COMPUTER NETWORKS

Sivaraman Eswaran Ph.D.
Department of Computer Science and Engineering

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Computer Networks and the Internet

Sivaraman Eswaran Ph.D.

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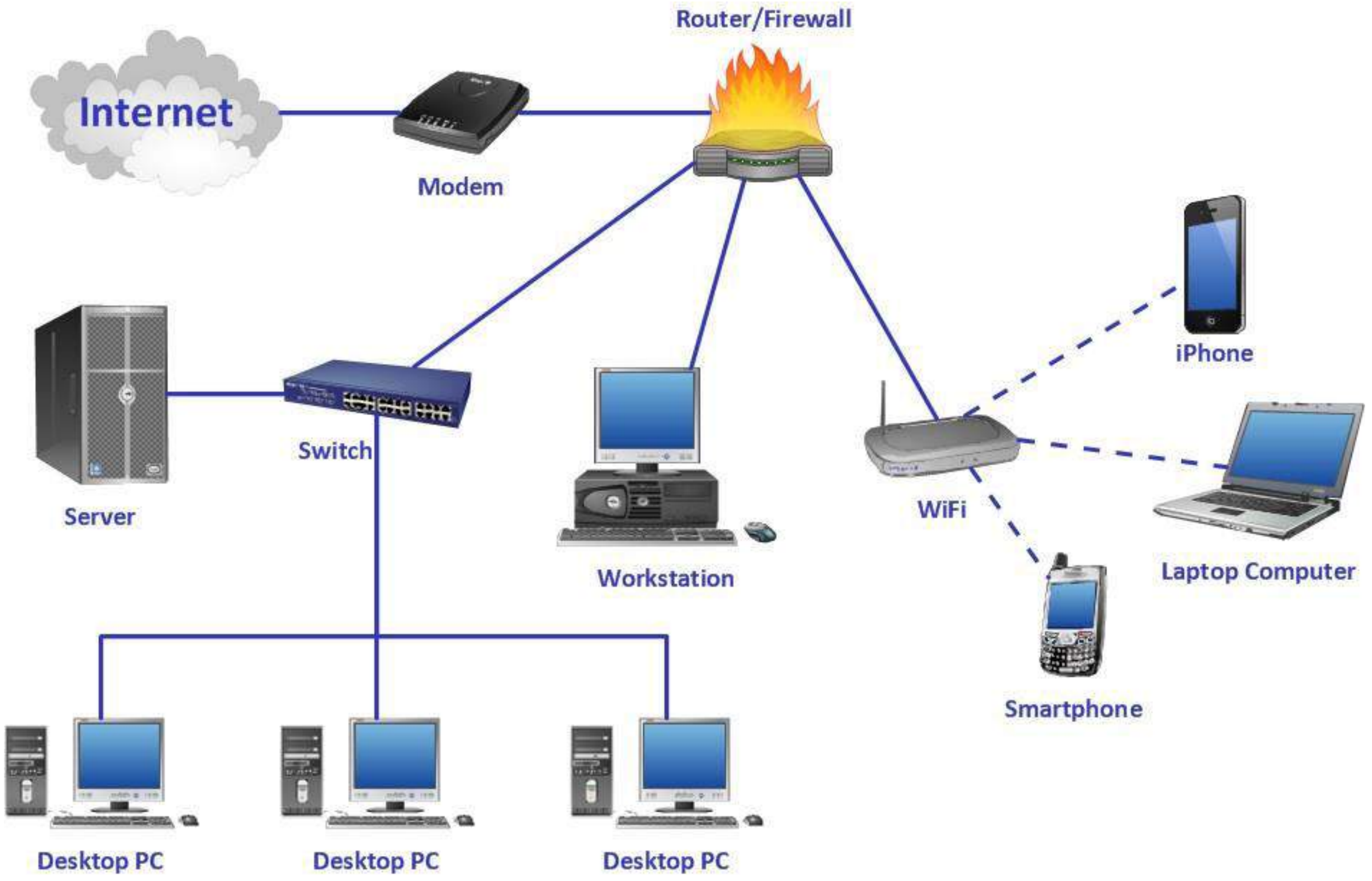


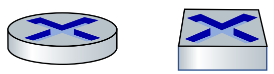
- Two or more devices connected together.
- Communicate with each other, share data or resources

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

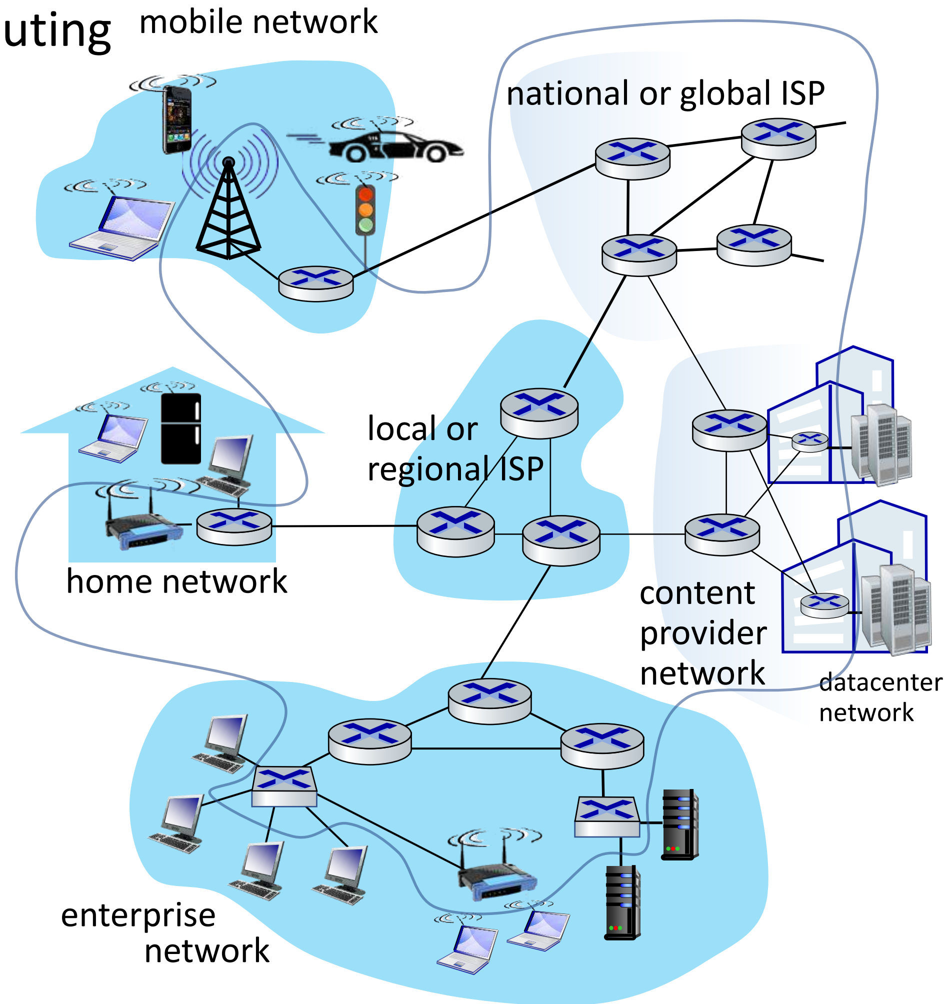
Billions of connected computing *devices*:
- *hosts = end systems*
- running *network apps* at Internet’s “edge”



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



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“Fun” Inter-connected Devices

Amazon Echo

Internet refrigerator

IP picture frame

Tweet-a-watt: monitor energy use

Web-enabled toaster + weather forecaster

Others?

Security Camera

Slingbox: remote control cable TV

There will be 41 Billion IoT devices by 2027*

AR *devices*

Internet phones

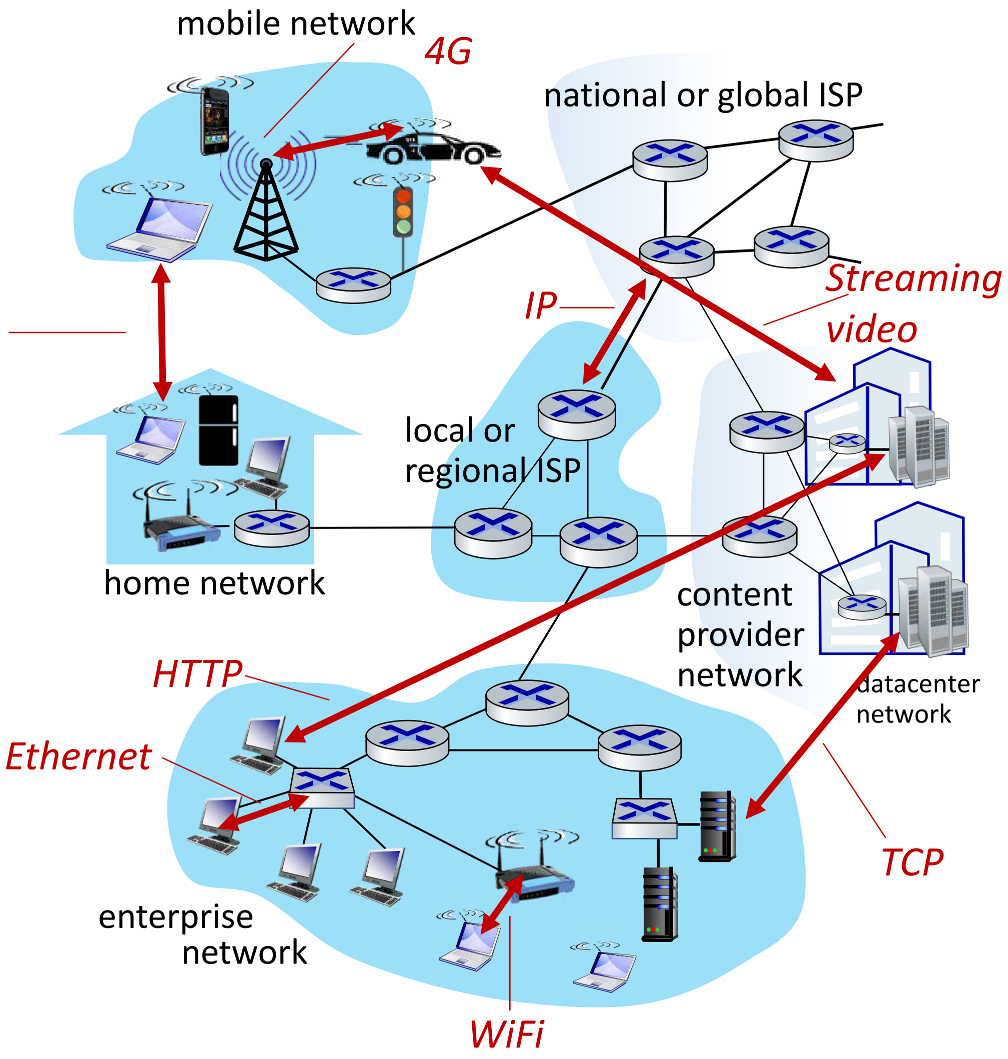
sensorized, bed mattress

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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Sivaraman Eswaran Ph.D.
Department of Computer Science and Engineering

sivaramane@pes.edu

+91 80 6666 3333 Extn 834

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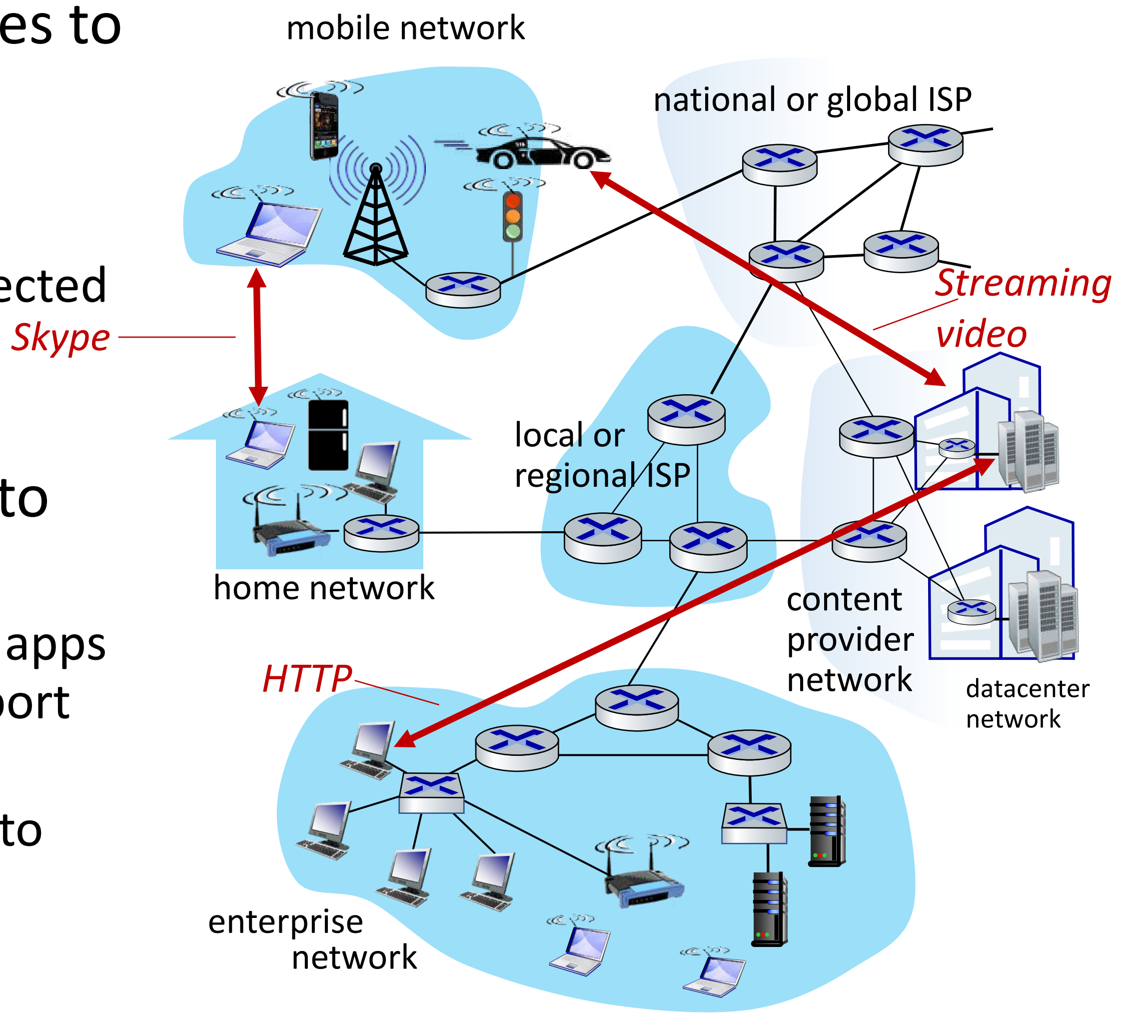
The Internet: A "Service" View

- *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?

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.

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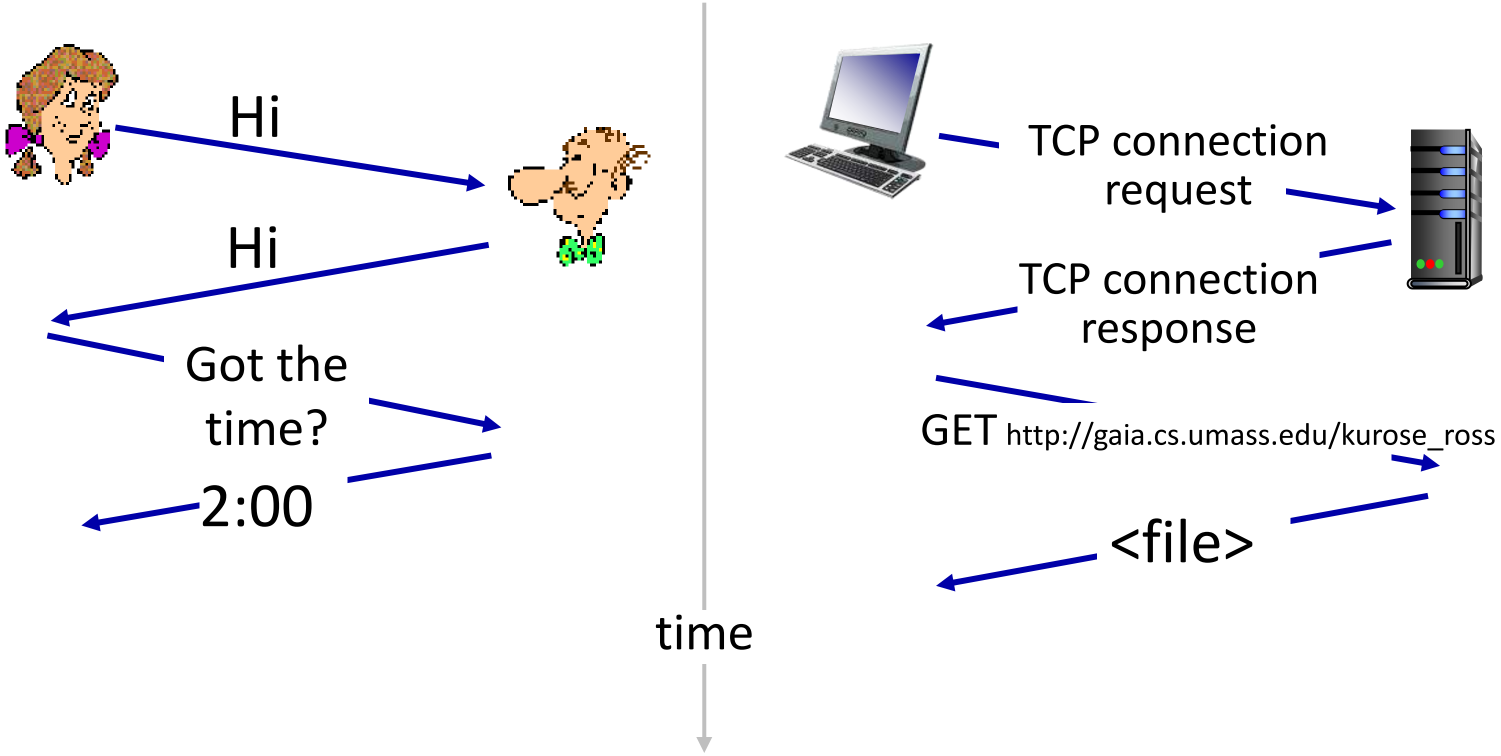
What's a Protocol?

A human protocol and a computer network protocol:



Q: other human protocols?

