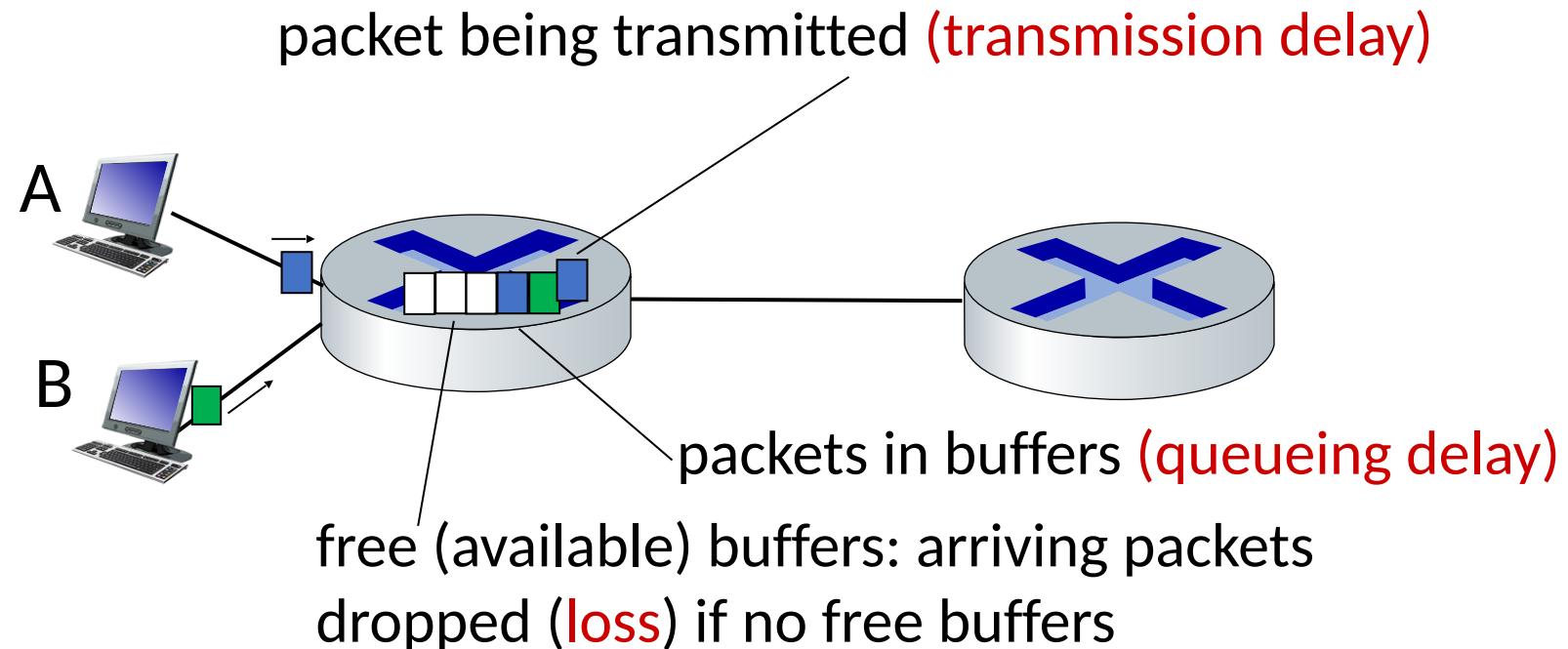
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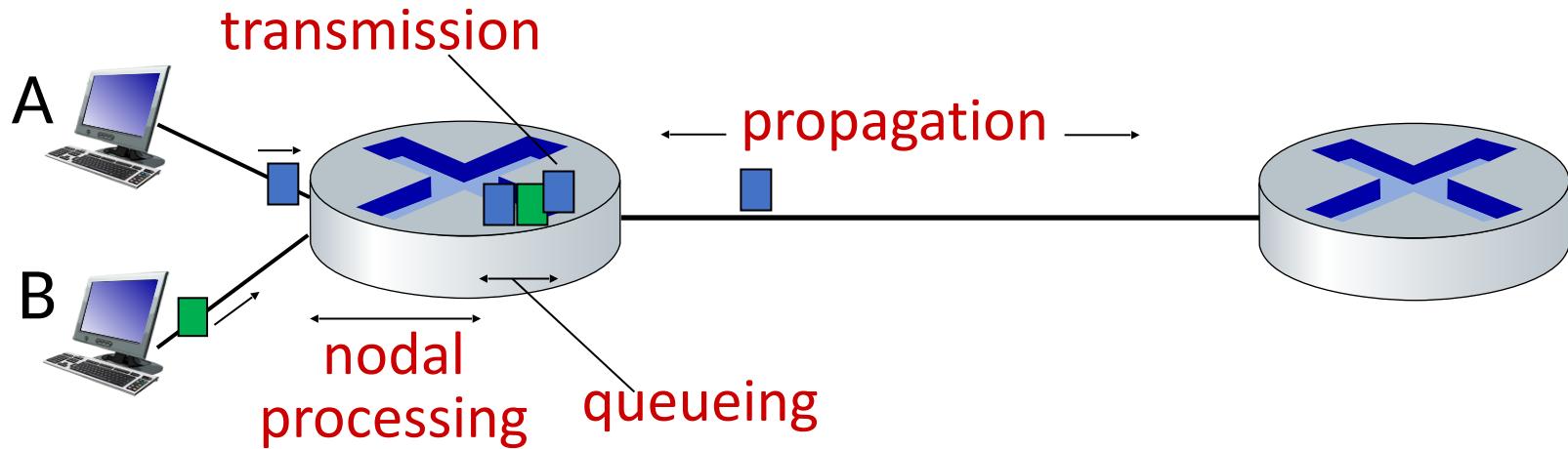


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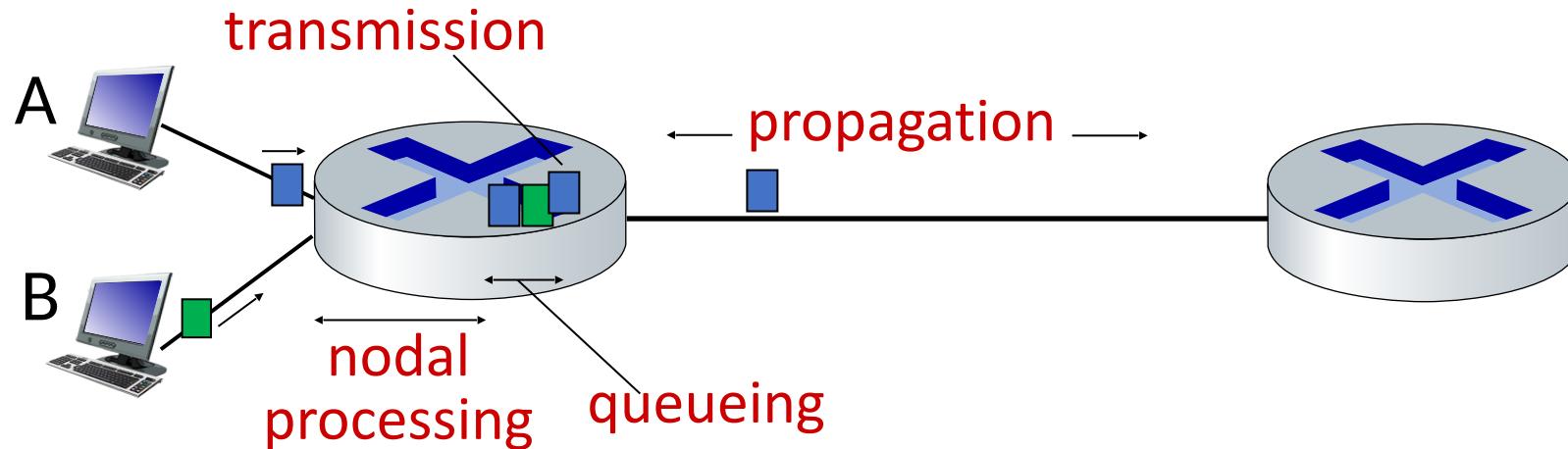


Packet delay: four sources



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

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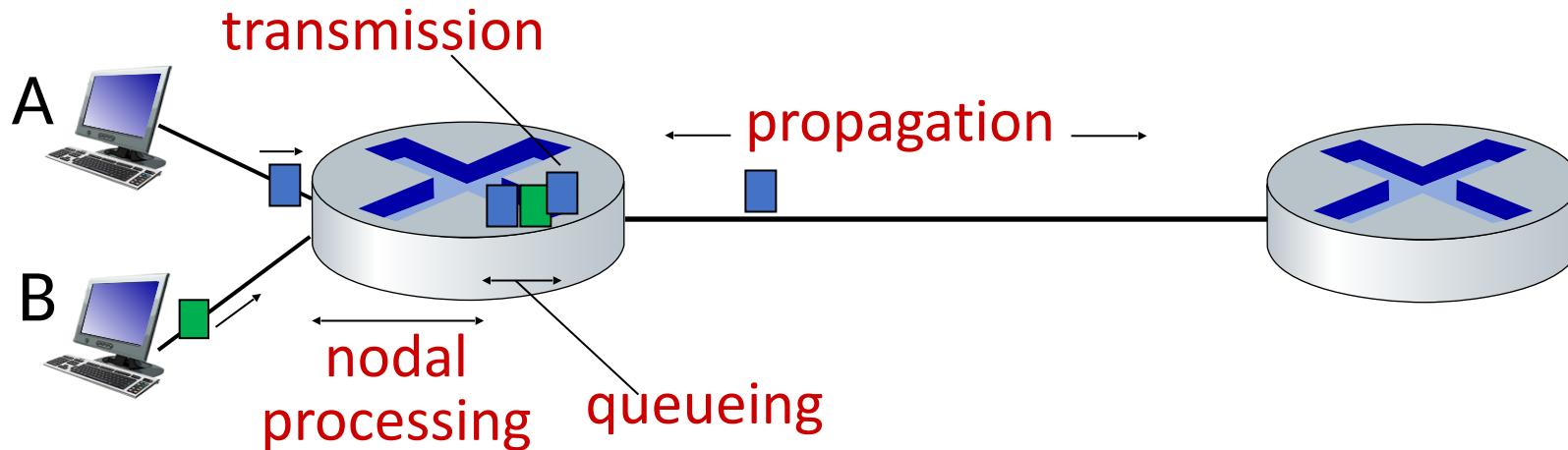


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d_{proc} : nodal processing

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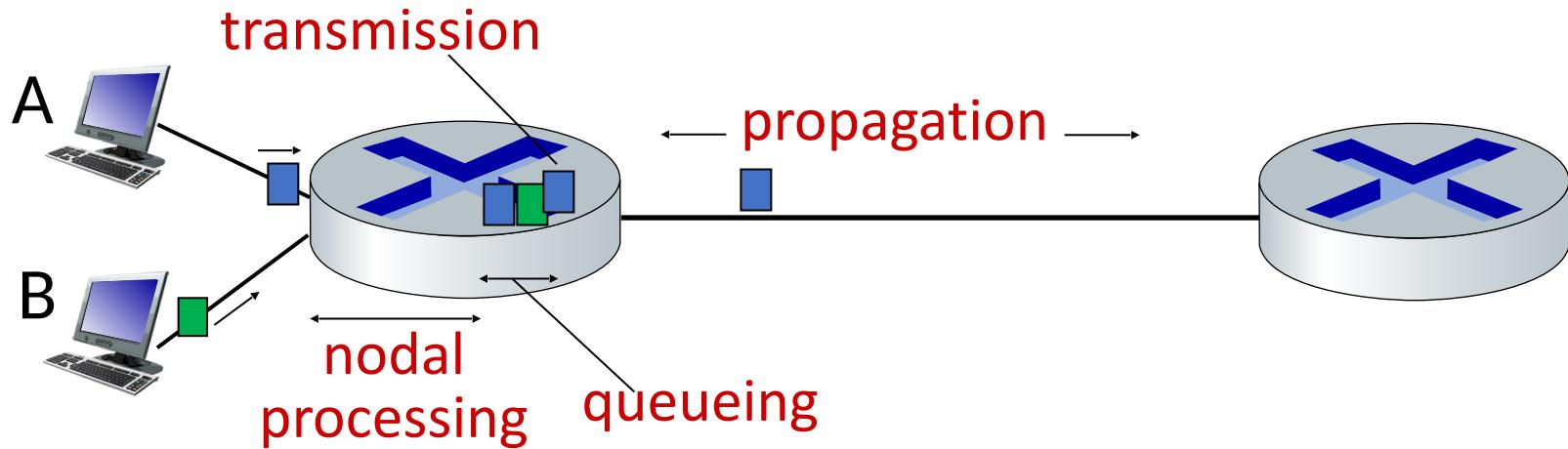
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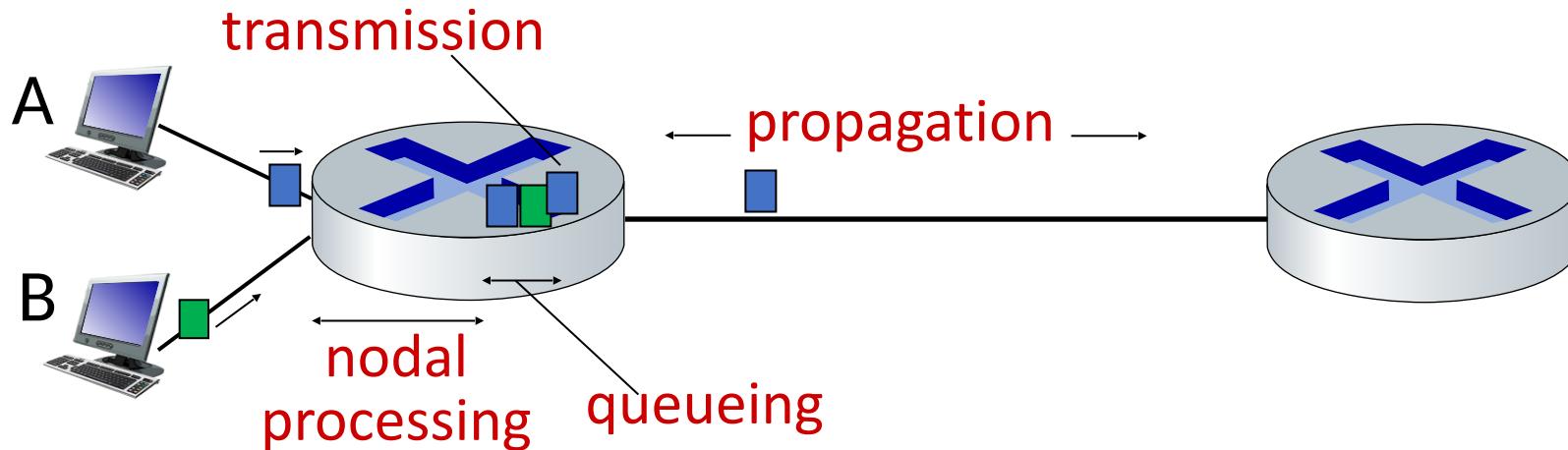
- time waiting at output link for transmission
- depends on congestion level of router

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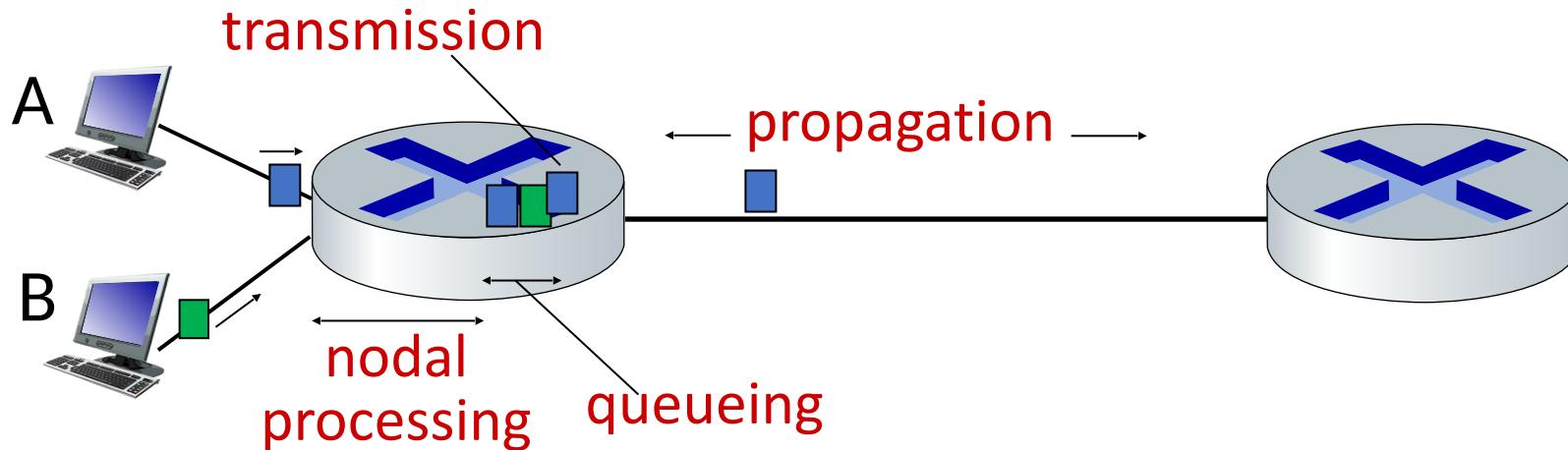


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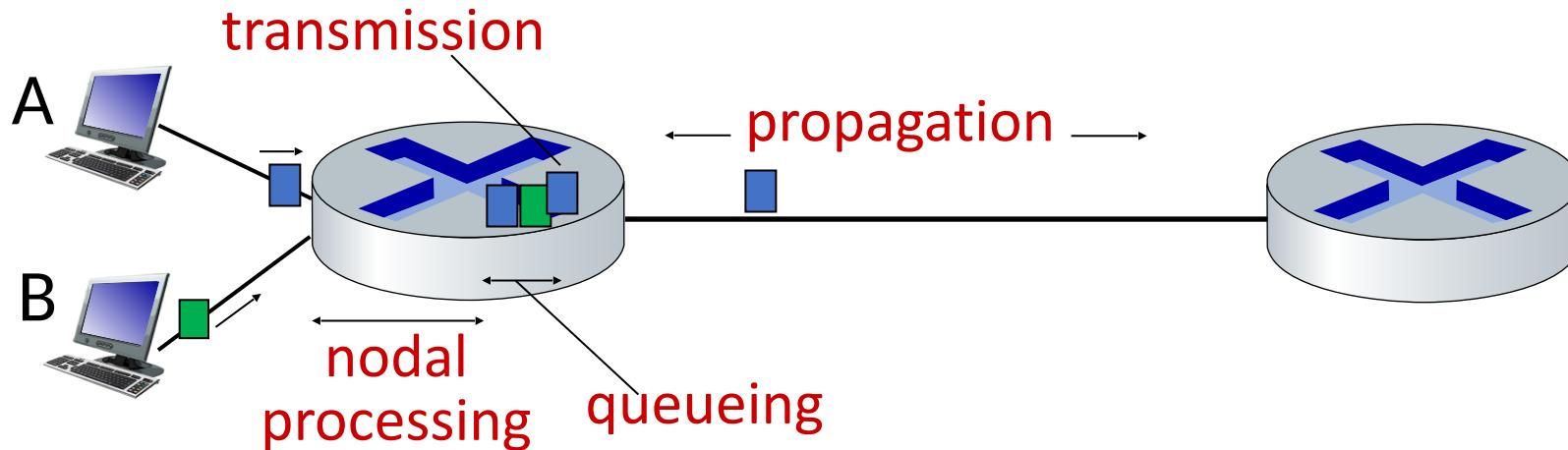
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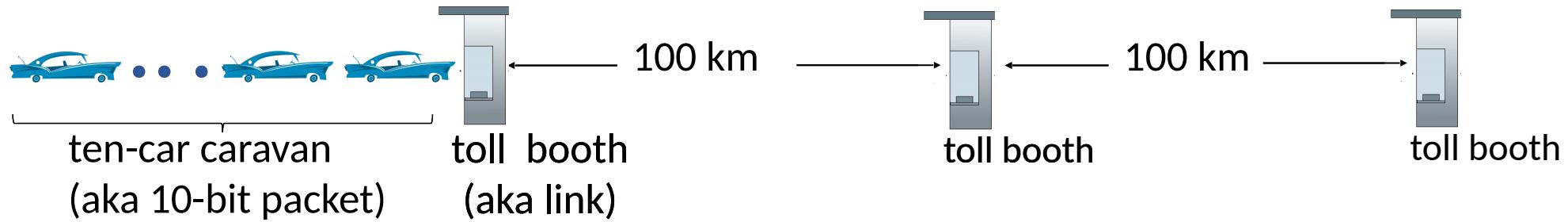
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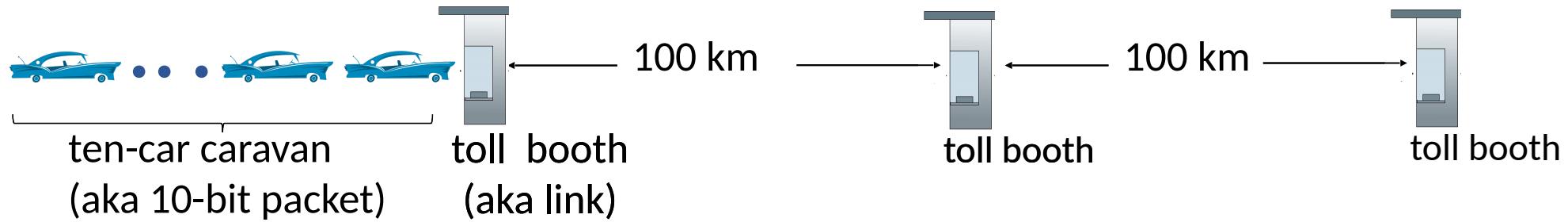
d_{trans} and d_{prop}
very different

