Computer Networks 1

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Some of material in these notes is taken from recommended text books & the internet

Introduction

our goal:

- get "feel" and terminology
- more depth, detail *later* in course
- approach:
  - use Internet as example

overview:

- What's the Internet?
- What's a protocol?
- network edge; hosts, access net, physical media
- network core: packet/circuit switching, Internet structure
- performance: loss, delay, throughput
- security
- protocol layers, service models
- history

Today?

our aim:

- Introduction to the contents of this course
- Learning Outcomes
- Course Syllabus
- Recommended text / resources
- Start with an overview

Our Aim

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- Introduction to the contents of this course
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- Assessment Strategy
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Contents of this course

This course provides students with a systematic understanding of the important aspects of network communication relevant for software engineers.

It will describe operation of LAN, WAN, RAN, MAN as well as Internet.

Contents of this course

It will provide a comprehensive overview of how communication networks are evolving to support new applications as well as giving the student an extensive appreciation of the infrastructure, protocols and services of the Internet and underlying heterogeneous networks.

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Learning Outcomes

On successful completion of this module the learner (you) will be able to:

- Describe how networks function and identify network components.
- Use the OSI reference model, the TCP/IP reference model and associated protocols to explain how data flows in a network.
- Implement a small switched and/or routed and/or wireless network including IP addressing.
- Identify and correct common network problems.
- Explain basic wireless networking options and configurations.
- Present and communicate ideas and work done for professional review.

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Assessment Strategy

- **Course Work: 50%**
  - Attendance
  - Labs – reports
  - MCQ's – there will be 2 during the semester

- **Final exam: 50%**
  - 2 hour written exam. Date & Time TBA

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Course Syllabus – Indicative

- Overview / Introduction to communication networks
- Different Network Models: OSI, TCP/IP
- Application layer protocols: service levels for different applications
- The Transport protocols: TCP, UDP

Course Syllabus – Indicative

Networks:

- Network diagrams; Network components; Path between two hosts across a network; Top-down vs bottom up design approaches.

Protocols & Protocol Architectures:

- OSI reference model, TCP-IP internet protocol architecture; Protocols at each layer.

Wireless Networks:

- Introduction to WLANs - AdHoc and Infrastructure; Introduction to PANs - Bluetooth.

Course Syllabus – Indicative

Small Switched/Routed Network:

- Media: cables, fibre, connectors; Devices and hosts; Switches; Routers; Routing concepts - packet forwarding, lookup process; IP addressing (IPv4 & IPv6); Configuration files

Network Problems:

- Network connectivity - ping, telnet, traceroute; Verifying hardware and software operation

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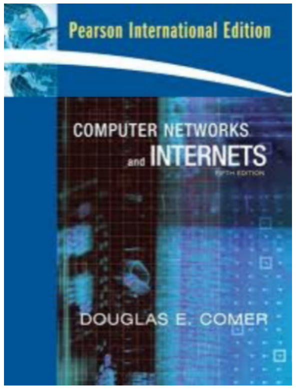
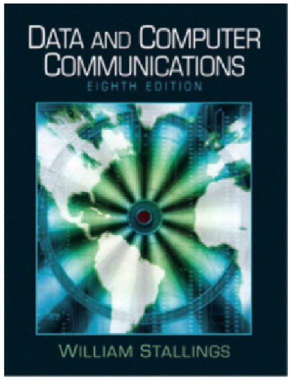
Recommended Texts

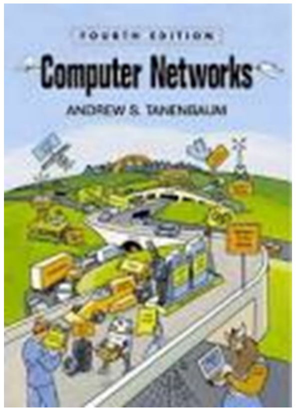
- Computer Networks and Internets,
  by Comer, (Prentice Hall)



- Data and Computer Communications,
  by Stallings, (Prentice Hall)



- Computer Networks,
  by Tannenbaum (Prentice Hall)



- These and many more texts are available in Library

Labs

- Room 827

- Designing, building and testing basic networks
  Linux and Windows
  Cabled and wireless
  Switches and routers
  Cable and Fibre

- PC for each student (subject to availability)

- Each student must submit report demonstrating results

Resources

- Hardback science copy for labs
- Lab reports to be handed up before leaving lab
- No late submissions
- Pens, pencils, paper, ruler....every class
- **2 GB USB Drive...dedicated to Linux!**
- Calculator

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Overview

1.1 what is a network? 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

1.6 networks under attack: security

1.7 history

What is a network?

- ❖ A Telecommunications Network which allows computers to exchange data. In computer networks, networked computing devices exchange data with each other along communication links (data connections). The connections between nodes are established using either cable media or wireless media.
- ➢ *The best-known computer network is the Internet.*

- ❖ Network computer devices that originate, route and terminate the data are called Network Nodes. Nodes can include hosts such as Servers, Personal Computers & Smartphones, as well as Networking Hardware.

What is a network?

- Two such devices can be said to be networked together when one device is able to exchange information with the other device, whether or not they have a direct connection to each other.

- Computer networks differ in the transmission media used to carry their signals, the communications protocols to organize network traffic, the network's size, topology and organizational intent.

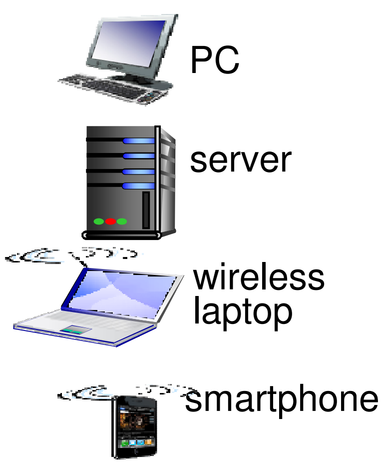
What is a network?