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sivaramane@pes.edu

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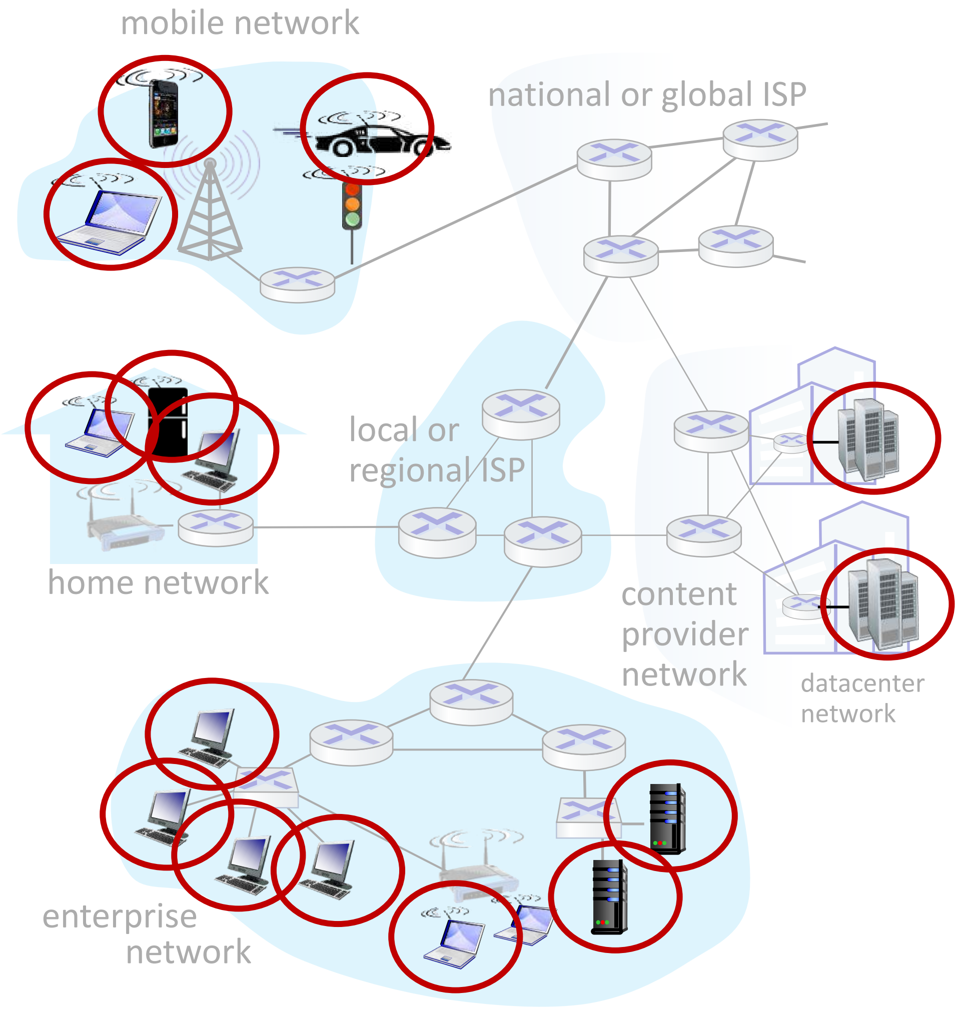
Network Edge: A closer look at network structure

Network edge:

- Hosts: clients & servers
- Servers in data centers



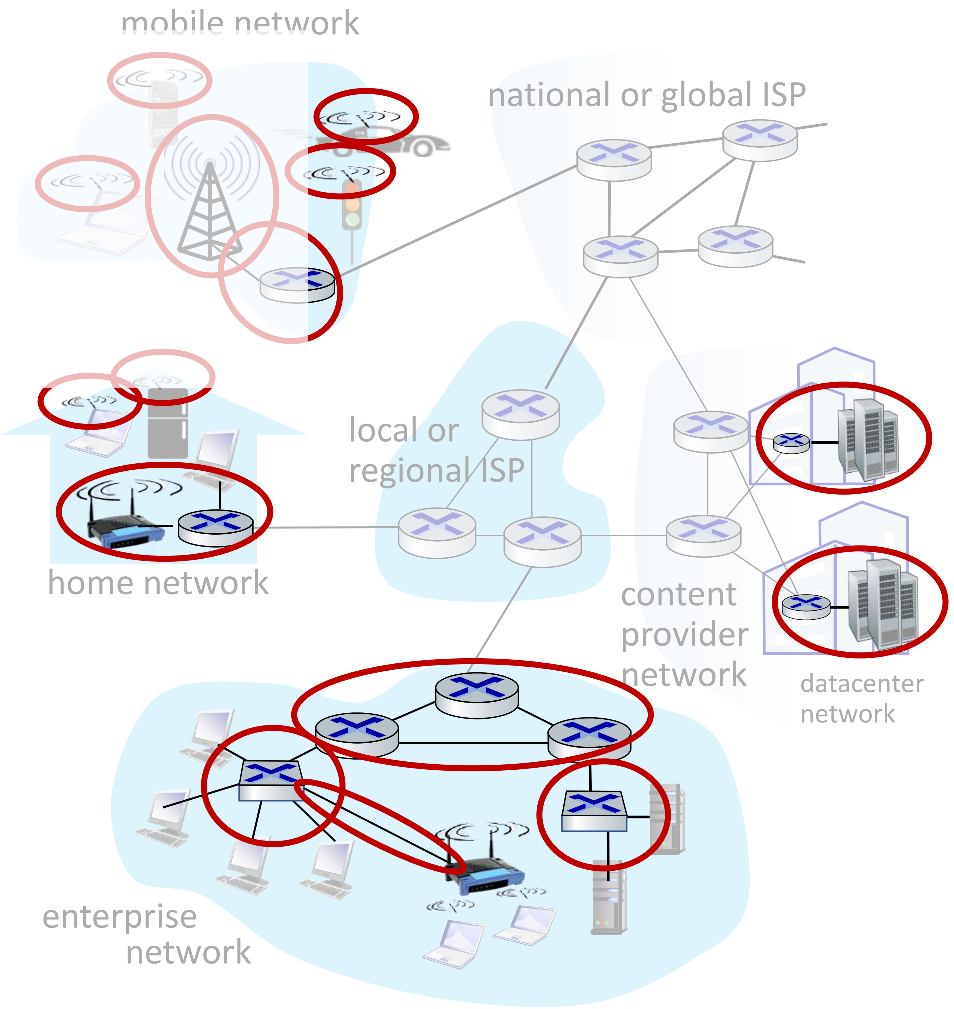
Network Edge: A closer look at network structure

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:

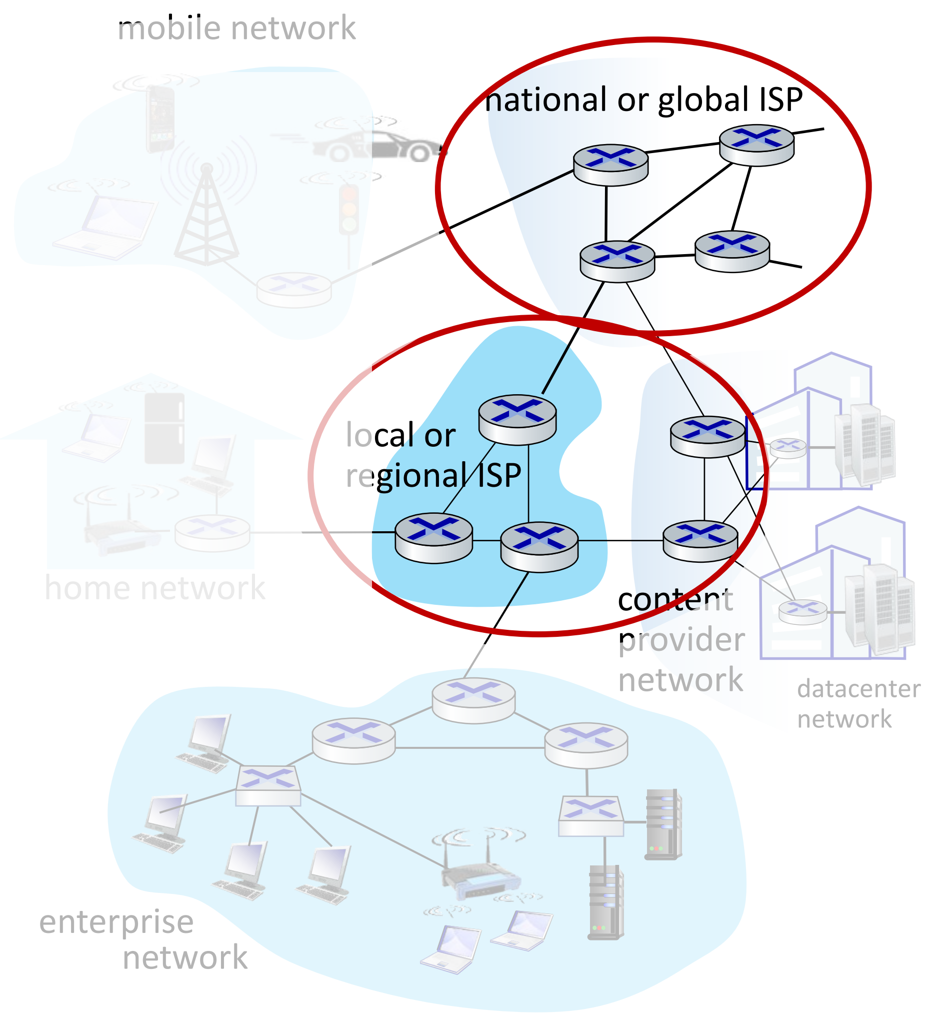
- Hosts: clients and servers
- Servers in data centers

Access networks, physical media:

- wired, wireless communication links

Network core:

- interconnected routers
- network of networks



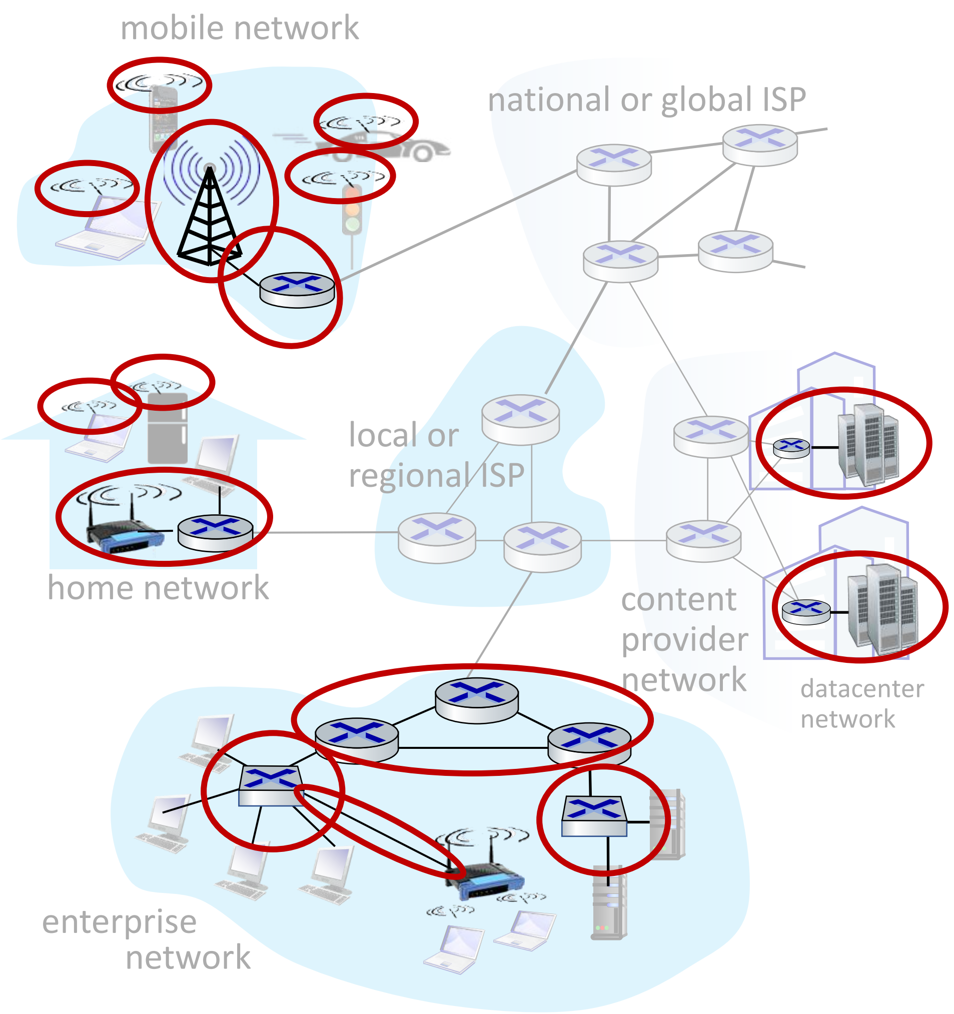
Network Edge: Access networks and Physical media

Q: How to connect end systems to edge router?

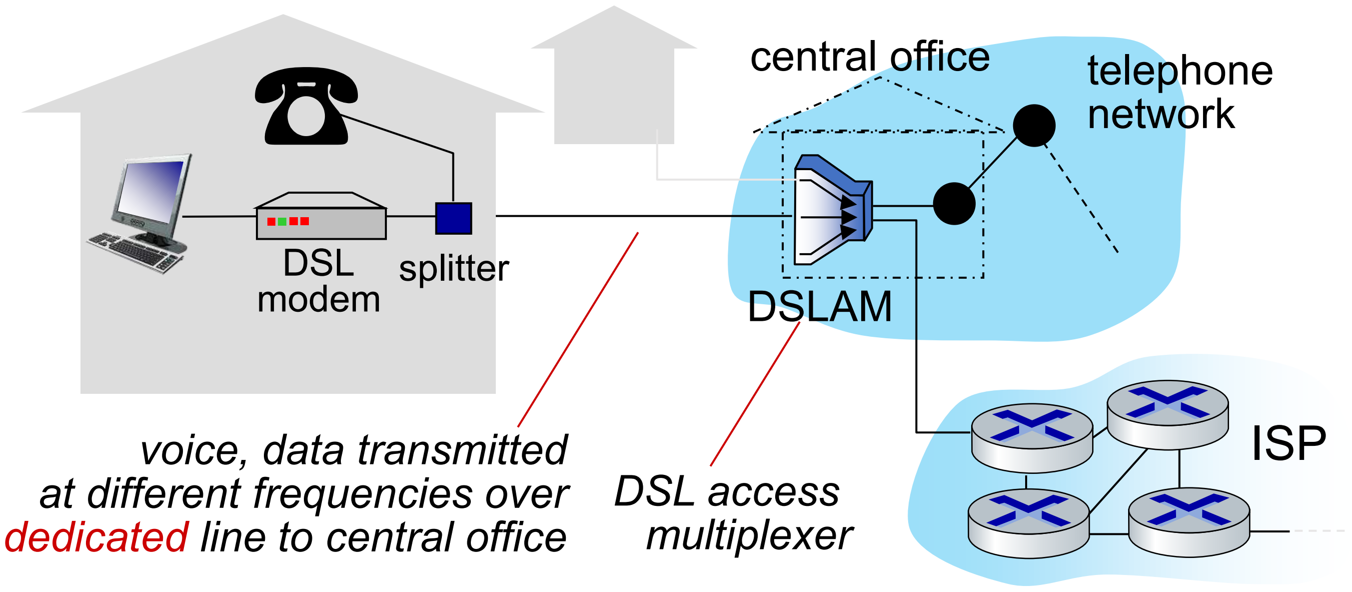
- Residential access networks
- Institutional access networks (school, company)
- Mobile access networks (WiFi, 4G/5G)

What to look for:

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



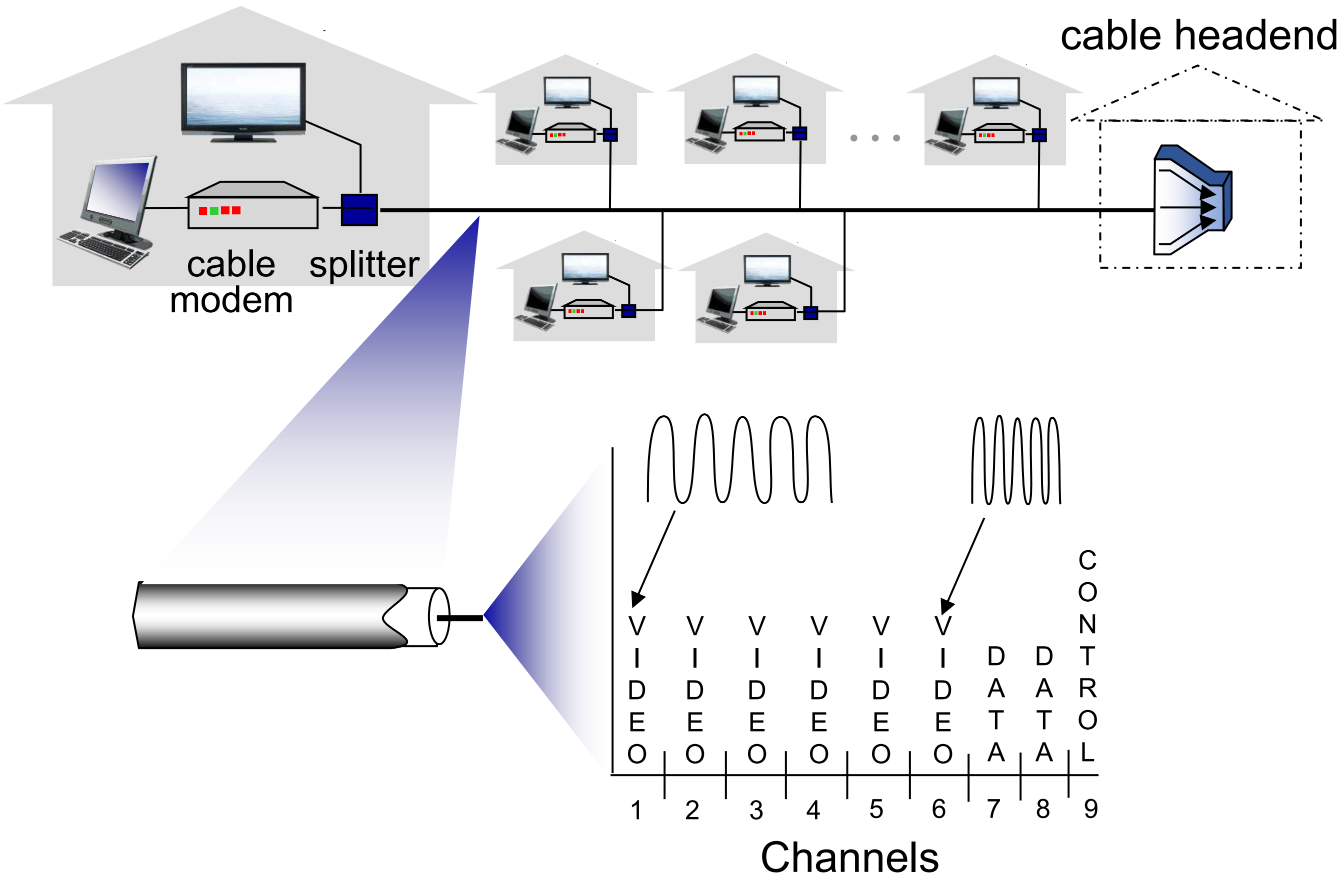
Network Edge: Access Networks - Digital Subscriber Line (DSL)



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

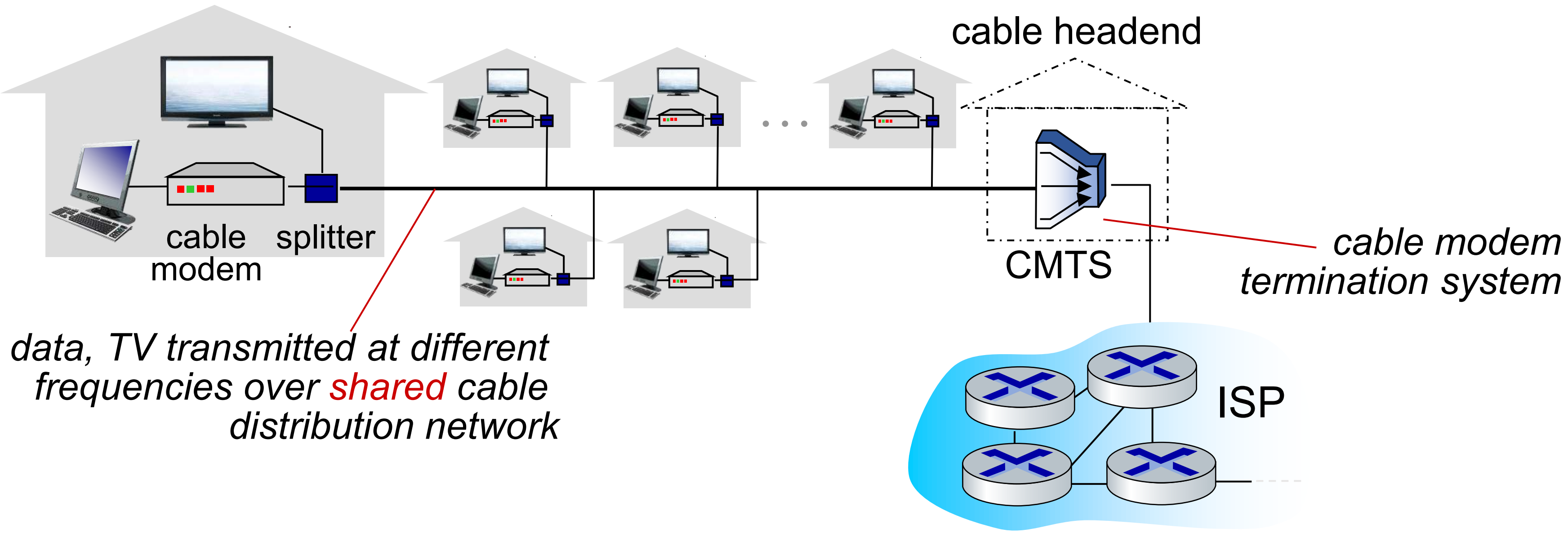
- use *existing* telephone line to central office DSLAM
  - **data** over DSL phone line goes to Internet
  - **voice** over DSL phone line goes to telephone net
- A high-speed downstream channel, in the 50 kHz to 1 MHz band
- A medium-speed upstream channel, in the 4 kHz to 50 kHz band
- An ordinary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

