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# Computer Networks

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# Syllabus

## Web-Page

<https://guilhermeir.github.io/teaching/L3Networks.html>



## Topics

1. Introduction (Internet, OSI model)
2. Physical Layer
3. Link Layer
4. Network Layer

## Bibliography

- J. Kurose, K. Ross. *Computer Networking: A Top-Down Approach*. 8<sup>th</sup> Edition. Pearson, 2020.
- A. Tanenbaum, N. Feamster, D. Wetherall. *Computer Networks*. 6<sup>th</sup> Edition. Pearson, 2021.
- Guy Pujolle. *Les Réseaux*. 9<sup>th</sup> Edition. Eyrolles, 2018.

## Evaluation

- 5 In-class Quizzes      1 pt/quiz
- Mid-term Test              5 pts
  - Intro., physical and link layers
- Final Exam                10 pts
  - M + network layer

$$\text{Final Grade} = Q + M + F$$

# Syllabus

## Schedule

Class	Date	Time	Topics (Tentative)	Content
1	13/02	15h30 – 18h45	Intro	[K] Ch. 1 [T] Ch. 1
2*	06/03	15h30 – 18h45	Q1 Physical Layer	[K] Chapters 1, 6, and 7 [T] Chapter 2
3	07/03	08h30 – 11h45	Physical Layer	
4*	20/03	15h30 – 18h45	Q2 Link Layer	[K] Chapter 6 [T] Chapters 3 and 4
5*	03/04	15h30 – 18h45	Q3 Link Layer	
6*	17/04	13h45 – 17h00	M Network Layer	
7	09/05	13h45 – 17h00	Network Layer	
8*	22/05	13h45 – 17h00	Q4 Network Layer	[K] Chapters 4 and 5 [T] Chapter 5
9	25/05	13h45 – 17h00	Network Layer	
10*	05/06	13h45 – 17h00	Q5 Network Layer	
	21/06	08h30 – 10h30	Final Exam	

# **Computer Networks**

## **Class 1: Introduction**

# Introduction

## Class goal:

- Get “feel,” “big picture,” introduction to terminology
  - more depth, detail *later* in course

## Overview/roadmap:

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

# 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)

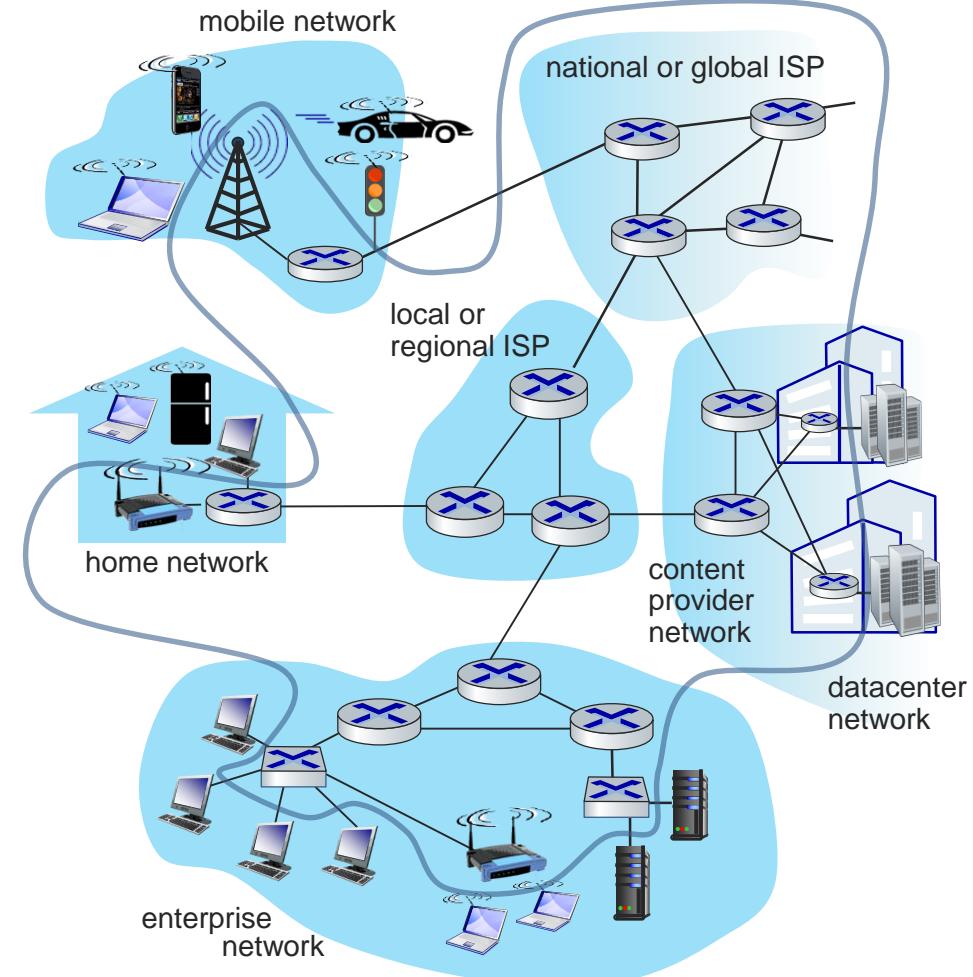
- routers, switches

*Communication links*:

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

*Networks*

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



## Introduction

# 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



Tweet-a-watt:  
monitor energy use

bikes



cars



scooters

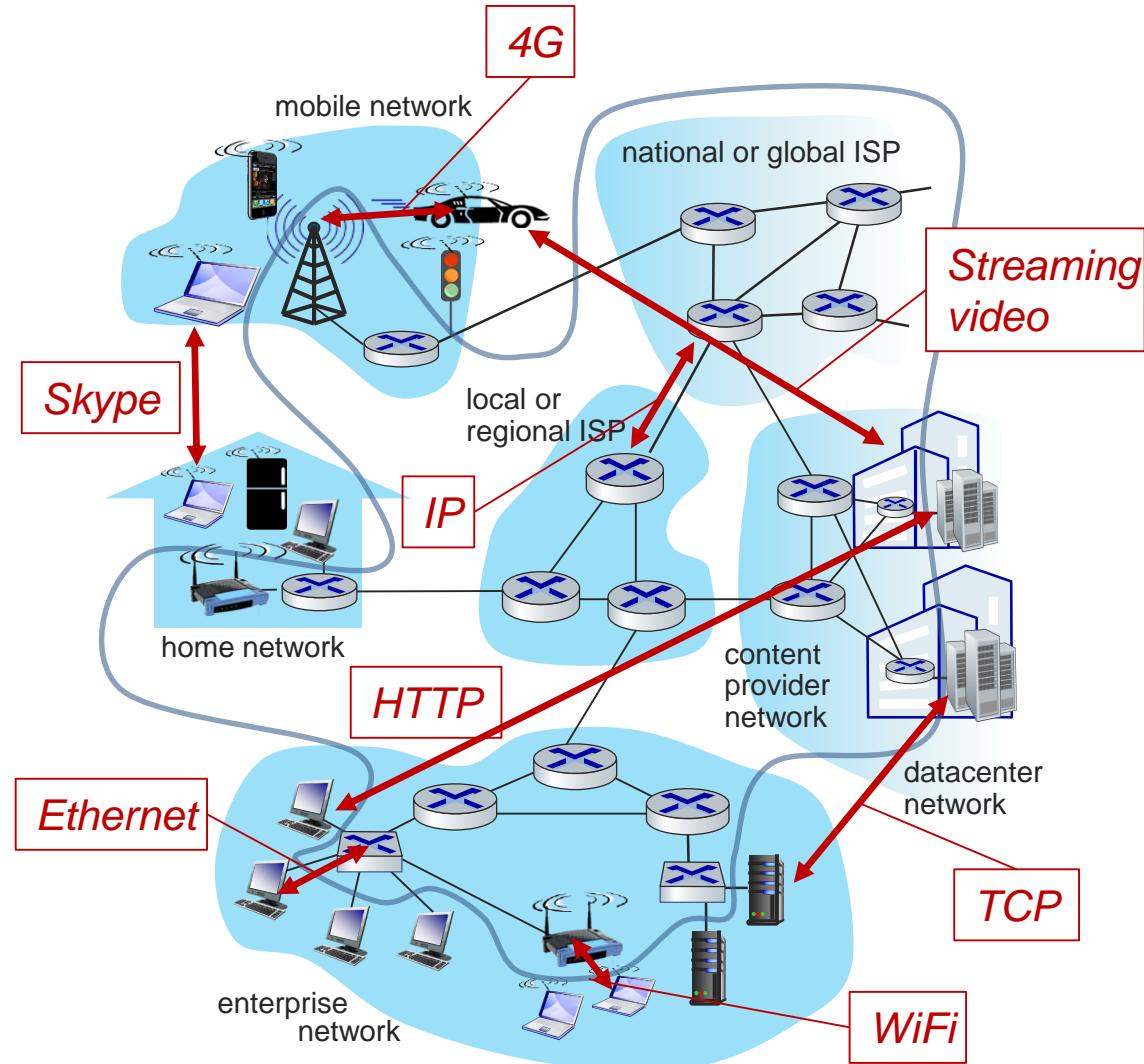


Fitbit

Others?

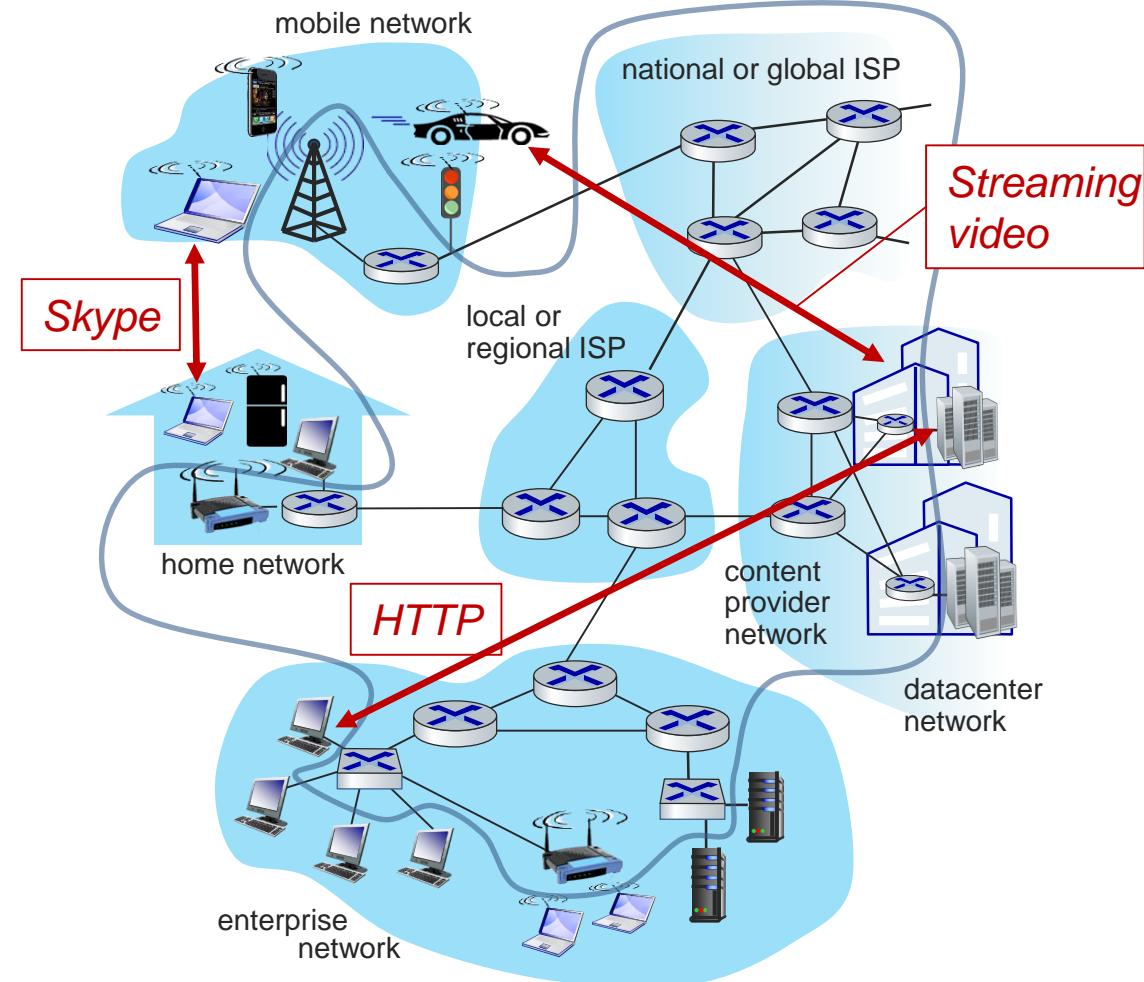
# The Internet: a “nuts and bolts” view

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



# The Internet: a “services” view

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



## What's a protocol?

### *Human protocols:*

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

### *Network protocols:*

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

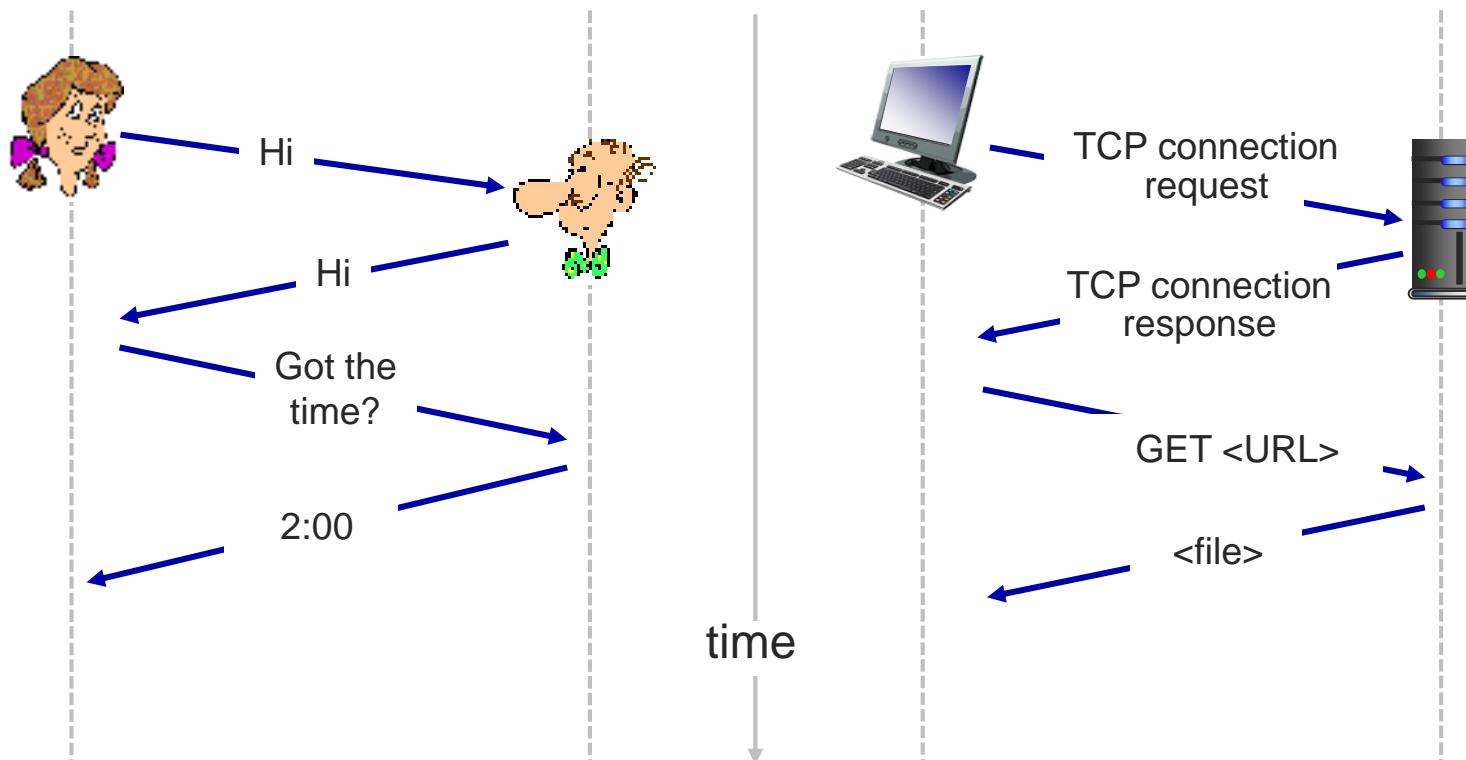
Rules for:

- ... specific messages sent
- ... specific actions taken when message received, or other events

*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?