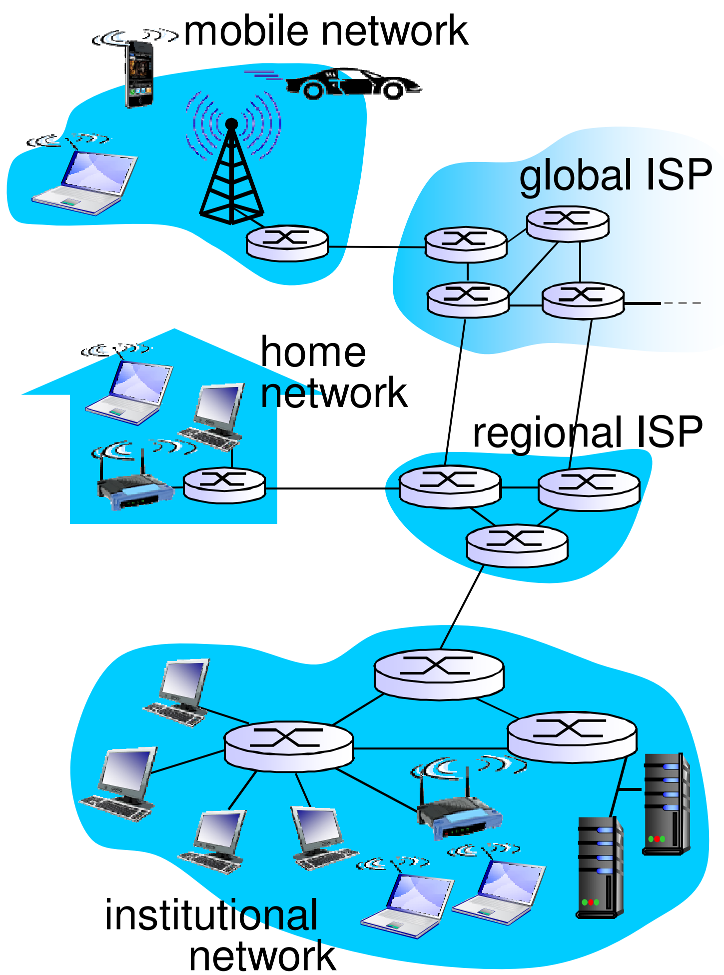
- In most cases, communications protocols are layered on (i.e. work using) other more specific or more general communications protocols, except for the *physical layer* that directly deals with the transmission media.

- Computer networks support an enormous number of applications such as access to the World Wide Web, video, digital audio, shared use of application and storage servers, printers, and fax machines, and use of email and instant messaging applications as well as many others.

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

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



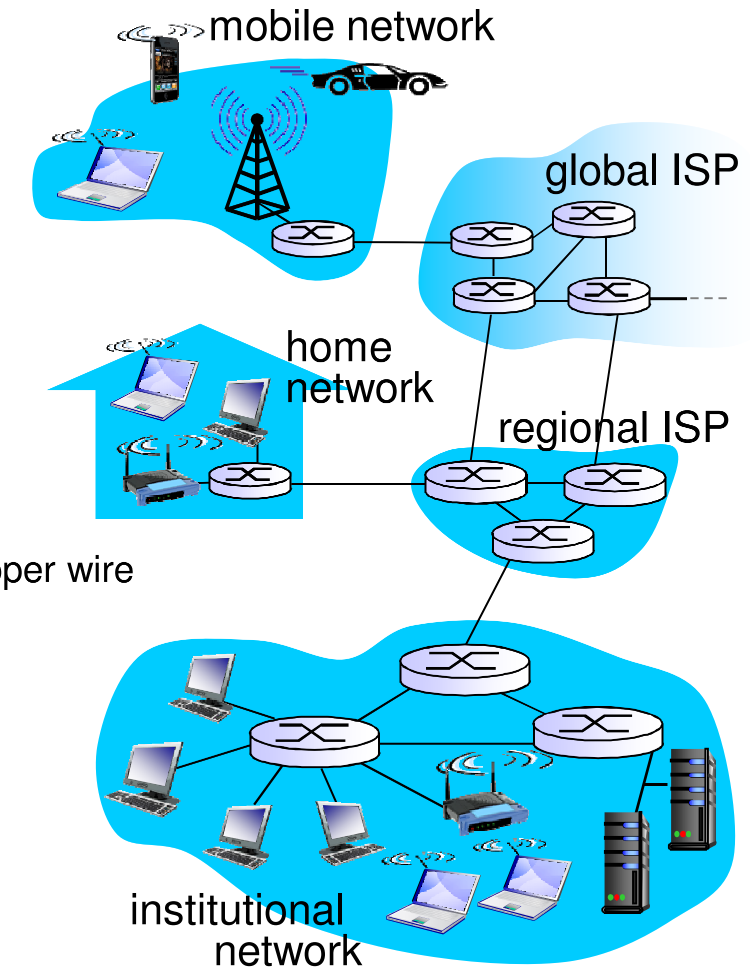


What's the Internet: "nuts and bolts" view

- *communication links – connect end systems together!*
  - fiber, copper, radio, satellite
  - transmission rate: *bandwidth*
    - *Bits/sec*

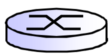
wireless
Links – radio spectrum

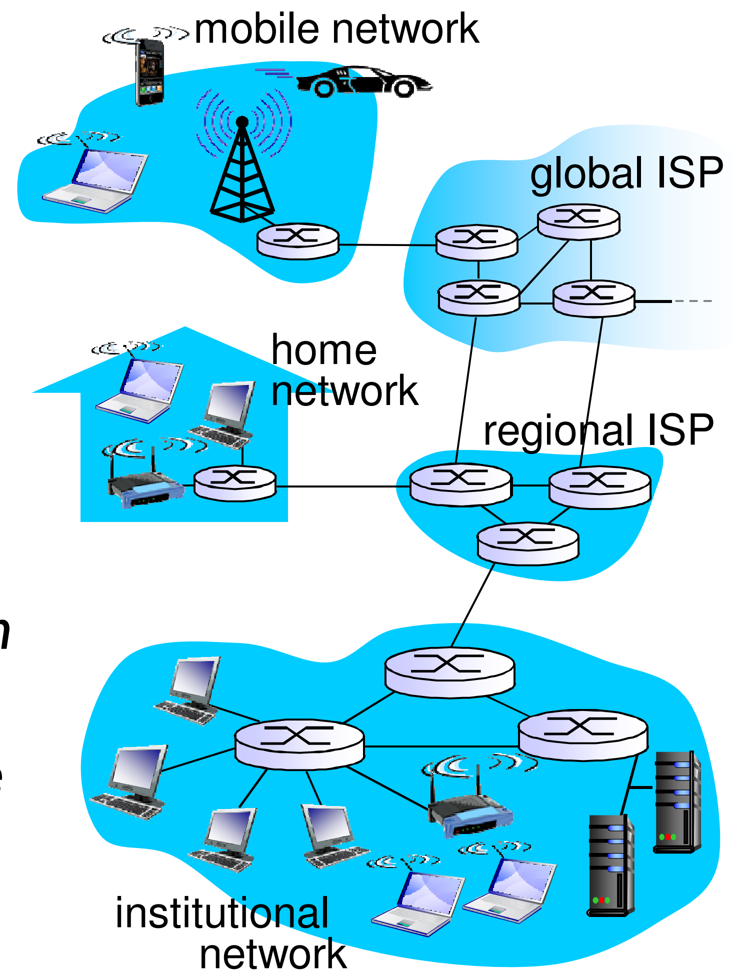
wired
Links – coaxial, fiber optic, copper wire



