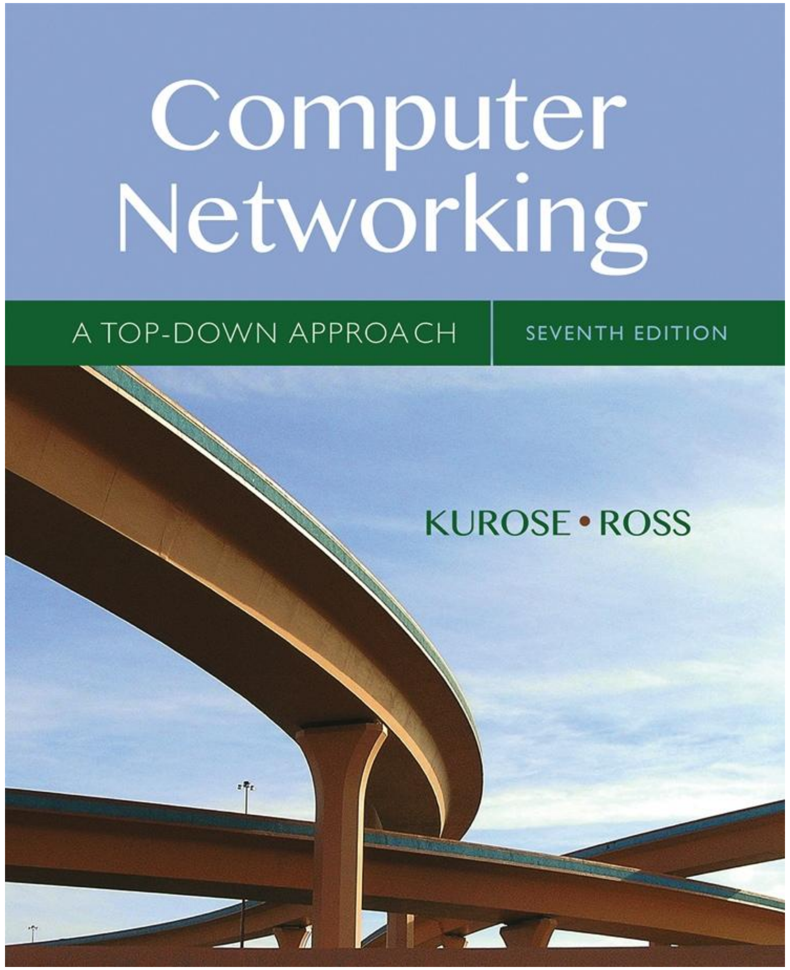
COMPUTER NETWORKS

Computer Networks and the Internet

Team Networks
Department of Computer Science and Engineering

Text Book



Computer Networking: A Top-Down Approach
Jim Kurose, Keith Ross
Pearson, 2017
7th Edition

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Computer Networks and the Internet

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Unit – 1 Computer Networks and the Internet

1.1 Introduction to Computer Networks

1.2 What is the Internet?

- A nuts-and-bolts and Services description, Protocol

1.3 Network edge

- End systems, Access networks, Physical media

1.4 Network core

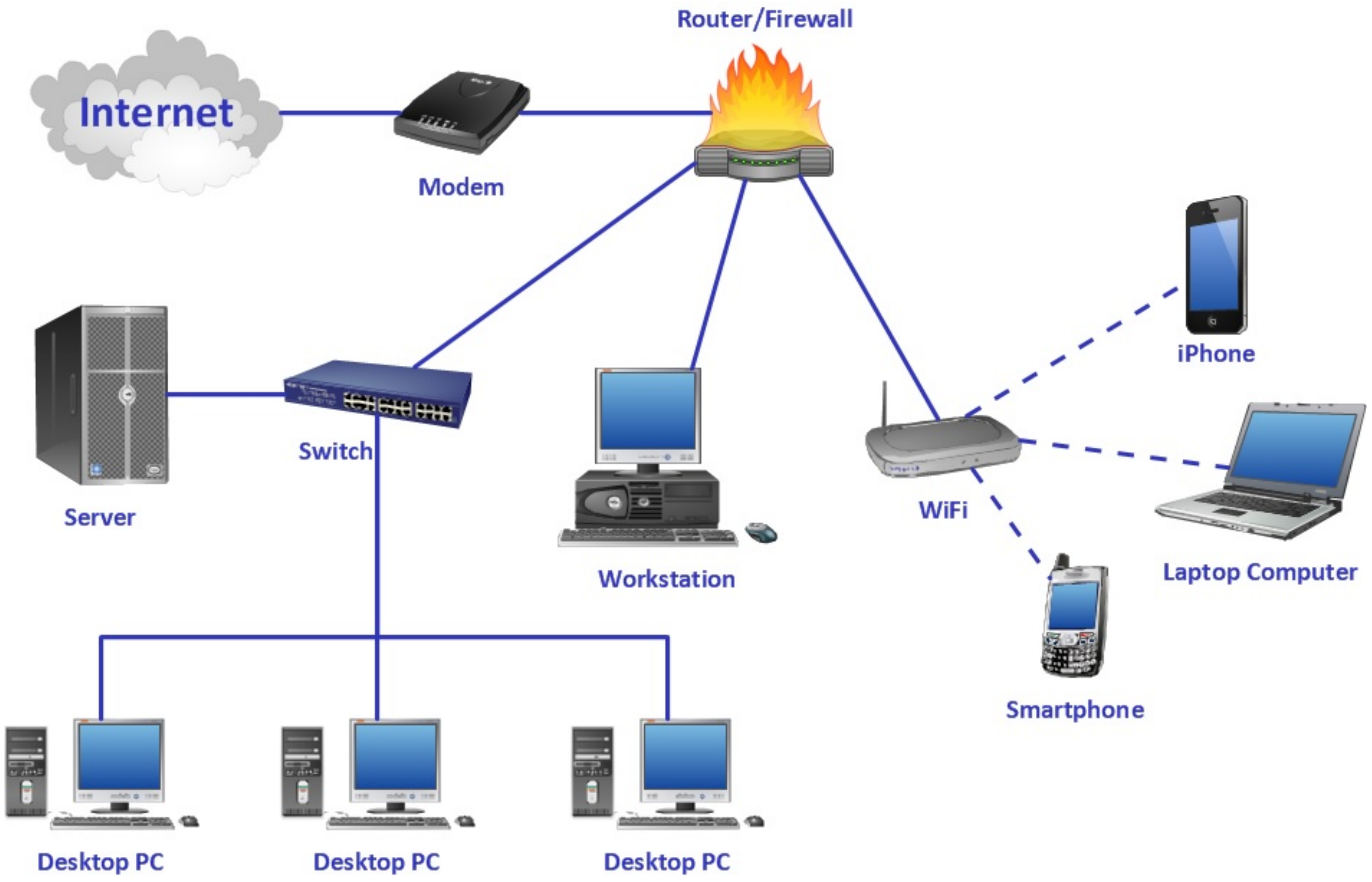
- Packet switching, Circuit switching, Network structure

1.5 Delay, Loss & Throughput in networks

1.6 Protocol layers, Service models

- OSI model and TCP/IP protocol suite

Introduction to Computer Networks



- Two or more devices connected together.
- Communicate with each other, share data or resources

What is the Internet?

- A massive network of networks.
- A computer network that interconnects billions of computing devices throughout the world.
- Traditional devices – PCs, Workstations, Servers – web pages, emails, etc.
- Internet "things" – laptops, PDAs, TVs, gaming consoles, home security systems, home appliances, watches, cars, traffic control systems, etc.,

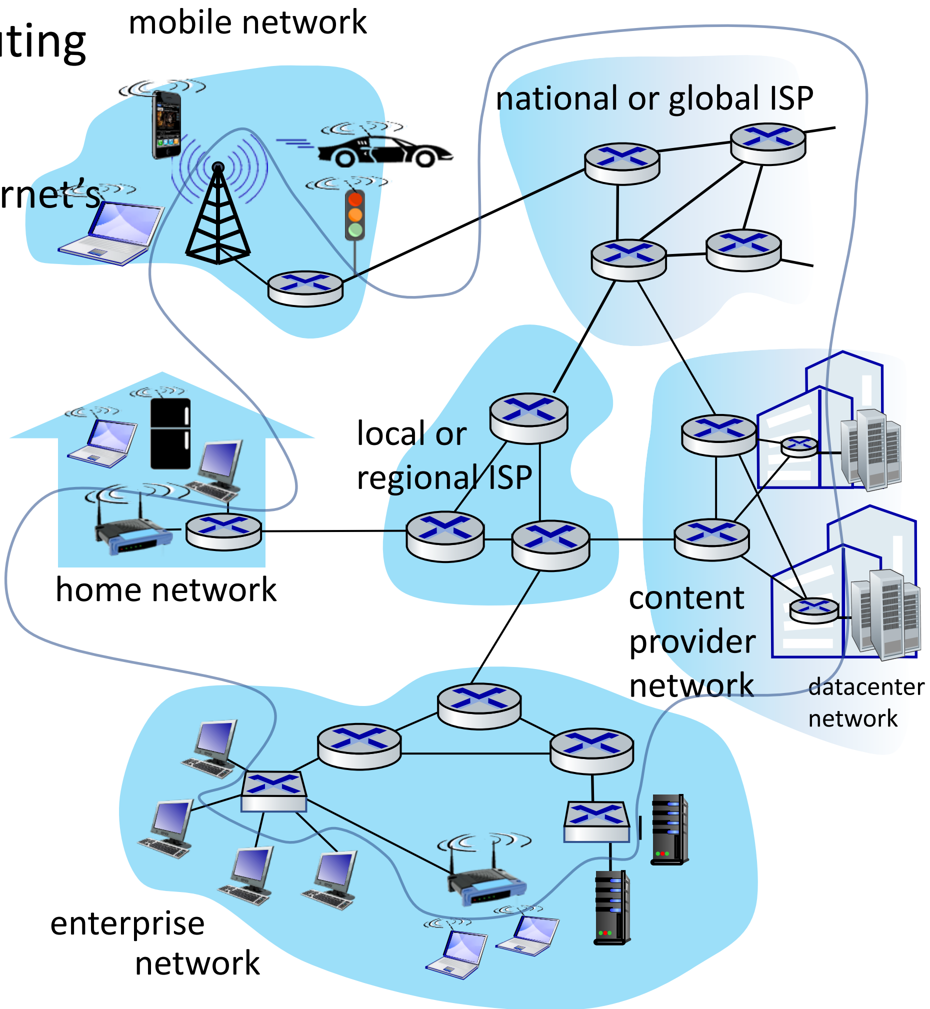
The Internet: A "Nuts and Bolts" View

Billions of connected computing *devices*:
- *hosts = end systems*
- running *network apps* at Internet's "edge"

Packet switches: forward packets (chunks of data)
- *routers, switches*

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

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



"Fun" Inter-connected Devices

Amazon Echo

Internet refrigerator

IP picture frame

Tweet-a-watt: monitor energy use

Security Camera

Slingbox: remote control cable TV

Web-enabled toaster + weather forecaster

Others?

AR *devices*

There will be 41 Billion IoT devices by 2027*

Internet phones

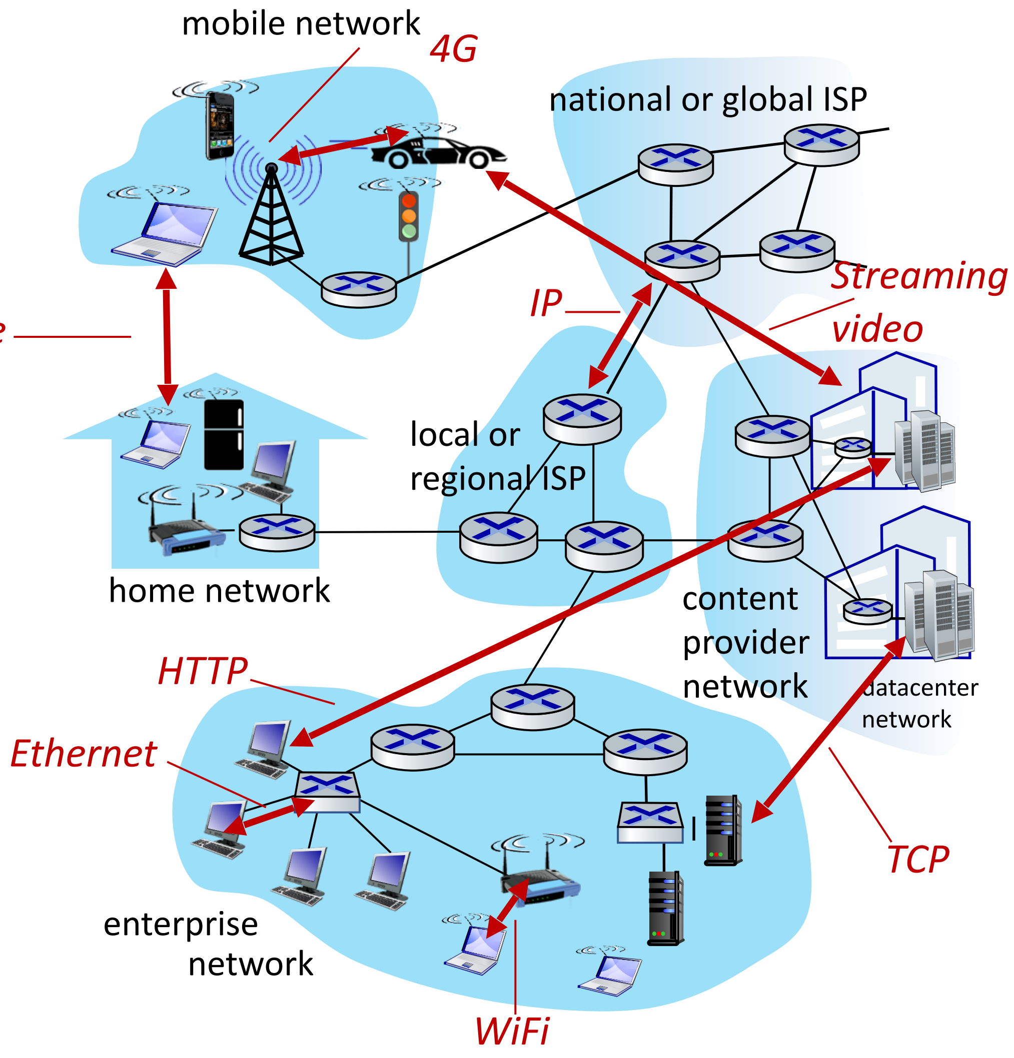
sensorized, bed mattress

Fitbit

[* https://www.businessinsider.com/internet-of-things-report?IR=T](https://www.businessinsider.com/internet-of-things-report?IR=T)

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



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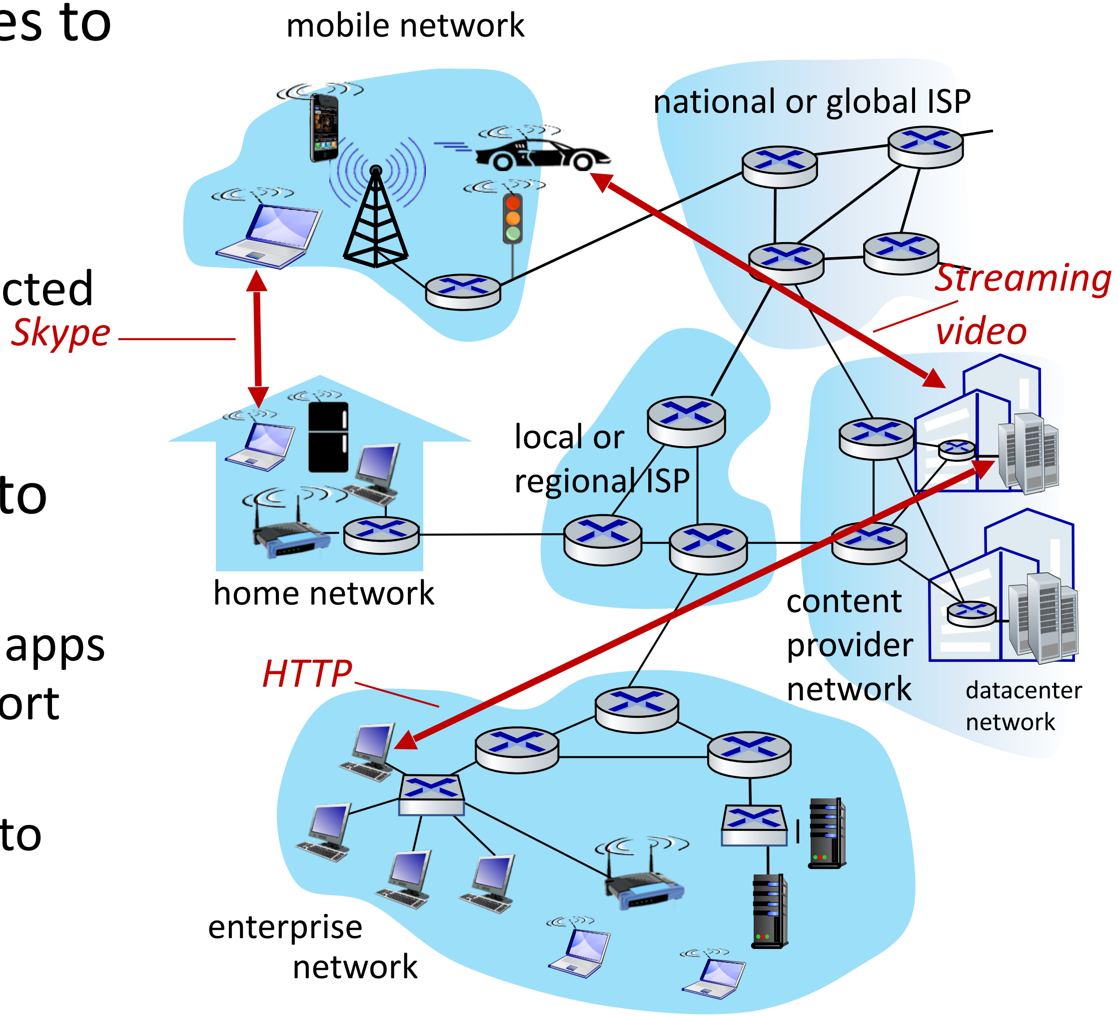
The Internet: A "Service" View

- *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 is a Protocol?

PES UNIVERSITY
CELEBRATING 50 YEARS

Human protocols:

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

… specific messages sent

… specific actions taken when message received, or other events

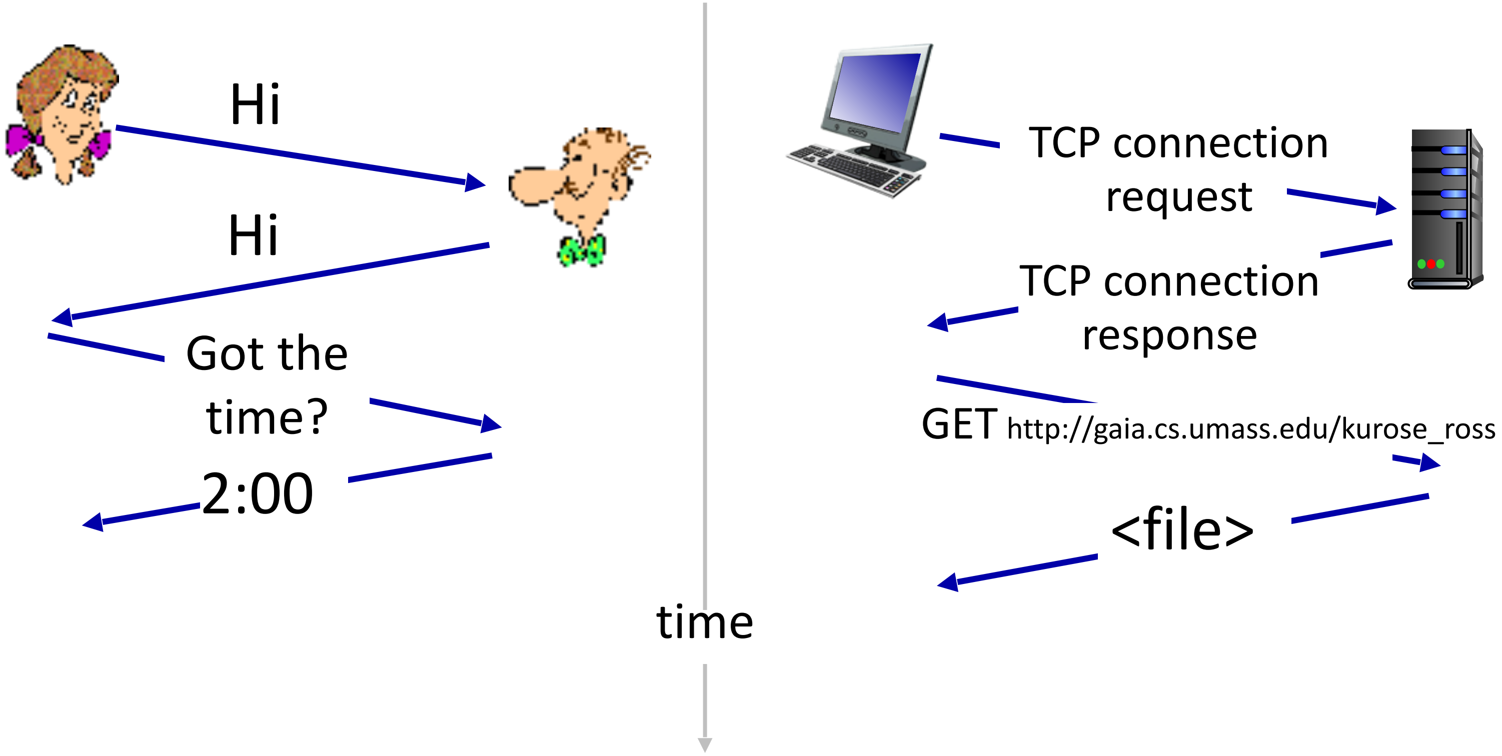
Network protocols:

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

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

What’s a Protocol?

A human protocol and a computer network protocol:

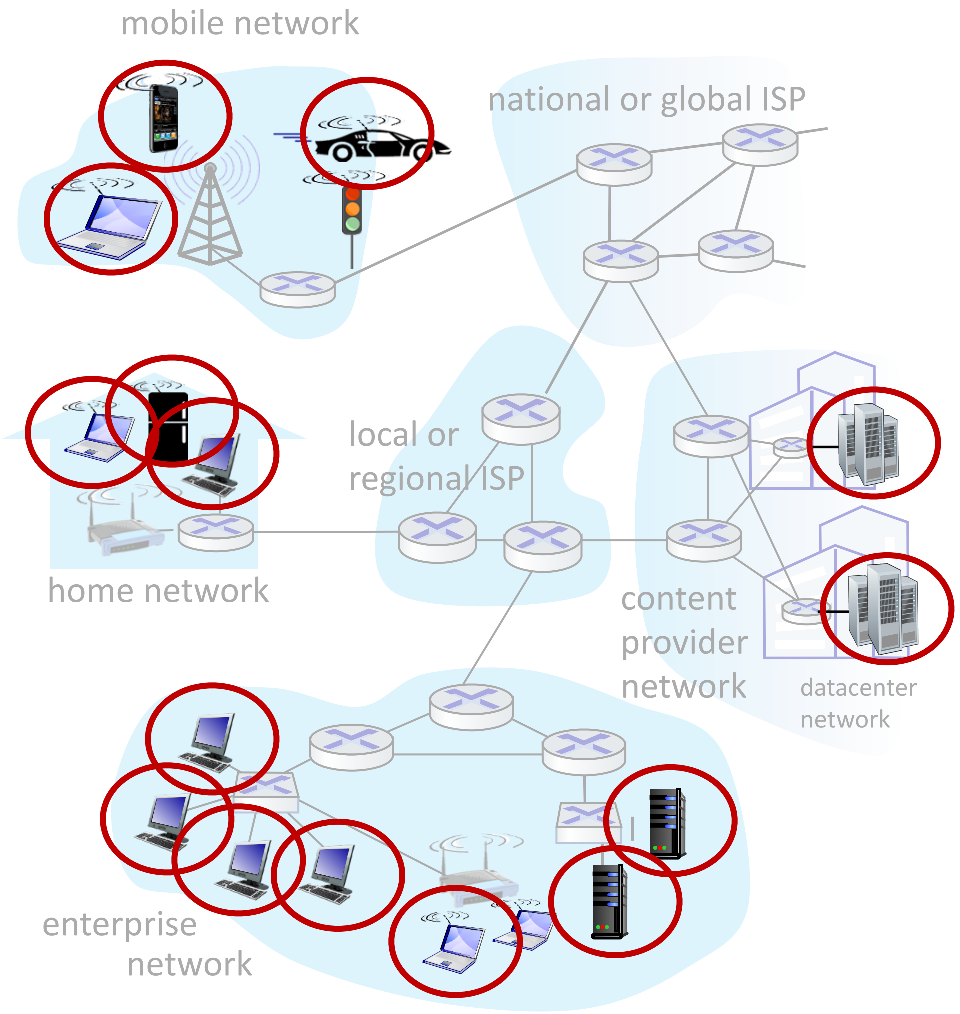


Q: other human protocols?