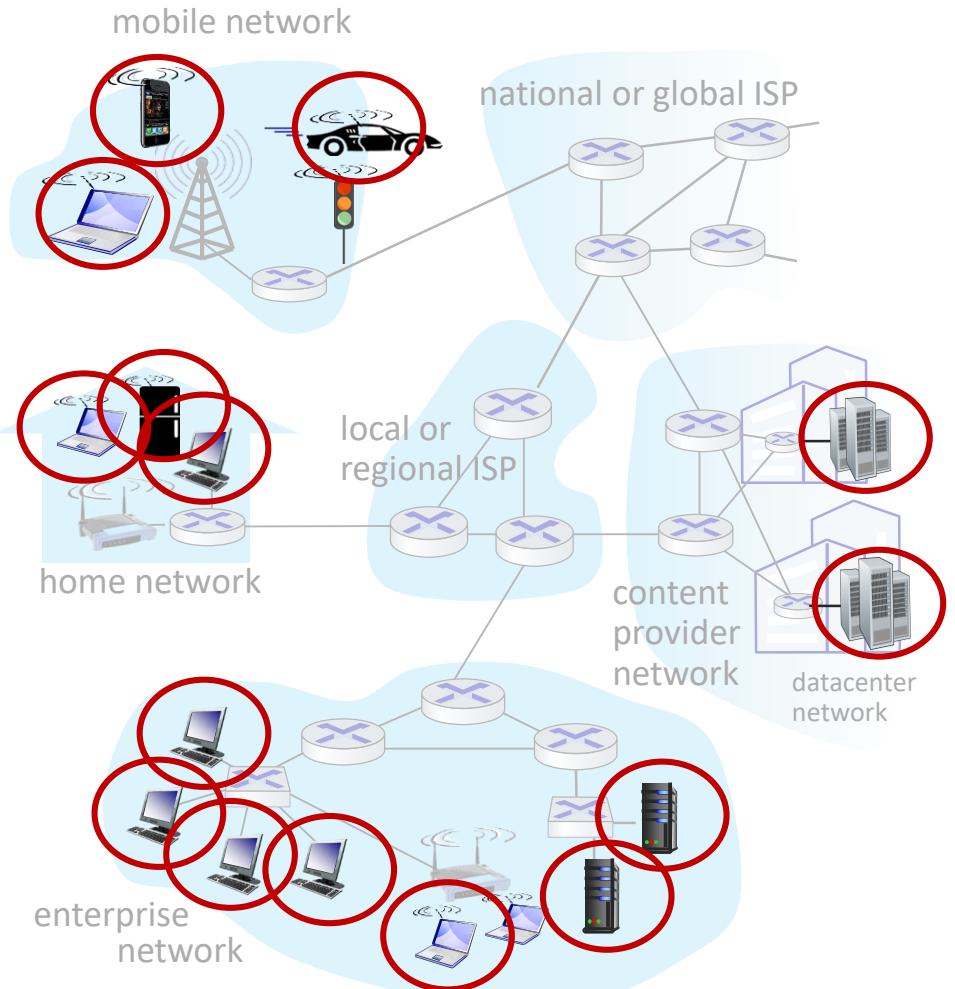
## Roadmap

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

## A closer look at Internet structure

### Network edge:

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



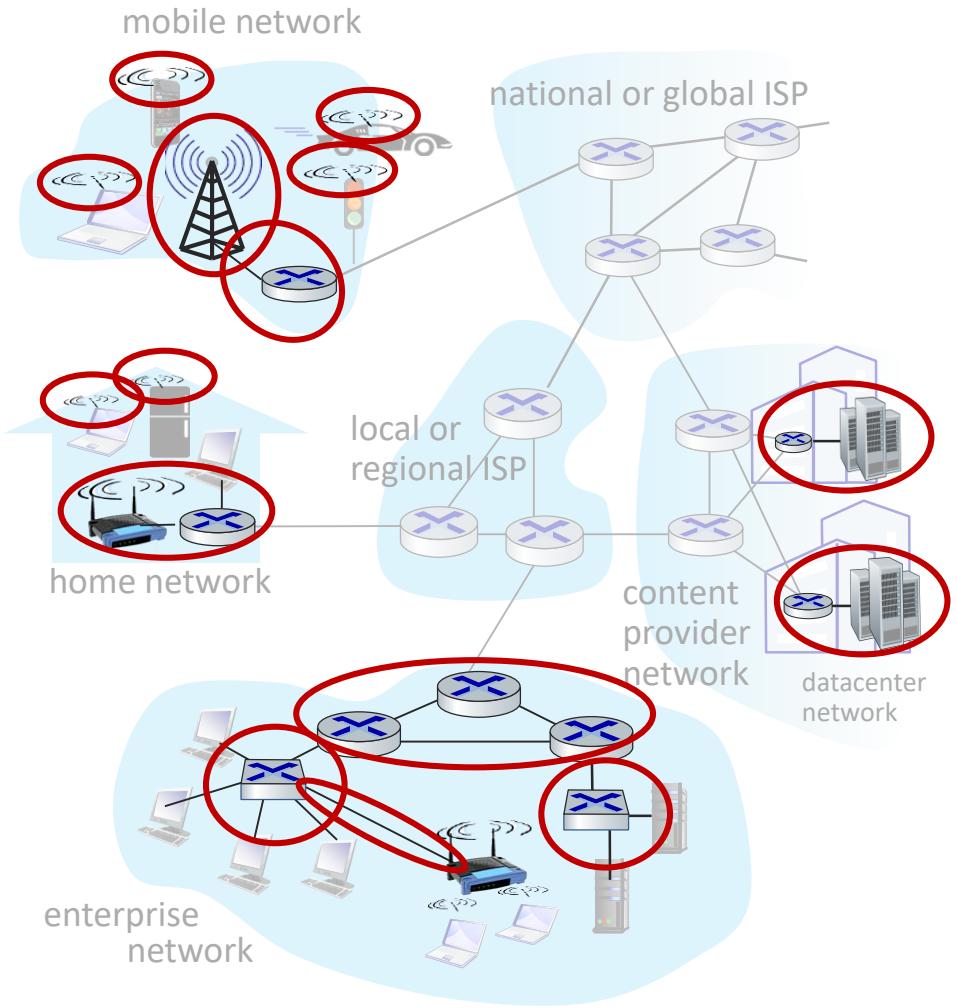
## A closer look at Internet structure

### Network edge:

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

### Access networks, physical media:

- wired, wireless communication links



## A closer look at Internet structure

### Network edge:

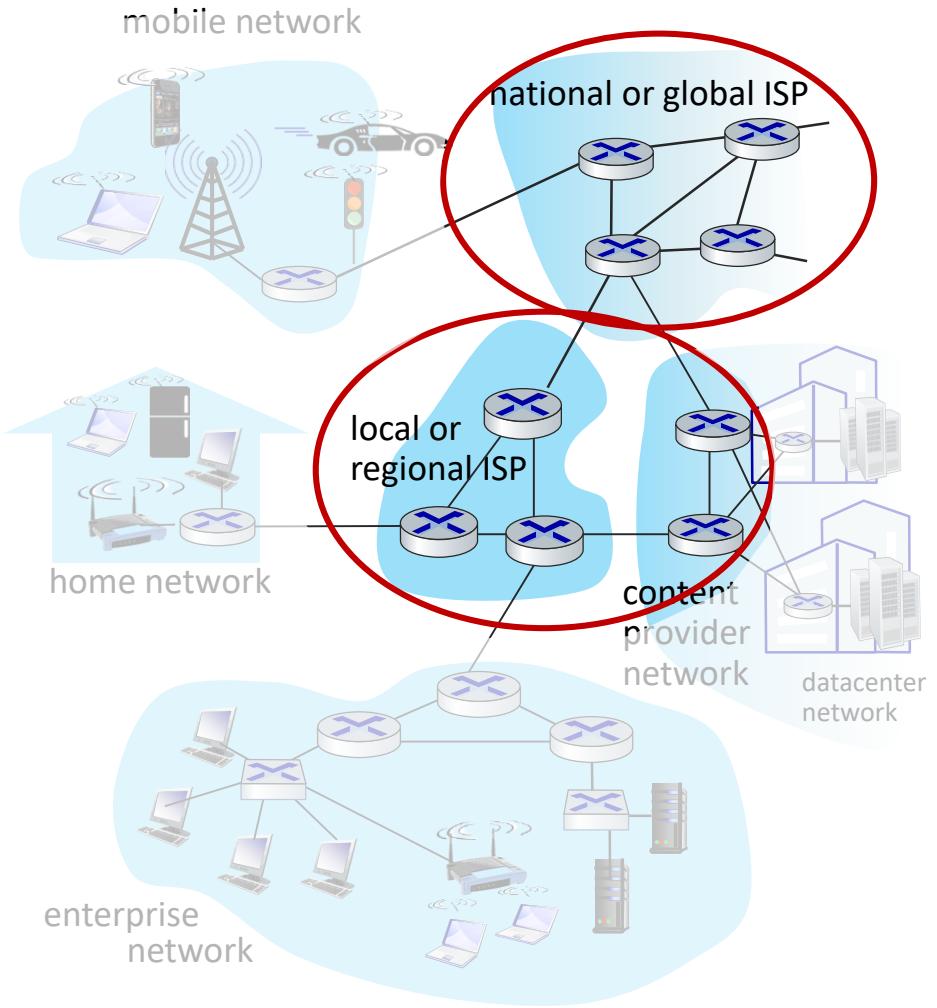
- hosts: clients and servers
- servers often in data centers

### Access networks, physical media:

- wired, wireless communication links

### Network core:

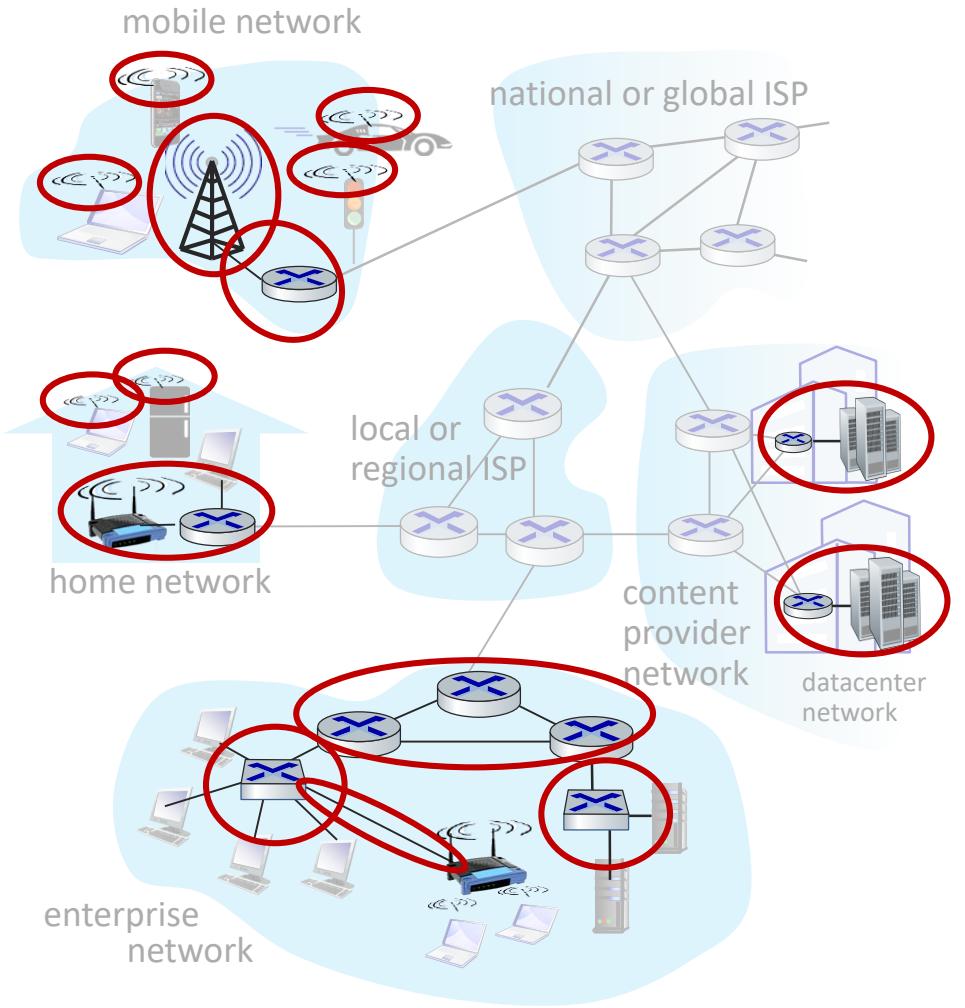
- interconnected routers
- network of networks



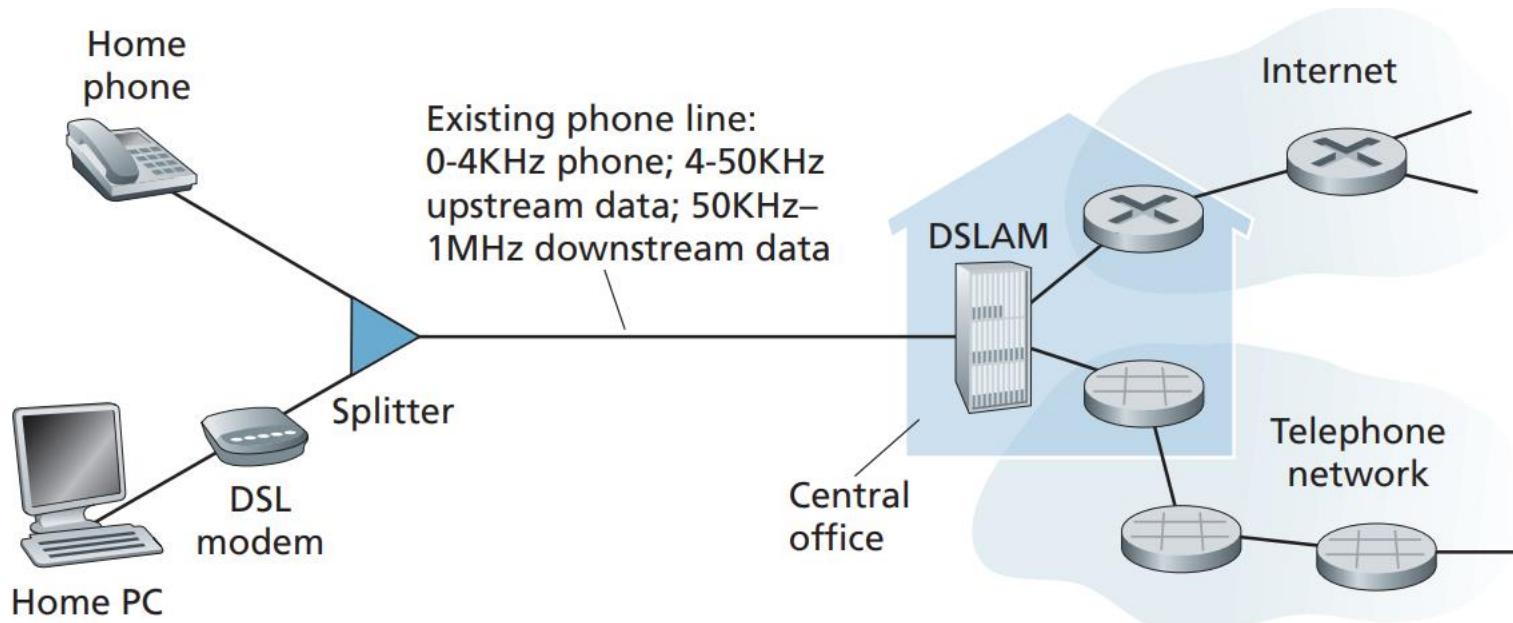
# Access Networks and Physical Media

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

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

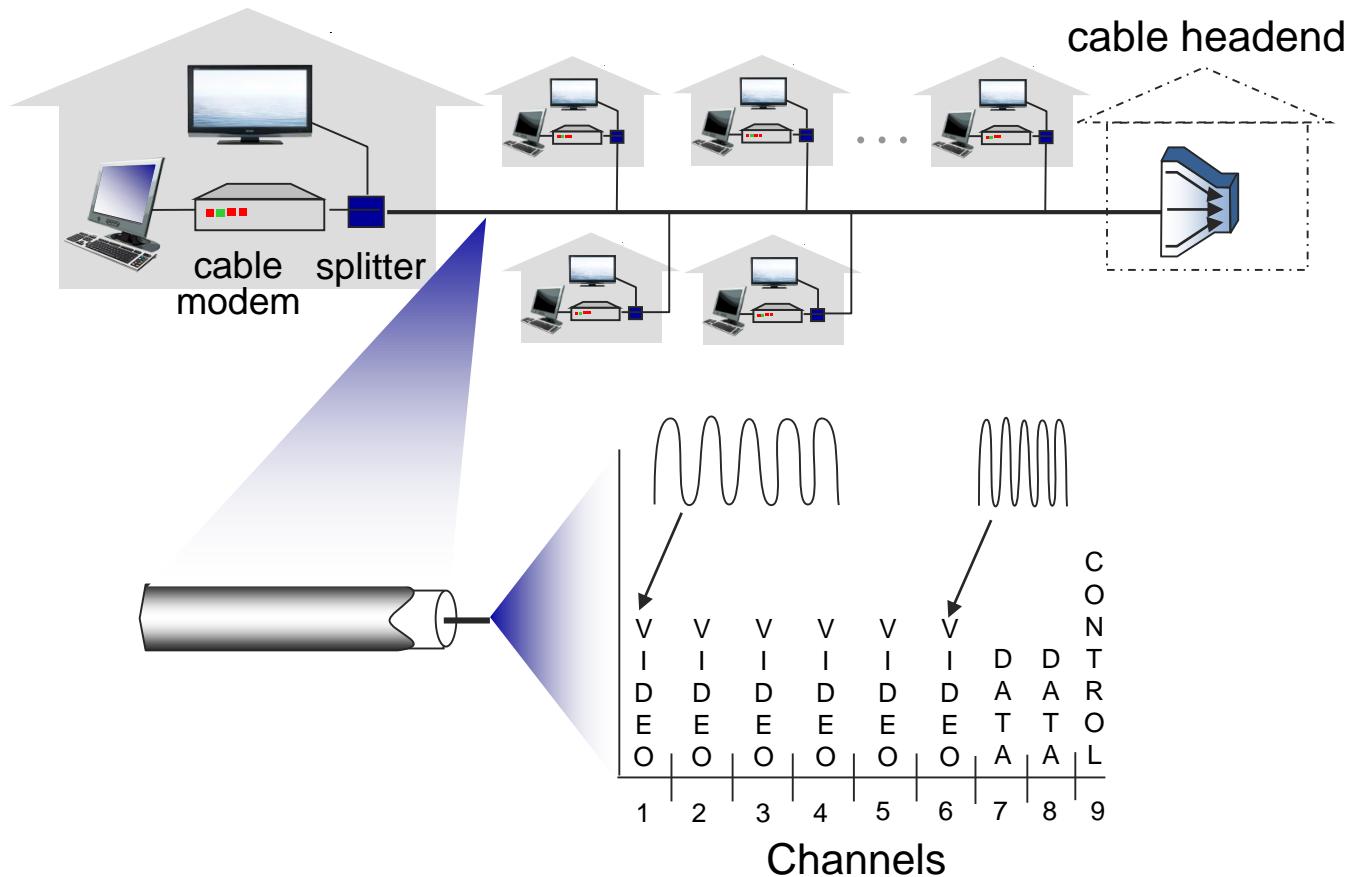


## Access Networks: Digital Subscriber Line (DSL)



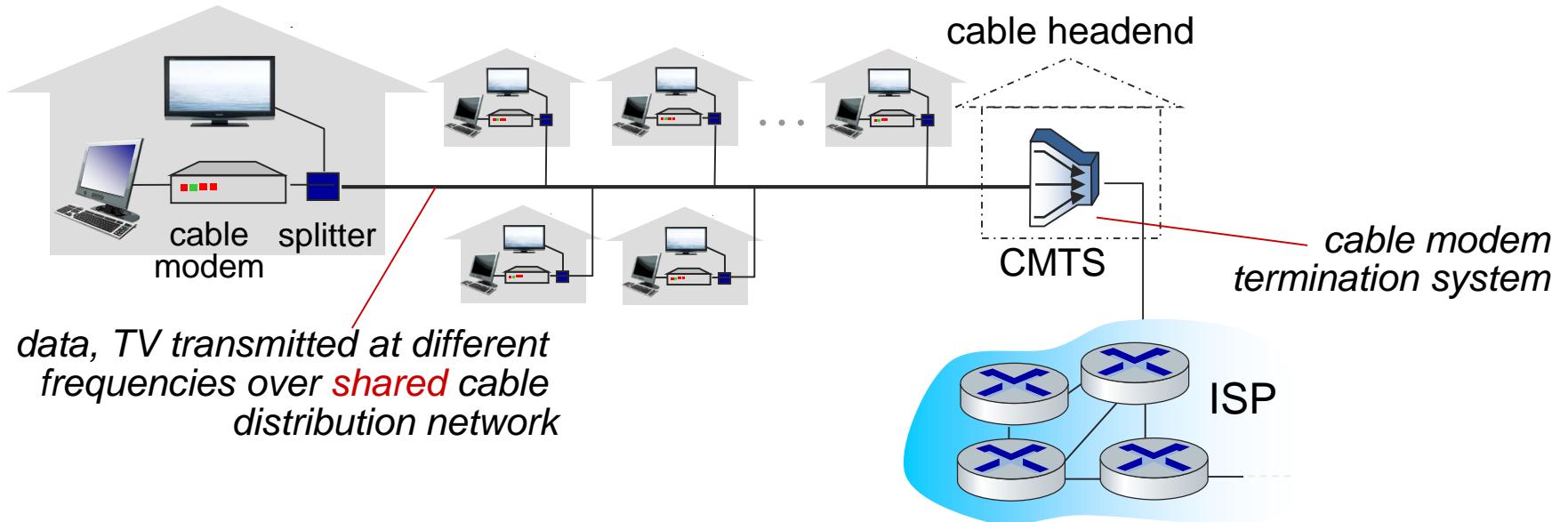
- use *existing* telephone line to central office DSLAM
  - data over DSL phone line goes to Internet
  - voice over DSL phone line goes to telephone net
- 24-52 Mbps dedicated downstream transmission rate
- 3.5-16 Mbps dedicated upstream transmission rate