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

- *Packet switches:* forward packets (chunks of data)
  - *routers* and *switches*
  - *Packets are the "packages" of information sent through the network.*
  - *A packet switch takes a packet arriving on one of its incoming links and forwards that packet on one of its outgoing links*
  - *Routers are used in network core*
  - *Link switches are used in access networks*


router



"Fun" internet appliances

IP picture frame
http://www.ceiva.com/

Web-enabled toaster +
weather forecaster

Tweet-a-watt:
monitor energy use

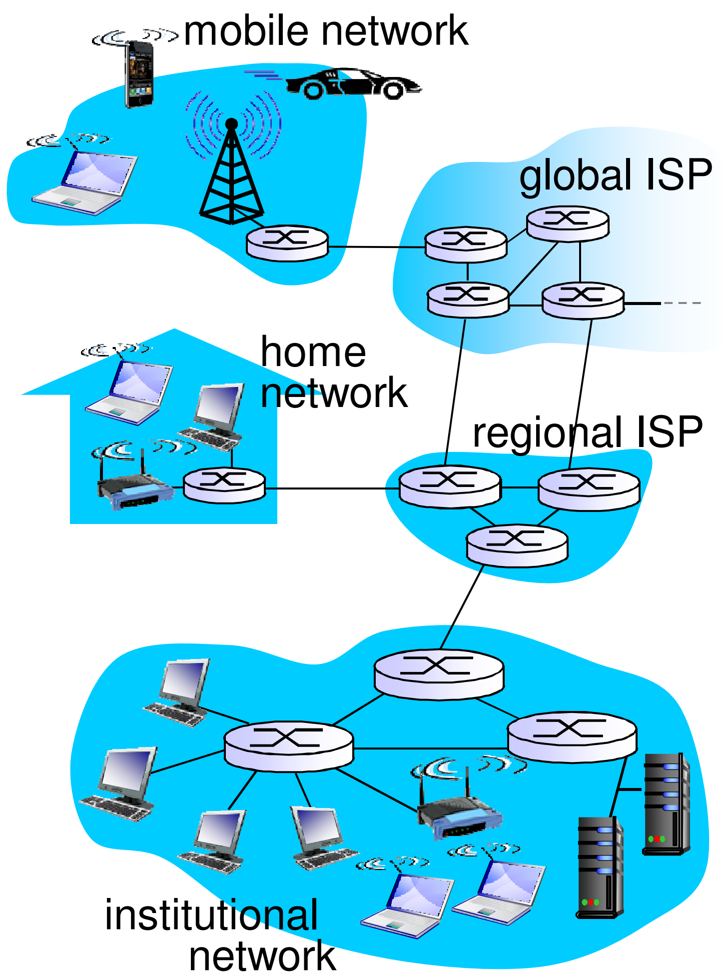
Internet
refrigerator

Slingbox: watch,
control cable TV remotely

Internet phones

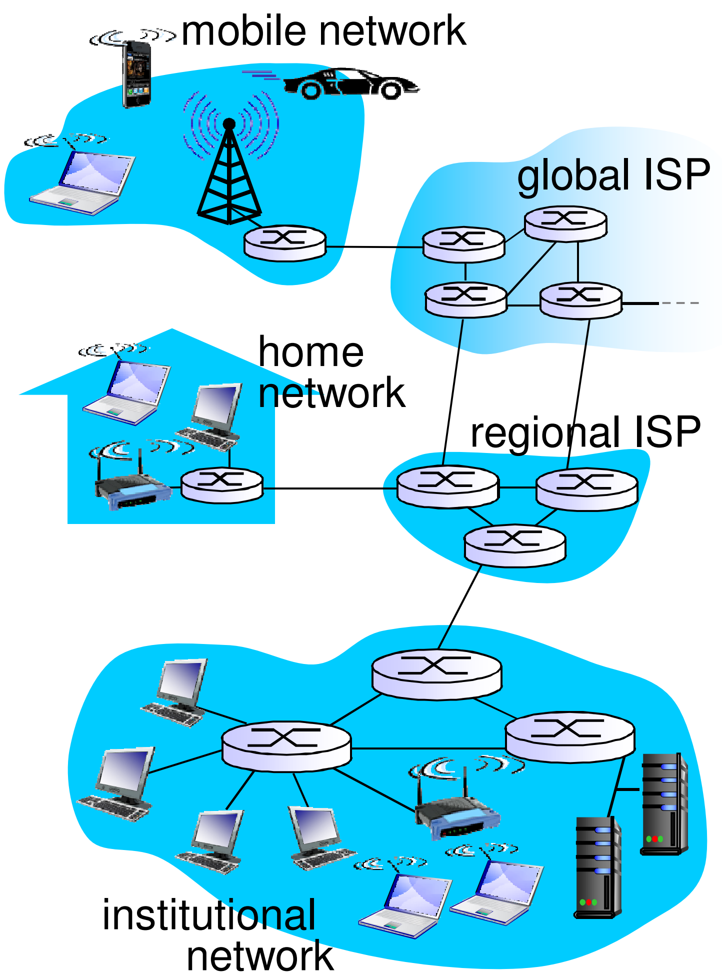
What is the Internet? Network viewpoint!

