COMP214-21121/21221 Computer Networks

Teacher: Dr. Xu Yang

General Information

- Teacher: Xu Yang
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- Office Hours: Monday and Tuesday Afternoon
- Assessment
  - Assignments, home-based, 30%
  - One Test, class-based, 20%
  - Final exam, class-based, 50%
- Textbook
  - J. F. Kurose and K. W. Ross, Computer Networking-A Top-Down Approach (6th edition). Addison Wesley Higher Education.

General Information

Five Chapters

- Chapter 1: Computer Networks and the Internet (2 weeks).
- Chapter 2: Application Layer (2 weeks)
- Chapter 3: Transport Layer (3 weeks+)
- Chapter 4: The Network Layer (3 weeks+)
- Chapter 5: The Link Layer (2 weeks)

Lab exercises: Wireshark

- 1. Architecture
- 2. Protocols

Why do you need to learn this course?

Average Salary (2018)

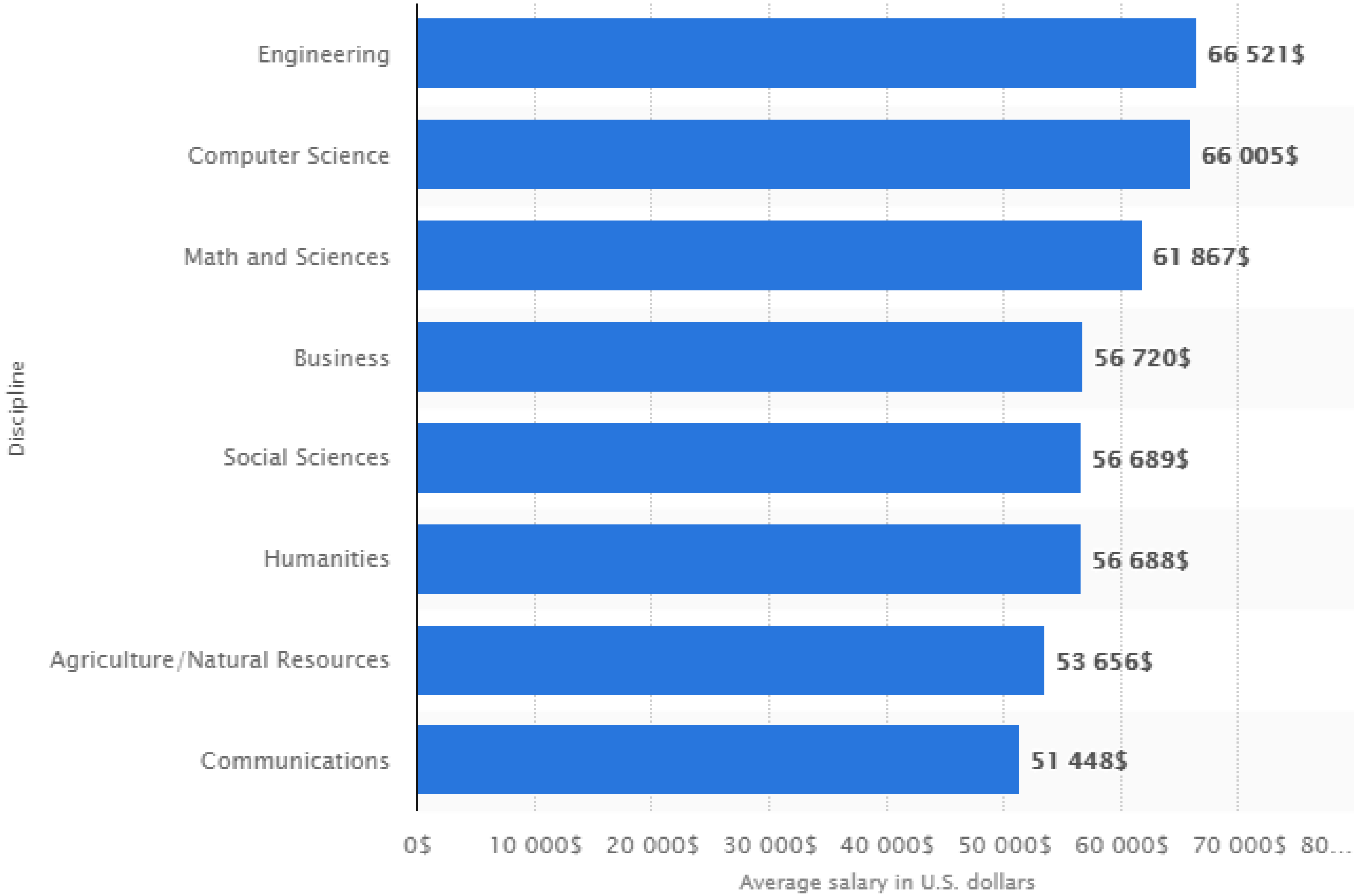
Why do you need to learn this course?

2018, China

互联网	
百度	13k*14.6
阿里	13k-18k*15
腾讯	12k-14k*16
网易	11k-15k*14
谷歌中国	研发年薪25W
亚马逊	9k-12k*13
京东	8k-11k*13
奇虎360	13k-16k*14
新浪	8.5-12.5k*14
搜狐	12-14k*14
搜狗	9-12k*13
美团	13k-16k*15
去哪儿	13-14k*14
携程	6-8k*13
创新工场	10k*13
网易游戏	12-14k*14
4399	7-9k*13

Why do you need to learn this course?

2018, average salaries for bachelor's degree in USA ($)



The Future of the Internet

- **2016 video :** https://www.youtube.com/watch?v=OQ9P1W_-E1U

- https://www.youtube.com/watch?v=A4fEVgILGos&vl=en

Chapter 1

Computer Networks and the Internet.

Chapter 1: roadmap

1.1 what *is* the Internet?

1.2 network edge

- end systems, access networks, links

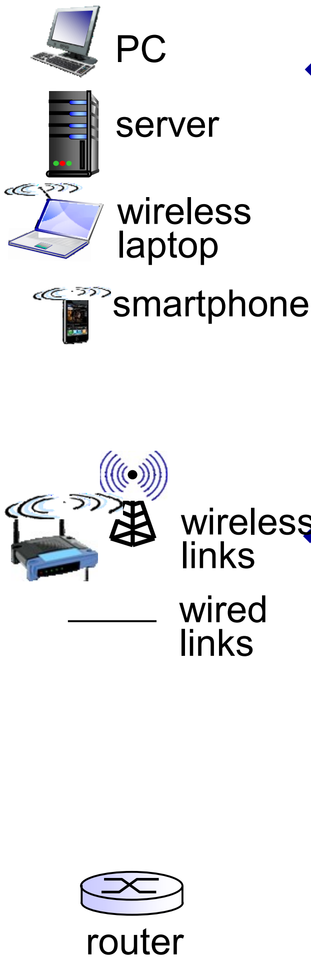
1.3 network core

- packet switching, circuit switching, network structure

1.4 delay, loss, throughput in networks

1.5 protocol layers, service models

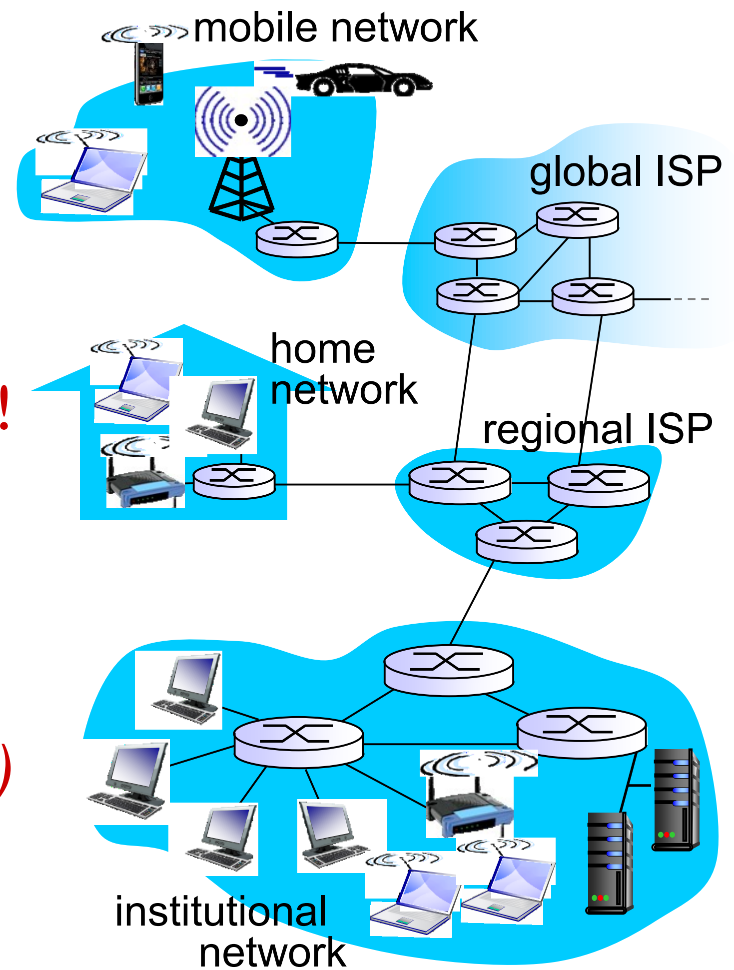
What's the Internet: "nuts and bolts" view



- Hundreds of millions of connected computing devices:
  - *hosts* = *end systems*
  - running *network apps*

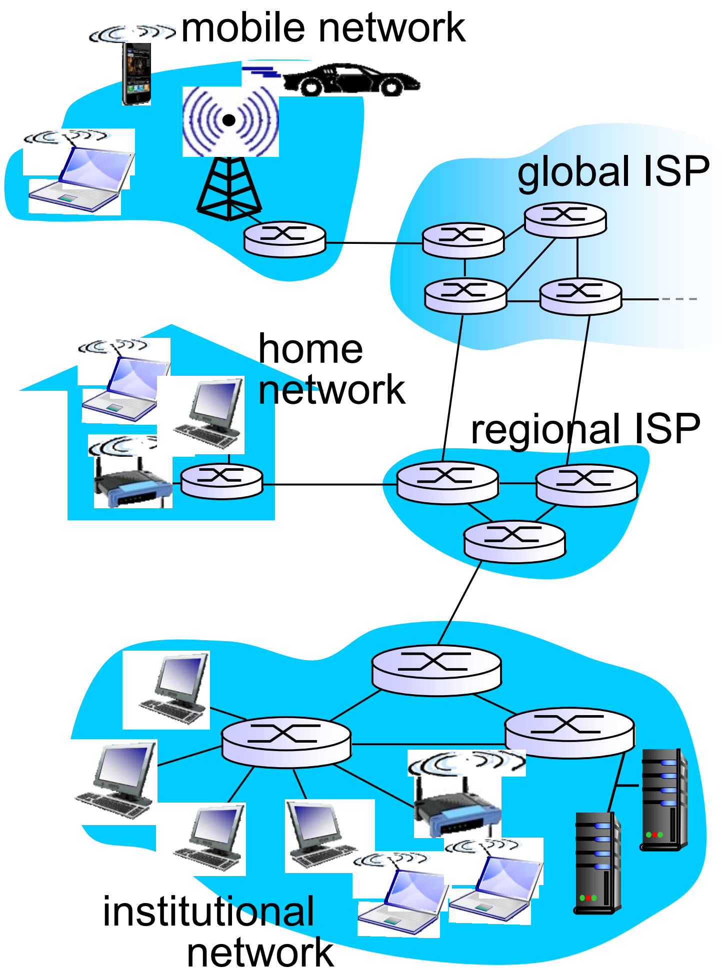
Even more in the future!

- *communication links*
  - fiber, copper, radio, satellite
  - transmission rate: *bandwidth (bits/second)*
- *Packet switches:* forward packets (chunks of data)
  - *routers* and *switches*



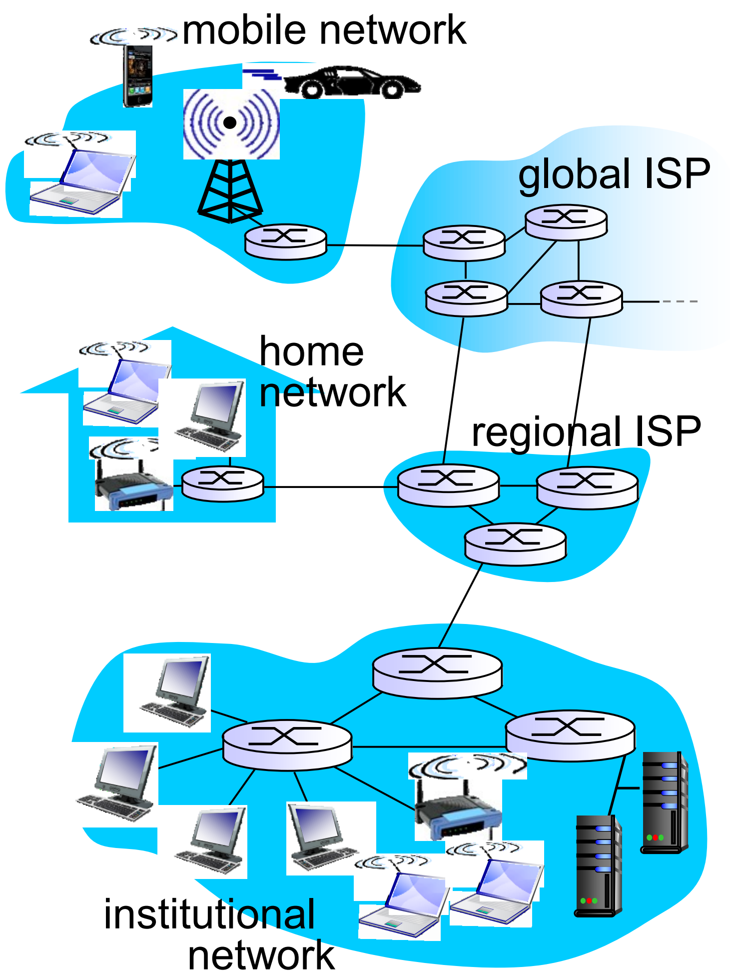
What's the Internet: "nuts and bolts" view

- *Internet:* "network of networks"
  - End systems access the internet through ISPs (Internet Service Provider)
  - Interconnected ISPs
  - ISPs provide network access to hosts and content provider.
- *protocols* control sending and receiving of msgs within the internet
  - e.g., TCP, IP, HTTP, Skype, 802.11
- *Internet standards*
  - RFC: Request for comments
  - IETF: Internet Engineering Task Force



What' s the Internet: a service view

- *Infrastructure that provides services to applications:*
  - Web, VoIP, email, games, e-commerce, social nets, …
- *provides application programming interface (API) to apps*
  - hooks that allow sending and receiving app programs to "connect" to Internet
  - provides service options, analogous to postal service



What's a protocol?

human protocols:

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

… specific msgs sent

… specific actions taken when msgs received, or other events

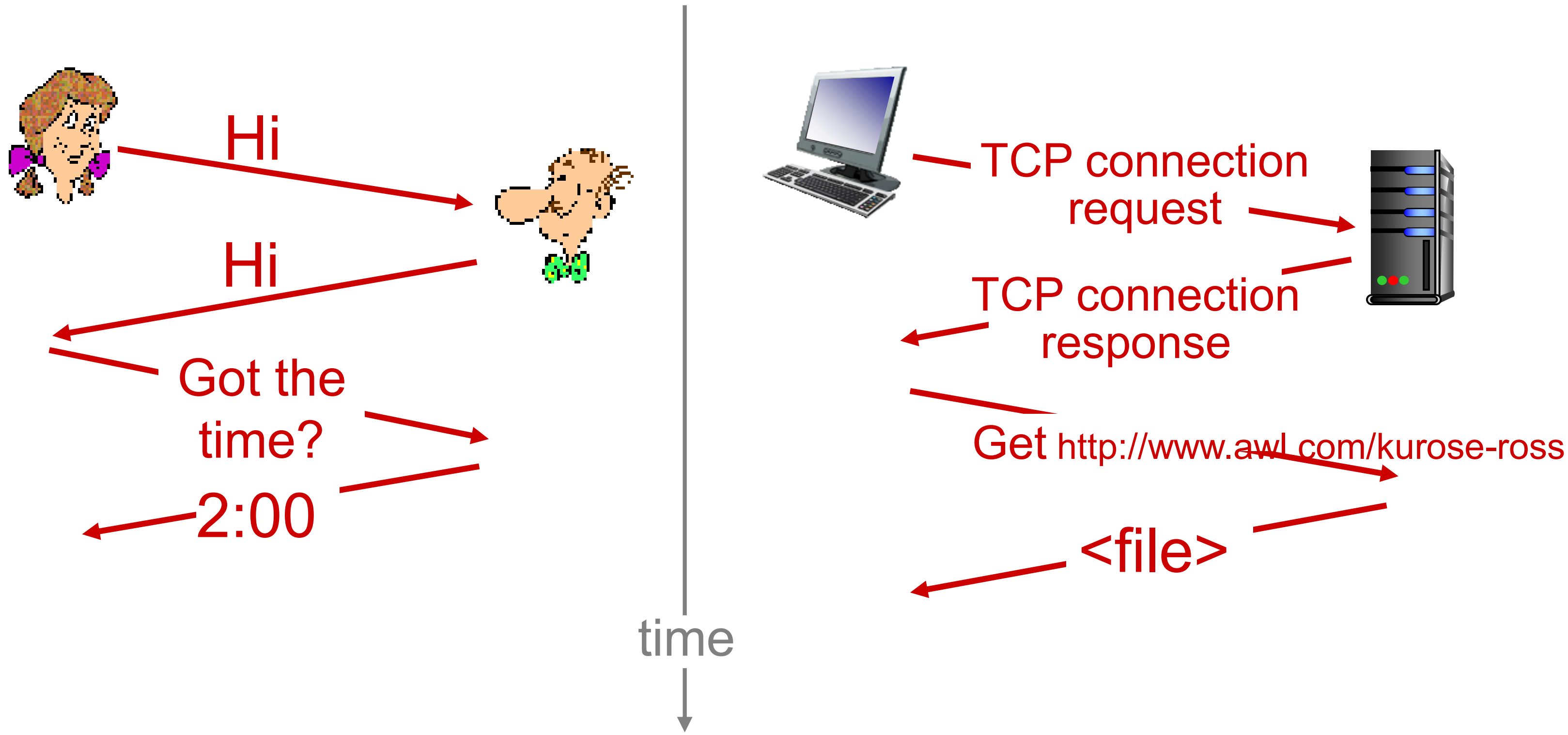
network protocols:

- machines rather than humans
- all communication activity in Internet governed by protocols

protocols define format, order of msgs sent and received among network entities, and actions taken on the transmission and/or receipt of a message or other events

What's a protocol?

a human protocol and a computer network protocol:



Q: other human protocols?