Caravan analogy



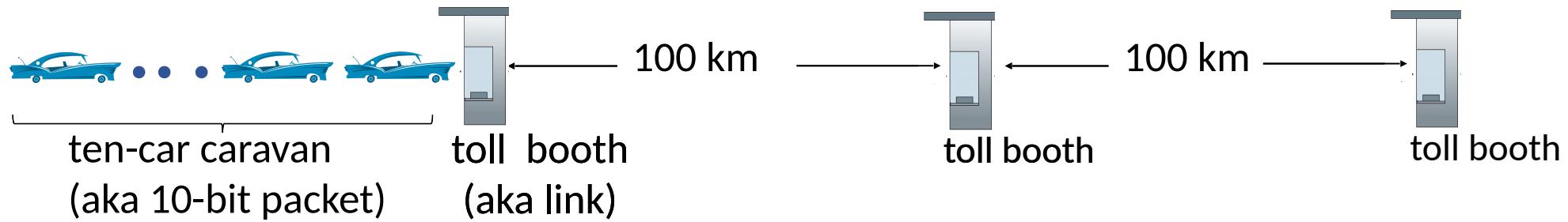
- car ~ bit; caravan ~ packet; toll service ~ link transmission
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- “propagate” at 100 km/hr
- *Q: How long until caravan is lined up before 2nd toll booth?*

Caravan analogy



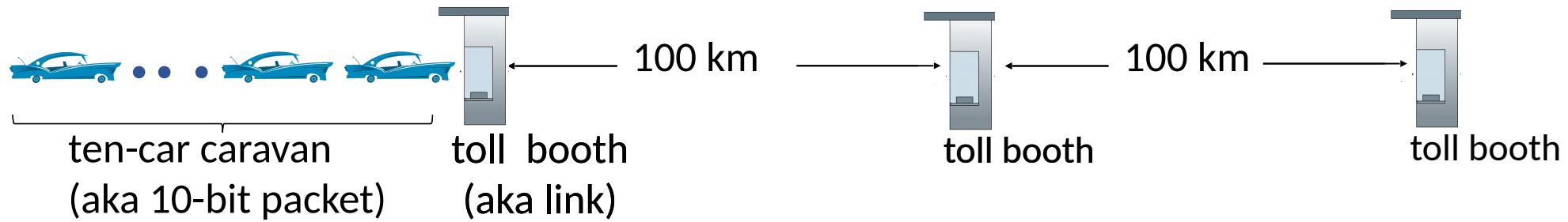
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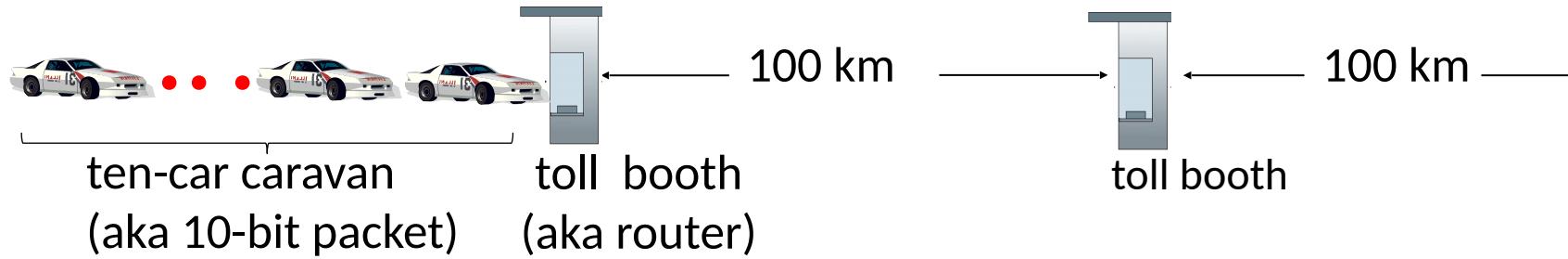
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- **A: 62 minutes**

Caravan analogy



- suppose cars now “propagate” at 1000 km/hr
- and suppose toll booth now takes one min to service a car
- ***Q: Will cars arrive to 2nd booth before all cars serviced at first booth?***

A: Yes! after 7 min, first car arrives at second booth; three cars still at first booth

Packet queueing delay (revisited)

- a : average packet arrival rate
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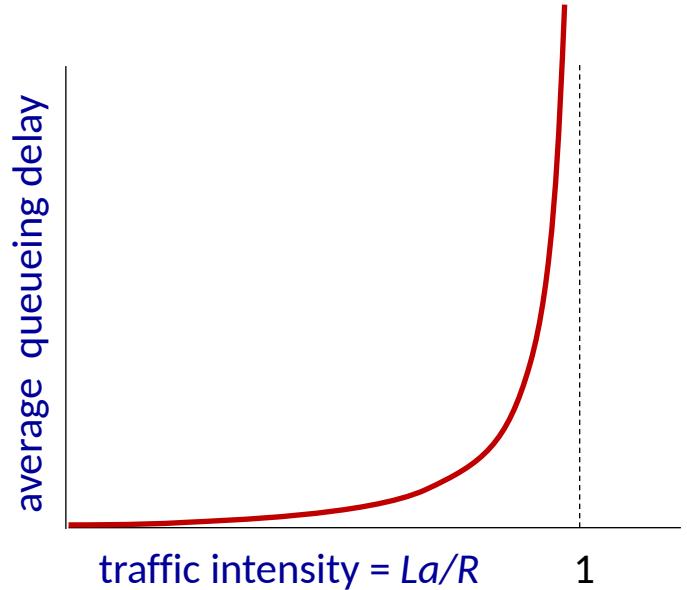
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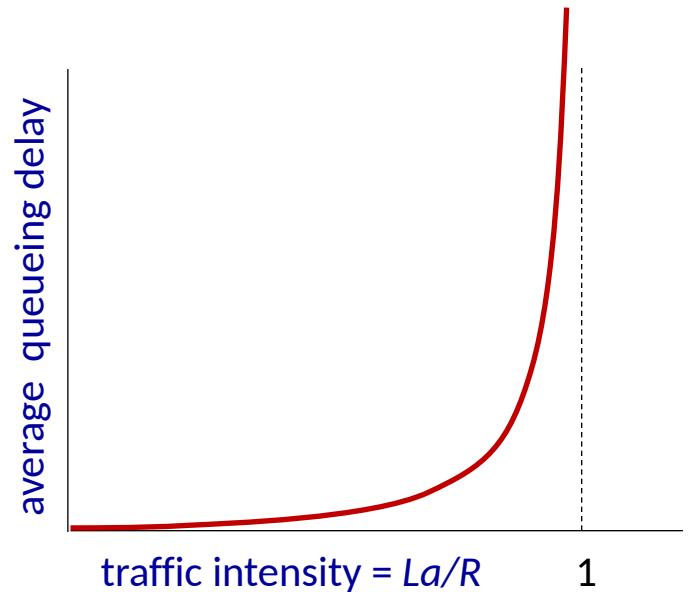
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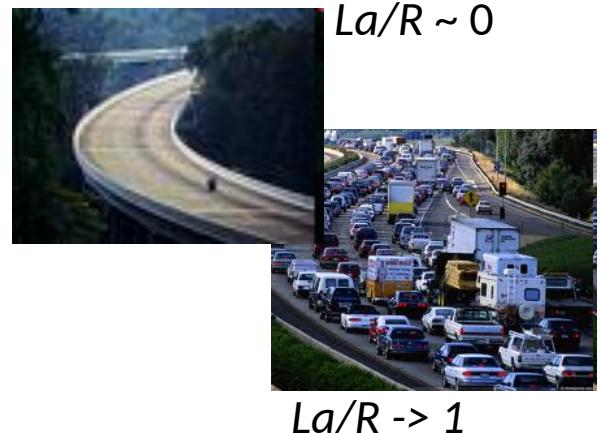
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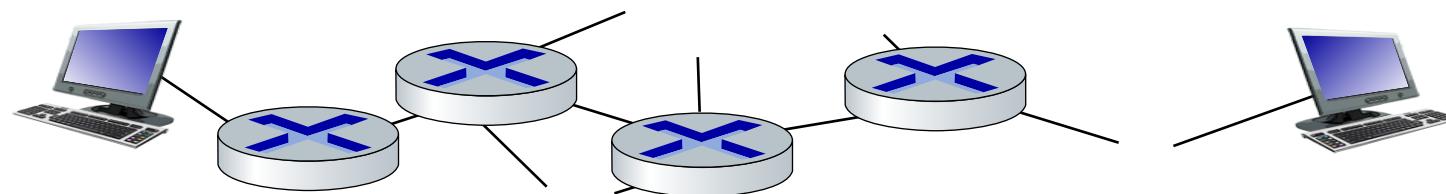


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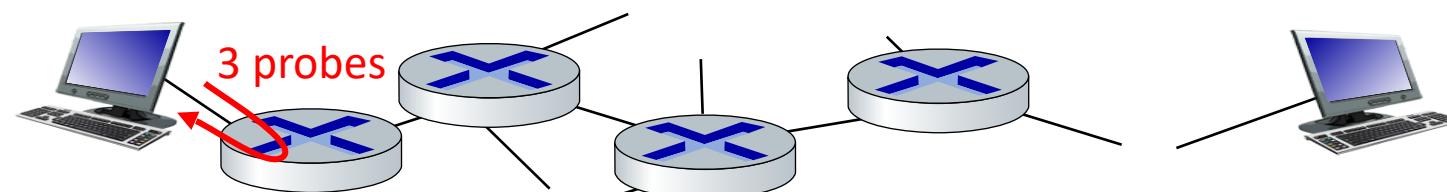
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- what do “real” Internet delay & loss look like?
- **traceroute** program: provides delay measurement from source to router along end-end Internet path towards destination. For all i :



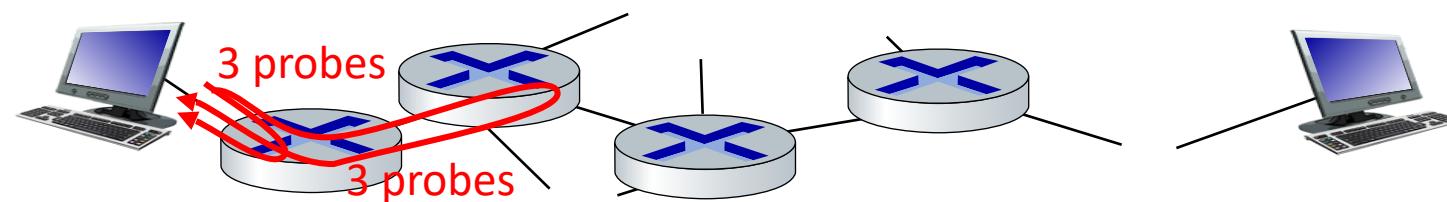
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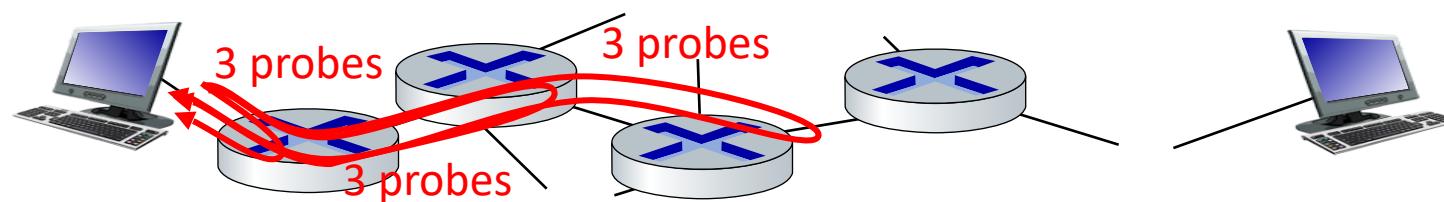
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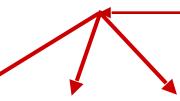
traceroute: gaia.cs.umass.edu to www.eurecom.fr

```
1 cs-gw (128.119.240.254) 1 ms 1 ms 2 ms
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3 delay measurements from
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trans-oceanic link

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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
```

looks like delays
decrease! Why?

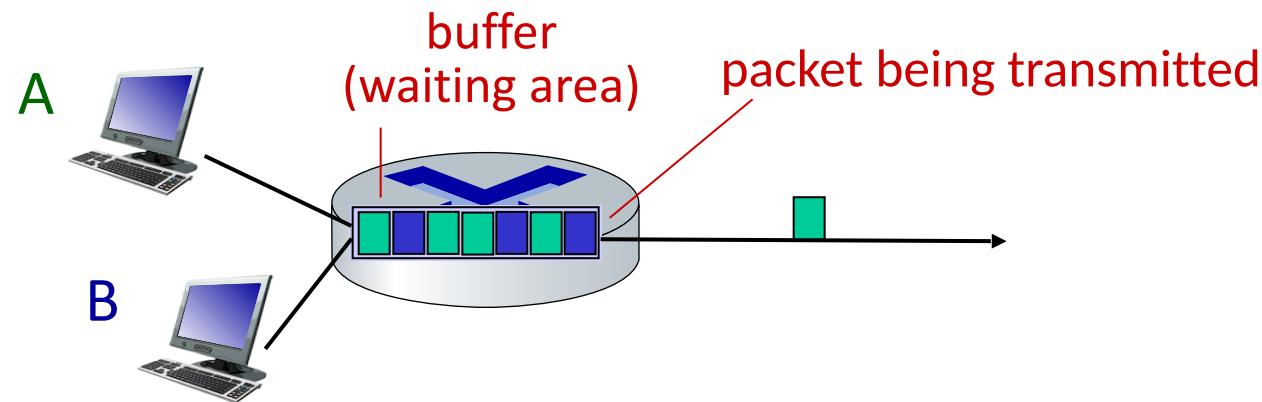
Real Internet delays and routes

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

```
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
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16 194.214.211.25 (194.214.211.25) 126 ms 128 ms 126 ms
17 * * *
18 * * * ← * means no response (probe lost, router not replying)
19 fantasia.eurecom.fr (193.55.113.142) 132 ms 128 ms 136 ms
```

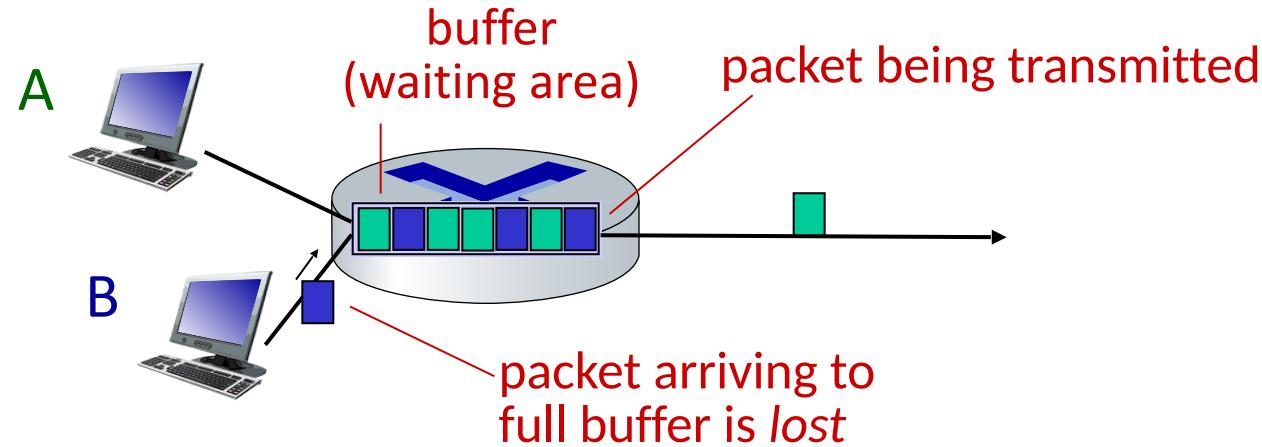
Packet loss

- queue (aka buffer) preceding link in buffer has finite capacity



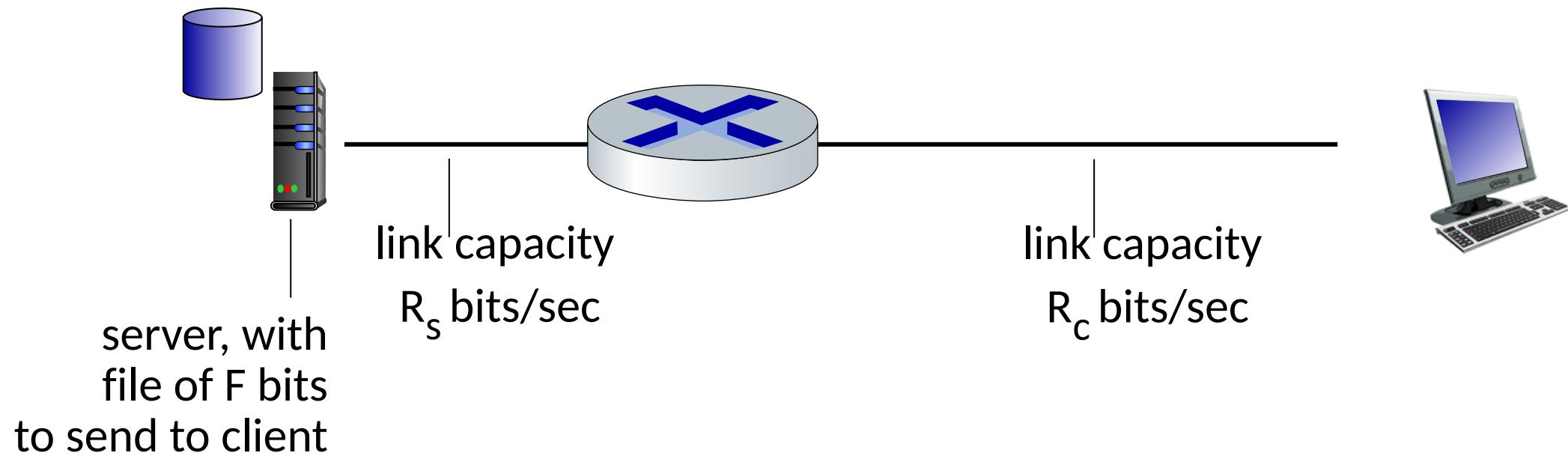
Packet loss

- 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



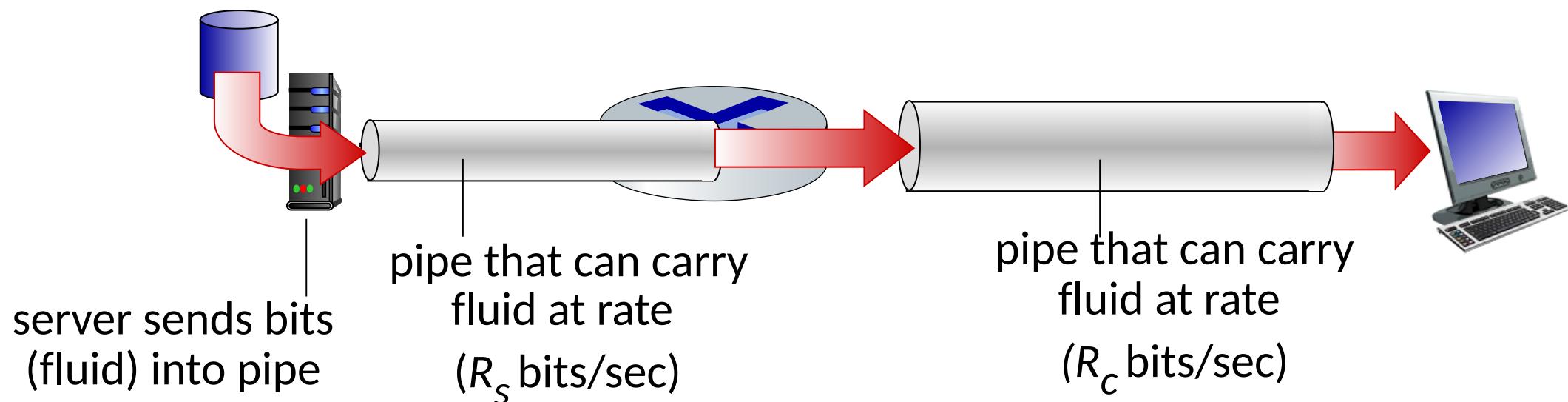
Throughput

- *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



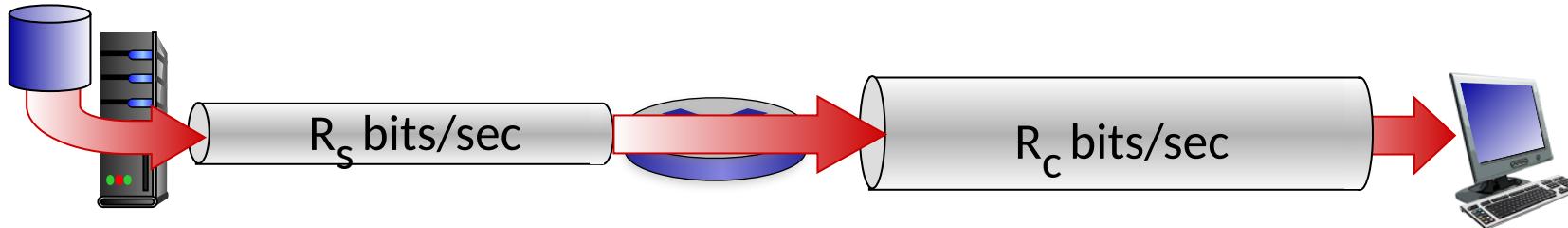
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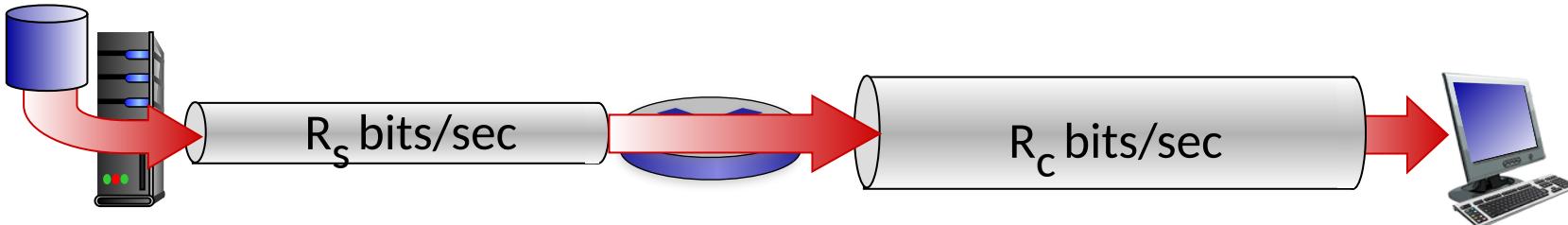
Throughput