## Access Networks: Cable-based Access



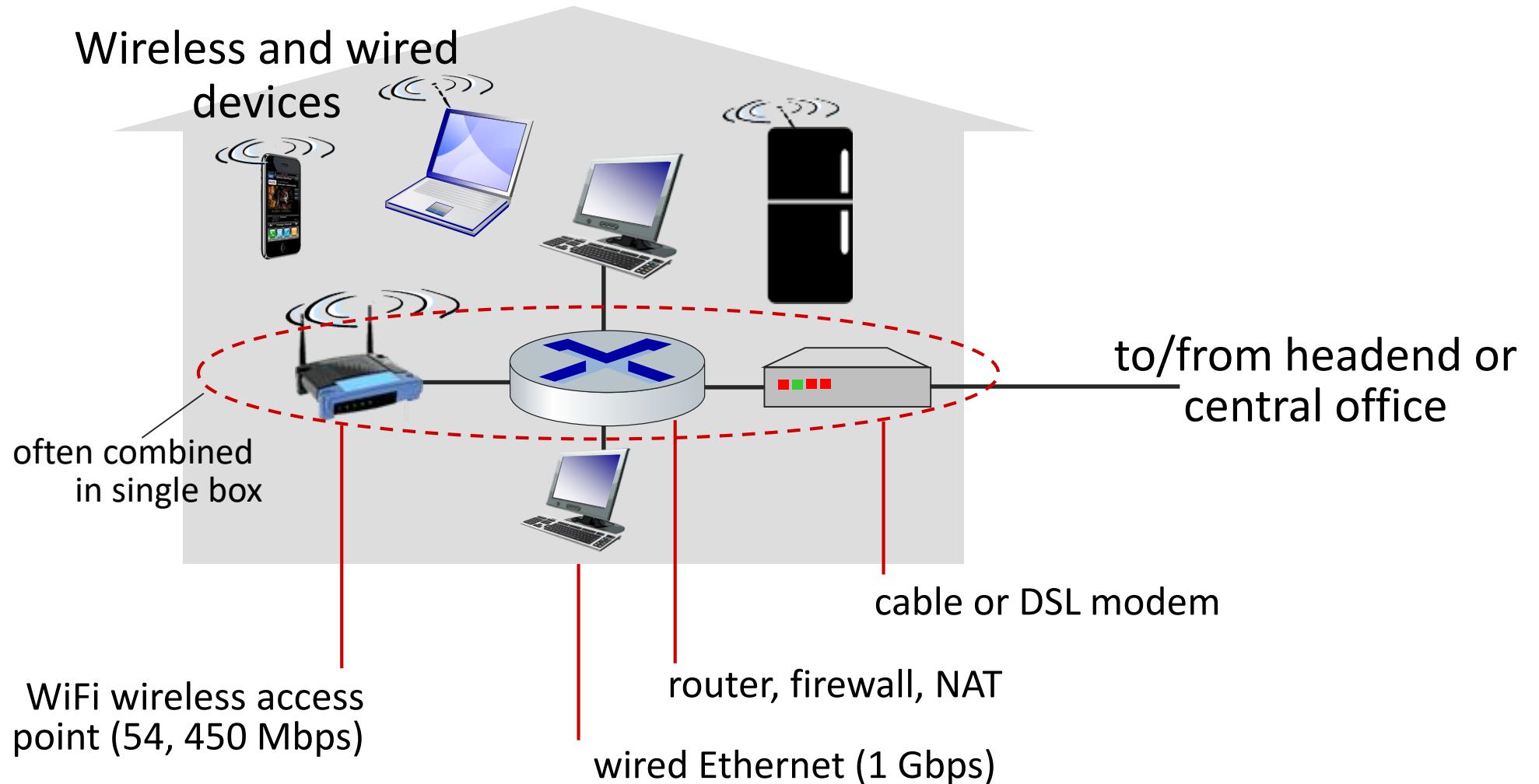
*Frequency Division Multiplexing (FDM):* Different channels transmitted in different frequency bands

## Access Networks: Cable-based Access

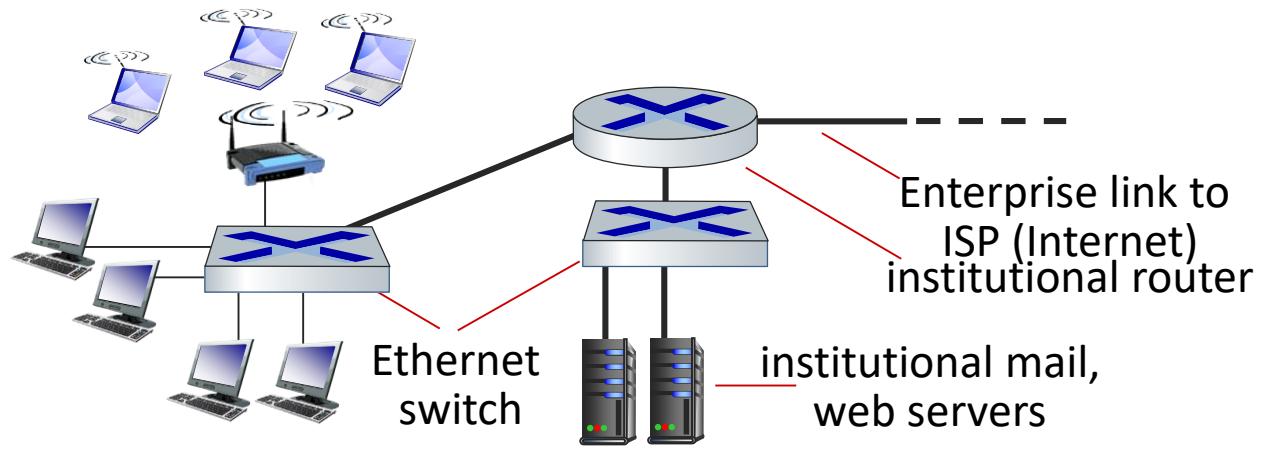


- HFC: hybrid fiber coax
  - asymmetric: up to 40 Mbps – 1.2 Gbps downstream transmission rate, 30-100 Mbps upstream transmission rate
- network of cable, fiber attaches homes to ISP router
  - homes **share access network** to cable headend

## Access Networks: Home Networks



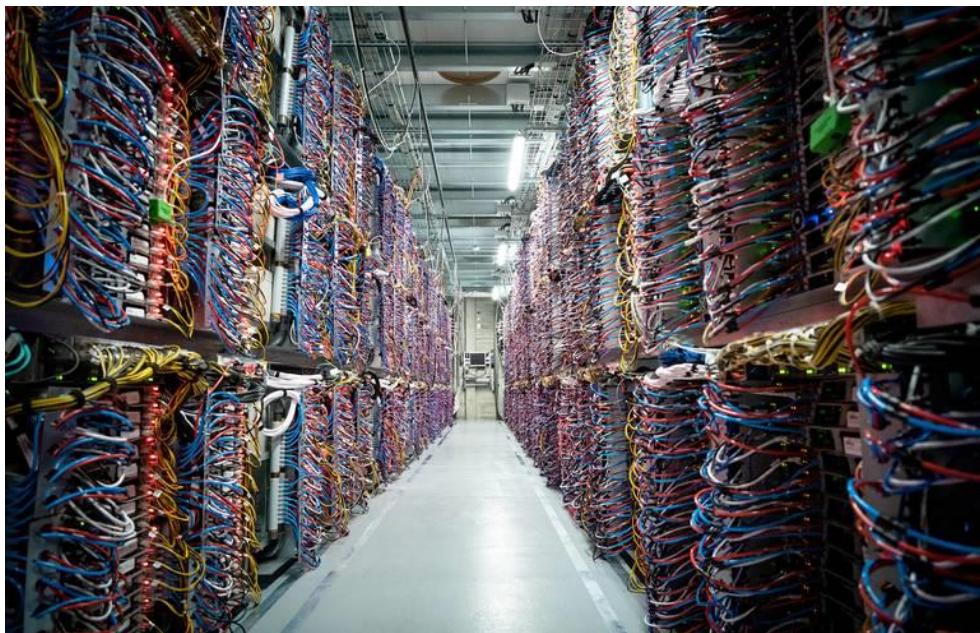
## Access Networks: Enterprise Networks



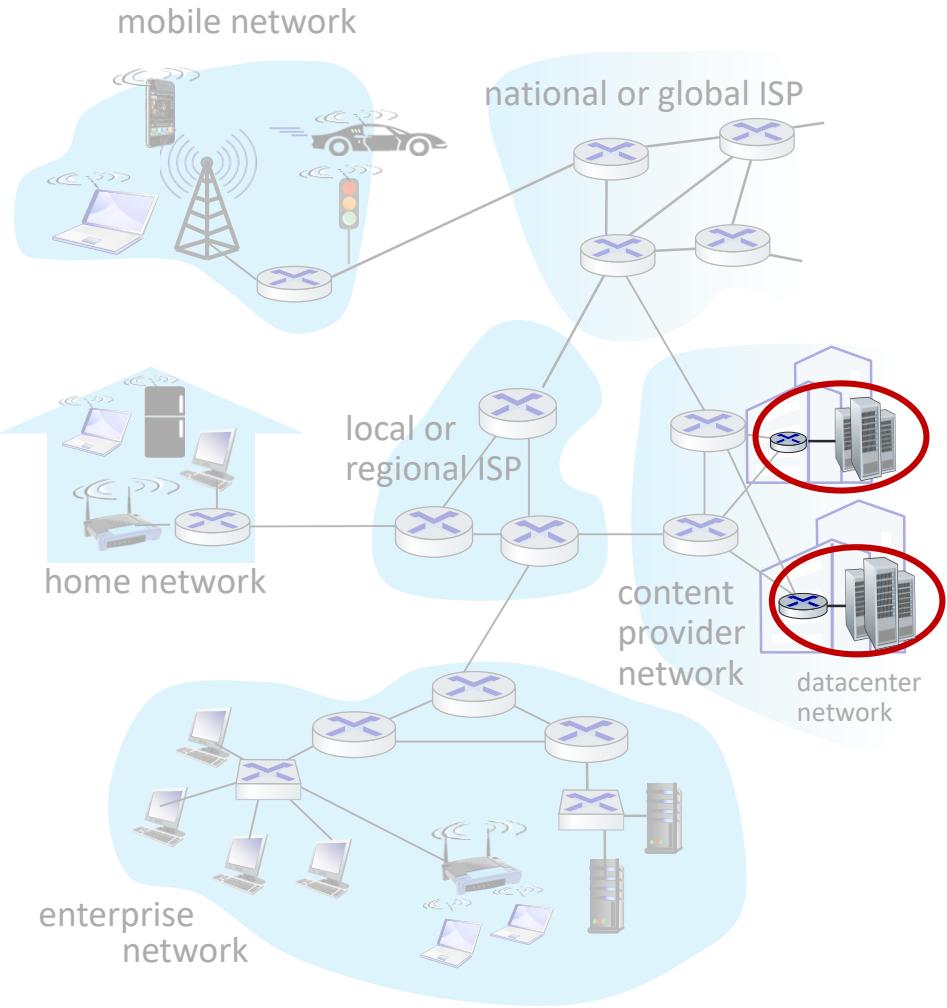
- companies, universities, etc.
- mix of wired, wireless link technologies, connecting a mix of switches and routers (we'll cover differences shortly)
  - Ethernet: wired access at 100Mbps, 1Gbps, 10Gbps
  - WiFi: wireless access points at 11, 54, 450 Mbps

## Access Networks: Datacenter Networks

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



Source: <https://www.20minutes.fr/economie/3157959-20211028-marseille-apportent-data-centers-ville>



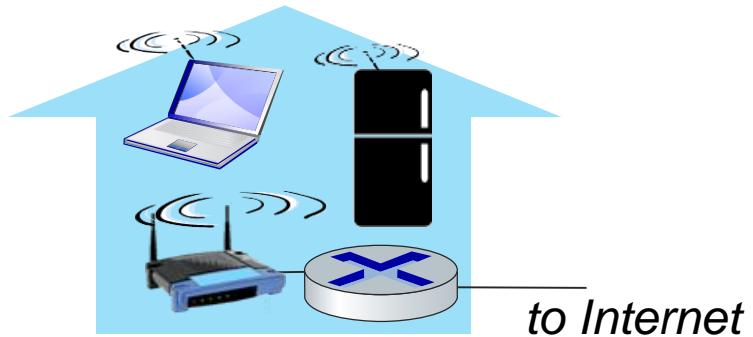
## Wireless Access Networks

Shared wireless access network connects end system to router

- via base station aka “access point”

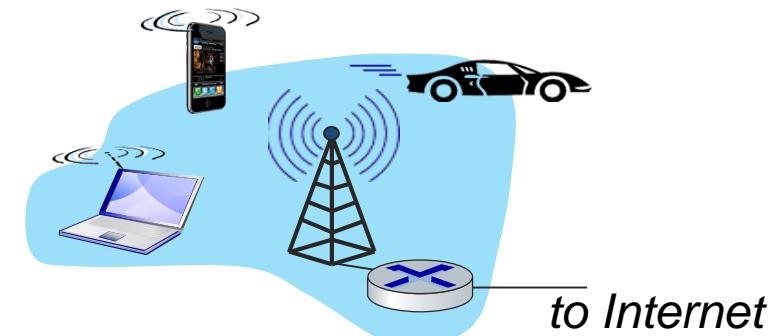
### Wireless local area networks (WLANs)

- typically within or around building (~30m)
- 802.11b/g/n (WiFi): 11, 54, 450 Mbps transmission rate



### Wide-area cellular access networks

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



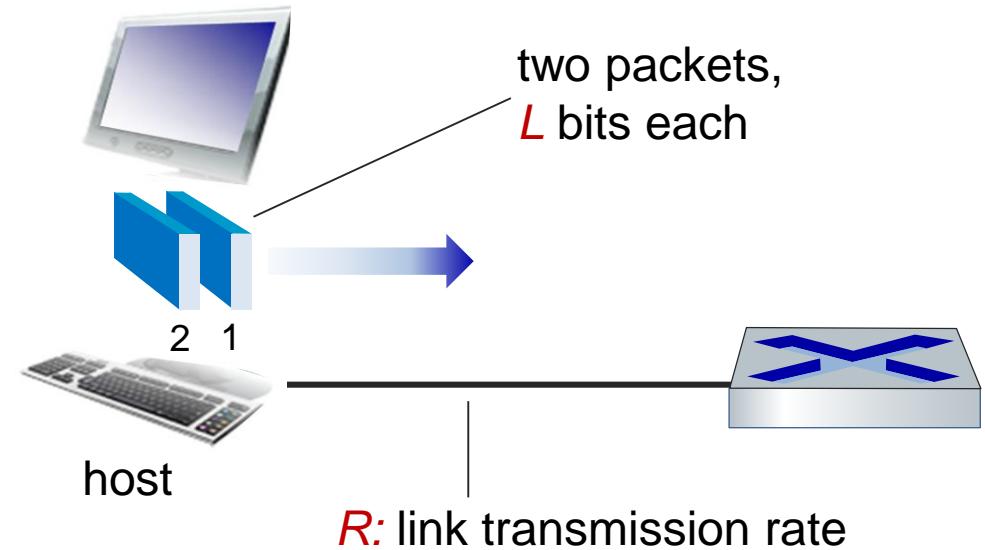
## Host: Sends *packets* of data

Shared wireless access network connects end system to router

- via base station aka “access point”

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*



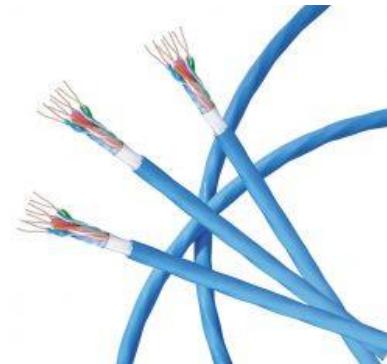
$$\text{packet transmission delay} = \frac{\text{time needed to transmit } L\text{-bit packet into link}}{= \frac{L \text{ (bits)}}{R \text{ (bits/sec)}}}$$

## Link: 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



## Link: Physical Media

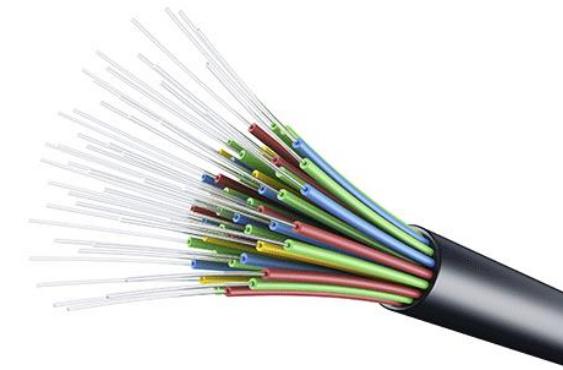
### Coaxial cable:

- 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



## Link: 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:

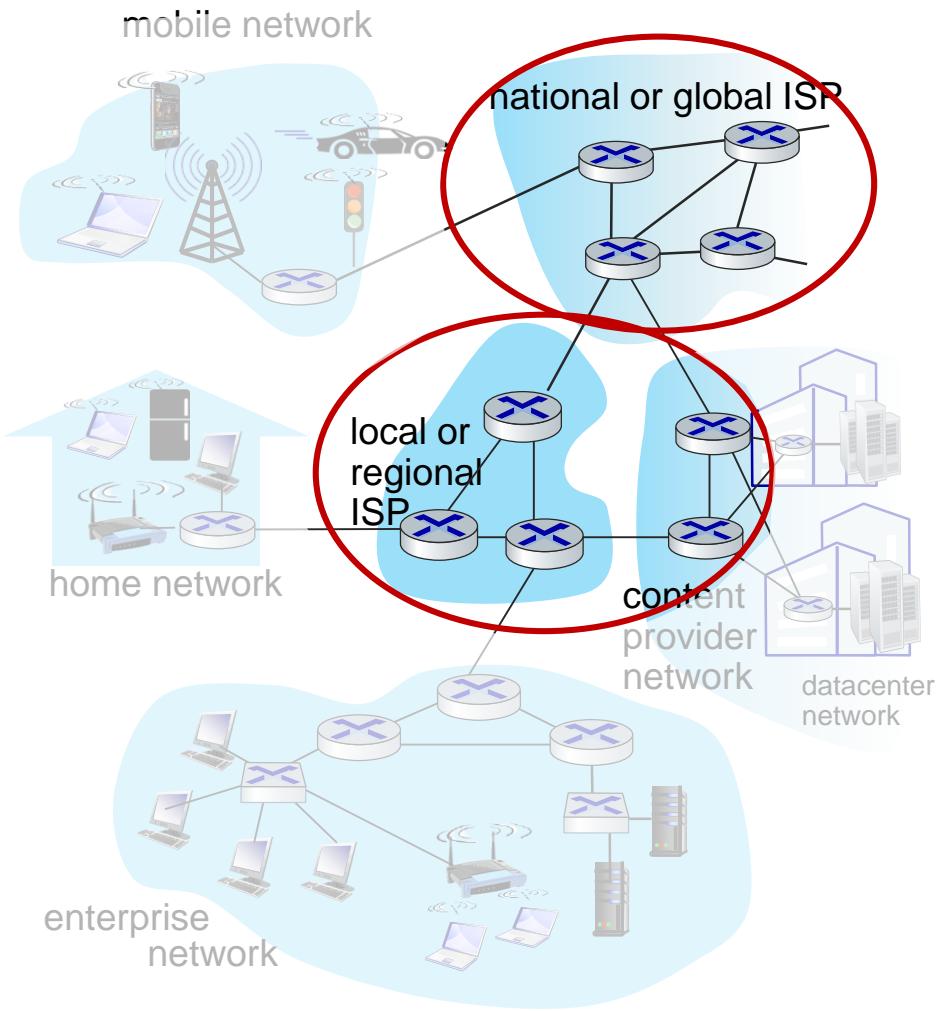
- **Wireless LAN (WiFi)**
  - 10-100's Mbps; 10's of meters
- **wide-area** (e.g., 4G cellular)
  - 10's Mbps over ~10 Km
- **Bluetooth:** cable replacement
  - short distances, limited rates
- **terrestrial microwave**
  - point-to-point; 45 Mbps channels
- **satellite**
  - up to 45 Mbps per channel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