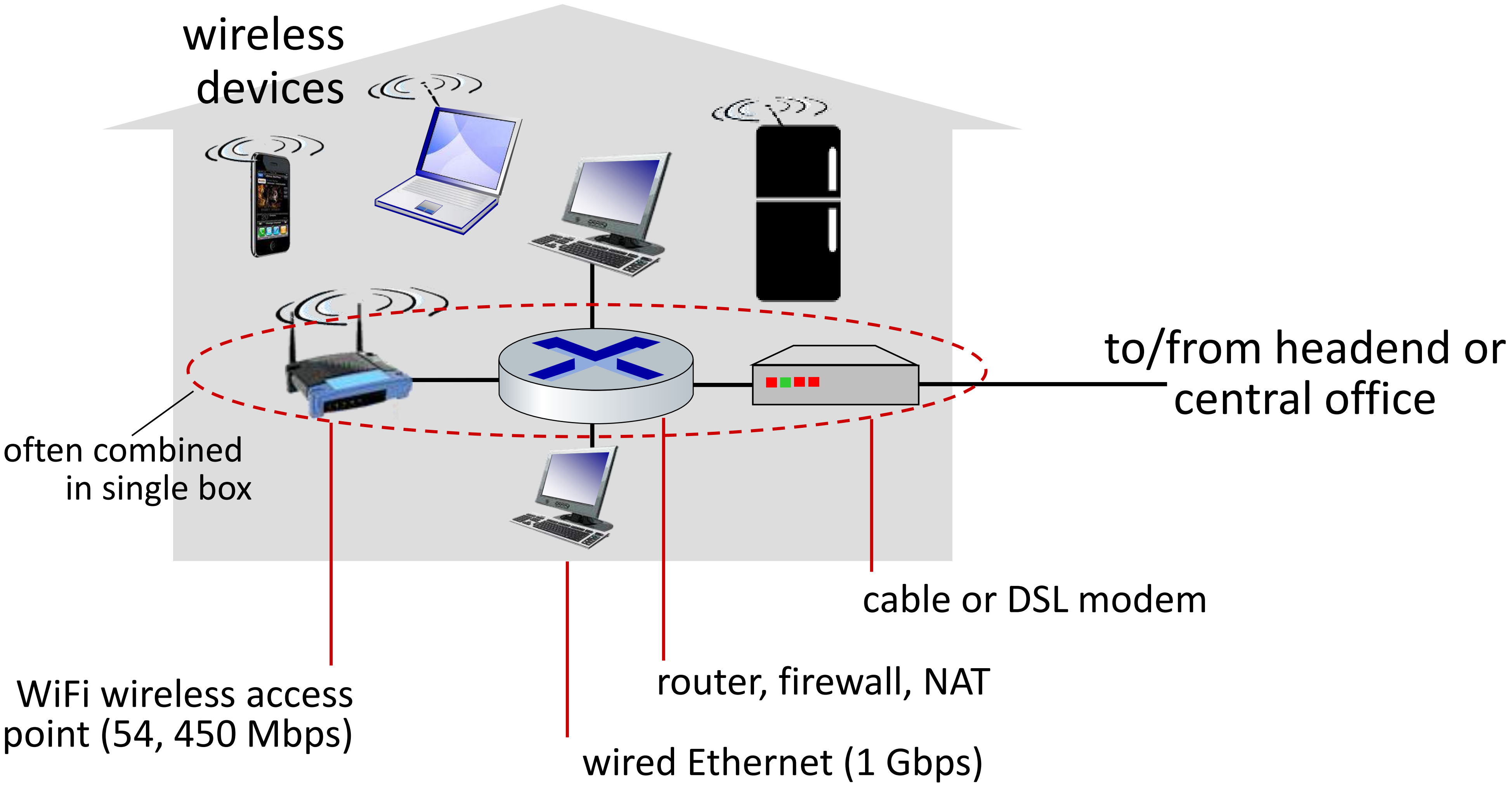


- HFC: hybrid fiber coax
  - Asymmetric:

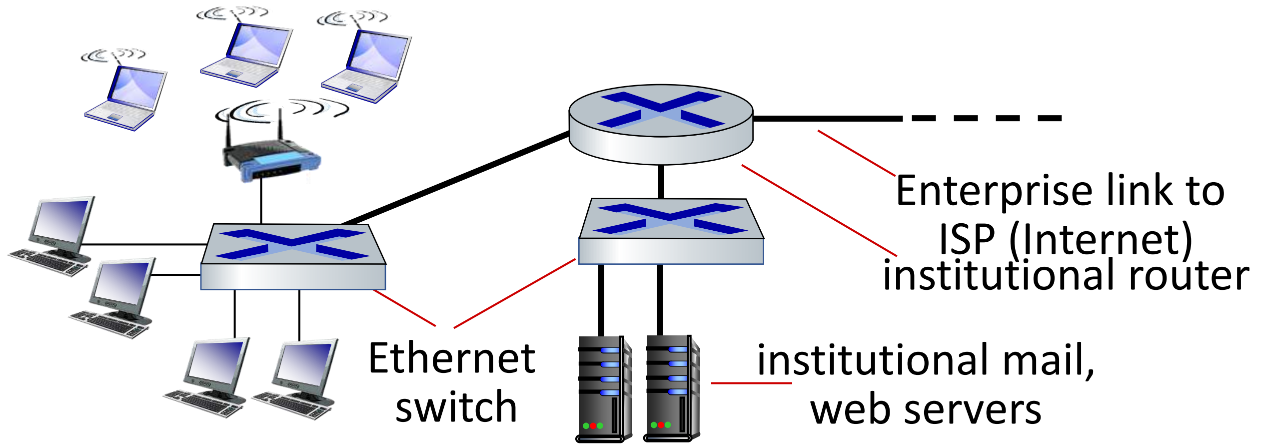
    up to 40 Mbps – 1.2 Gbs downstream transmission rate,

    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

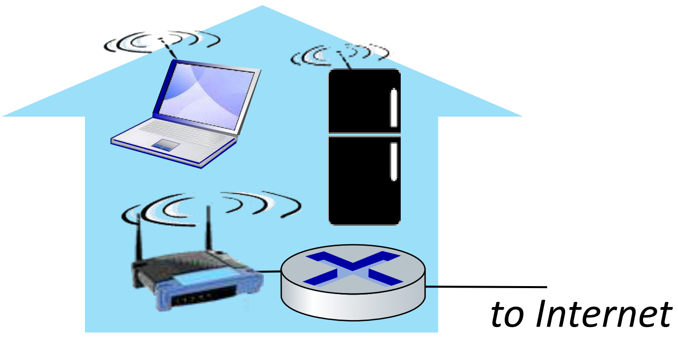
Network Edge: Wireless Access Networks

Shared *wireless* access network connects end system to router

- via base station aka "access point"

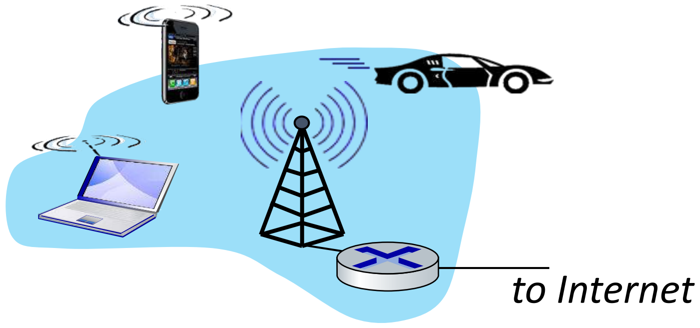
Wireless local area networks (WLANs)

- 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)



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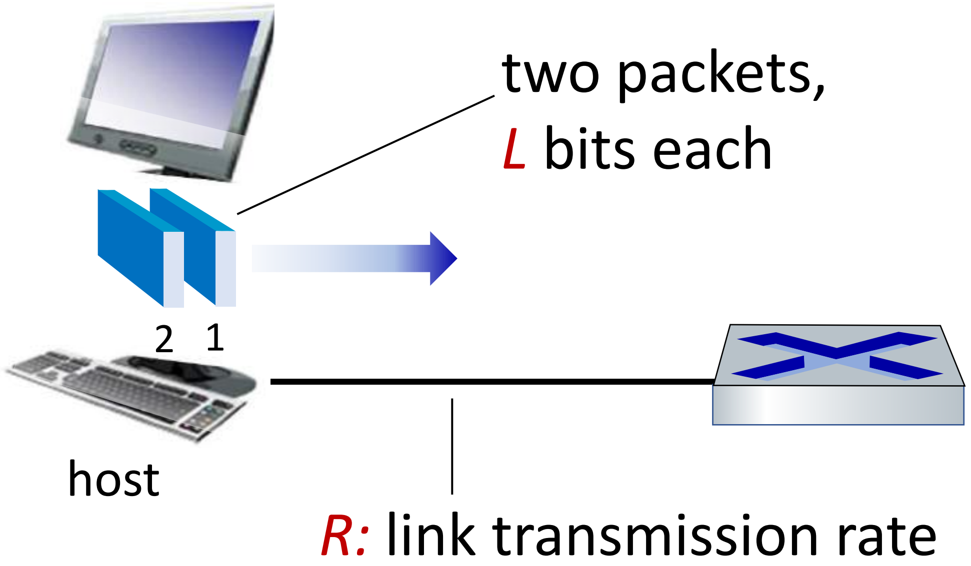
Hosts: Send packets of data

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*



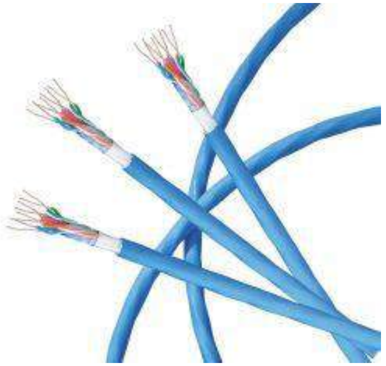
$$\text{packet transmission delay} = \text{time needed to transmit } L\text{-bit packet into link} = \frac{L \text{ (bits)}}{R \text{ (bits/sec)}}$$

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
  - Category 5: 100 Mbps, 1 Gbps Ethernet
  - Category 6: 10Gbps Ethernet



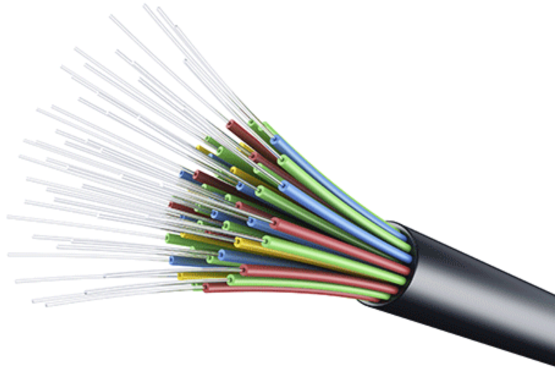
Network Edge: Physical media

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



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
  - 270 msec end-end delay
  - geosynchronous versus low-earth-orbit

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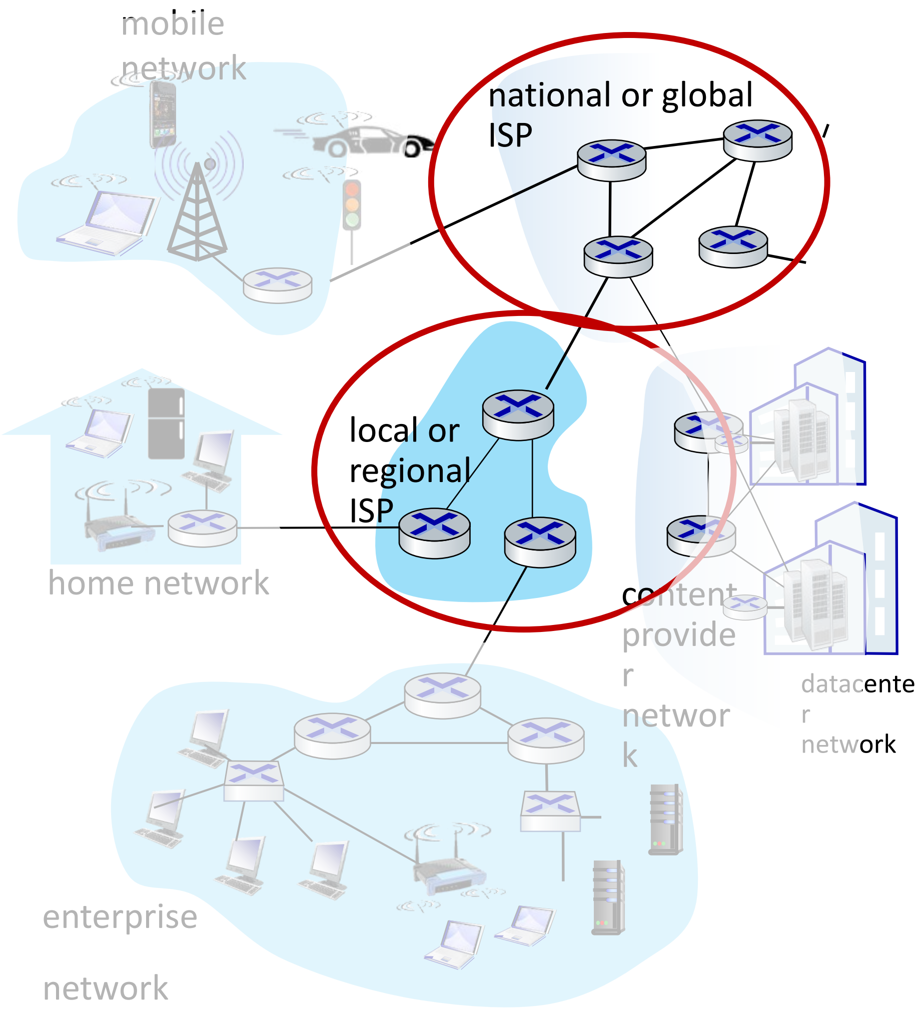
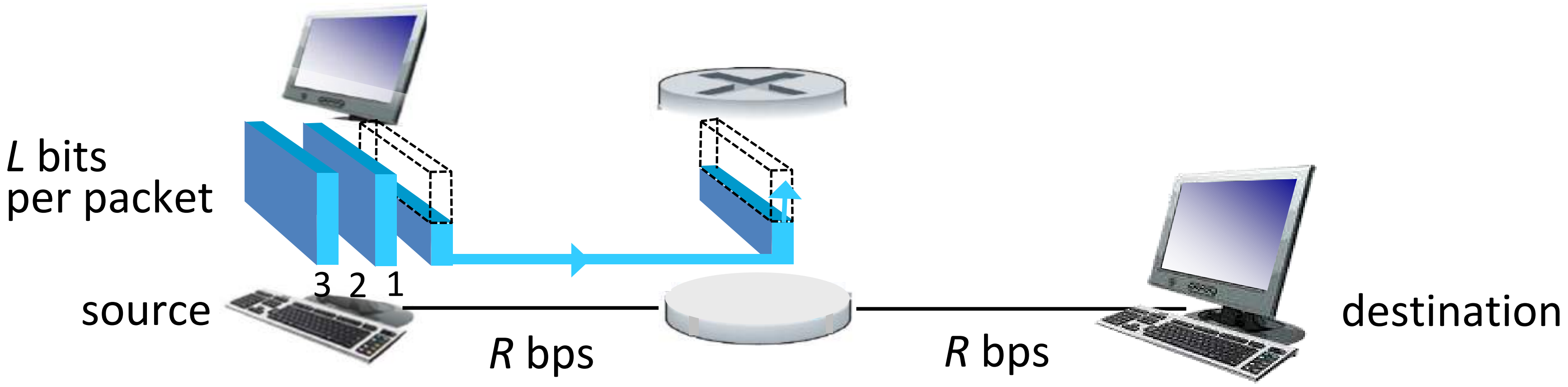
Network Core

- 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

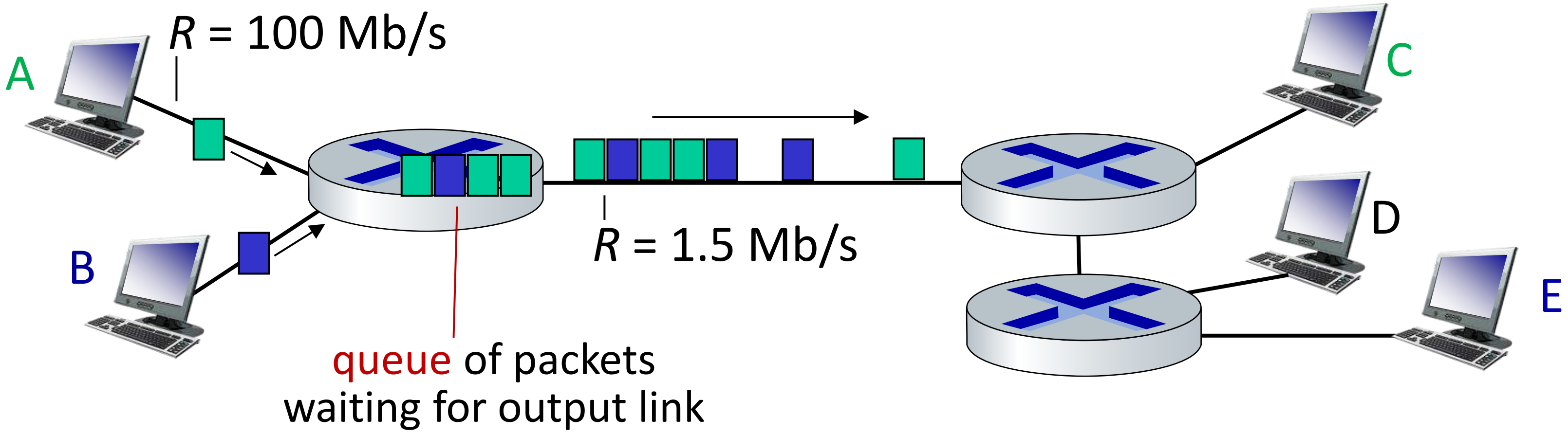


- Transmission delay: takes L/R seconds to transmit (push out) L-bit packet into link at R bps
- *Store and forward: entire* packet must arrive at router before it can be transmitted on next link
- *End-end delay:* $2L/R$ (above), assuming zero propagation delay (more on delay shortly)

One-hop numerical example:

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

Network Core: Packet Switching: queuing delay, loss



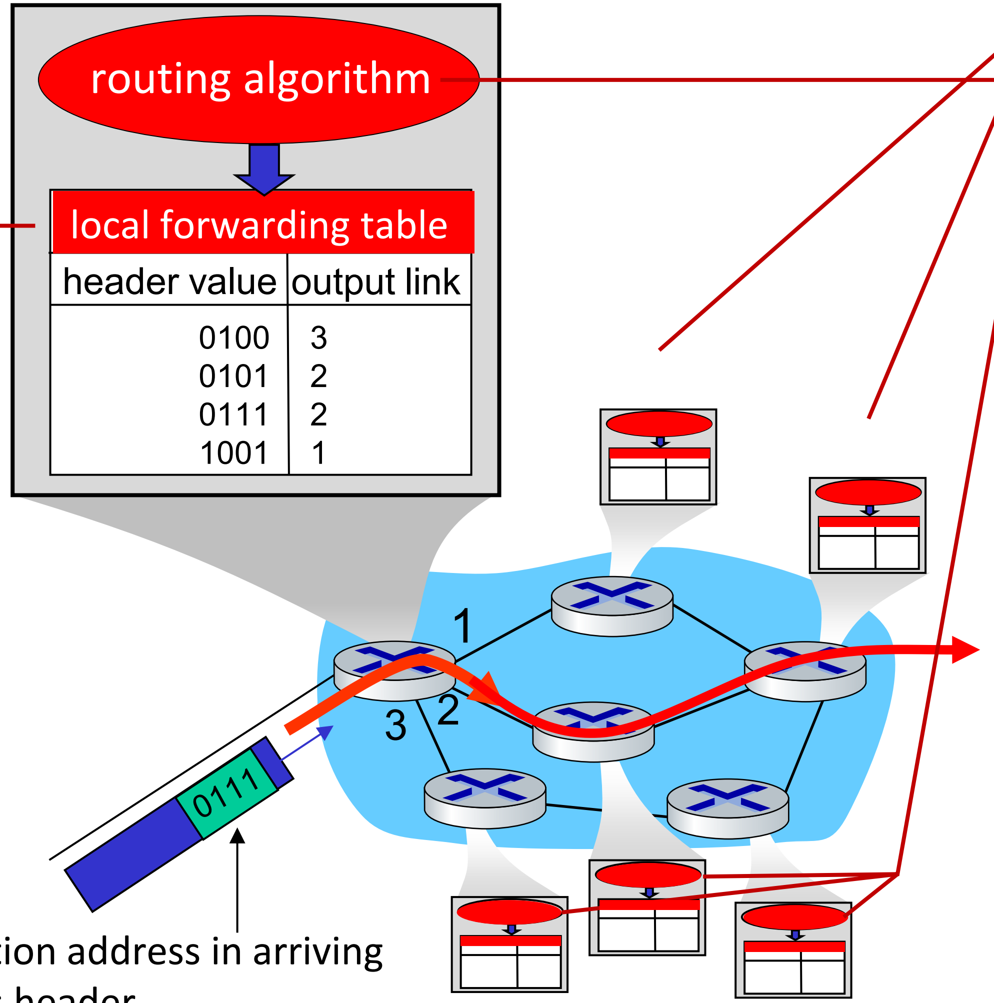
Packet queuing and loss: if arrival rate (in bps) to link exceeds transmission rate (bps) of link for a period of time:

- 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



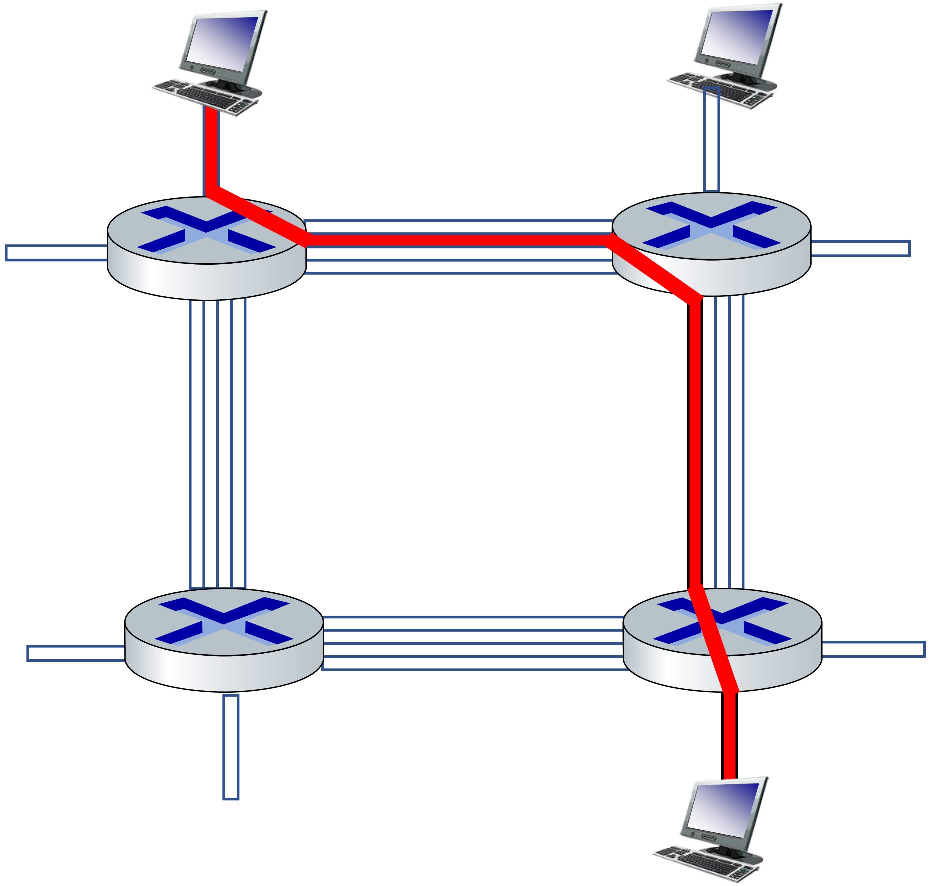
Routing:

- *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

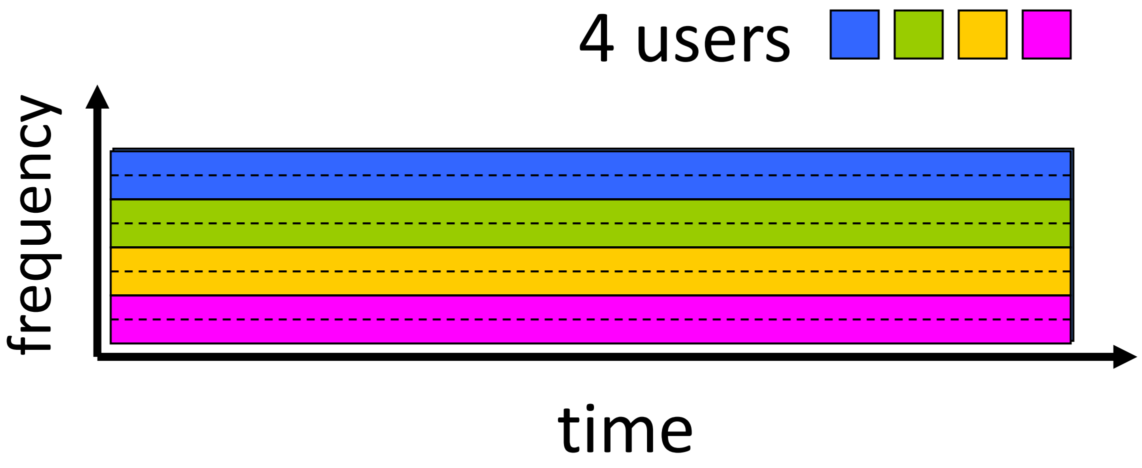
- in diagram, each link has four circuits.
    - call gets 2nd circuit in top link and 1st circuit in right link.
- dedicated resources: no sharing
    - circuit-like (guaranteed) performance
- circuit segment idle if not used by call (no sharing)
- commonly used in traditional telephone networks



Multiplexing in Circuit Switched Networks: FDM & TDM

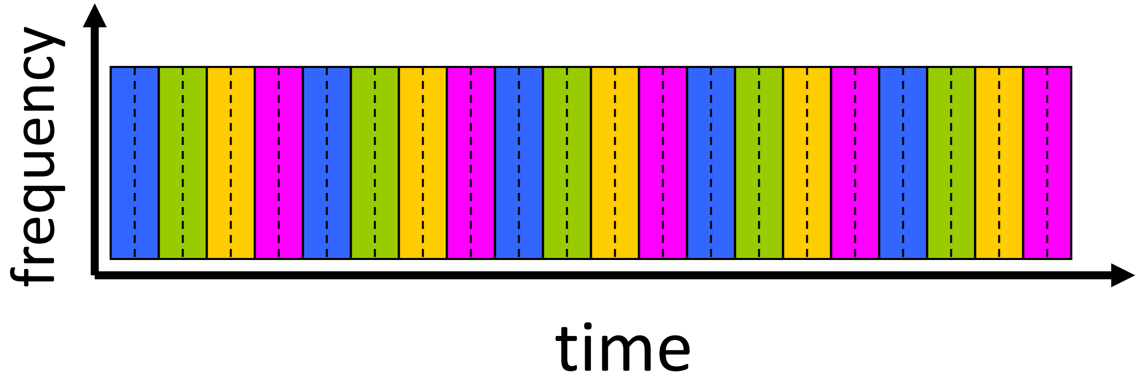
Frequency Division Multiplexing (FDM)

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

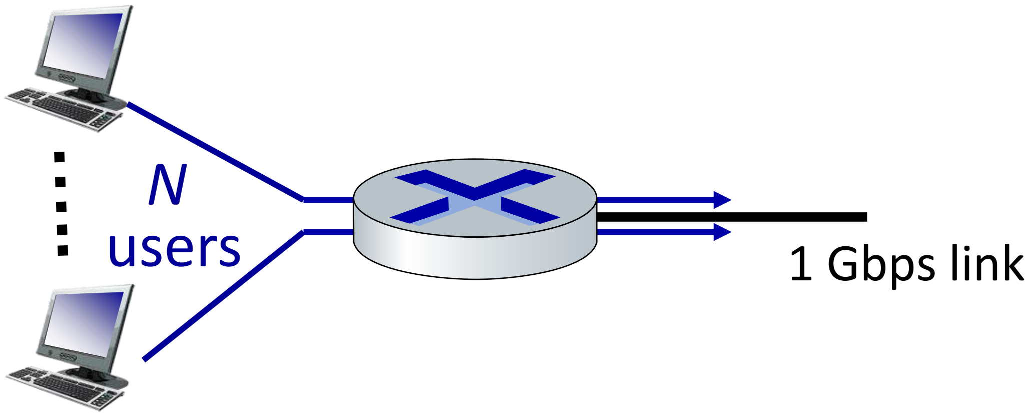


Network Core: Packet Switching vs Circuit Switching

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

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)?

Queries

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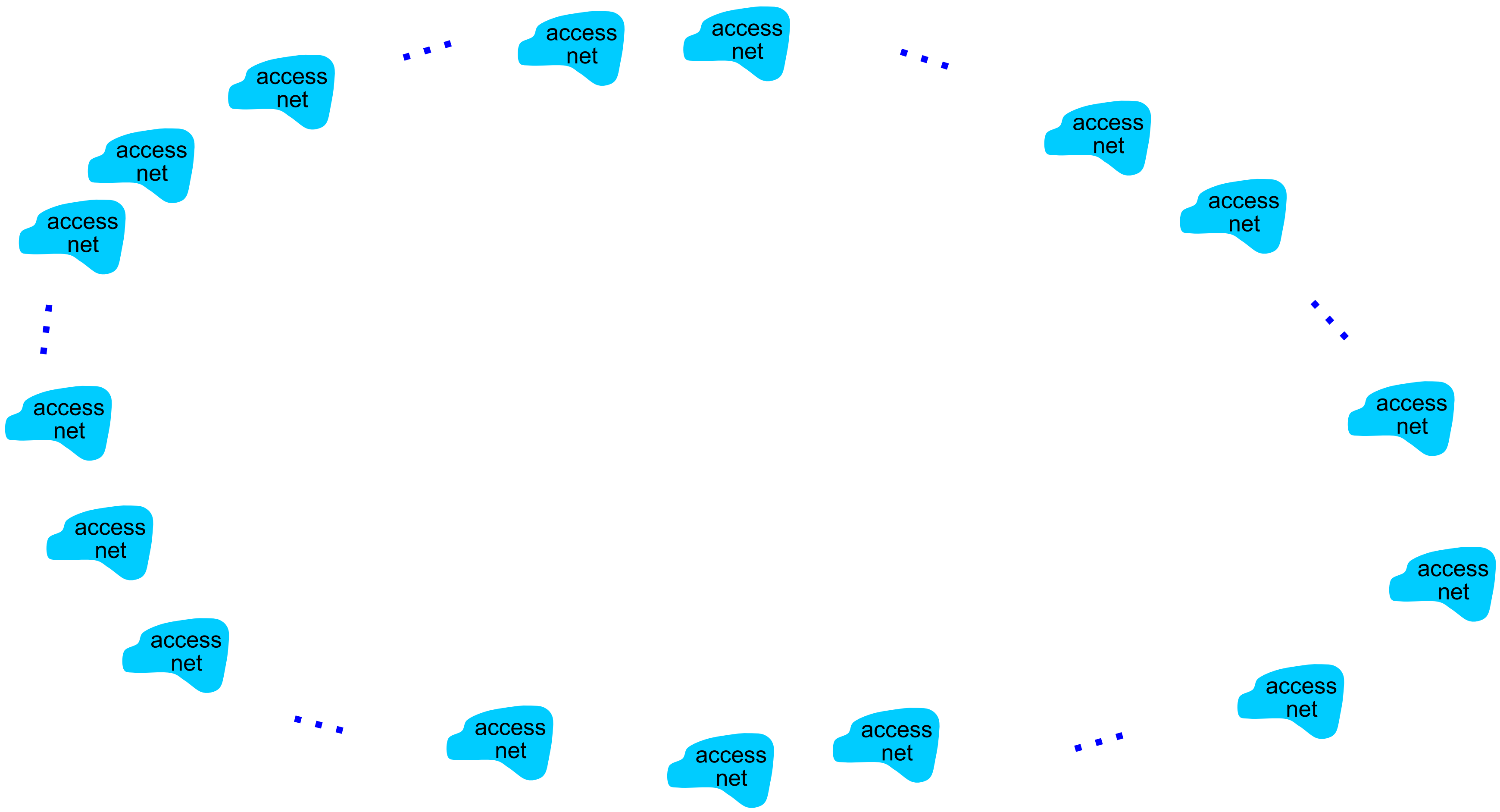
Internet Structure: a “network of networks”

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



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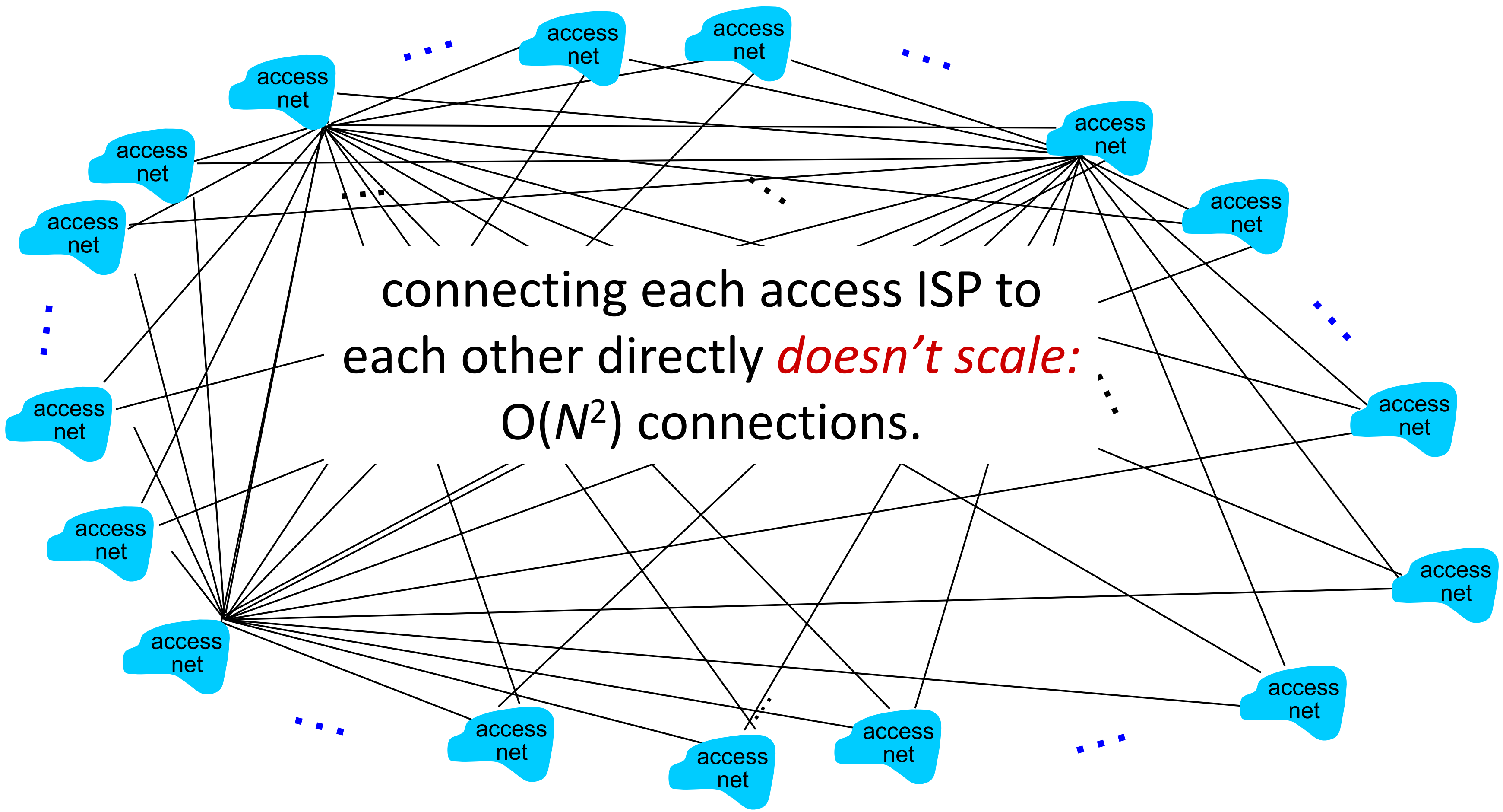
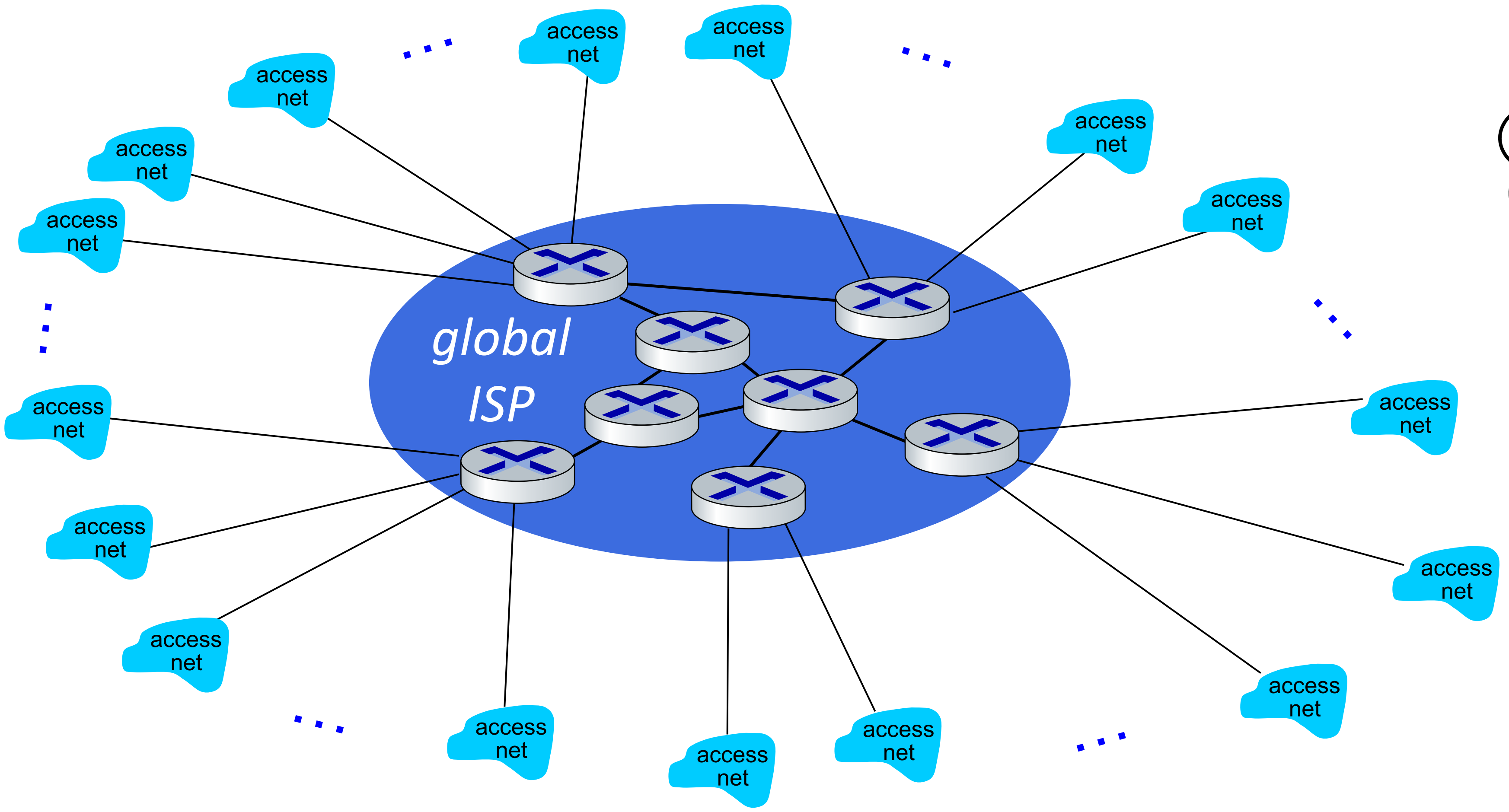


Internet Structure: a "network of networks"

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



Network Structure 1

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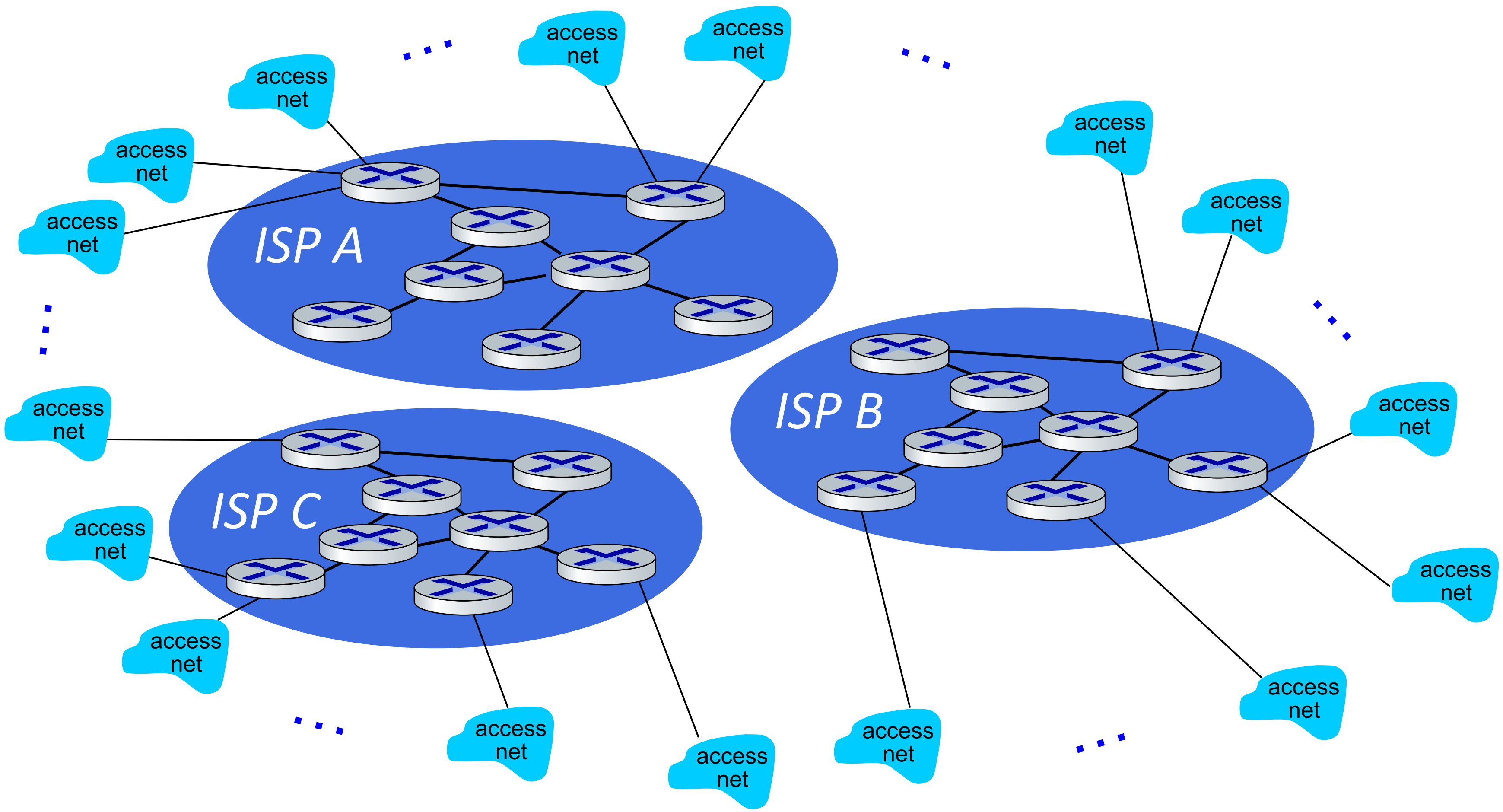
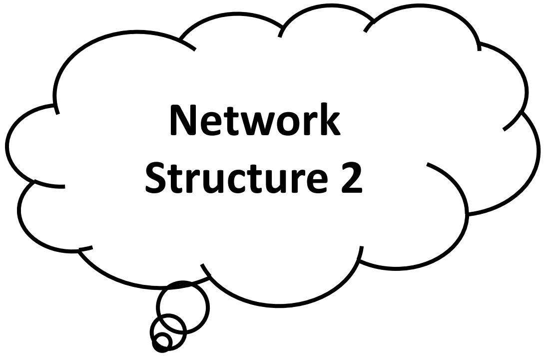
Internet Structure: a “network of networks”