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

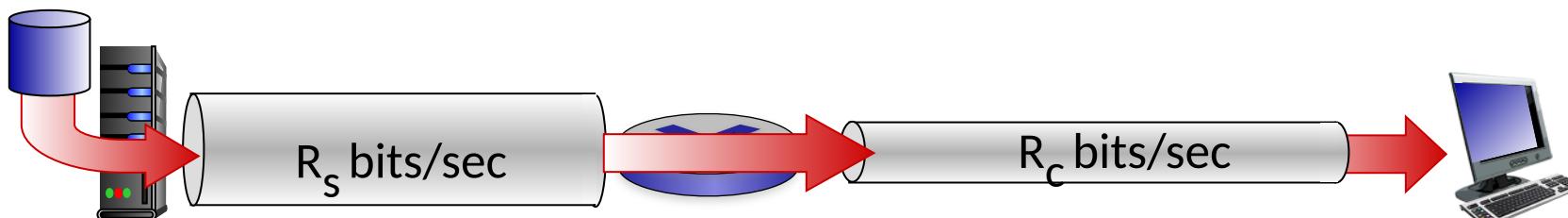


Throughput

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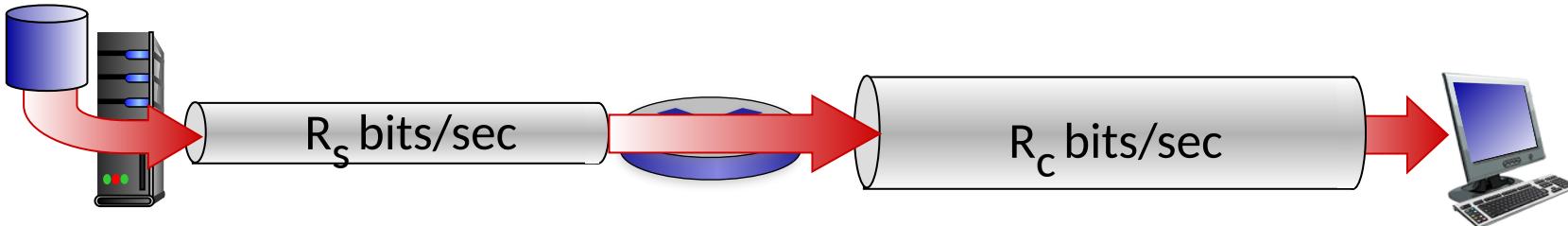


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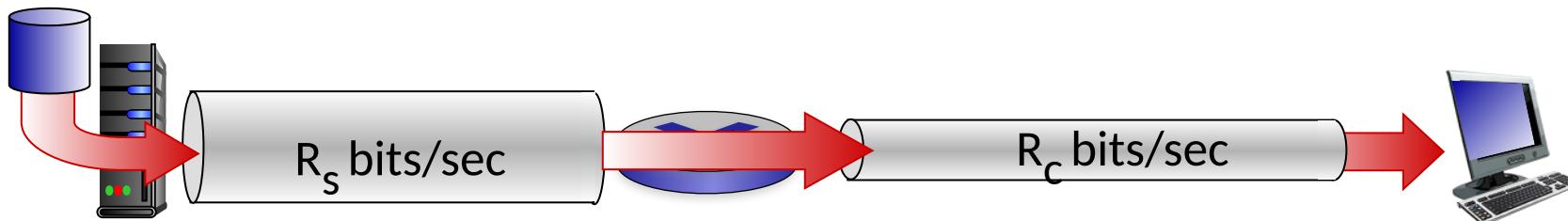


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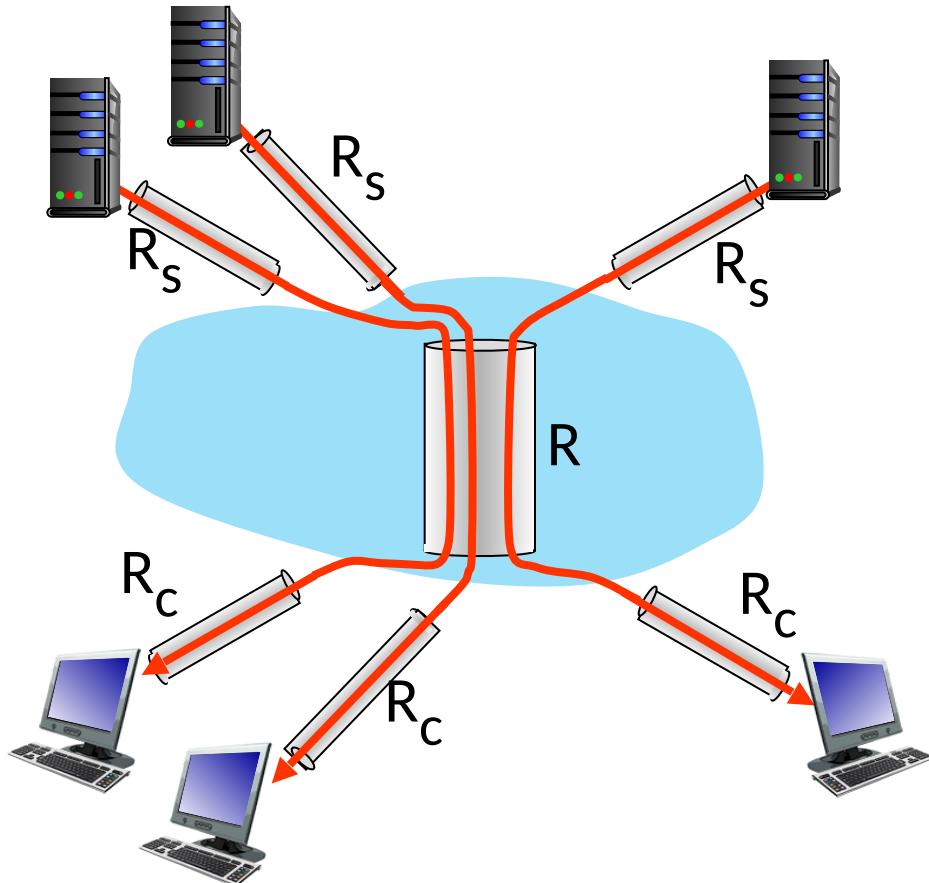
$R_s > R_c$ What is average end-end throughput?



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

Chapter 1: roadmap

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

Protocol “layers” and reference models

Networks are complex,
with many “pieces”:

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

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

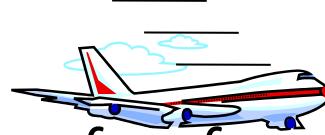
Example: organization of air travel



end-to-end transfer of person plus baggage

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

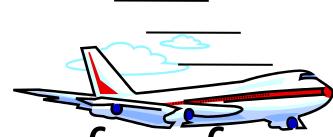
Example: organization of air travel



end-to-end transfer of person plus baggage

- a series of steps, involving many services

Example: organization of air travel



end-to-end transfer of person plus baggage

ticket (purchase)

baggage (check)

gates (load)

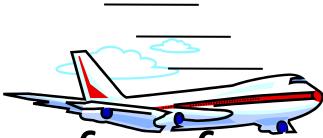
runway takeoff

airplane routing

airplane routing

- a series of steps, involving many services

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)

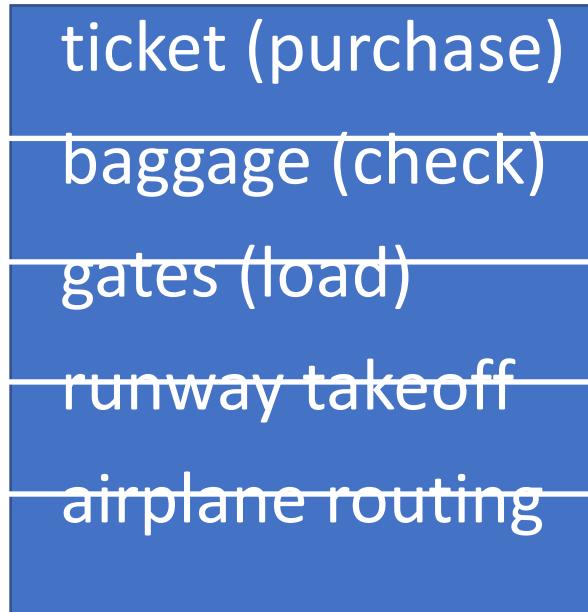
runway landing

airplane routing

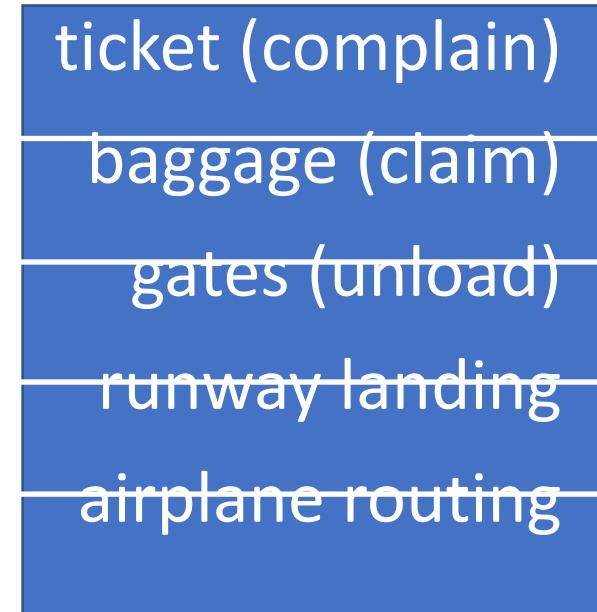
airplane routing

- a series of steps, involving many services

Example: organization of air travel



airplane routing



layers: each layer implements a service

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

Example: organization of air travel



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Why layering?

Approach to designing/discussing complex systems:

Why layering?

Approach to designing/discussing complex systems:

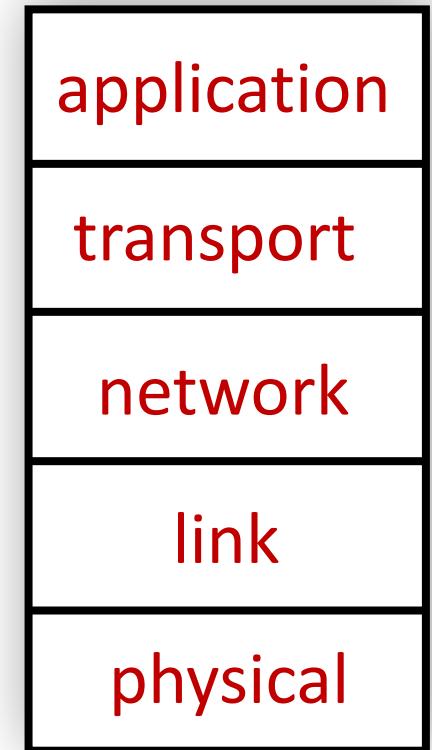
- explicit structure allows identification, relationship of system's pieces
 - layered *reference model* for discussion

Why layering?

Approach to designing/discussing complex systems:

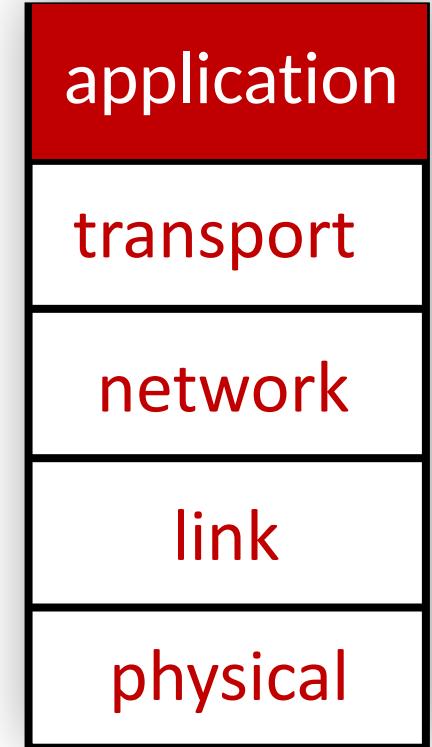
- explicit structure allows identification, relationship of system's pieces
 - layered *reference model* for discussion
- modularization eases maintenance, updating of system
 - change in layer's service *implementation*: transparent to rest of system
 - e.g., change in gate procedure doesn't affect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

Layered Internet protocol stack



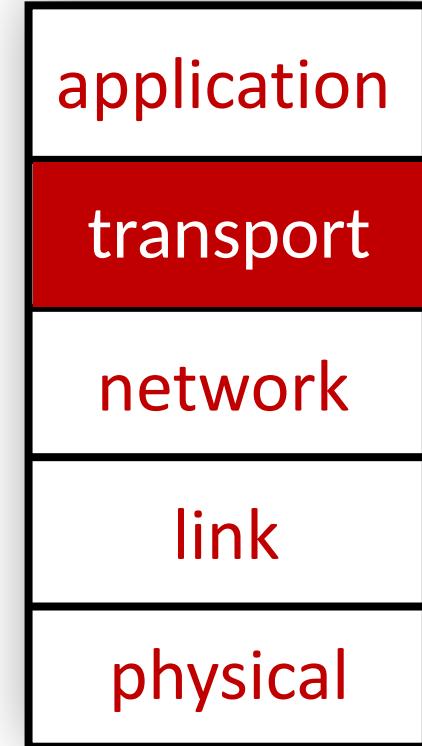
Layered Internet protocol stack

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



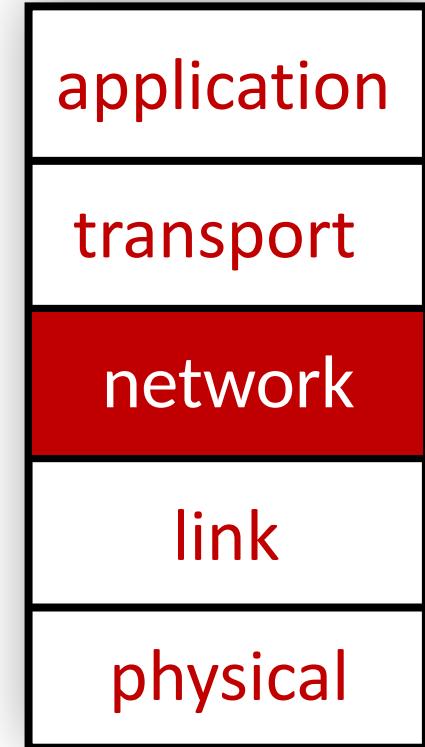
Layered Internet protocol stack

- *application*: supporting network applications
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- *transport*: process-process data transfer
 - TCP, UDP



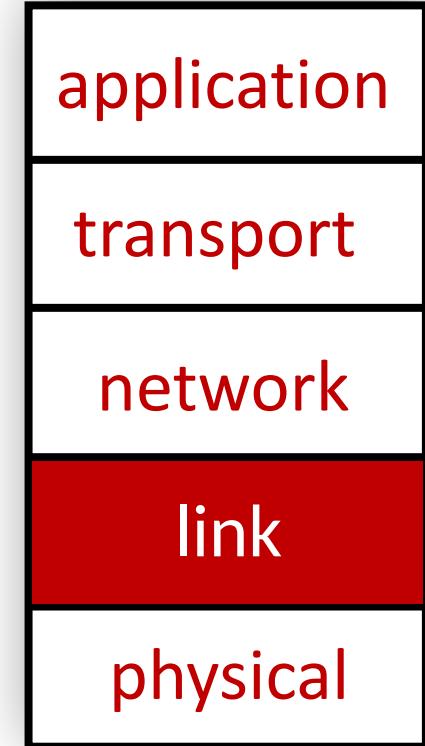
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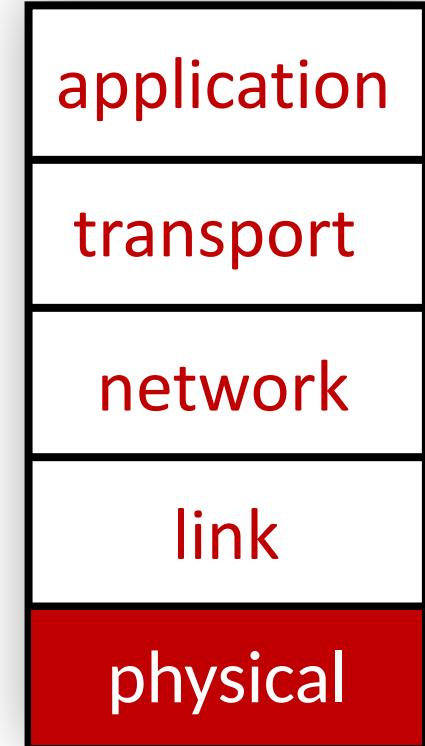
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Layered Internet protocol stack

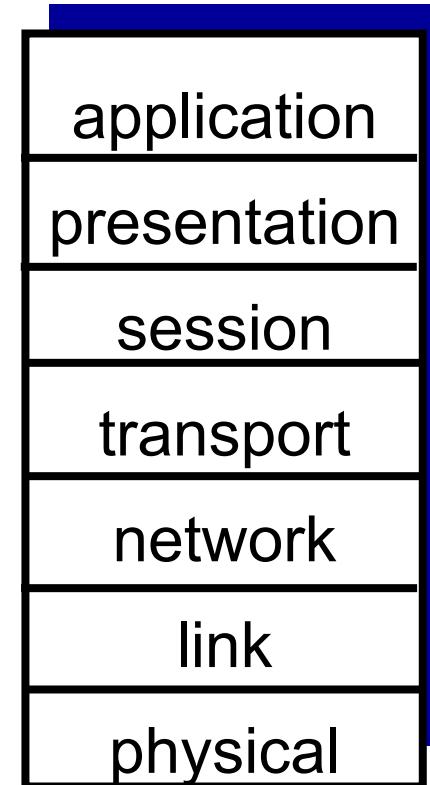
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- *link*: data transfer between neighboring network elements
 - Ethernet, 802.11 (WiFi), PPP
- *physical*: bits “on the wire”



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?