## Roadmap

- What *is* the *Internet*? What *is* a *protocol*?
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## The Network Core

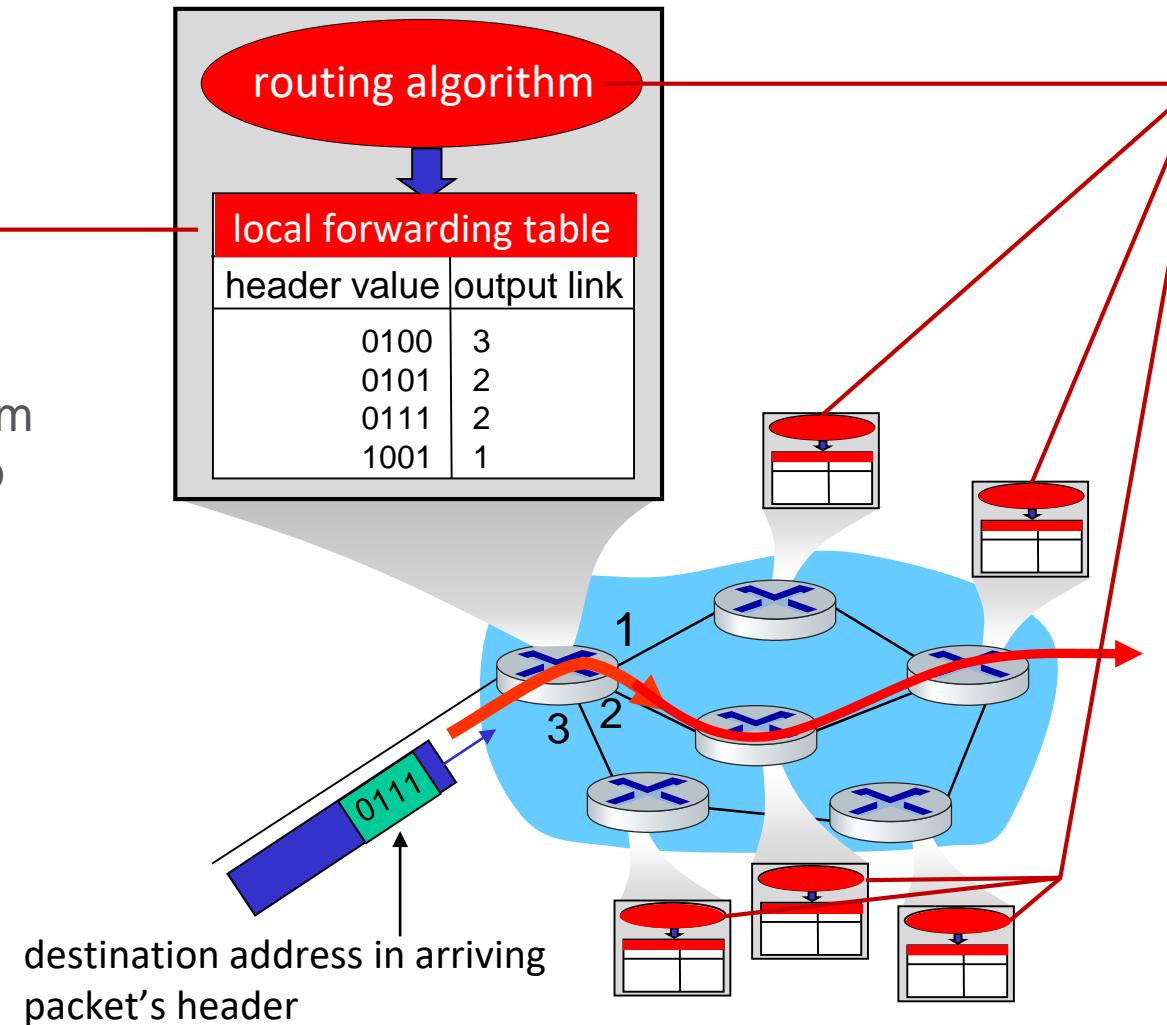
- mesh of interconnected routers
- **packet-switching**: hosts break application-layer messages into *packets*
  - network **forwards** packets from one router to the next, across links on path from **source to destination**



# Internet's Network-Core Functions

## Forwarding:

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



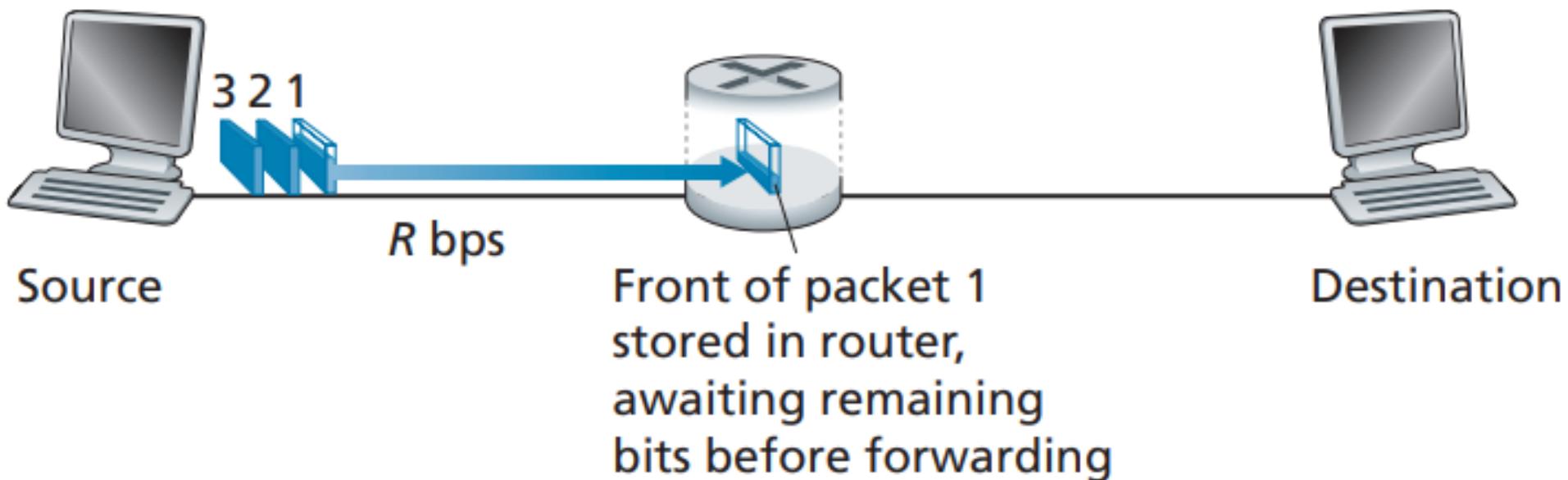
## Routing:

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





## Packet Switching: Store-and-Forward

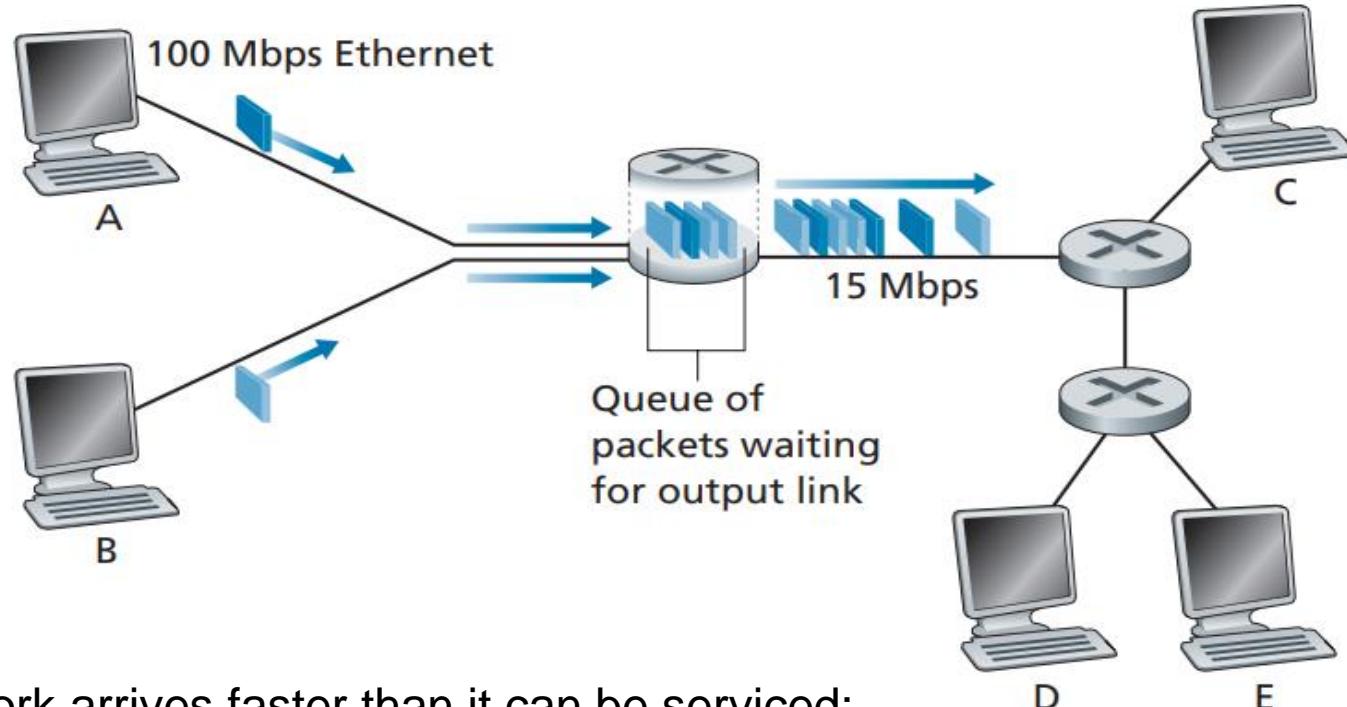


- **packet transmission delay:** takes  $L/R$  seconds to transmit (push out)  $L$ -bit packet into link at  $R$  bps
- **store and forward:** entire packet must arrive at router before it can be transmitted on next link

*One-hop numerical example:*

- $L = 10$  Kbits
- $R = 100$  Mbps
- one-hop transmission delay = 0.1 ms

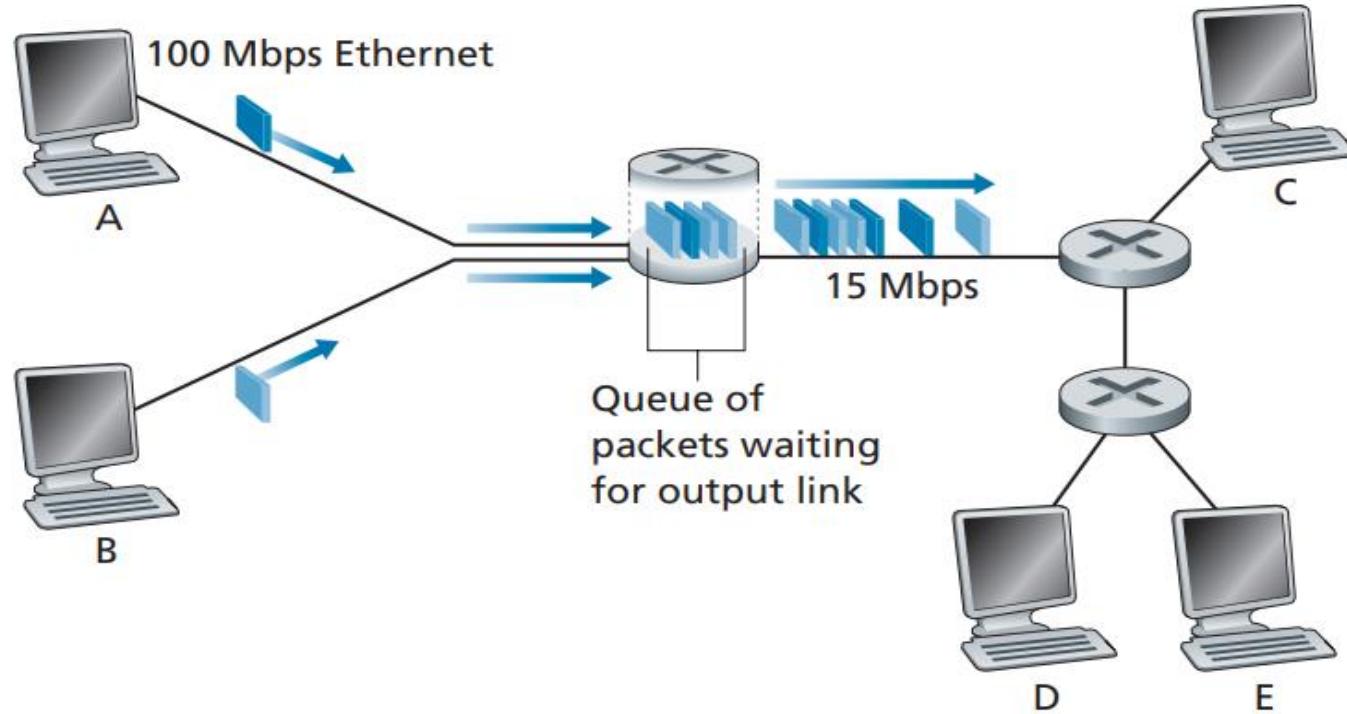
## Packet Switching: Queueing



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



## Packet Switching: Queueing



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

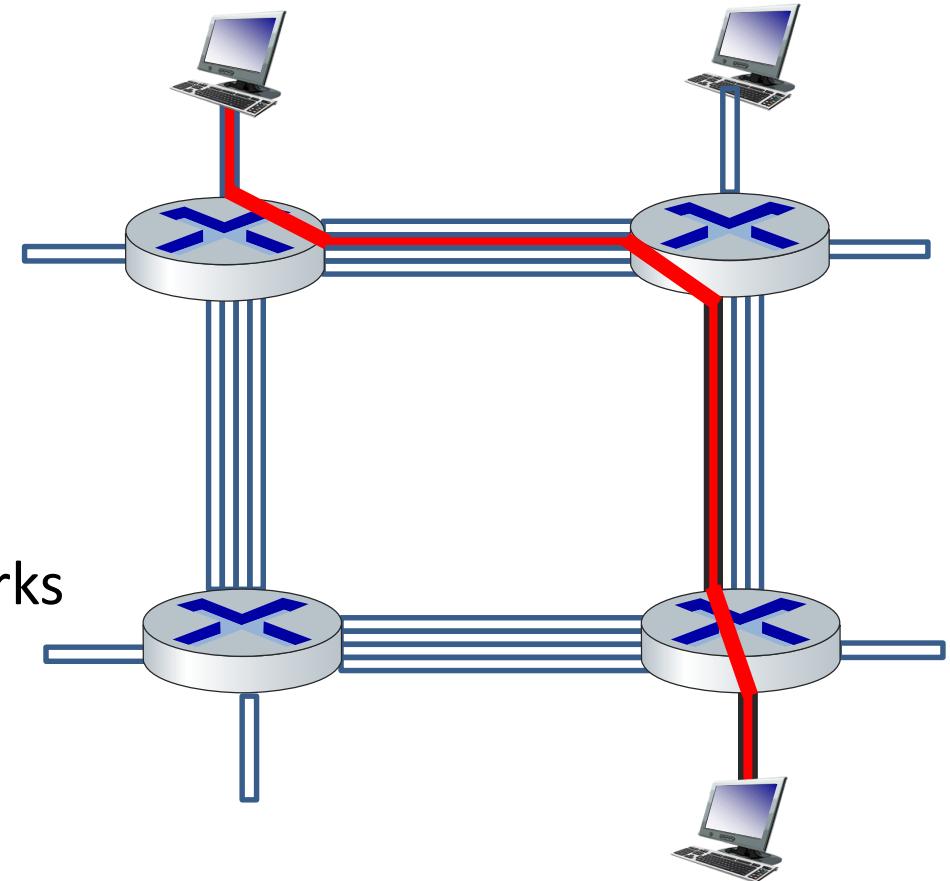
- packets will queue, waiting to be transmitted on output link
- packets can be dropped (lost) if memory (buffer) in router fills up

## Alternative to Packet Switching: Circuit Switching



End-end resources allocated to, reserved for “call” between source and destination

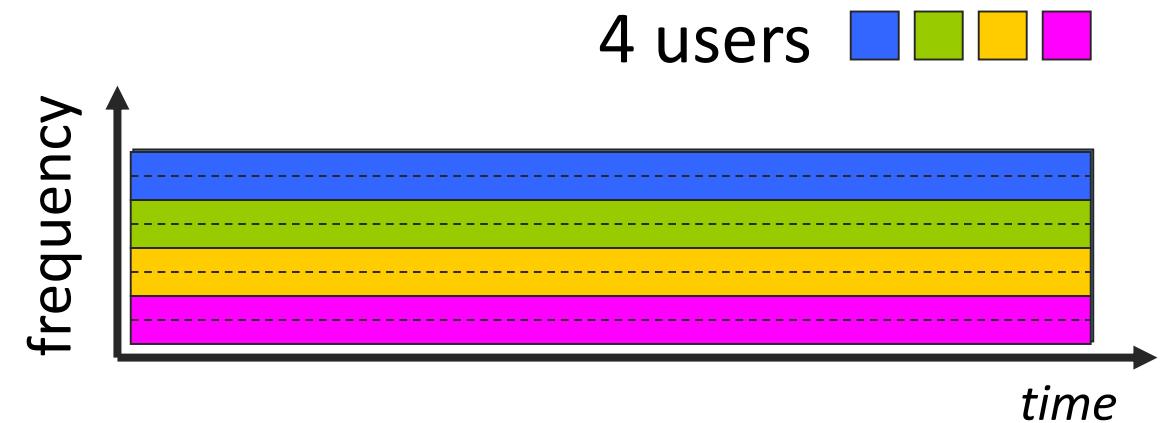
- in diagram, each link has four circuits.
    - call gets 2<sup>nd</sup> circuit in top link and 1<sup>st</sup> circuit in right link.
  - dedicated resources: no sharing
    - circuit-like (guaranteed) performance
  - circuit segment idle if not used by call (no sharing)
- 
- commonly used in traditional telephone networks



## Circuit Switching: FDM and TDM

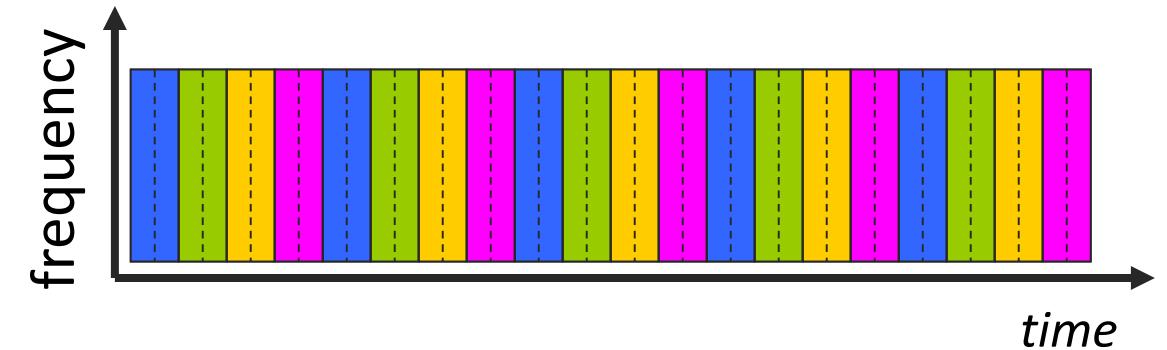
### Frequency Division Multiplexing (FDM)