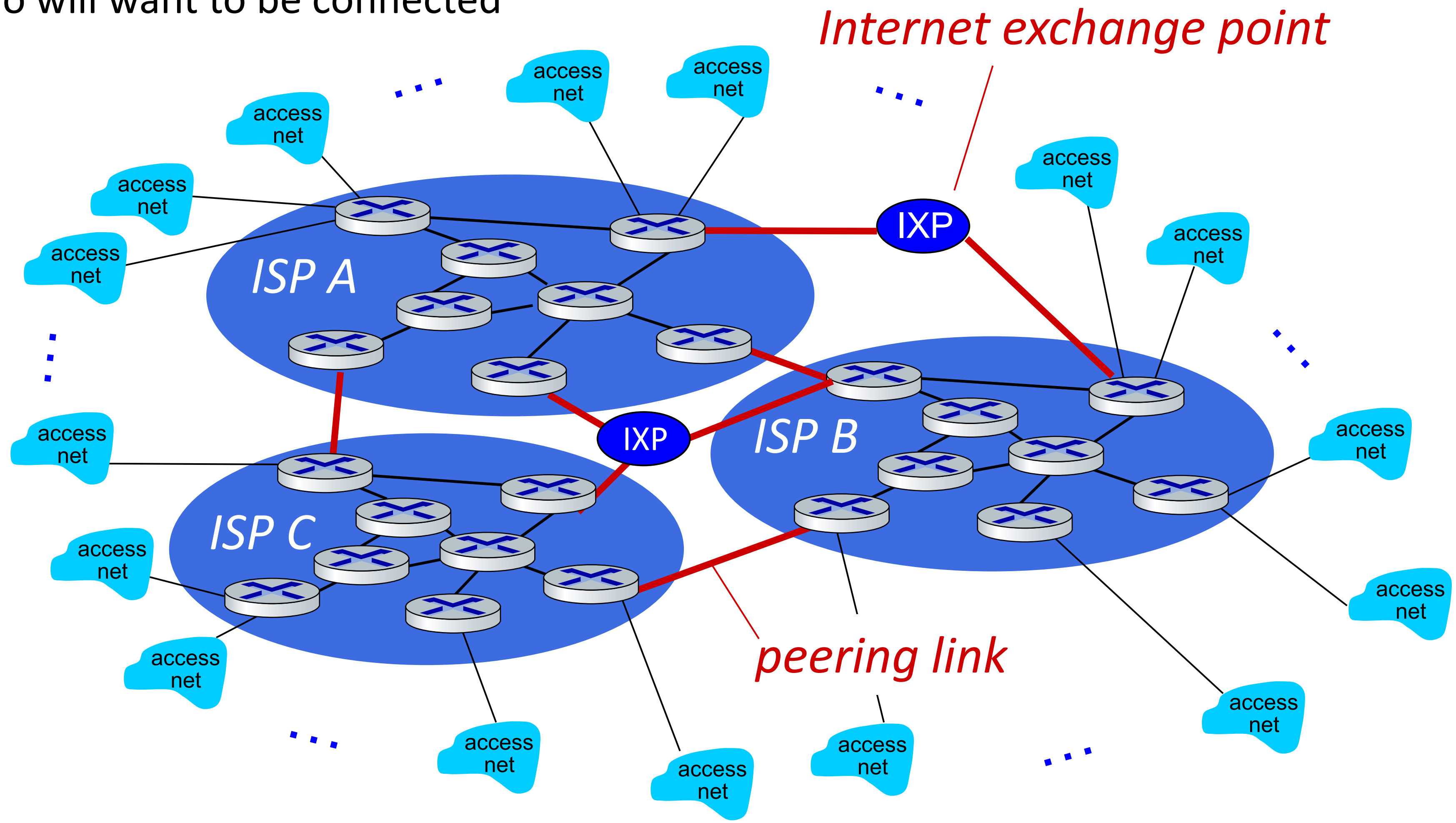
But if one global ISP is viable business, there will be competitors ….

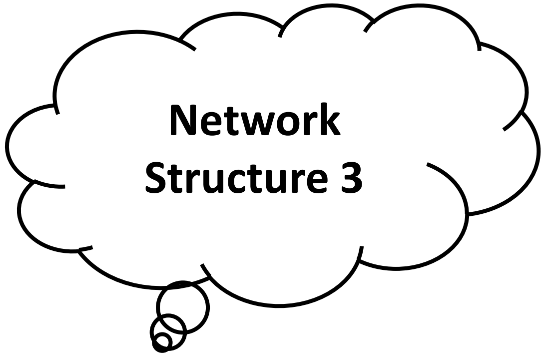




Internet Structure: a "network of networks"

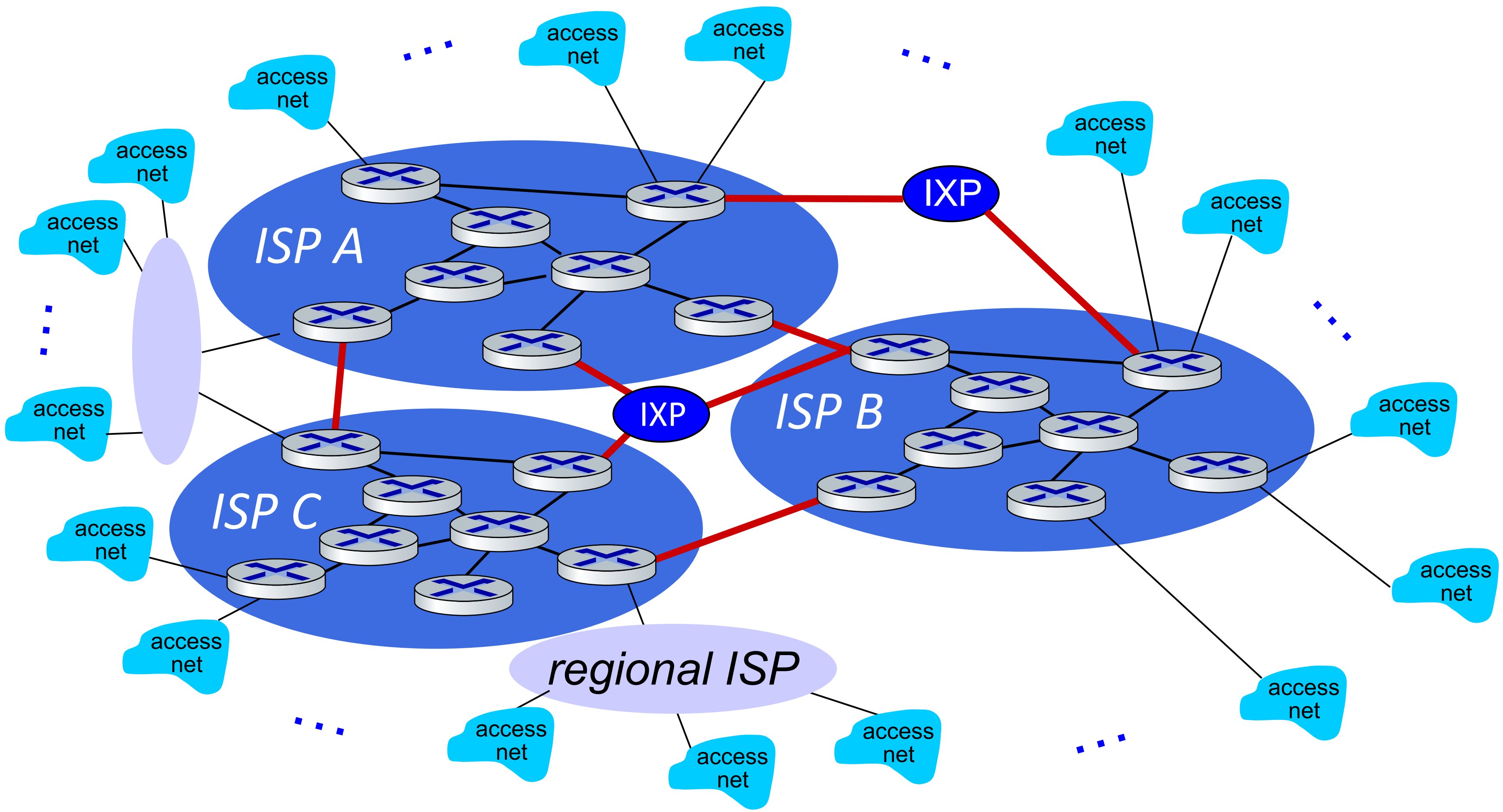
But if one global ISP is viable business, there will be competitors ….
who will want to be connected

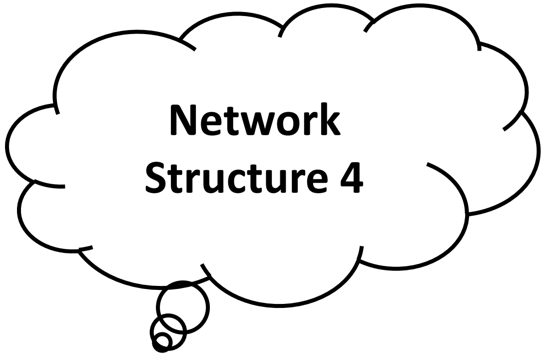




Internet Structure: a “network of networks”

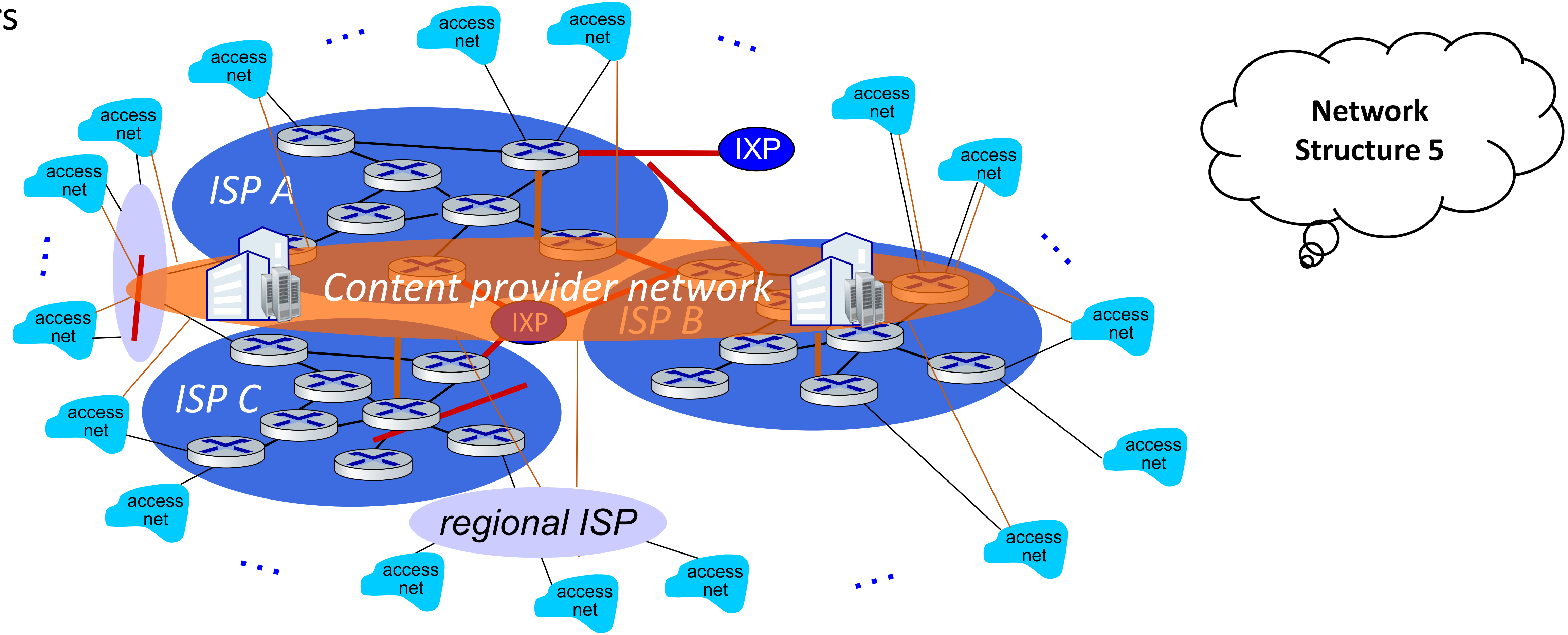
… and regional networks may arise to connect access nets to ISPs



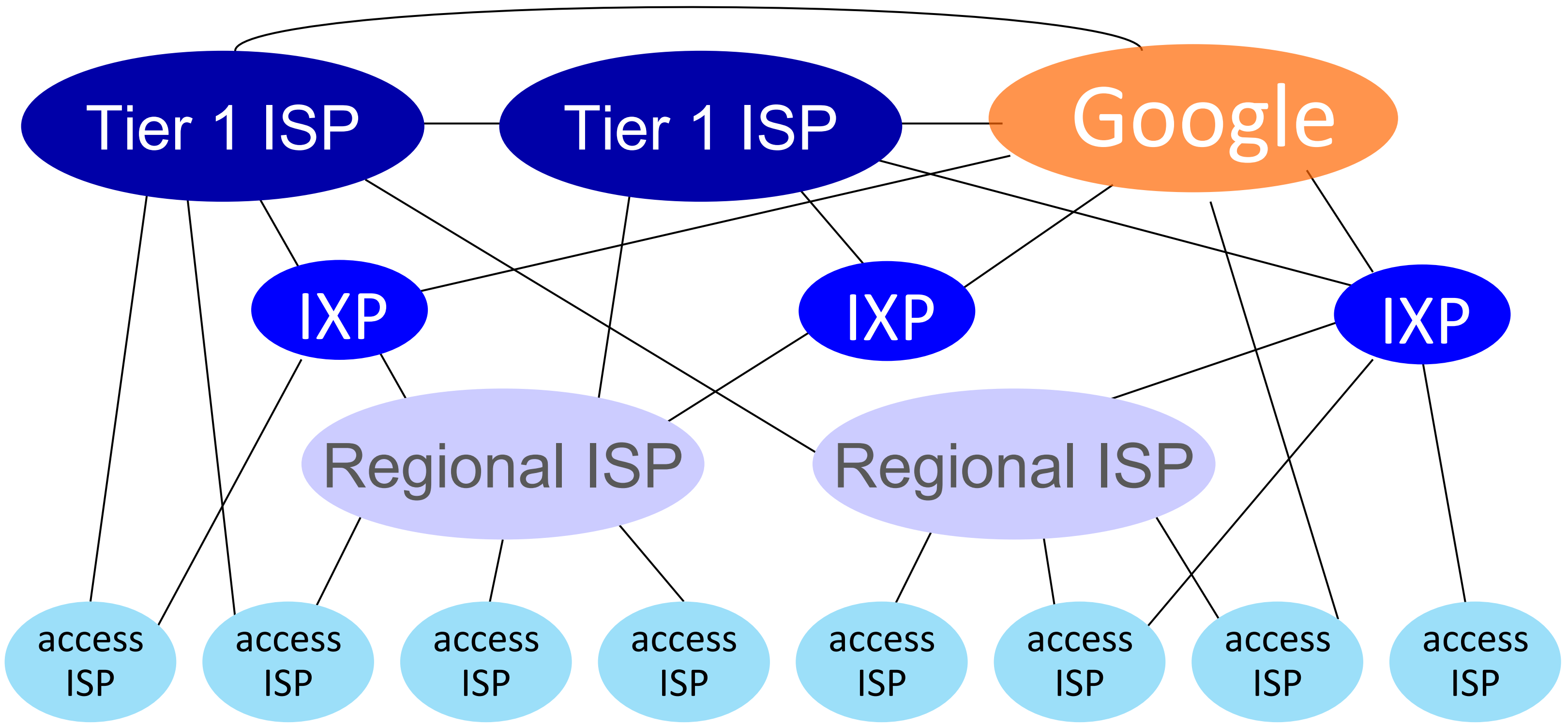


Internet Structure: a "network of networks"

… 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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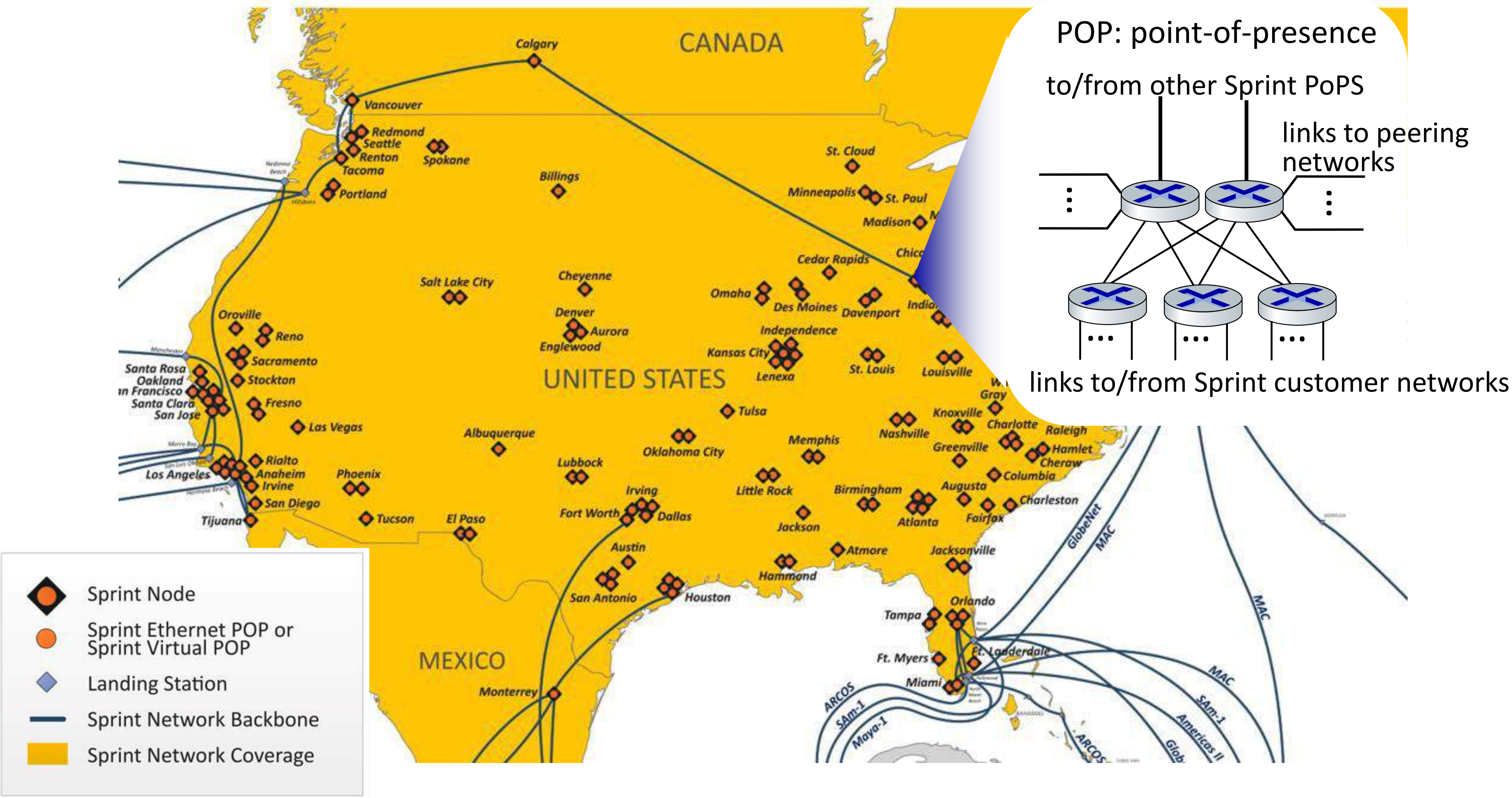
Network Core: Tier 1 ISP Network Map: Sprint 2019



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+91 80 6666 3333 Extn 834

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Sivaraman Eswaran Ph.D.
Department of Computer Science and Engineering

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Computer Networks and the Internet