- *Internet:* "network of networks"
  - End systems access the Internet through Internet Service Providers (ISP)
  - ISP's provide a variety of types of network access (residential broadband, high speed LAN access, Wireless Access etc)



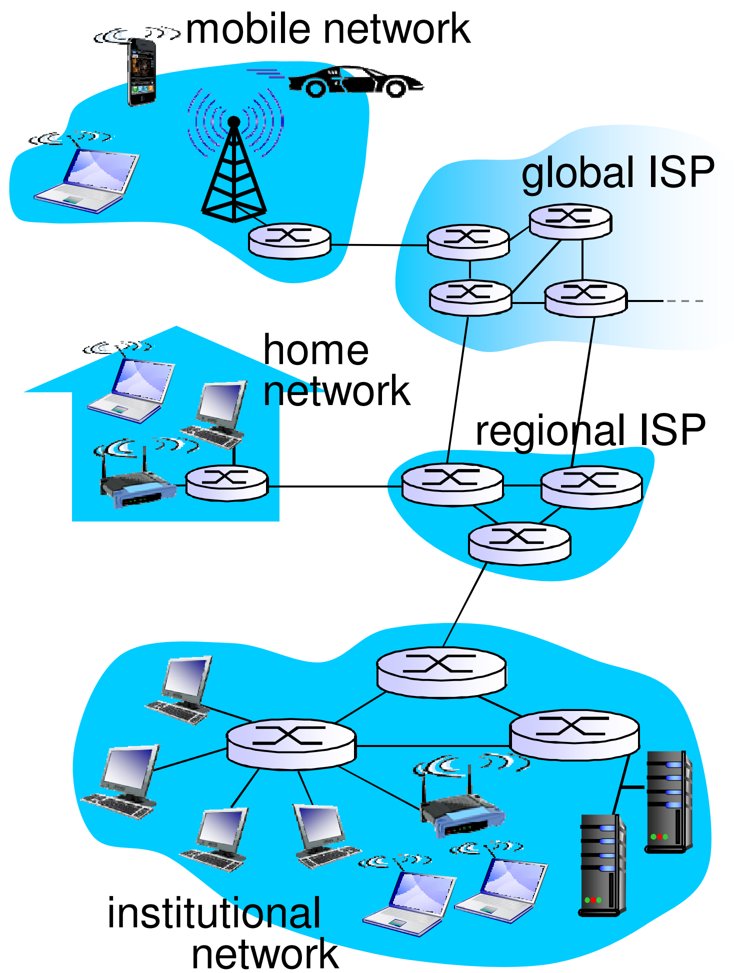
What is the Internet? Network viewpoint!

- *Protocols* – are used by end systems, switches etc. to control the sending and receiving of information within the Internet.
  - e.g., TCP, IP, HTTP, Skype, 802.11
- *Internet standards*
  - IETF: Internet Engineering Task Force
  - IETF standards documents: request for comments – are literally that – a "request for comments" on network and protocol design problems!
  - IETF working groups organized by topic e.g. routing, transport, security