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



### Time Division Multiplexing (TDM)

- time divided into slots

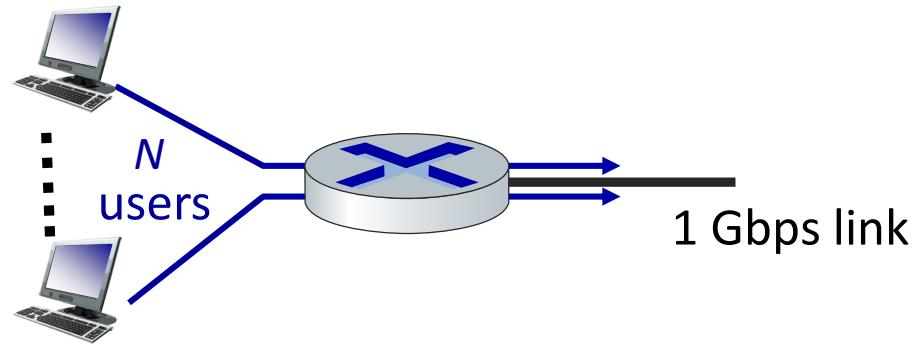


# Packet Switching versus Circuit Switching



Example:

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



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

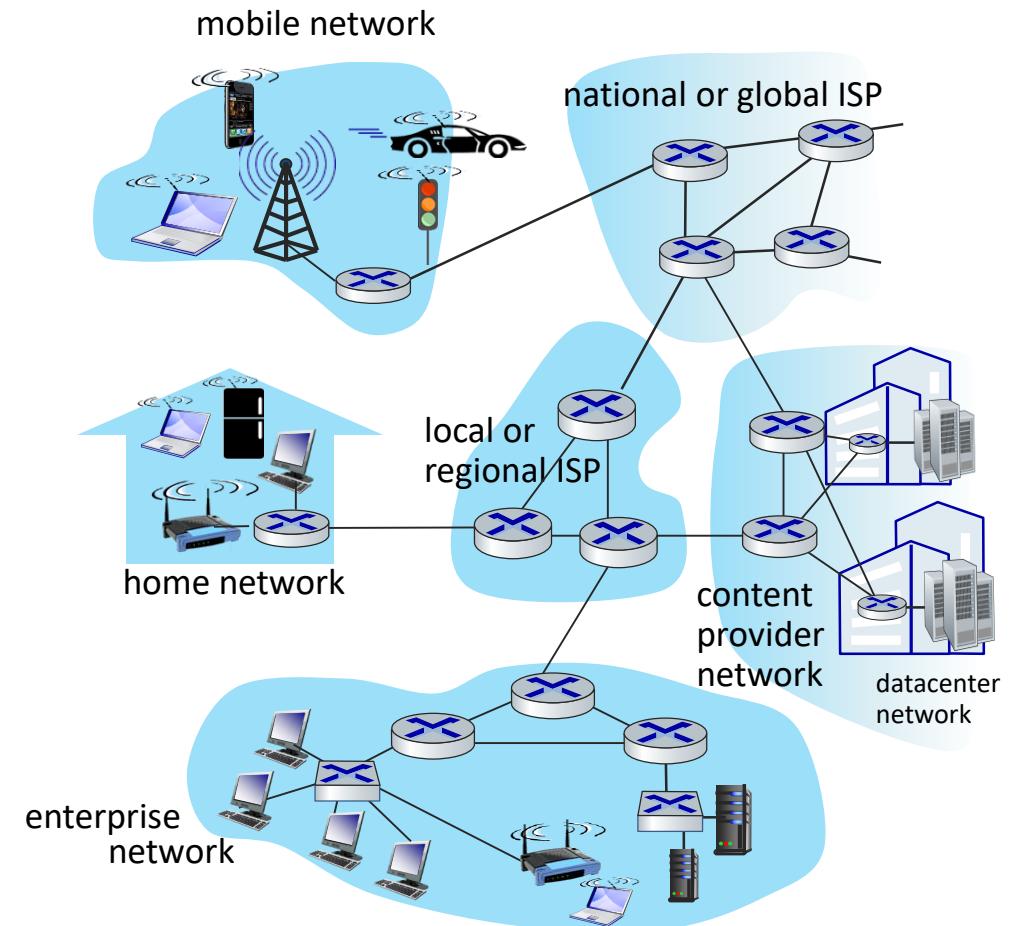
- *circuit switching:* 10 users
- *packet switching:* with 35 users, probability > 10 active at same time is less than .0004

**Q:** how did we get value 0.0004?

## Internet Structure: a “Network of networks”

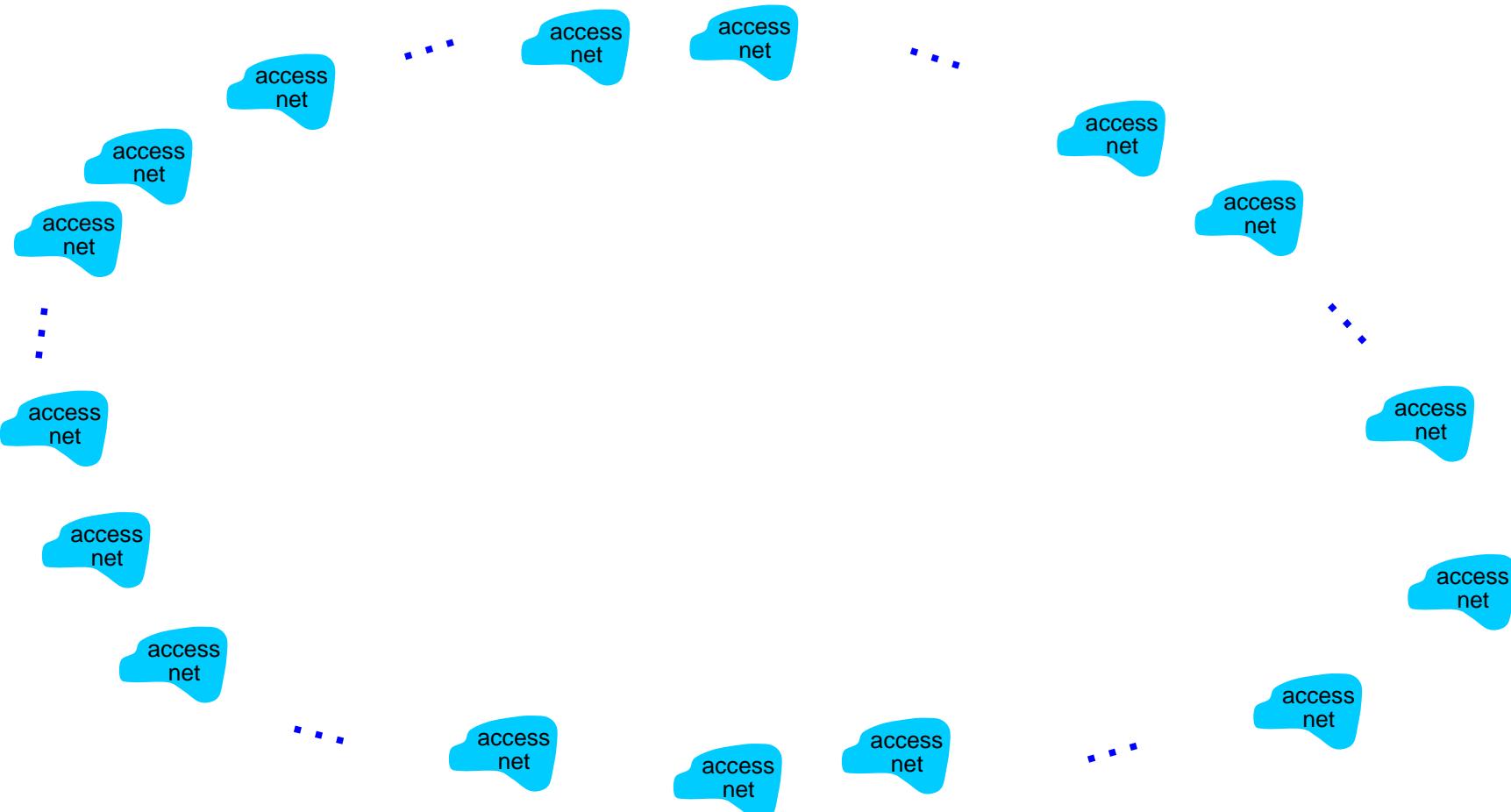
- hosts connect to Internet via **access** Internet Service Providers (ISPs)
- access ISPs in turn must be interconnected
  - so that *any two hosts (anywhere!)* can send packets to each other
- resulting network of networks is very complex
  - evolution driven by **economics, national policies**

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



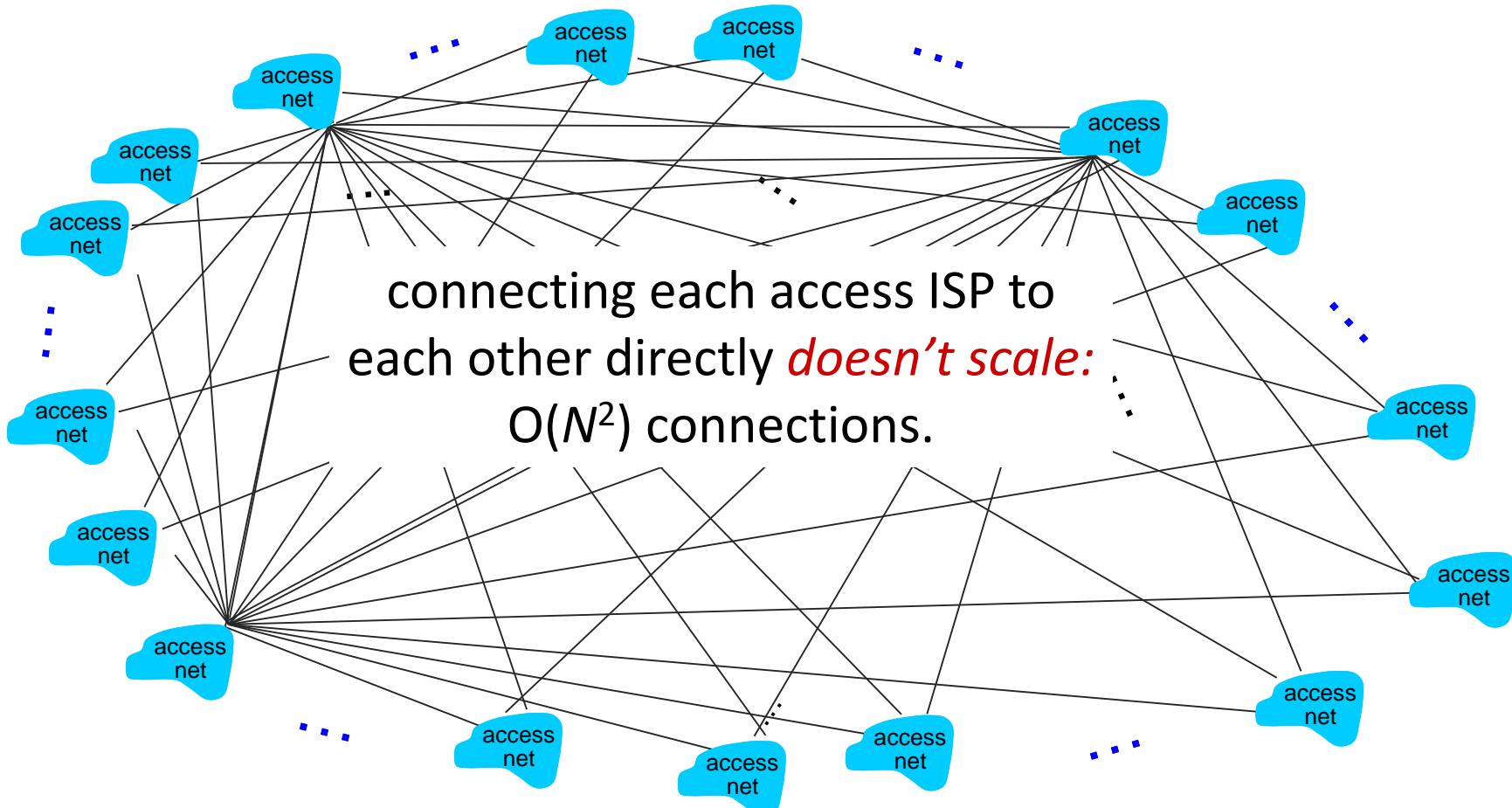
# Internet Structure: a “Network of networks”

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



# Internet Structure: a “Network of networks”

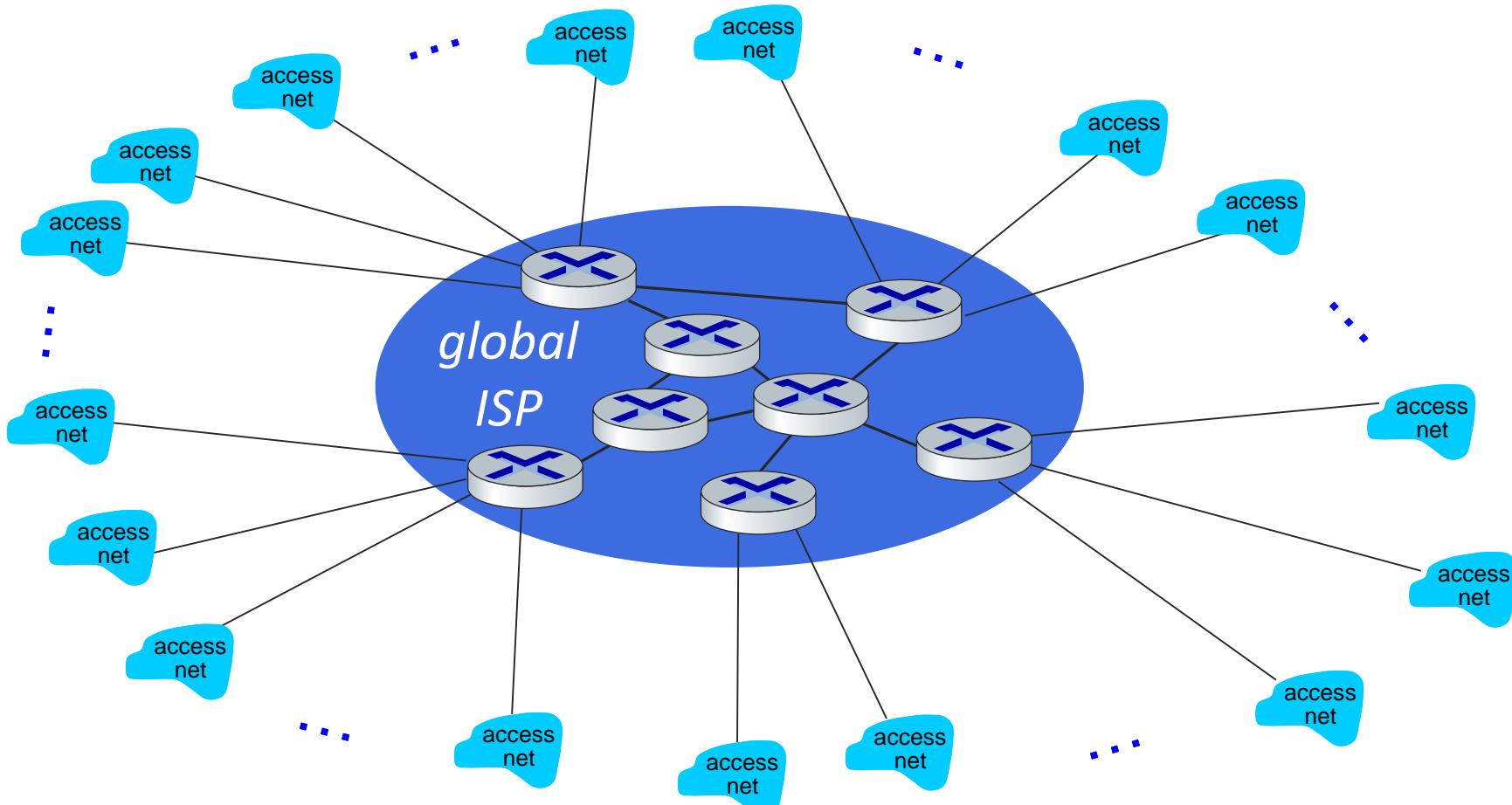
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# Internet Structure: a “Network of networks”

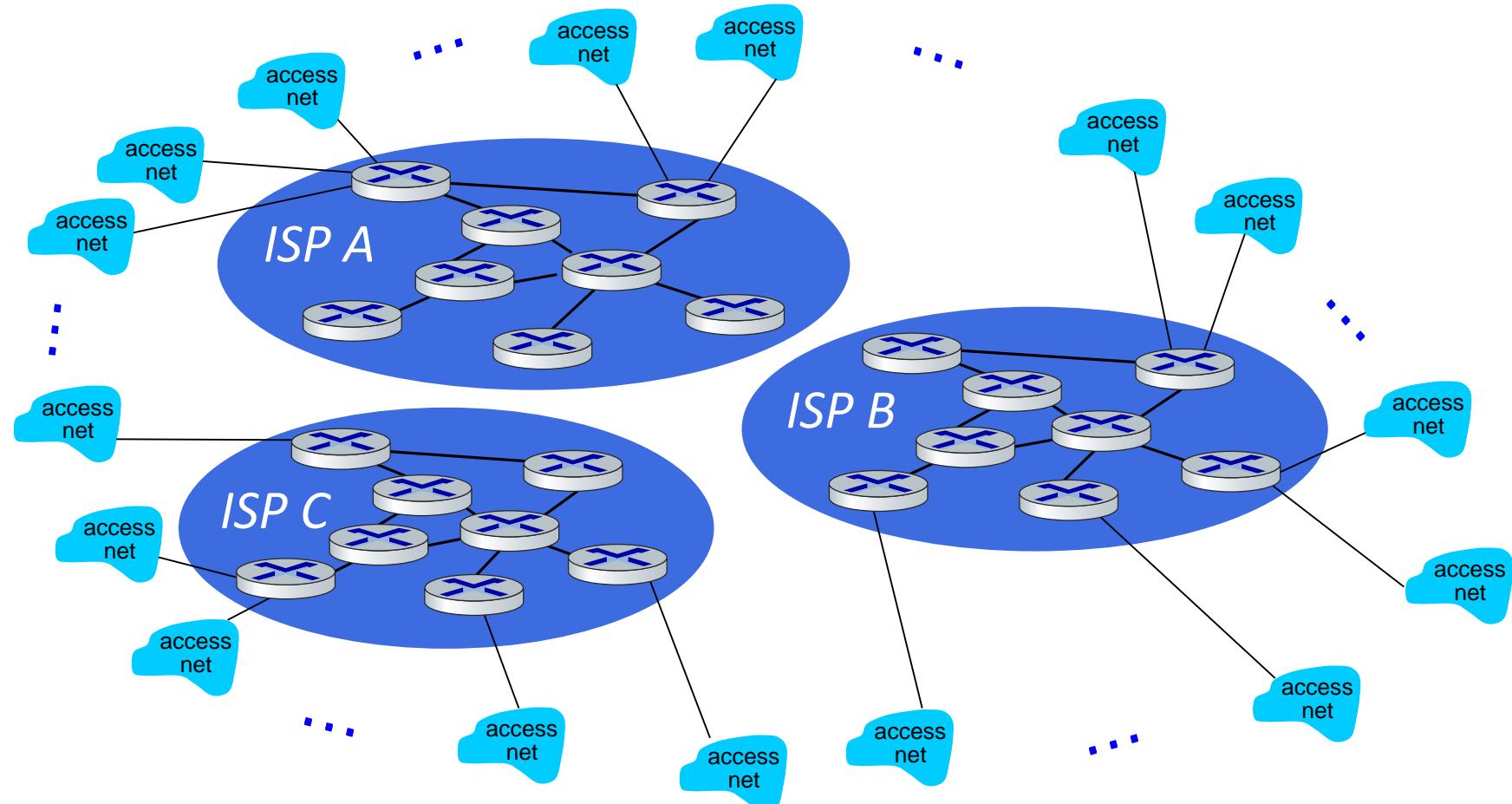
*Option:* connect each access ISP to one global transit ISP?