Chapter 1: roadmap

1.1 what *is* the Internet?

1.2 network edge

- end systems, access networks, links

1.3 network core

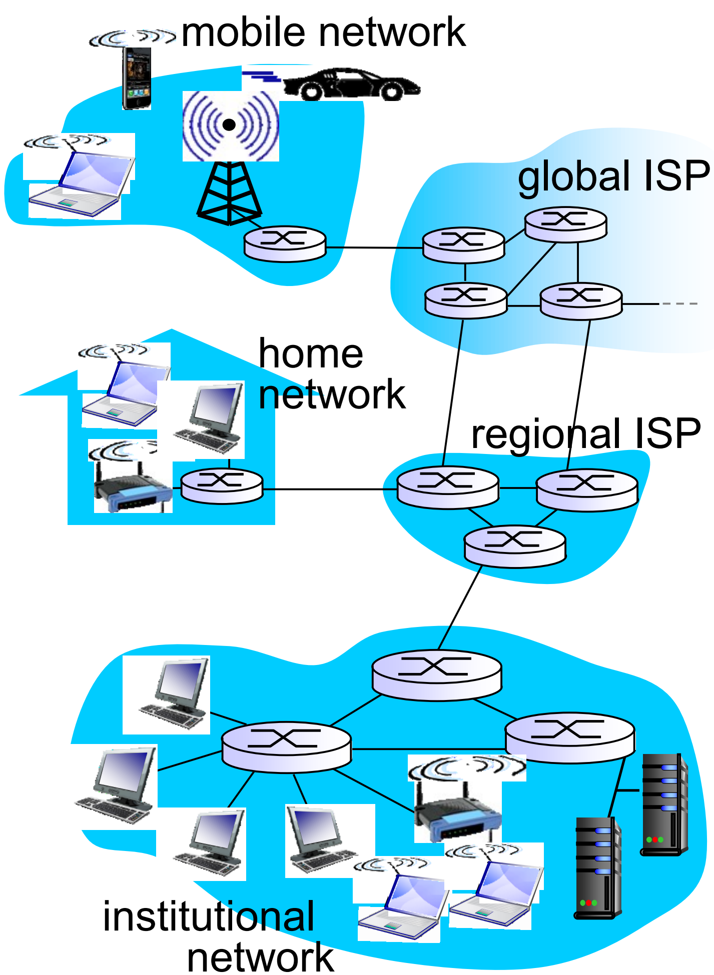
- packet switching, circuit switching, network structure

1.4 delay, loss, throughput in networks

1.5 protocol layers, service models

A closer look at network structure:

- *network edge: at the edge of the network*
  - The devices (such as computer, mobile phone…), referred as hosts (clients and servers).
- *Access Networks, physical media:*
  - Physically connects an end system to the first router (edge router)
  - wired, wireless communication links
- *network core:*
  - interconnected routers
  - network of networks



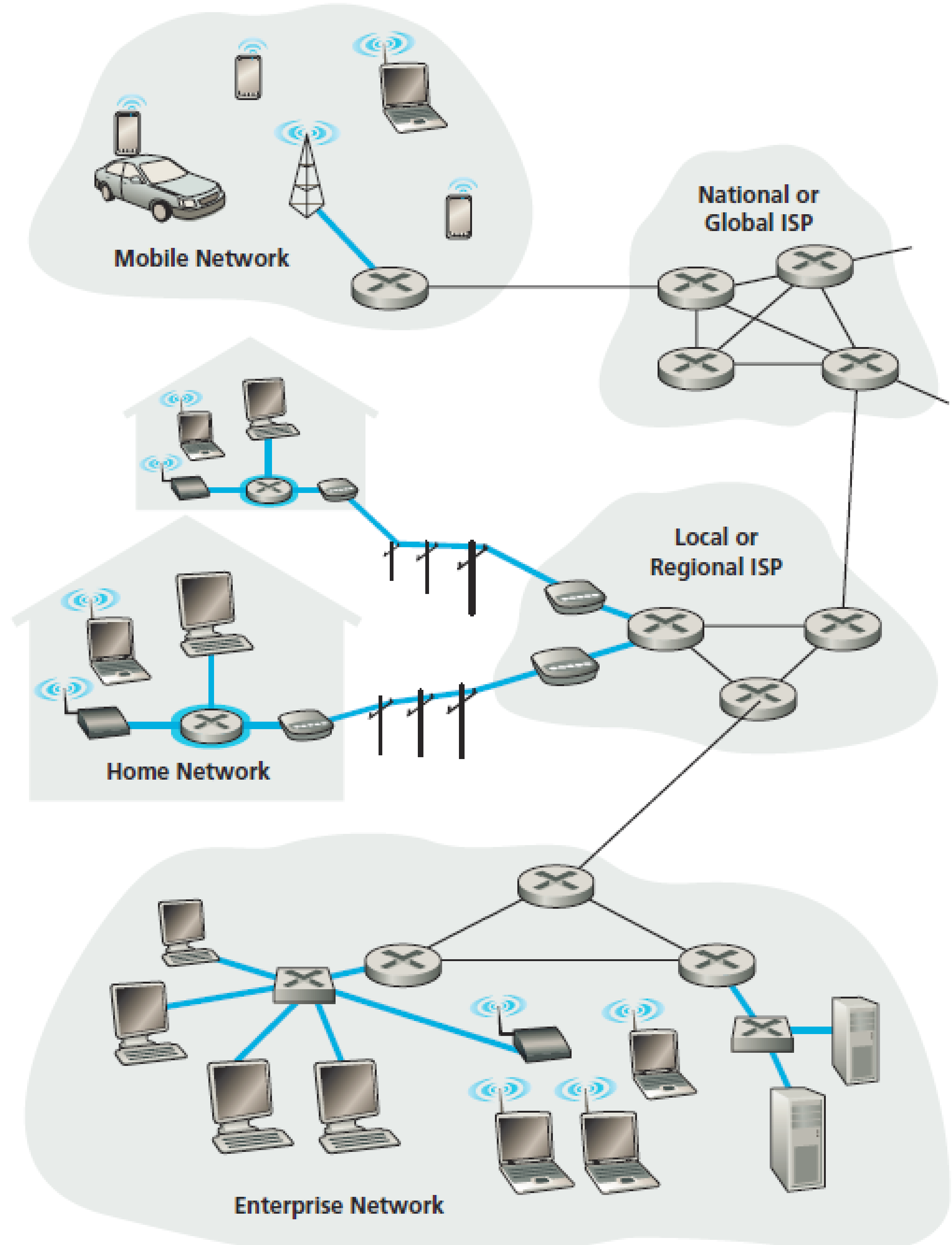
Access network and access links

- *The access link*
  - The communication links that connect an end system to the edge router (the first router on a path).
  - Fiber optics, twisted-pair copper wire, coaxial cable, radio, satellite.
  - Different links have different capability of transmitting messages.
- *Access network*
  - The part of network that connects end systems to its edge router.
  - It is the network sitting at the edge of the network, and the name of access network is contrasted with the core network, which sits at the central of the network.
- *network core:*
  - interconnected routers
  - network of networks

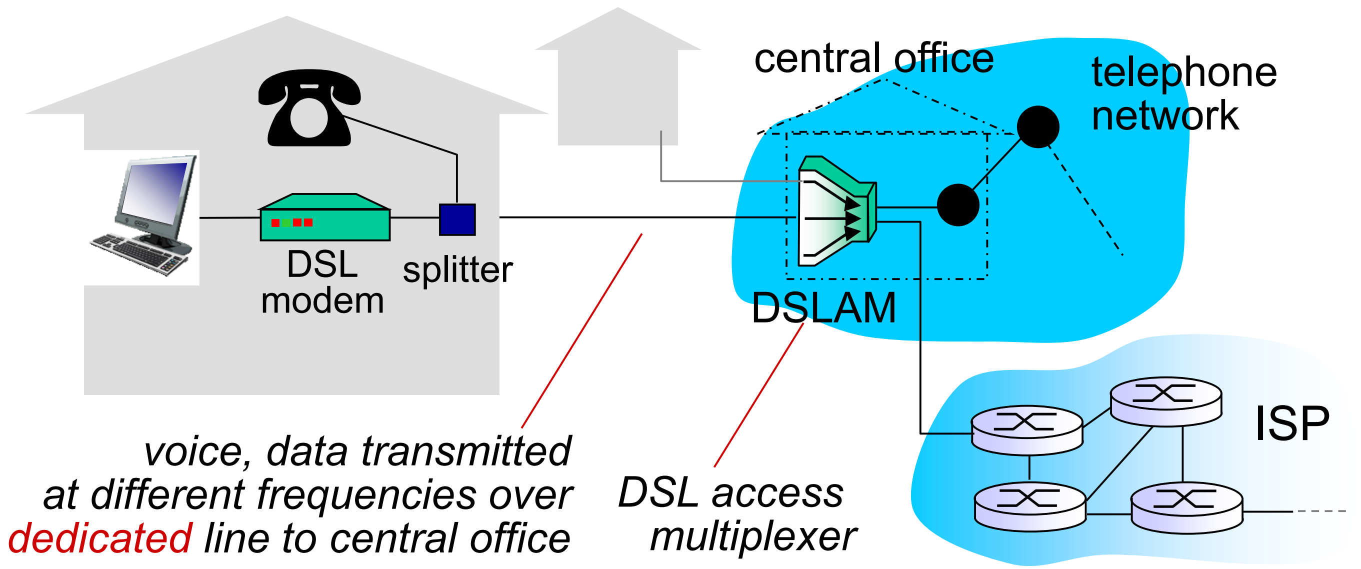
Access networks

Q: How to connect end systems to edge router?

- residential access networks
- institutional access networks (school, company)
- mobile access networks

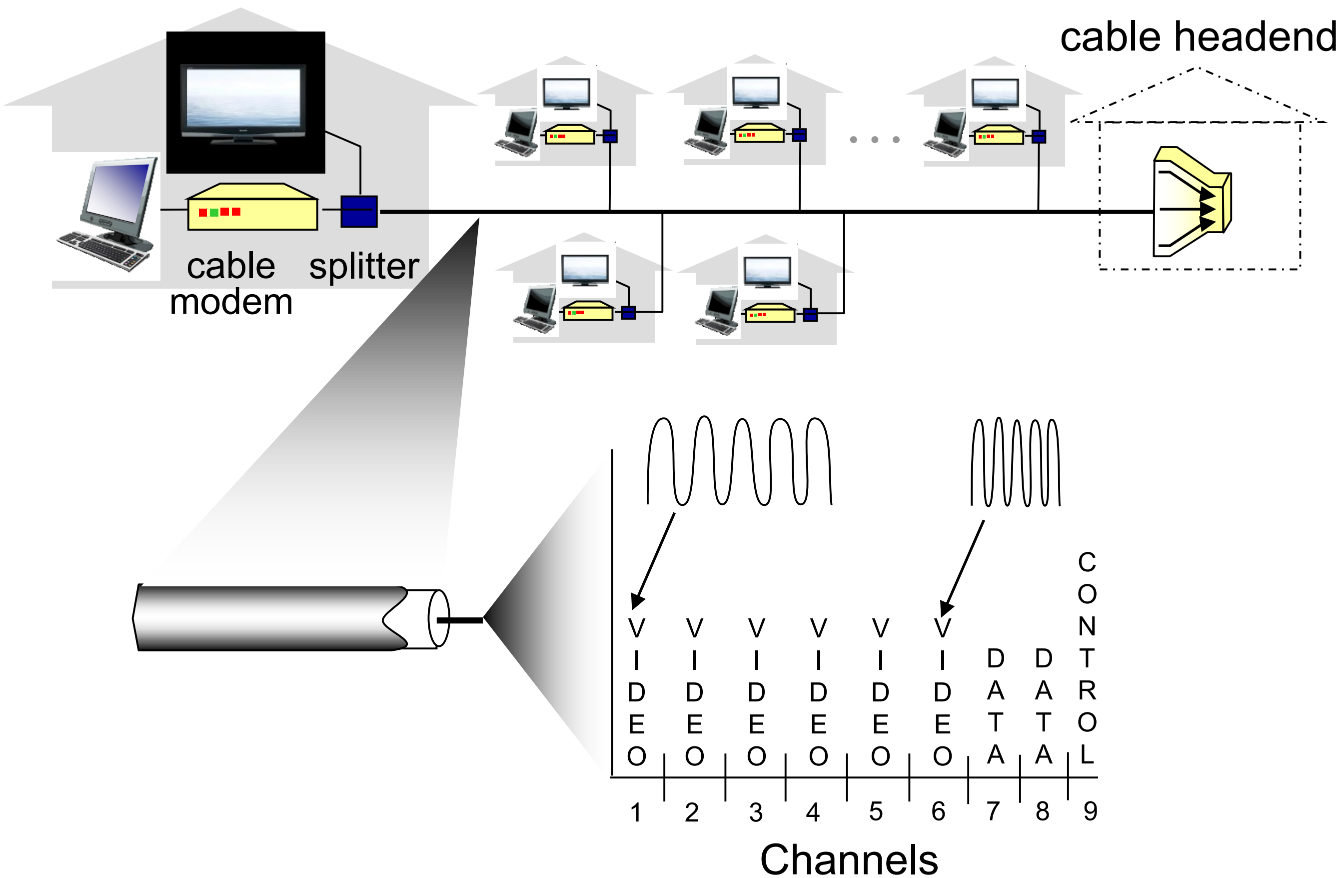


Access net: digital subscriber line (DSL)



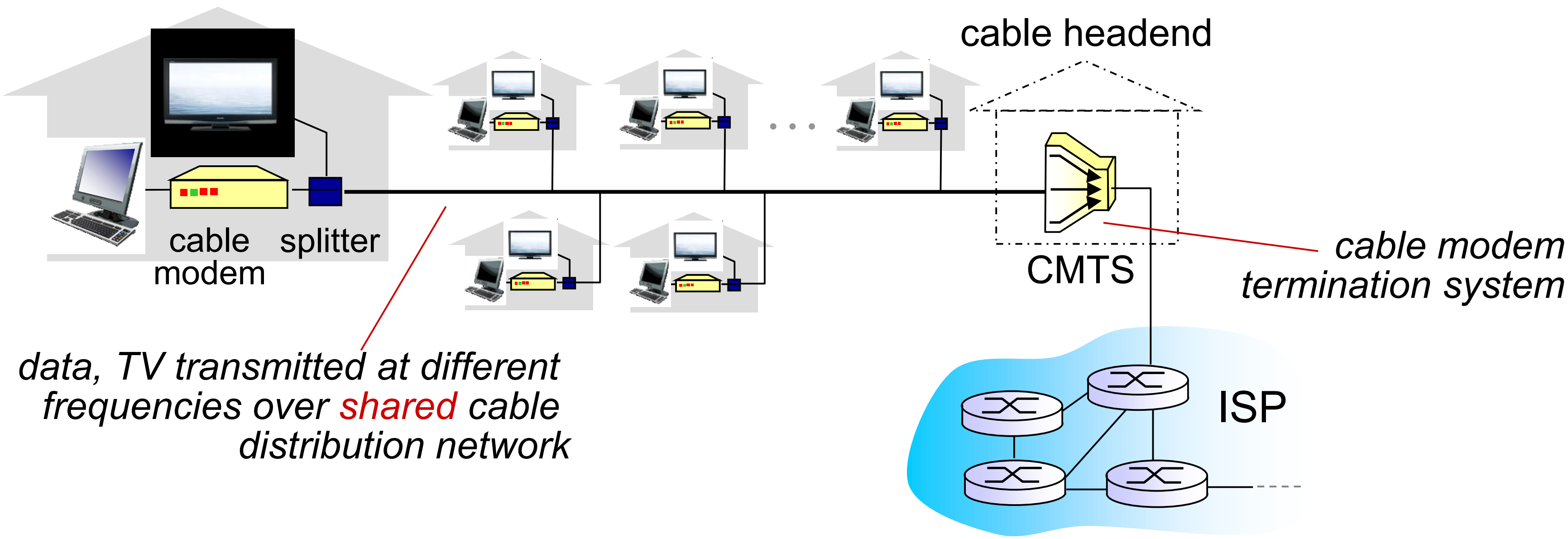
- use *existing* telephone line to central office DSLAM
  - data over DSL phone line goes to Internet
  - voice over DSL phone line goes to telephone net
- < 2.5 Mbps upstream transmission rate (typically < 1 Mbps)
- < 24 Mbps downstream transmission rate (typically < 10 Mbps)