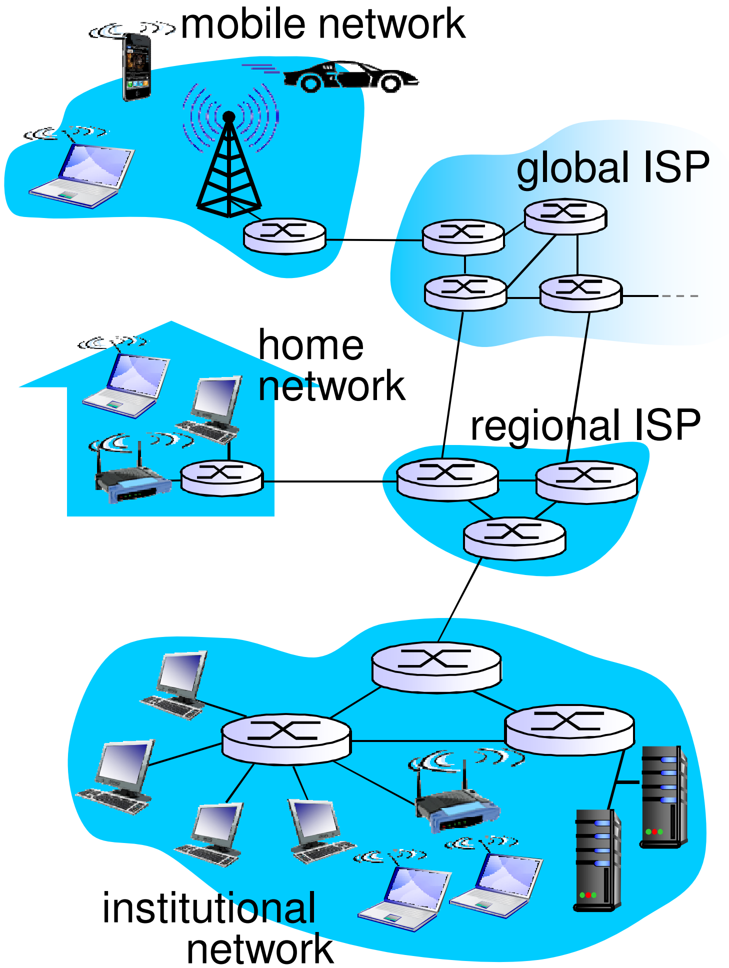
What's the Internet: a service view

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



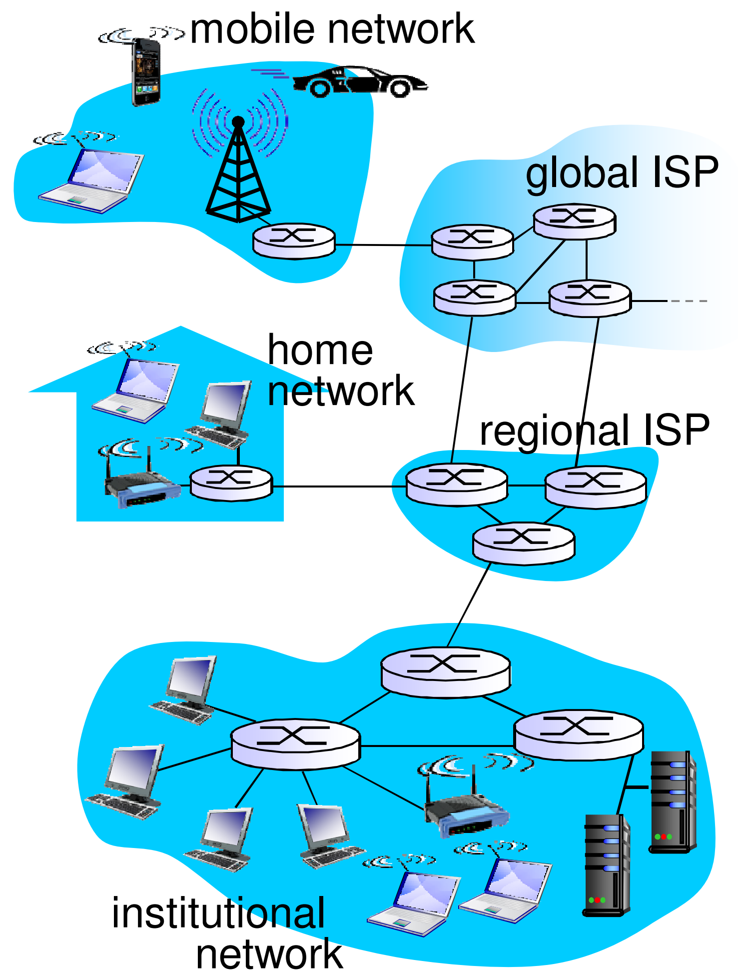
What's the Internet: a service view

- *Infrastructure that provides services to applications:*
  - Web, VoIP, email, games, e-commerce, social nets, …
  - Are such applications "distributed"?
  - Answer: Yes, explain?



What's the Internet: a service view

- *Infrastructure that provides services to applications:*
  - Web, VoIP, email, games, e-commerce, social nets, …
  - Are such applications are "distributed"?
  - Answer: Yes, explain?
  - Because they involve multiple end systems that exchange information with each other.



What's a protocol?

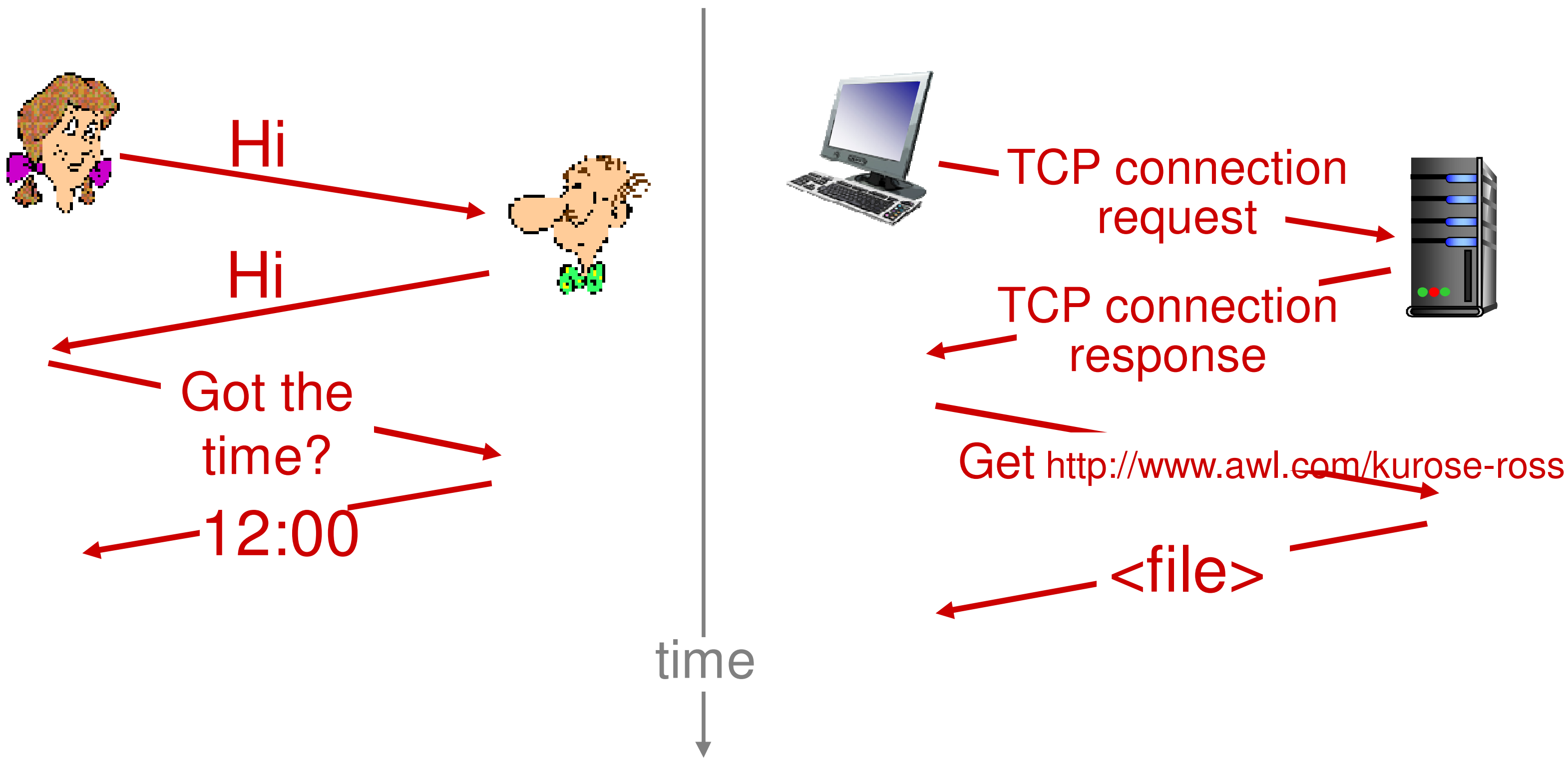
network protocols:

- How machines, software or hardware exchange messages and take actions.
- Example is how we request a web page as shown on the next slide.
- all communication activity in Internet governed by protocols
- Different protocols are used to achieve different tasks.

protocols define format, order of messages sent and received among network entities, and actions taken on message transmission & receipt

What's a protocol?

a human protocol and a computer network protocol:



Q: other human protocols?