Network Edge: A closer look at network structure

Network edge:

- Hosts: clients & servers
- Servers in data centers



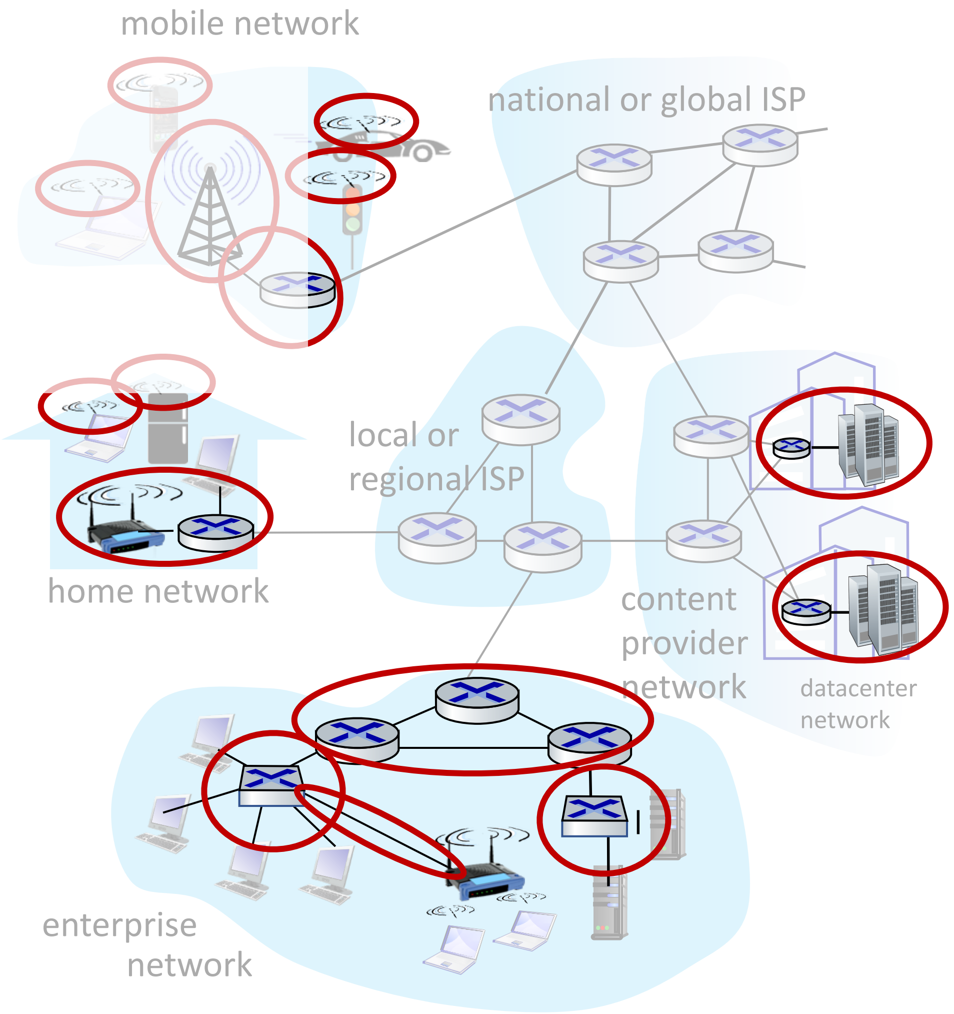
Network Edge: A closer look at network structure

Network edge:

- Hosts: clients & servers
- Servers in data centers

Access networks, physical media:

- wired, wireless communication links



Network Edge: A closer look at network structure

Network edge:

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Access networks, physical media:

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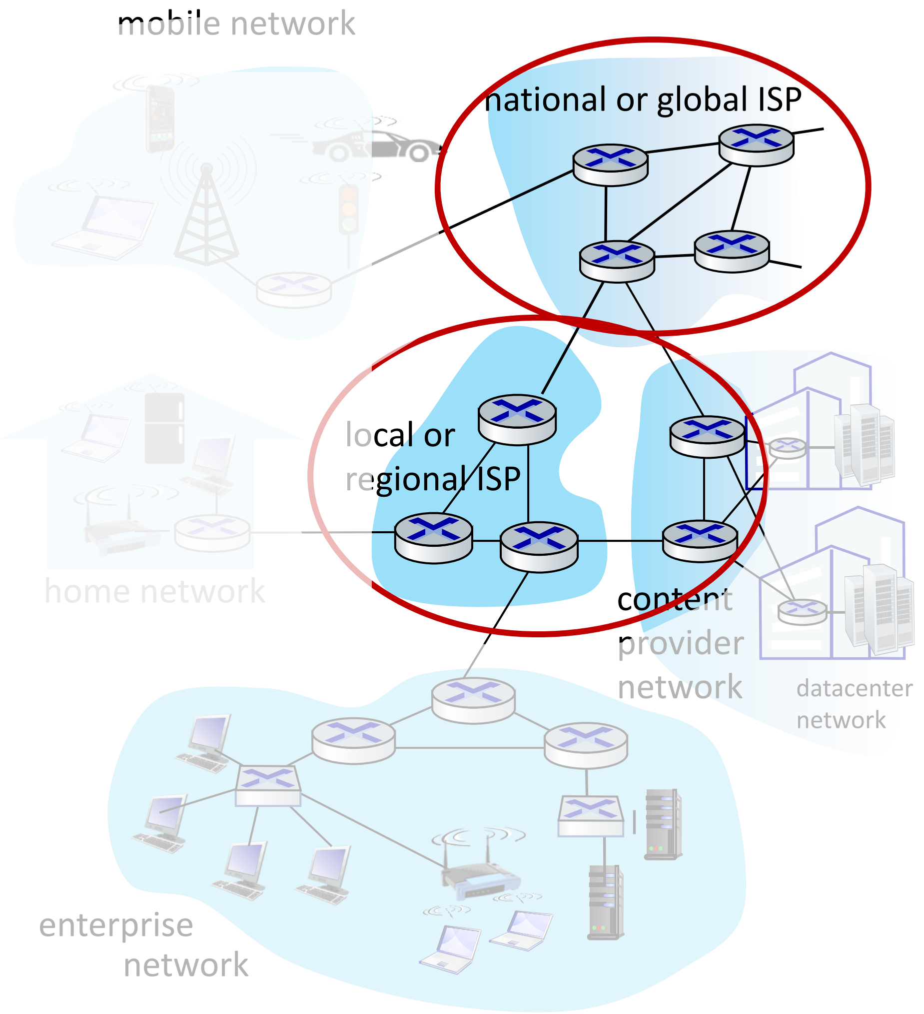
Network core:

- interconnected routers
- network of networks



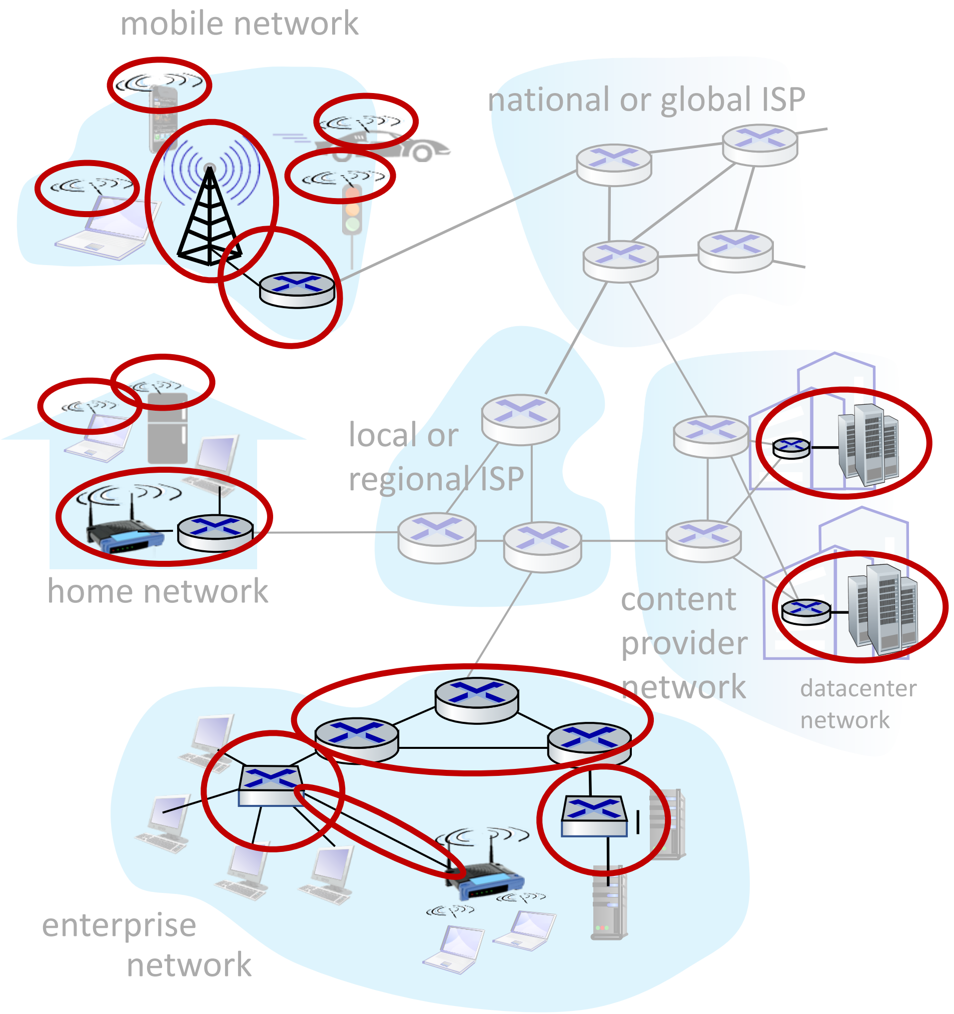
Network Edge: Access networks and Physical media

Q: How to connect end systems to edge router?

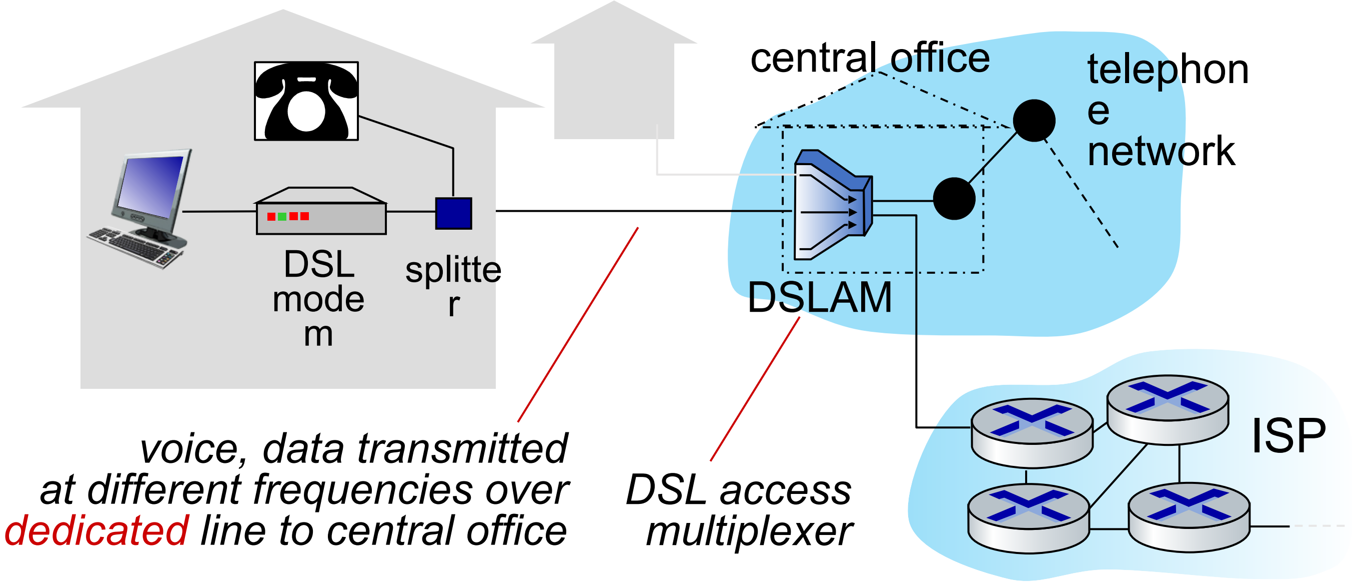
- Residential access networks
- Institutional access networks (school, company)
- Mobile access networks (WiFi, 4G/5G)

What to look for:

- Transmission rate (bits per second) of access network?
- Shared or dedicated access among users?



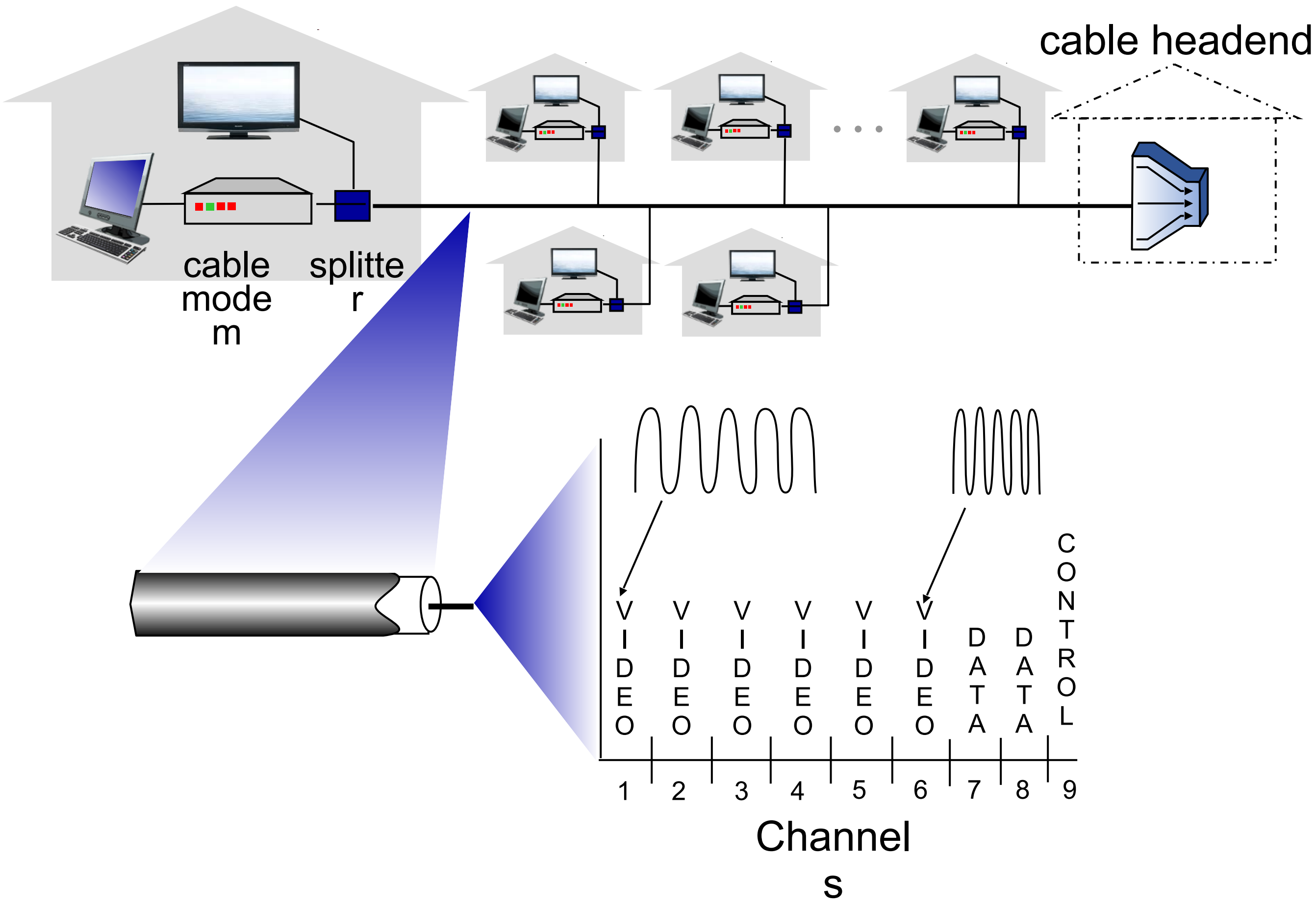
Network Edge: Access Networks - Digital Subscriber Line (DSL)



- 24-52 Mbps – downstream transmission rate
- 3.5-16 Mbps – upstream transmission rate
- Asymmetric access

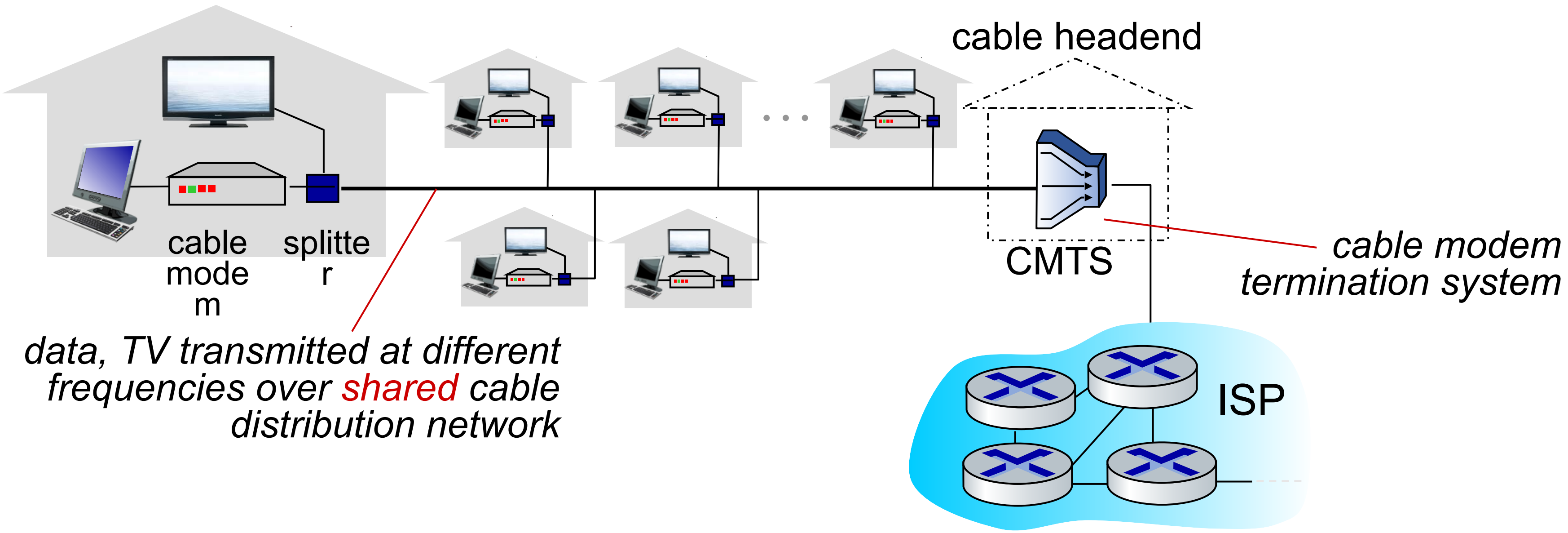
- use *existing* telephone line to central office DSLAM
  - **data** over DSL phone line goes to Internet
  - **voice** over DSL phone line goes to telephone net
- A high-speed downstream channel, in the 50 kHz to 1 MHz band
- A medium-speed upstream channel, in the 4 kHz to 50 kHz band
- An ordinary two-way telephone channel, in the 0 to 4 kHz band

Network Edge: Access Networks: Cable-based access



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

Network Edge: Access Networks: Cable-based access

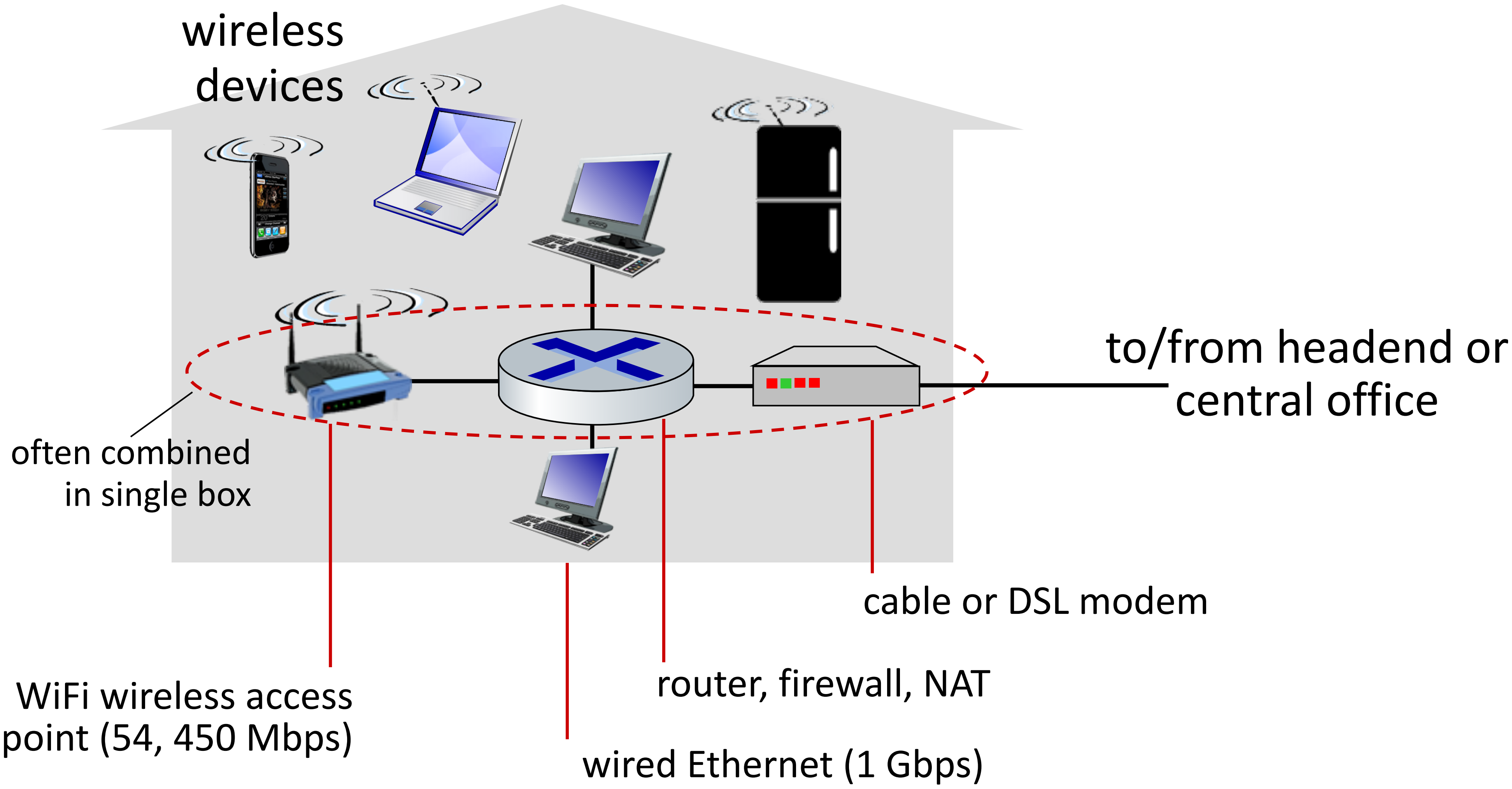


- HFC: hybrid fiber coax
  - Asymmetric:

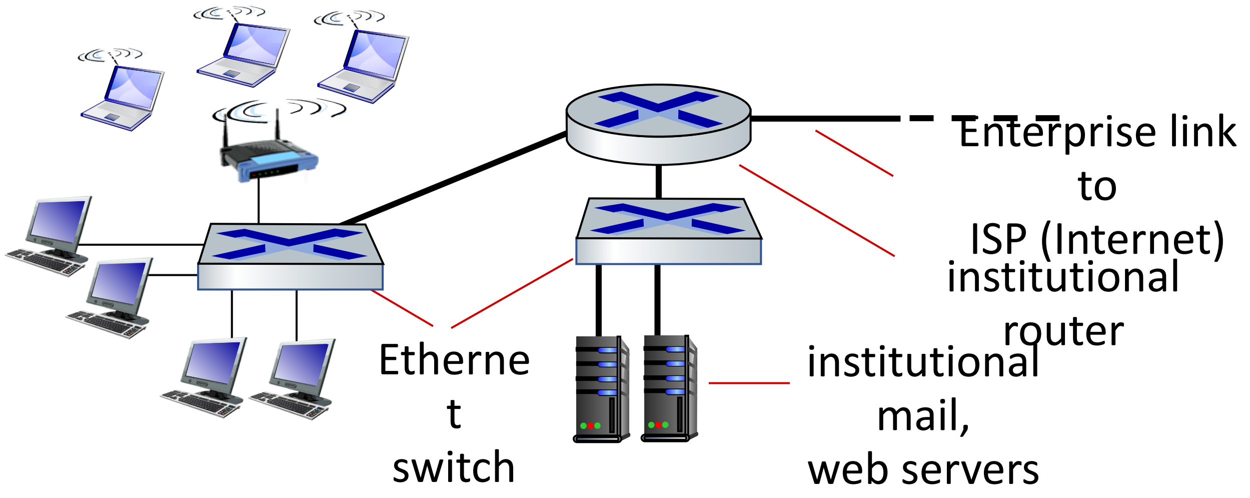
    up to 40 Mbps – 1.2 Gbs downstream transmission rate,

    30-100 Mbps upstream transmission rate
- Network of cable, fiber attaches homes to ISP router
  - homes *share access network* to cable headend

Network Edge: Access Networks – Home access



Network Edge: 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

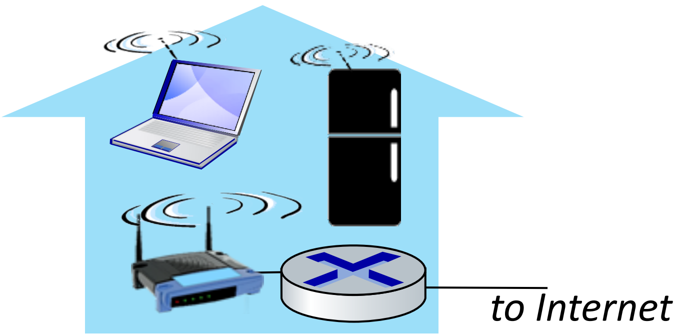
Network Edge: Wireless Access Networks

Shared *wireless* access network connects end system to router

- via base station aka "access point"

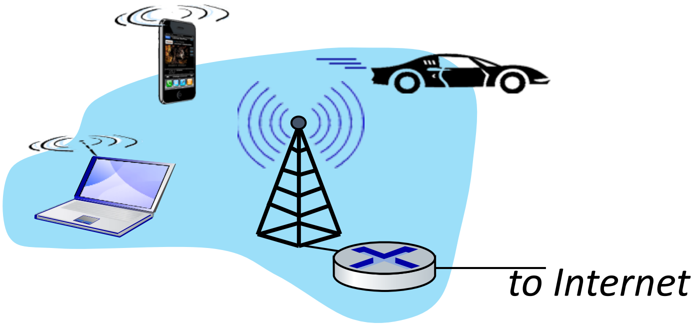
Wireless local area networks (WLANs)