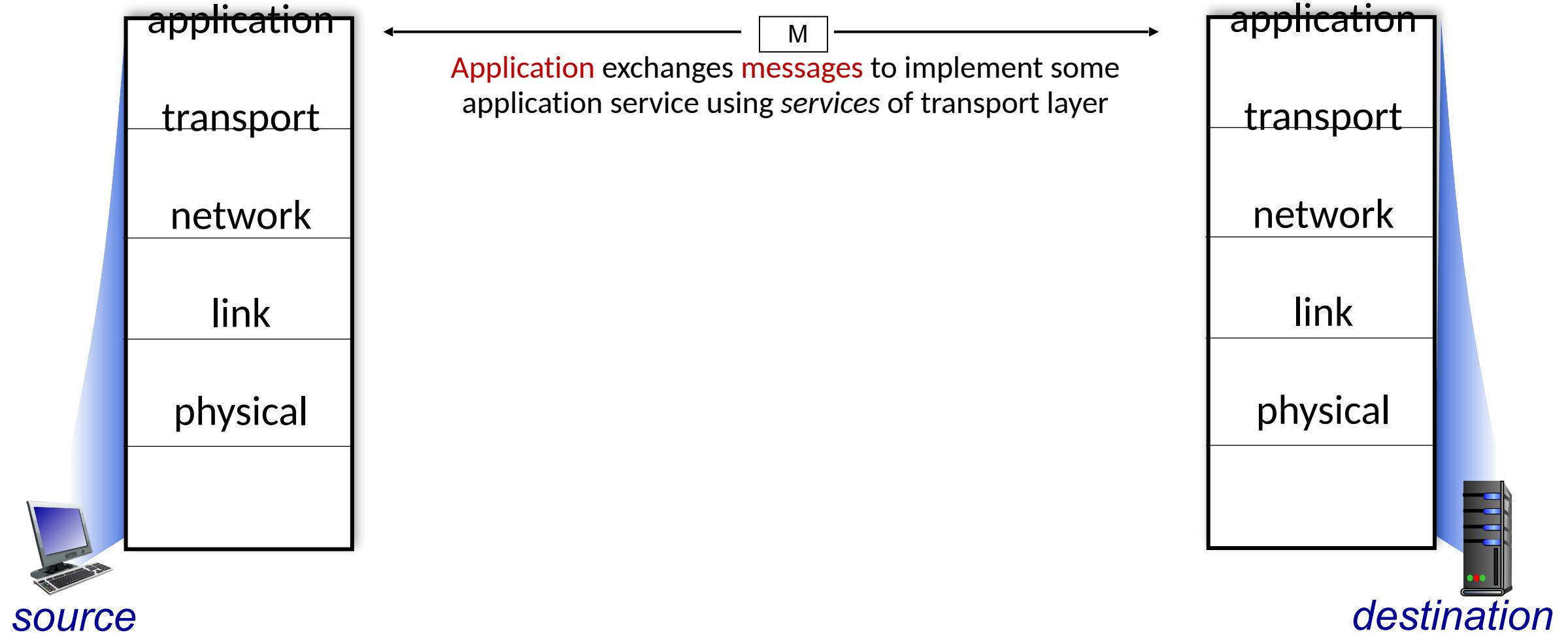


The seven layer OSI/ISO reference model

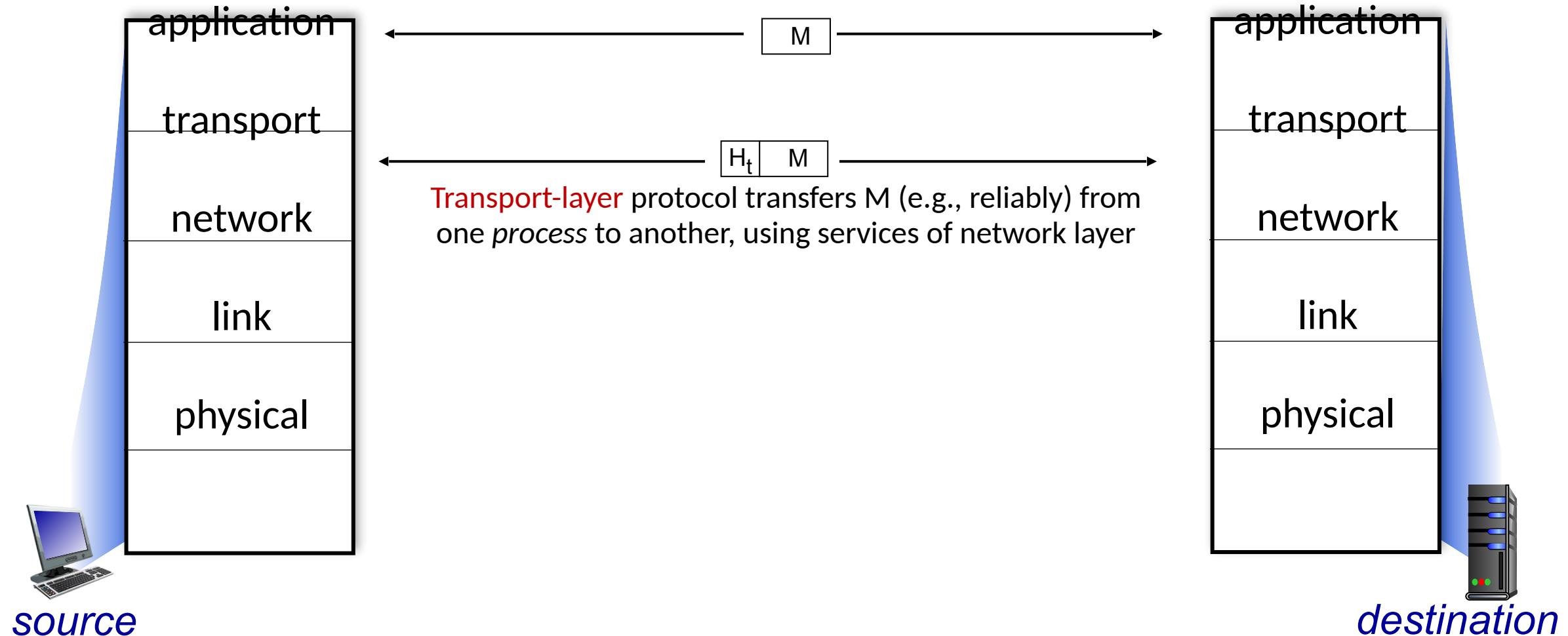
Services, Layering and Encapsulation



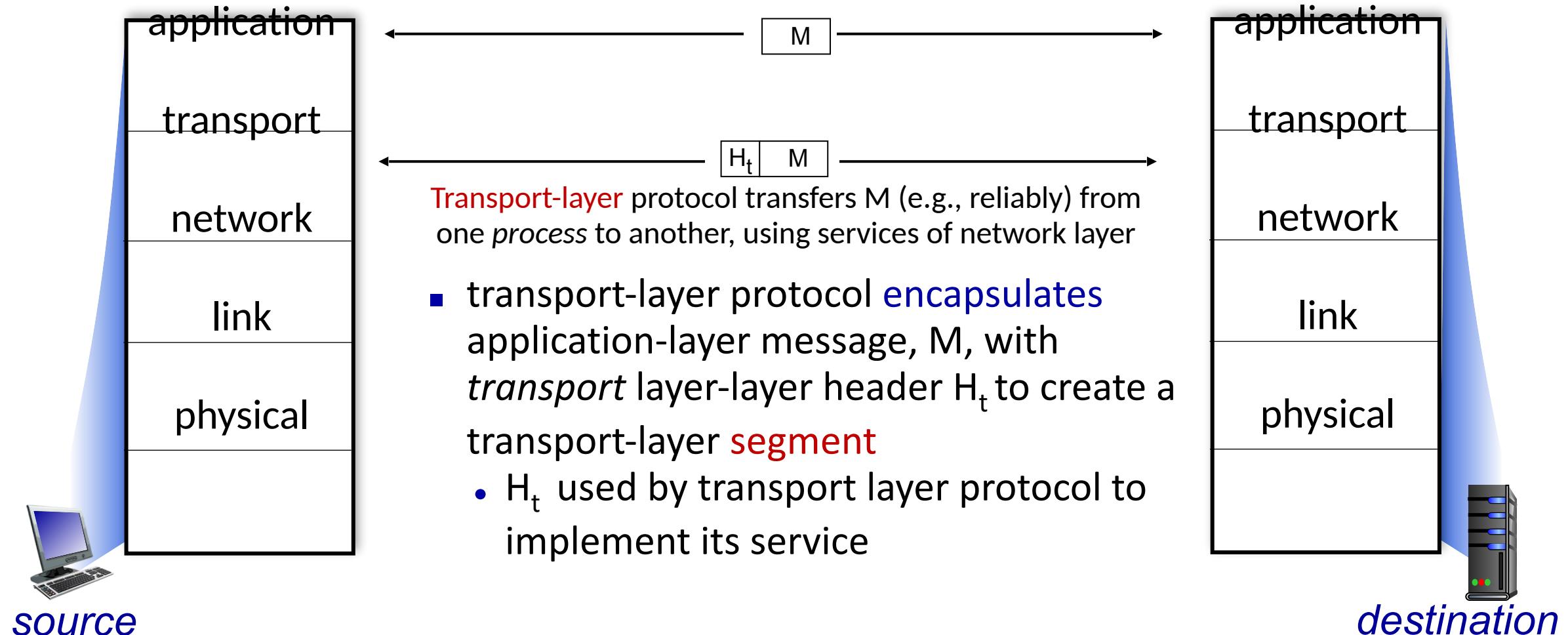
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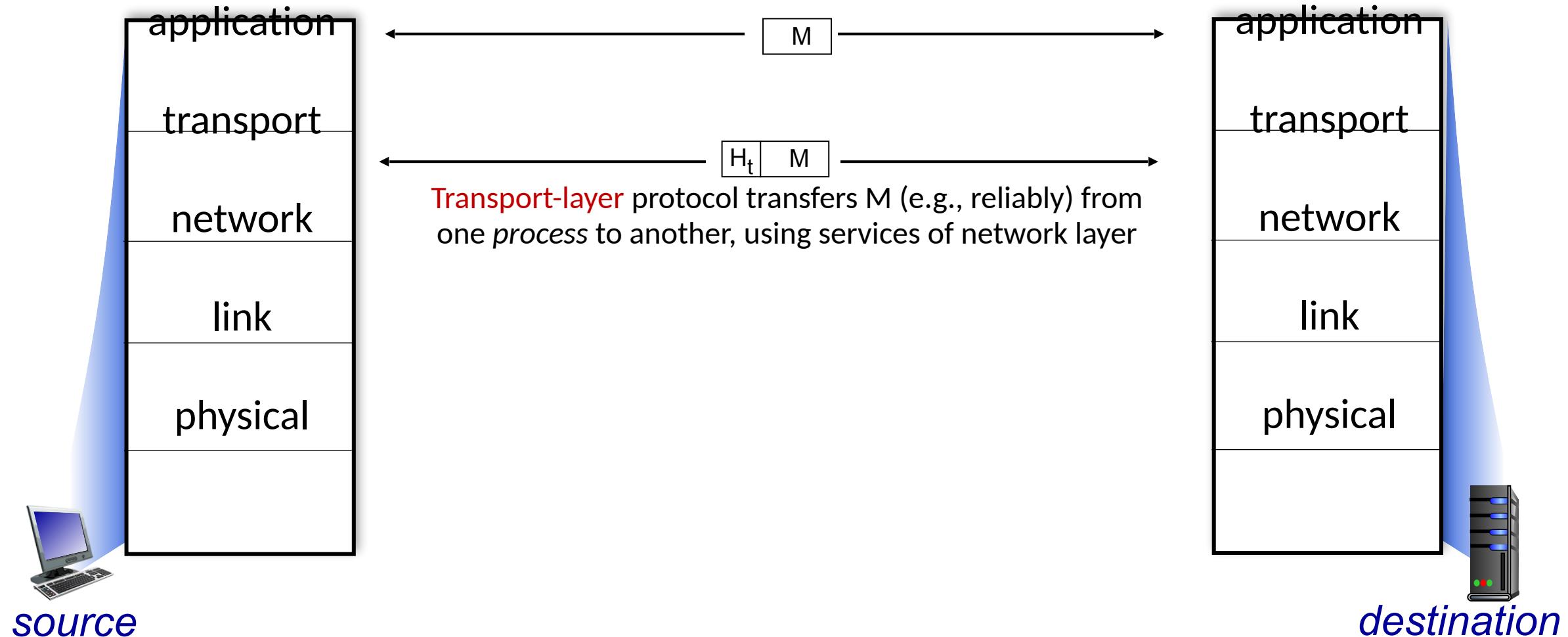
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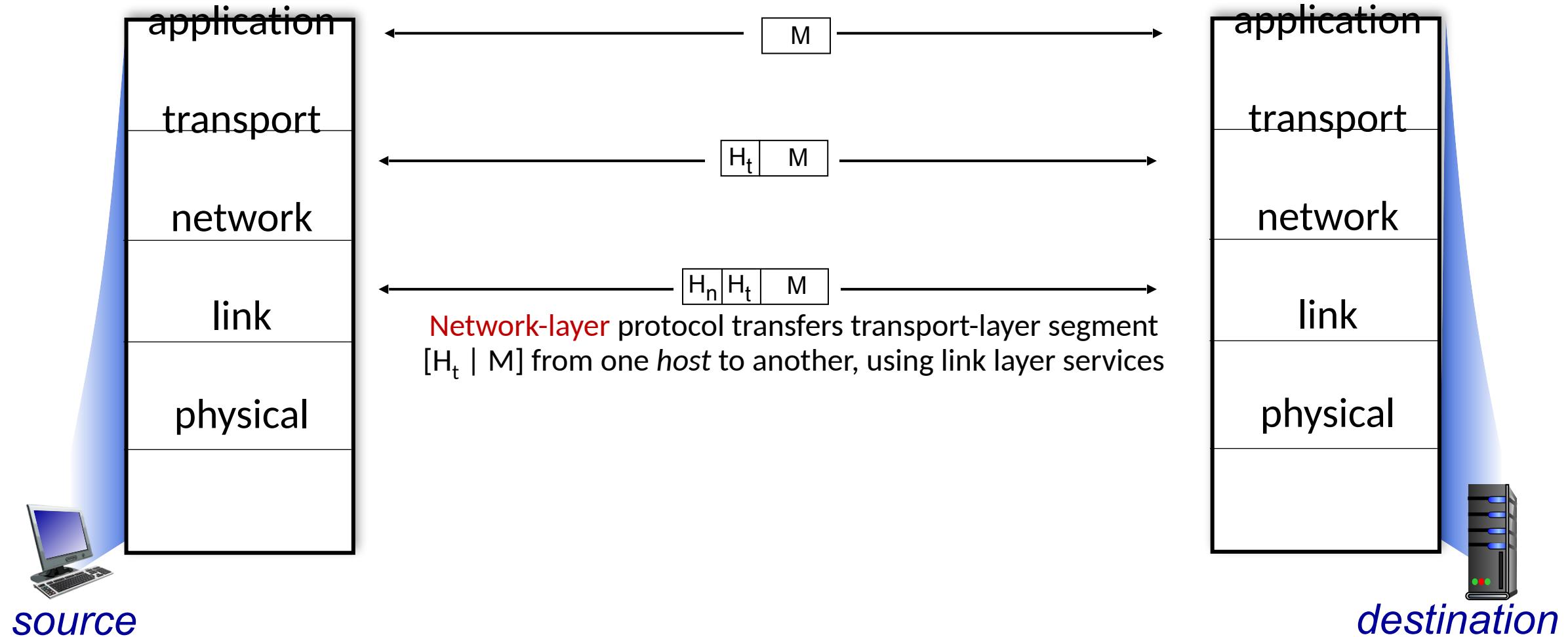
Services, Layering and Encapsulation