Network Edge

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

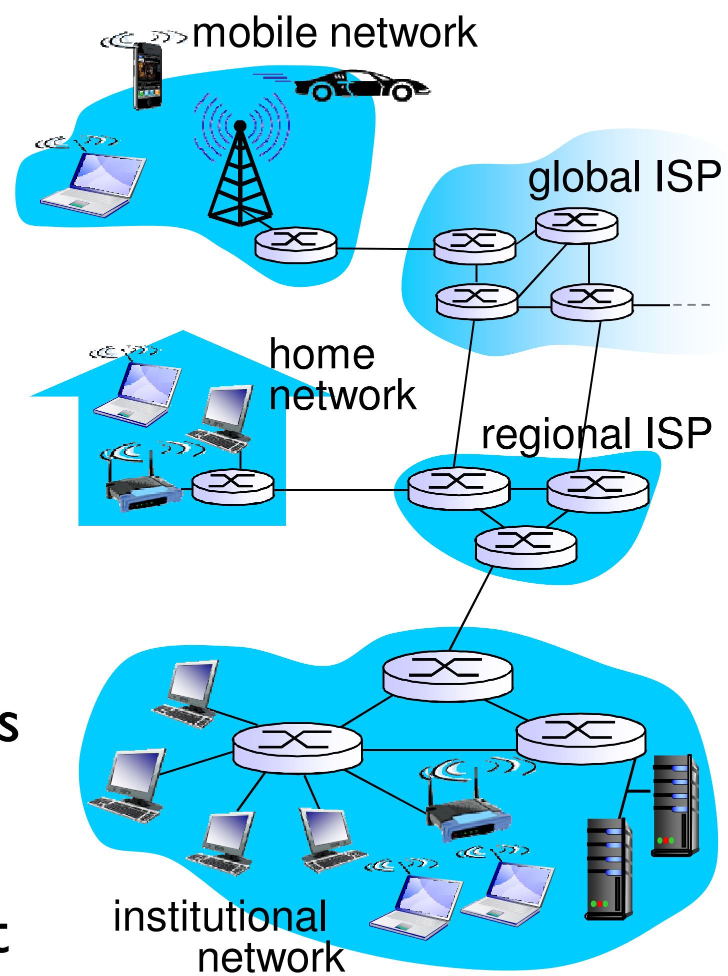
1.4 delay, loss, throughput in networks

1.5 history

A closer look at network structure:

- *network edge:*
  - Hosts (common name for end systems): clients and servers – can we think of examples of either of these?
  - servers often in data centers

- ***access networks, physical media:*** wired, wireless communication links
- the ***access network*** physically connects an end system to the edge router – see red lines on next slide



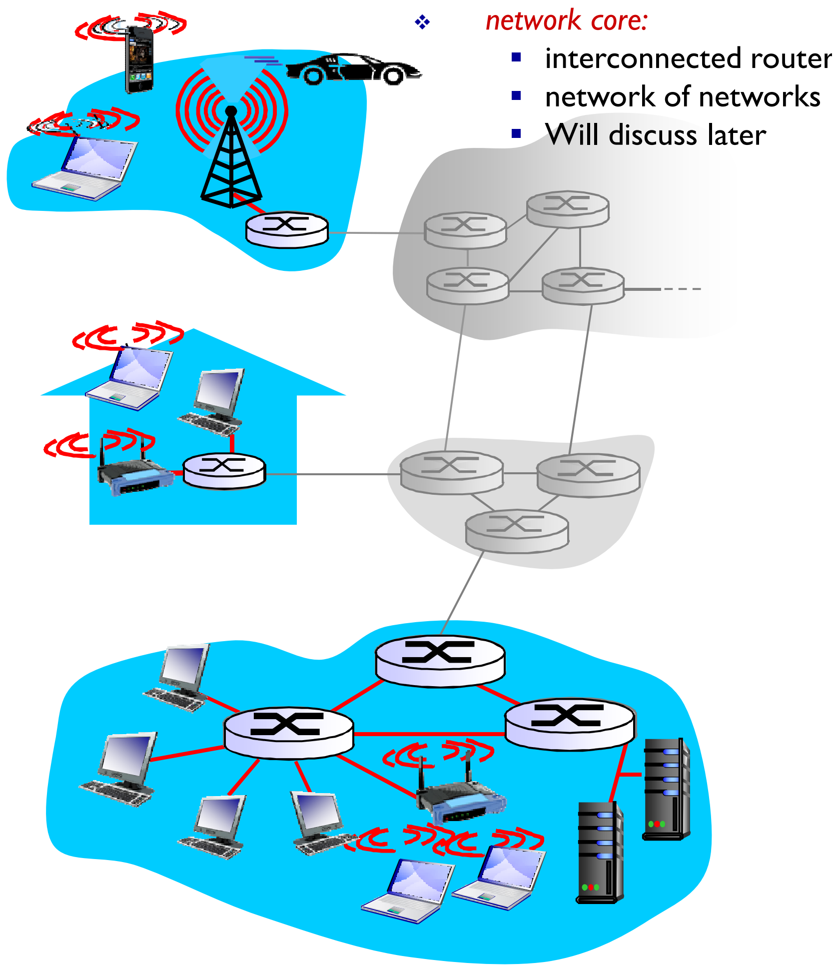
Access networks and physical media

Q: How to connect end systems to edge router?