*Customer and provider ISPs have economic agreement.*



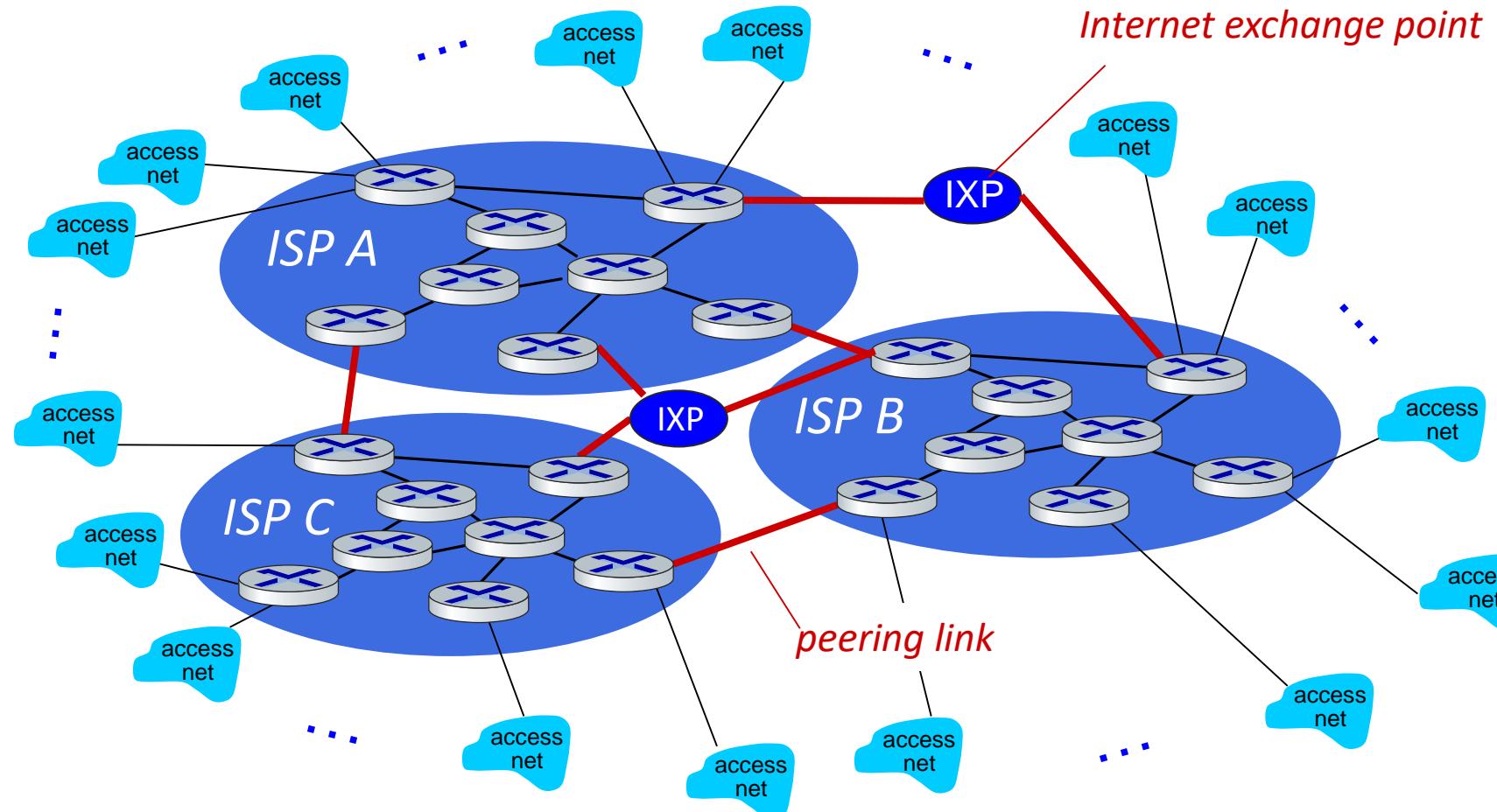
# Internet Structure: a “Network of networks”

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



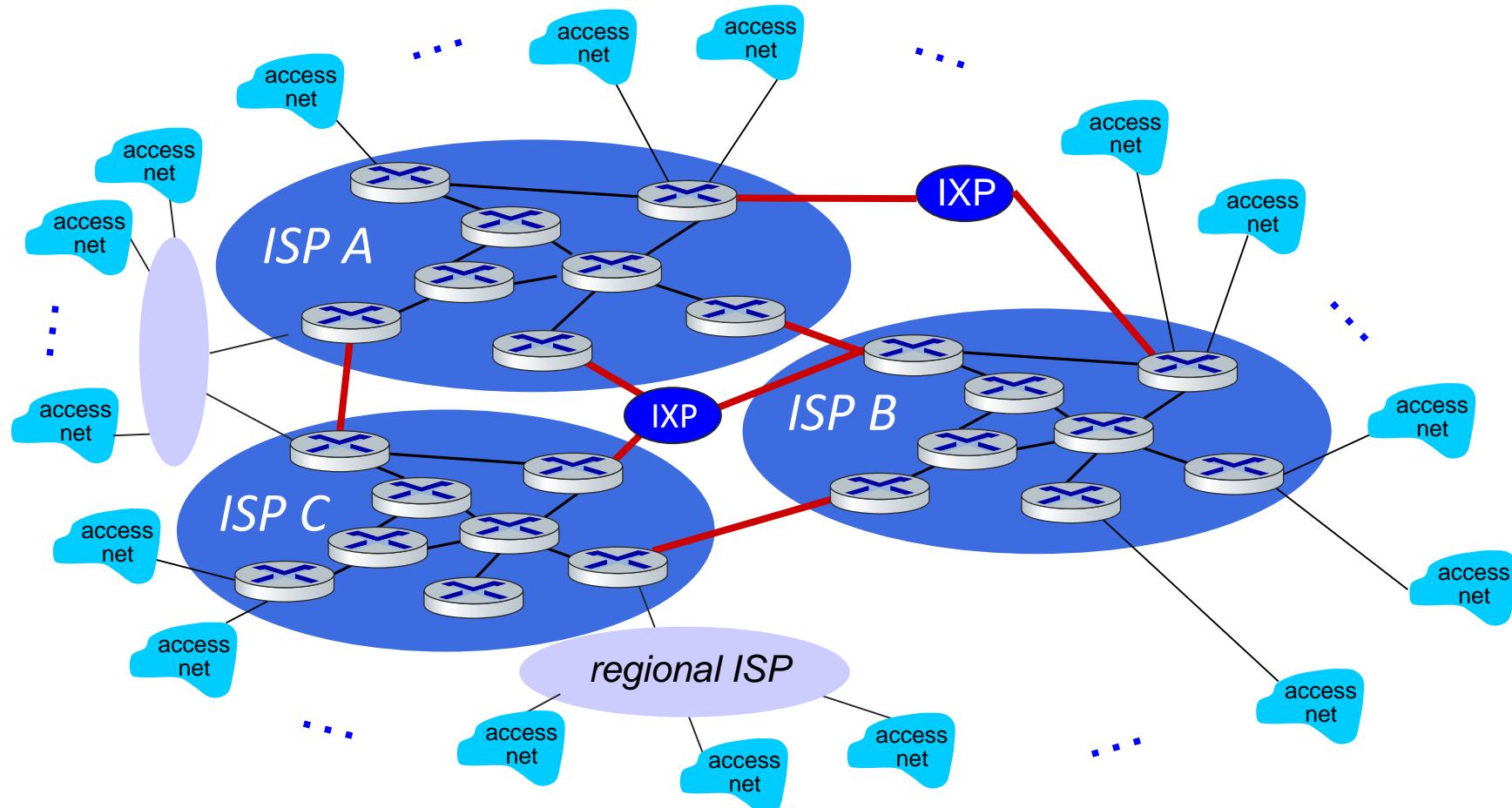
# Internet Structure: a “Network of networks”

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



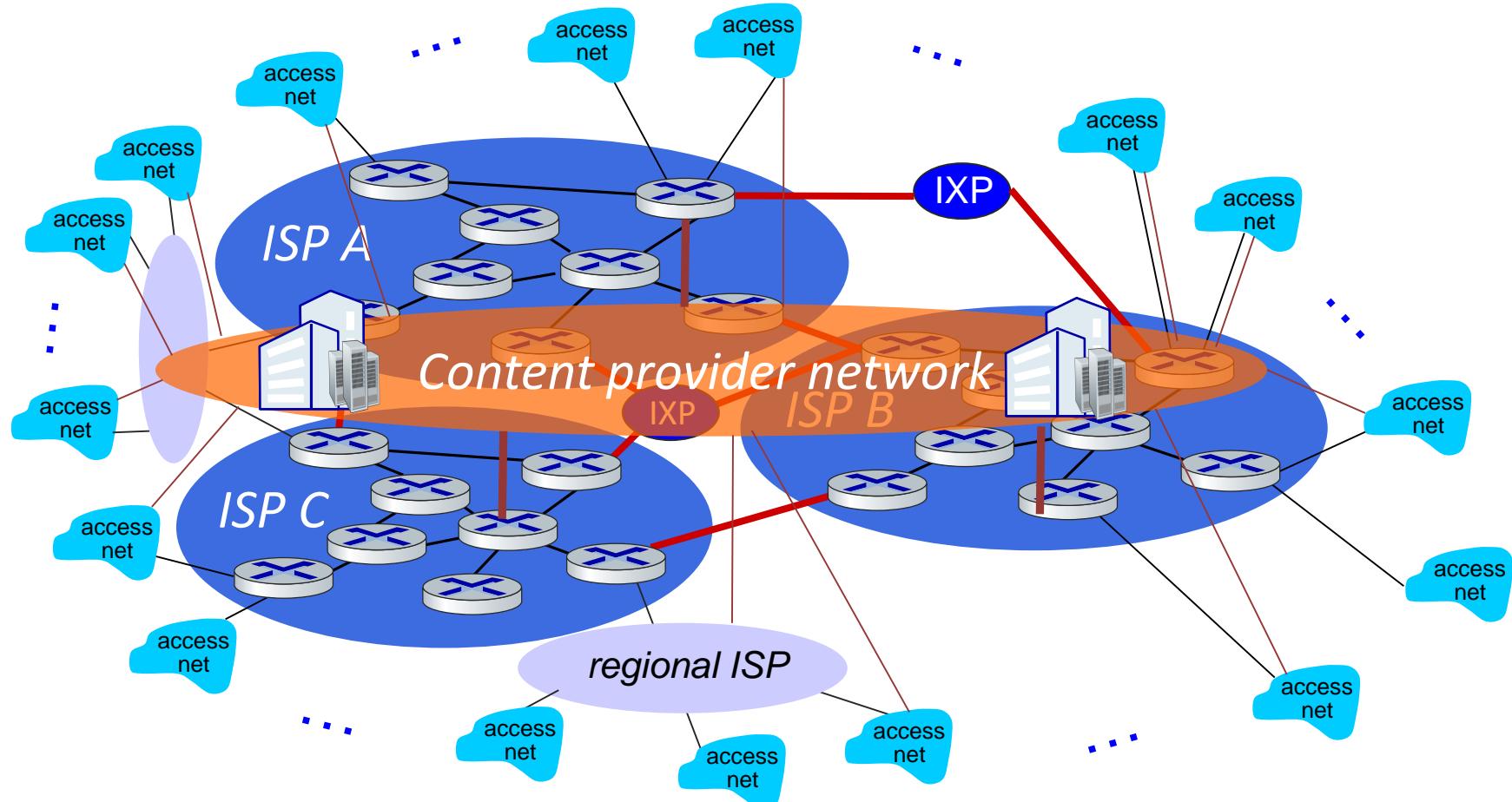
# Internet Structure: a “Network of networks”

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

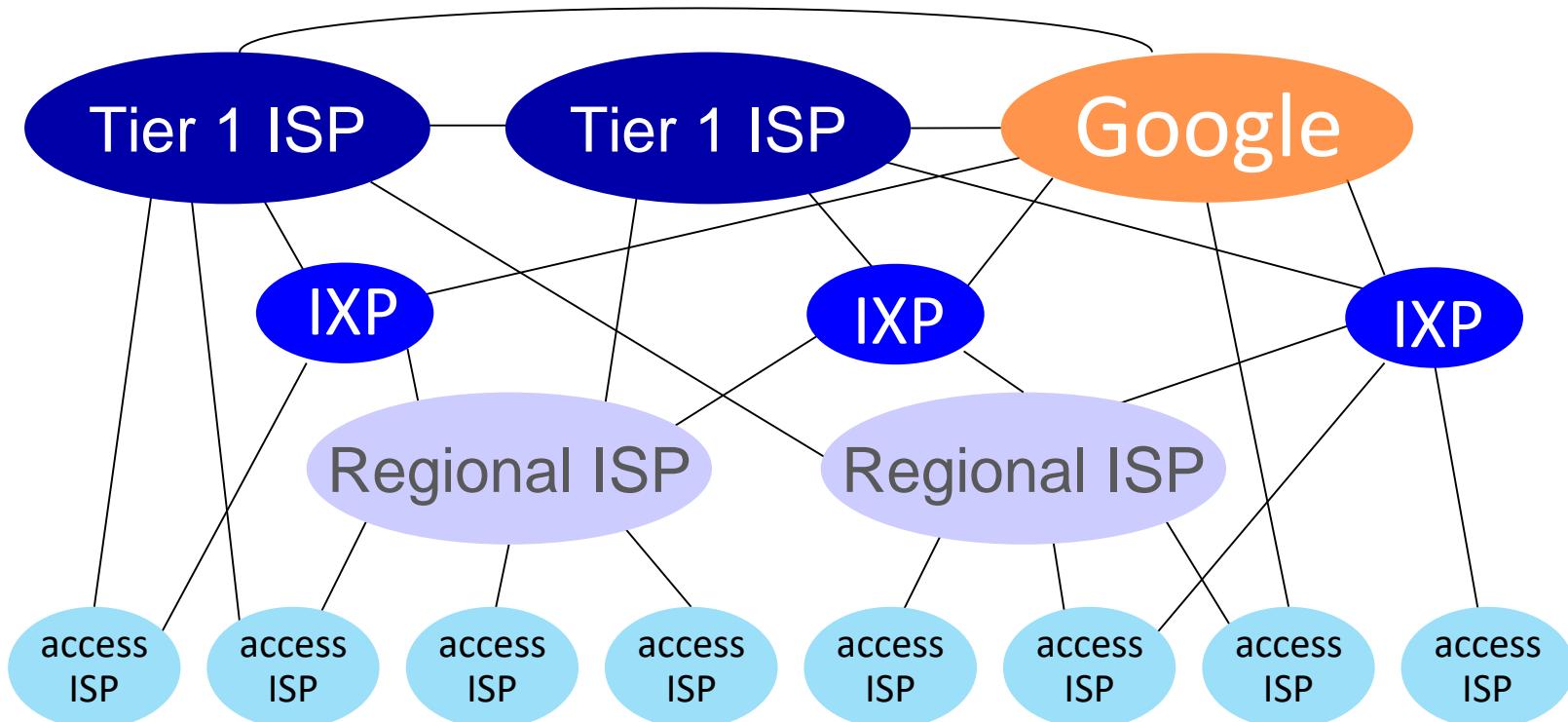


# Internet Structure: a “Network of networks”

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



# Internet Structure: a “Network of networks”



At “center”: small # of well-connected large networks

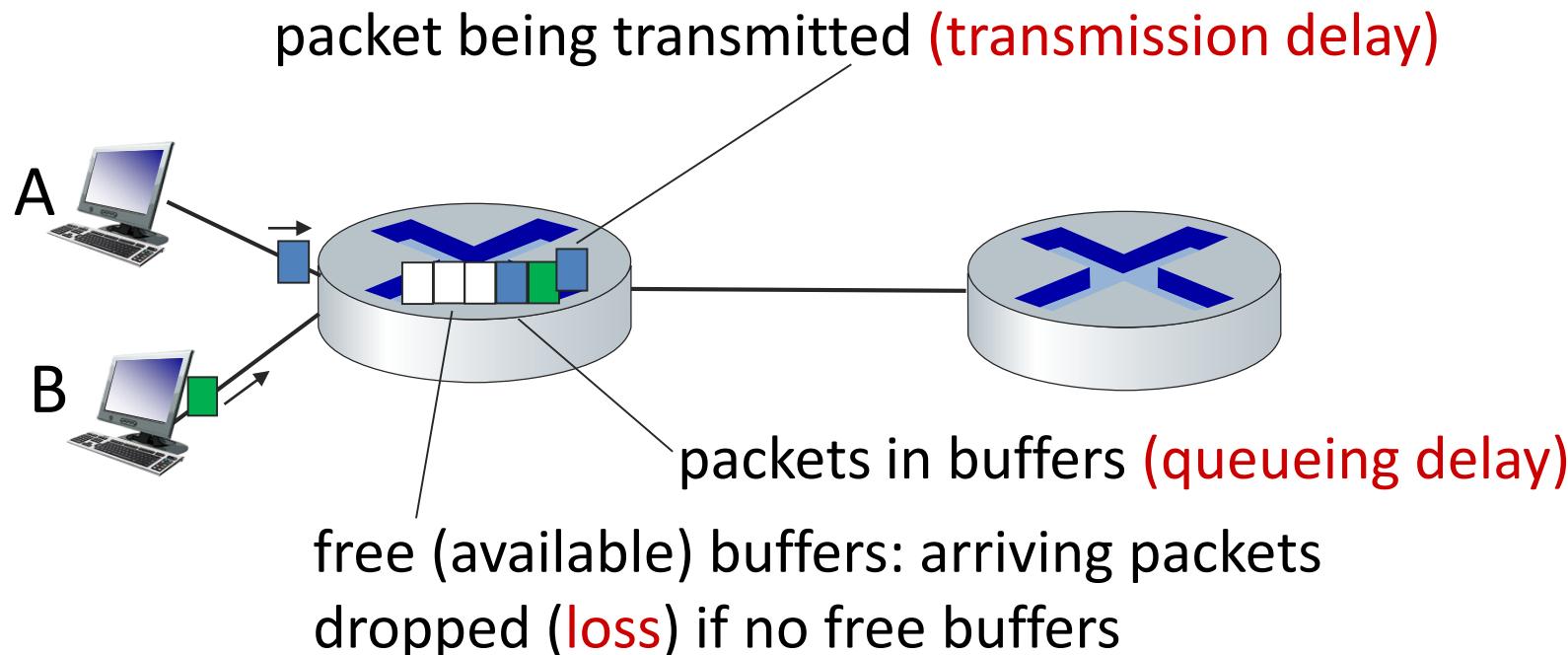
- “tier-1” commercial ISPs (e.g., Level 3, Sprint, AT&T, NTT), national & international coverage
- content provider networks (e.g., Google, Facebook): private network that connects its data centers to Internet, often bypassing tier-1, regional ISPs

## Roadmap

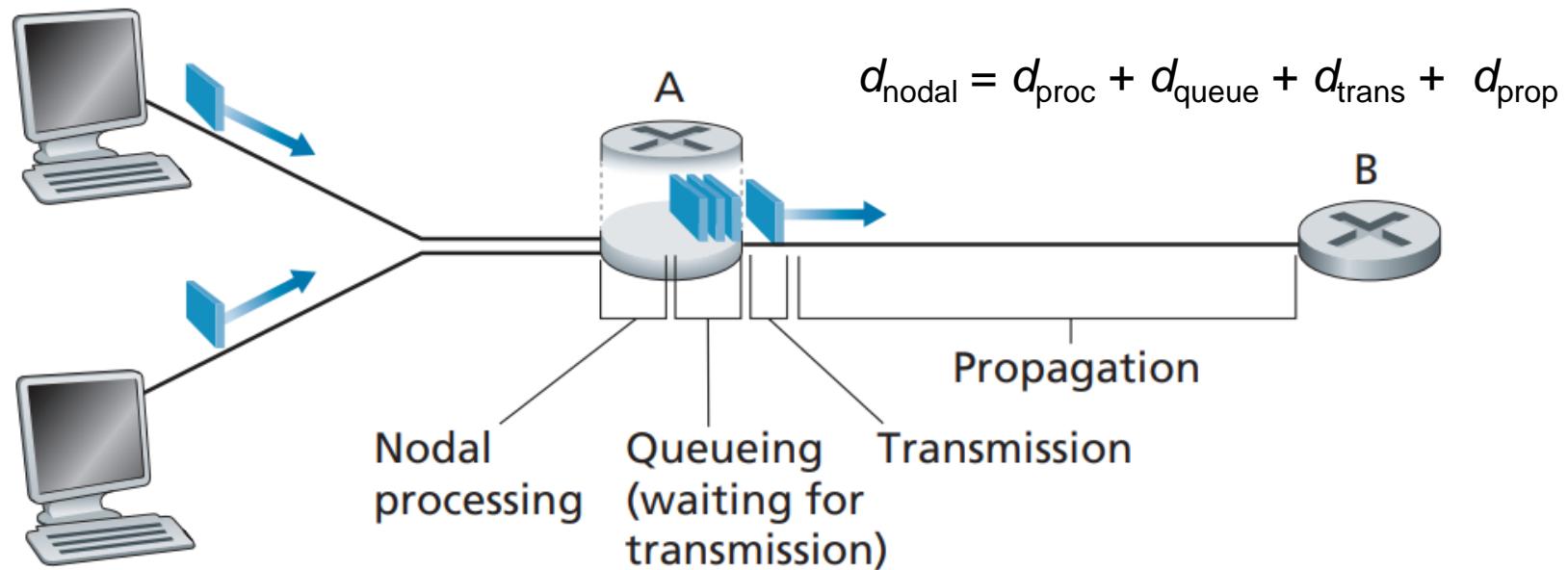
- What *is* the *Internet*? What *is* a *protocol*?
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- **Performance: loss, delay, throughput**
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## Reminder: How do packet delay and loss occur?