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



Wide-area cellular access networks

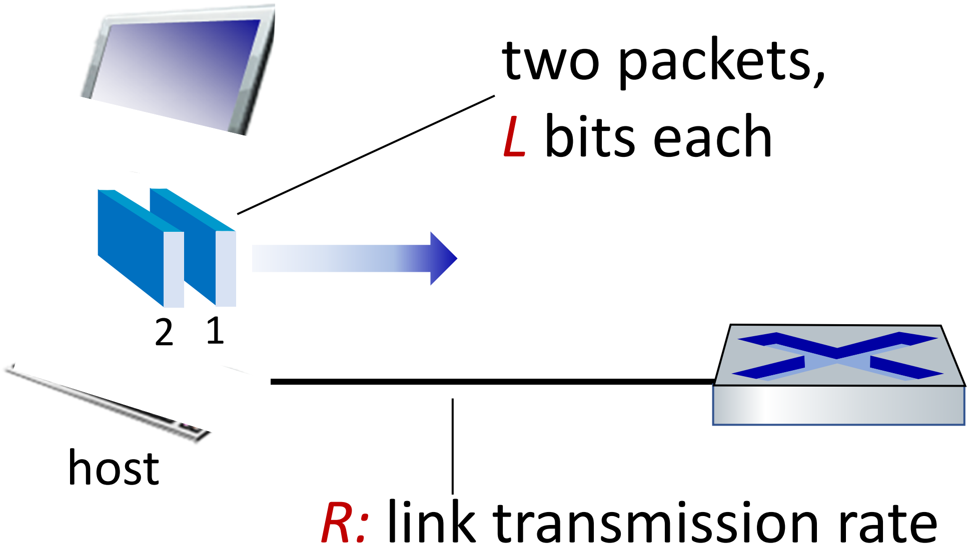
- provided by mobile, cellular network operator (10's km)
- 10's Mbps
- 4G cellular networks (5G coming)



Hosts: Send packets of data

Host sending function:

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



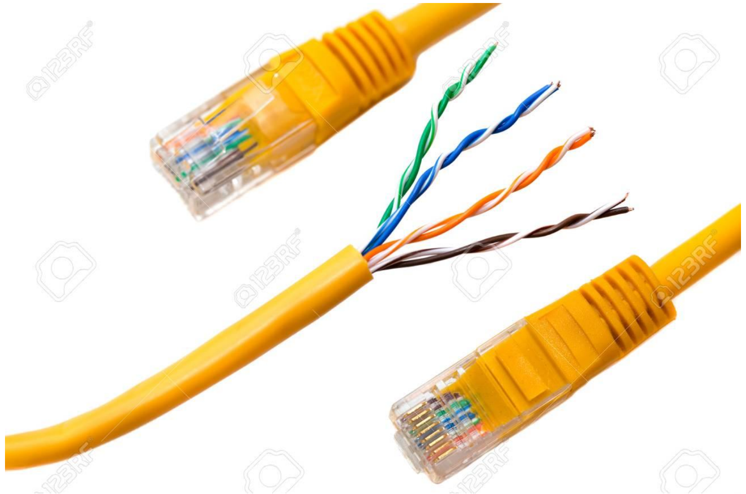
$$\text{packet transmission delay} = \text{time needed to transmit } L\text{-bit packet into link} = \frac{L \text{ (bits)}}{R \text{ (bits/sec)}}$$

Network Edge: 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)

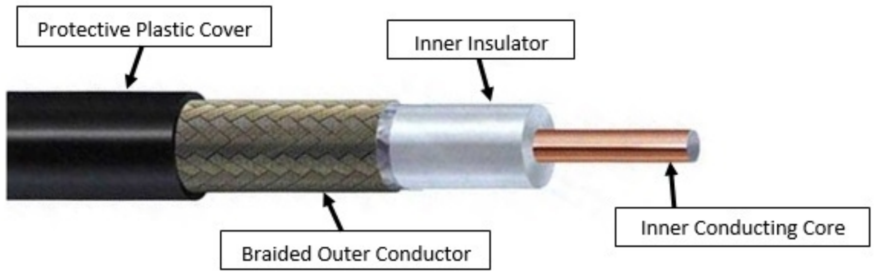
- two insulated copper wires (STP & UTP)
  - Category 5: 100 Mbps, 1 Gbps Ethernet
  - Category 6: 10Gbps Ethernet



Network Edge: Physical media

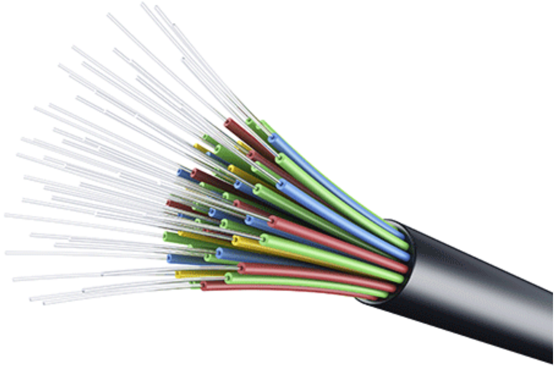
Coaxial cable:

- two concentric copper conductors
- concentric rather than parallel
- 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



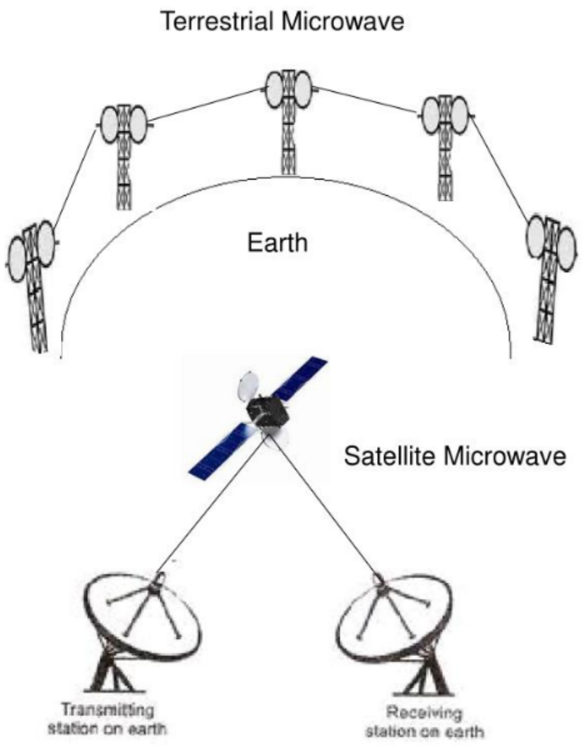
Network Edge: Physical media

Wireless radio

- signal carried in electromagnetic spectrum
- no physical "wire"
- broadcast and "half-duplex" (sender to receiver)
- propagation environment effects:
  - reflection
  - obstruction by objects
  - interference

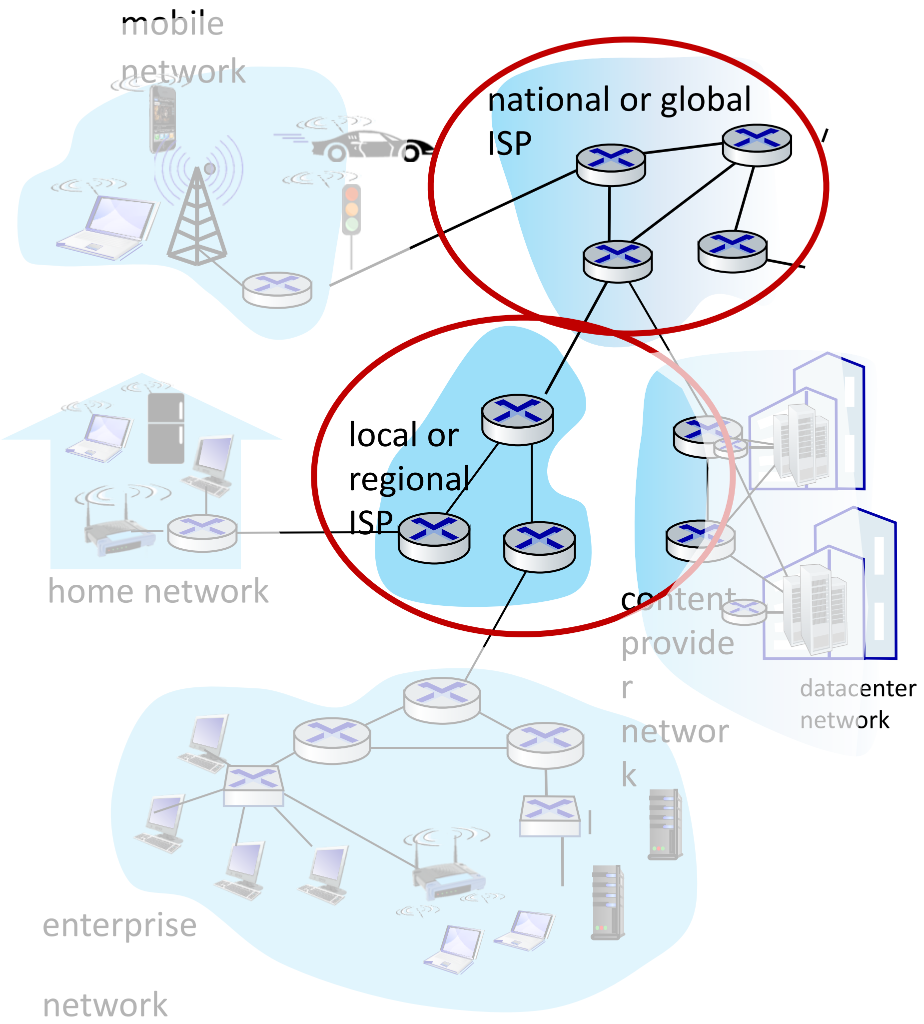
Radio link types:

- terrestrial microwave
  - up to 45 Mbps channels
- Wireless LAN (WiFi)
  - Up to 100's Mbps
- wide-area (e.g., cellular)
  - 4G cellular: ~ 10's Mbps
- satellite
  - up to 45 Mbps per channel
  - 280 msec end-end delay
  - geosynchronous vs. low-earth-orbit

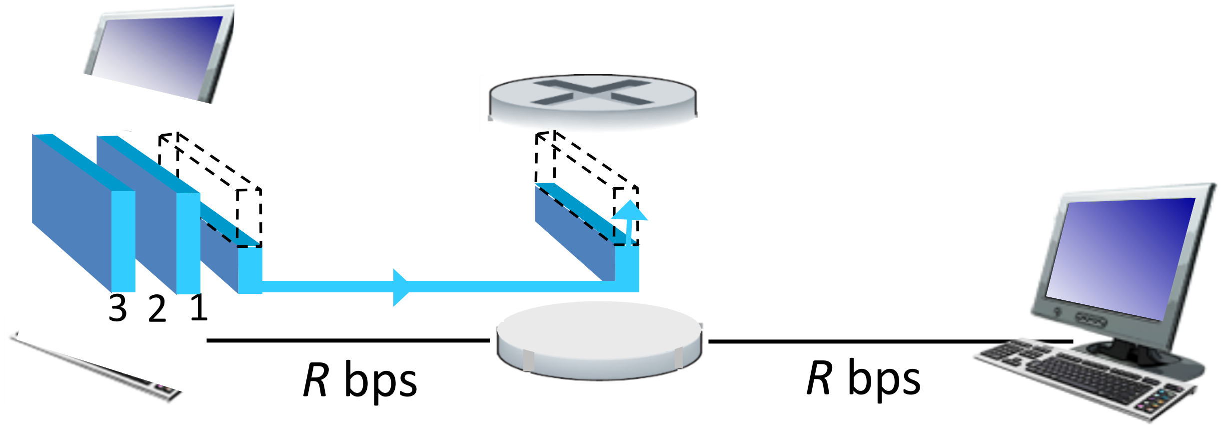


Network Core

- mesh of interconnected routers
- packet-switching: hosts break application-layer messages into *packets*
  - forward packets from one router to the next, across links on path from source to destination
  - each packet transmitted at full link capacity



Network Core: Packet Switching: store-and-forward

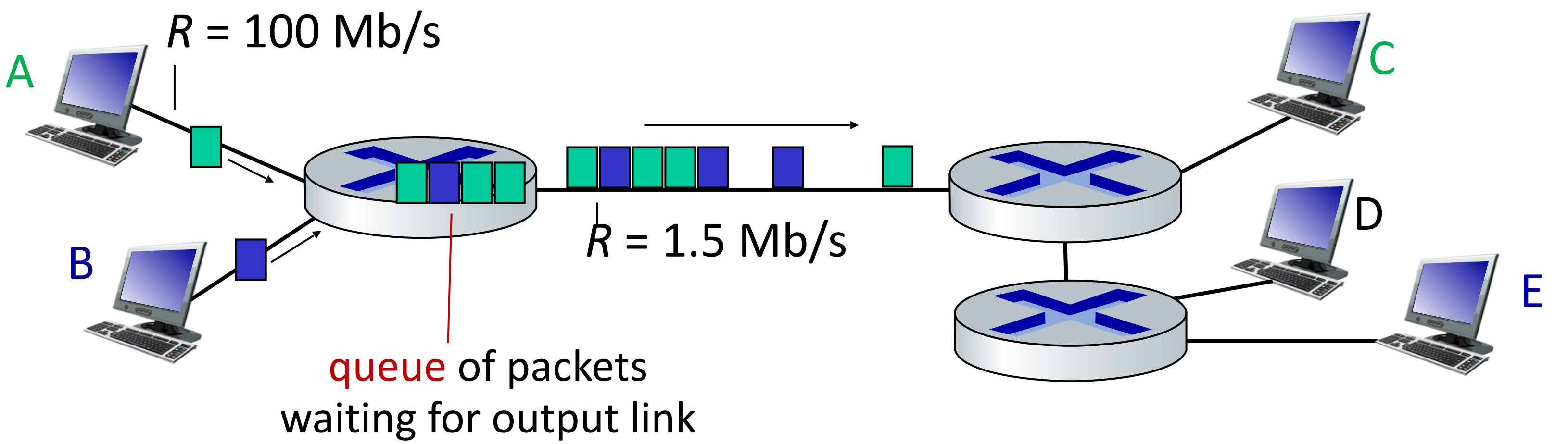


- Transmission delay: takes L/R seconds to transmit (push out) L-bit packet into link at R bps
- *Store and forward: entire* packet must arrive at router before it can be transmitted on next link
- *End-end delay:* $2L/R$ (above), assuming zero propagation delay (more on delay shortly)

One-hop numerical example:

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

Network Core: Packet Switching: queuing delay, loss



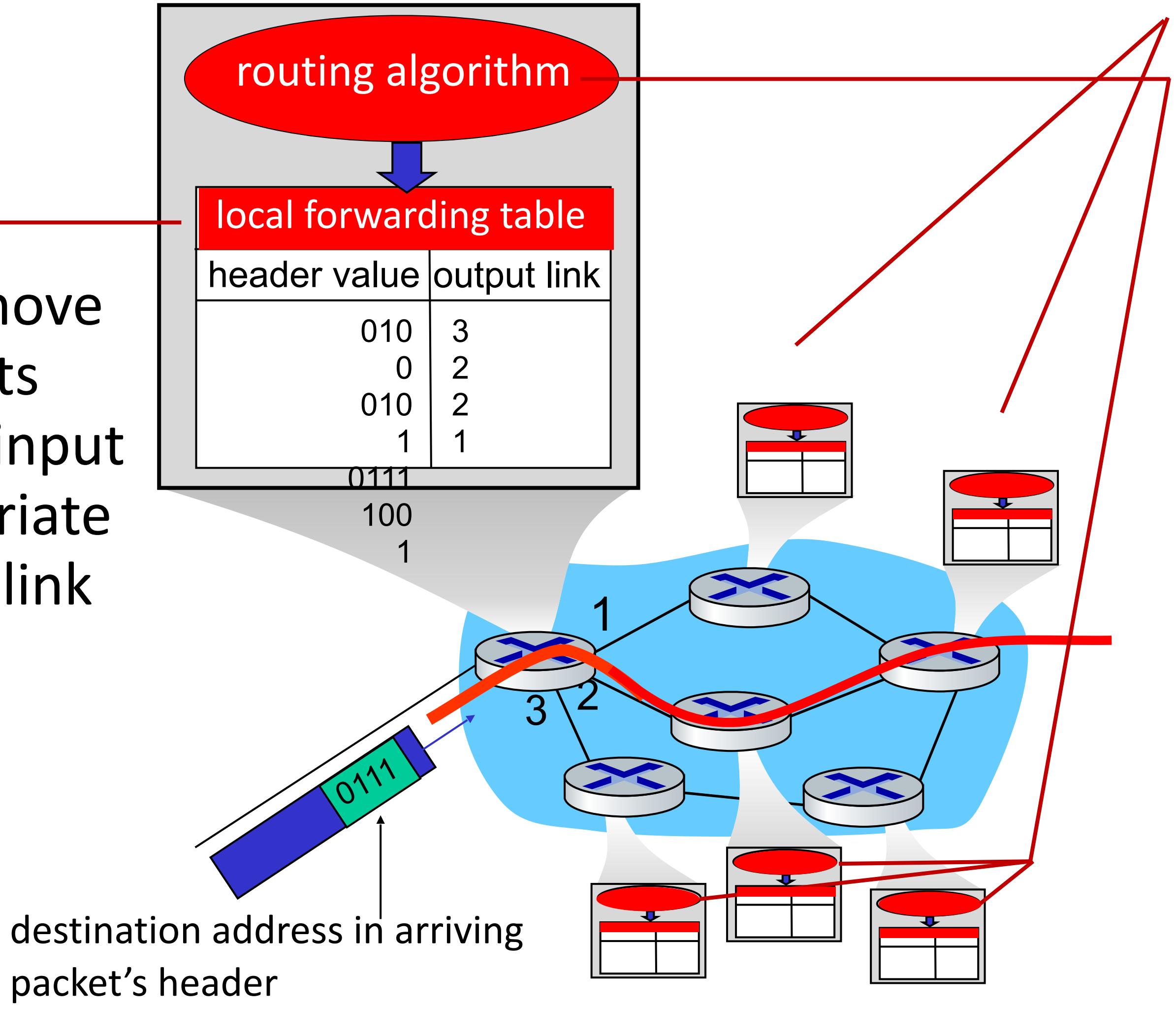
Packet queuing and loss: if arrival rate (in bps) to link exceeds transmission rate (bps) of link for a period of time:

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

Network Core: Two Key Network Core Functions

Forwarding:

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



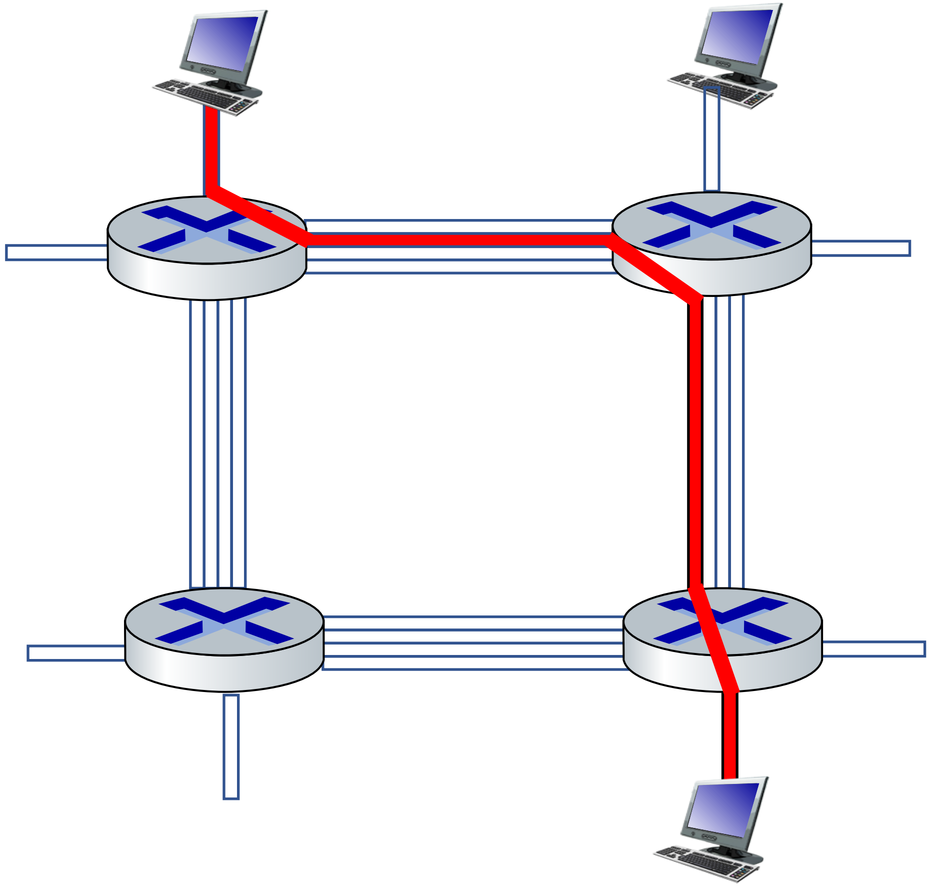
Routing:

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

Network Core: Circuit Switching

end-end resources allocated to, reserved for “call” between source and destination (eg: telephone)

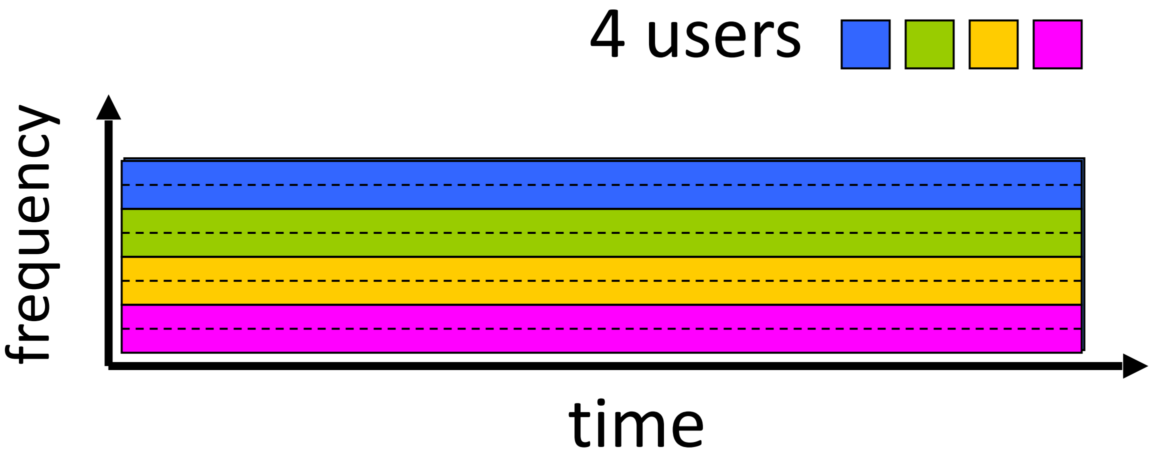
- in diagram, each link has four circuits.
  - call gets 2nd circuit in top link and 1st circuit in right link.
- dedicated resources: no sharing
  - circuit-like (guaranteed) performance
- circuit segment idle if not used by call (no sharing)
- commonly used in traditional telephone networks



Multiplexing in Circuit Switched Networks: FDM & TDM

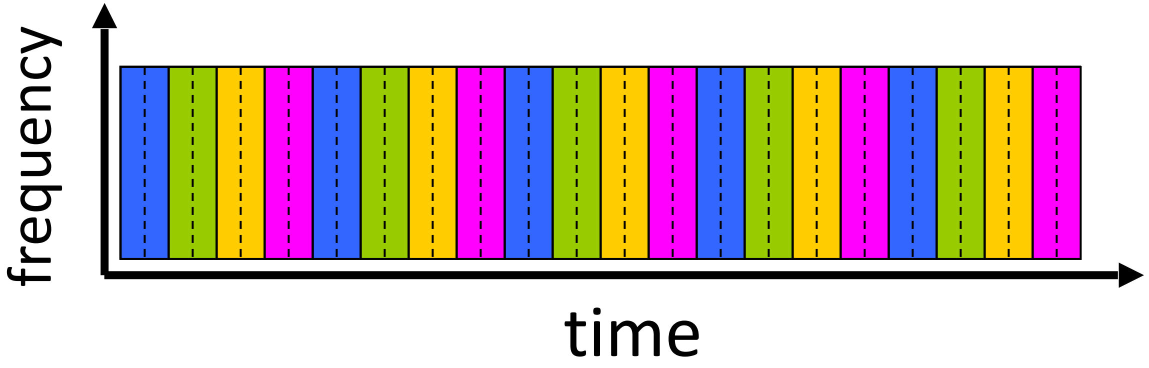
Frequency Division Multiplexing (FDM)

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

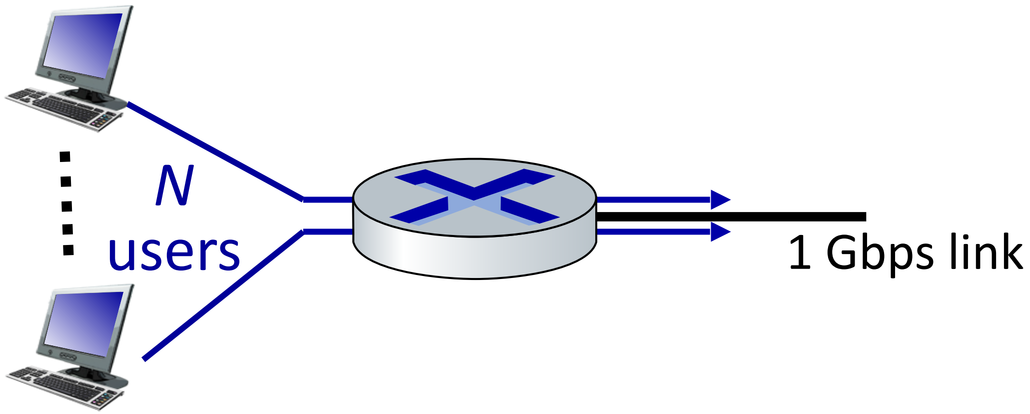


Network Core: Packet Switching vs Circuit Switching

packet switching allows more users to use network!

Example:

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



- *circuit-switching:* 10 users
- *packet switching:* with 35 users,
- probability > 10 active users at same time is less than .0004 *
- 10 or few active users, probability 0.9996

Q: how did we get value 0.0004?

Q: what happens if > 35 users ?

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

Network Core: Packet Switching vs Circuit Switching

Is packet switching a “slam dunk winner”?

- great for “bursty” data – sometimes has data to send, but at other times not
  - resource sharing
  - simpler, no call setup
- excessive congestion possible: packet delay and loss due to buffer overflow
  - protocols needed for reliable data transfer, congestion control
- *Q:* How to provide circuit-like behavior?
  - bandwidth guarantees traditionally used for audio/video applications

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

Packet Switching vs Circuit Switching – Numerical Example

- How long does it take to send a file of 640,000 bits (1 byte = 8 bits) from host A to host B over a circuit-switched network?
  - All links are 1.536 Mbps
  - Each link uses TDM with 24 slots/sec
  - 500 msec to establish end-to-end circuit

Let's work it out!