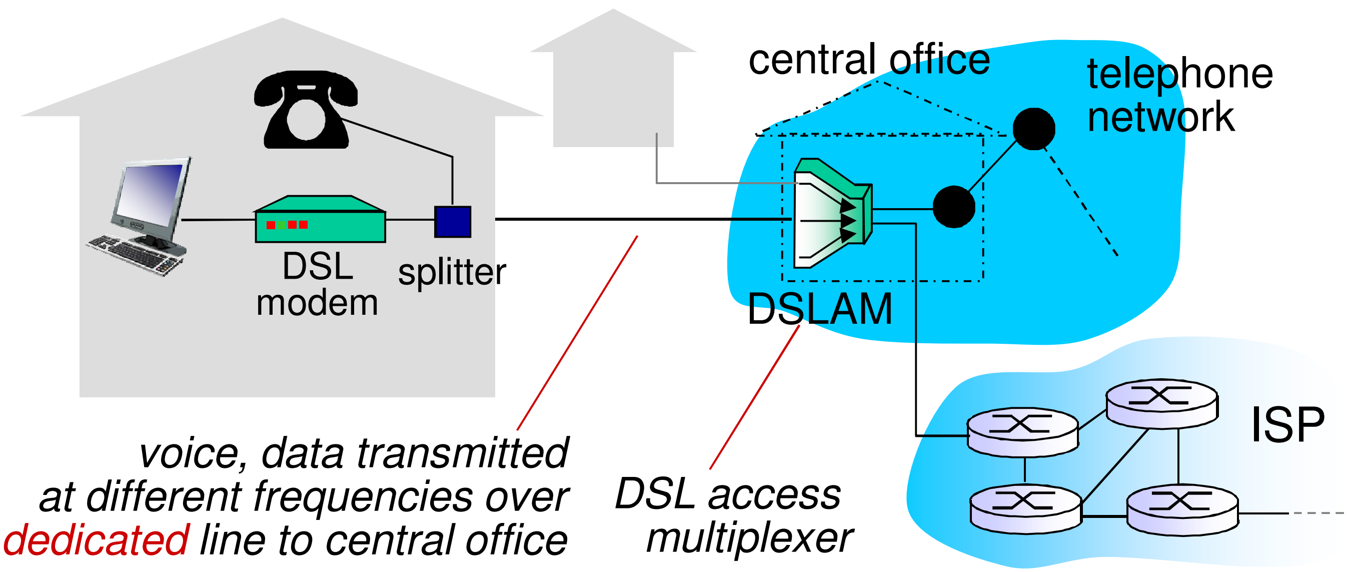
- residential access nets
- institutional access networks (school, company)
- mobile access networks

keep in mind:

- bandwidth (bits per second) of access network?
- shared or dedicated?

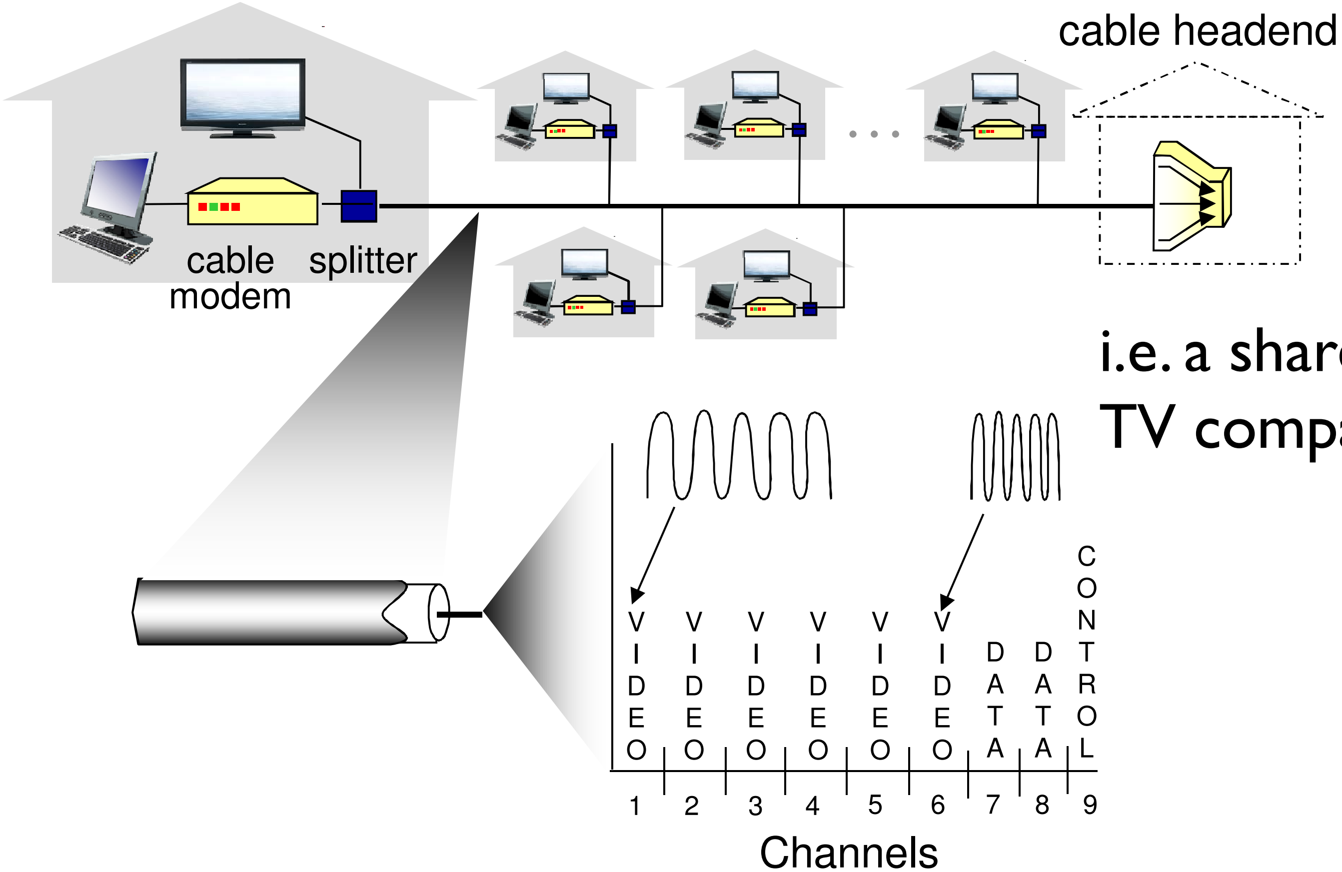


Popular Broadband Residential **Access** net: digital subscriber line (DSL)



- use *existing* telephone line to central office DSLAM i.e. a shared line with telecos!
  - 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)