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



## Packet Delay: 4 Sources



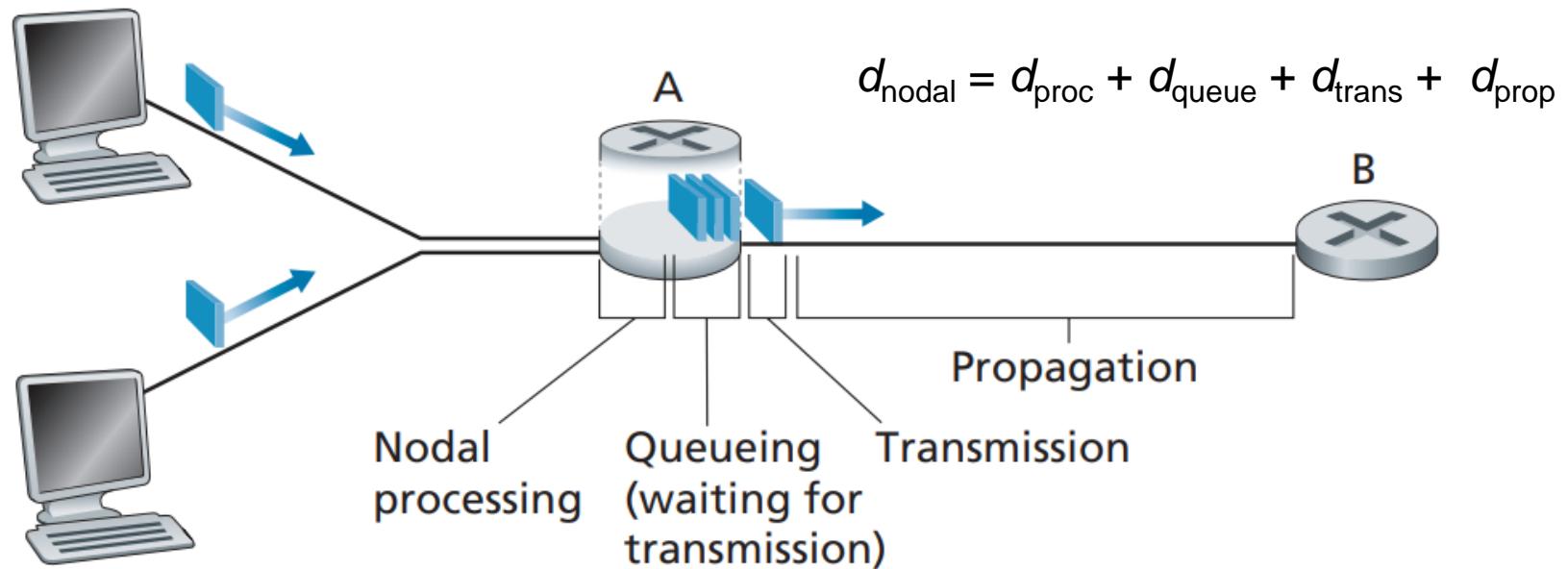
$d_{\text{proc}}$ : nodal processing

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

$d_{\text{queue}}$ : queueing delay

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

# Packet Delay: 4 Sources



$d_{\text{trans}}$ : transmission delay:

- $L$ : packet length (bits)
- $R$ : link *transmission rate (bps)*

$$\boxed{\mathbf{d_{trans} = L/R}}$$

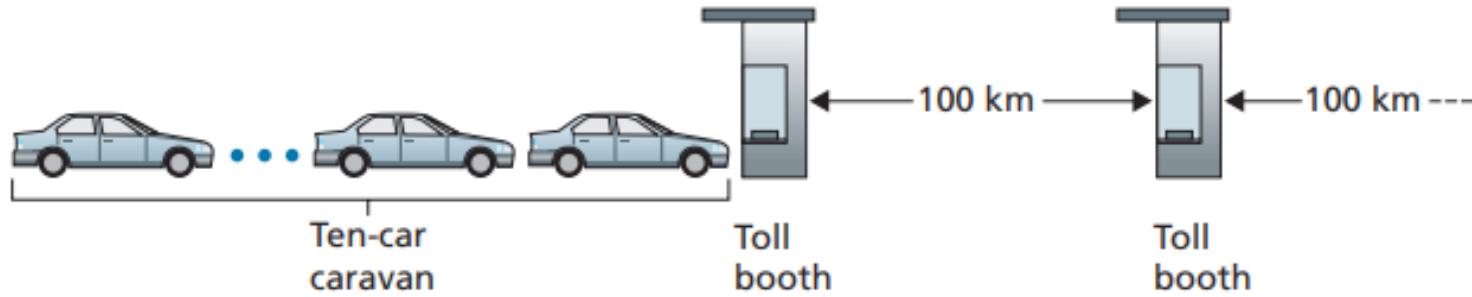
$d_{\text{prop}}$ : propagation delay:

- $d$ : length of physical link
- $s$ : propagation speed ( $\sim 2 \times 10^8$  m/sec)

$$\boxed{\mathbf{d_{prop} = d/s}}$$

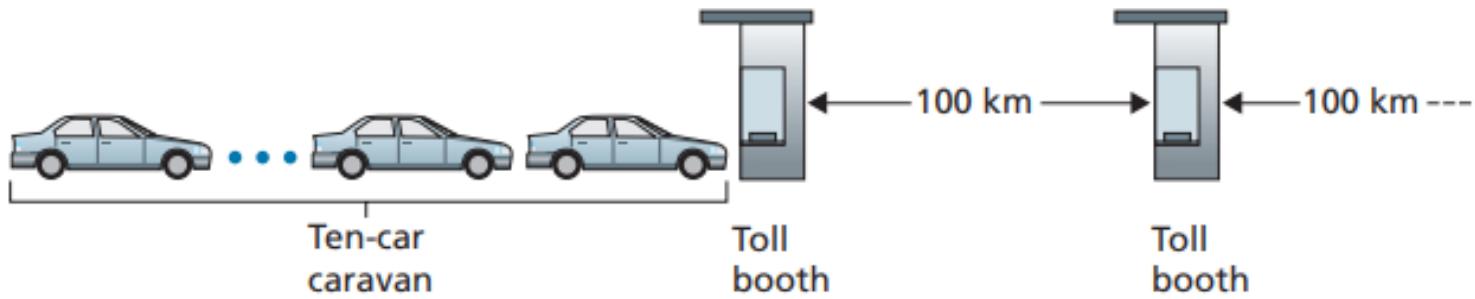
$d_{\text{trans}}$  and  $d_{\text{prop}}$   
very different

## Caravan Analogy



- car ~ bit; caravan ~ packet; toll service ~ link transmission
- toll booth takes 12 sec to service car (bit transmission time)
- “propagate” at 100 km/hr
- Q: How long until caravan is lined up before 2nd toll booth?
- time to “push” entire caravan through toll booth onto highway =  $12 * 10 = 120$  sec
- time for last car to propagate from 1st to 2nd toll both:  $100\text{km}/(100\text{km/hr}) = 1$  hr
- **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

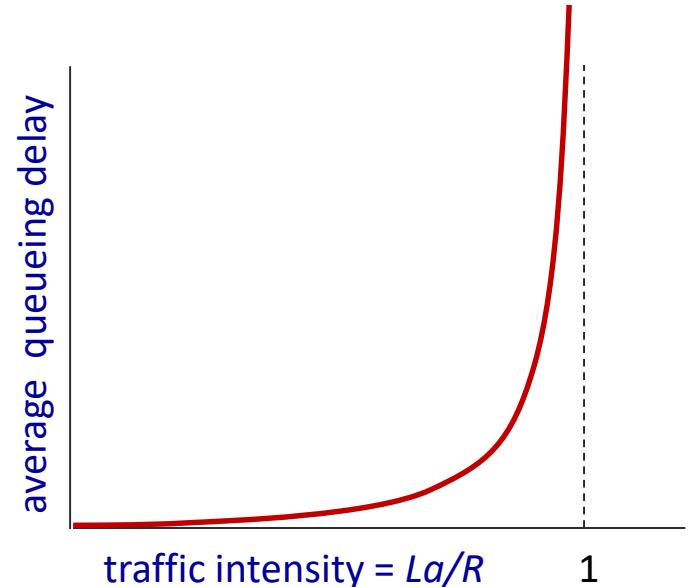
# Packet queueing delay (revisited)

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

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

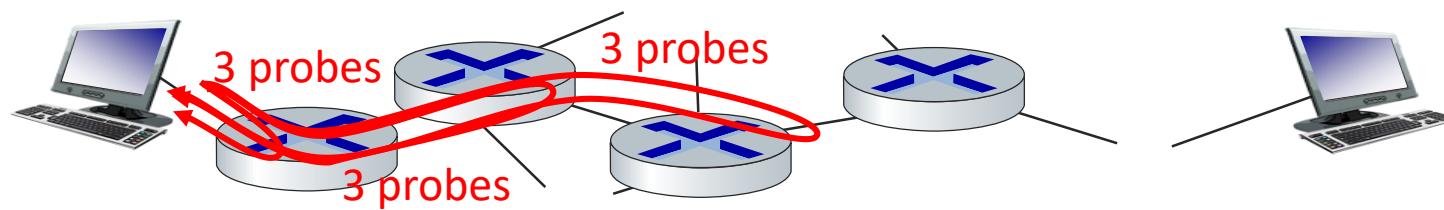
*"traffic intensity"*

- $La/R \sim 0$ : avg. queueing delay small
- $La/R \rightarrow 1$ : avg. queueing delay large
- $La/R > 1$ : more “work” arriving is more than can be serviced - average delay infinite!



## “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



\* Do some traceroutes from other countries at [www.traceroute.org](http://www.traceroute.org)

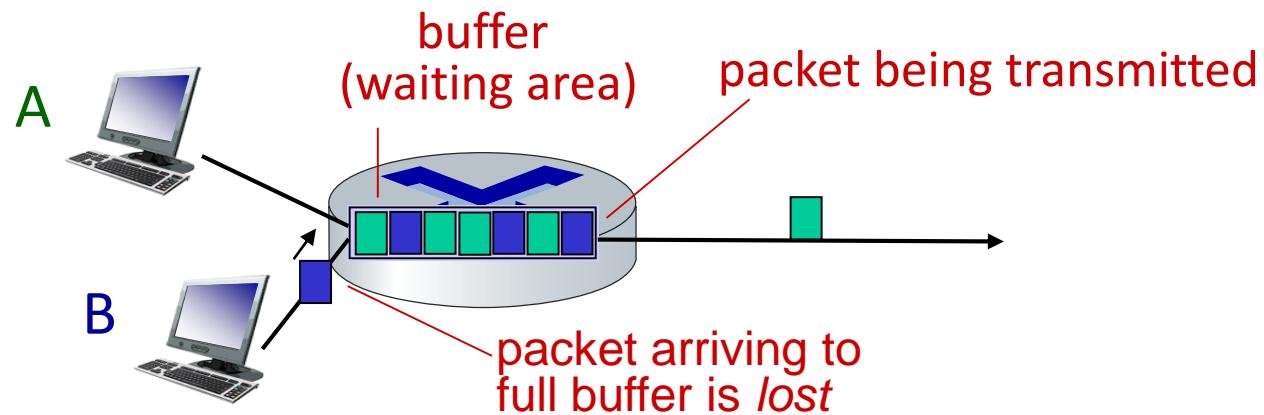
## Traceroute Example

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

							3 delay measurements from gaia.cs.umass.edu to cs-gw.cs.umass.edu
1	cs-gw (128.119.240.254)	1 ms	1 ms	2 ms			
2	border1-rt-fa5-1-0.gw.umass.edu (128.119.3.145)	1 ms	1 ms	2 ms			3 delay measurements to border1-rt-fa5-1-0.gw.umass.edu
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			trans-oceanic link
9	de2-1.de1.de.geant.net (62.40.96.129)	109 ms	102 ms	104 ms			
10	de.fr1.fr.geant.net (62.40.96.50)	113 ms	121 ms	114 ms			
11	renater-gw.fr1.fr.geant.net (62.40.103.54)	112 ms	114 ms	112 ms			
12	nio-n2.cssi.renater.fr (193.51.206.13)	111 ms	114 ms	116 ms			
13	nice.cssi.renater.fr (195.220.98.102)	123 ms	125 ms	124 ms			
14	r3t2-nice.cssi.renater.fr (195.220.98.110)	126 ms	126 ms	124 ms			
15	eurecom-valbonne.r3t2.ft.net (193.48.50.54)	135 ms	128 ms	133 ms			
16	194.214.211.25 (194.214.211.25)	126 ms	128 ms	126 ms			
17	***						
18	***				* means no response (probe lost, router not replying)		
19	fantasia.eurecom.fr (193.55.113.142)	132 ms	128 ms	136 ms			

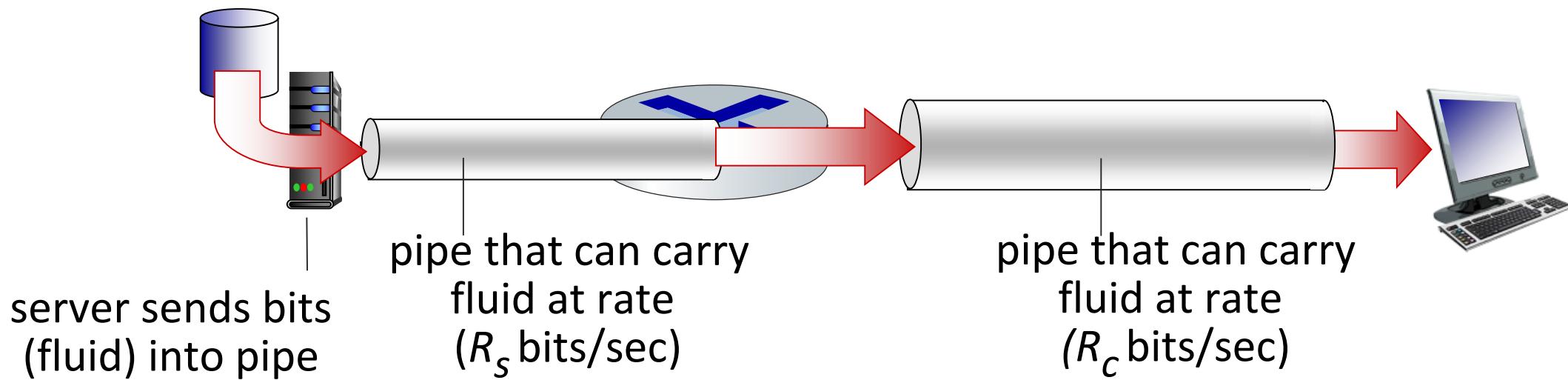
## Packet Loss

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



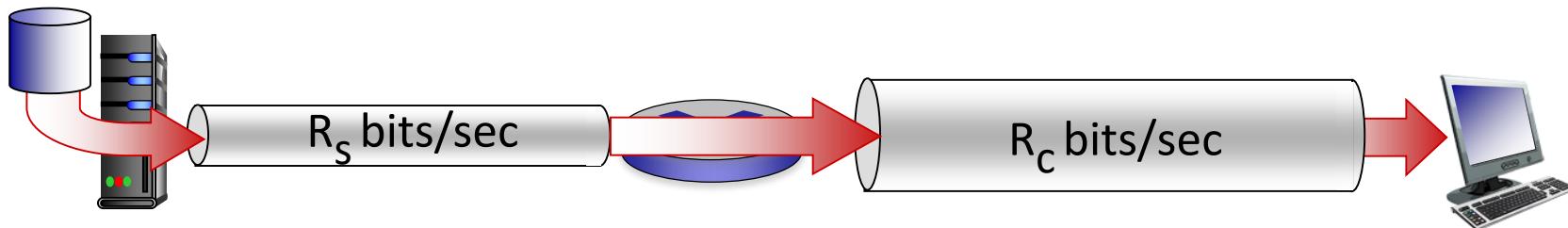
# Throughput

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

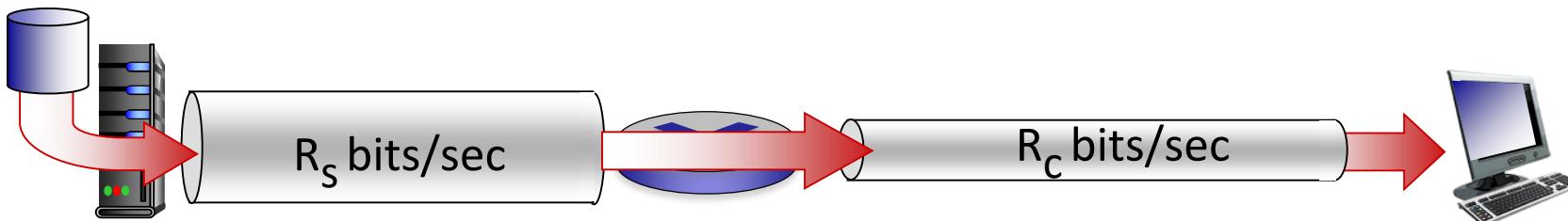


# Throughput

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



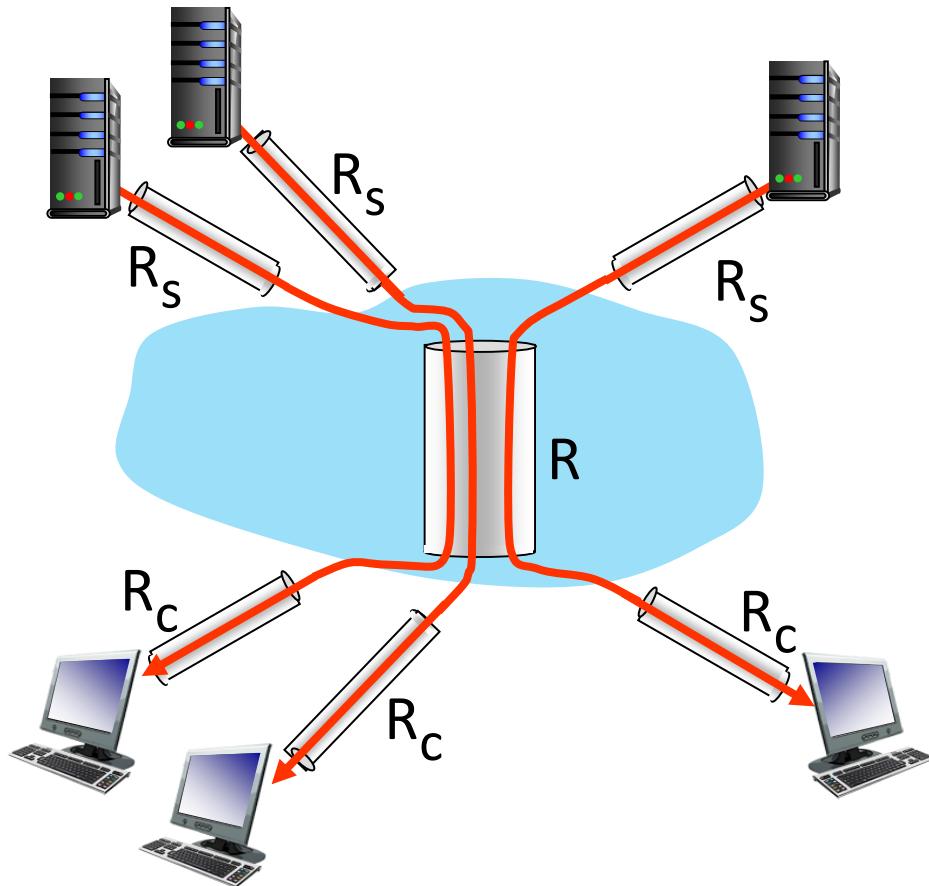
$R_s > R_c$  What is average end-end throughput?