Solution:

- Each circuit has a transmission rate of (1.536 Mbps)/24 = 64 kbps
- It takes (640,000 bits)/(64 kbps) = 10 seconds to transmit the file
- To this 10 seconds we add the circuit establishment time, giving 10.5 seconds to send the file

Network Core: Packet Switching vs Circuit Switching

- Connectionless
- Designed for data
- Flexible
- Out of order, assembled at the dest
- Forward, Store & Fwd
- Network layer
- Bandwidth is saved (dynamic)
- Transmission of data – Source, routers
- Transmission delay

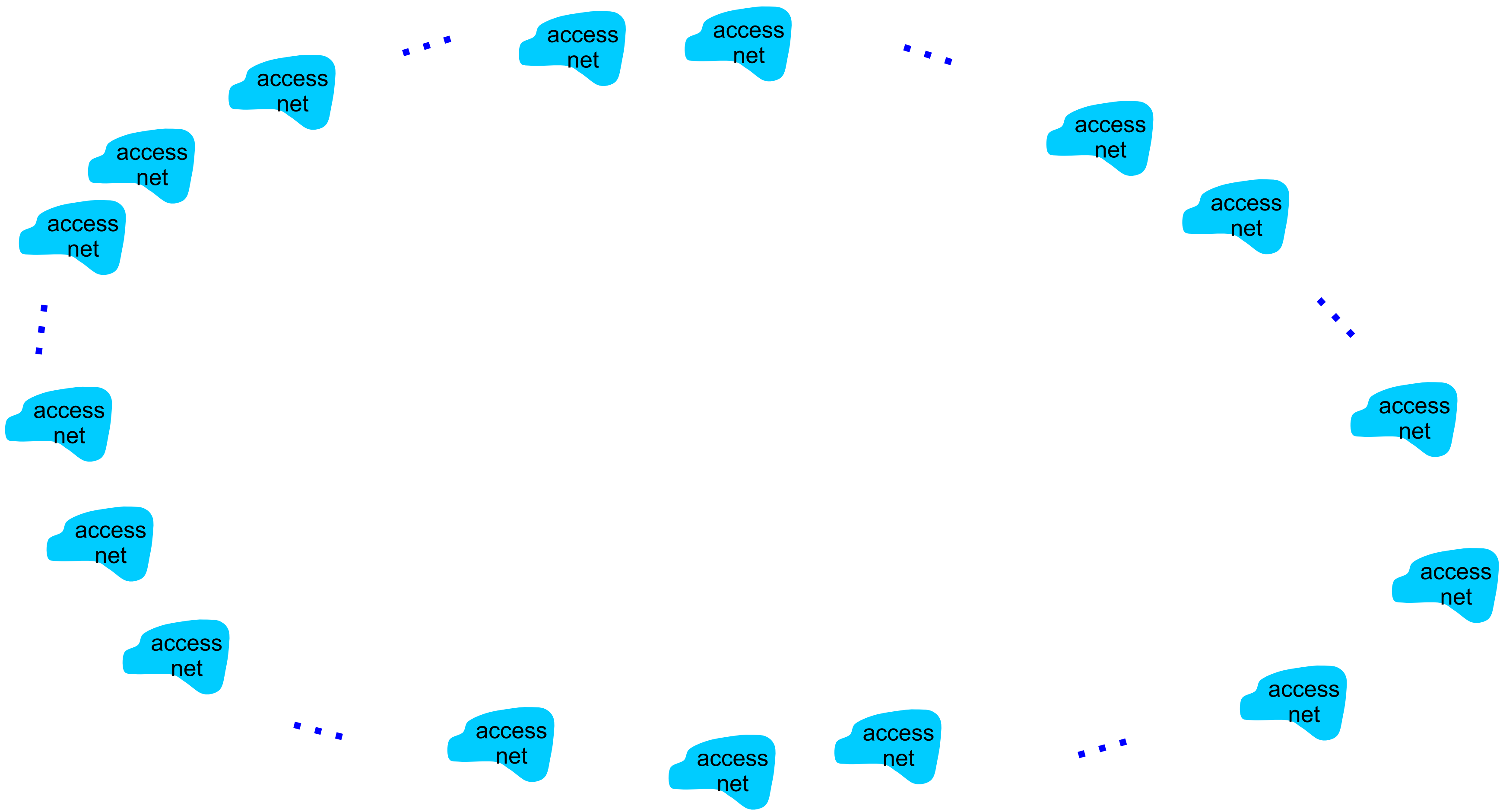
- Connection oriented
- Designed for voice
- Inflexible
- Message received in same order
- FDM & TDM
- Physical layer
- Bandwidth is wasted (fixed)
- Transmission of data – source
- Call setup delay

Internet Structure: a “network of networks”

- End systems connect to Internet via access ISPs (Internet Service Providers)
  - Residential, company and university ISPs
- Access ISPs in turn must be interconnected.
  - So that any two hosts can send packets to each other
- Resulting network of networks is very complex
  - Evolution was driven by economics and 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?



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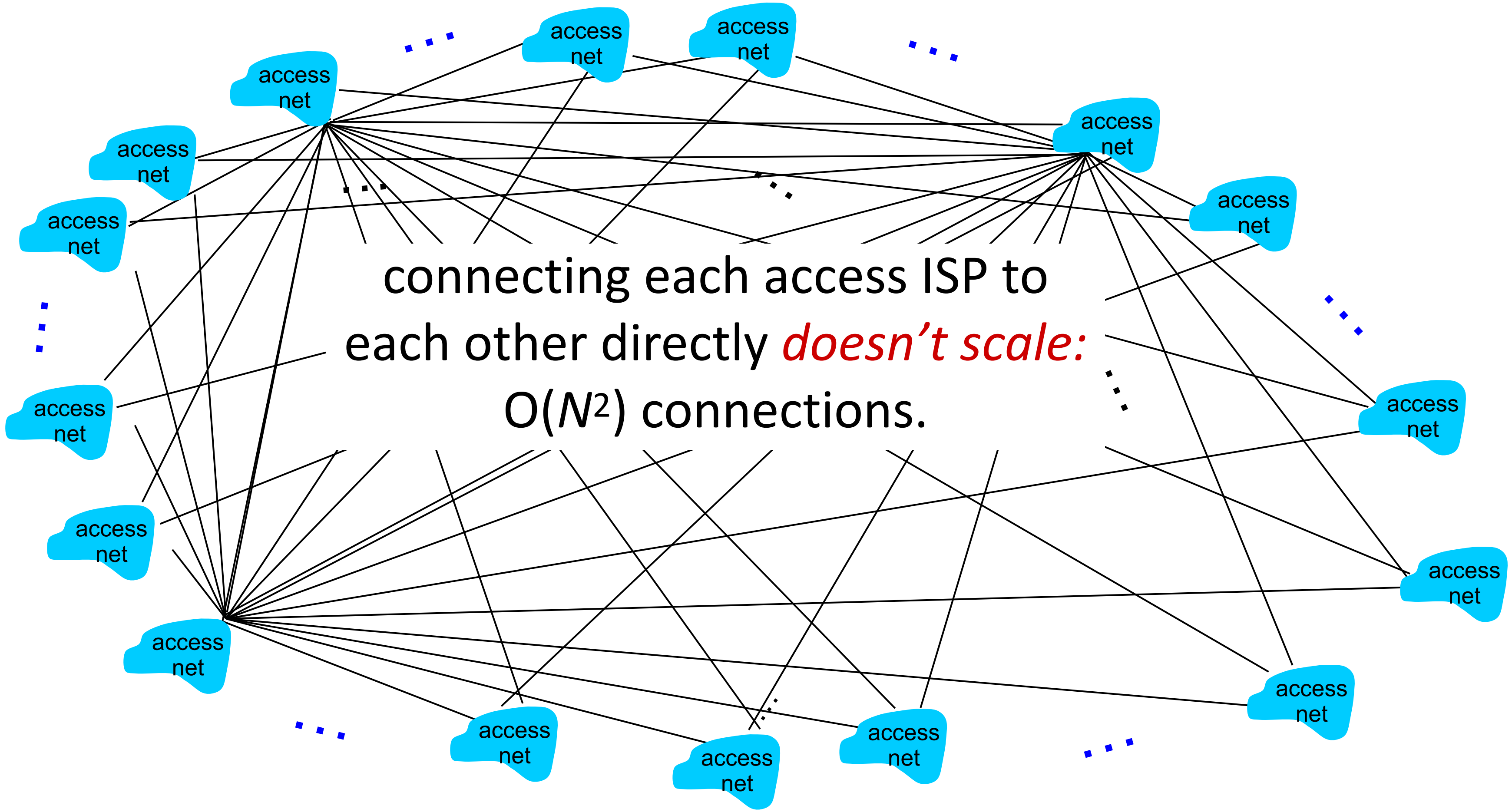
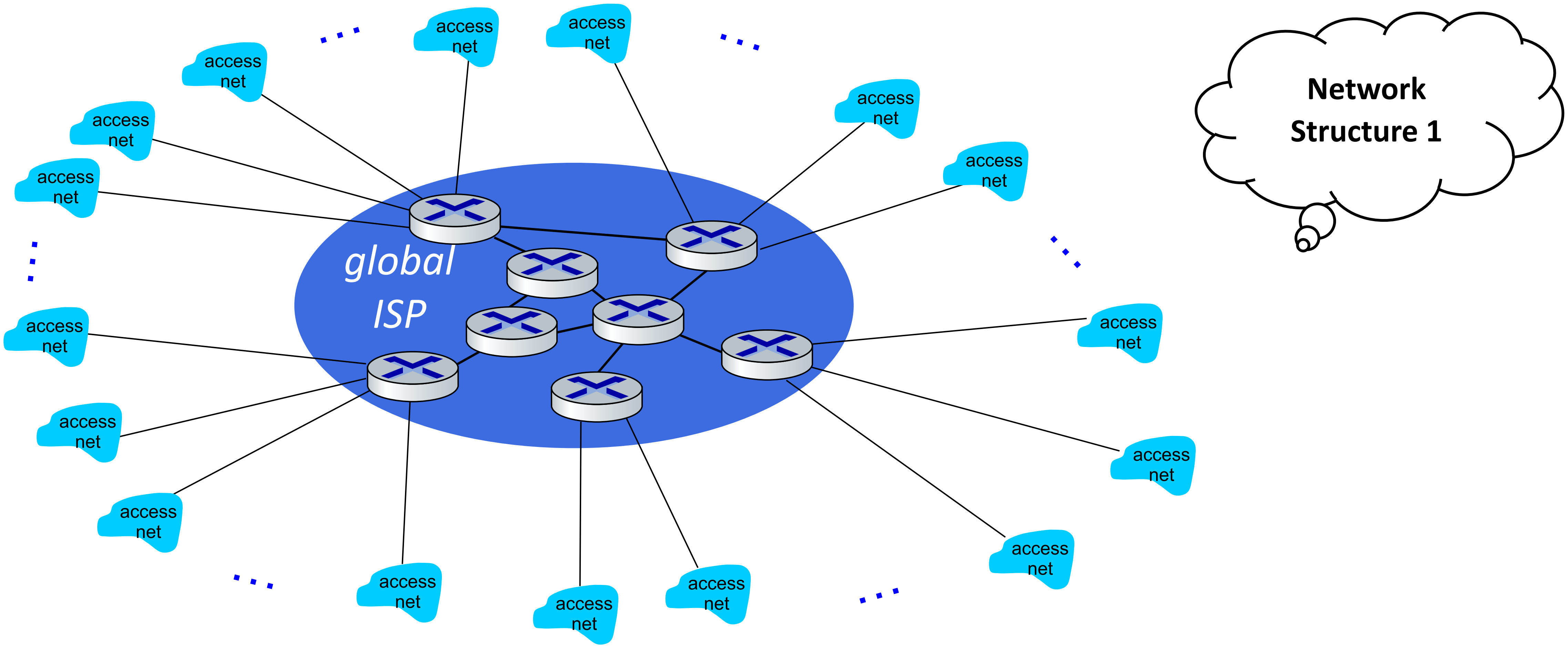


connecting each access ISP to each other directly *doesn't scale:* $O(N^2)$ connections.

Internet Structure: a "network of networks"

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



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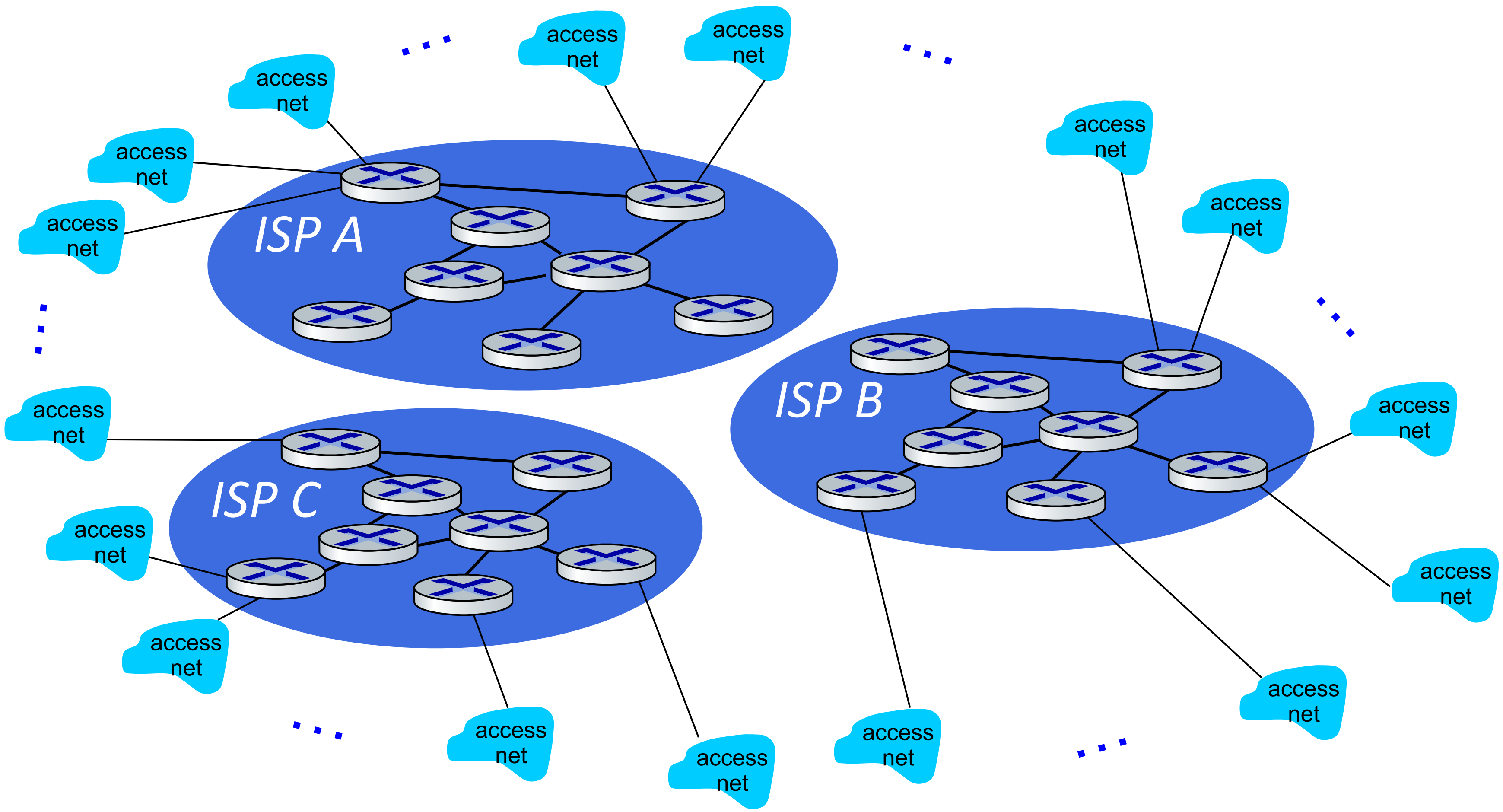
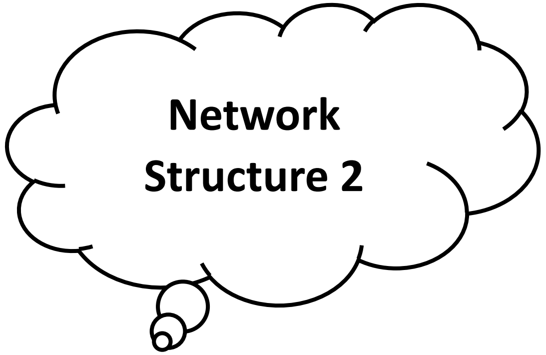
Internet Structure: a “network of networks”

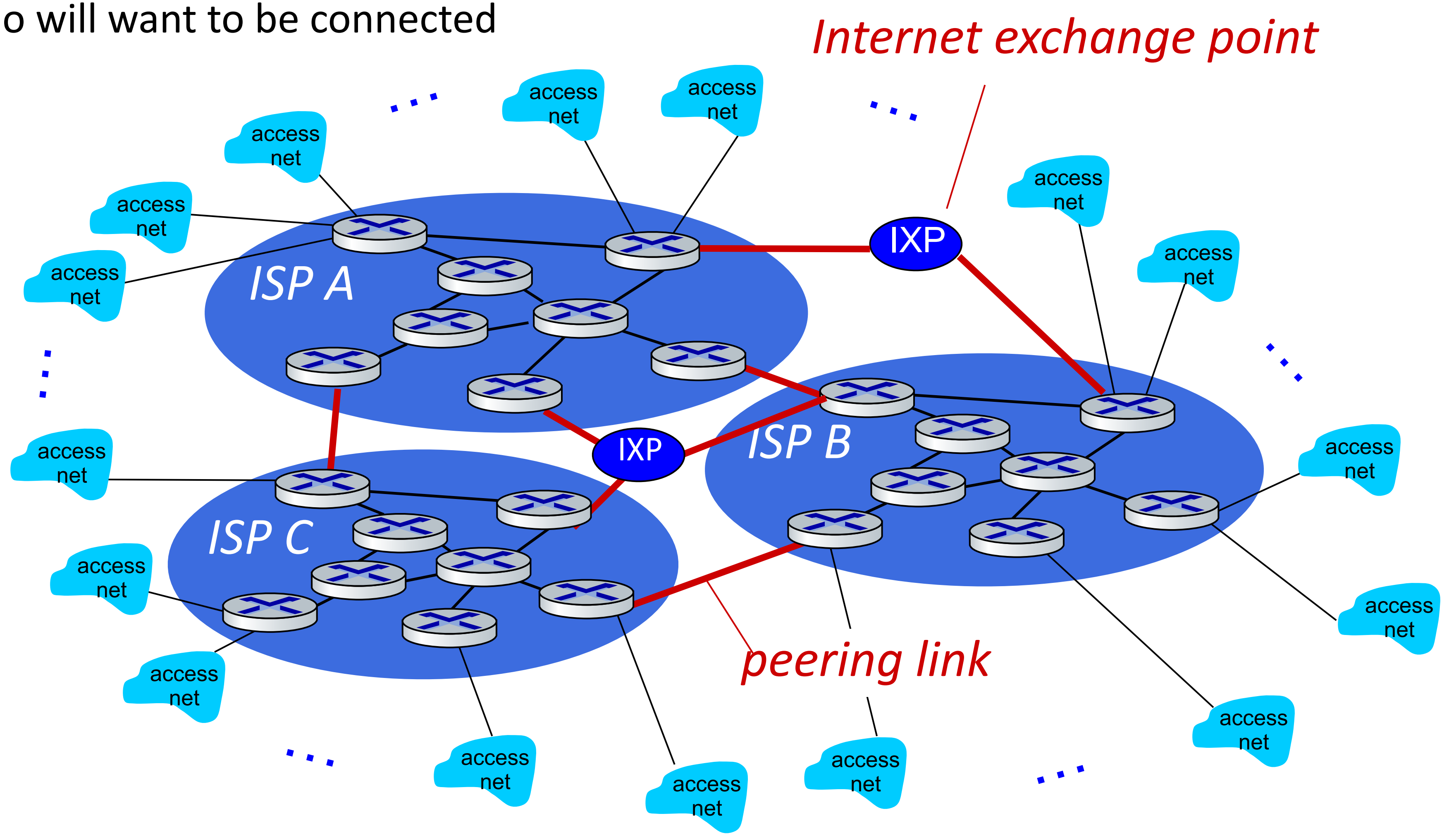
But if one global ISP is viable business, there will be competitors ….

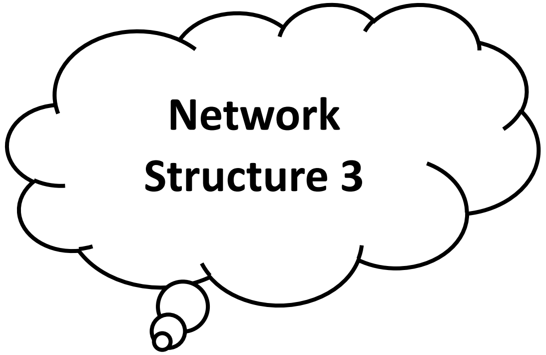




Internet Structure: a “network of networks”

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





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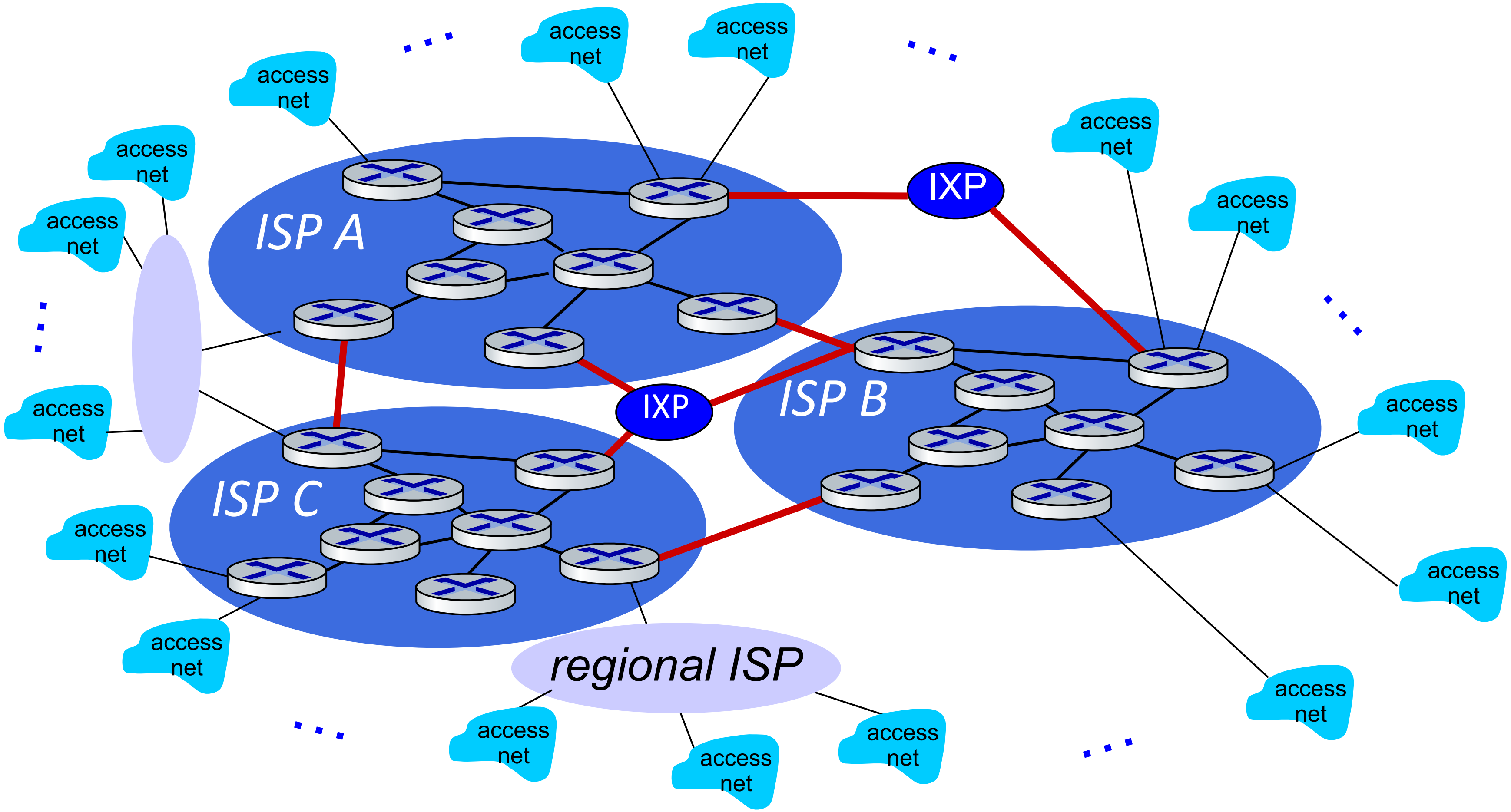
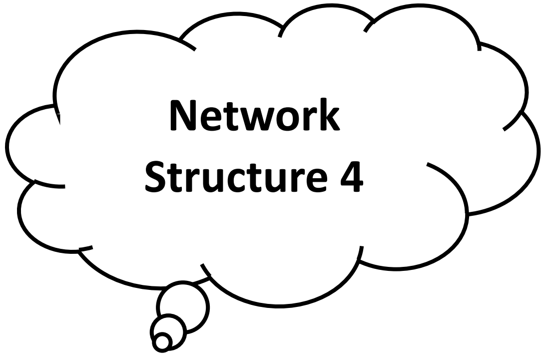
Internet Structure: a “network of networks”