Access net: cable network



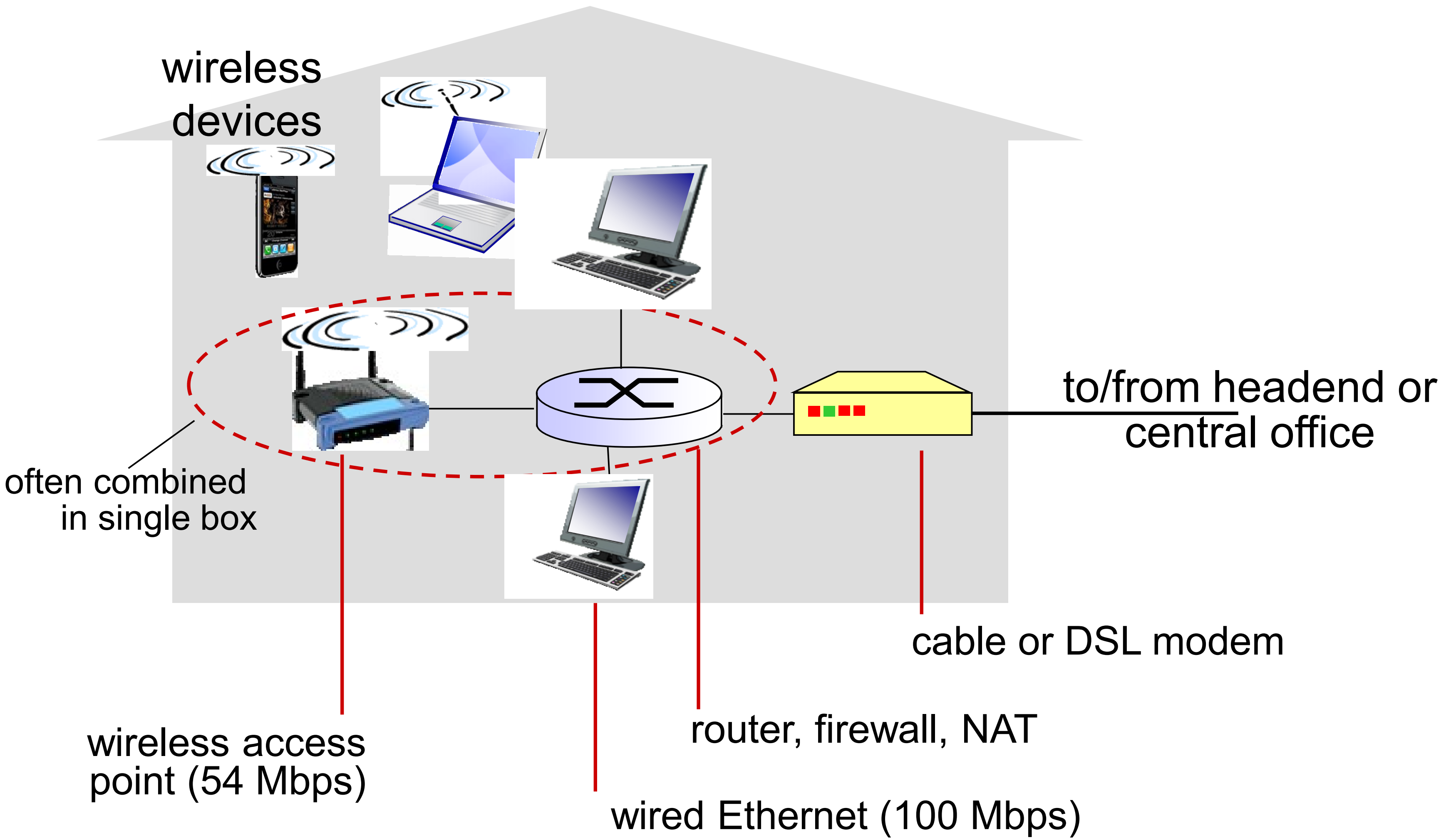
frequency division multiplexing: different channels transmitted in different frequency bands

Access net: cable network

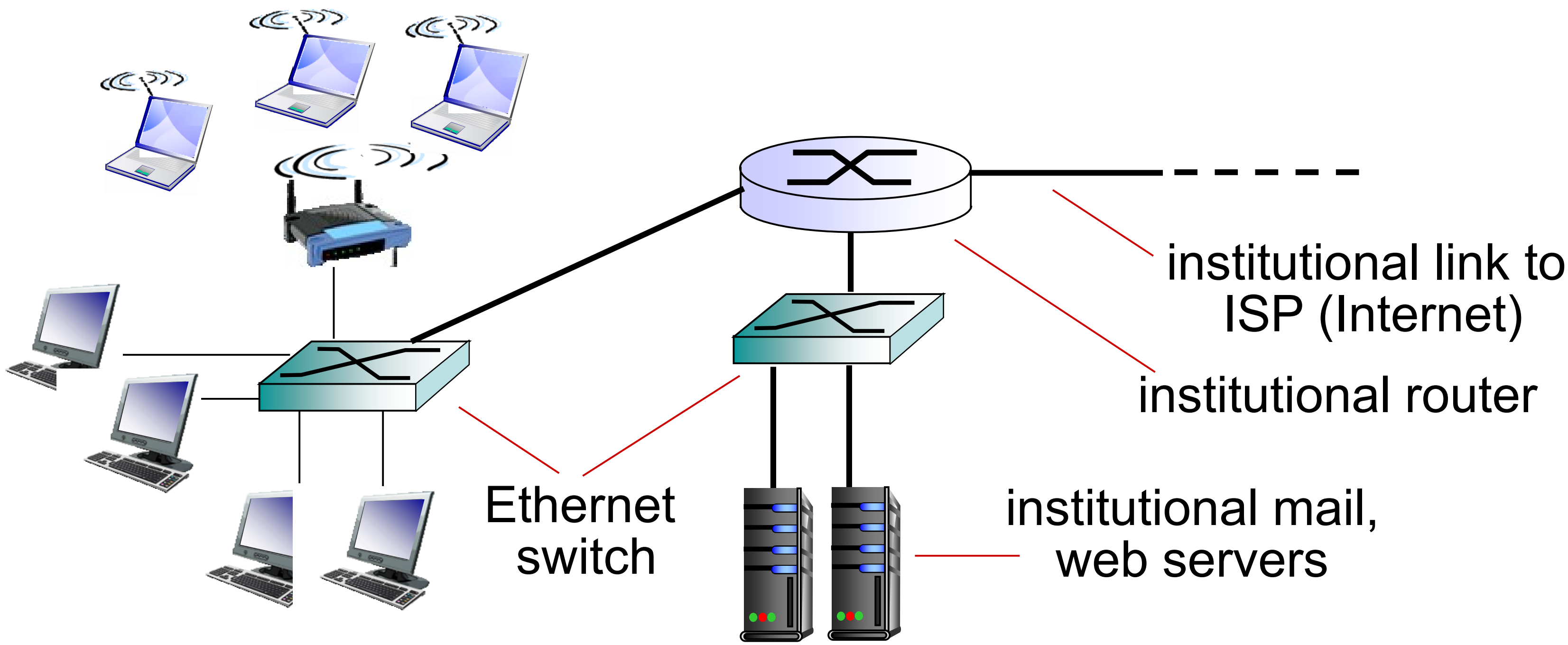


- HFC: hybrid fiber coax
  - asymmetric: up to 30Mbps downstream transmission rate, 2 Mbps upstream transmission rate
- network of cable, fiber attaches homes to ISP router
  - homes *share access network* to cable headend
  - unlike DSL, which has dedicated access to central office

Access net: home network



Enterprise access networks (Ethernet)



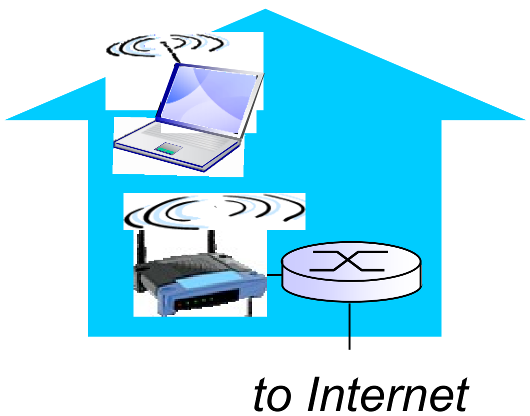
- typically used in companies, universities, etc
- 10 Mbps, 100Mbps, 1Gbps, 10Gbps transmission rates
- today, end systems typically connect into Ethernet switch

Wireless access networks

- shared *wireless* access network connects end system to router
  - via base station aka "access point"

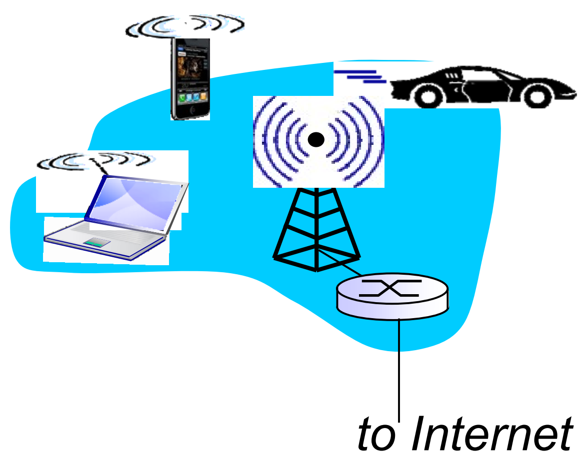
wireless LANs:

- within building (100 ft)
- 802.11b/g (WiFi): 11, 54 Mbps transmission rate



wide-area wireless access

- provided by telco (cellular) operator, 10's km
- between 1 and 10 Mbps
- 3G, 4G: LTE



Physical media

For each transmitter-receiver pair, the bit is sent by propagating electromagnetic waves or optical pulses across a **physical medium**.

- 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 (atmosphere, outerspace), e.g., radio

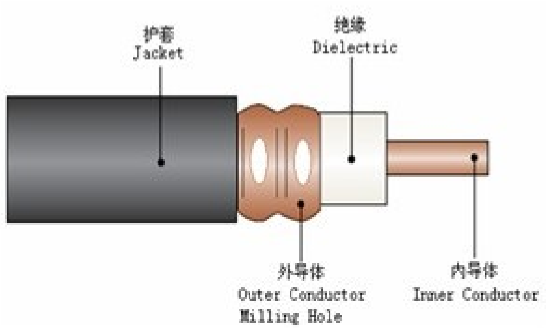
twisted pair (TP)

- two insulated copper wires in a regular spiral pattern
  - Category 5: 100 Mbps, 1 Gpbs Ethernet
  - Category 6: 10Gbps

Physical media: coax, fiber

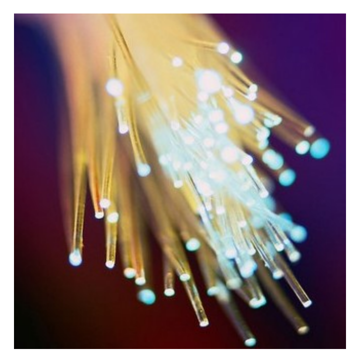
coaxial cable:

- two concentric copper conductors
- bidirectional
- broadband:
  - multiple channels on cable
  - HFC
  - Around tens of Mbps



fiber optic cable:

- glass fiber carrying light pulses, each pulse a bit
- high-speed operation:
  - high-speed point-to-point transmission (e.g., 10’s-100’s Gbps transmission rate)
- low error rate:
  - repeaters spaced far apart
- Backbone of the Internet, long distance telephone networks.



Physical media: radio

- signal carried in electromagnetic spectrum
- no physical "wire"
- bidirectional
- propagation environment effects:
  - reflection
  - obstruction by objects
  - interference

radio link types:

- terrestrial microwave
  - e.g. up to 45 Mbps channels
- LAN (e.g., WiFi)
  - 11Mbps, 54 Mbps
- wide-area (e.g., cellular)
  - 3G cellular: ~ few Mbps
- satellite
  - Kbps to 45Mbps channel (or multiple smaller channels)
  - 270 msec end-end delay
  - geosynchronous versus low altitude
- LIFI !

Chapter 1: roadmap

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1.2 network edge

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1.3 network core

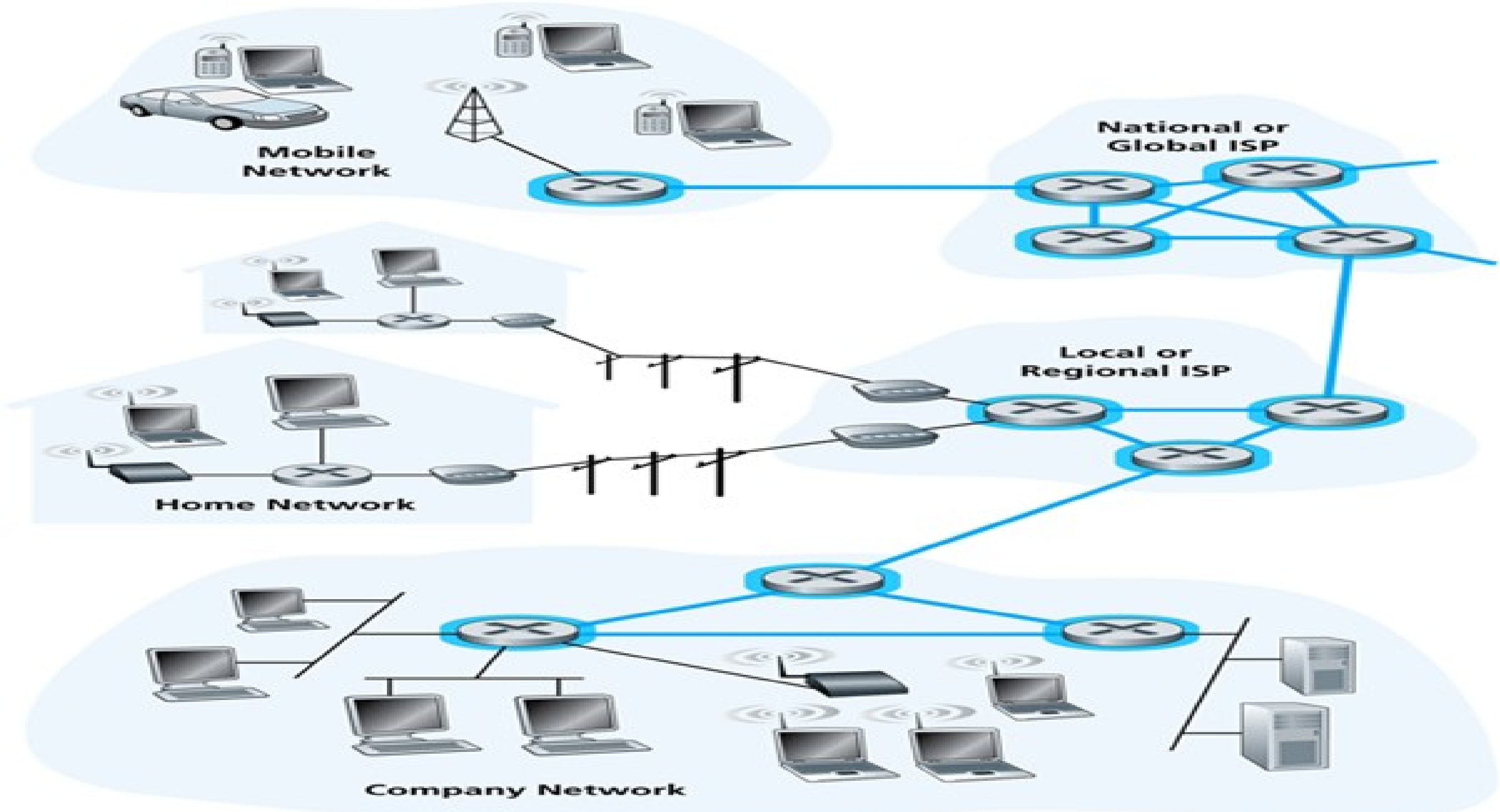
- packet switching, circuit switching, network structure