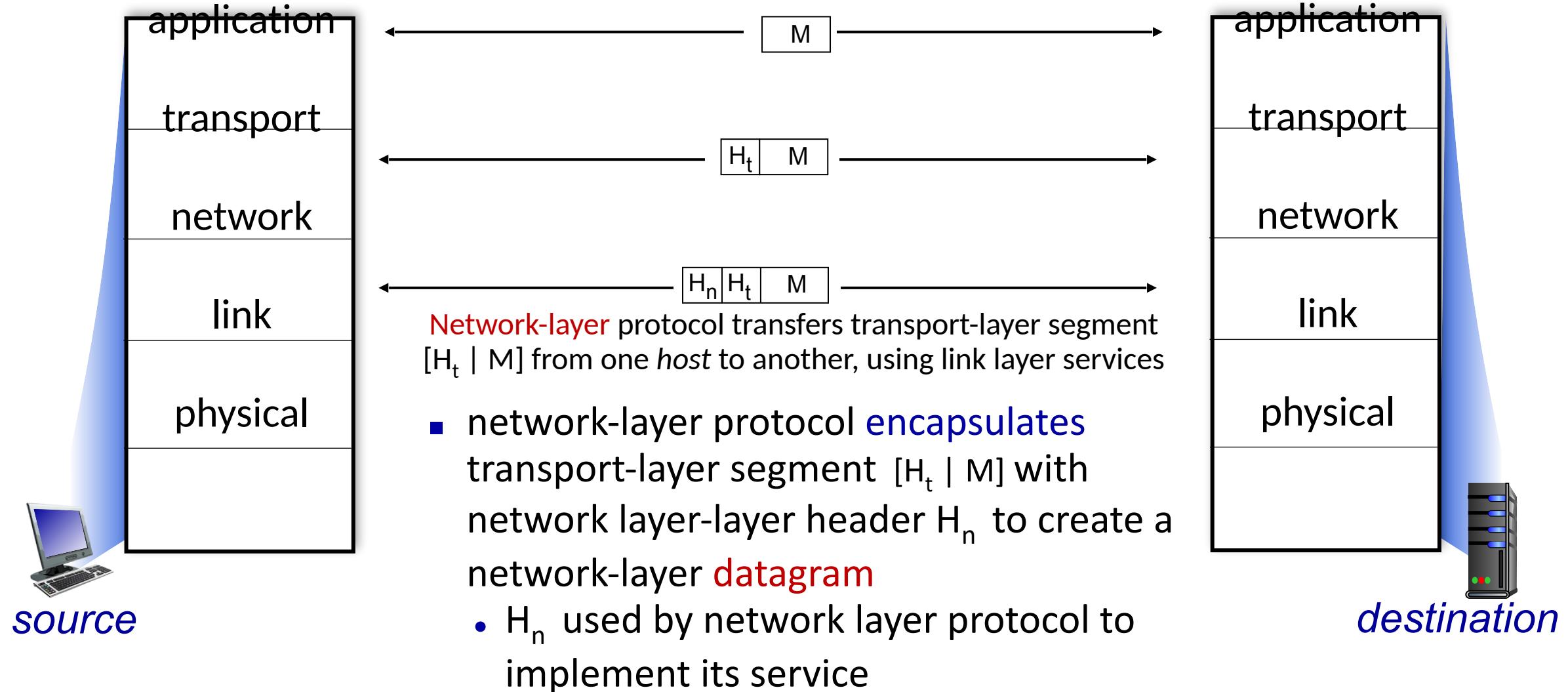
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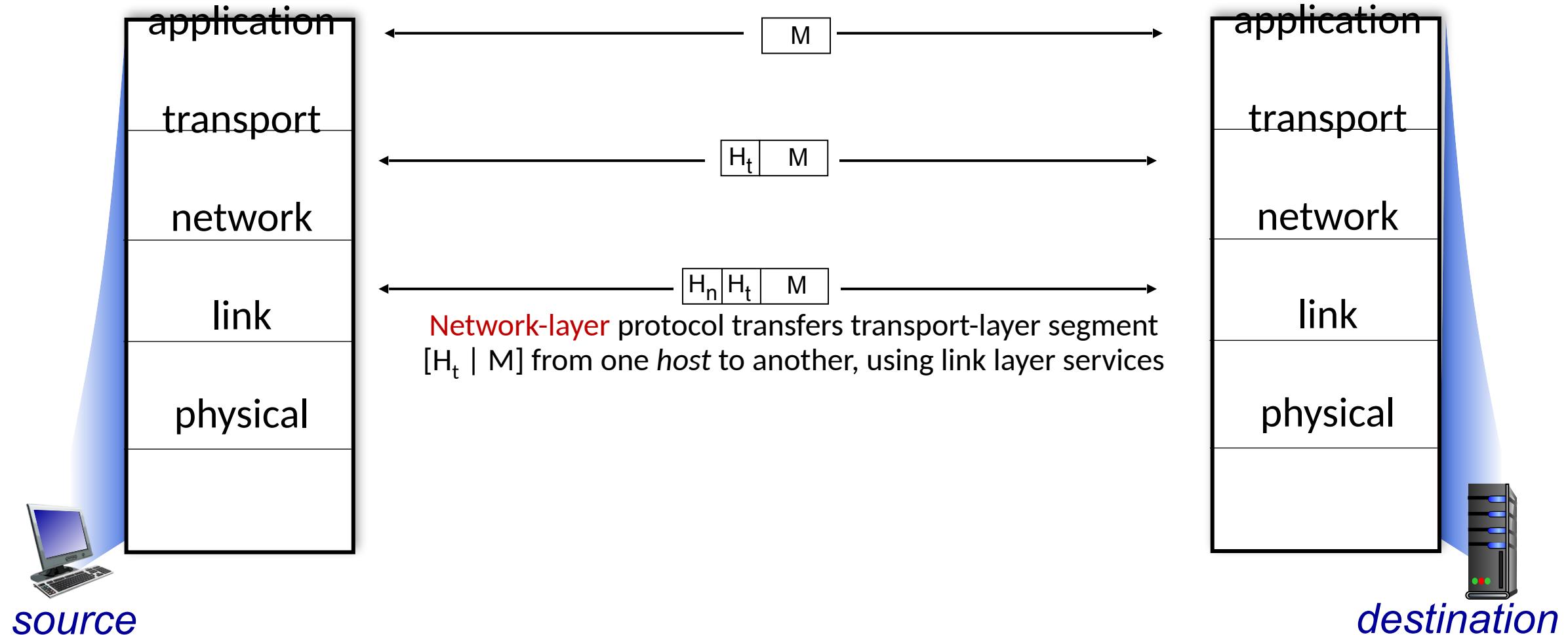
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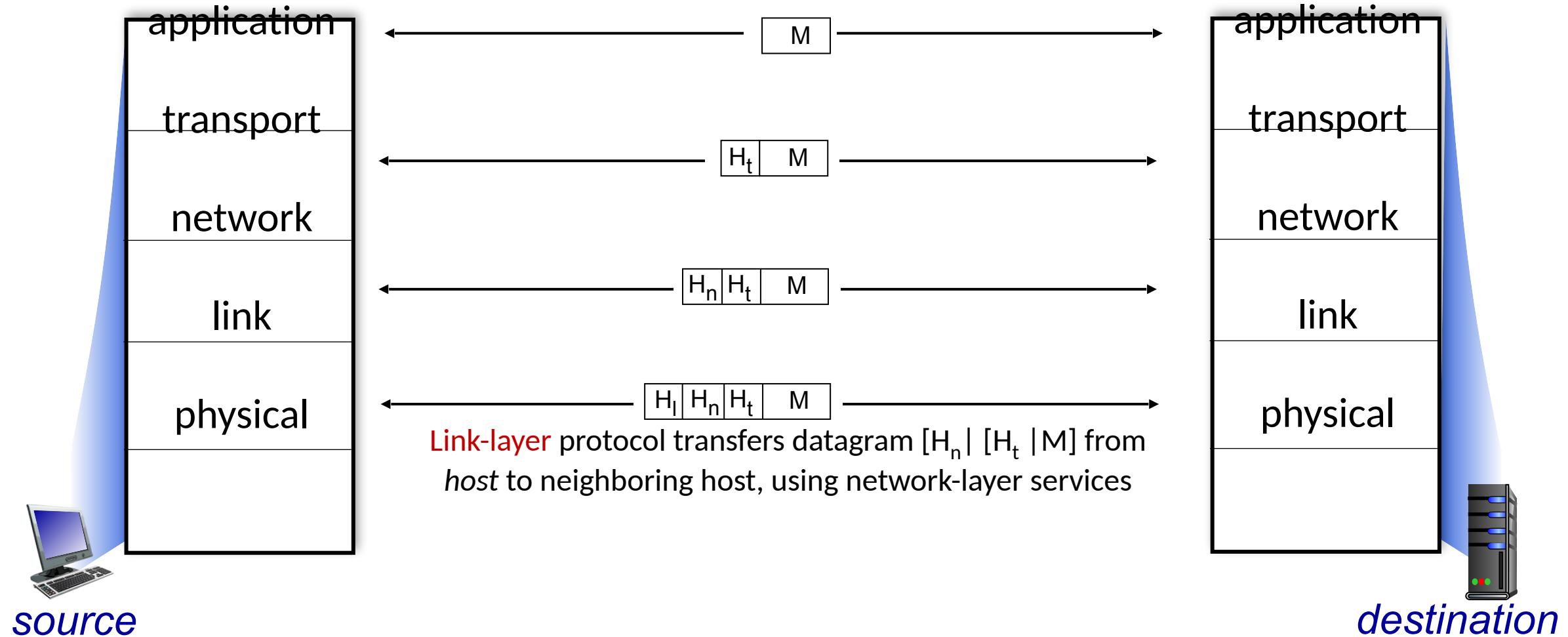
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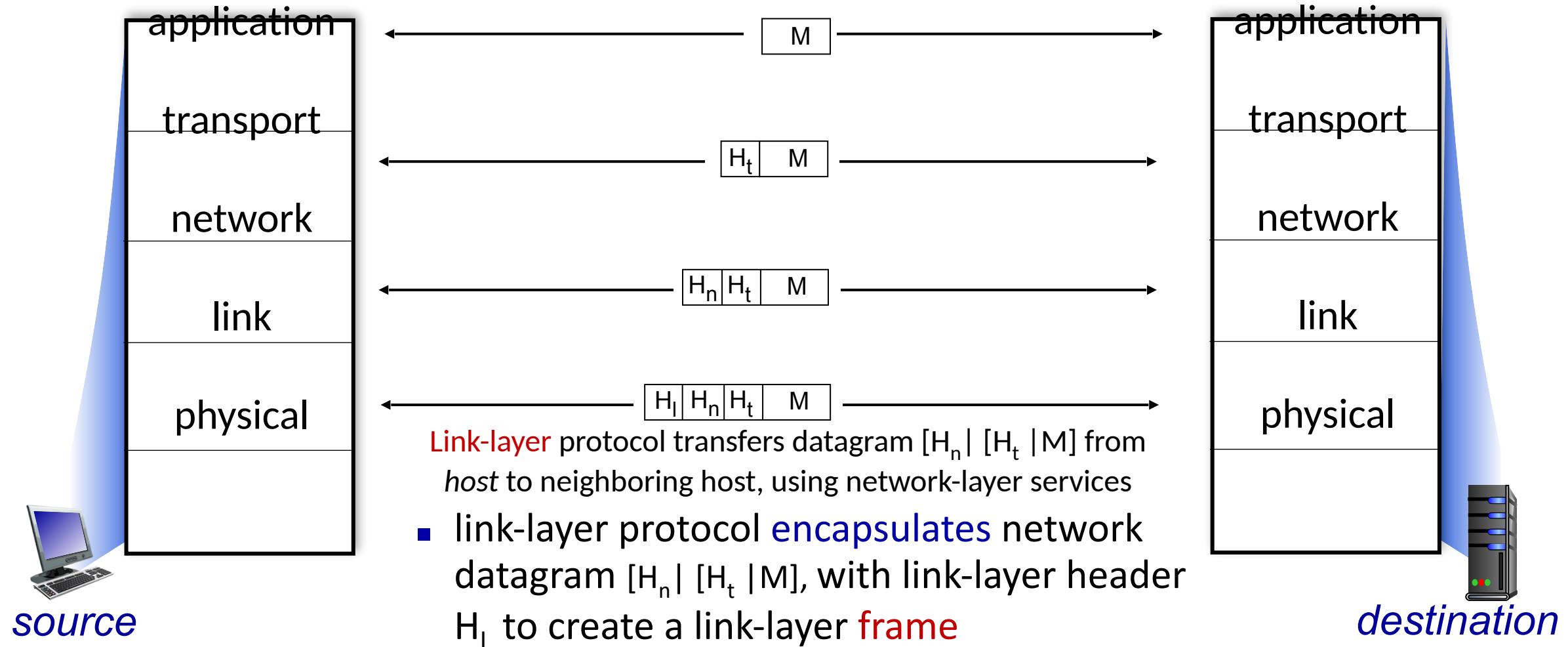
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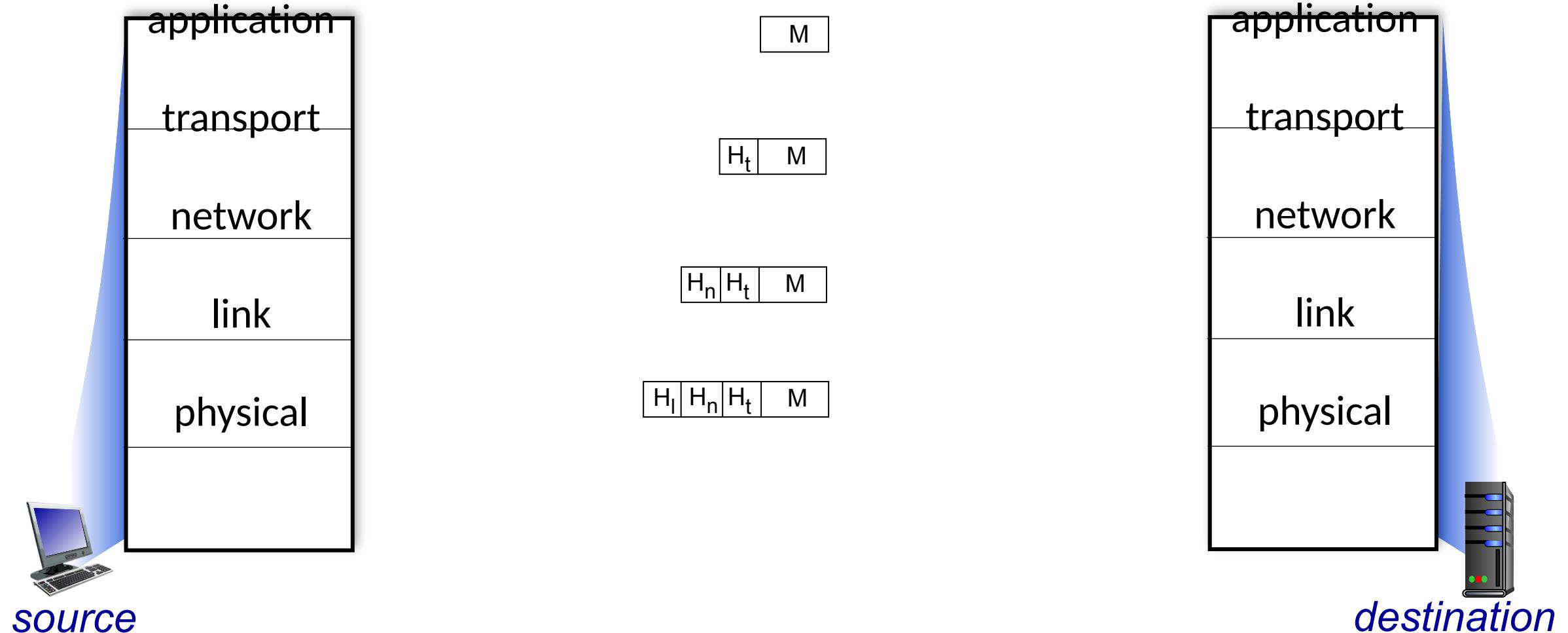
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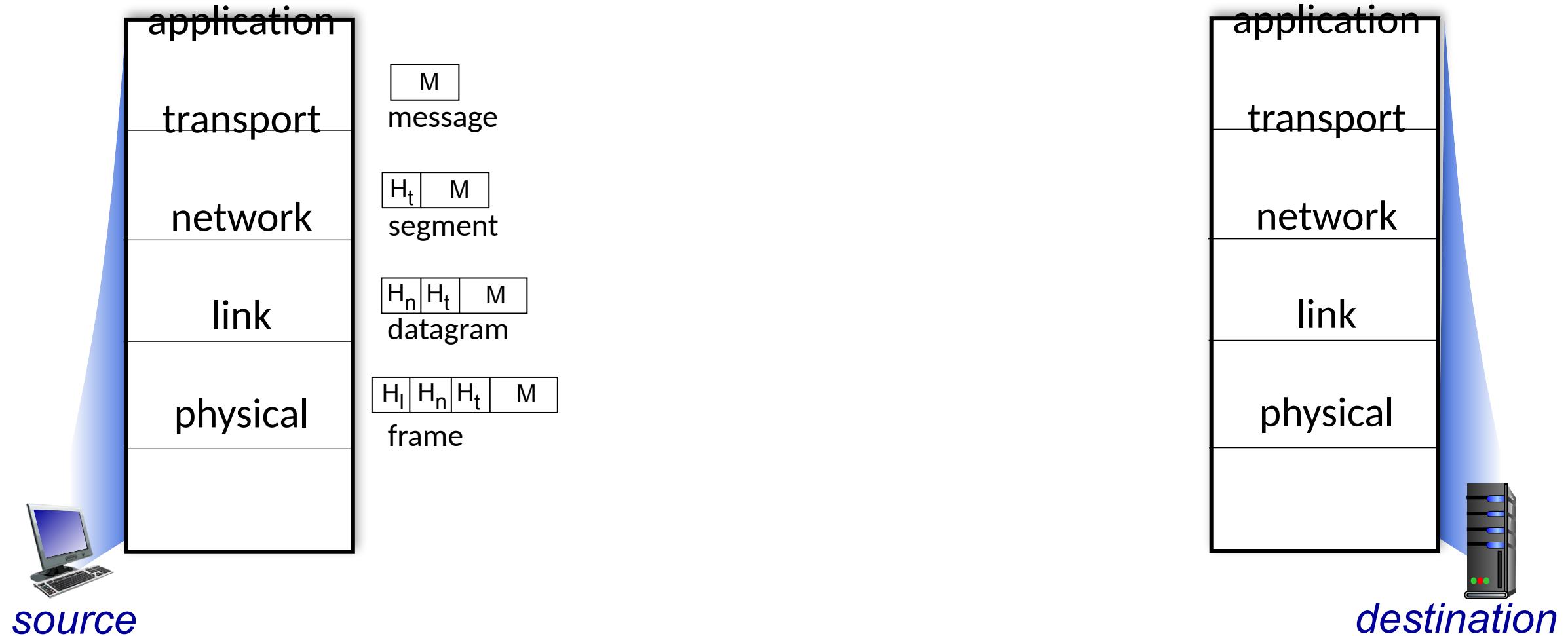
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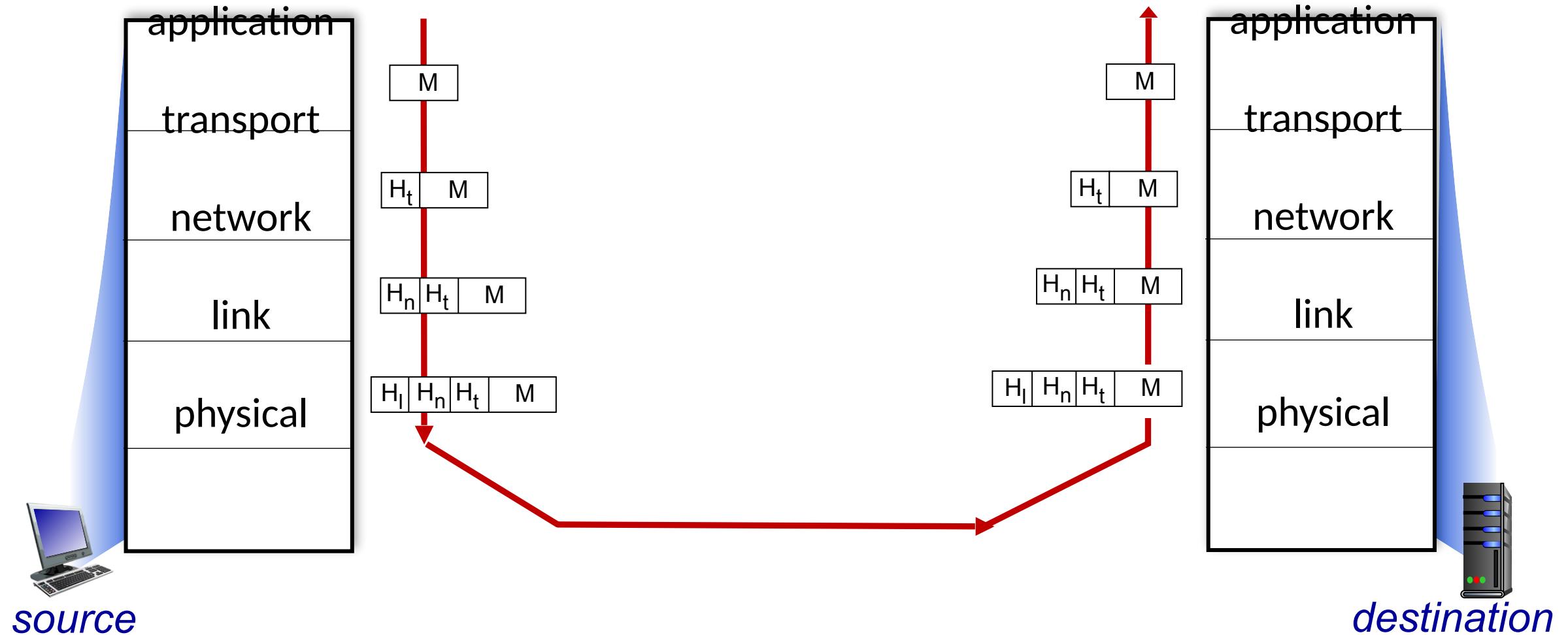
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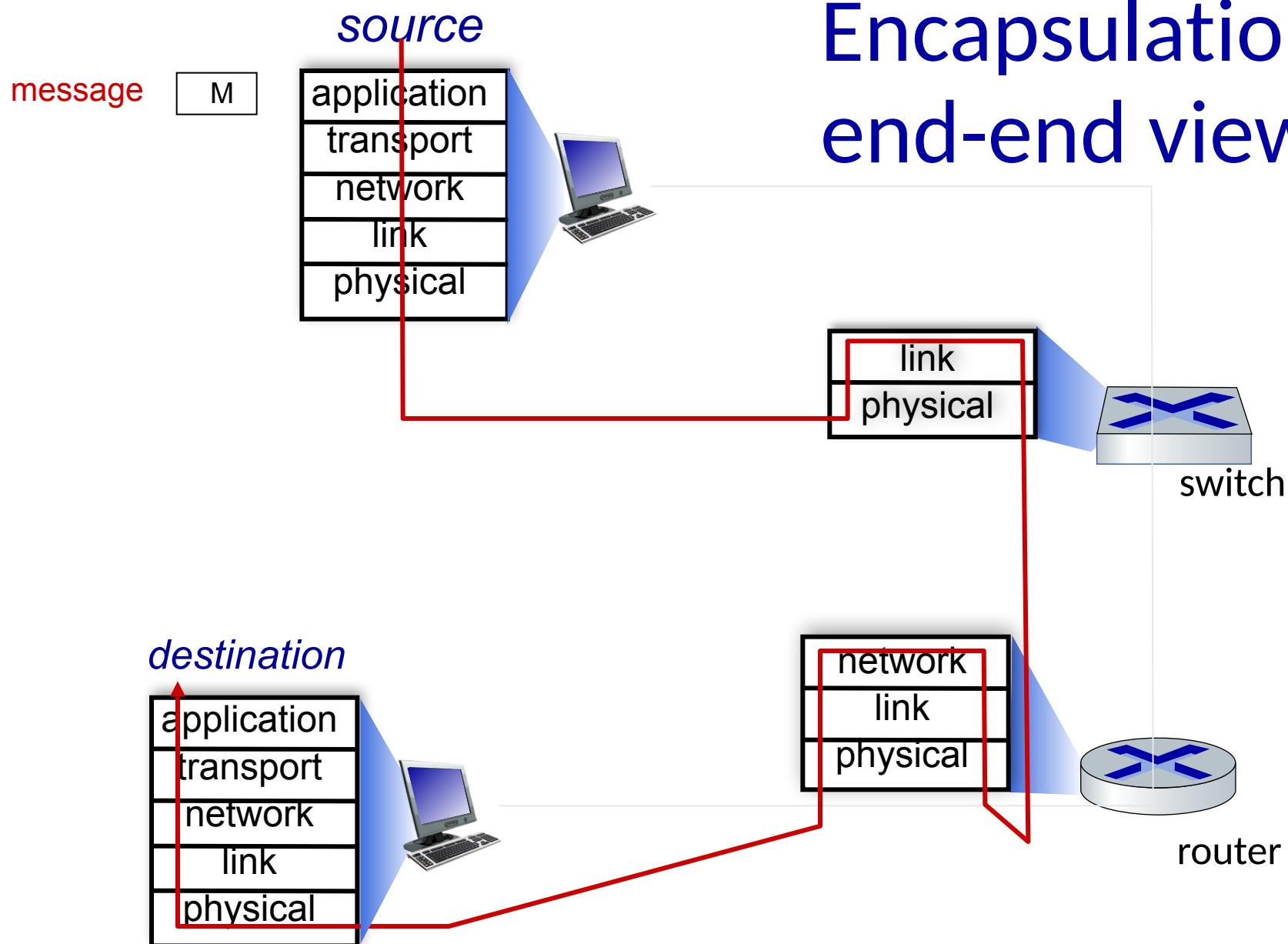
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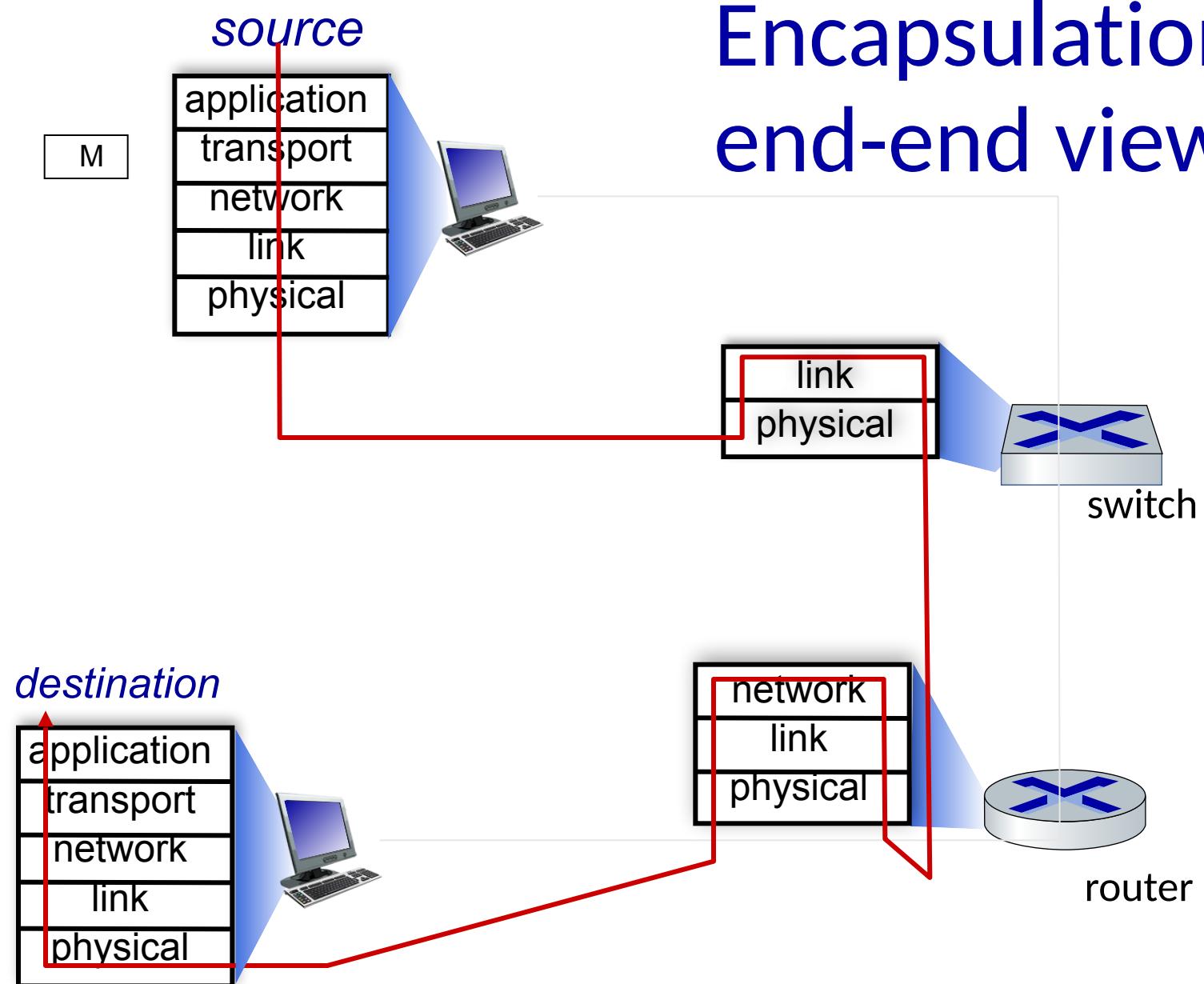
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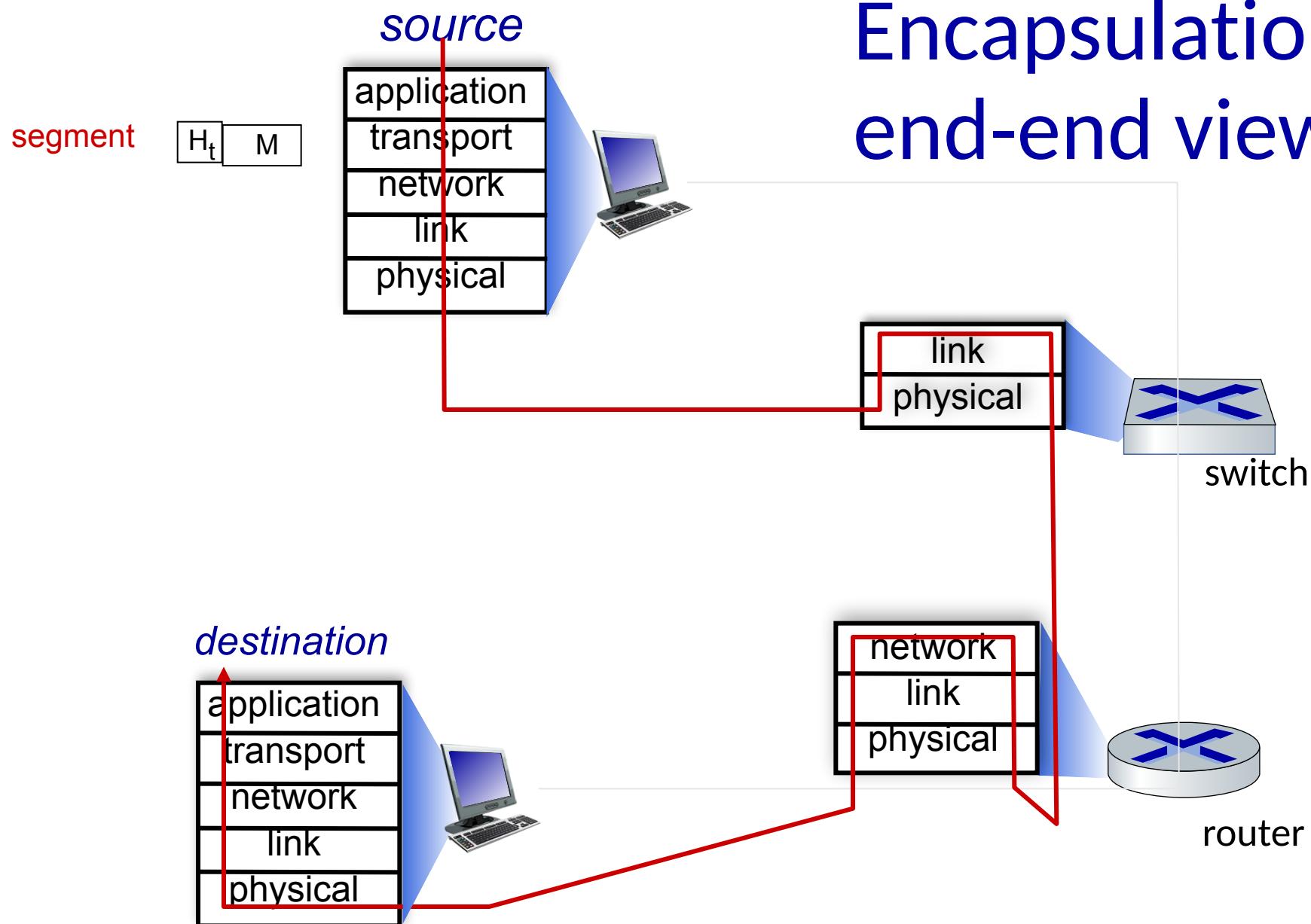
Encapsulation: an end-end view