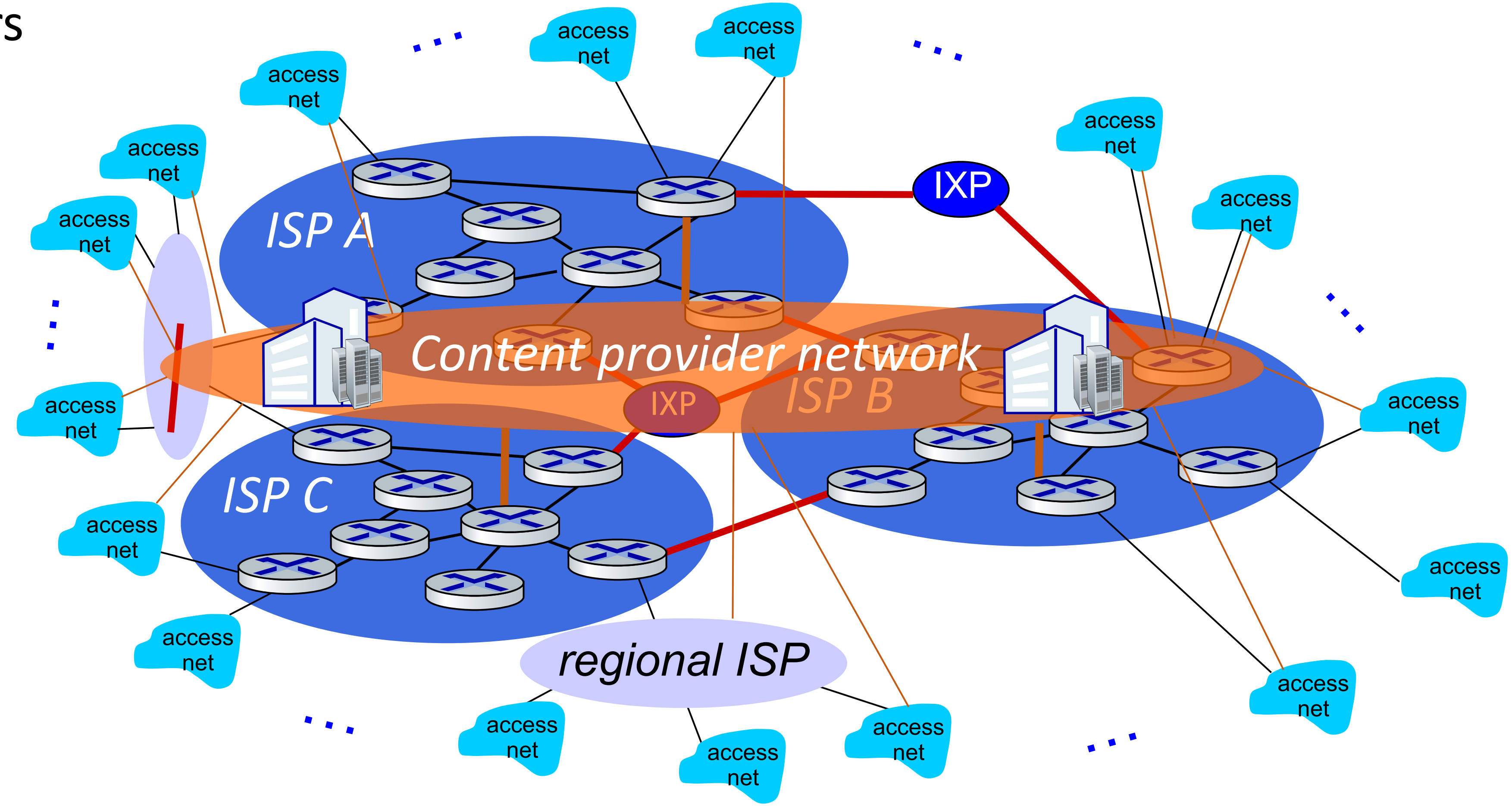
… and regional networks may arise to connect access nets to ISPs

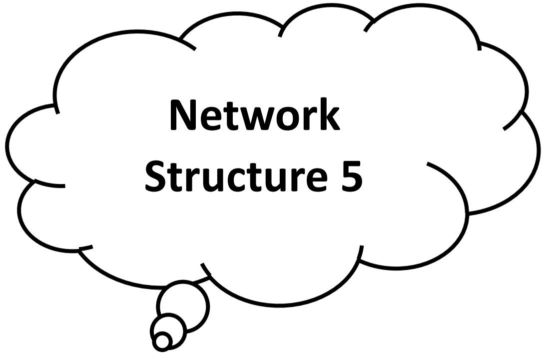




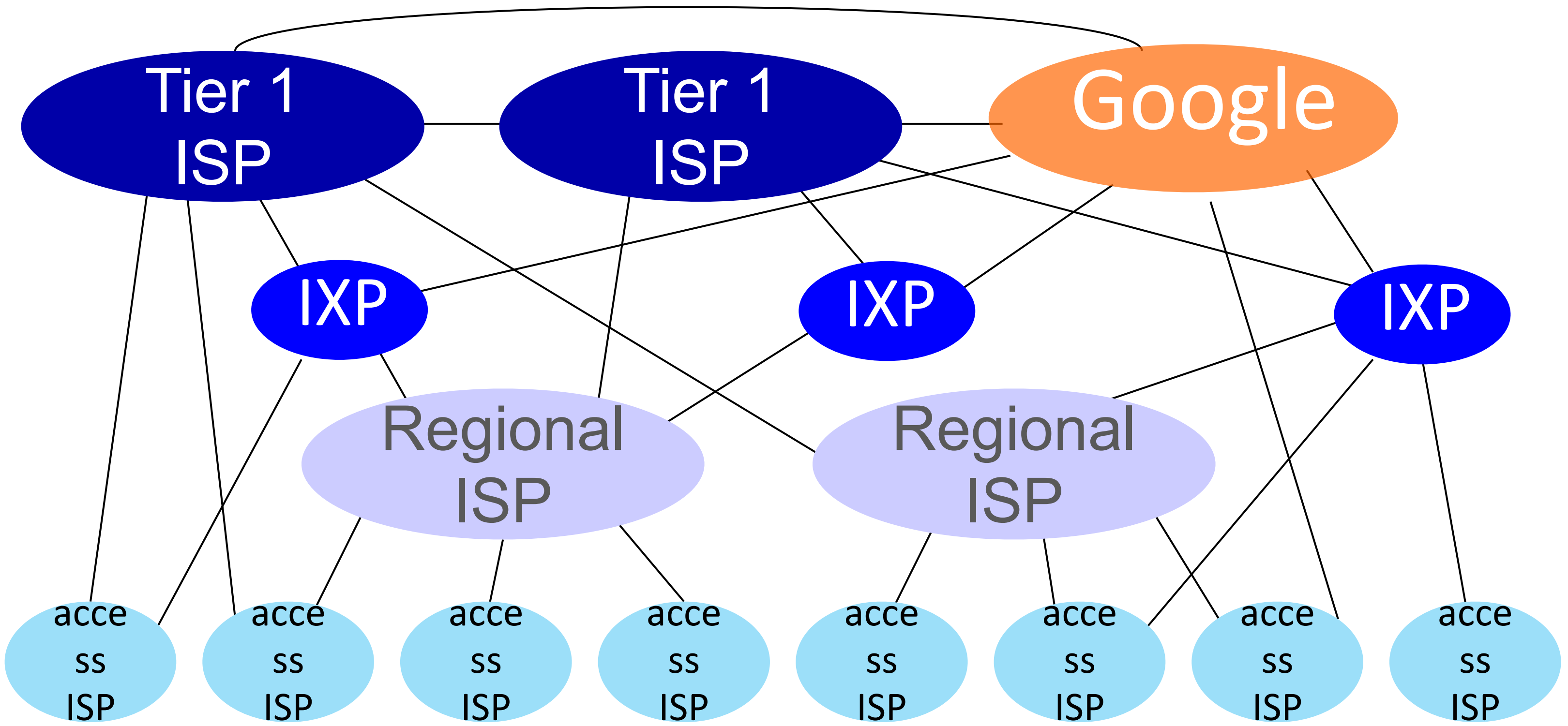
Internet Structure: a “network of networks”

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





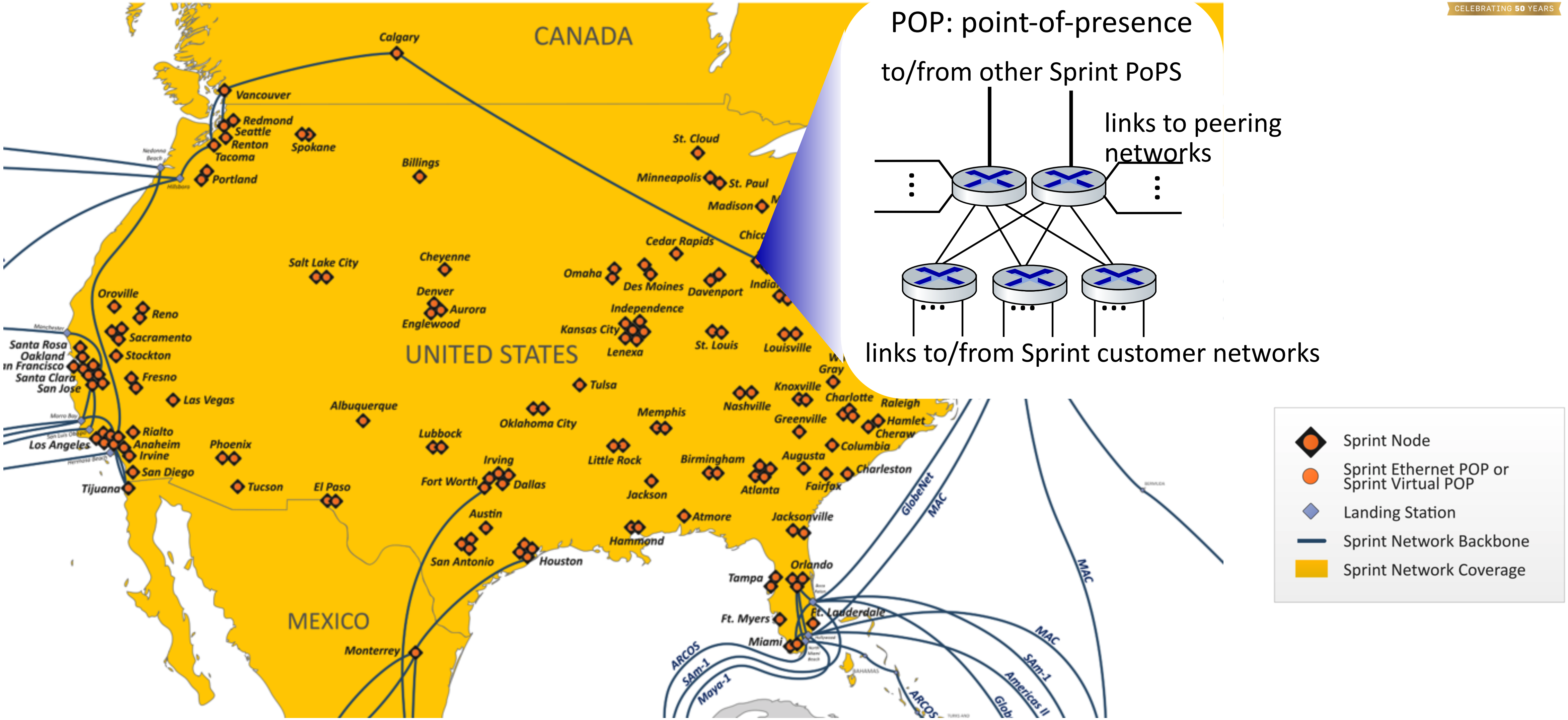
Internet Structure: a "network of networks"



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

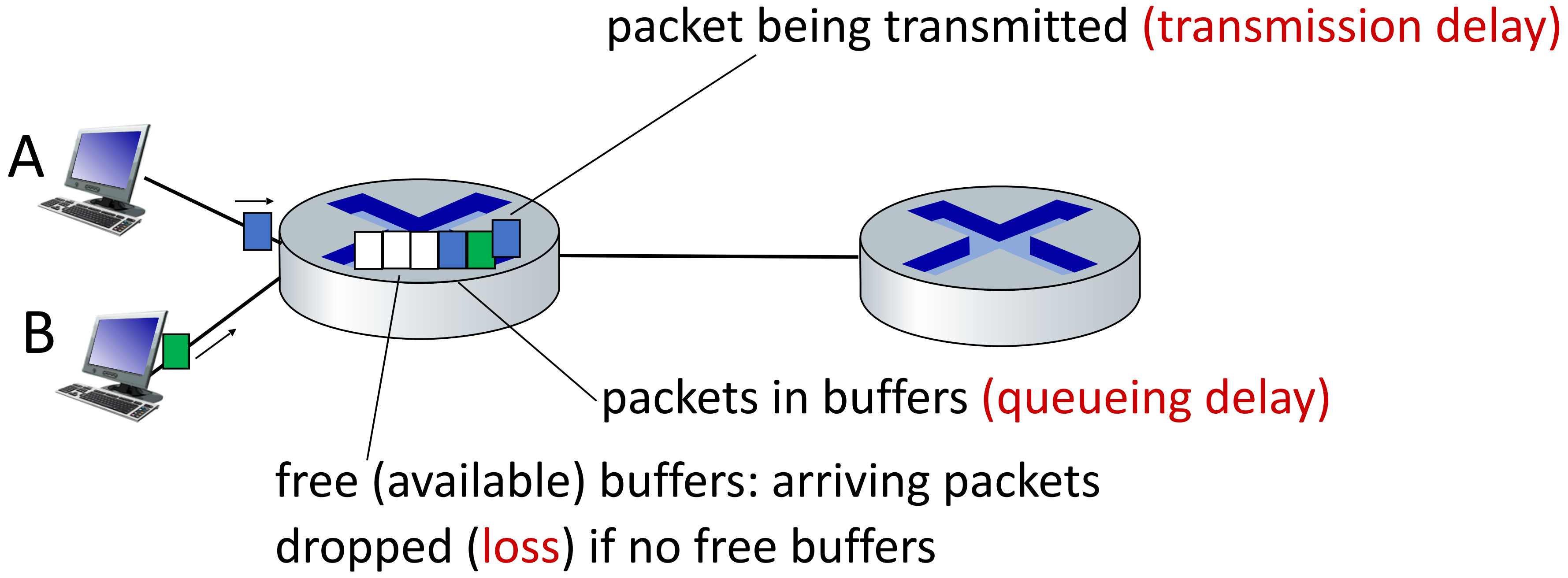
Network Core: Tier 1 ISP Network Map: Sprint 2019



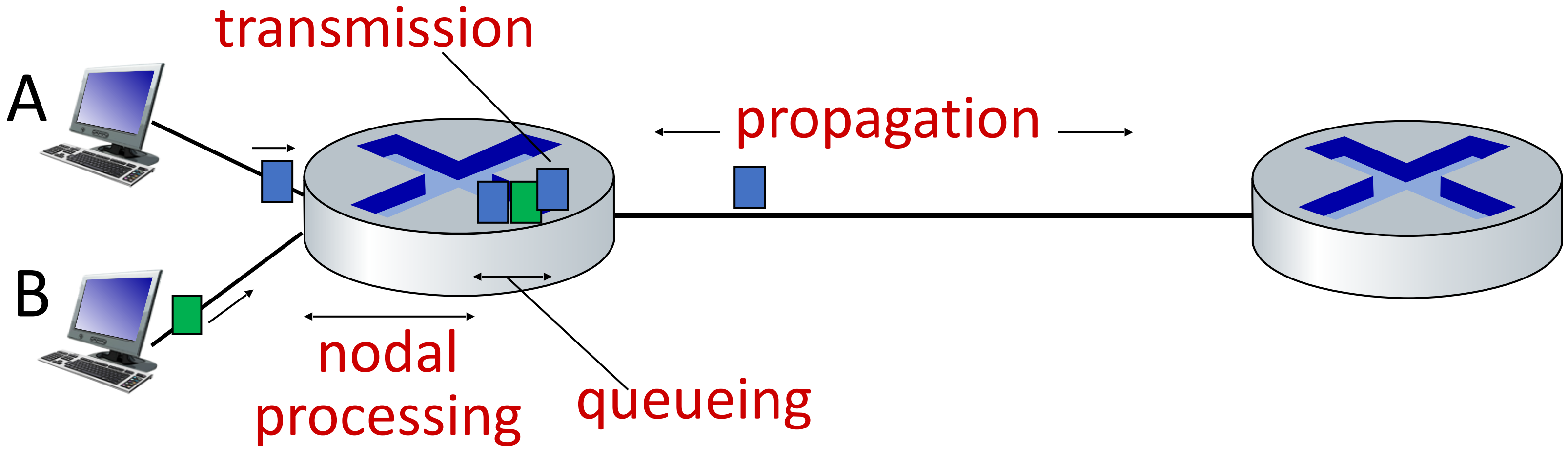
How do packet loss and delay occurs?

packets *queue* in router buffers

- packets queue, wait for turn
- arrival rate to link (temporarily) exceeds output link capacity: packet loss



Performance: Packet Delay – 4 Sources



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

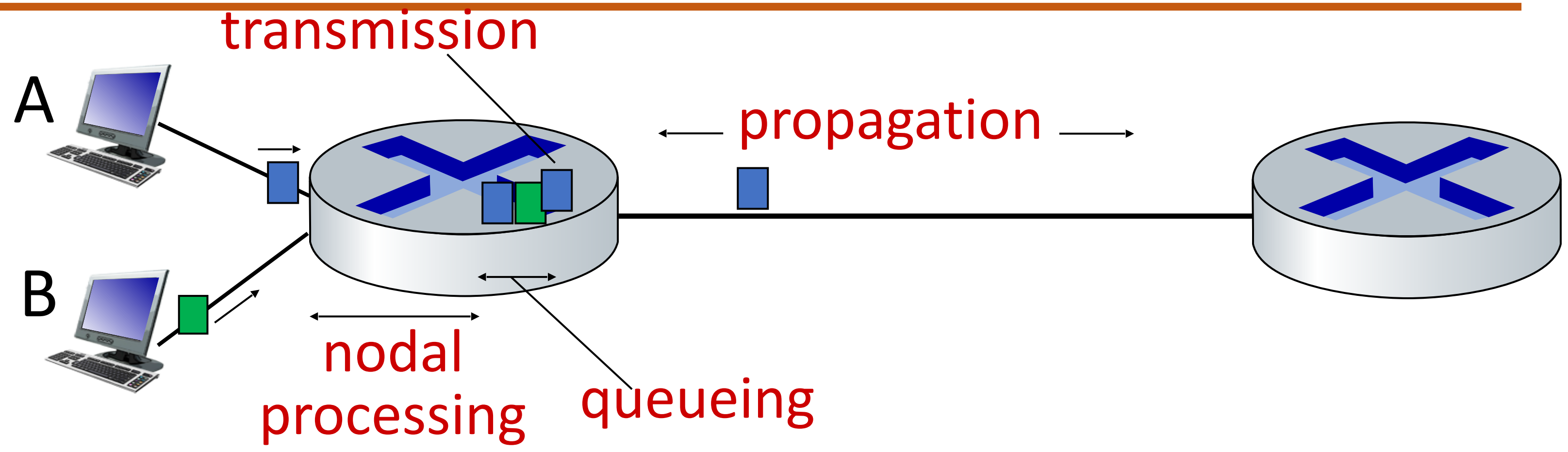
d_{proc}: nodal processing

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

d_{queue}: queueing delay

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

Performance: Packet Delay – 4 Sources



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

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

d_{trans}: transmission delay:

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

d_{prop}: propagation delay:

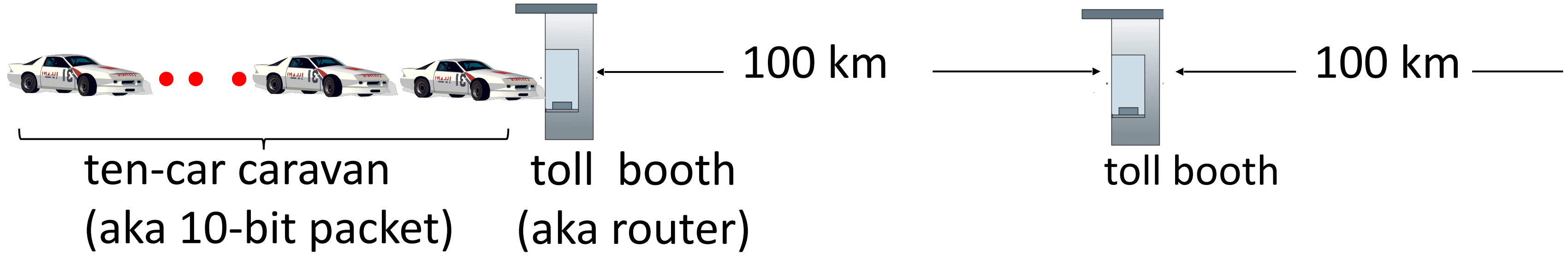
- d: length of physical link
- s: propagation speed (~2×10^8 m/sec)
- $d_{prop} = d/s$

d_{trans} and d_{prop}
very different

Transmission Delay vs Propagation Delay

Transmission Delay	Propagation Delay
Time required for the router to push out the packet.	Time it takes a bit to propagate from one router to the next.
A function of the **packet's length** and the **transmission rate** of the link.	A function of the **distance** between the two routers.
$d_{trans} = L/R$	$d_{prop} = d/s$
Nothing to do with the distance between the two routers.	Nothing to do with the packet's length or the transmission rate of the link.

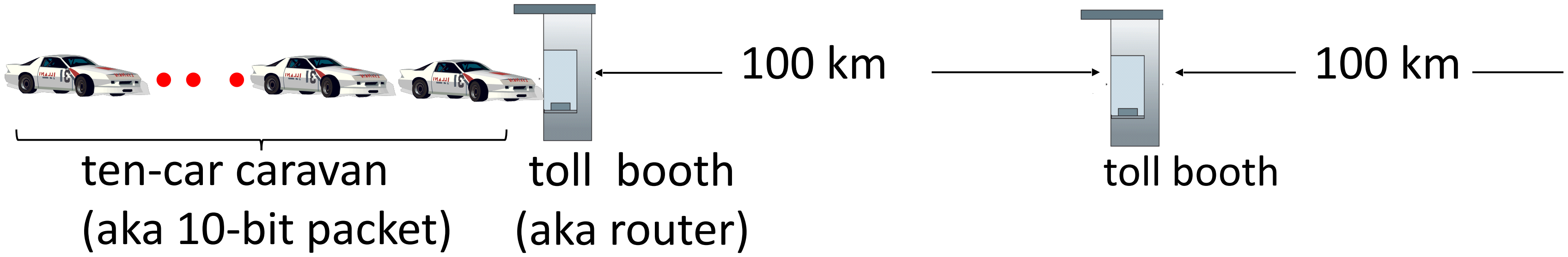
Performance: Delay – Caravan Analogy



- cars "propagate" at 100 km/hr
- toll booth takes 12 sec to service car (bit transmission time)
- car ~ bit; caravan ~ packet
- *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: 100km/(100km/hr) = 1 hr
- *A:* 62 minutes

Performance: Delay – Caravan Analogy (more)



- 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

Performance: Packet Queueing Delay revisited

Unlike other delays (dproc, dtrans, dprop), dqueue is interesting.

- Can vary from packet to packet.
- Characterize $\boldsymbol{d}_{\textbf{queue}}$ -> average, variance, probability that it exceeds some specified value.

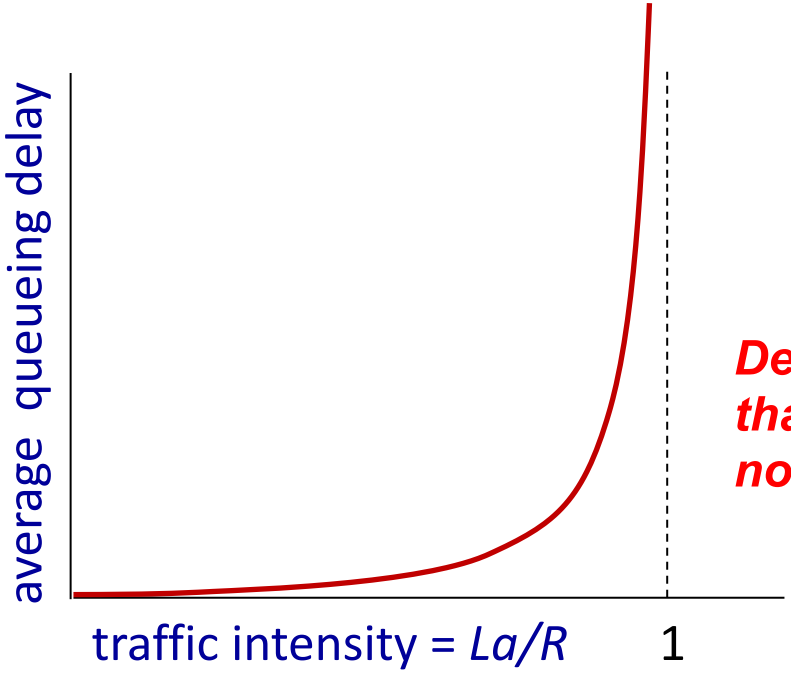
When is the queuing delay large and when is it insignificant?

- Rate at which traffic arrives at the queue,
- Transmission rate of the link,
- Nature of the arriving traffic – periodically or in bursts

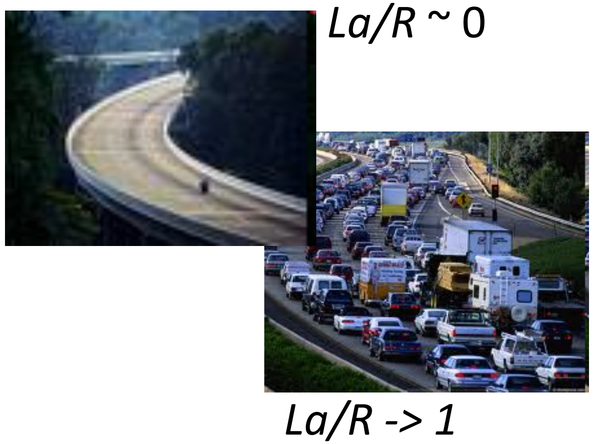
Performance: Packet Queueing Delay revisited

- *R:* link bandwidth (bps)
- *L:* packet length (bits)
- *a:* average packet arrival rate (pps)
- La: avg. rate at which bits arrive at the queue

- La/R > 1: more "work" arriving is more than can be serviced - average delay infinite!
- La/R <= 1: nature of arriving traffic
- *La/R* ~ 0: avg. queueing delay small



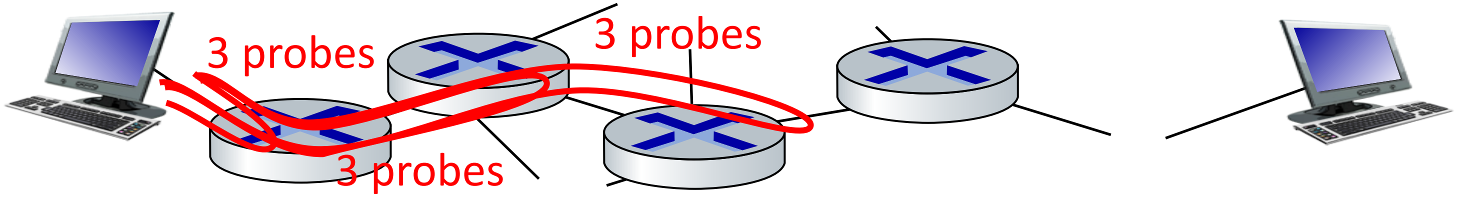
Design your system so that the traffic intensity is no greater than 1.