1.4 delay, loss, throughput in networks

1.5 protocol layers, service models

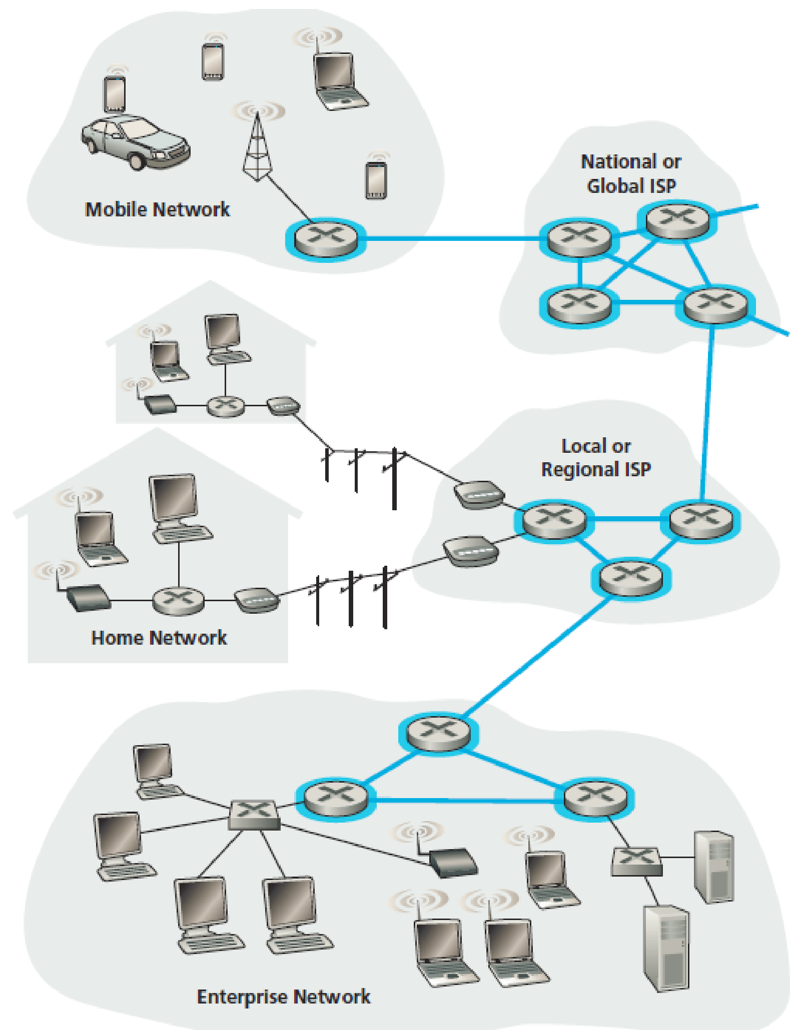
How is data transferred through a network

Network provides services for end systems/hosts by sending and receiving data over the networks. How is data transmitted through the core network?



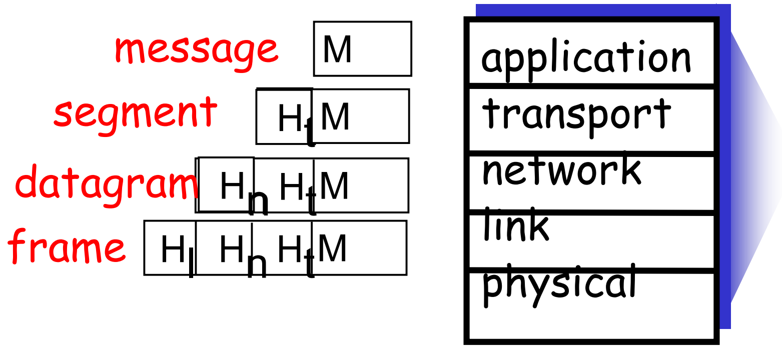
The network core

- Core Network: mesh of interconnected routers
- Some natural questions
  - How is data transferred through network core?
  - How is data transmitted through each link, switch, or router in a network?
- Two fundamental approaches:
  - Circuit-switching
  - Packet-switching

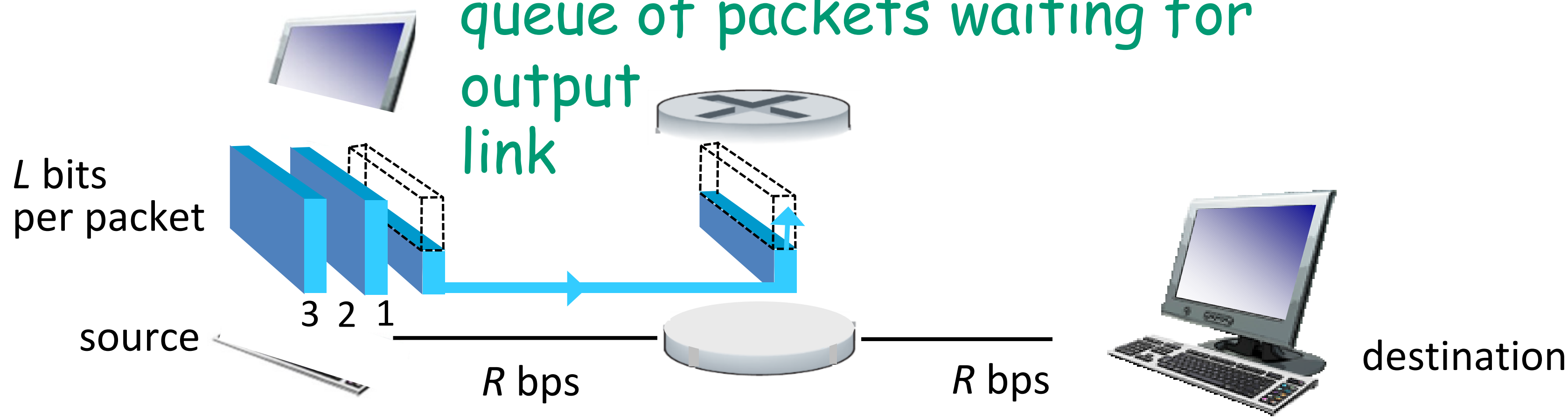


Packet Switching

- packet-switching:
  - hosts break application-layer messages into *packets.* Packet is specially formatted unit.
  - forward packets from one router to the next, across links on path from source to destination
  - each packet transmitted at full link capacity.
  - Each packet has to find its own route to the destination, and there are no predefined path.
  - Once all the packets forming a message arrive at the destination, they are recompiled into the original message.



Packet-switching: store-and-forward



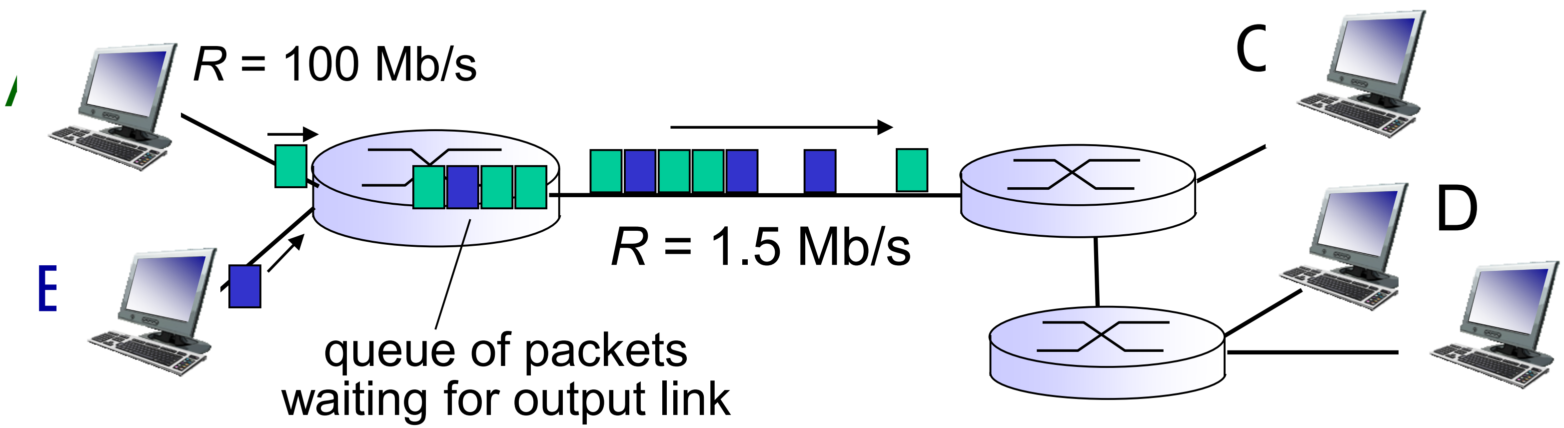
- takes *L*/*R* seconds to transmit (push out) *L*-bit packet into link at *R* bps
- *store and forward:* entire packet must arrive at router before it can be transmitted on next link
- end-end delay = 2*L*/*R* (assuming zero propagation delay)

more on delay shortly …

one-hop numerical example:

- *L* = 7.5 Mbits
- *R* = 1.5 Mbps
- one-hop transmission delay = L/R=5 sec

Packet Switching: queueing delay, packet loss



queuing and loss:

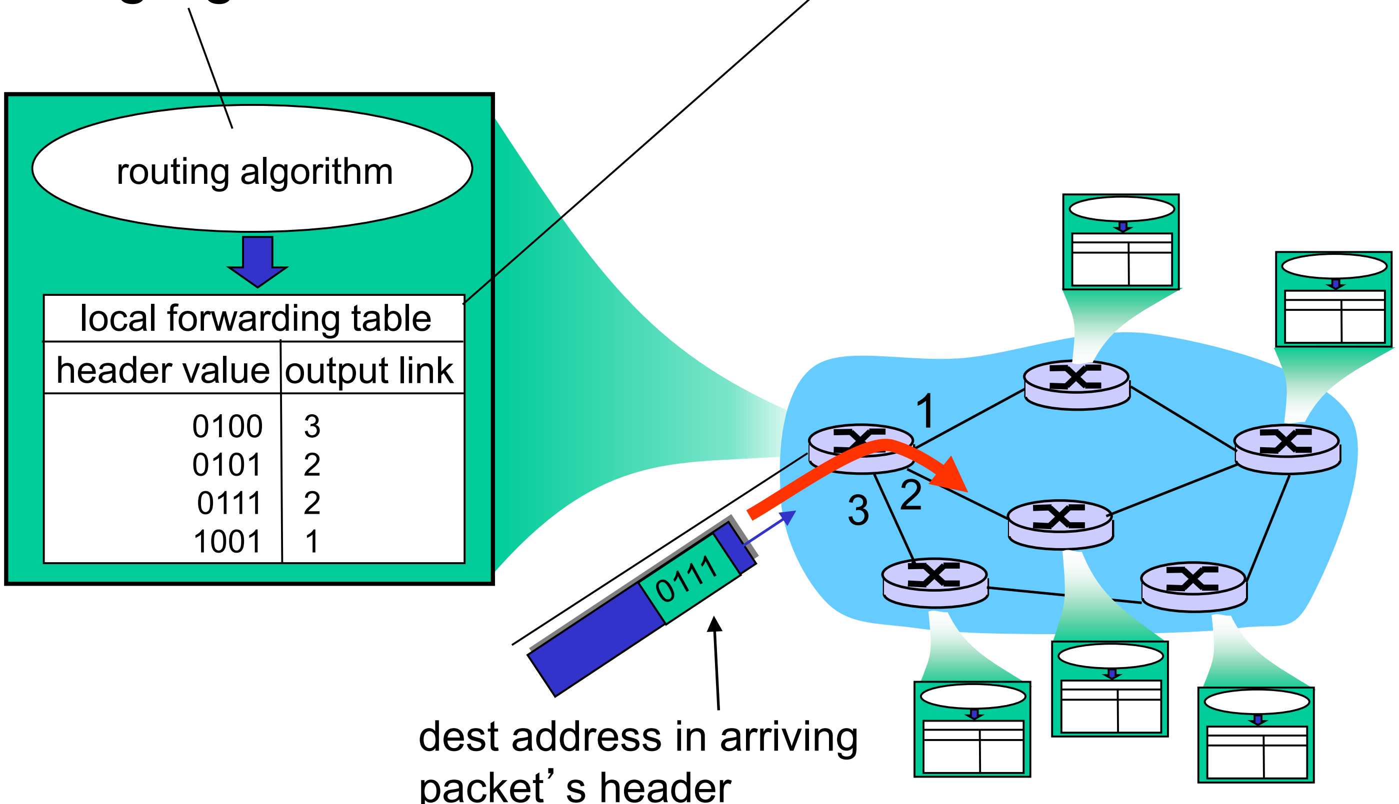
- If arrival rate (in bits) to link exceeds transmission rate of link for a period of time:
  - packets will queue, wait to be transmitted on link
  - packets can be dropped (lost) if memory (buffer) fills up

Two key network-core functions

routing: determines source-destination route taken by packets

- *routing algorithms*

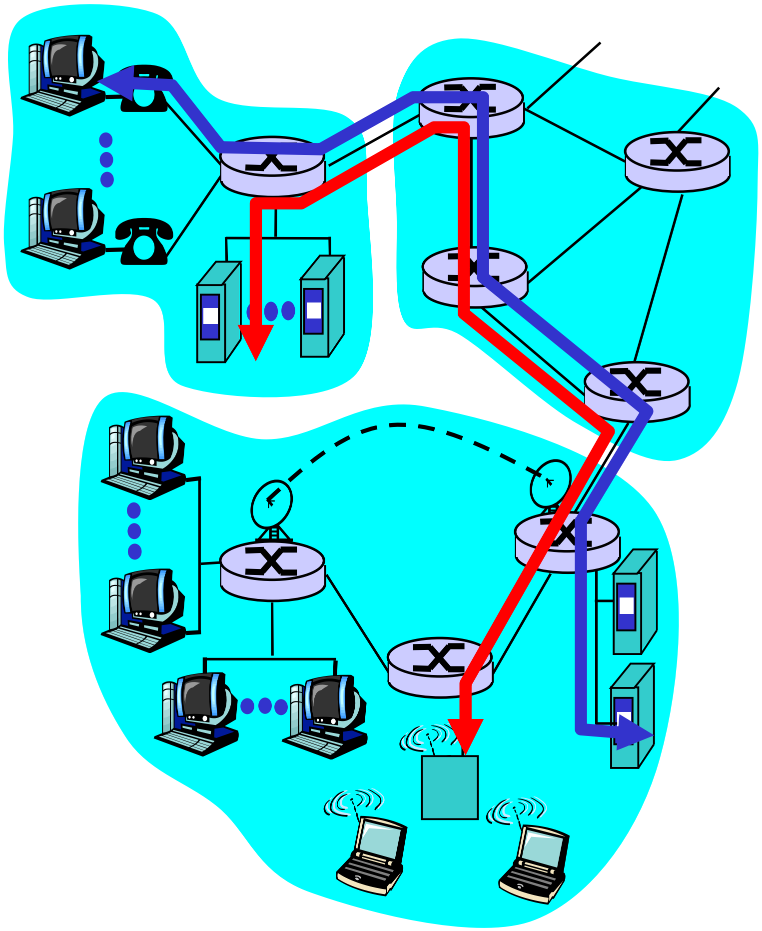
forwarding: move packets from router's input to appropriate router output



Alternative core: circuit switching

Two nodes establish a dedicated communication path (circuit) through the network before the nodes start to communicate.

For the whole length of the communication session between the two communicating nodes, the circuit is dedicated and exclusive, and released only when the session terminates.



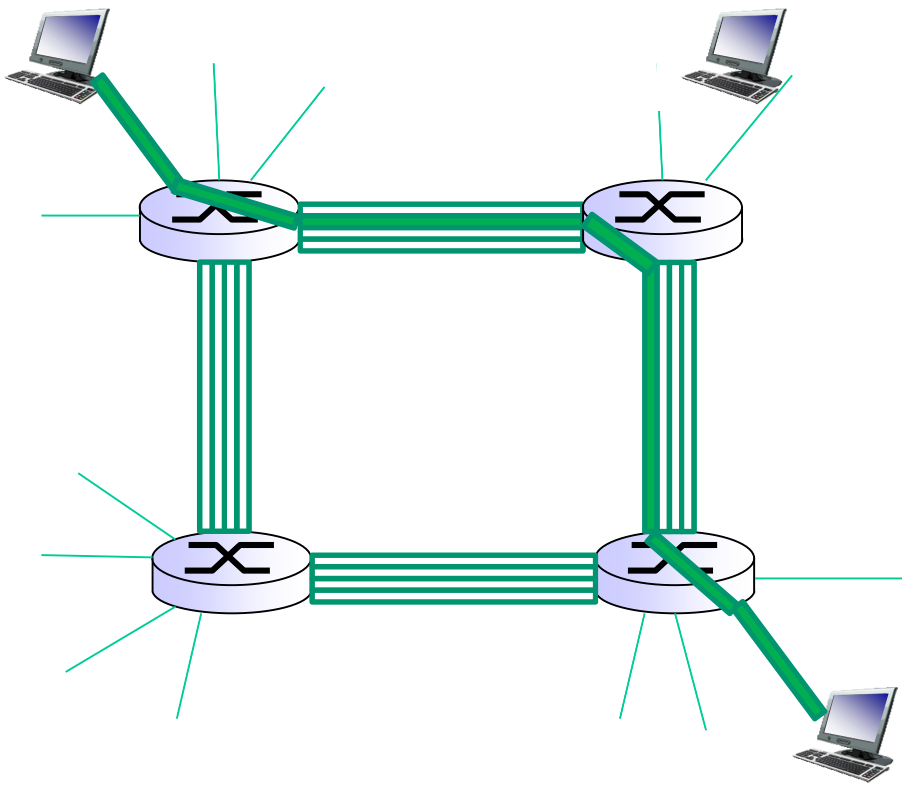
Alternative core: circuit switching

In diagram, each link has four circuits.