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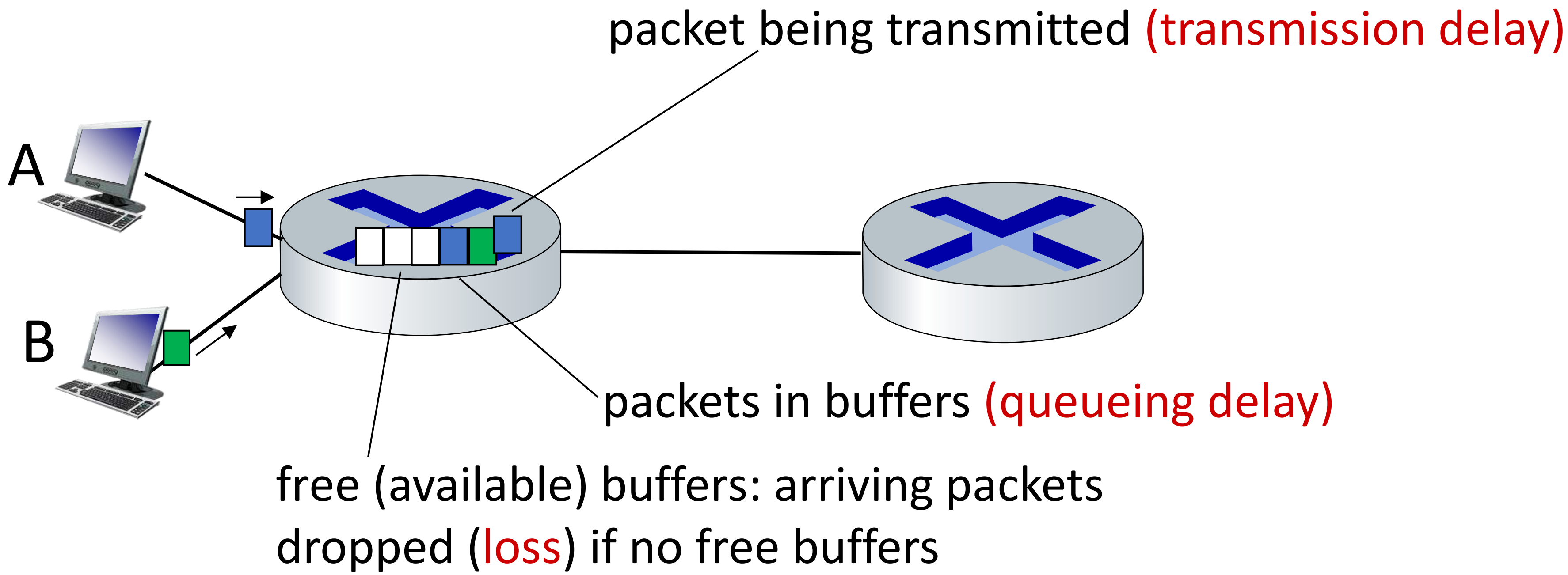
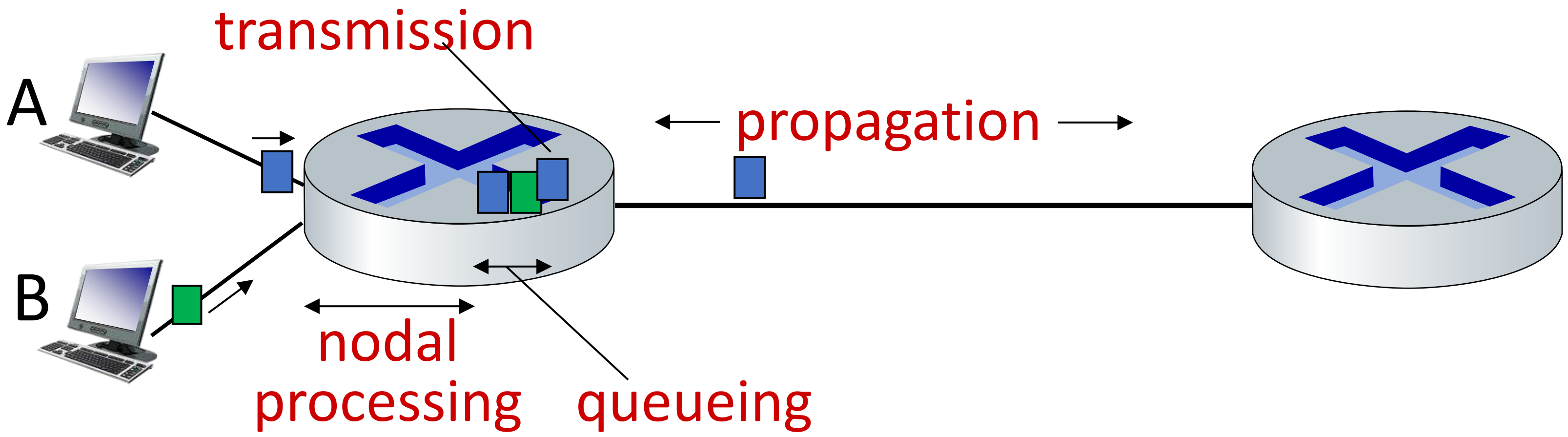
How do packet loss and delay occurs?

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



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

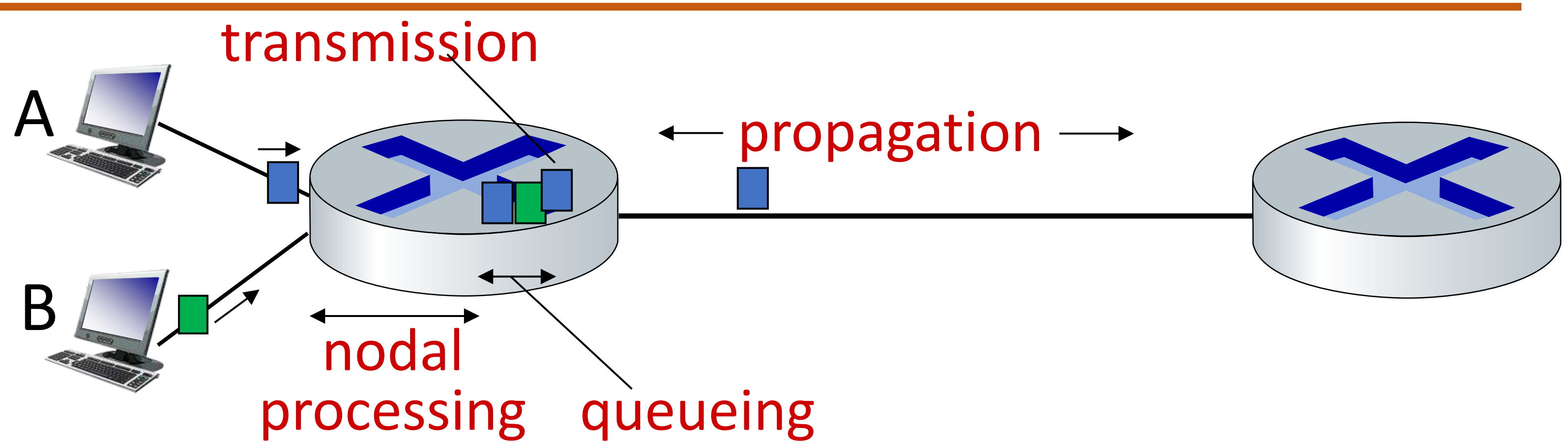
d_{proc}: nodal processing

- 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

Performance: Packet Delay – 4 Sources



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

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

d_{trans}: transmission delay:

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

d_{prop}: propagation delay:

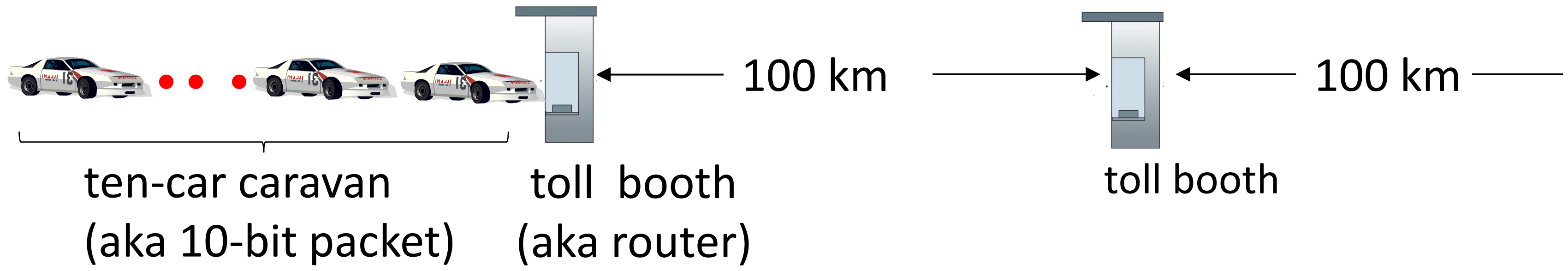
- d: length of physical link
- s: propagation speed (~2×10^8 m/sec)
- $d_{prop} = d/s$

d_{trans} and d_{prop}
very different

Transmission Delay vs Propagation Delay

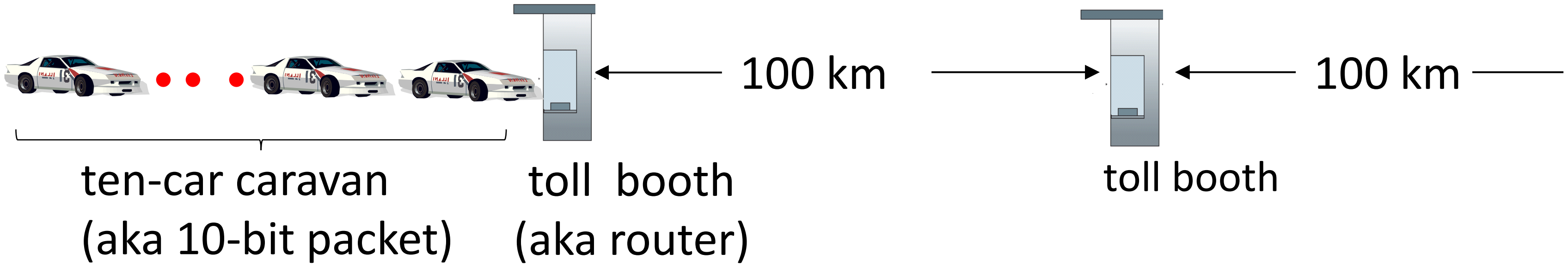
Transmission Delay	Propagation Delay
Time required for the router to push out the packet.	Time it takes a bit to propagate from one router to the next.
A function of the **packet's length** and the **transmission rate** of the link.	A function of the **distance** between the two routers.
$d_{trans} = L/R$	$d_{prop} = d/s$
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

Queries

Thank You
For Your Attention

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Department of Computer Science and Engineering

sivaramane@pes.edu

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Performance: Packet Queueing Delay revisited

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

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

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

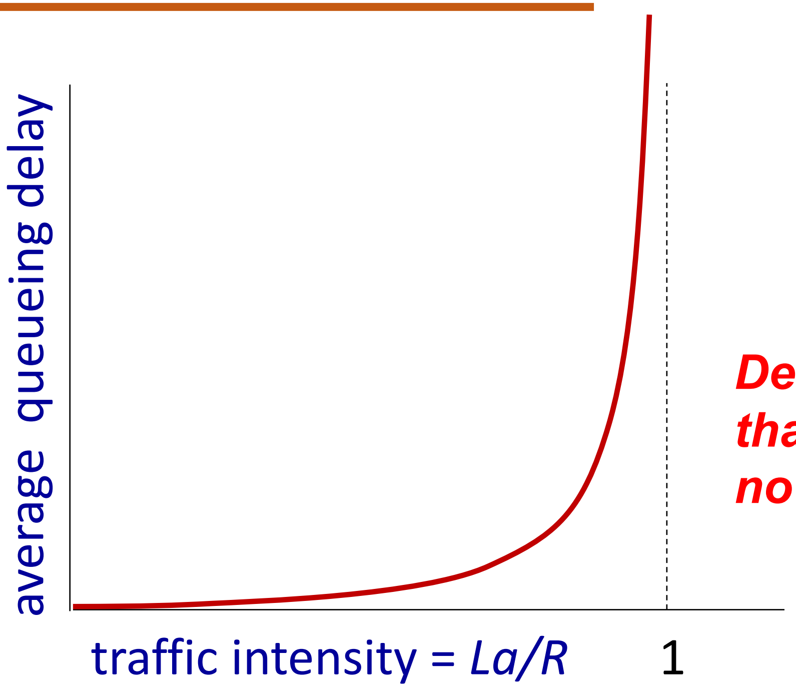
- Rate at which traffic arrives at the queue,
- Transmission rate of the link,
- Nature of the arriving traffic – periodically or in bursts

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

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.



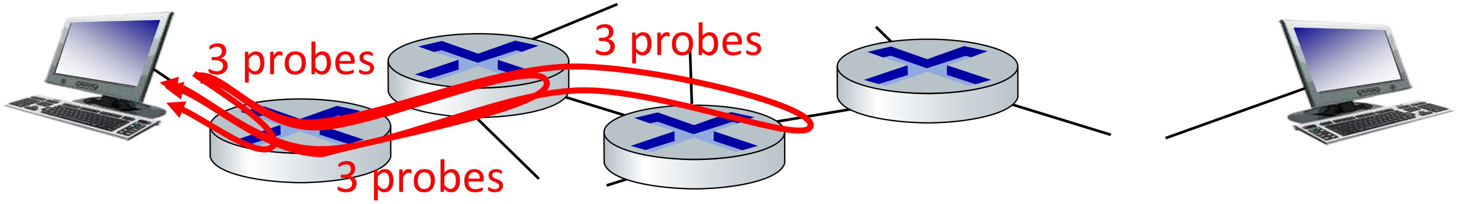
Design your system so that the traffic intensity is no greater than 1.

La/R ~ 0

La/R -> 1

"Real" Internet Delays and Routes

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



"Real" Internet Delays and Routes

PES UNIVERSITY ONLINE

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

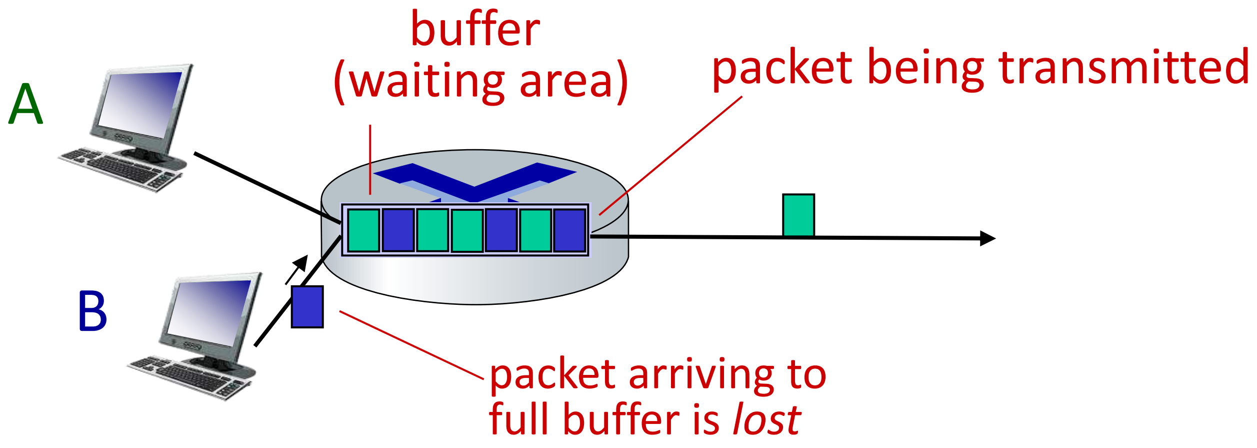
looks like delays *decrease*! Why?

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

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

Performance: Packet loss

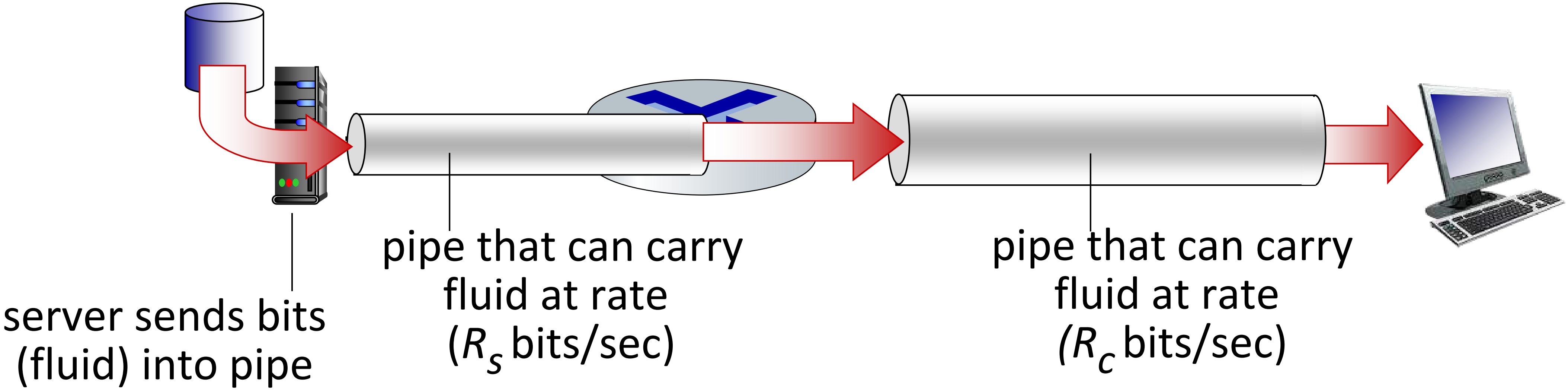
- queue (aka buffer) preceding link in buffer has finite capacity
- packet arriving to full queue dropped (aka lost)
- lost packet may be retransmitted by previous node, by source end system, or not at all



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

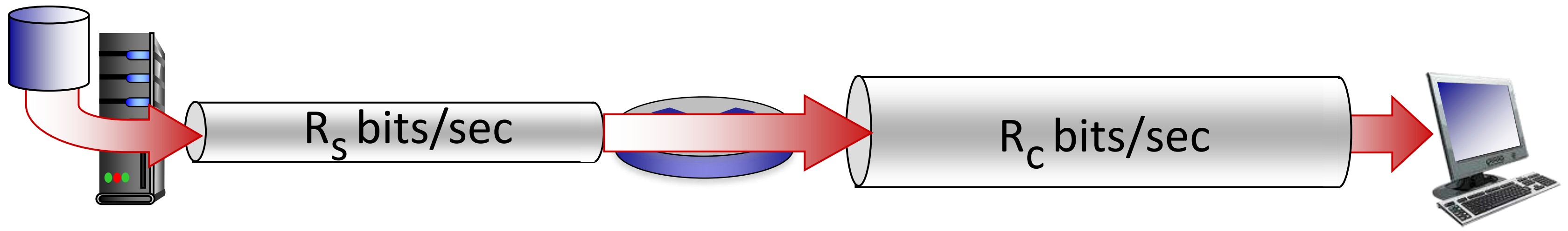
Performance: Throughput

- *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

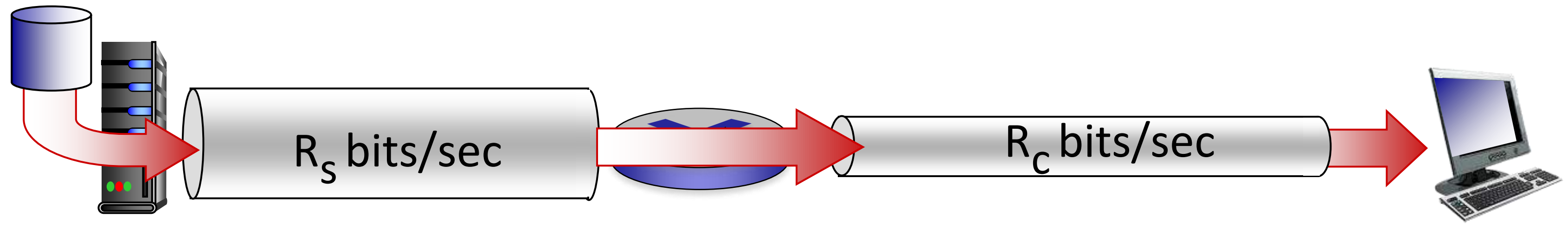


Performance: Throughput (more)

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



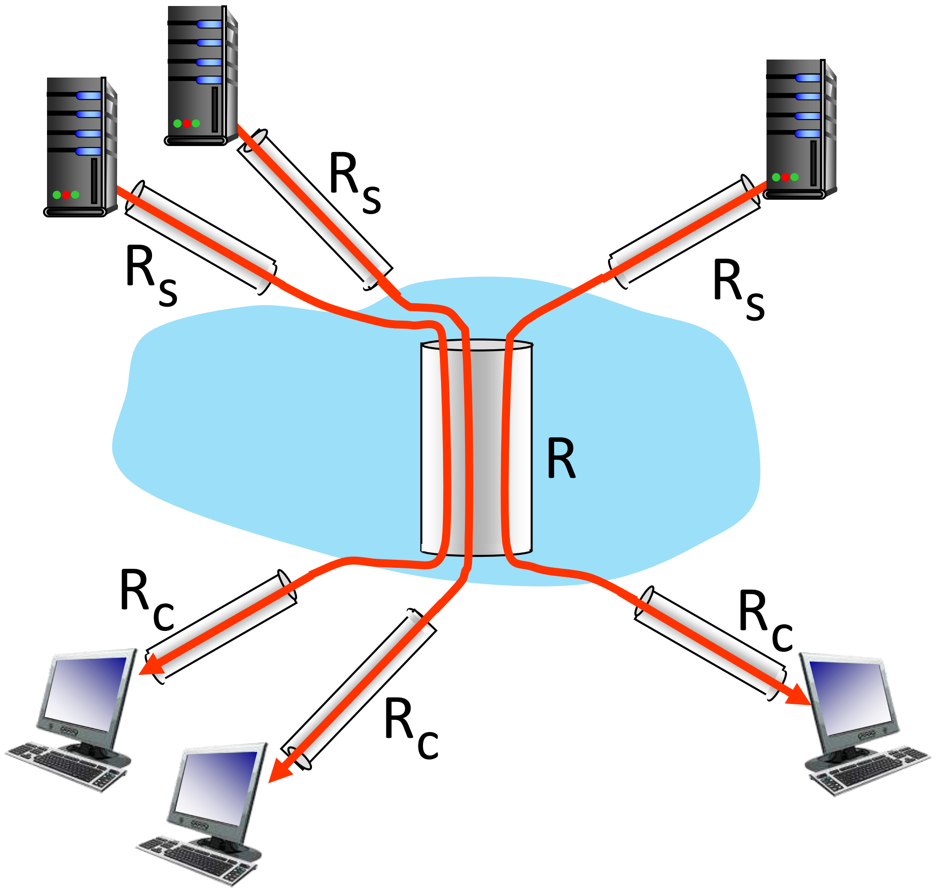
$R_s > R_c$ What is average end-end throughput?



bottleneck link

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

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.