La/R > 1: Average rate at which bits arrive at the queue exceeds the rate at which the bits can be transmitted from the queue.

“Real” Internet Delays and Routes

- what do “real” Internet delay & loss look like?
- **traceroute** program: provides delay measurement from source to router along end-end Internet path towards destination. For all *i:*
  - sends three packets that will reach router *i* on path towards destination (with time-to-live field value of *i*)
  - router *i* will return packets to sender
  - sender measures time interval between transmission and reply



"Real" Internet Delays and Routes

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

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

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

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

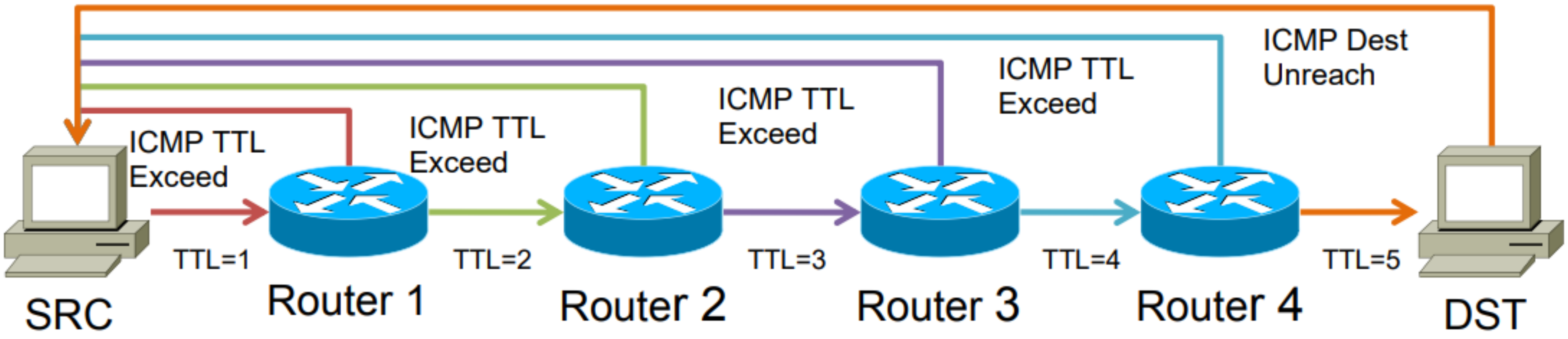
trans-oceanic link

looks like delays *decrease*! Why?

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

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

How Traceroute works?

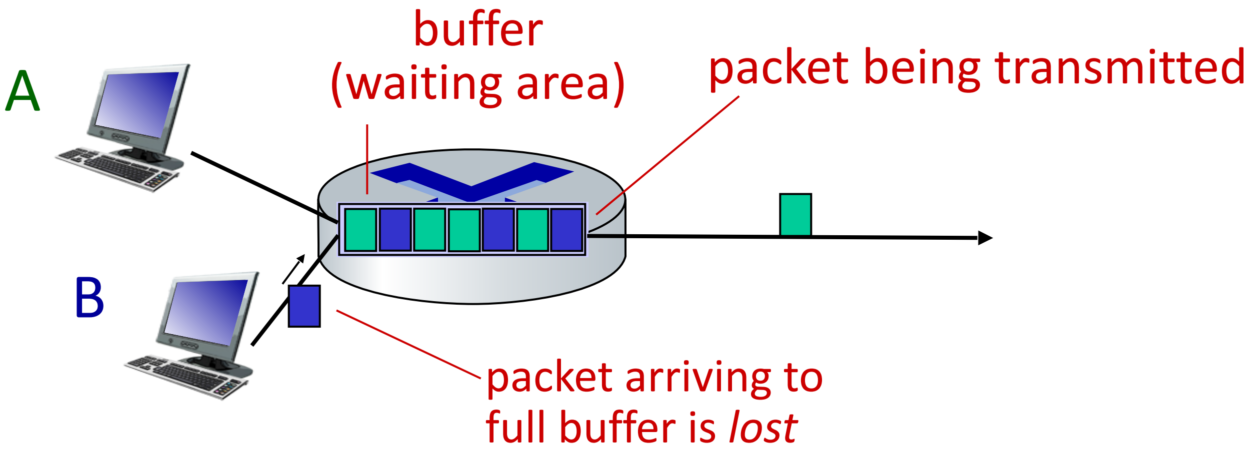


Refer RFC 1393, **Traceroute Using an IP Option**

Don't Trust Traceroute (Completely)

Performance: Packet loss

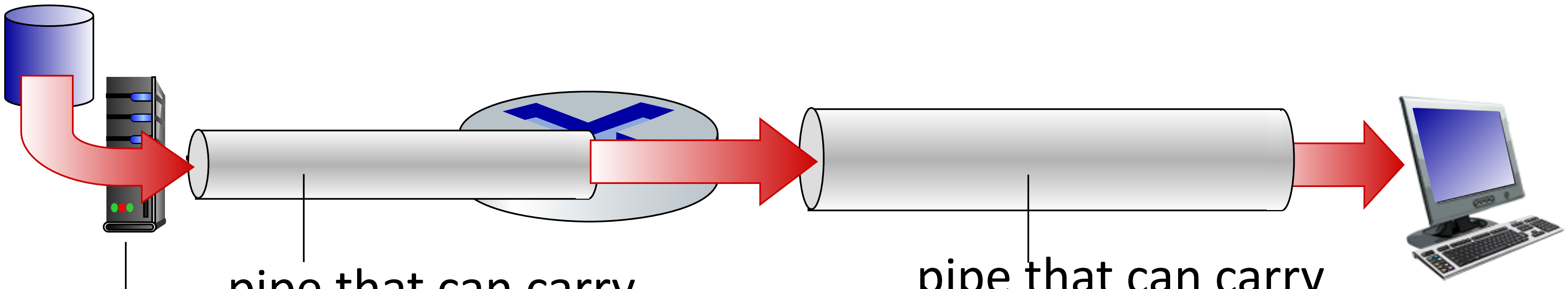
- queue (aka buffer) preceding link in buffer has finite capacity
- packet arriving to full queue dropped (aka lost)
- lost packet may be retransmitted by previous node, by source end system, or not at all



* Check out the Java applet for an interactive animation on queuing and loss

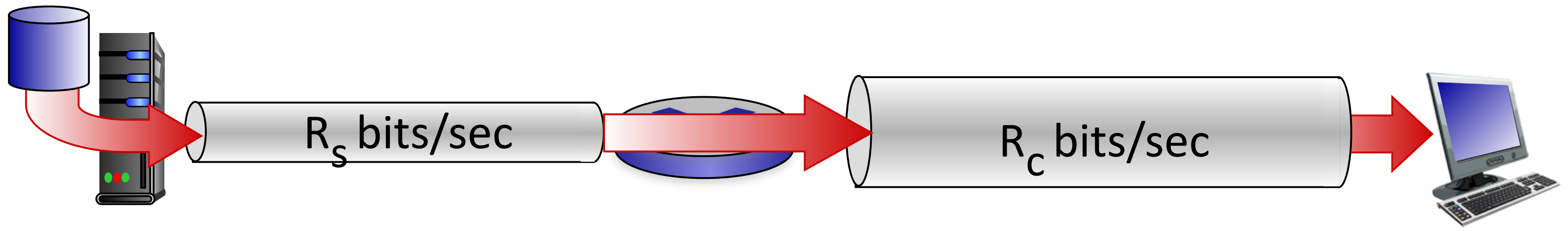
Performance: Throughput

- *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



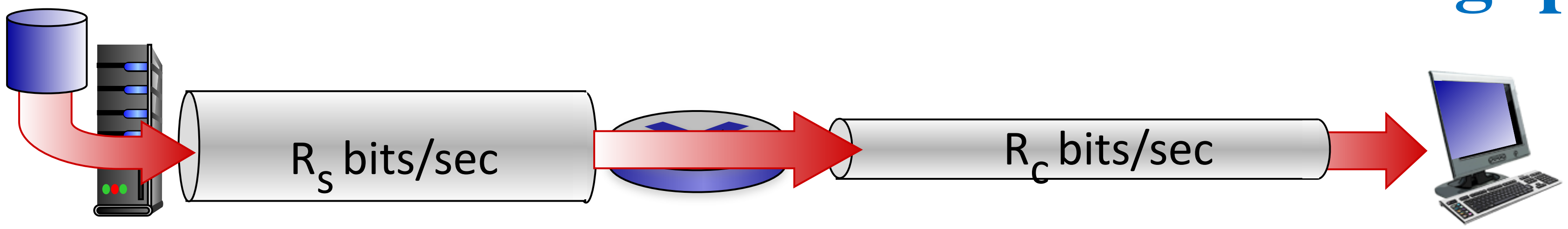
Performance: Throughput (more)

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



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

Throughput = min{R_s, R_c}



bottleneck link

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

Throughput – Numerical Example

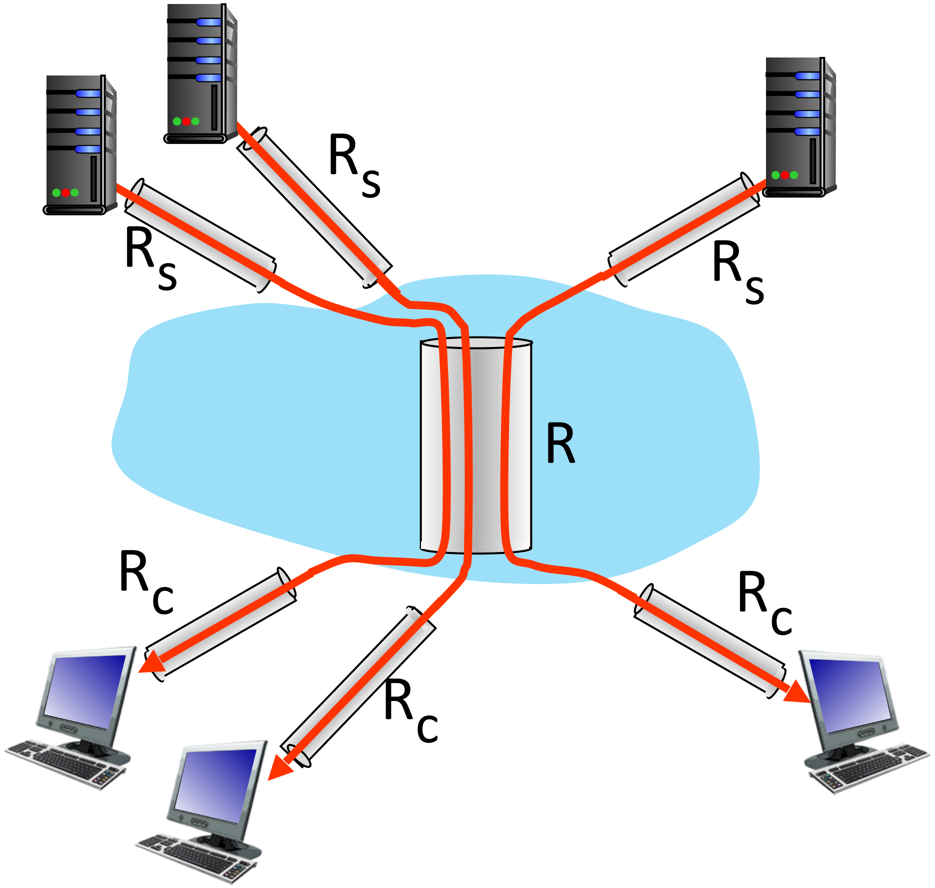
- Suppose you are downloading an MP3 file of F = 32 million bits.
- The server has a transmission rate of R_s = 2 Mbps and you have an access link of R_c = 1 Mbps.
- What is the time needed to transfer the file?

Let's work it out!

Solution:

- 32 seconds!

Performance: Throughput – Network Scenario



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

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

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

- Suppose Rs = 2 Mbps, Rc = 1 Mbps, R = 5 Mbps
- 10 clients from 10 servers = 10 downloads

End-to-end throughput for each download is now reduced to 500 kbps.

Computer Networks and the Internet

Protocol Layers

Team Networks

Department of Computer Science and Engineering

Networks are complex, with many “pieces”:

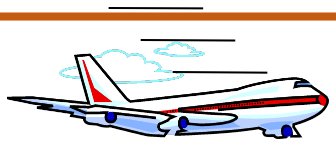
- hosts
- routers
- links of various media
- applications
- protocols
- hardware, software

Question:

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

.... or at least our *discussion* of networks?

Example: Organization of Air Travel



ticket (purchase)

baggage (check)

gates (load)

runway takeoff

airplane routing

ticket (complain)

baggage (claim)

gates (unload)

runway landing

airplane routing

airplane routing

airline travel: a series of steps, involving many services

Layering of Airline functionality

layers: each layer implements a service

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

Q: describe in words the service provided in each layer above

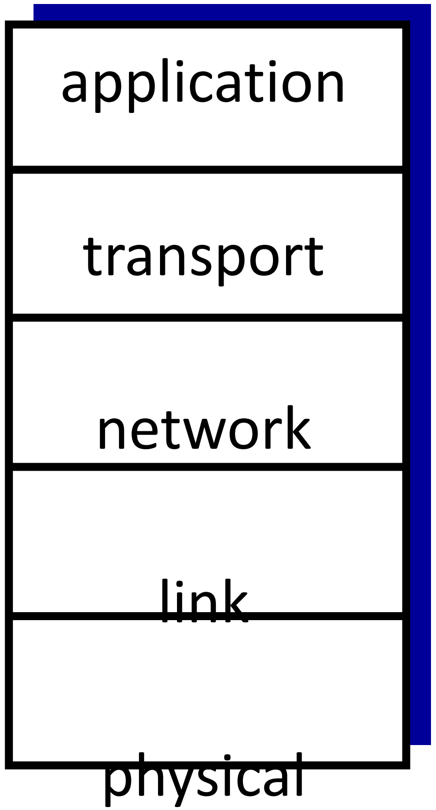
Why layering?

dealing with complex systems:

- explicit structure allows identification, relationship of complex 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
- layering considered harmful?
- layering in other complex systems?

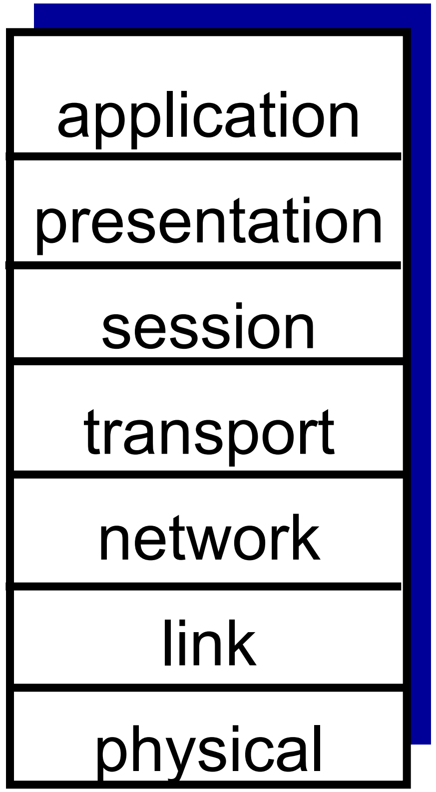
Internet Protocol Stack

- *application:* supporting network applications (access to network resources)
  - IMAP, SMTP, HTTP
- *transport:* process-process data transfer (segmentation & reassembly, sockets, connection, flow and error control)
  - TCP, UDP
- *network:* routing of datagrams from source to destination (addressing, routing)
  - IP, routing protocols
- *link:* data transfer between neighboring network elements (framing, addressing, flow & error control)
  - Ethernet, 802.11 (WiFi), PPP
- *physical:* bits "on the wire"



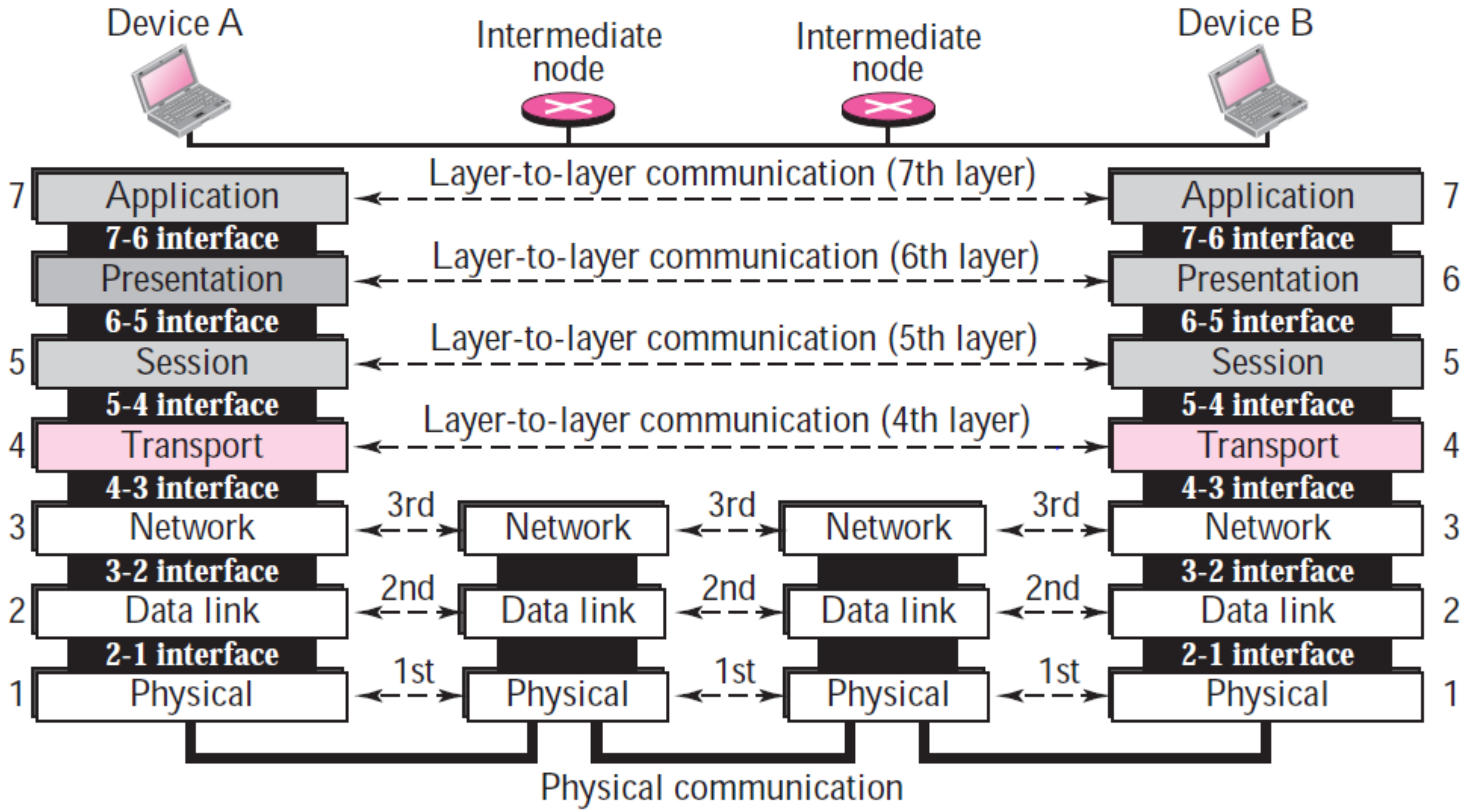
OSI reference model

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



Open **S**ystems **I**nterconnection (OSI) model – introduced in late 1970s by ISO.

OSI reference model (more)

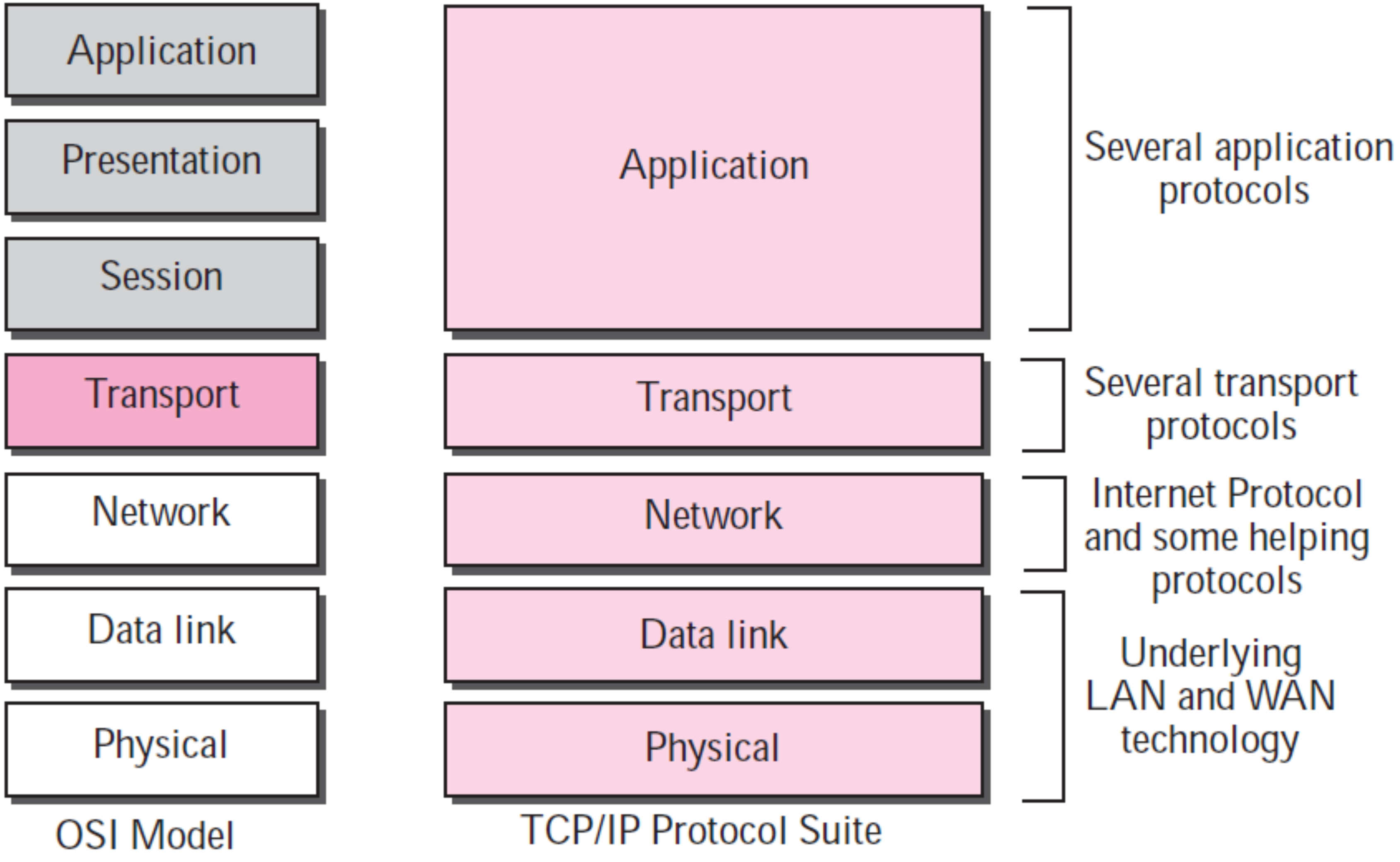


User support layers

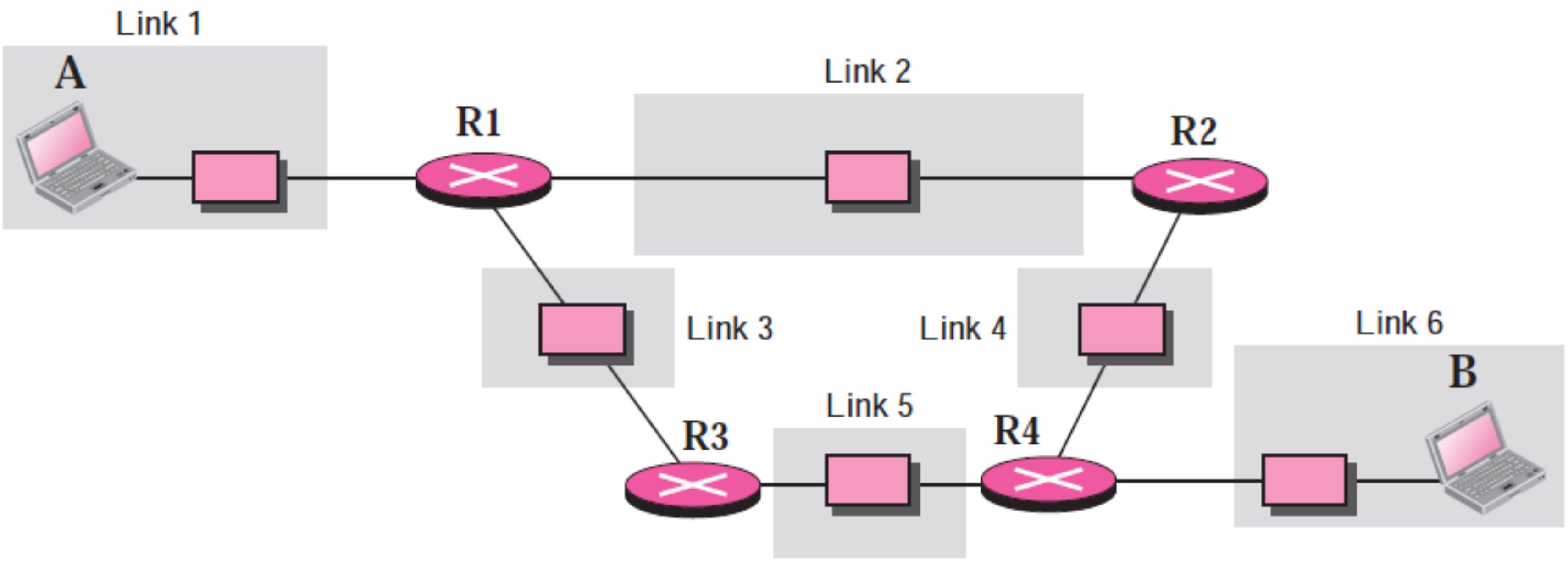
Heart

Network support layers

TCP/IP vs OSI reference model

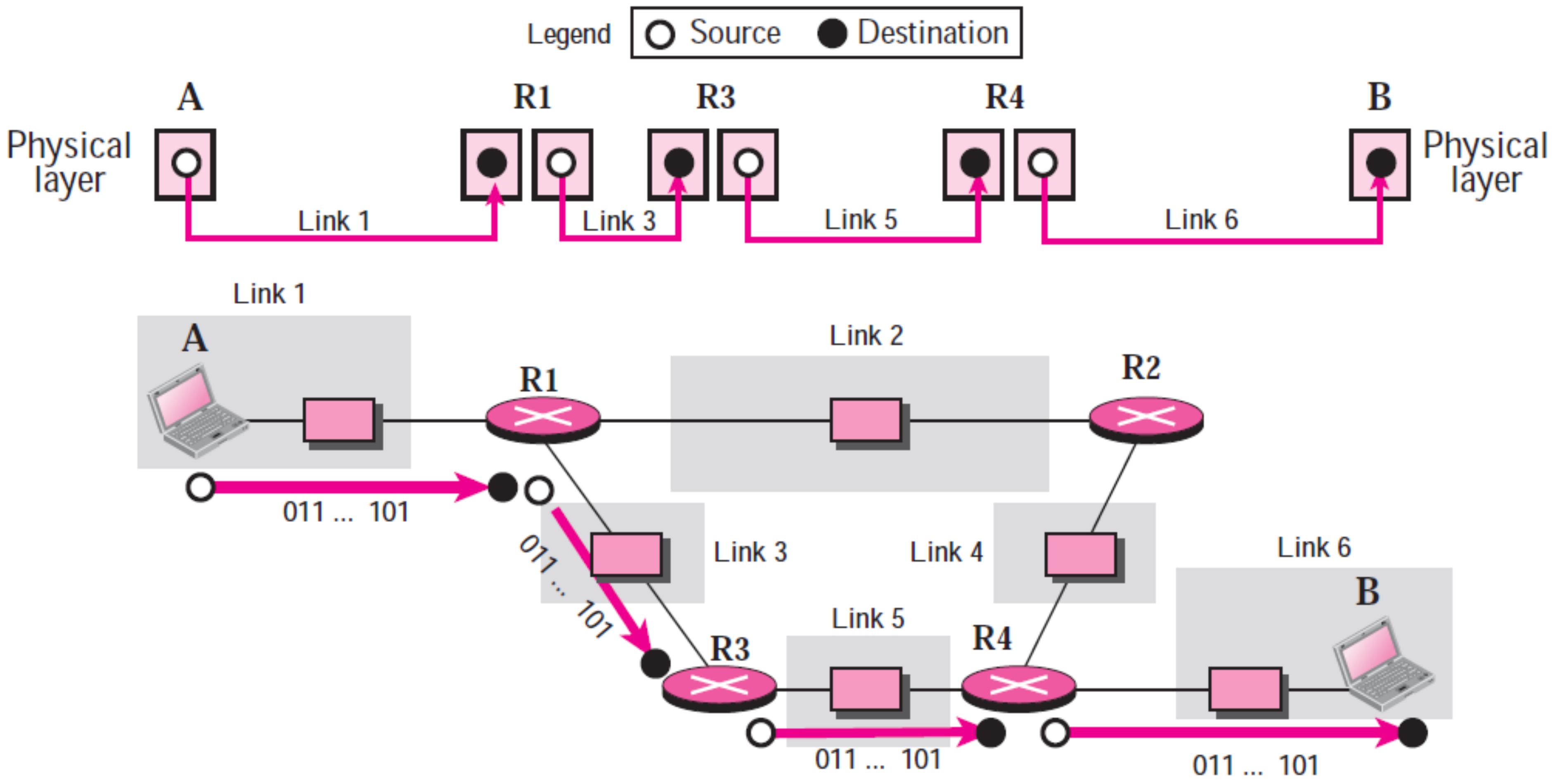


Layers in the TCP/IP Protocol Suite (more)