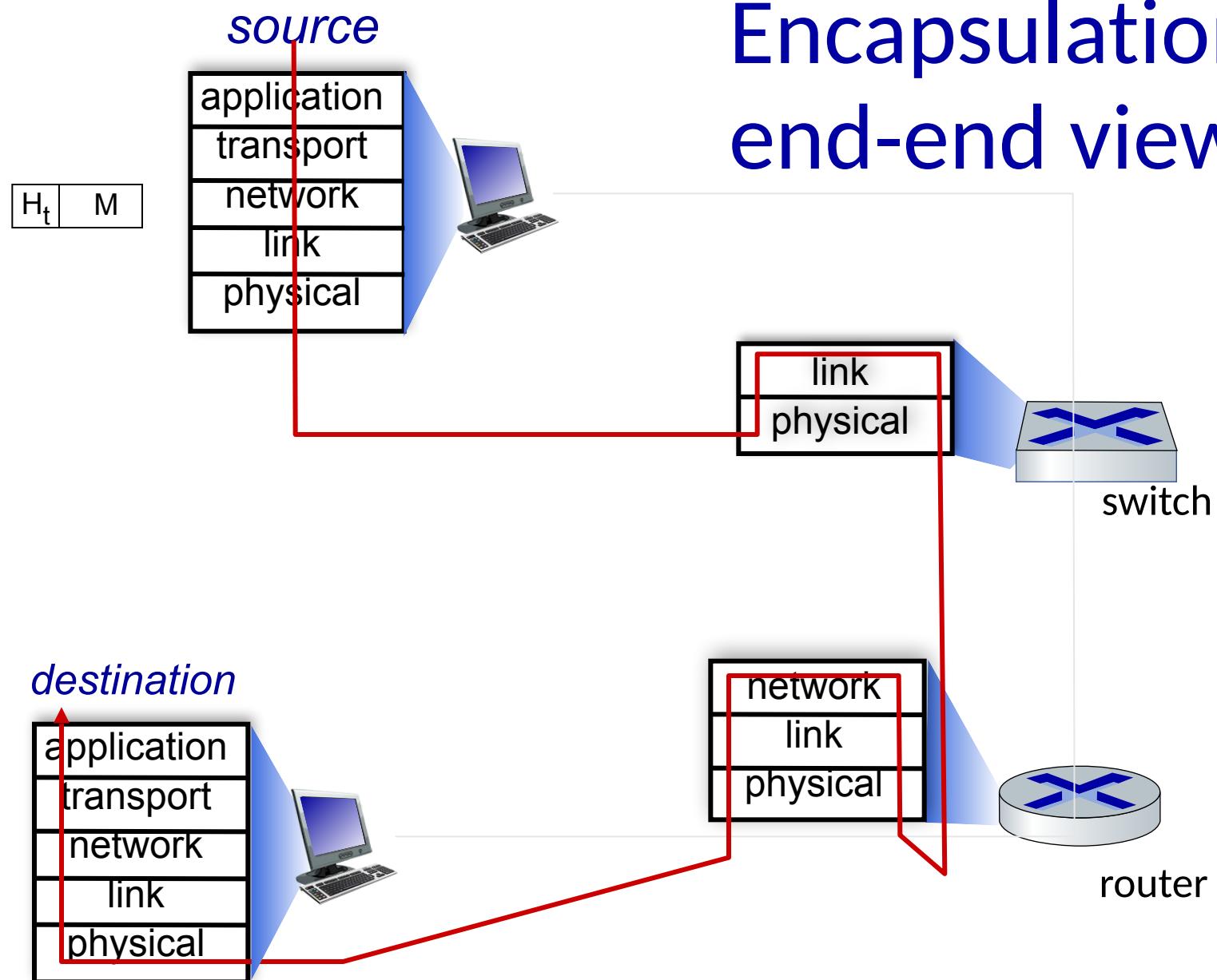
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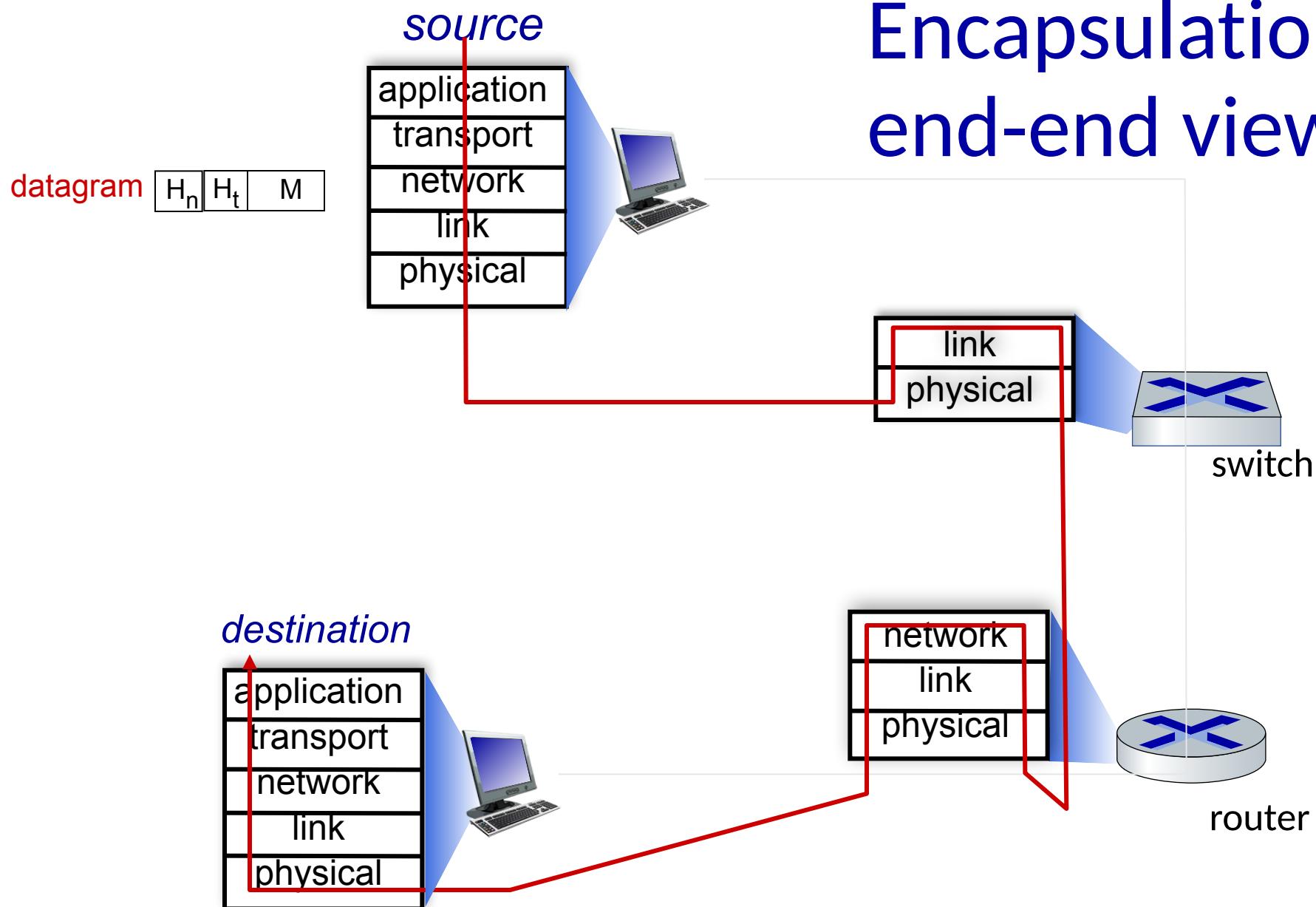
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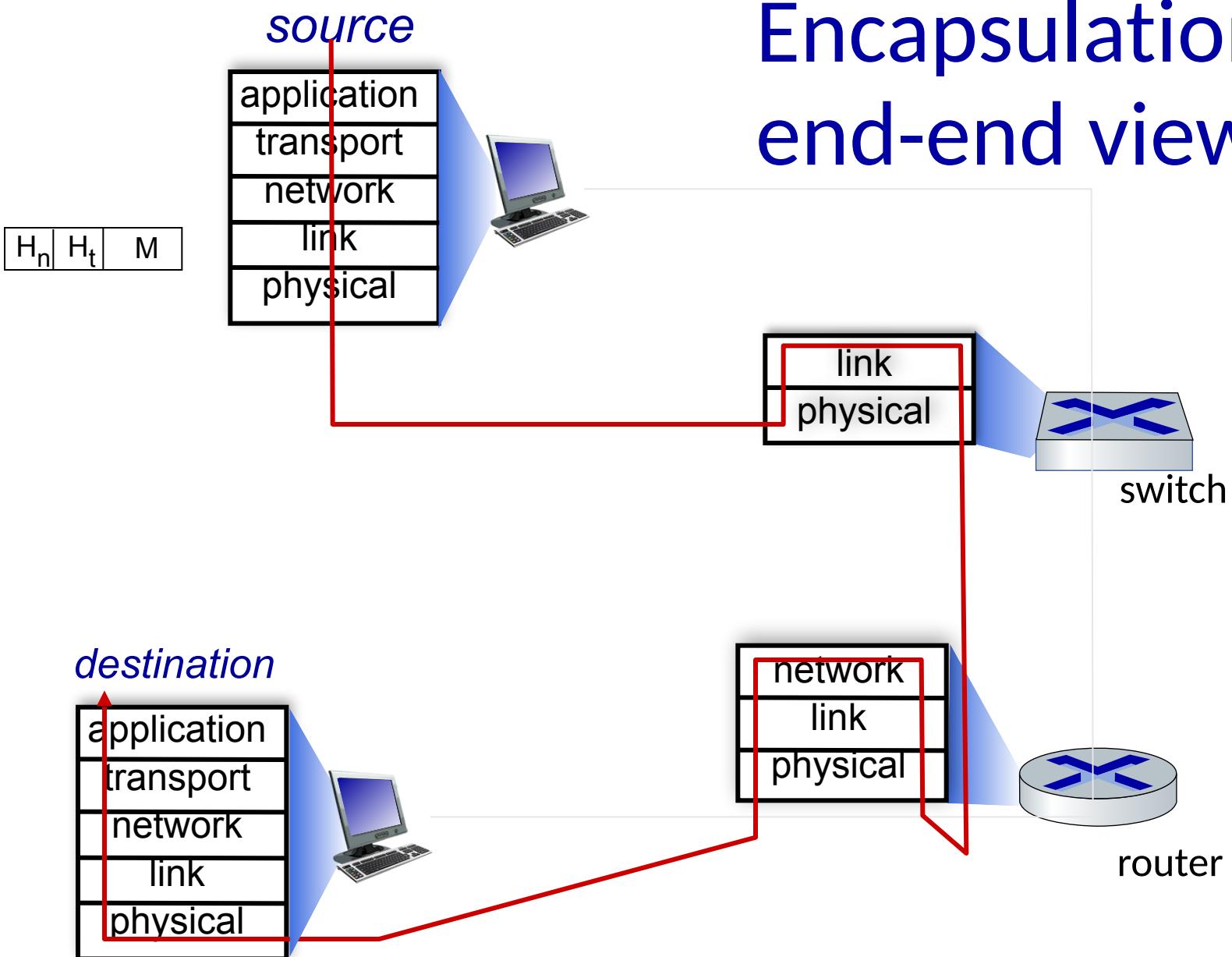
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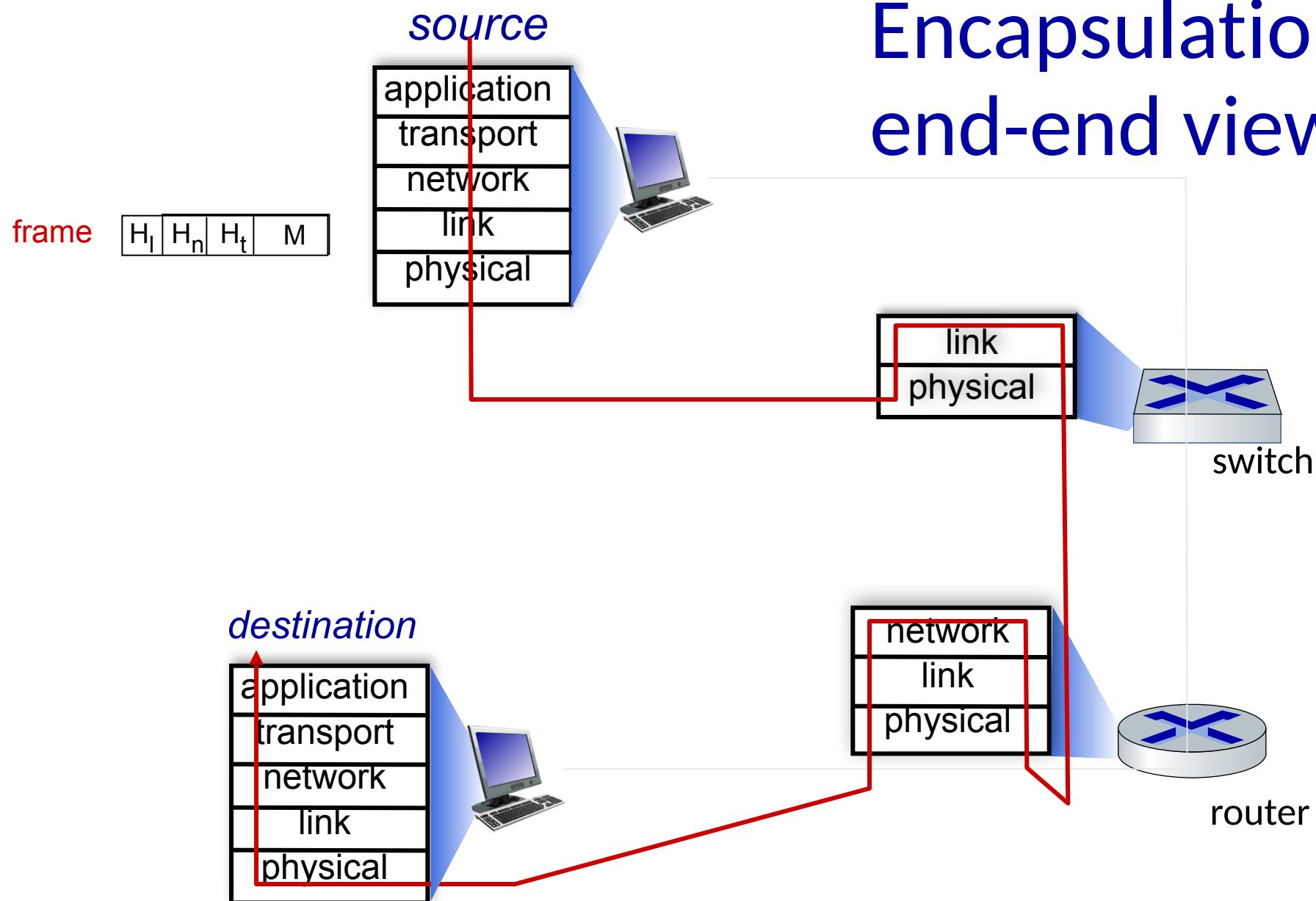
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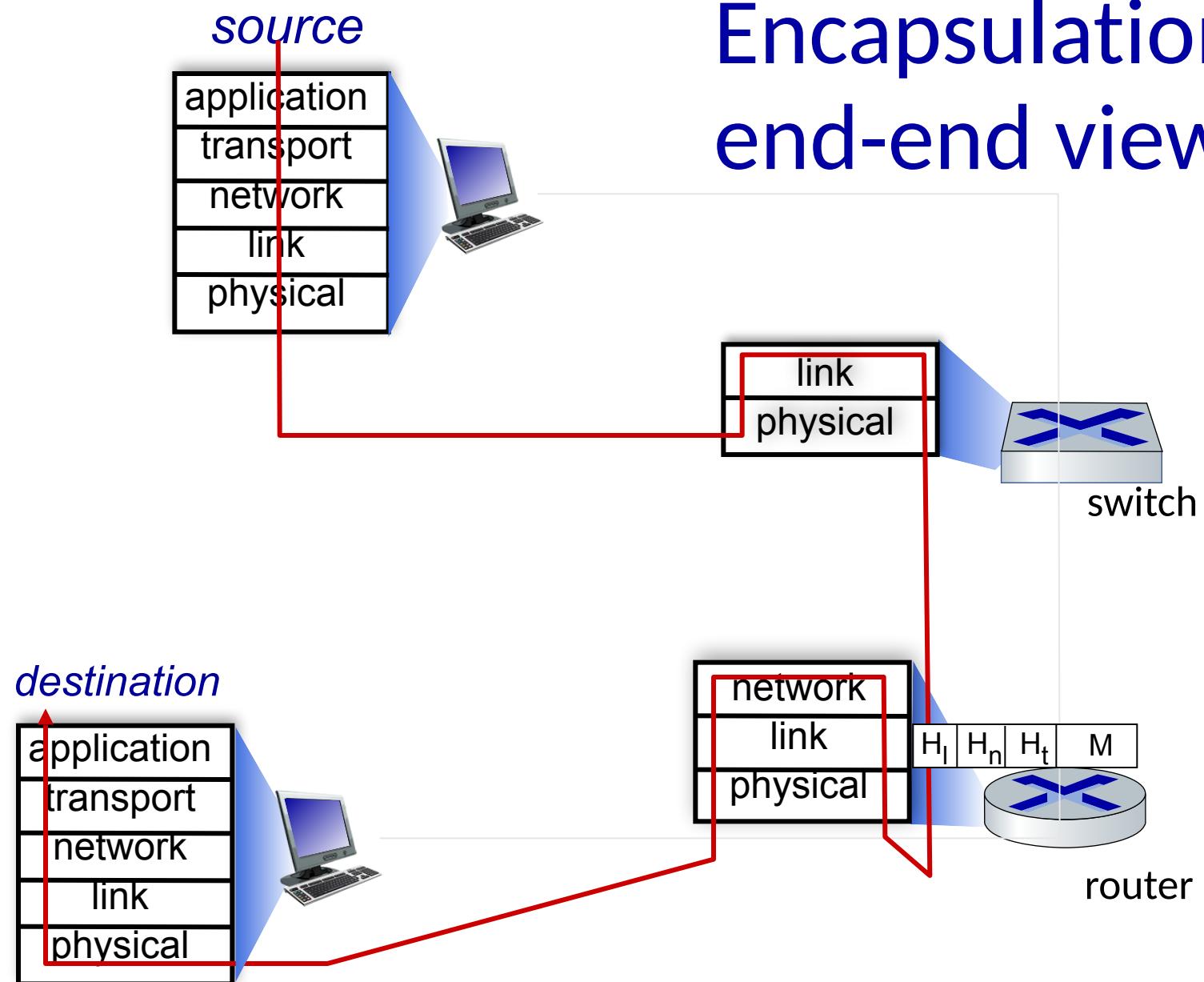
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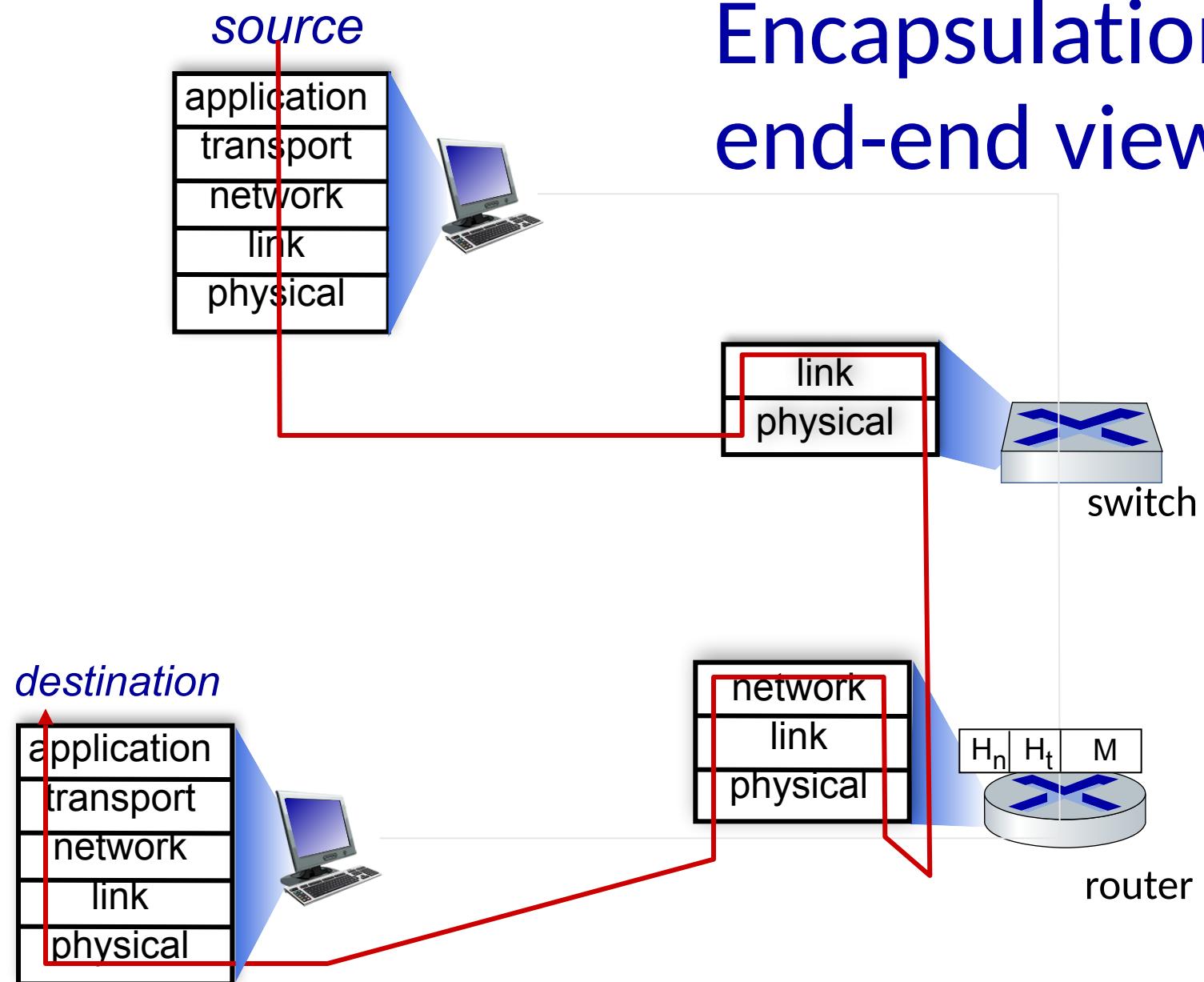
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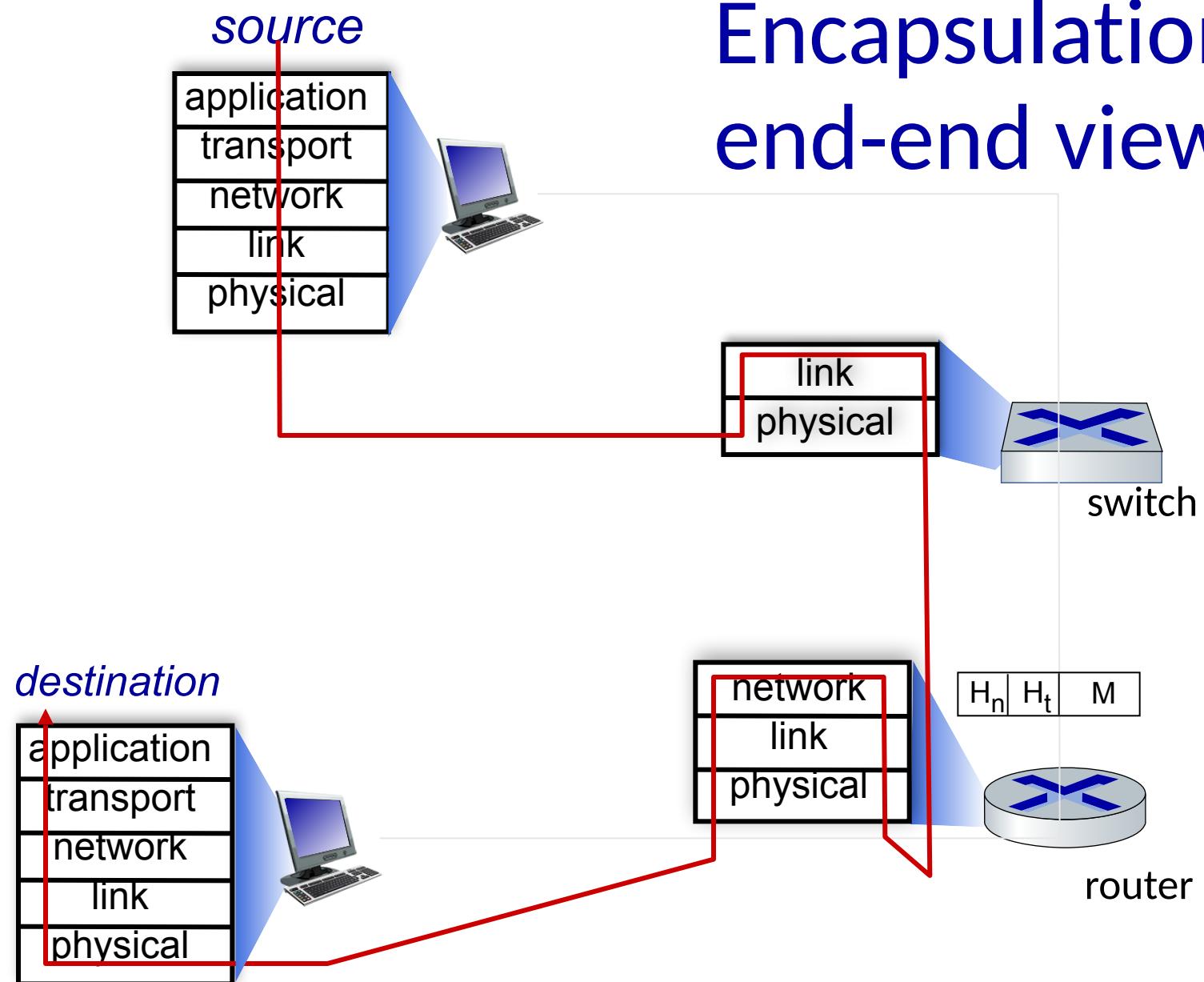
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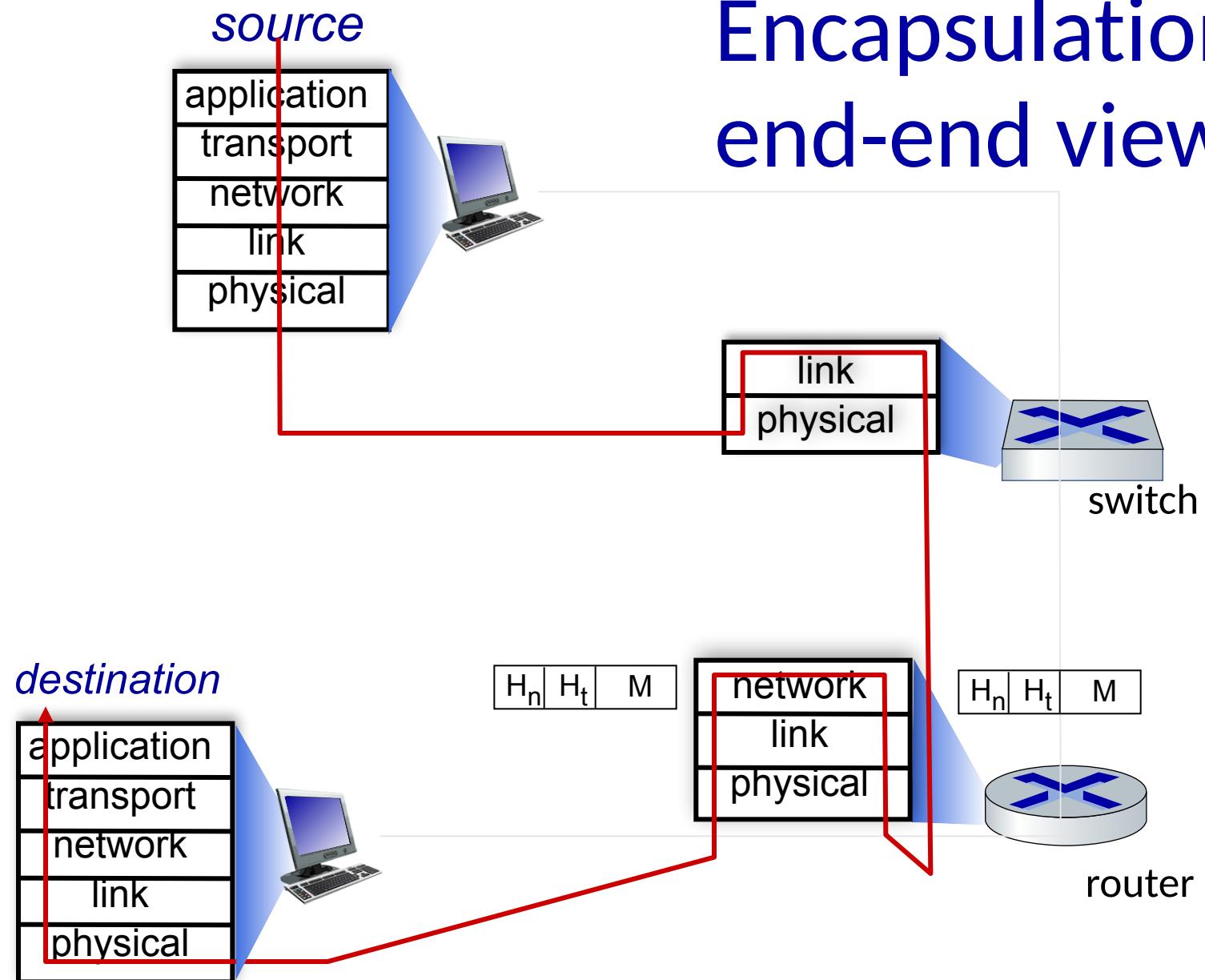
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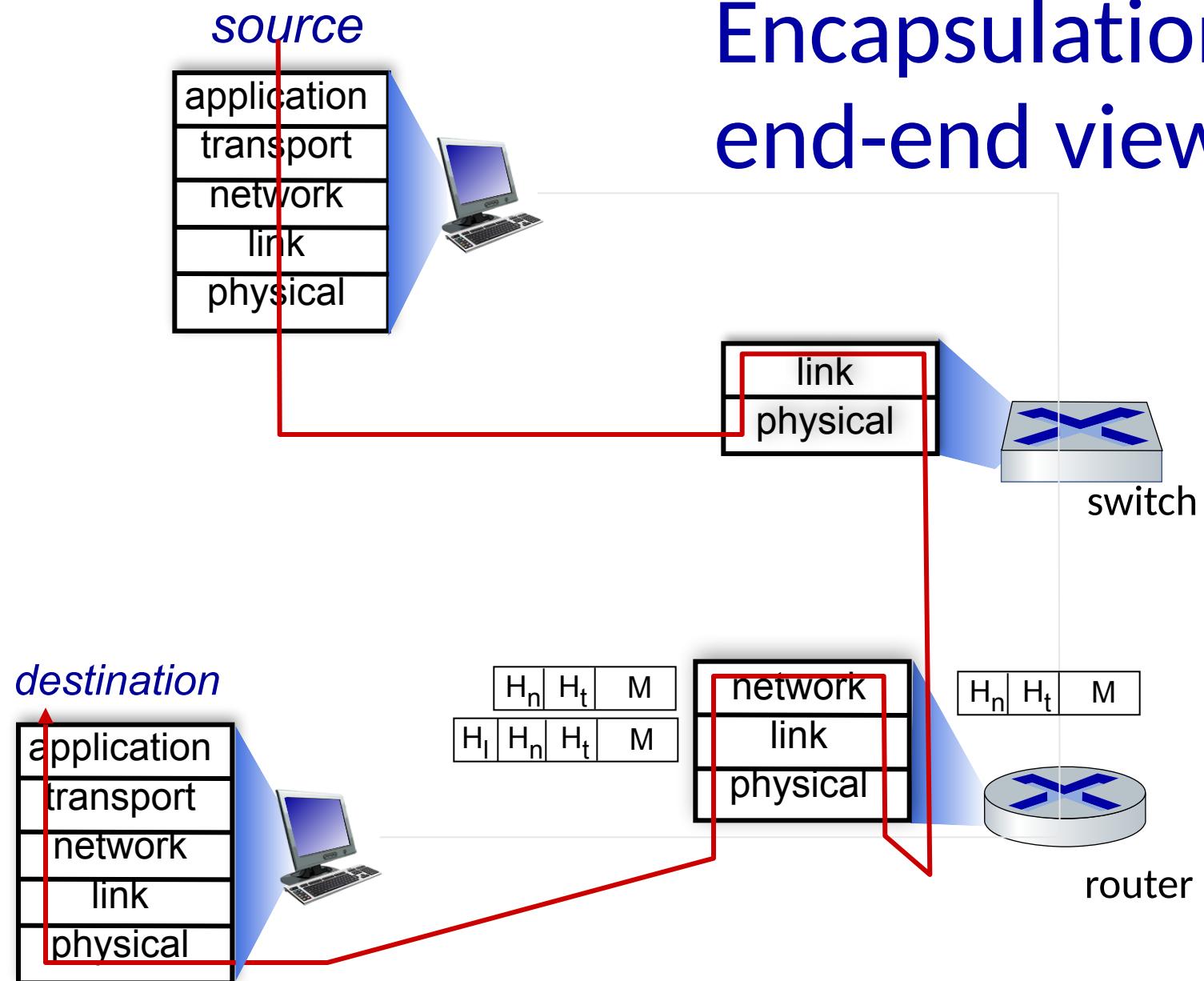
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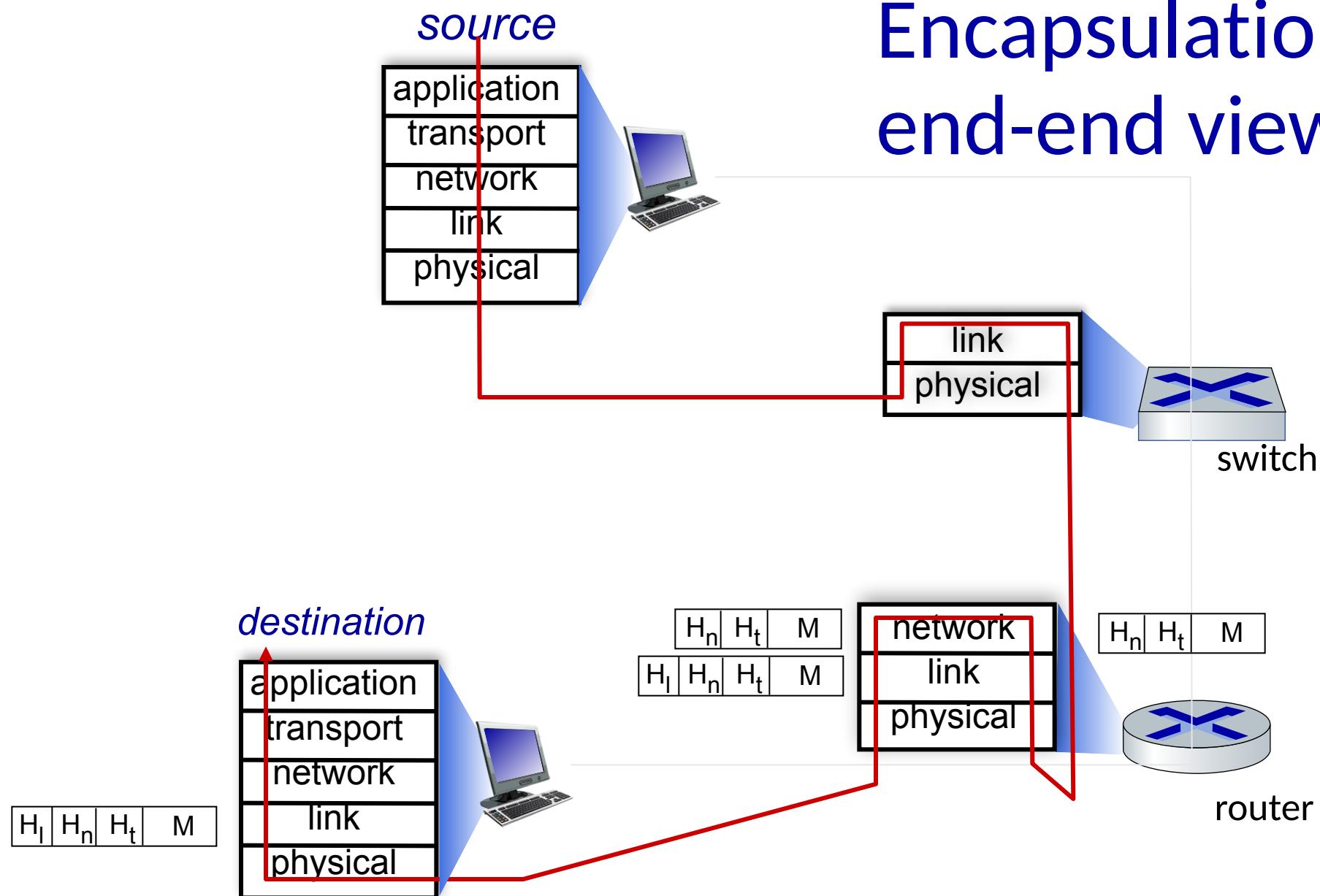
Encapsulation: an end-end view