- call gets 2nd circuit in top link and 1st circuit in right link.

❖ **Properties**

- Dedicated circuit per call. The end to end resources are reserved for "per call"
- Dedicated resources: no sharing
- Guaranteed transmission capacity
- Call setup is required.
- circuit segment idle if not used by call *(no sharing)*

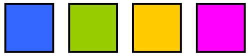


Commonly used in traditional telephone networks

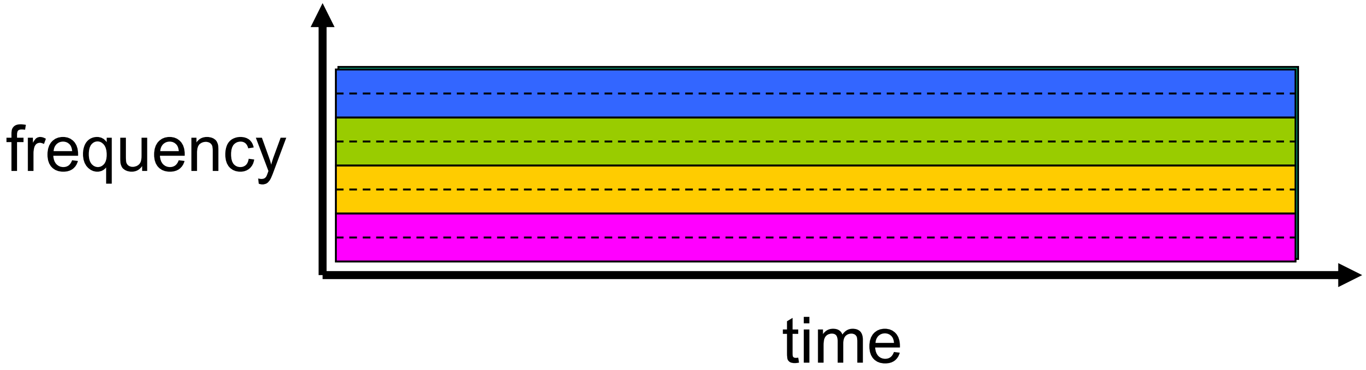
Circuit switching: FDM versus TDM

Example:

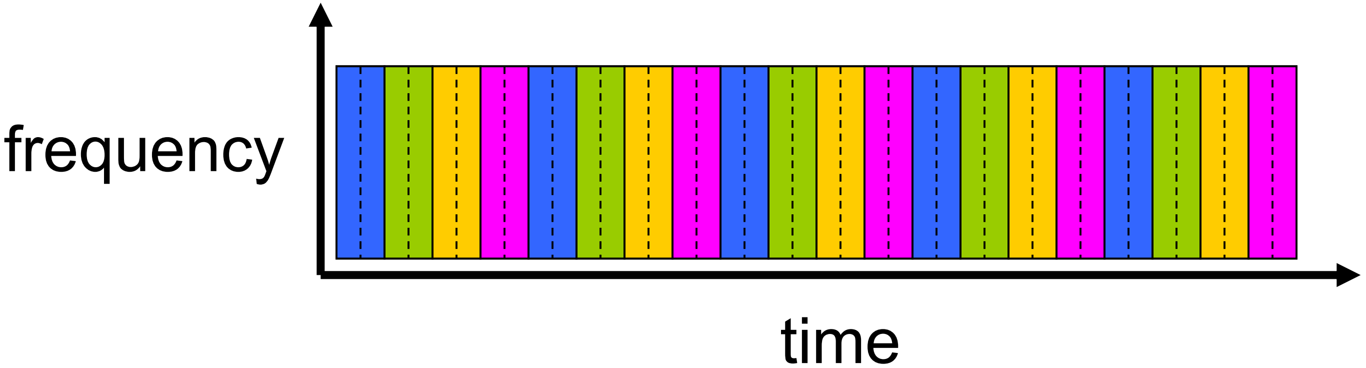
4 users



FDM

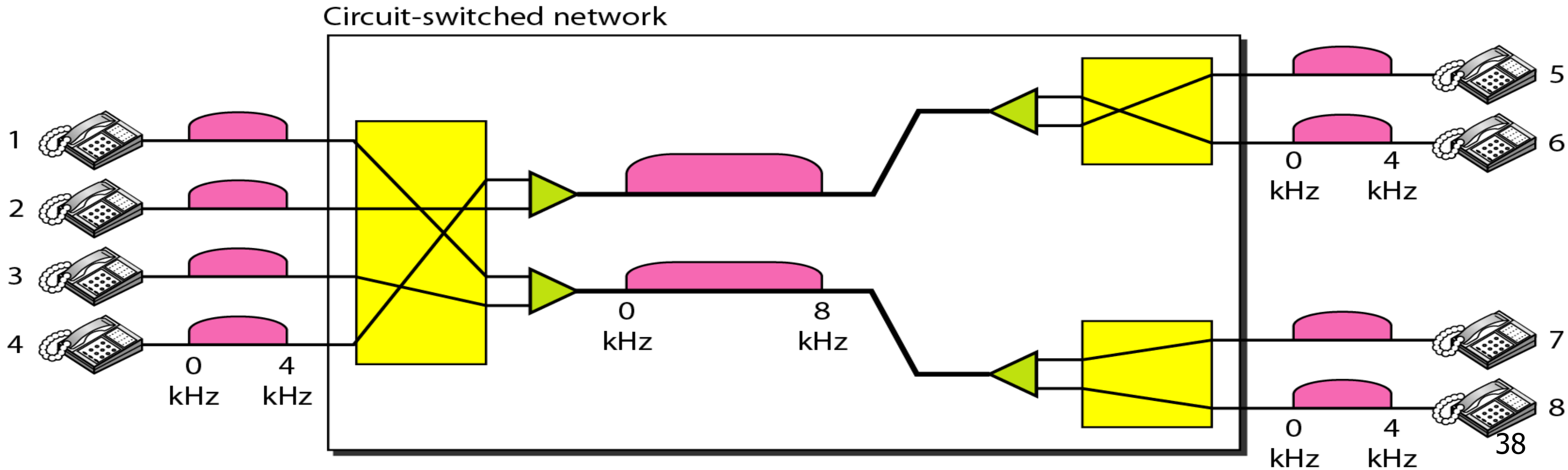


TDM



Circuit-switched Network

- A circuit-switched network consists of a set of switches connected by physical links, in which each link is divided into n channels by using FDM or TDM.
- In circuit-switched network, the resources need to be reserved during the setup phase, and the resources remain dedicated for the entire duration of each collection until the teardown phase.

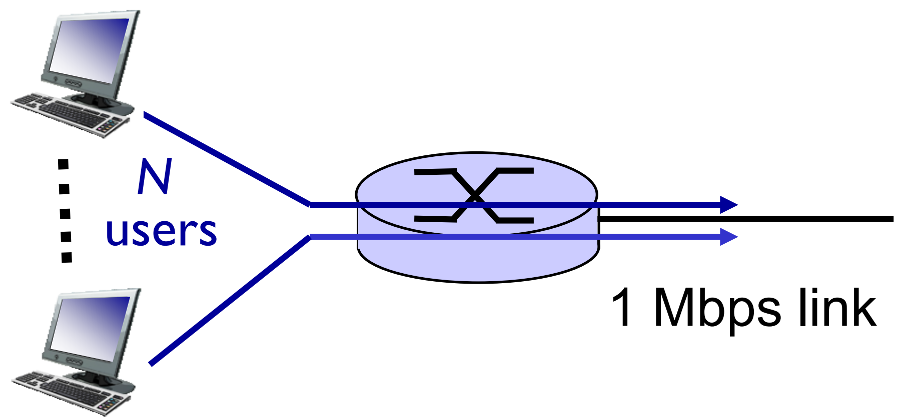


Packet switching versus circuit switching

packet switching allows more users to use network!

example:

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



❖ *circuit-switching:*
- 10 users

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

Q: what happens if > 35 users ?

* Check out the online interactive exercises for more examples

Packet switching versus circuit switching

is packet switching a "slam dunk winner?"

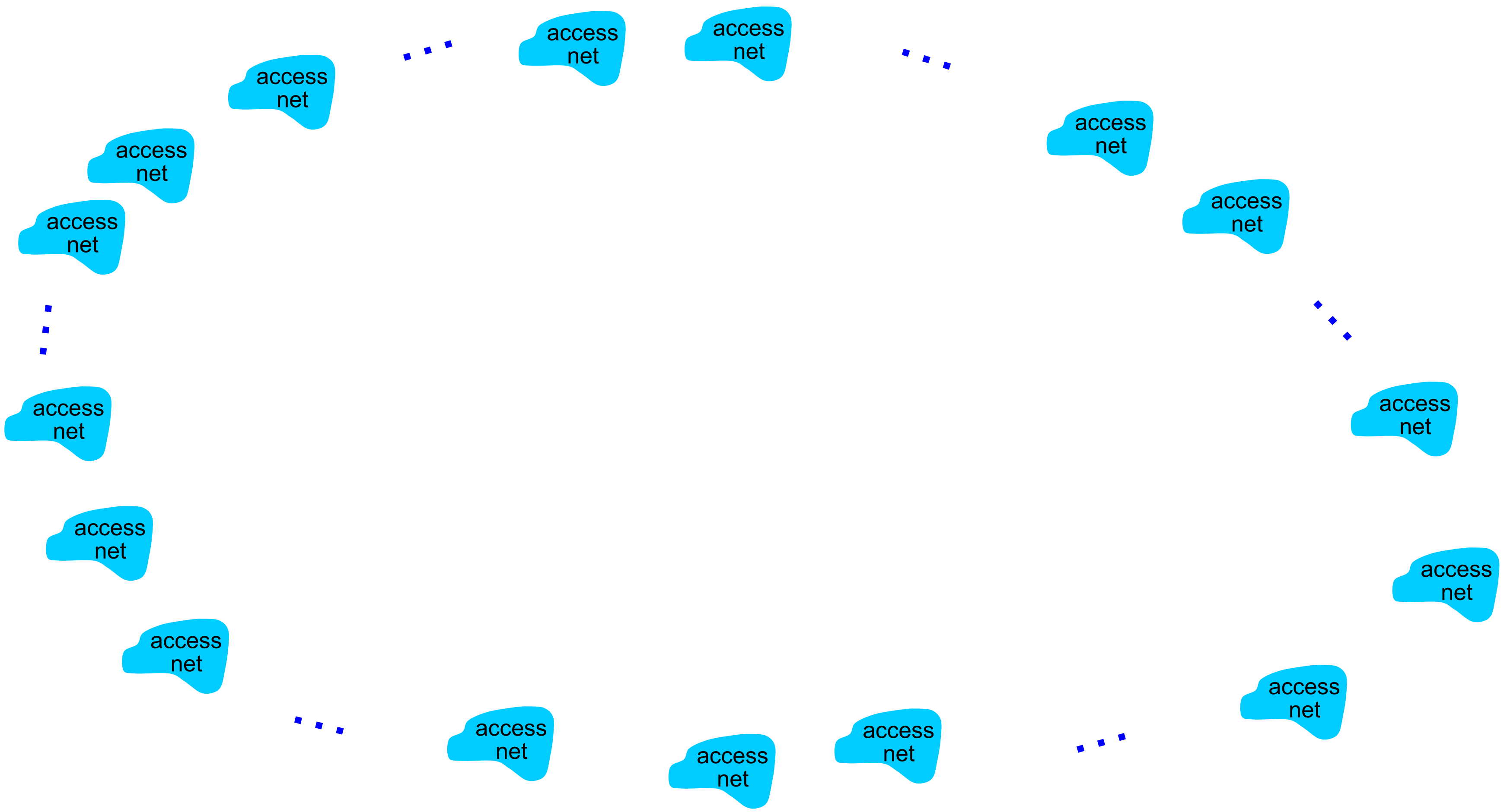
- great for bursty data
  - resource sharing
  - simpler, no call setup
  - No resource reservation.
- excessive congestion possible: packet delay and loss
  - protocols needed for reliable data transfer, congestion control
- *Q:* How to provide circuit-like behavior?
  - bandwidth guarantees needed for audio/video apps
  - still an unsolved problem