Queries

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sivaramane@pes.edu

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Networks are complex, with many "pieces":

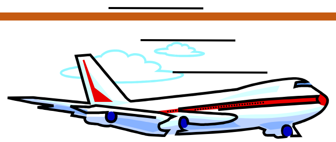
- hosts
- routers
- links of various media
- applications
- protocols
- hardware, software

Question:

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

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

Example: Organization of Air Travel



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

airplane routing

airline travel: a series of steps, involving many services

Layering of Airline functionality

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

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

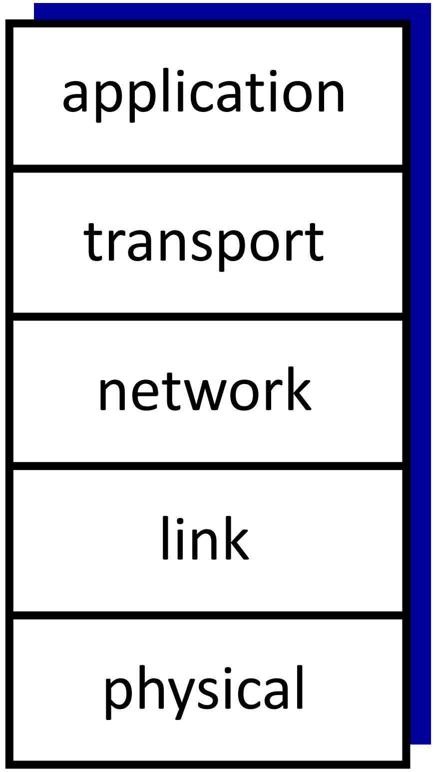
Why layering?

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”



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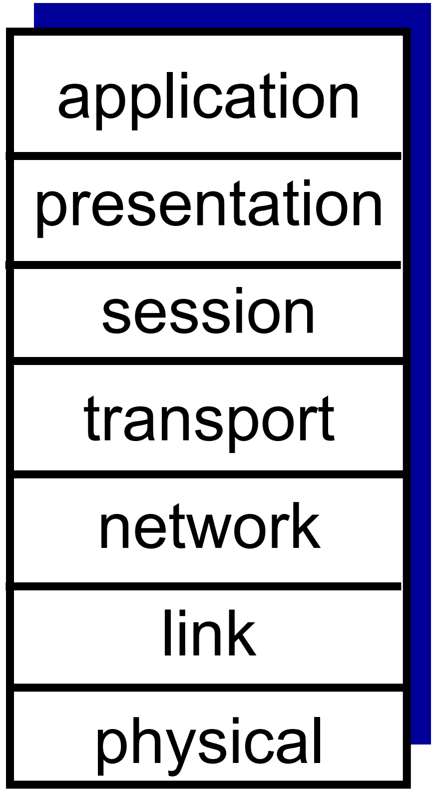
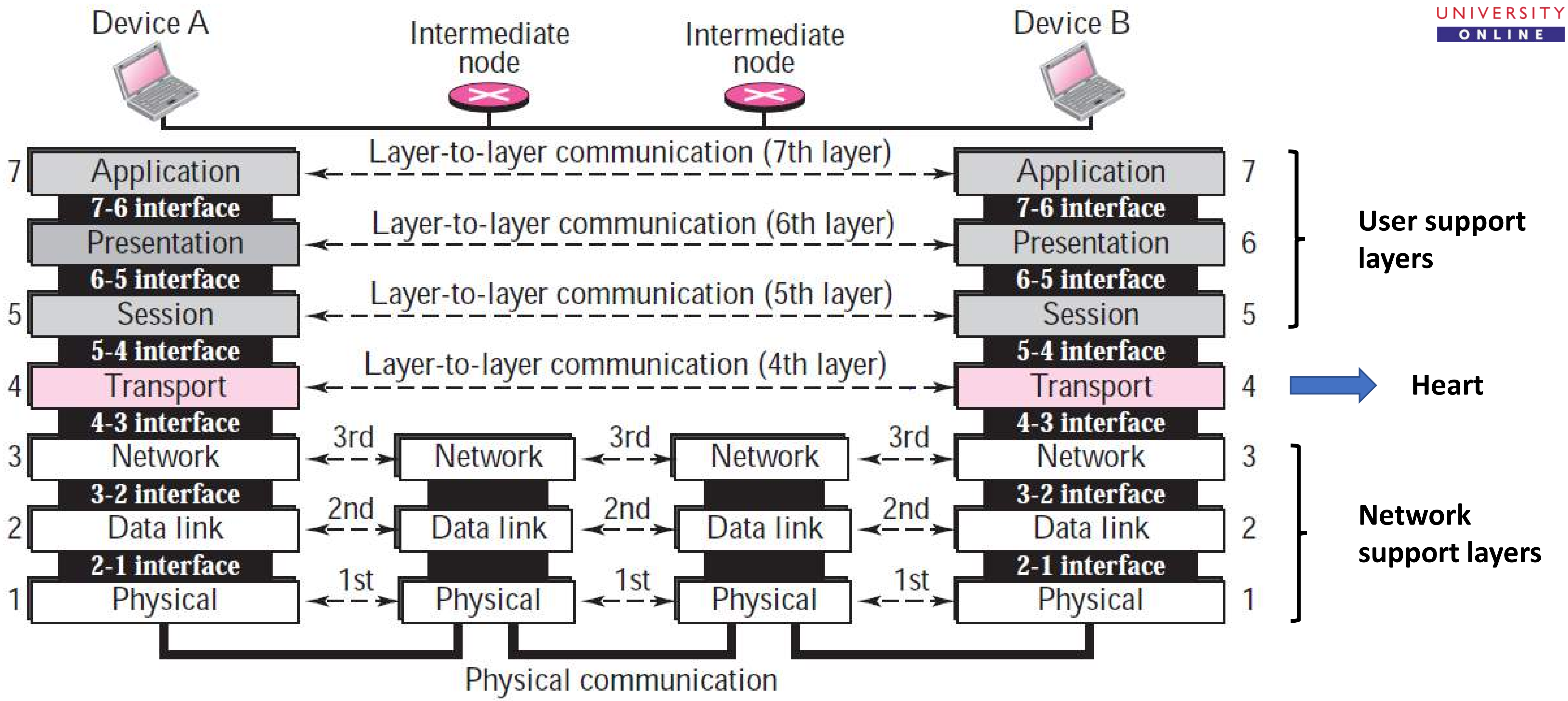
OSI reference model

- *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?

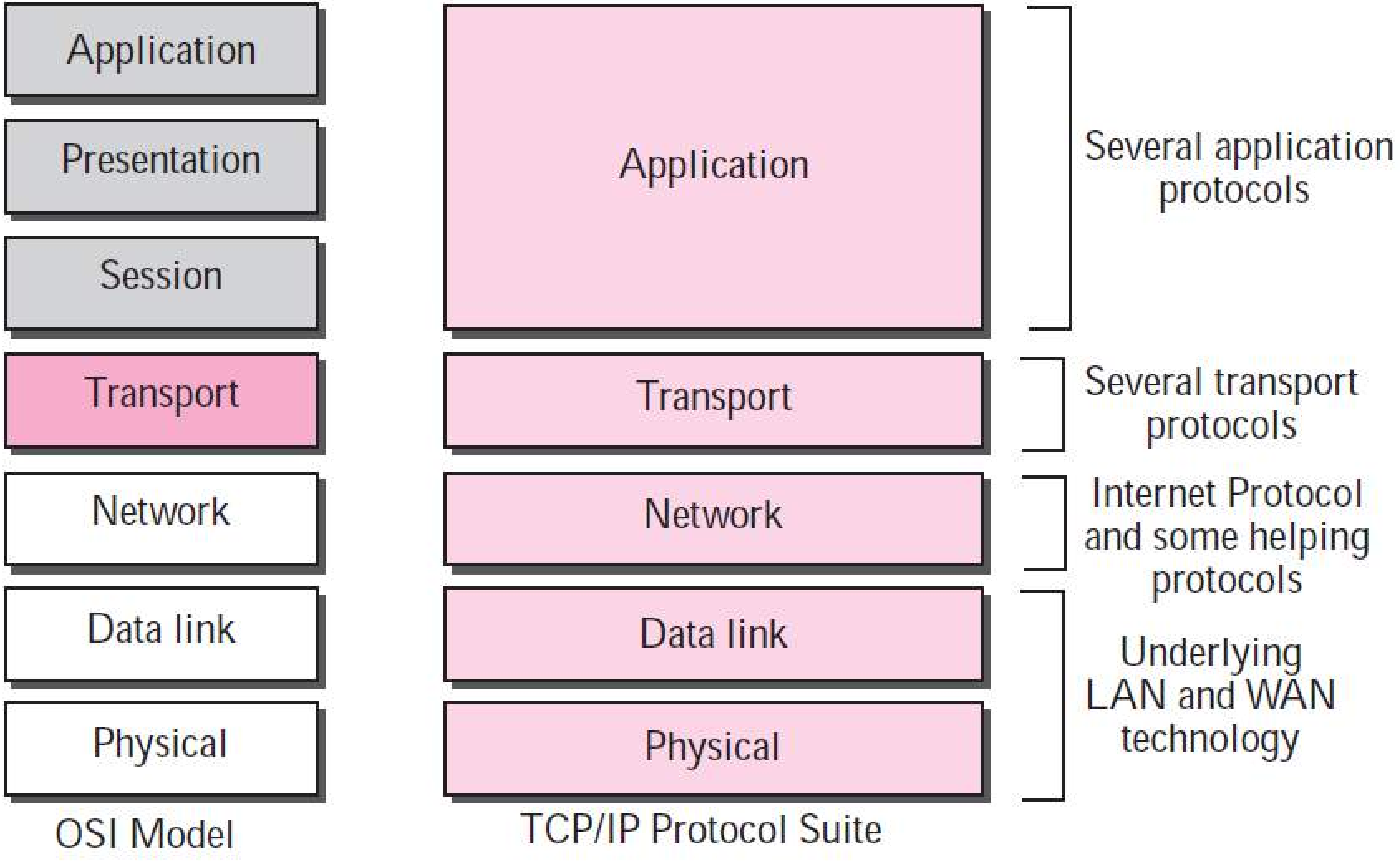


Open **S**ystems **I**nterconnection (OSI) model – introduced in late 1970s by ISO.

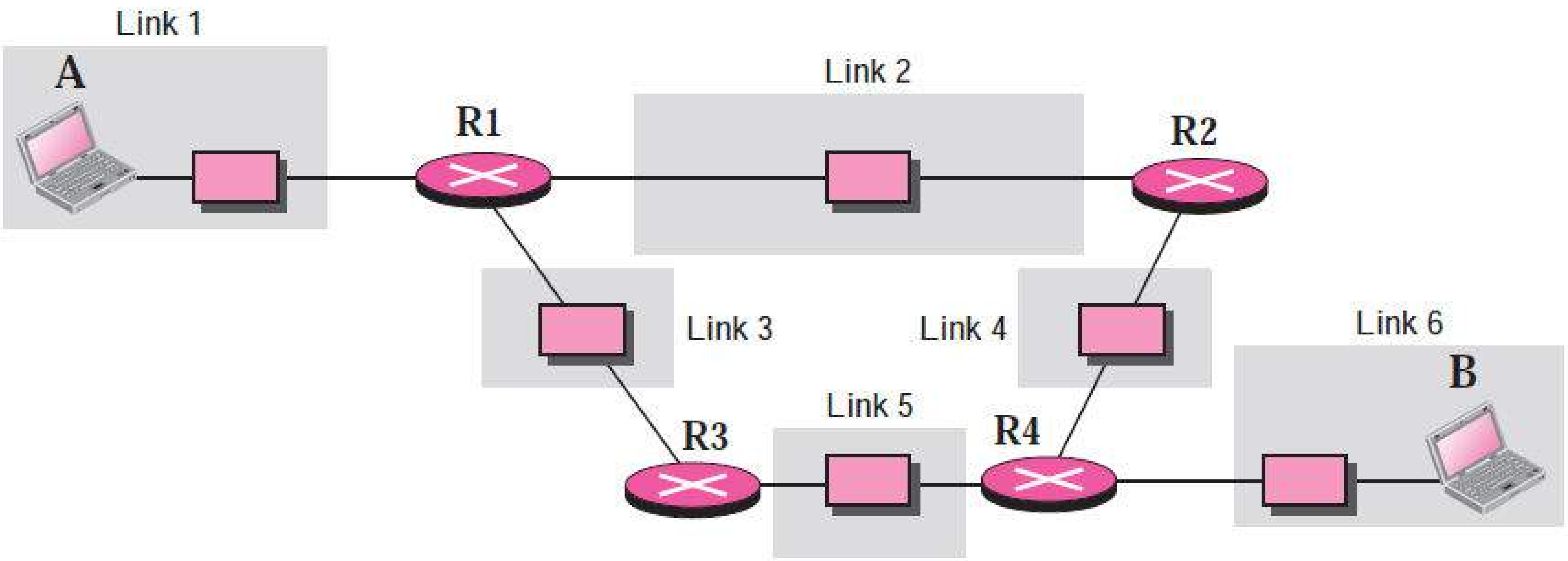
OSI reference model (more)



TCP/IP vs OSI reference model



Layers in the TCP/IP Protocol Suite (more)



A private internet

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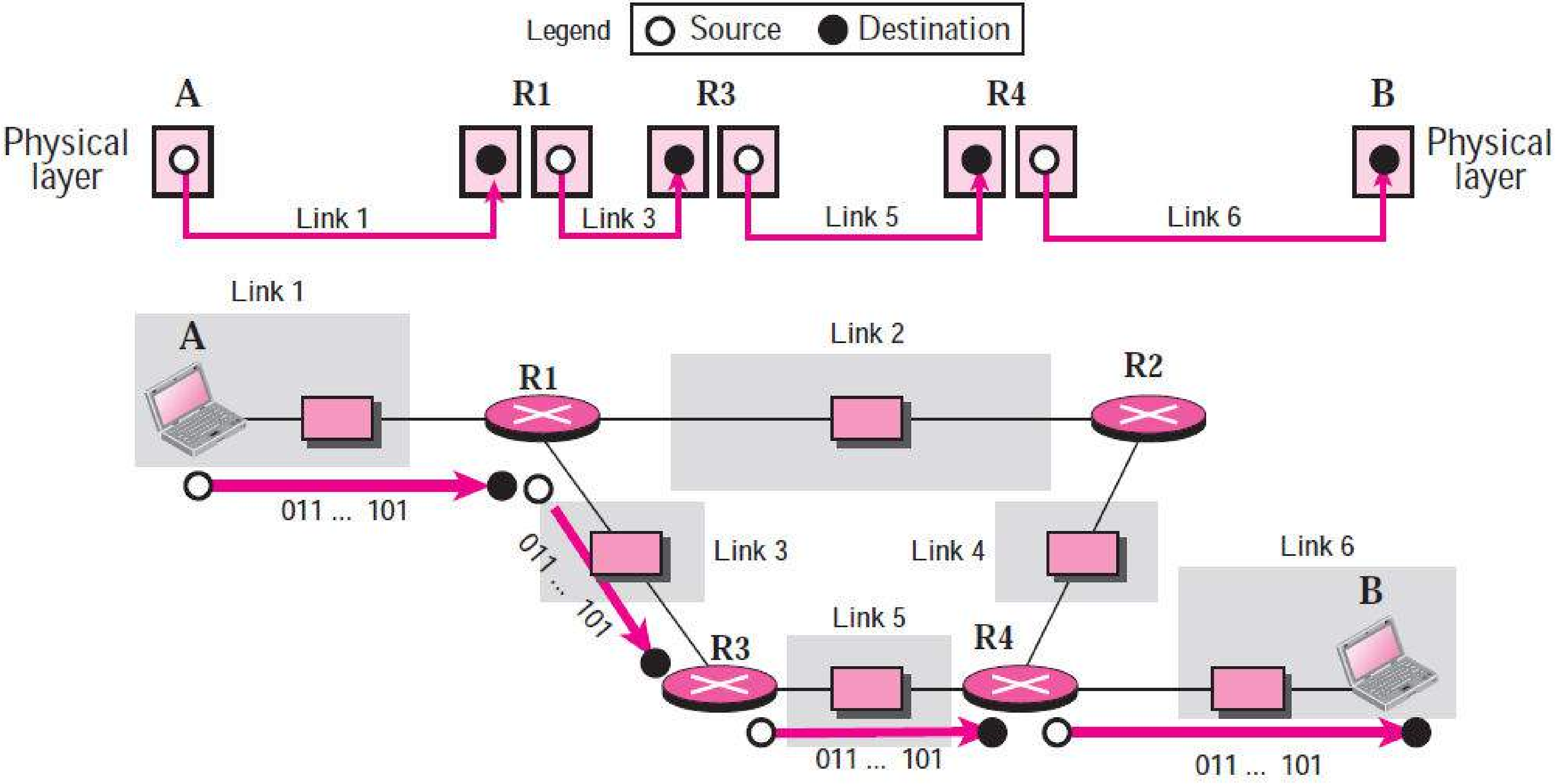
Layers in the TCP/IP Protocol Suite (more)