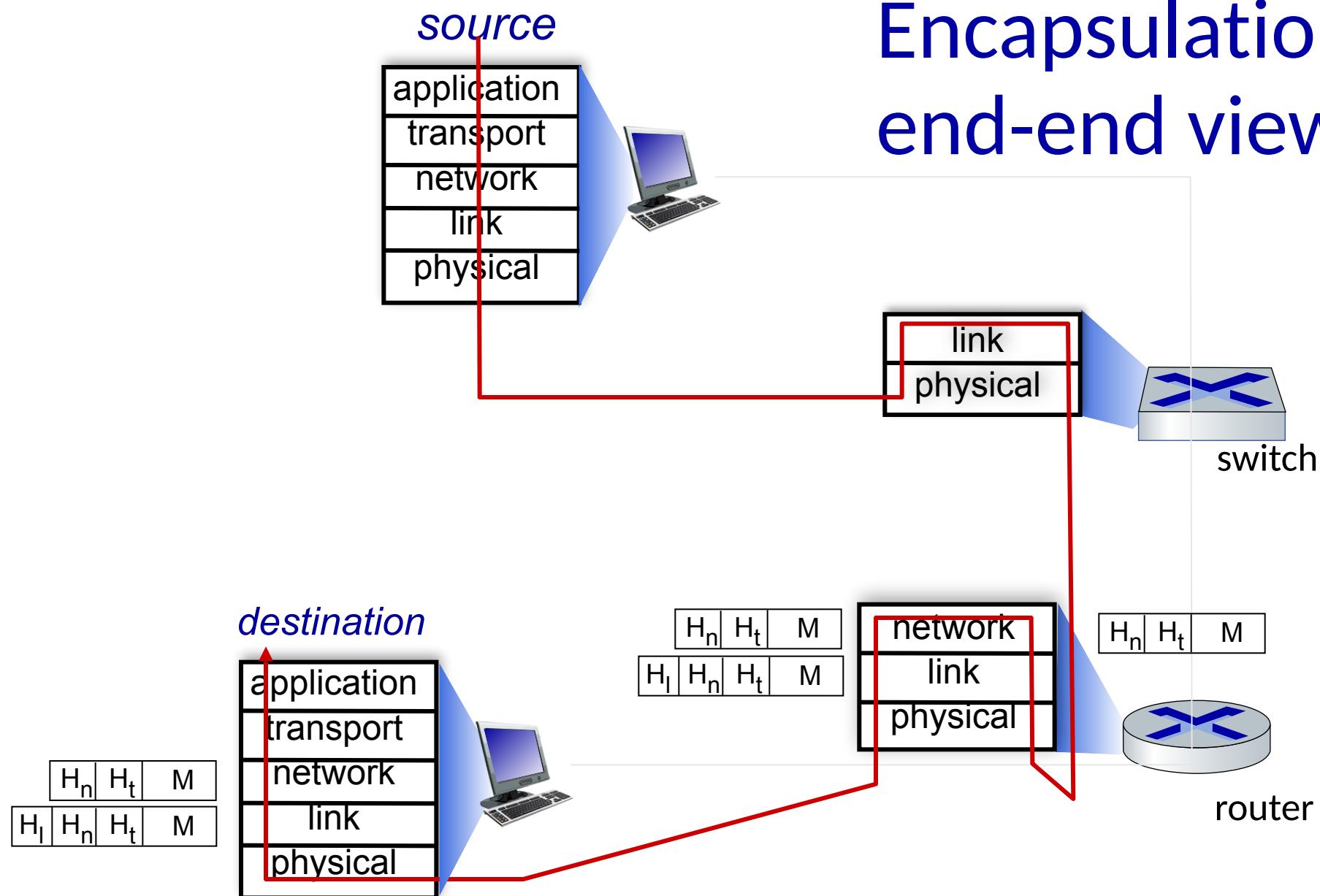
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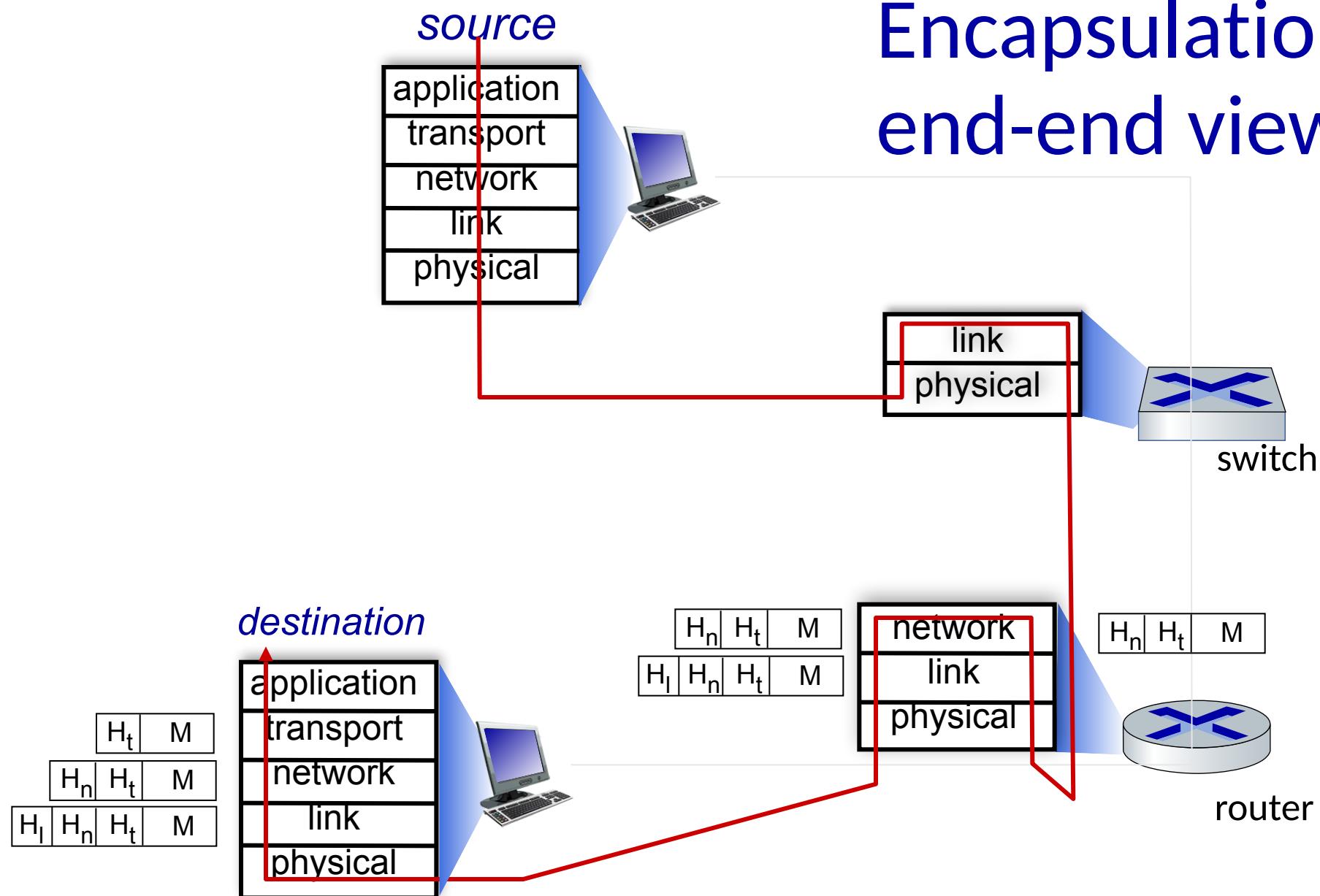
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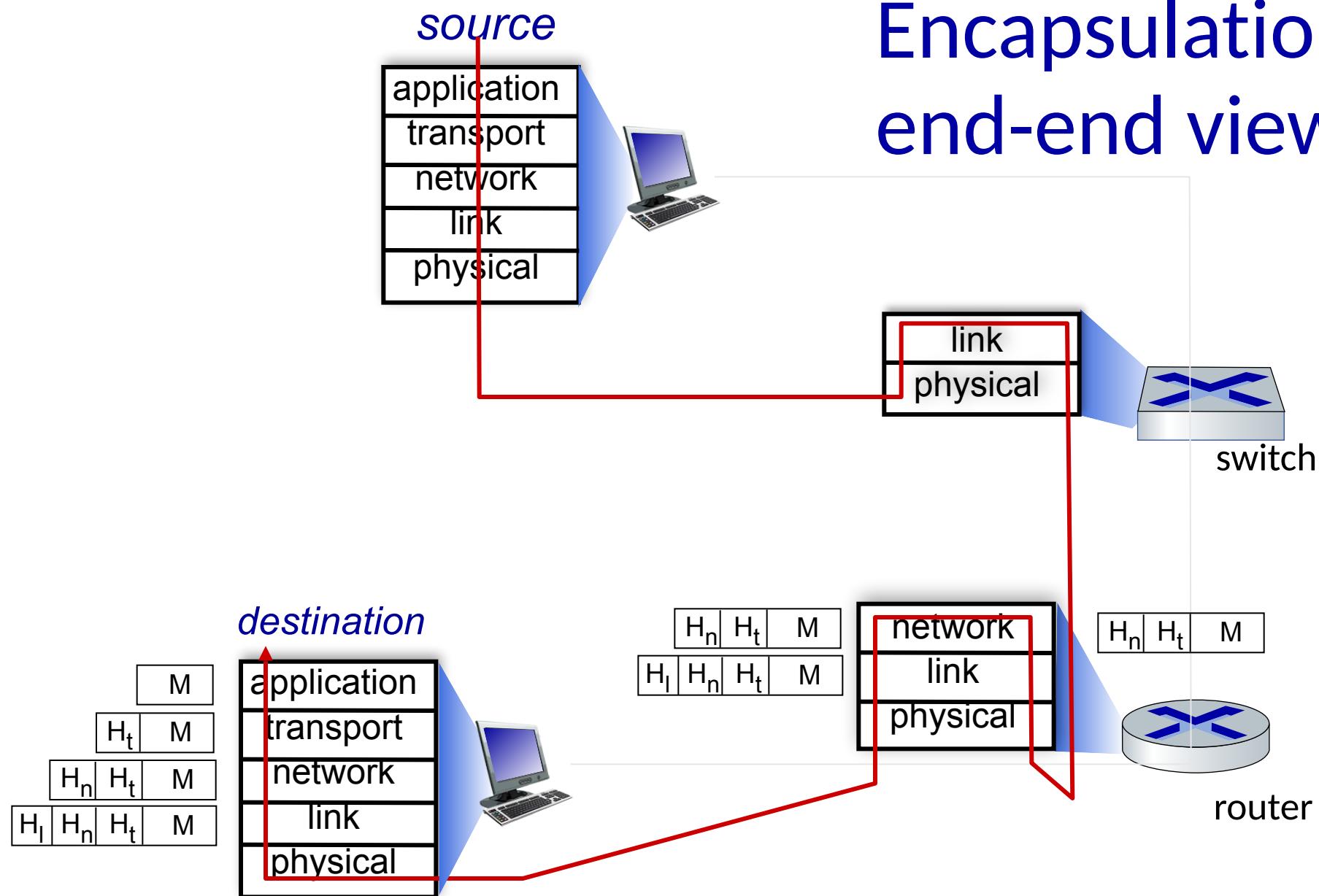
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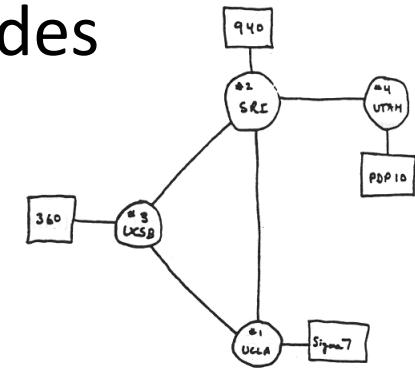
Chapter 1: roadmap