Internet structure: 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

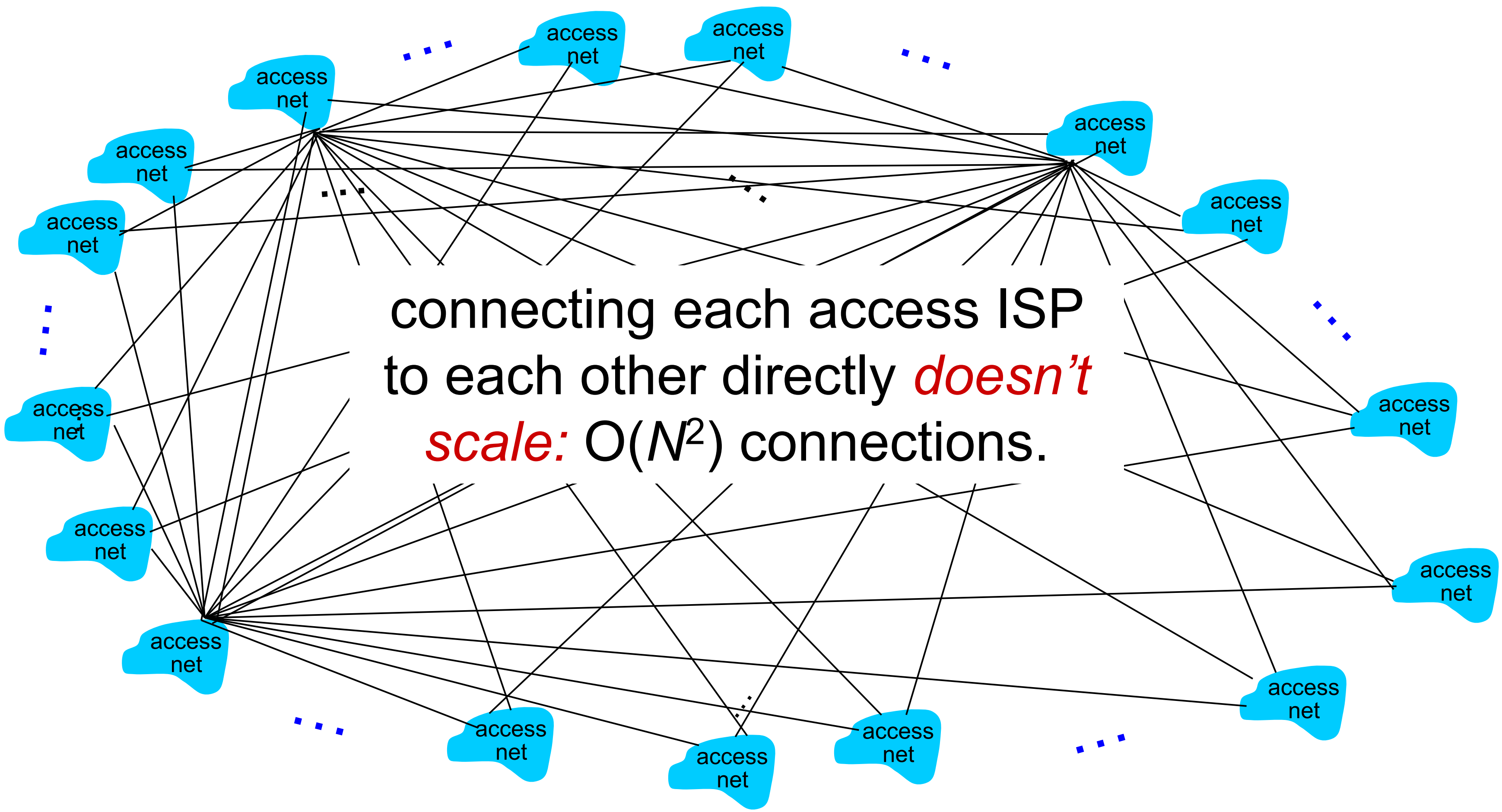
Internet structure: network of networks

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



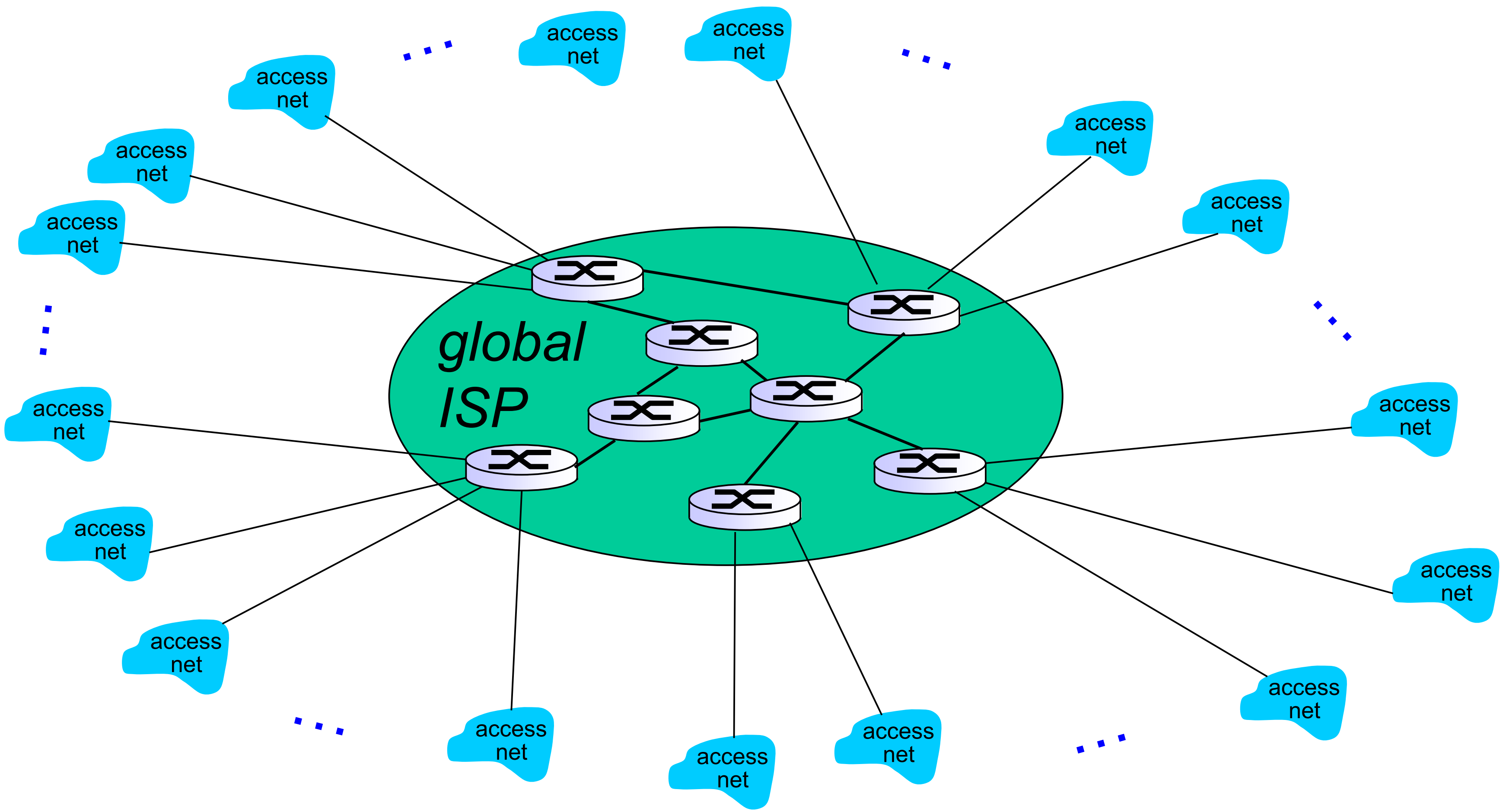
Internet structure: network of networks

Option: connect each access ISP to every other access ISP?