A private internet

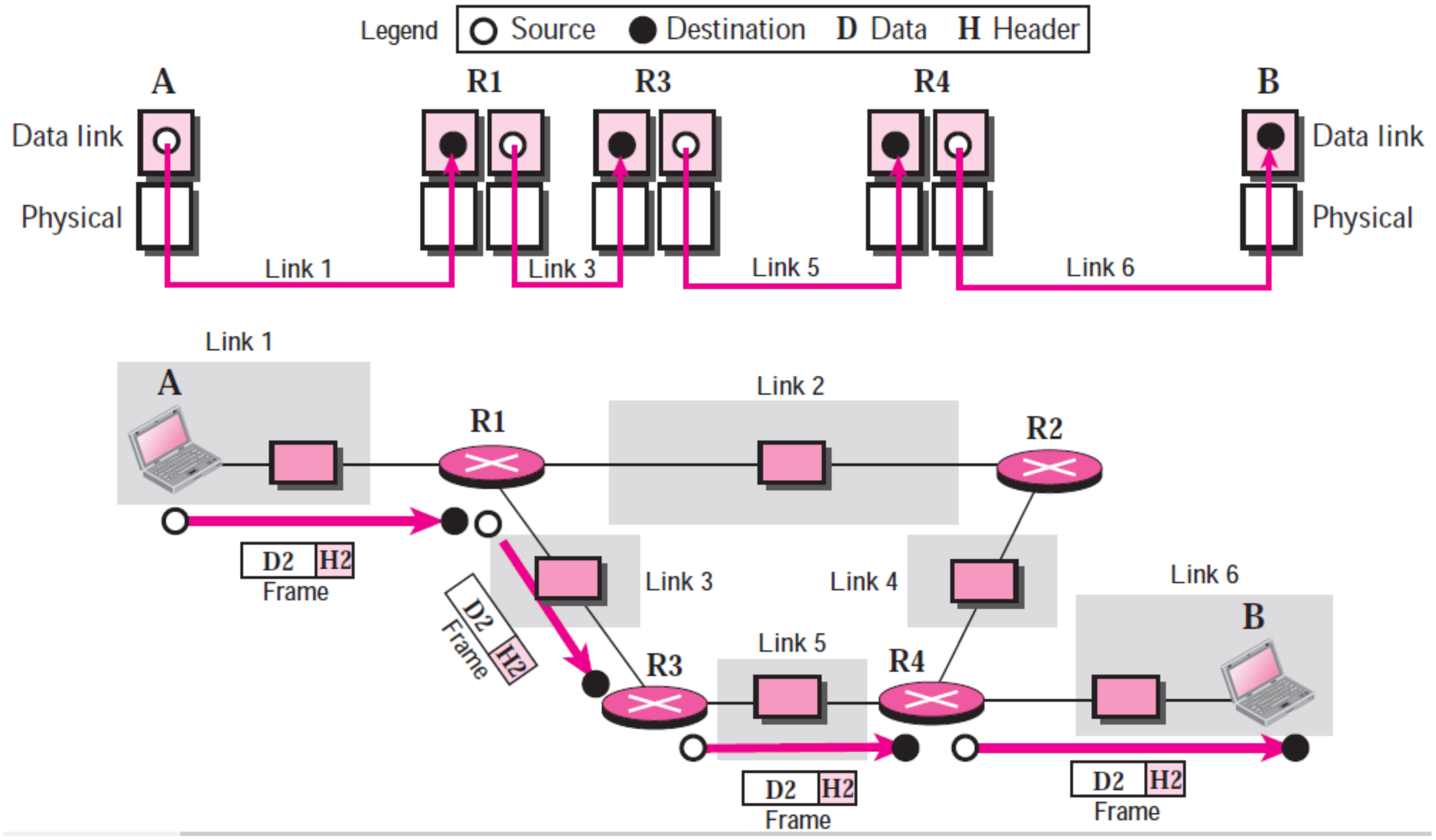
Layers in the TCP/IP Protocol Suite (more)



Communication at the physical layer

Unit of Communication – bit

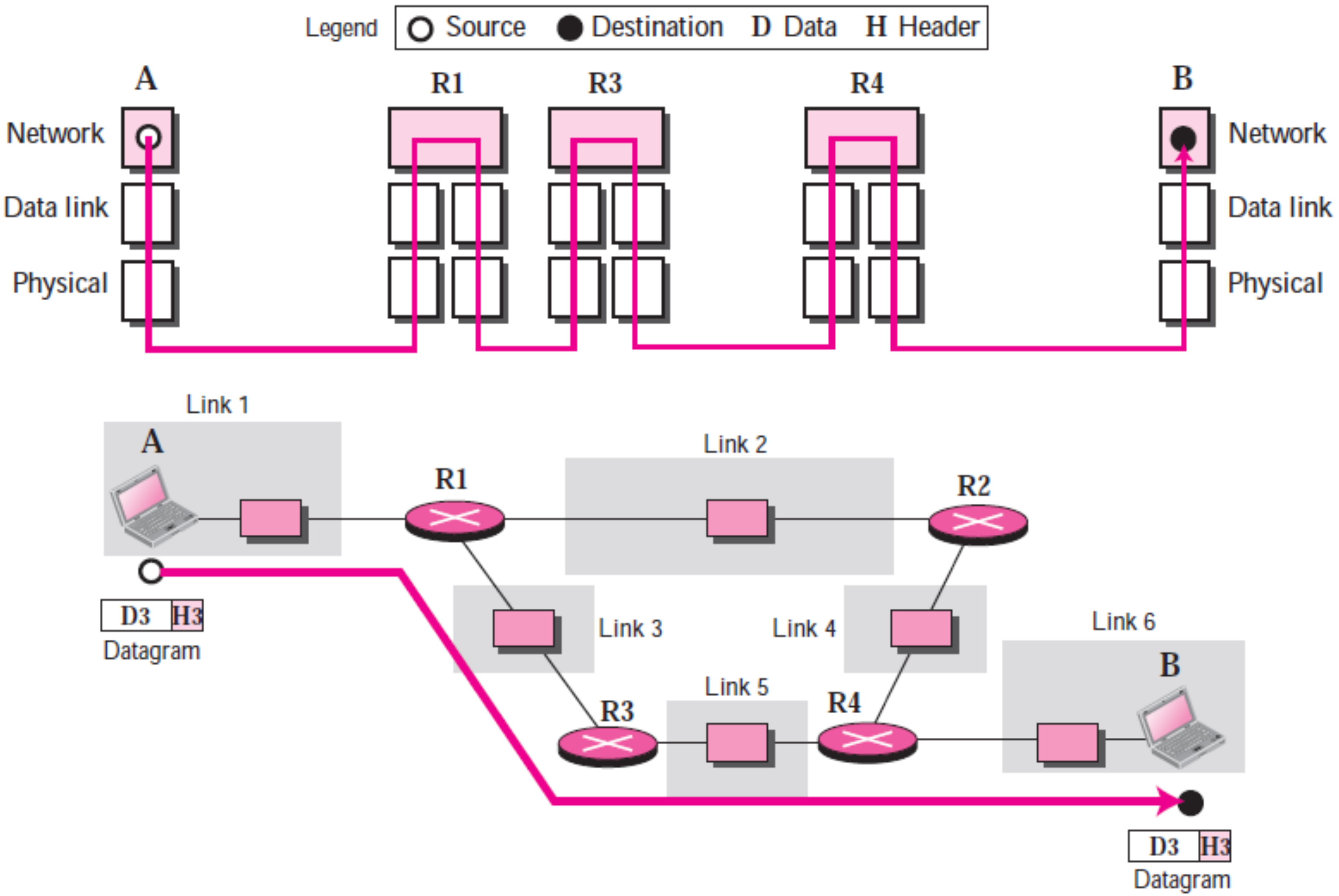
Layers in the TCP/IP Protocol Suite (more)



Communication at the data link layer

Unit of Communication – frame

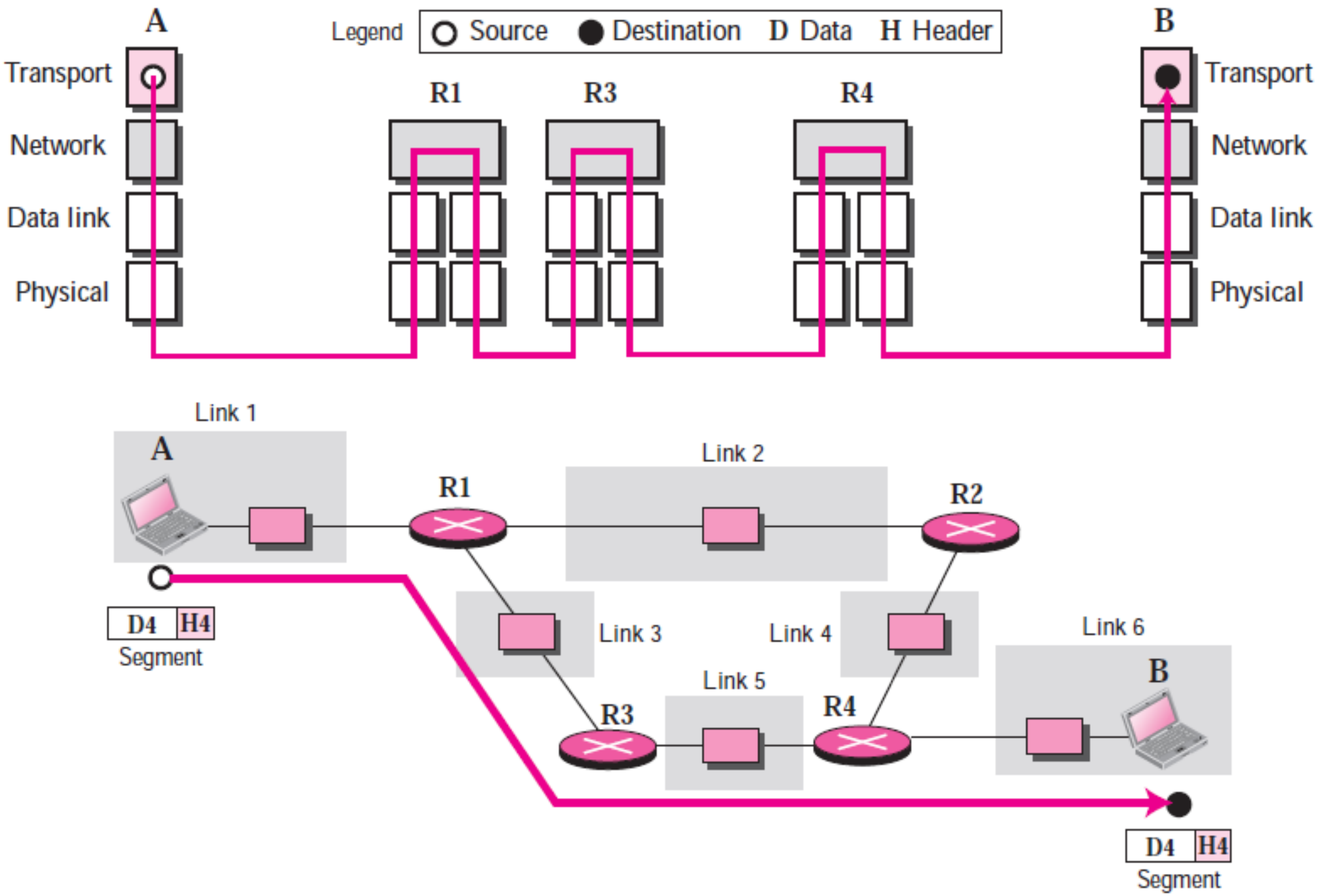
Layers in the TCP/IP Protocol Suite (more)



Communication at the network layer

Unit of Communication – datagram

Layers in the TCP/IP Protocol Suite (more)

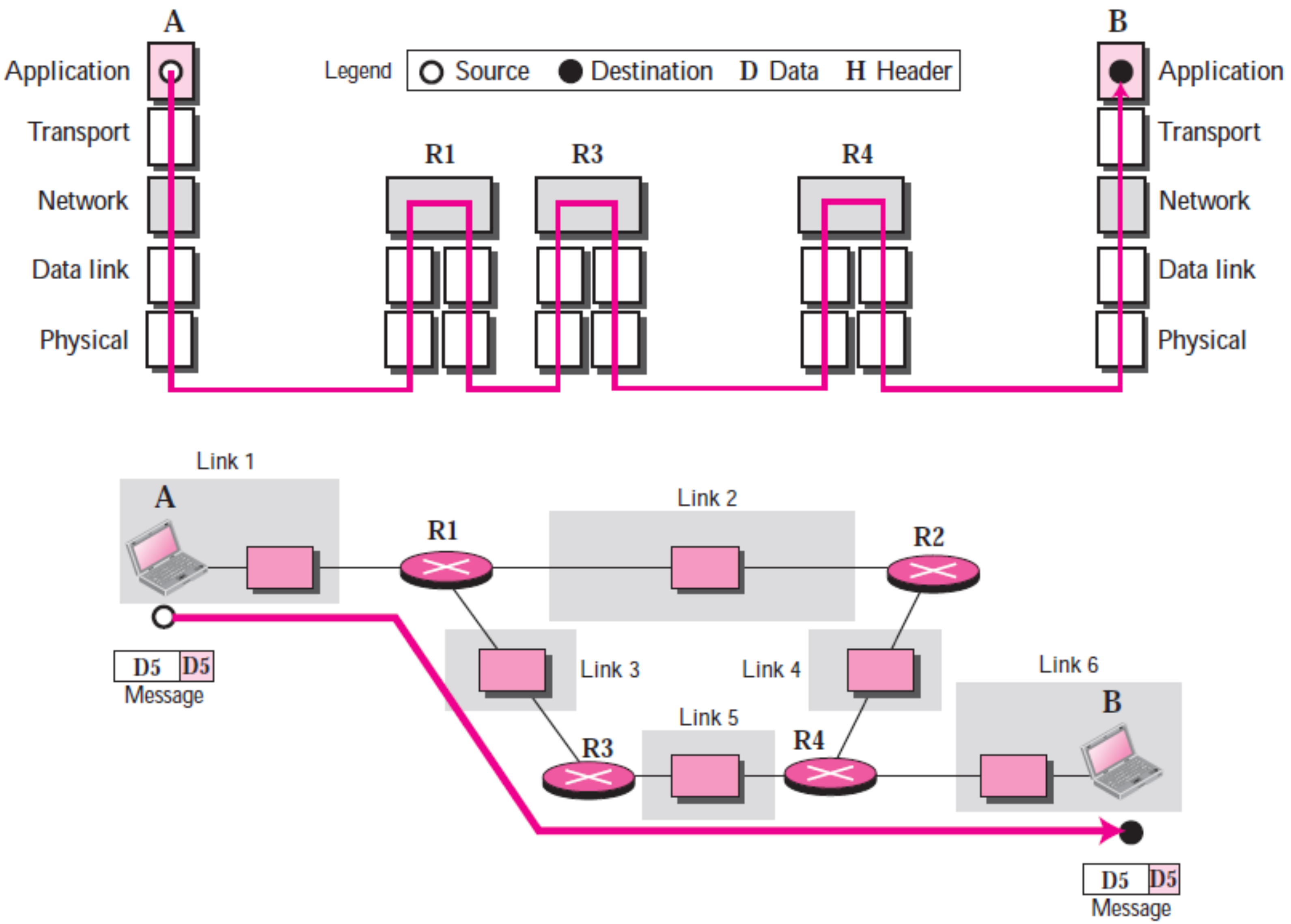


Communication at the transport layer

Unit of Communication – segment/packet

COMPUTER NETWORKS

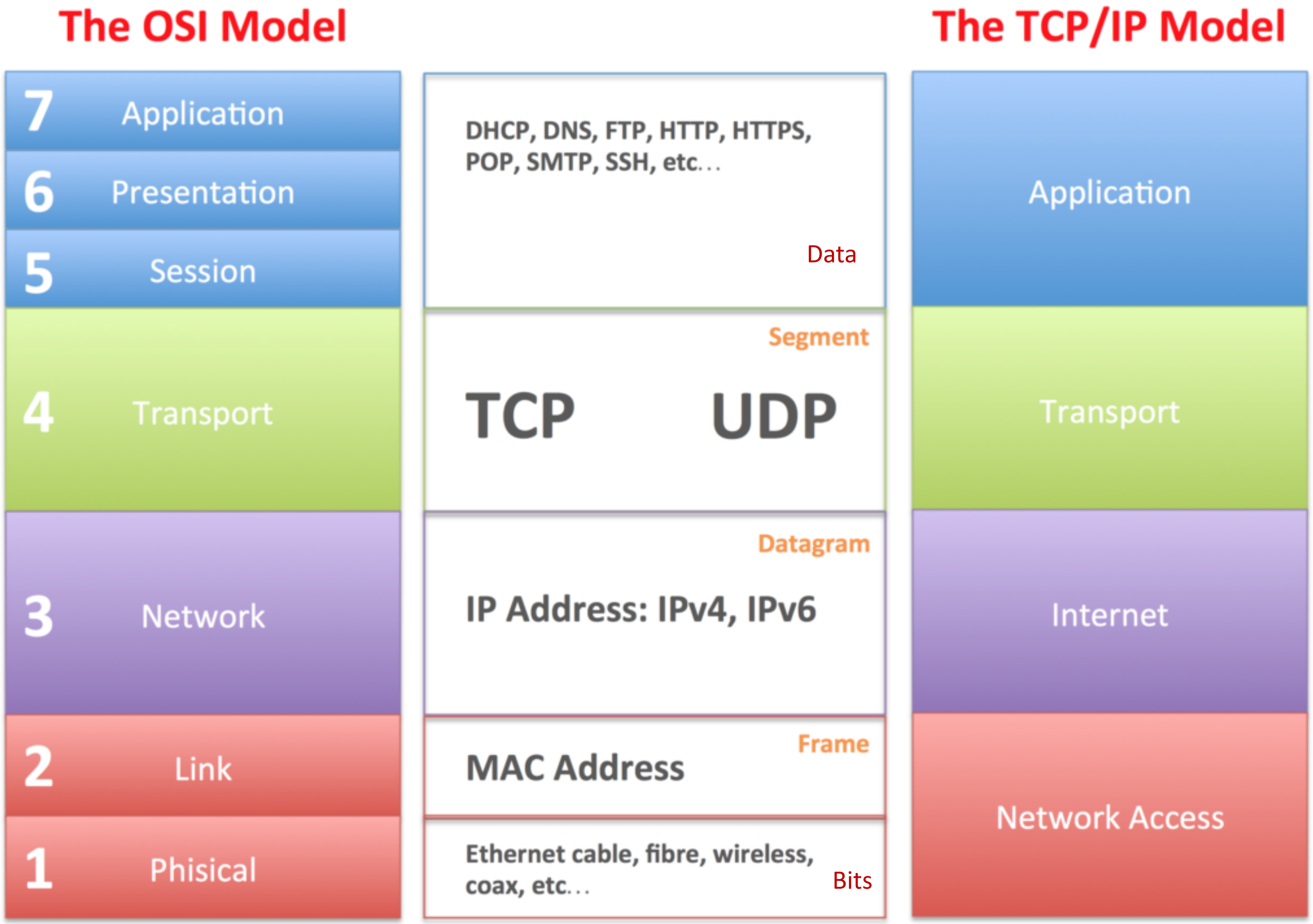
Layers in the TCP/IP Protocol Suite (more)