Communication at the physical layer

Unit of Communication – bit

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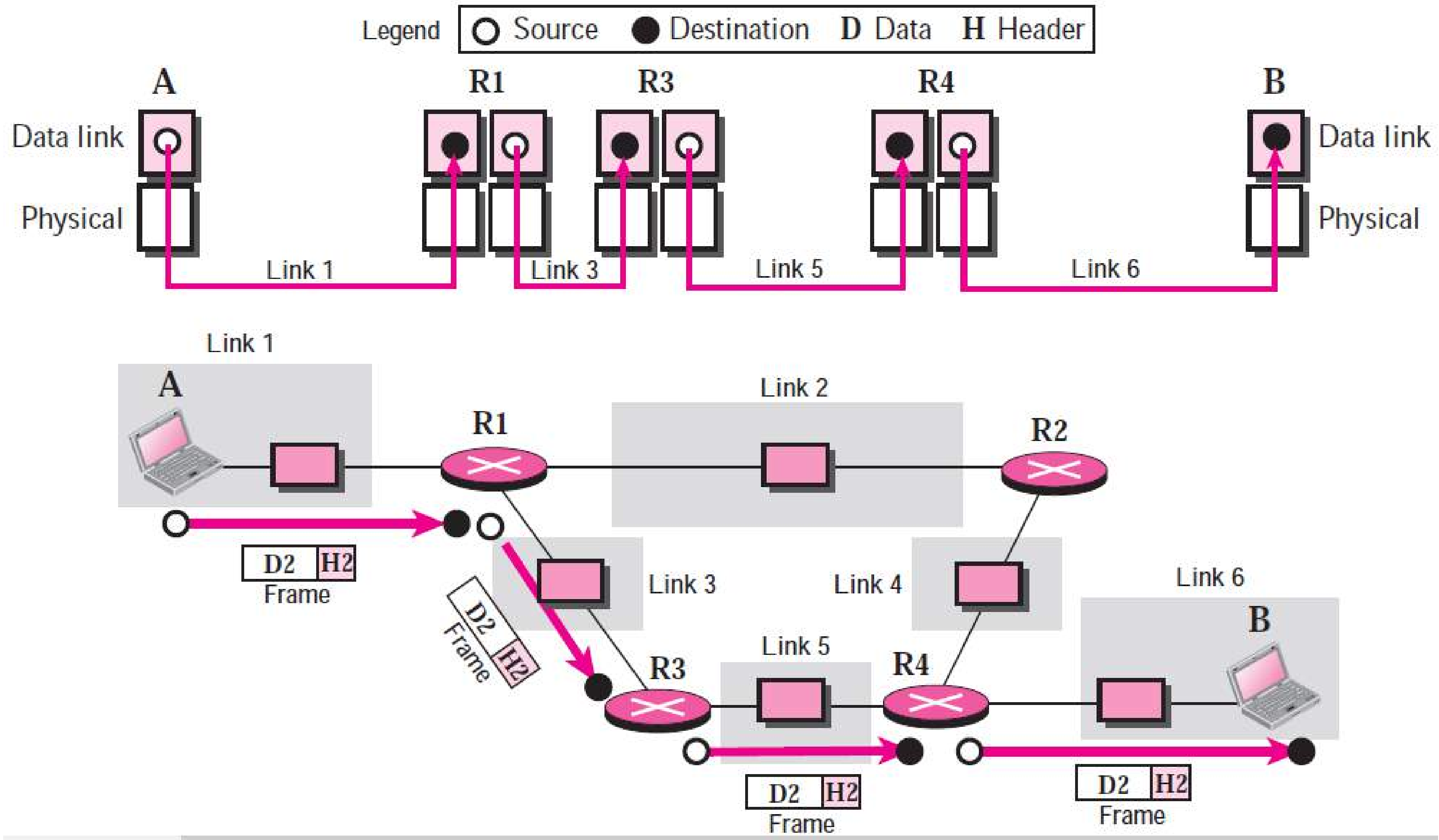
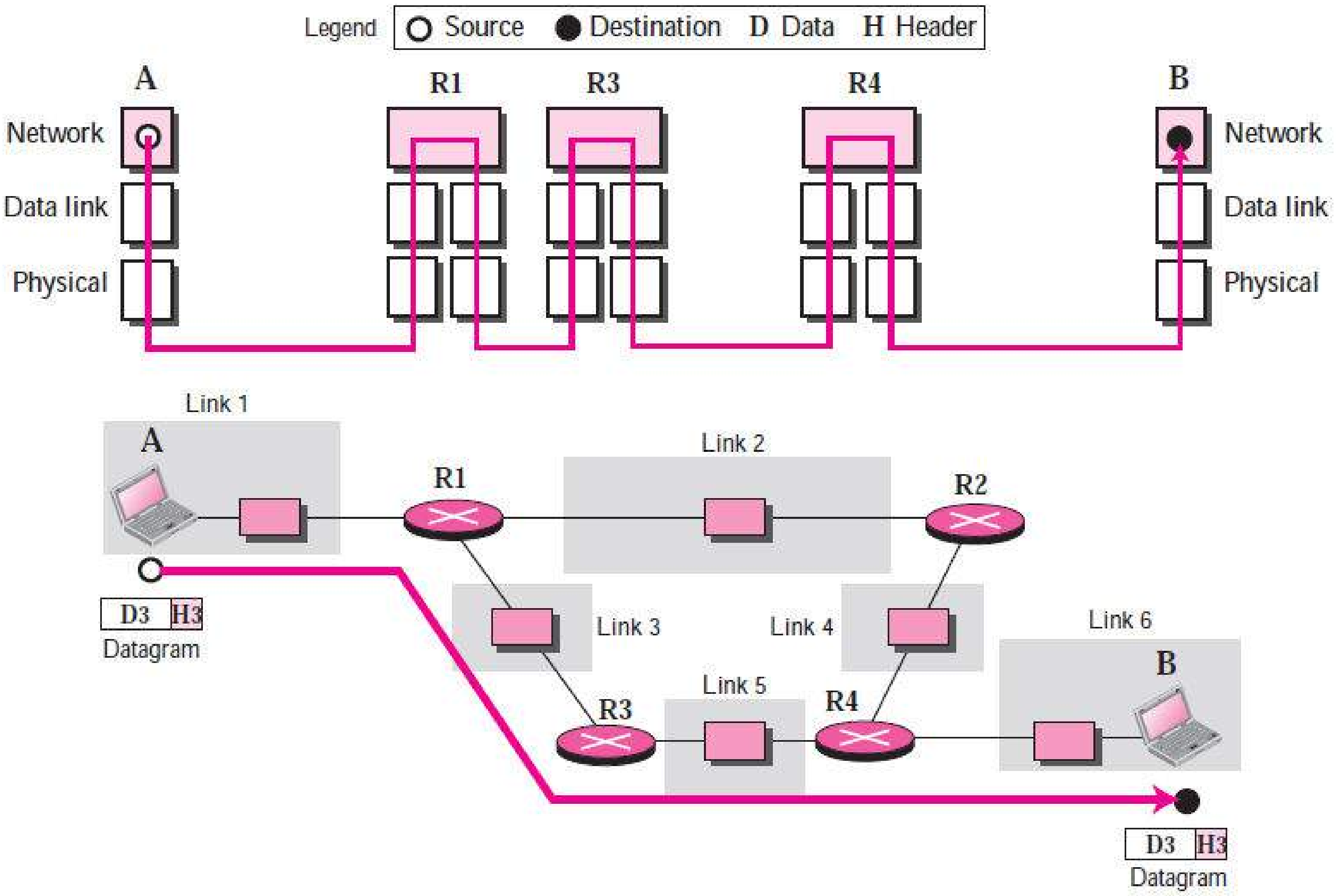
Layers in the TCP/IP Protocol Suite (more)



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

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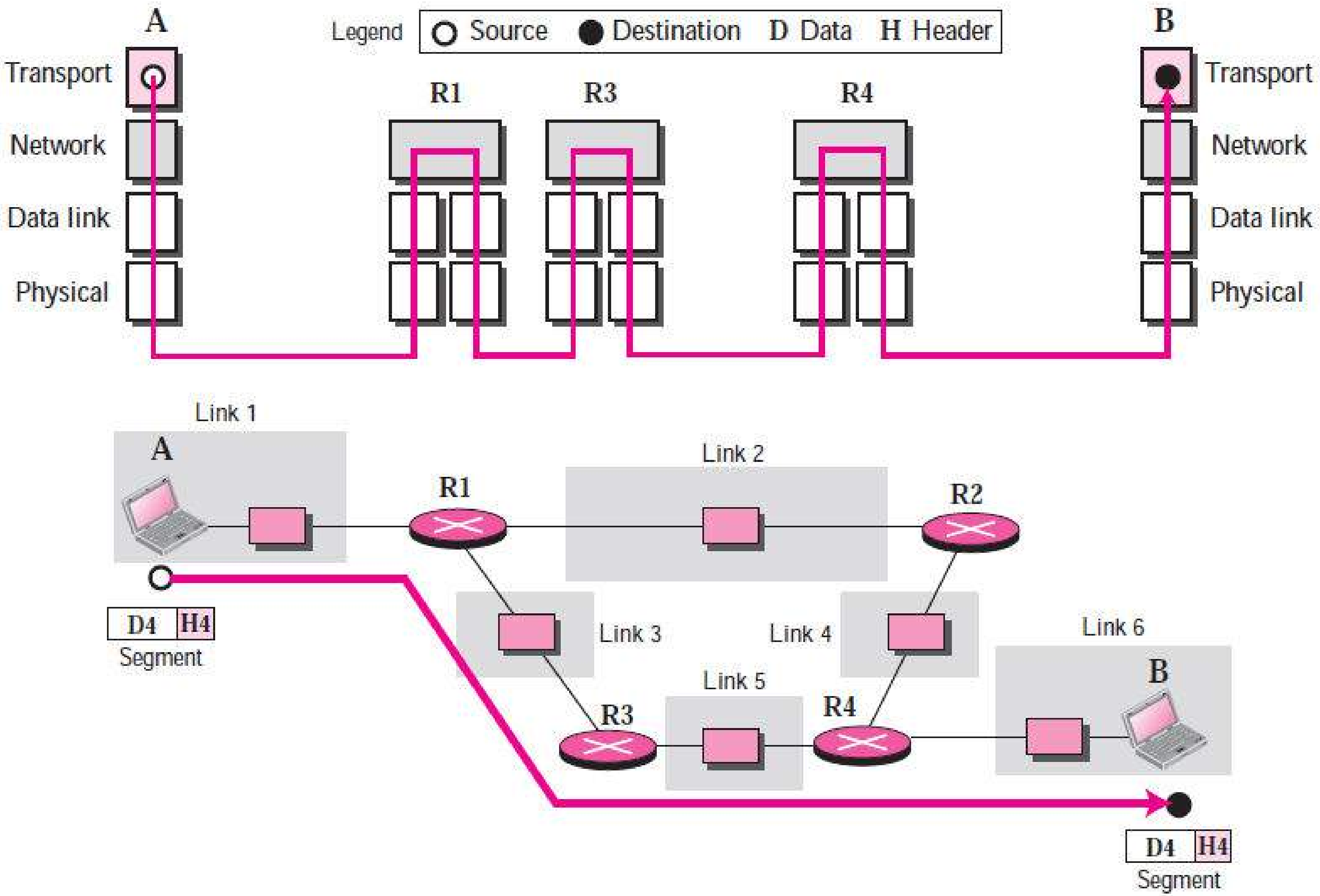
Layers in the TCP/IP Protocol Suite (more)



Communication at the transport layer

Unit of Communication – segment/packet

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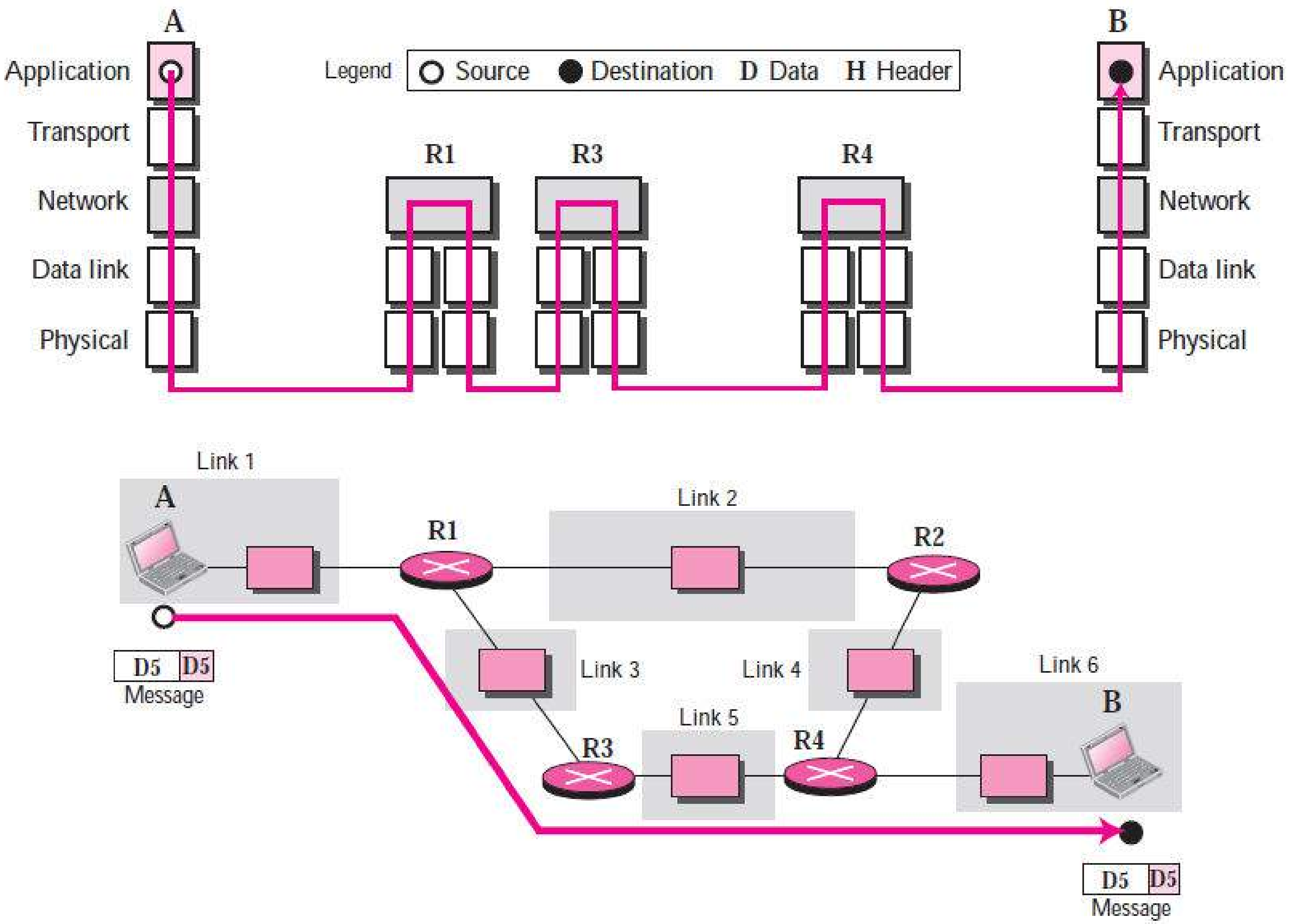
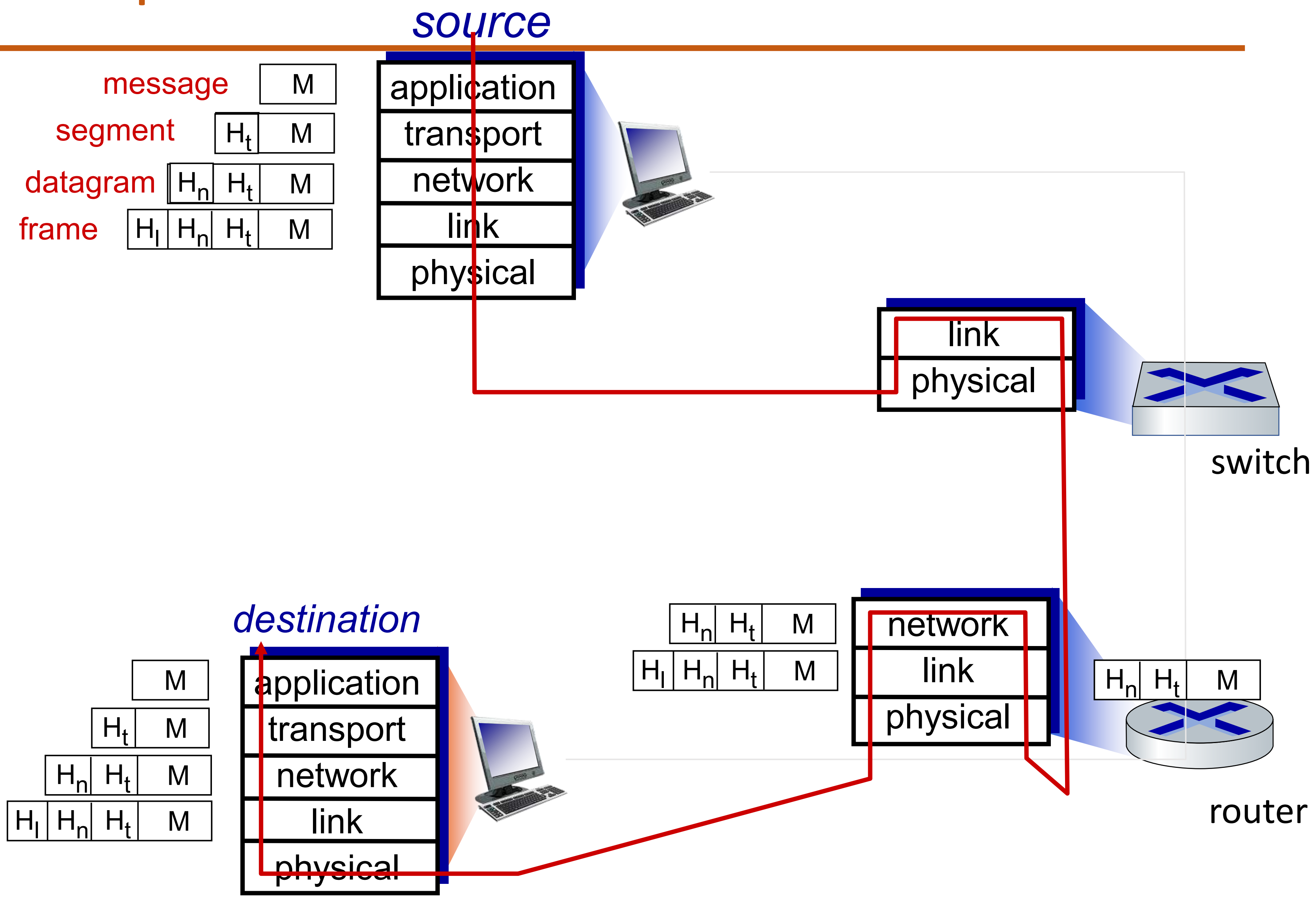
Layers in the TCP/IP Protocol Suite (more)



Communication at the application layer

Unit of Communication – message

Encapsulation – Data Communication in Protocol Stack



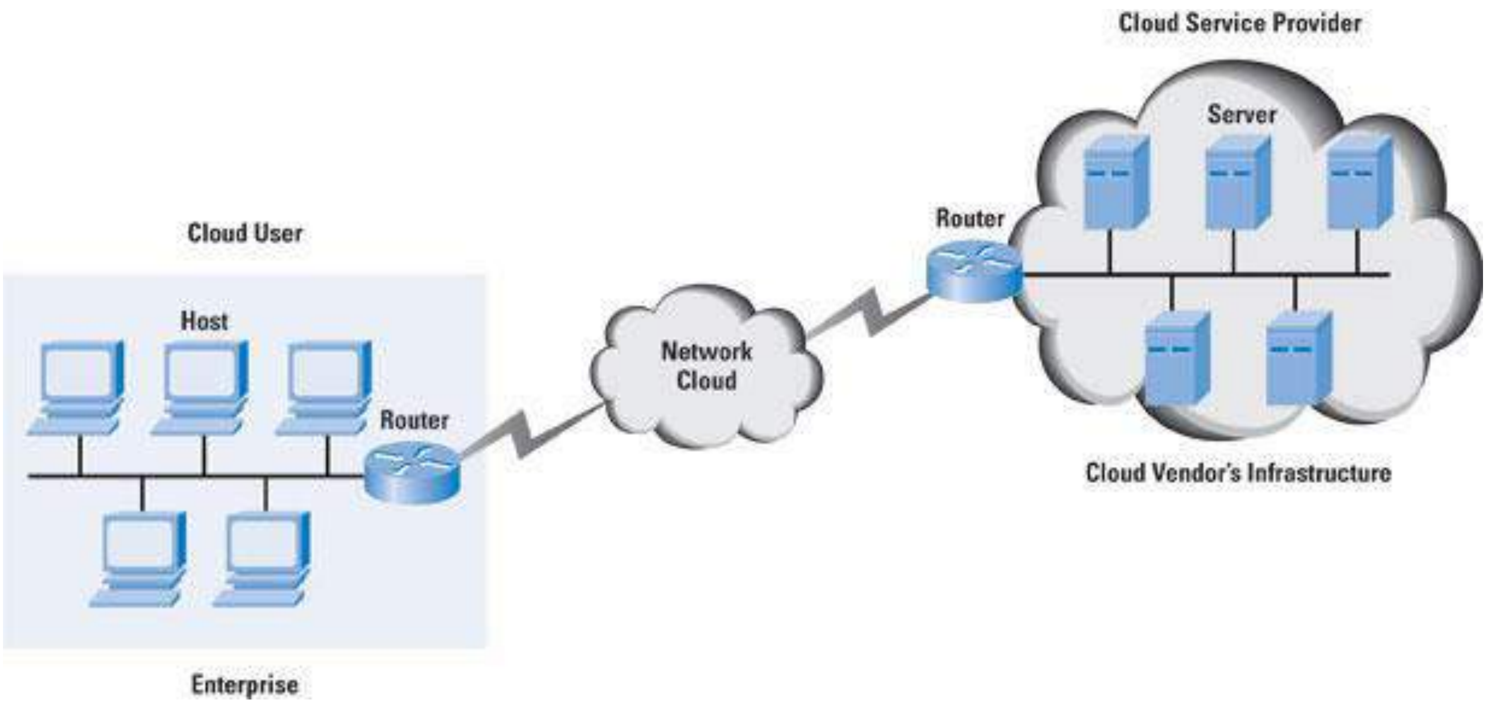
Definition

- Cloud computing is a model
  - for enabling ubiquitous, convenient, on-demand network access
  - a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services)
  - can be rapidly provisioned and released with minimal management effort or service provider interaction.
- This cloud model is composed of:
  - five essential characteristics
  - three service models
  - four deployment models

NIST Cloud Computing Program

Cloud Networking (SD-CN)

- Hosting some or all of an organization's networking resources/services from the cloud.
- Network -> cloud-enabled or entirely cloud-based.



Cloud enabled networking

- Network is on premises, but some or all resources used to manage it are in the cloud.
- Core network infrastructure – packet forwarding, routing, and data— remains in-house.
- Others like network management, monitoring, maintenance, and security services are done through the cloud.

Cloud based networking

- Entire network is in the cloud.
- Includes network management resources and physical hardware

Summary

We've covered a "ton" of material!

- Computer Networks overview
- 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
- Introduction to cloud computing

You now have:

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

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Q&A

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