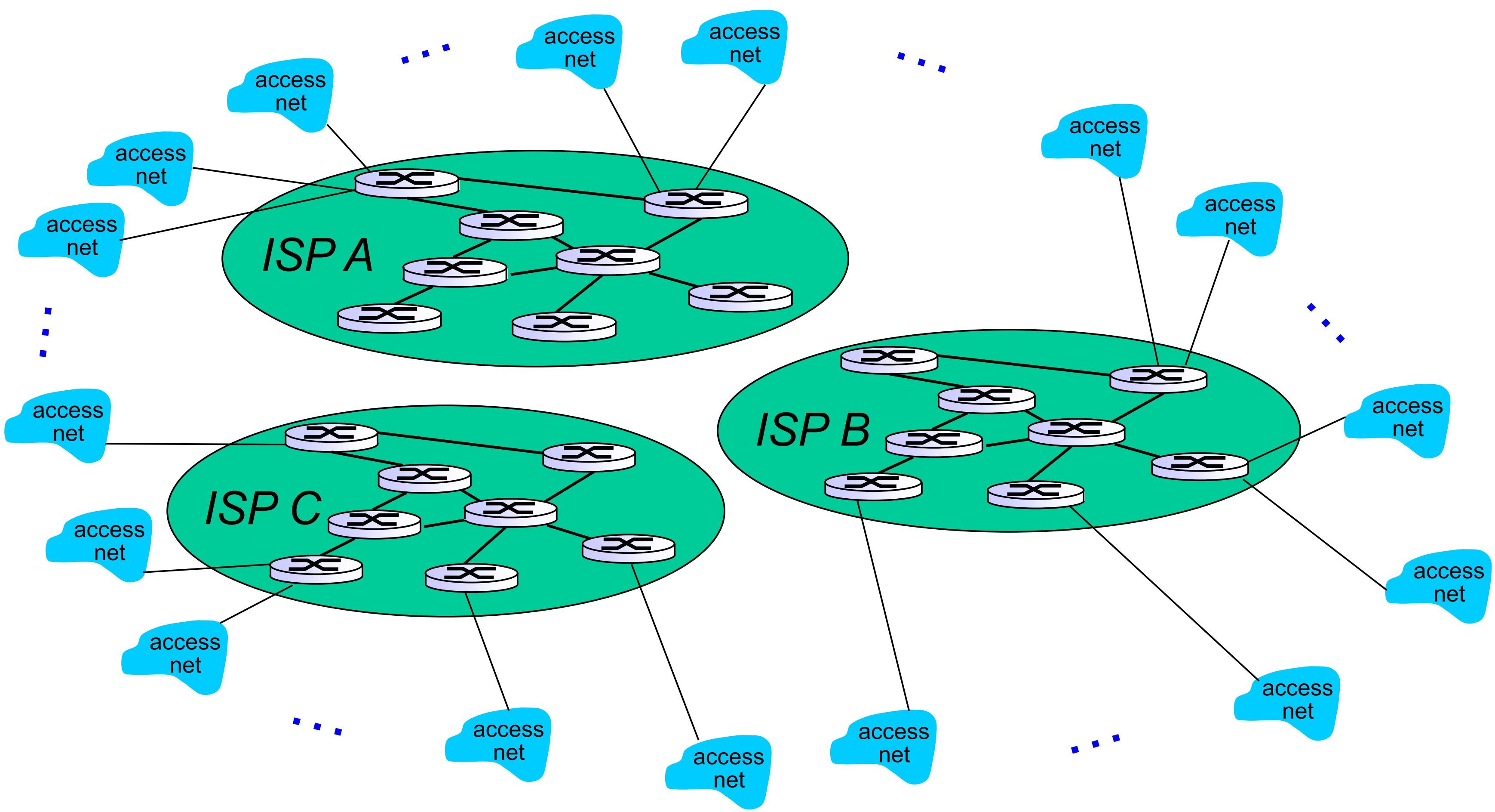
Internet structure: network of networks

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



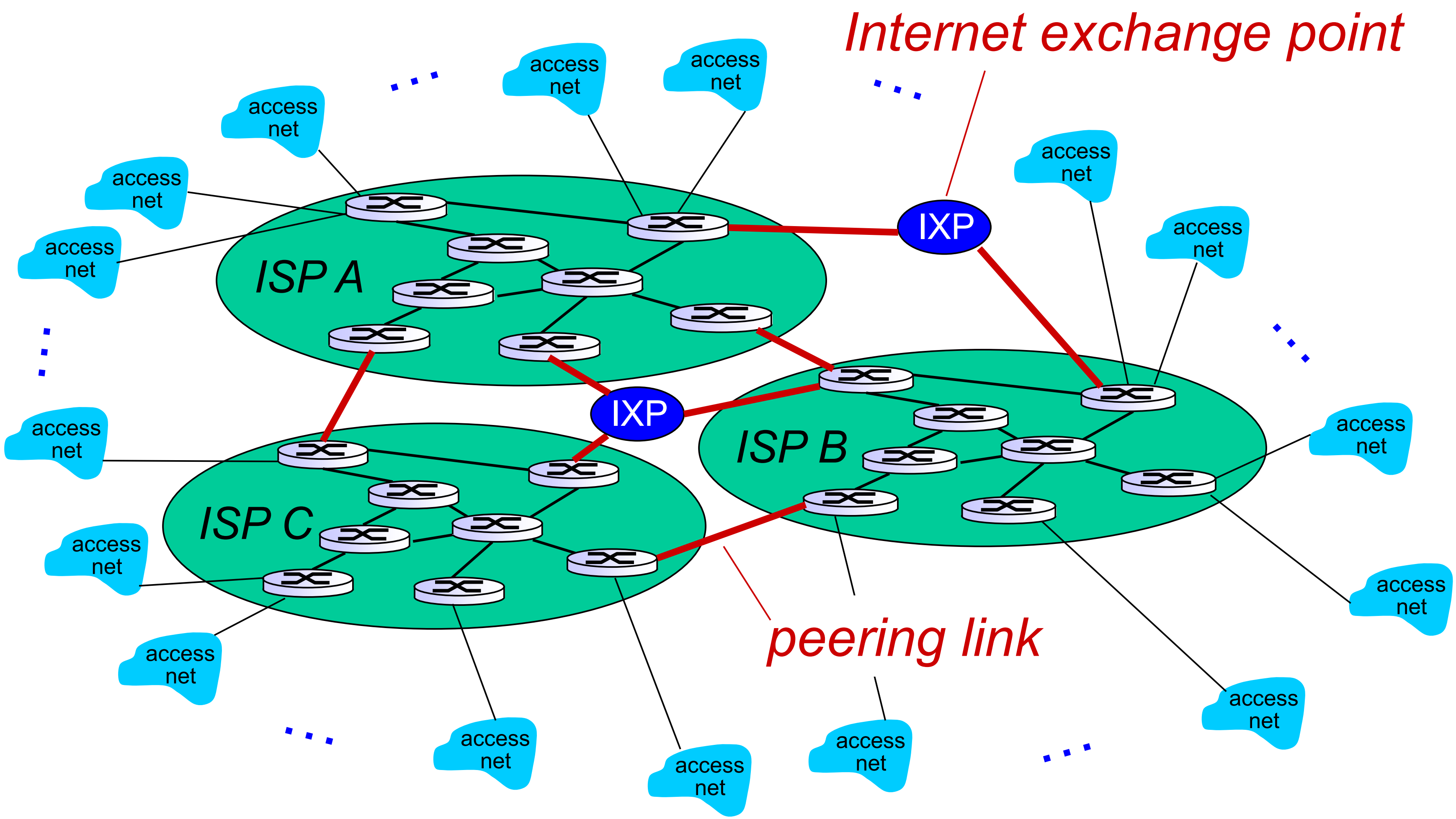
Internet structure: network of networks

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



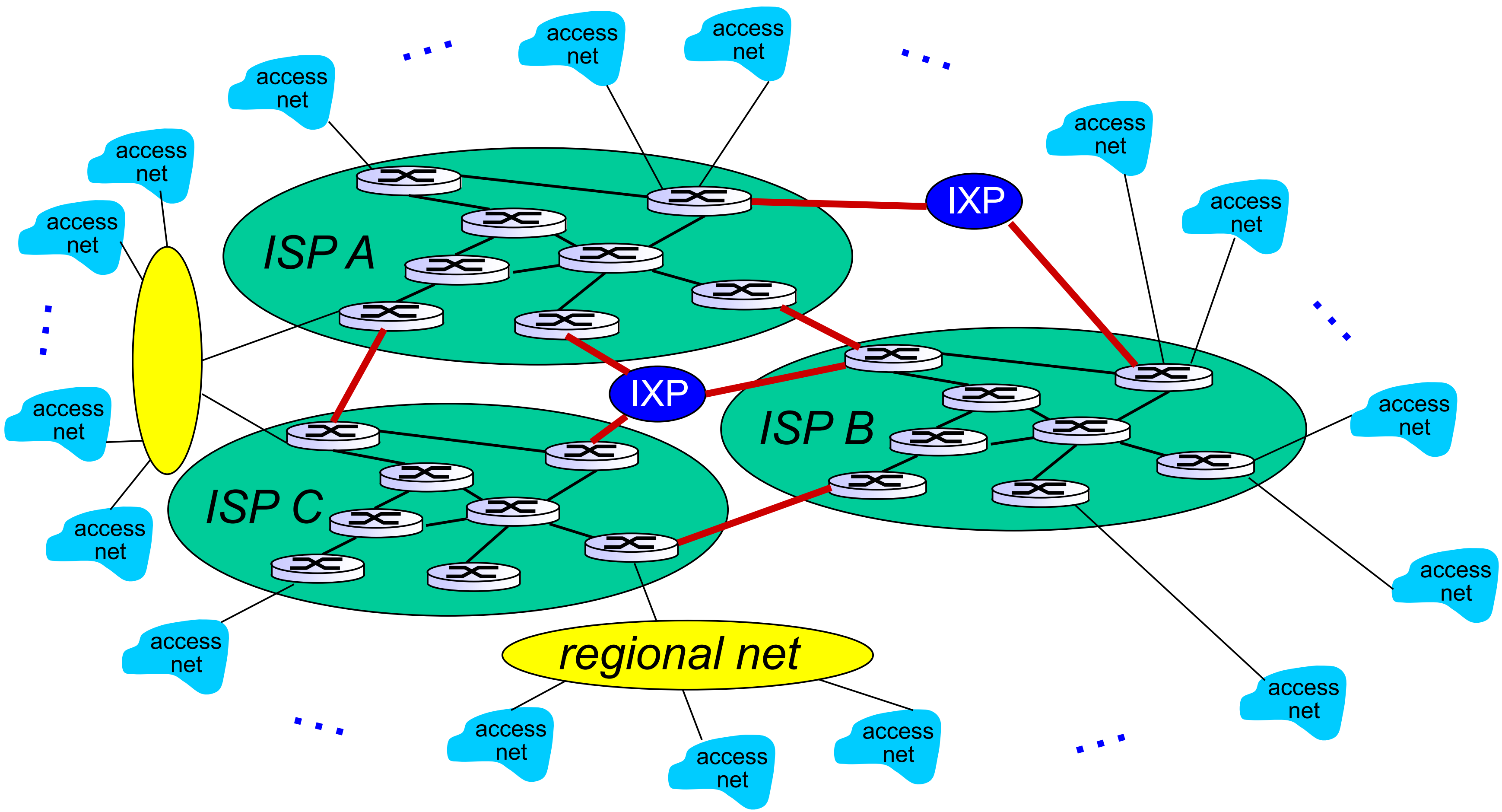
Internet structure: network of networks

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



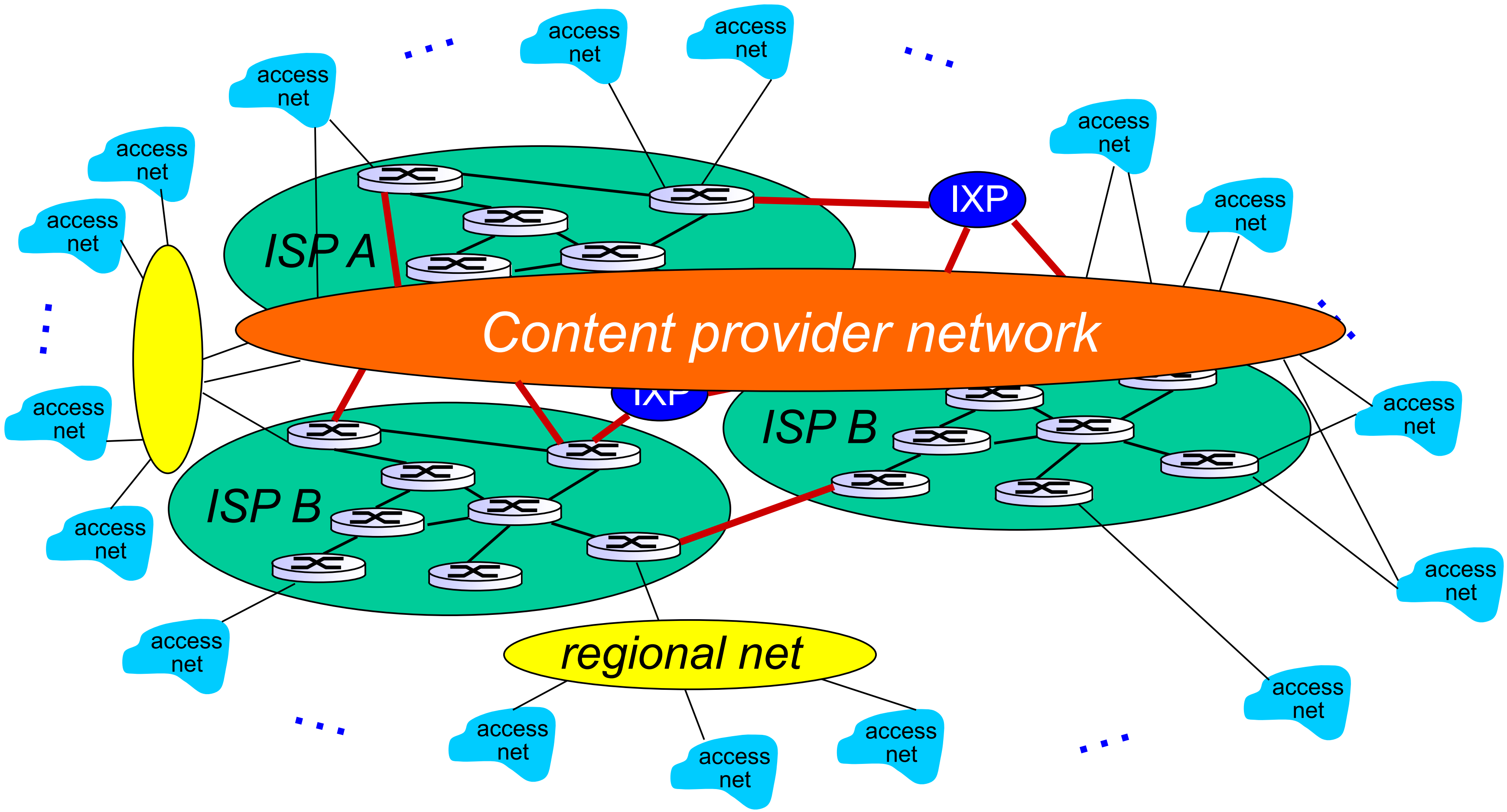
Internet structure: network of networks

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

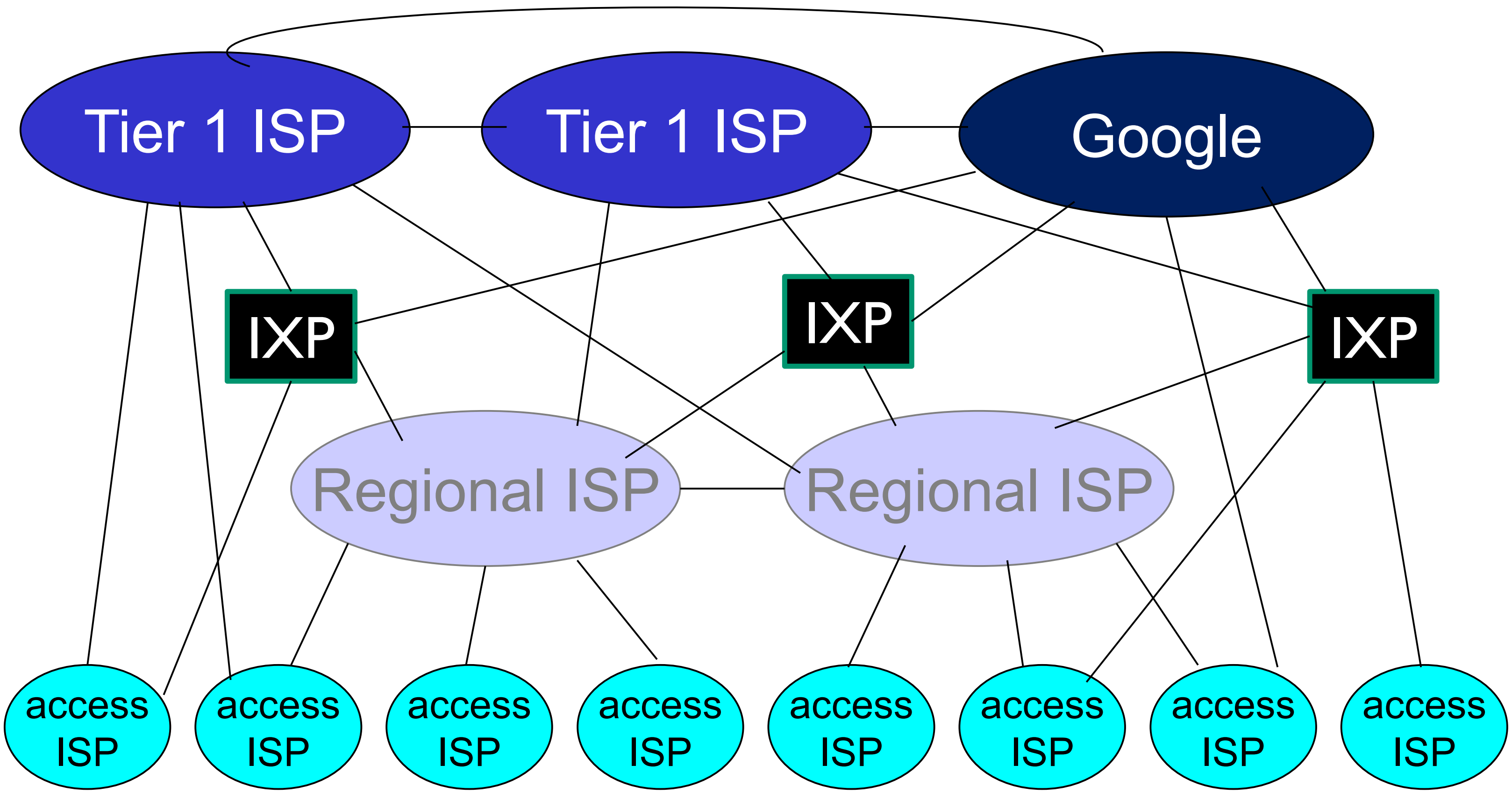


Internet structure: network of networks

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



Internet structure: 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 network (e.g, Google): private network that connects it data centers to Internet, often bypassing tier-1, regional ISPs

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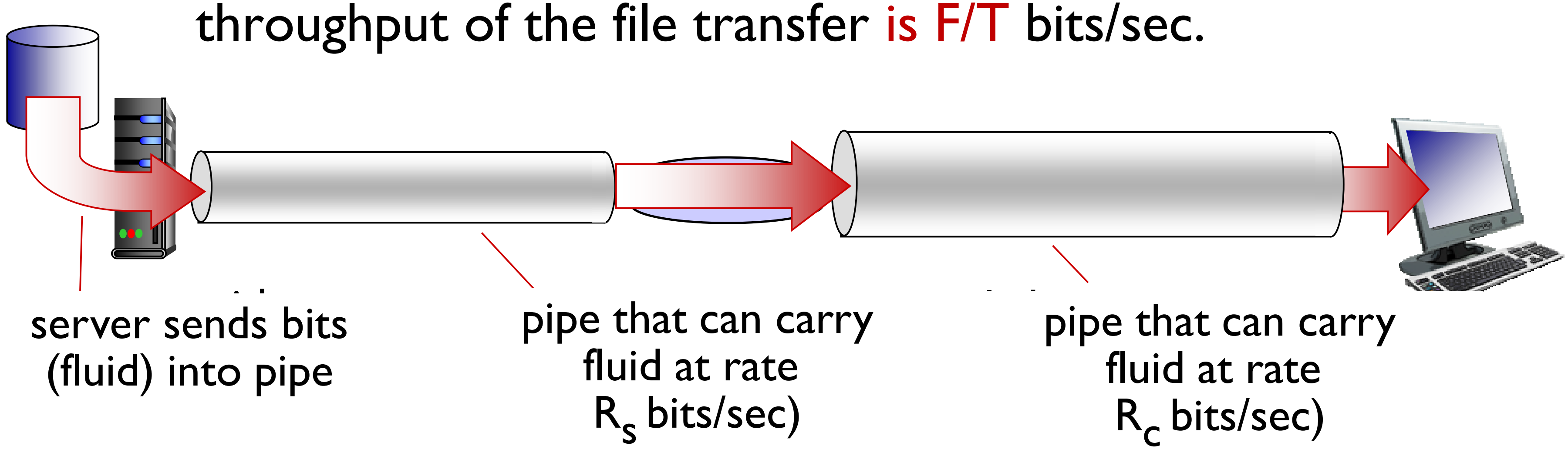
Bandwidth

- In computer networking, we use the term bandwidth in two contexts:
  - The first, **bandwidth in hertz**, which refers to the range of frequencies in composite signal or the range of frequencies that a link or a channel can pass.
  - The second, **bandwidth in bits per second (bps),** which refers to the speed of bit transmission in a link or channel. In this case, it is also called as capacity or link transmission rate.
- For example,
  - The bandwidth of a subscriber line is 4 kHz for voice data.
  - The bandwidth of a link for data transmission is56kbps.

Throughput

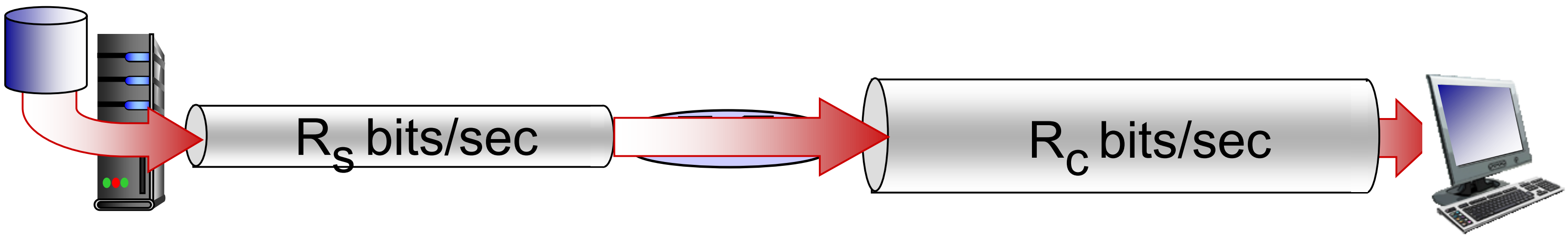
- *throughput:* rate (bits/time unit) at which bits transferred between sender/receiver
  - *instantaneous:* at any instant of time is the rate (in bits/sec) at which Host B is receiving the file.
  - *average:* rate over longer period of time. If the file consists of F bits and the transfer takes T seconds for Host B to receive all F bits, then the average throughput of the file transfer is F/T bits/sec.



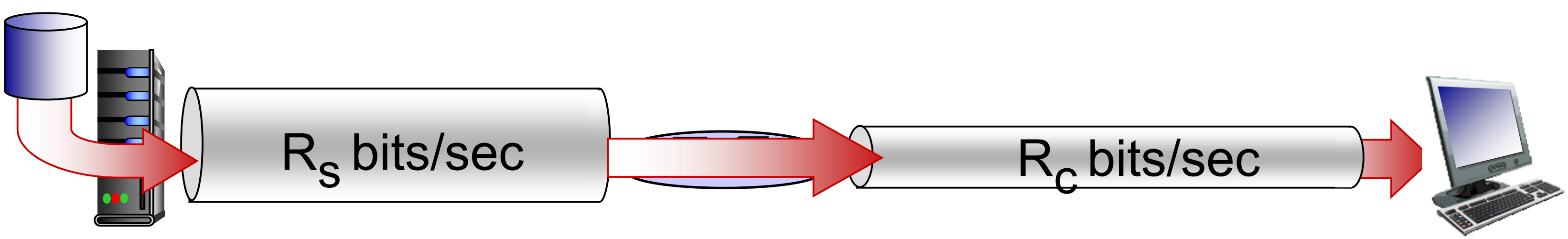
Throughput (more)

min{*Rc*, *Rs*},

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



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

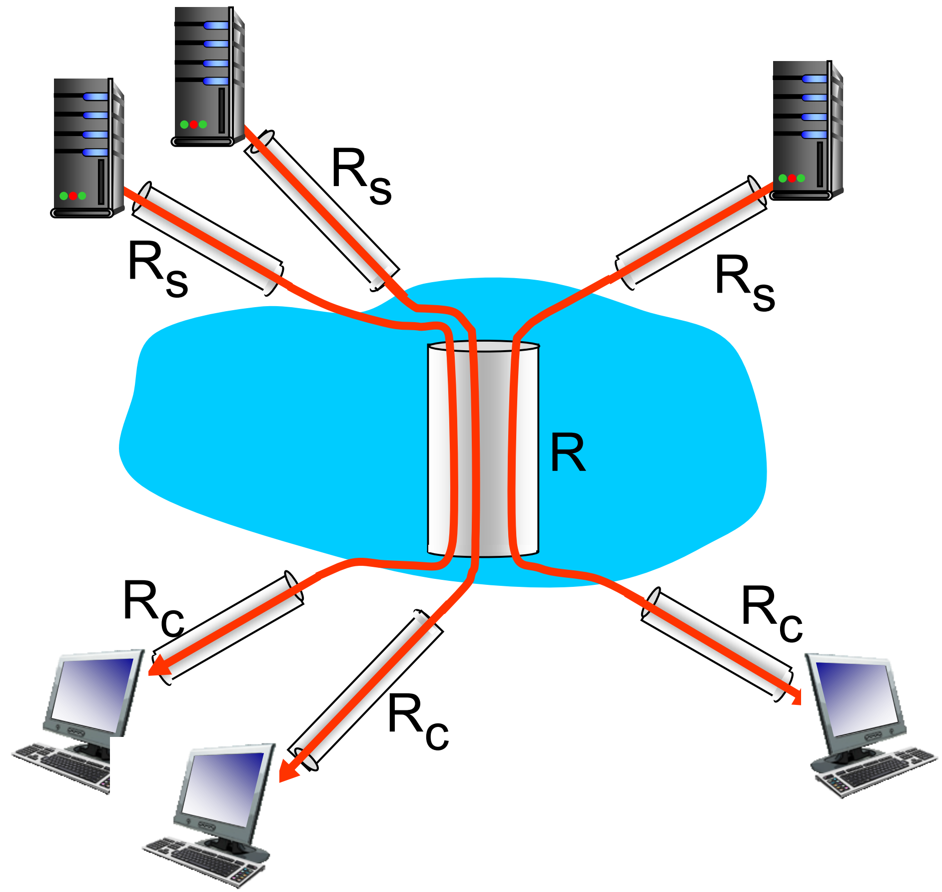


bottleneck link

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

Throughput: Internet scenario

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

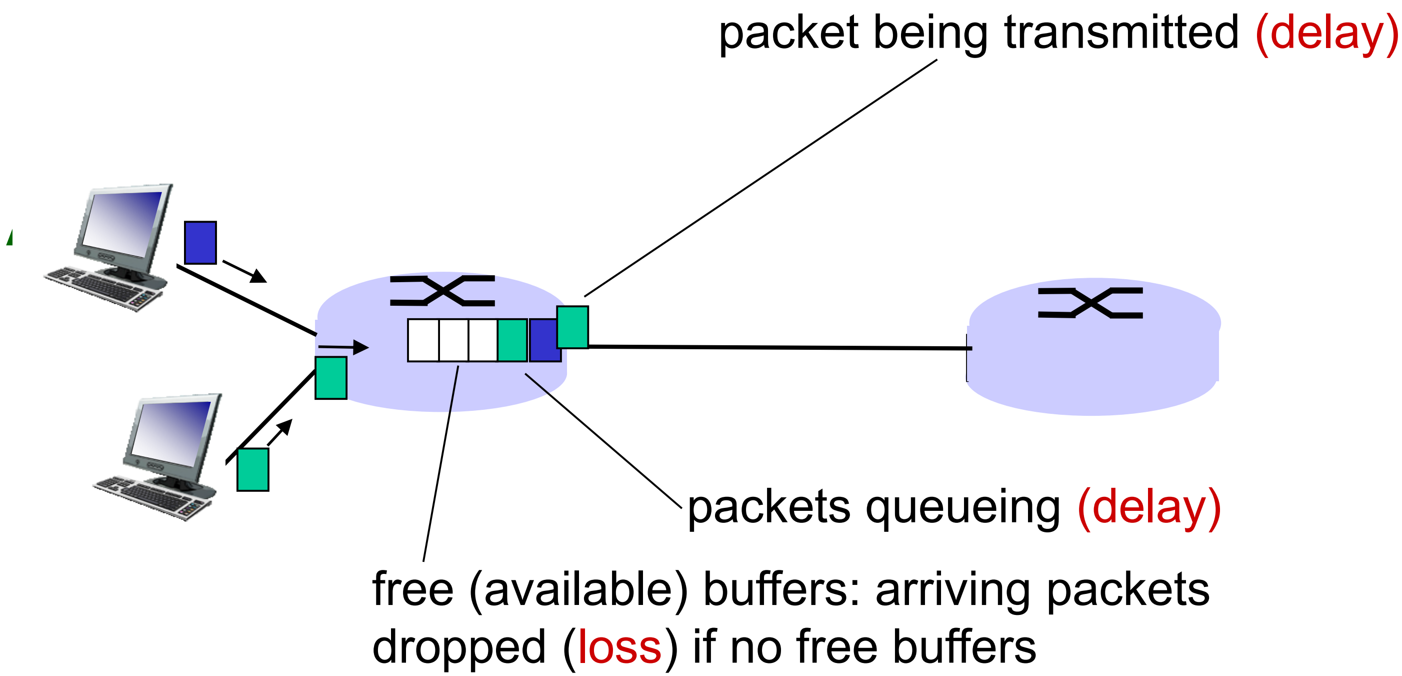


10 connections (fairly) share backbone bottleneck link R bits/sec

How do Packet loss and delay occur?