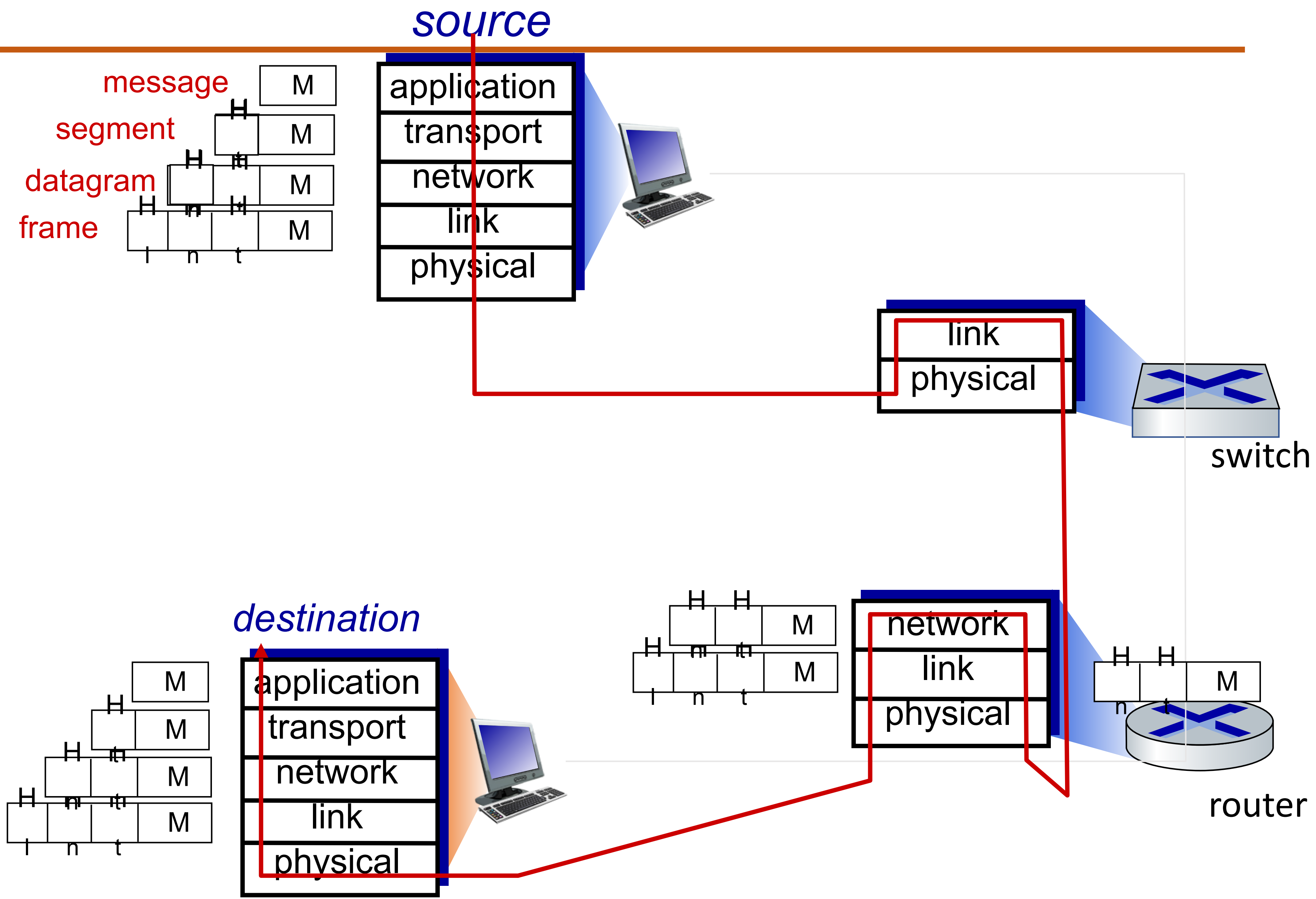
Communication at the application layer

Unit of Communication – message

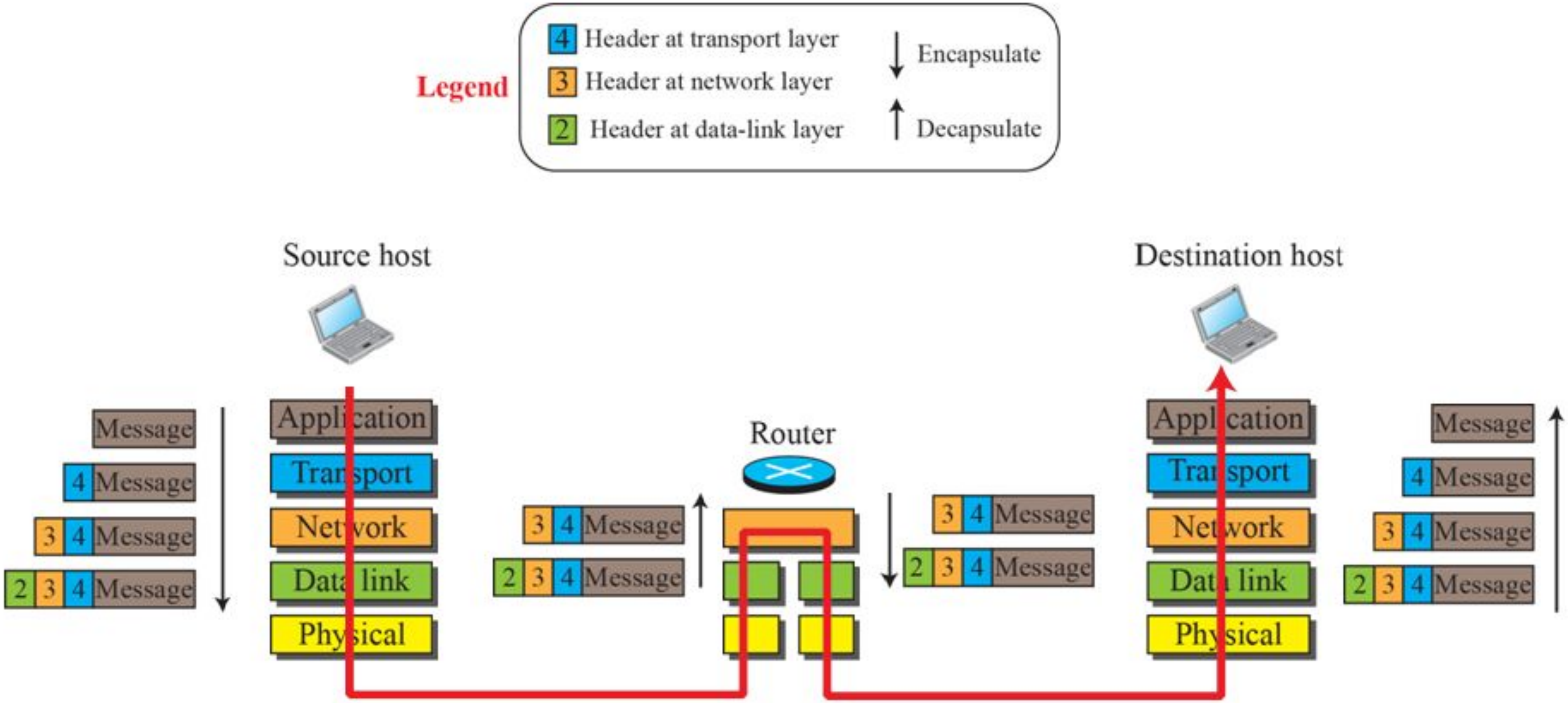
OSI vs TCP/IP Protocol Suite



Encapsulation – Data Communication in Protocol Stack



Encapsulation & Decapsulation



Computer Networks and the Internet

Interactive Exercises

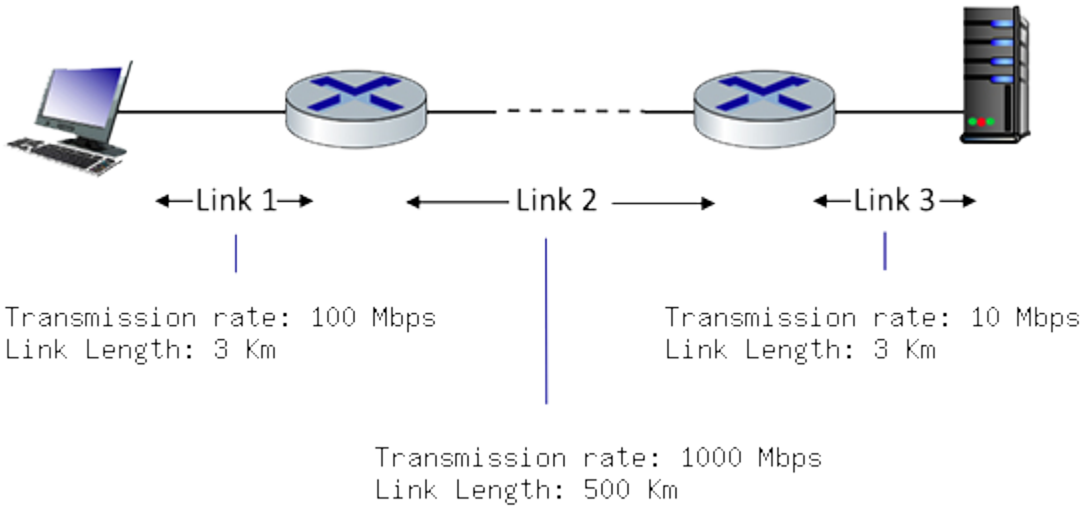
Team Networks

Department of Computer Science and Engineering

Interactive Exercise – 1

Computing end-end delay (transmission and propagation delay)

Consider the figure below, with three links, each with the specified transmission rate and link length.



Find the end-to-end delay (including the transmission delays and propagation delays on each of the three links, but ignoring queueing delays and processing delays) from when the left host begins transmitting the first bit of a packet to the time when the last bit of that packet is received at the server at the right.

The speed of light propagation delay on each link is 3x10**8 m/sec.

Note that the transmission rates are in Mbps and the link distances are in Km.

Assume a packet length of 8000 bits. Give your answer in milliseconds.

Interactive Exercise – 2 (Solution)

Link 1 transmission delay = L/R = 8000 bits / 100 Mbps =

Link 1 propagation delay = d/s = 3 Km / 3*10**8 m/sec =

Link 1 total delay =

Link 2 transmission delay = L/R = 8000 bits / 1000 Mbps =

Link 2 propagation delay = d/s = 500 Km / 3*10**8 m/sec =

Link 2 total delay =

Link 3 transmission delay = L/R = 8000 bits / 10 Mbps =

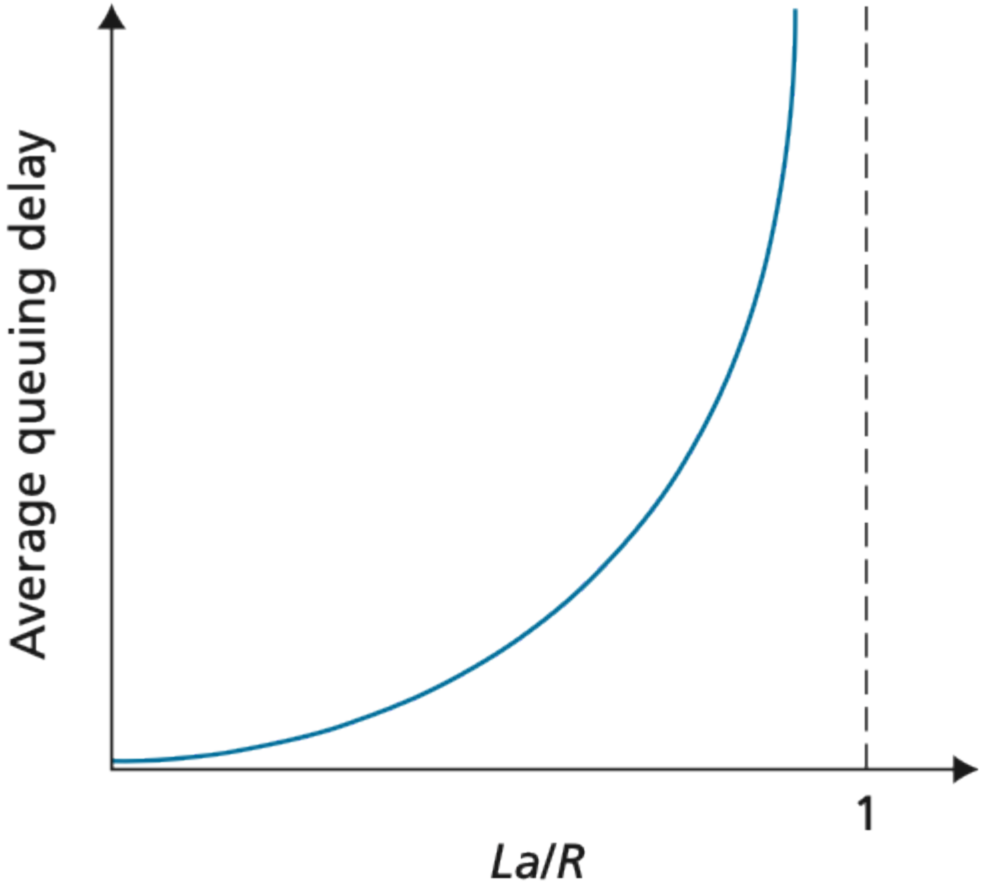
Link 3 propagation delay = d/s = 3 Km / 3*10**8 m/sec =

Link 3 total delay =

Total end-to-end delay is the sum of these six delays: 0.0026 **msecs**.

Computing Queuing Delay

Consider the queuing delay in a router buffer.



Assume:

a constant transmission rate of

R = 1800000 bps,

a constant packet-length L = 6700 bits, and

a is the average rate of packets/second.

Traffic intensity I = La/R, and

Queuing delay is calculated as:

I(L/R)(1 - I) for I < 1.

Interactive Exercise – 2 (Questions)

1. In practice, does the queuing delay tend to vary a lot? Answer with Yes or No

2. Assuming that a = 30, what is the queuing delay?

3. Assuming that a = 76, what is the queuing delay?

4. Assuming the router's buffer is infinite, the queuing delay is 0.8647 ms, and 1762 packets arrive. How many packets will be in the buffer 1 second later?

5. If the buffer has a maximum size of 956 packets, how many of the packets would be dropped upon arrival from the previous question?

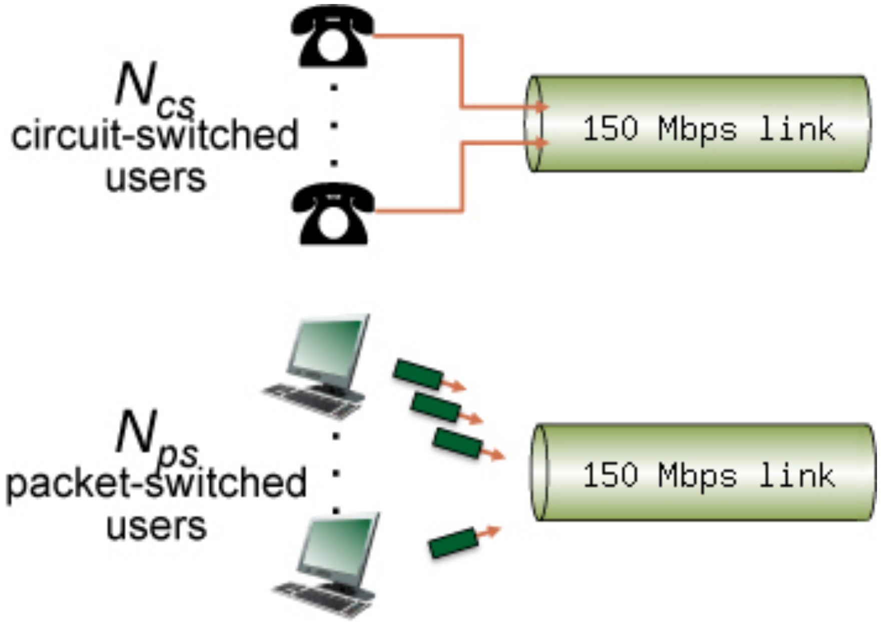
Interactive Exercise – 2 (Solutions)

1. Yes, in practice, queuing delay can vary significantly. We use the above formulas as a way to give a rough estimate, but in a real-life scenario it is much more complicated.
2. Queuing Delay = I(L/R)(1 - I) * 1000 = 0.1217*(7300/1800000)*(1-0.1217) * 1000 = 0.4335 ms.
3. Queuing Delay = I(L/R)(1 - I) * 1000 = 0.3082*(7300/1800000)*(1-0.3082) * 1000 = 0.8647 ms.
4. Packets left in buffer = a - floor(1000/delay) = 1762 - floor(1000/0.8647) = 606 packets.
5. Packets dropped = packets - buffer size = 1762 - 956 = 806 dropped packets.

Quantitative Comparison of Packet Switching and Circuit Switching

Consider the two scenarios below:

- A circuit-switching scenario in which N_{cs} users, each requiring a bandwidth of 10 Mbps, must share a link of capacity 150 Mbps.
- A packet-switching scenario with N_{ps} users sharing a 150 Mbps link, where each user again requires 10 Mbps when transmitting, but only needs to transmit 30 percent of the time.



Round your answer to two decimals after leading zeros

Interactive Exercise – 3 (Questions)

Answer the following questions:

1. When circuit switching is used, what is the maximum number of circuit-switched users that can be supported? Explain your answer.
2. For rest of the questions, suppose packet switching is used. Suppose there are 29 packet-switching users (i.e., N_{ps} = 29). Can this many users be supported under circuit-switching? Explain.
3. What is the probability that a given (*specific*) user is transmitting, and the remaining users are not transmitting?
4. What is the probability that one user (*any* one among the 29 users) is transmitting, and the remaining users are not transmitting? When one user is transmitting, what fraction of the link capacity will be used by this user?
5. What is the probability that any 15 users (of the total 29 users) are transmitting and the remaining users are not transmitting? (Hint: you will need to use the binomial distribution [1, 2]).
6. What is the probability that *more* than 15 users are transmitting? Comment on what this implies about the number of users supportable under circuit switching and packet switching.

Interactive Exercise – 3 (more)

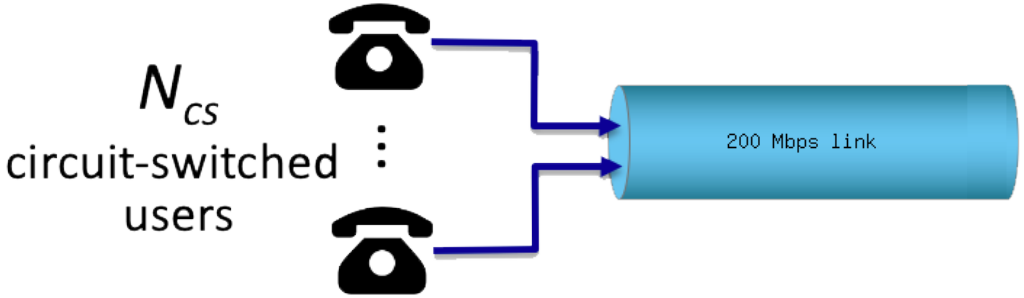
Answers:

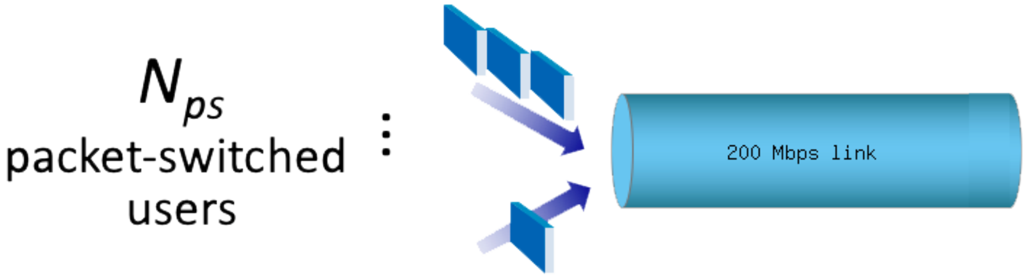
1. 15
2. No.
3. 1.37
4. 0.0004
5. 0.00754
6. 0.011653

Quantitative Comparison of Packet Switching and Circuit Switching

Consider the two scenarios below:

- A circuit-switching scenario in which N_{cs} users, each requiring a bandwidth of 25 Mbps, must share a link of capacity 200 Mbps.
- A packet-switching scenario with N_{ps} users sharing a 150 Mbps link, where each user again requires 25 Mbps when transmitting, but only needs to transmit 20 percent of the time.





Interactive Exercise – 4 (Questions)

Answer the following questions:

1. When circuit switching is used, what is the maximum number of users that can be supported?
2. Suppose packet switching is used. If there are 15 packet-switching users, can this many users be supported under circuit-switching? Yes or No.
3. Suppose packet switching is used. What is the probability that a given (specific) user is transmitting, and the remaining users are not transmitting?
4. Suppose packet switching is used. What is the probability that one user (*any* one among the 15 users) is transmitting, and the remaining users are not transmitting?
5. When one user is transmitting, what fraction of the link capacity will be used by this user? Write your answer as a decimal.
6. What is the probability that any 10 users (of the total 15 users) are transmitting and the remaining users are not transmitting?
7. What is the probability that *more* than 8 users are transmitting?

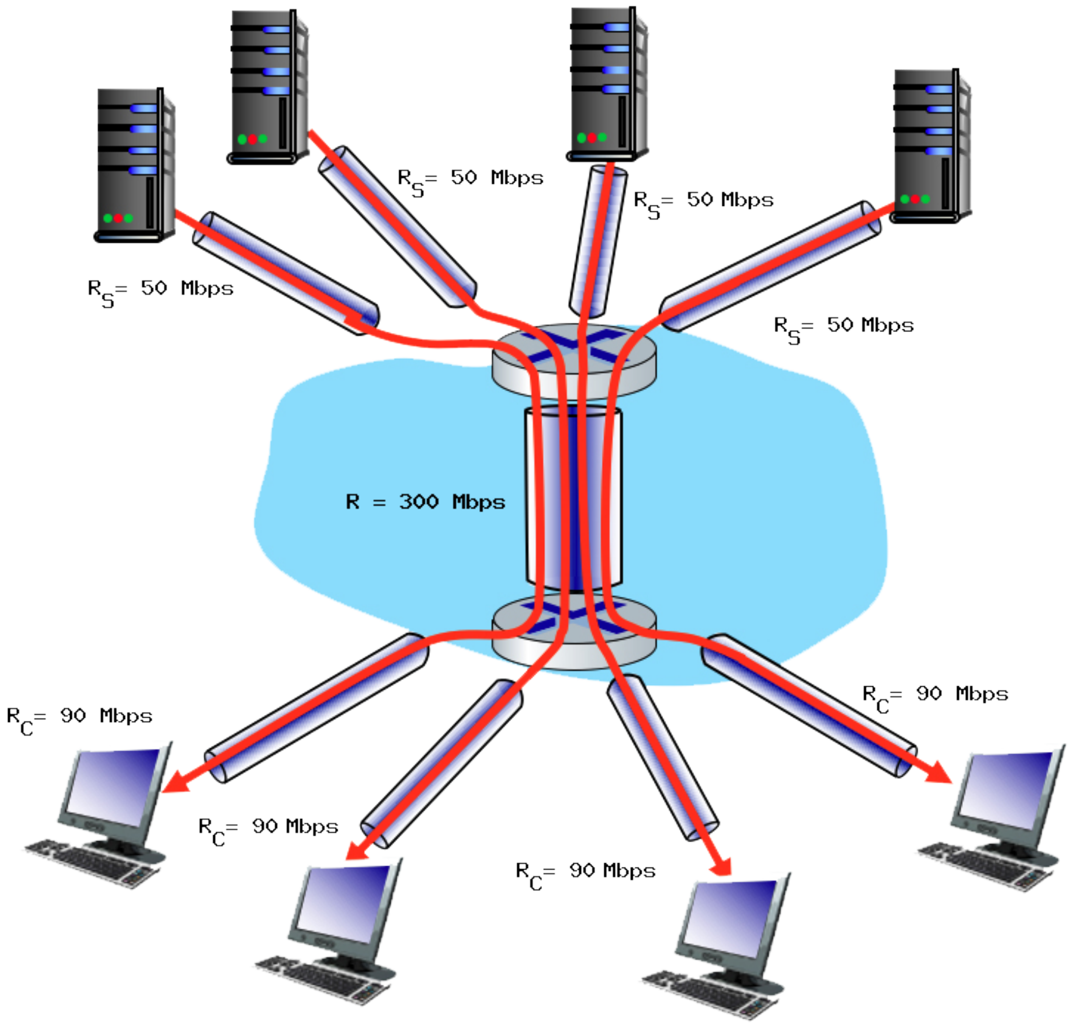
END TO END THROUGHPUT AND BOTTLENECK LINKS

Consider the scenario shown below, with four different servers connected to four different clients over four three-hop paths.

The four pairs share a common middle hop with a transmission capacity of R = 300 Mbps.

The four links from the servers to the shared link have a transmission capacity of R_S = 50 Mbps.

Each of the four links from the shared middle link to a client has a transmission capacity of R_C = 90 Mbps.



Interactive Exercise – 5 (Questions)

Answer the following questions:

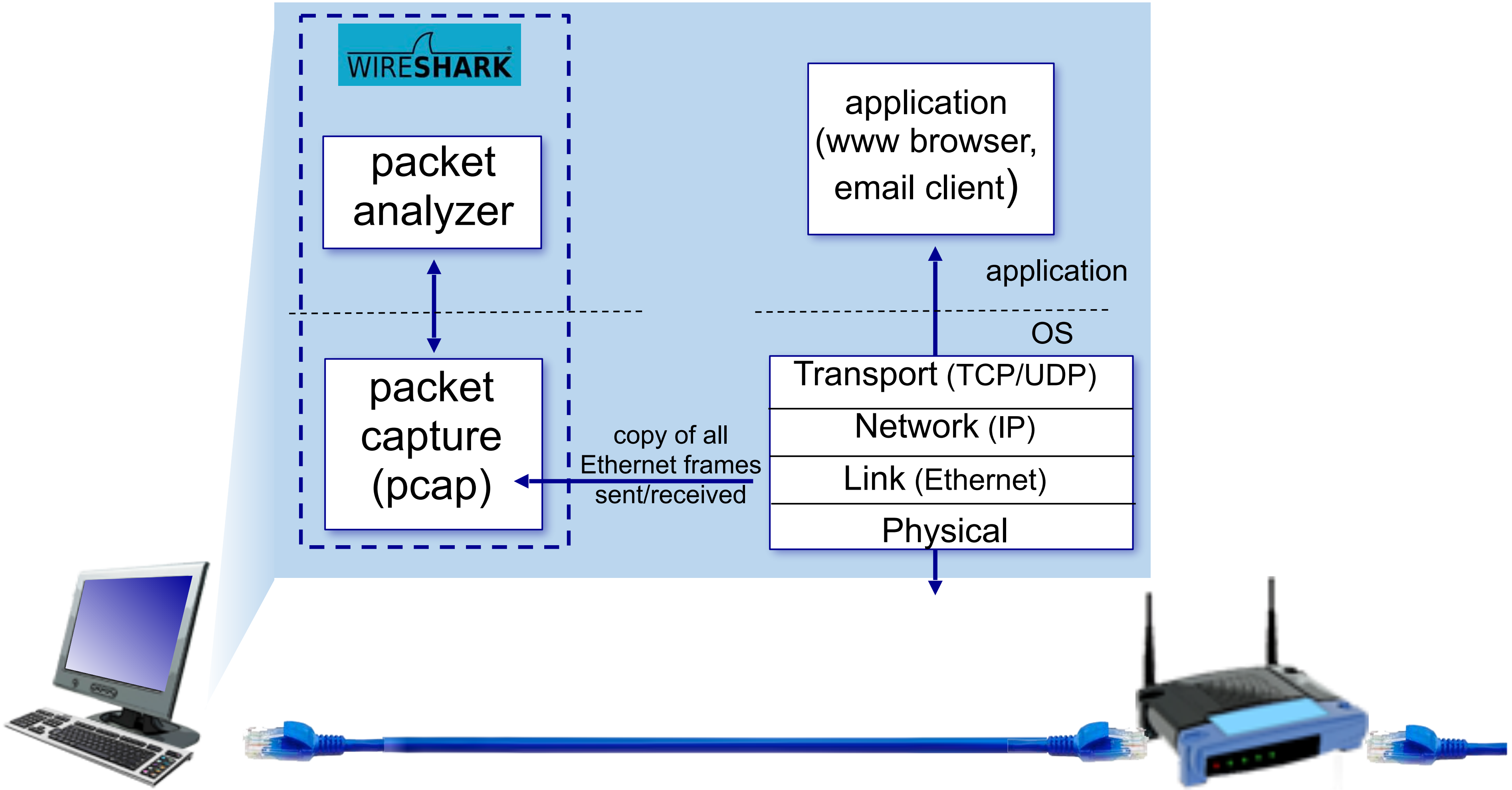
1. What is the maximum achievable end-end throughput (in Mbps) for each of four client-to-server pairs, assuming that the middle link is fairly shared (divides its transmission rate equally)?
2. Which link is the bottleneck link? Format as Rc, Rs, or R
3. Assuming that the servers are sending at the maximum rate possible, what are the link utilizations for the server links (R_S)? Answer as a decimal
4. Assuming that the servers are sending at the maximum rate possible, what are the link utilizations for the client links (R_C)? Answer as a decimal
5. Assuming that the servers are sending at the maximum rate possible, what is the link utilizations for the shared link (R)? Answer as a decimal

Interactive Exercise – 5 (Answers)

Solutions:

1. The maximum achievable end-end throughput is the capacity of the link with the minimum capacity, which is 50 Mbps
2. The bottleneck link is the link with the smallest capacity between R_S, R_C, and R/4. The bottleneck link is Rs.
3. The server's utilization = $R_{bottleneck} / R_S = 50 / 50 = 1$
4. The client's utilization = $R_{bottleneck} / R_C = 50 / 90 = 0.56$
5. The shared link's utilization = $R_{bottleneck} / (R / 4) = 50 / (300 / 4) = 0.67$

Wireshark


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

THANK YOU

Team Networks
Department of Computer Science and Engineering