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

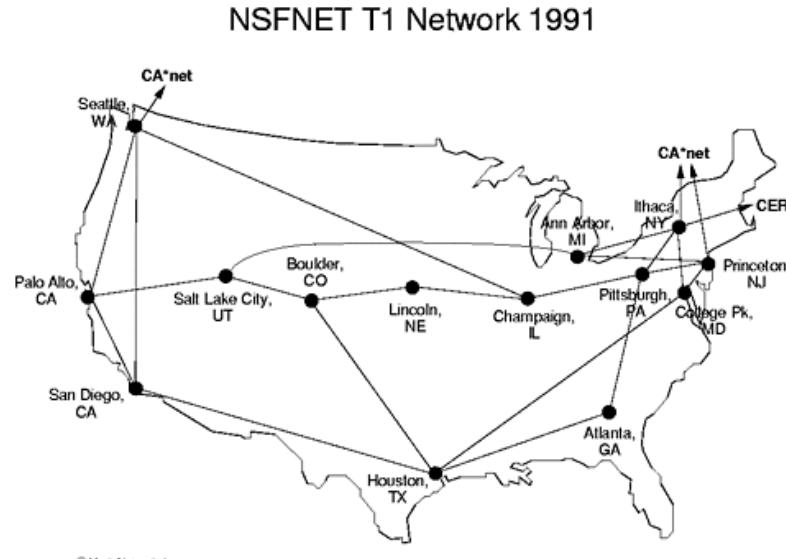
Cerf and Kahn's internetworking principles:

- 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)
- ~18B devices attached to Internet (2017)

Chapter 1: 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
- history

You now have:

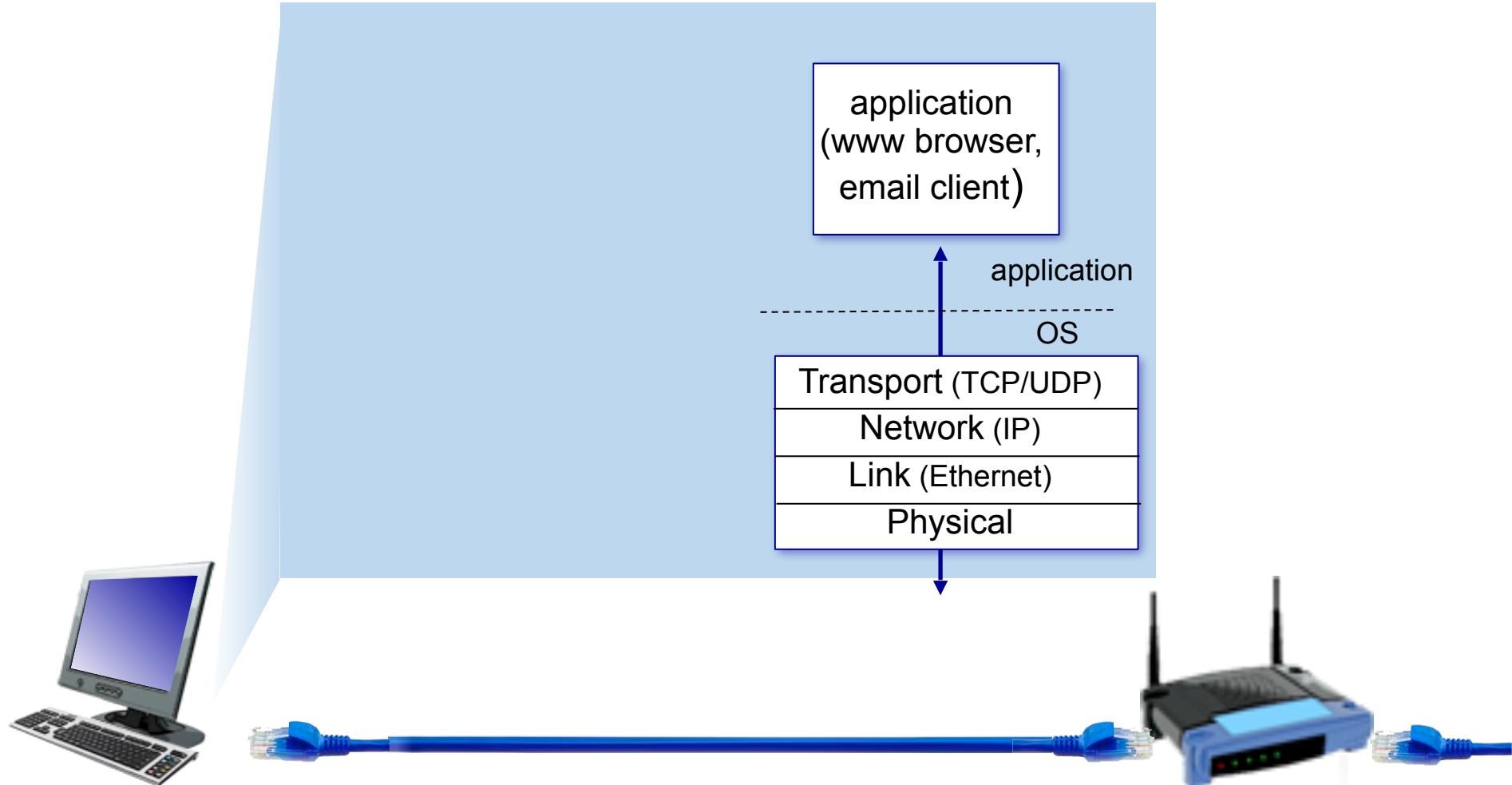
- context, overview, vocabulary, “feel” of networking
- more depth, detail, *and fun* to follow!

Additional Chapter 1 slides

Wireshark



Wireshark



Wireshark