*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

## Roadmap

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

## Protocol “layers” and reference models

Networks are complex,  
with many “pieces”:

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

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

- and/or our *discussion* of  
networks?

## Example: Organization of an 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 an air travel



***layers:*** each layer implements a service

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

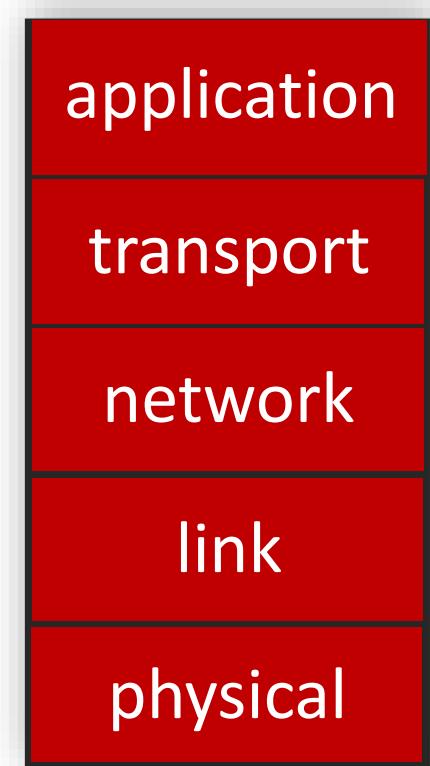
## Why layering?

Approach to designing/discussing complex systems:

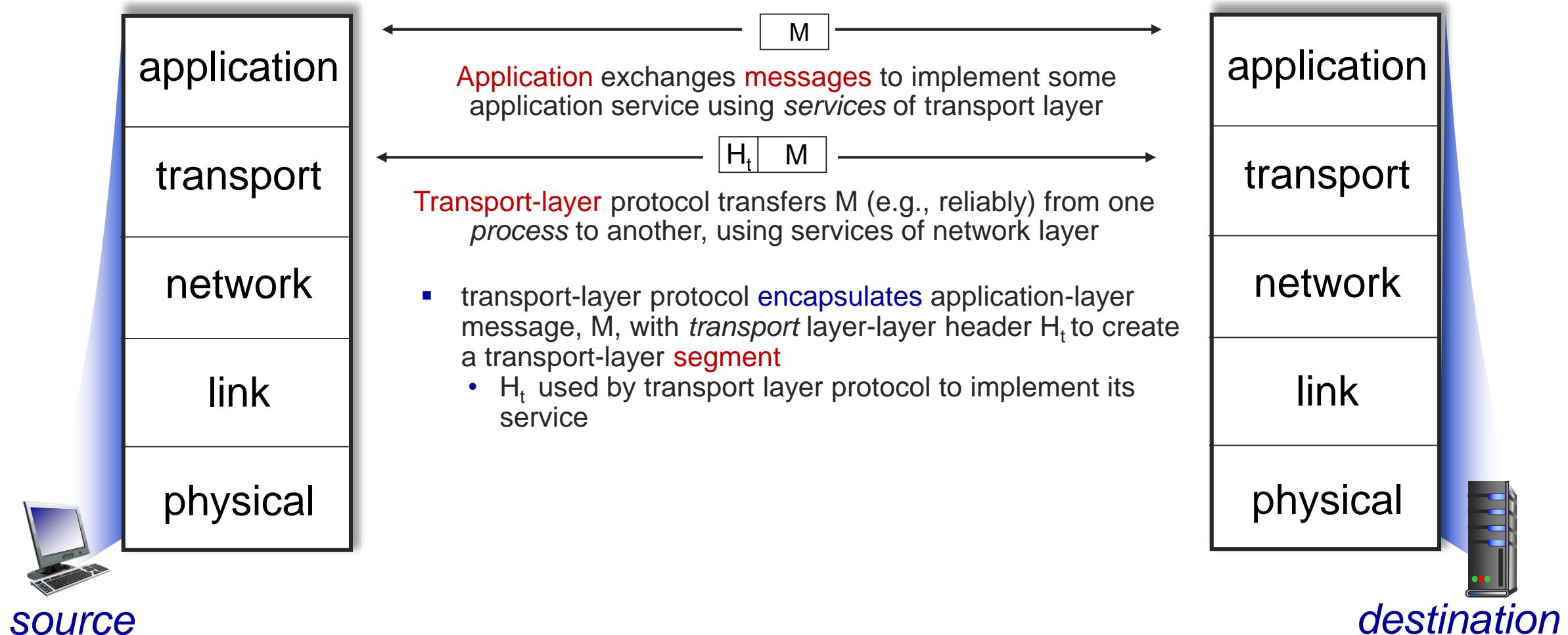
- explicit structure allows identification, relationship of system's pieces
  - layered *reference model* for discussion
- modularization eases maintenance, updating of system
  - change in layer's service *implementation*: transparent to rest of system
  - e.g., change in gate procedure doesn't affect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

## Layered Internet Protocol Stack

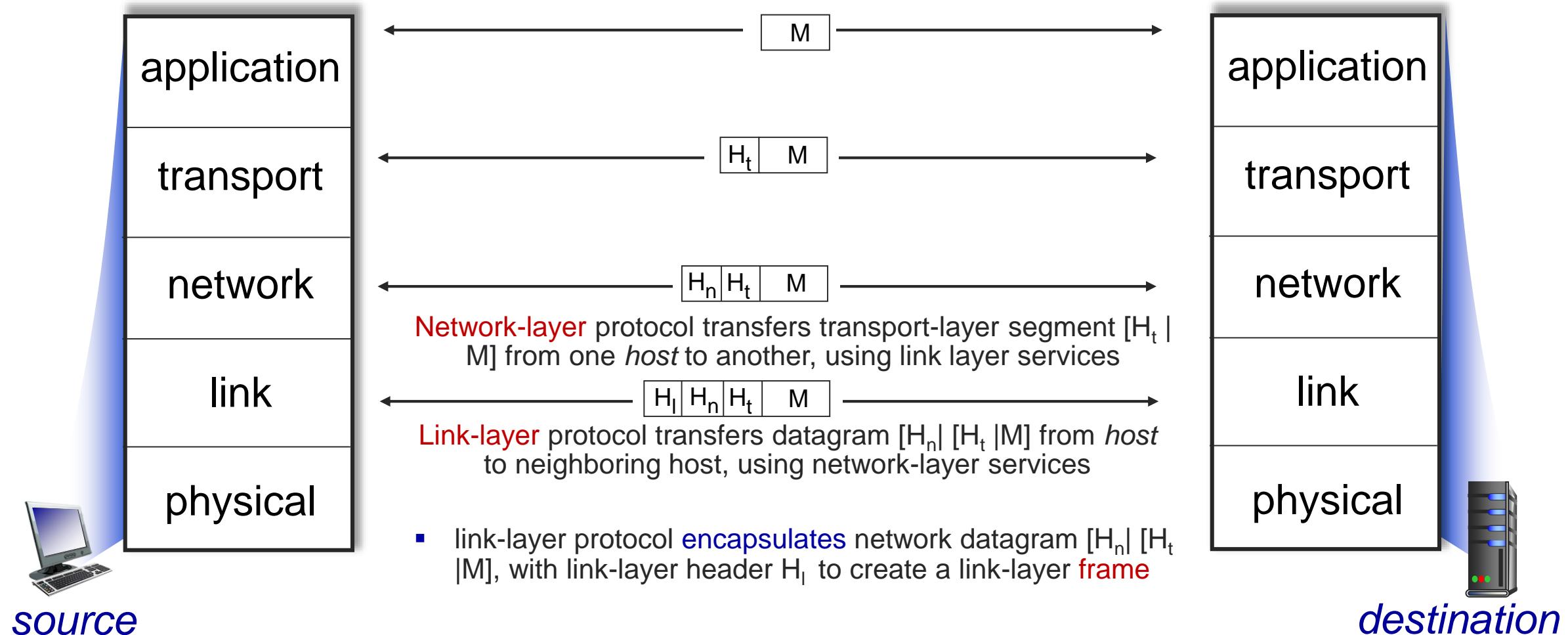
- *application*: supporting network applications
  - HTTP, IMAP, SMTP, DNS
- *transport*: process-process data transfer
  - TCP, UDP
- *network*: routing of datagrams from source to destination
  - IP, routing protocols
- *link*: data transfer between neighboring network elements
  - Ethernet, 802.11 (WiFi), PPP
- *physical*: bits “on the wire”



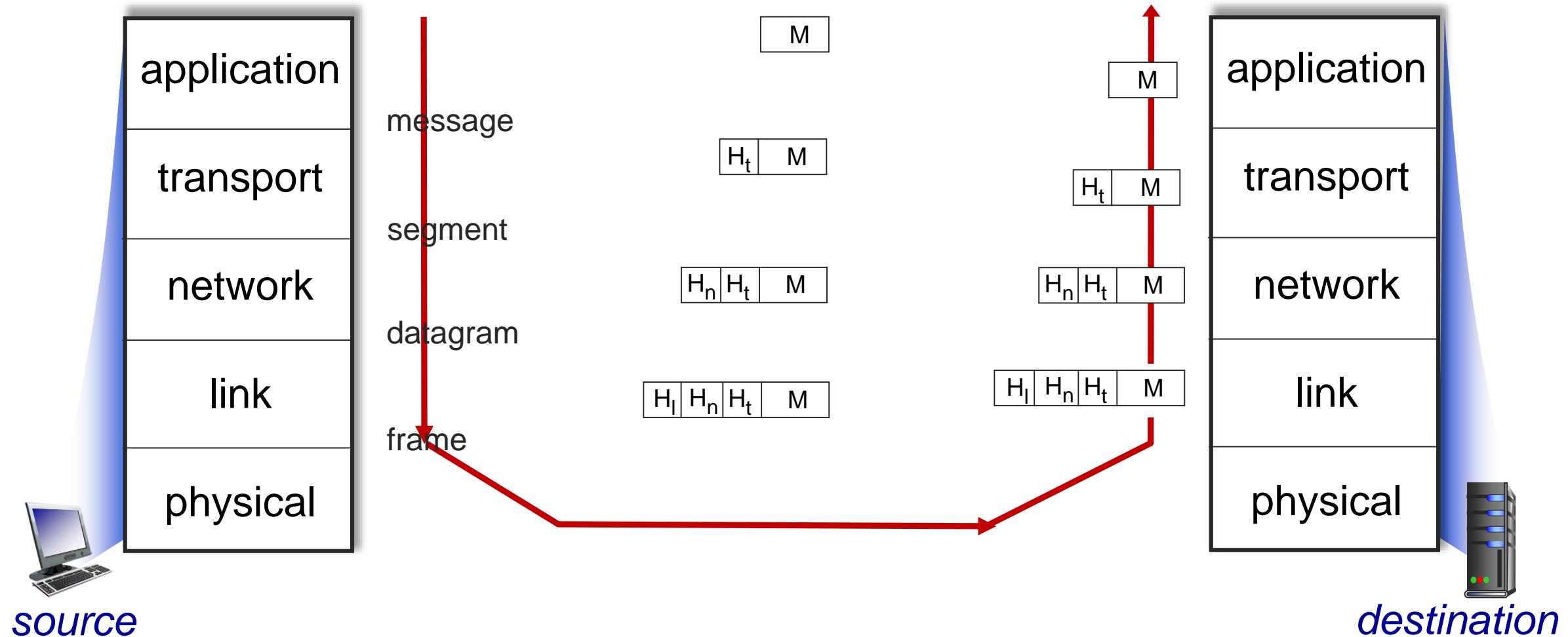
# Services, Layering, and Encapsulation



# Services, Layering, and Encapsulation

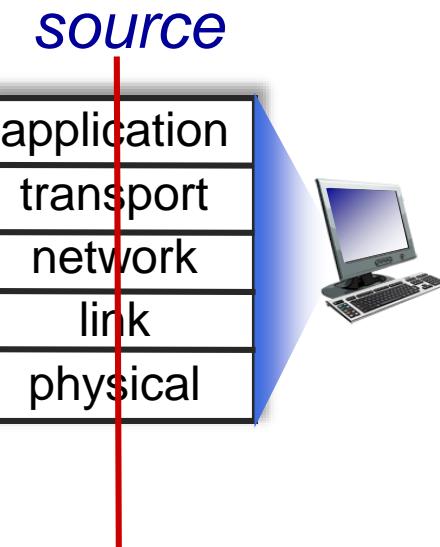


# Services, Layering, and Encapsulation

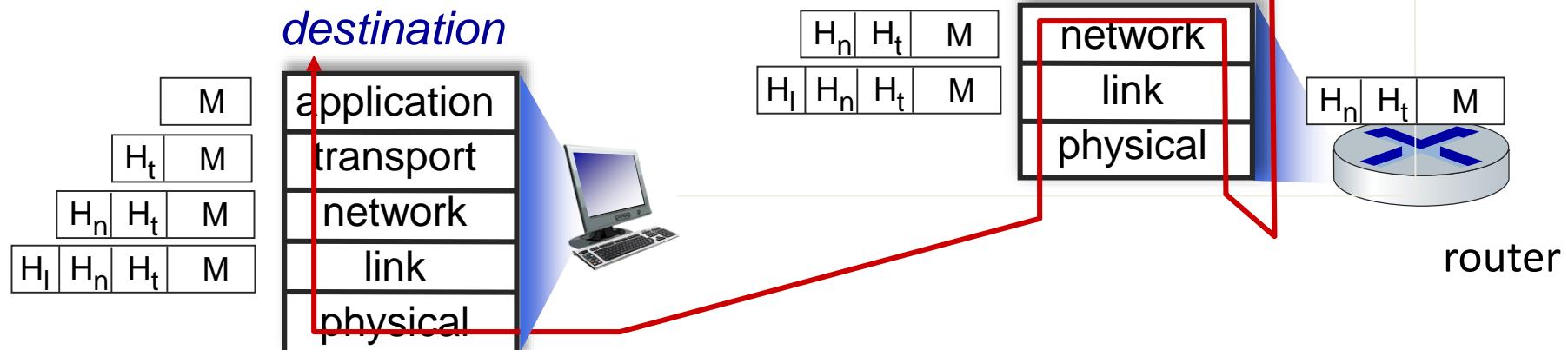
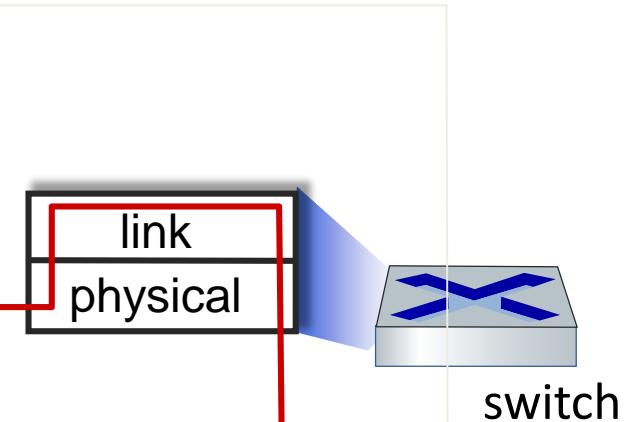


## Introduction

message	M
segment	H <sub>t</sub> M
datagram	H <sub>n</sub> H <sub>t</sub> M
frame	H <sub>l</sub> H <sub>n</sub> H <sub>t</sub> M



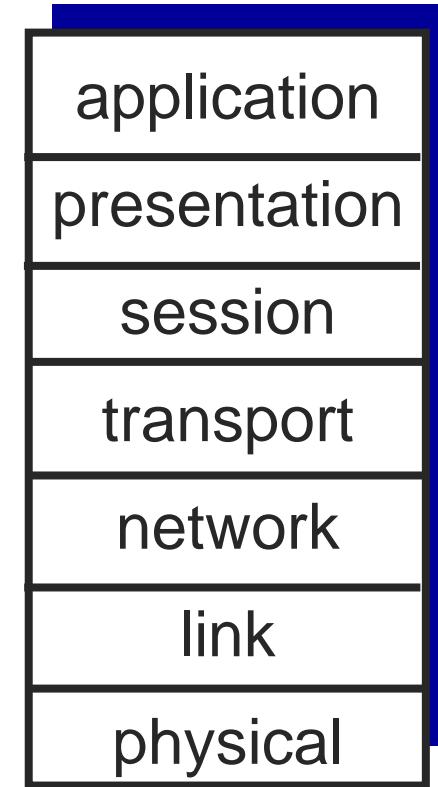
## Encapsulation: An End-to-End View



## ISO/OSI Reference Model

Two layers not found in Internet protocol stack!

- ***presentation***: allow applications to interpret meaning of data, e.g., encryption, compression, machine-specific conventions
- ***session***: synchronization, checkpointing, recovery of data exchange
- Internet stack “missing” these layers!
  - these services, *if needed*, must be implemented in application
  - needed?



The seven layer OSI/ISO  
reference model



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