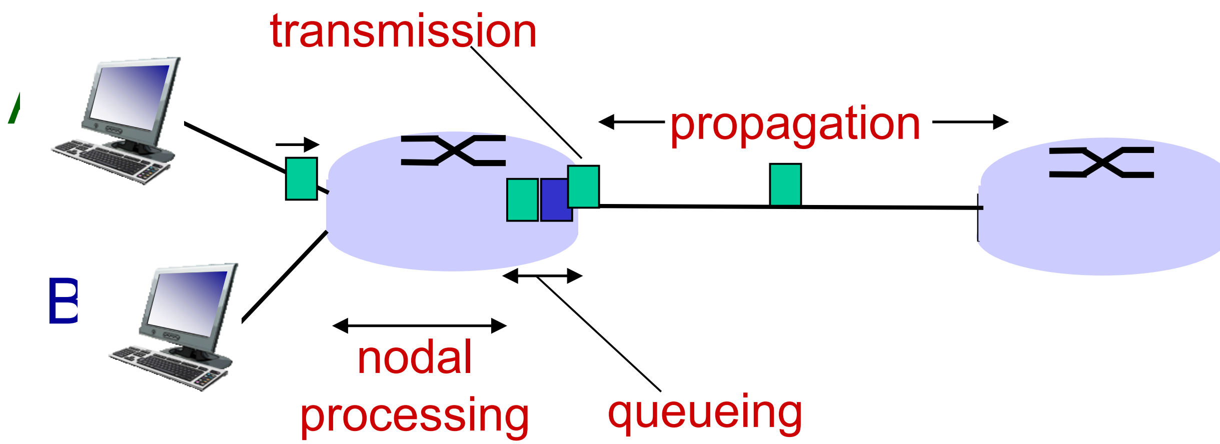
packets *queue* in router buffers

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



http://media.pearsoncmg.com/aw/aw_kurose_network_2/applets/queuing/queuing.html

Four sources of packet delay



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

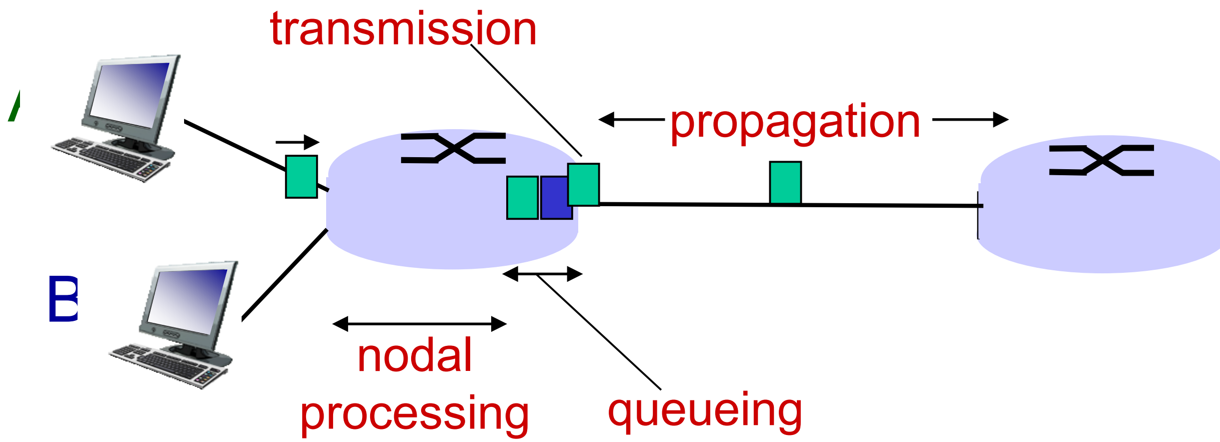
d_{proc}: nodal processing

- the time to do the nodal processing such as bit error detection, to determine where to direct the packet, check the packet's header, etc.
- typically < micro seconds

d_{queue}: queueing delay

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

Four sources of packet delay



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

d_{trans}: transmission delay:

- *The amount of time required to push all the packet's bits into the link.*
- *L*: packet length (bits)
- *R*: link *bandwidth (bps)*
- $d_{trans} = L/R$

d_{prop}: propagation delay:

- *The time required for each bit to transmit from the beginning of the link to the next router.*
- *d*: length of physical link
- *s*: propagation speed in medium (~2x10^8 m/sec)
- $d_{prop} = d/s$

Examples

- The distance between two routers is 12,000km and propagation speed is 2.4×10^8m/s in cable. The propagation delay is

$$\text{Propagation time} = \frac{12{,}000 \times 1000}{2.4 \times 10^8} = 50 \text{ ms}$$

- The example shows that a bit can go over the Atlantic Ocean in only 50 ms if there is a direct cable.

Examples

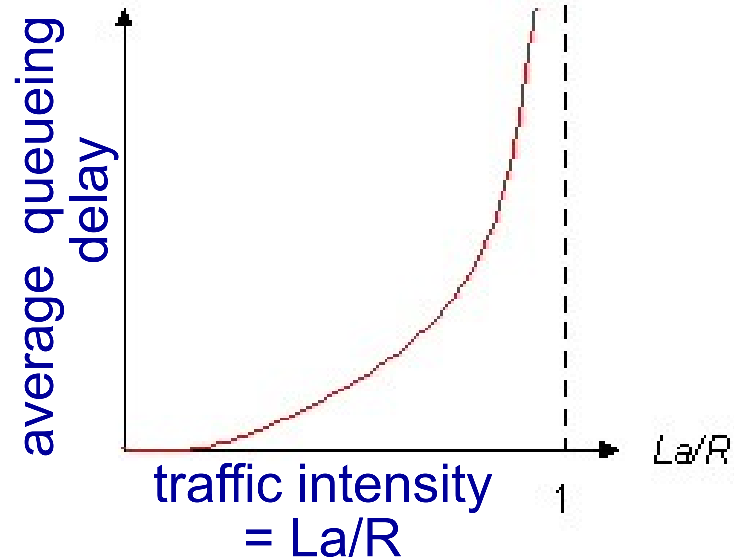
- The bandwidth of a link is 1Gbps. The transmission time for a 2.5-kbyte message (an e-mail) is

$$\text{Transmission time} = \frac{2500 \times 8}{10^9} = 0.020 \text{ ms}$$

- Comparing the propagation time (50ms) and transmission time (0.02ms), we note that because the message is short and the bandwidth is high, the dominant factor is the propagation time, not the transmission time.

Queueing delay

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



- *R:* link bandwidth (bps)
- *L:* packet length (bits)
- a: average packet arrival rate
- *La/R traffic intensity*

- *La/R* 0: avg. queueing delay small
- *La/R* 1: avg. queueing delay large
- *La/R* > 1: more "work" arriving than can be serviced, average delay infinite!

La/R ~ 0

La/R -> 1

http://media.pearsoncmg.com/aw/aw_kurose_network_2/applets/queuing/queuing.html

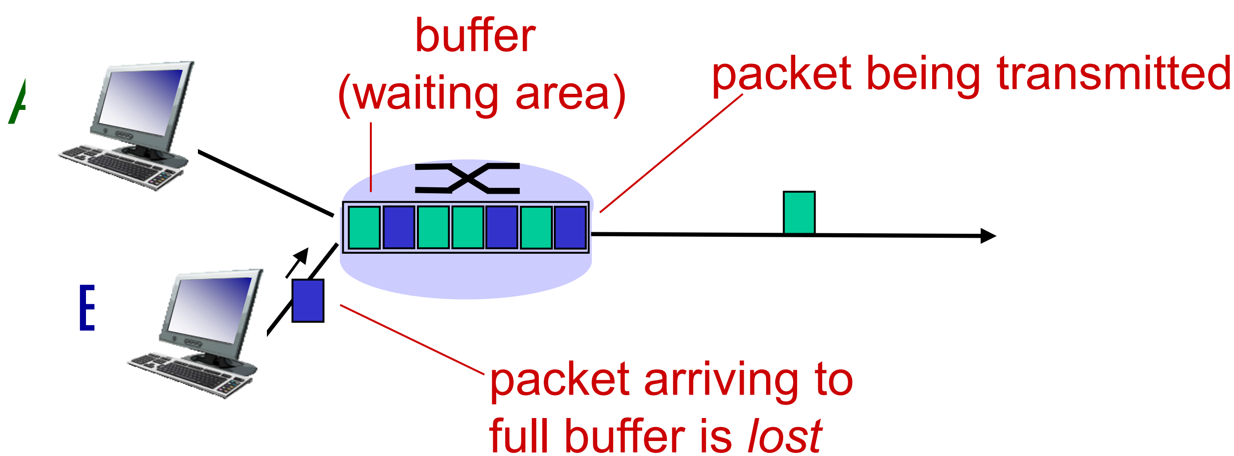
Total Nodal Delay

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

- d_{proc} : Processing Delay
  - Typically a few microsecs or less
- d_{queue} : Queuing Delay
  - Depends on congestion
- d_{trans} : Transmission Delay (L/R)
  - Depends on transmission rate and packet length.
  - Negligible for transmission rates of 10Mpbs and higher (e.g., LANs), but significant for low-speed links (e.g., dial-up modem links)
- d_{prop} : Propagation Delay (d/s)
  - Depends on distance of two routers and medium speed.
  - A couple of microseconds to hundreds of milliseconds.

Packet loss

- queue (also known as 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

Chapter 1: roadmap

1.1 what *is* the Internet?

1.2 network edge

- end systems, access networks, links

1.3 network core

- packet switching, circuit switching, network structure

1.4 delay, loss, throughput in networks

1.5 protocol layers, service models

Protocol "layers"

Networks are complex, with many "pieces":

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

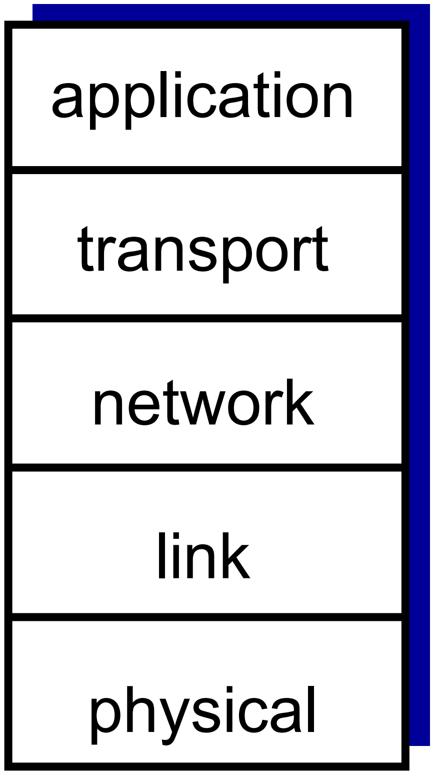
Question:

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

…. or at least our discussion of networks?

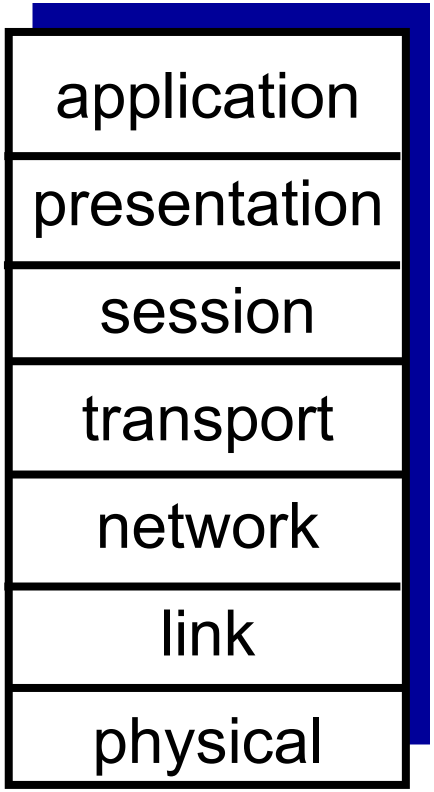
Internet protocol stack

- *application:* supporting network applications
  - FTP, SMTP, HTTP
- *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, 802.111 (WiFi), PPP
- *physical:* bits "on the wire"

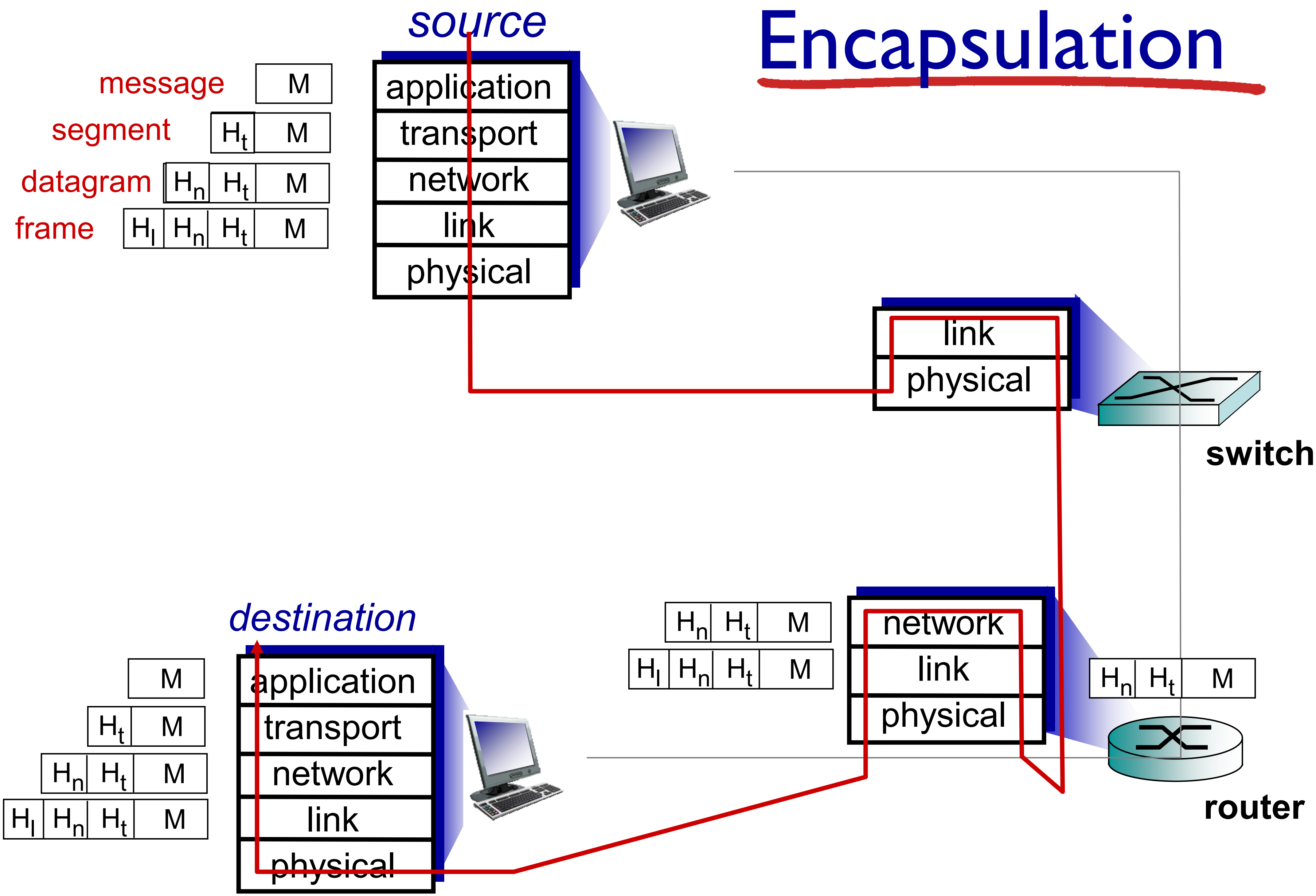


ISO/OSI reference model

- *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?



Encapsulation



Introduction: summary

covered a "ton" of material!

- Internet overview
- what's a protocol?
- network edge, core, access network
  - packet-switching versus circuit-switching
  - Internet structure
- performance: loss, delay, throughput
- layering, service models