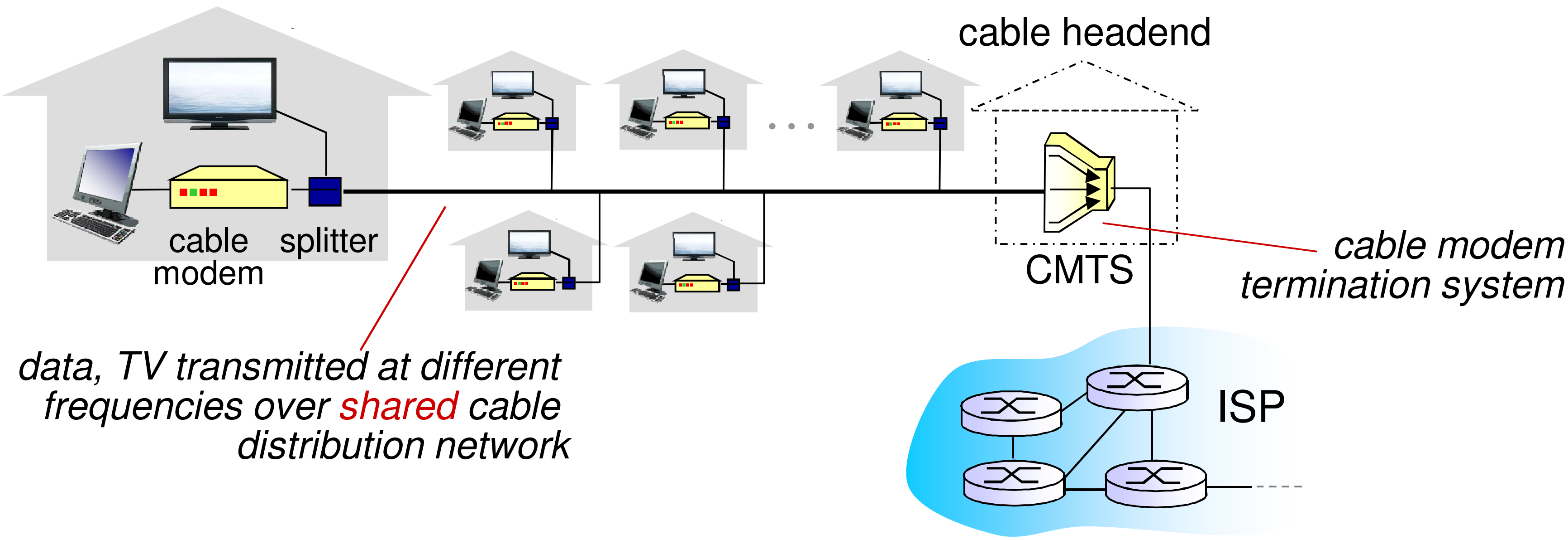
Another Popular Access net: cable network



i.e. a shared line with cable TV companies!

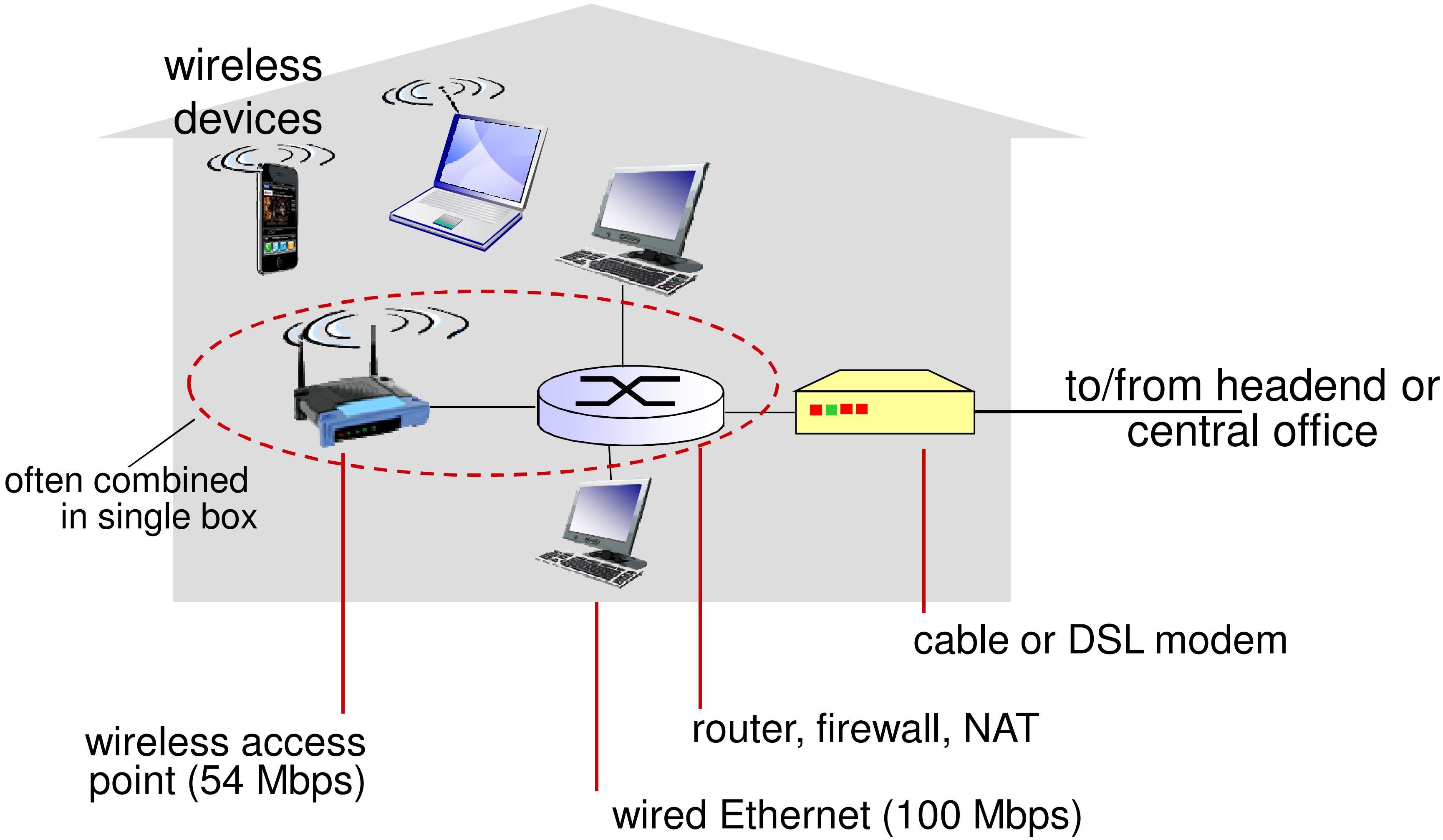
frequency division multiplexing: different channels transmitted in different frequency bands

Access net: cable network

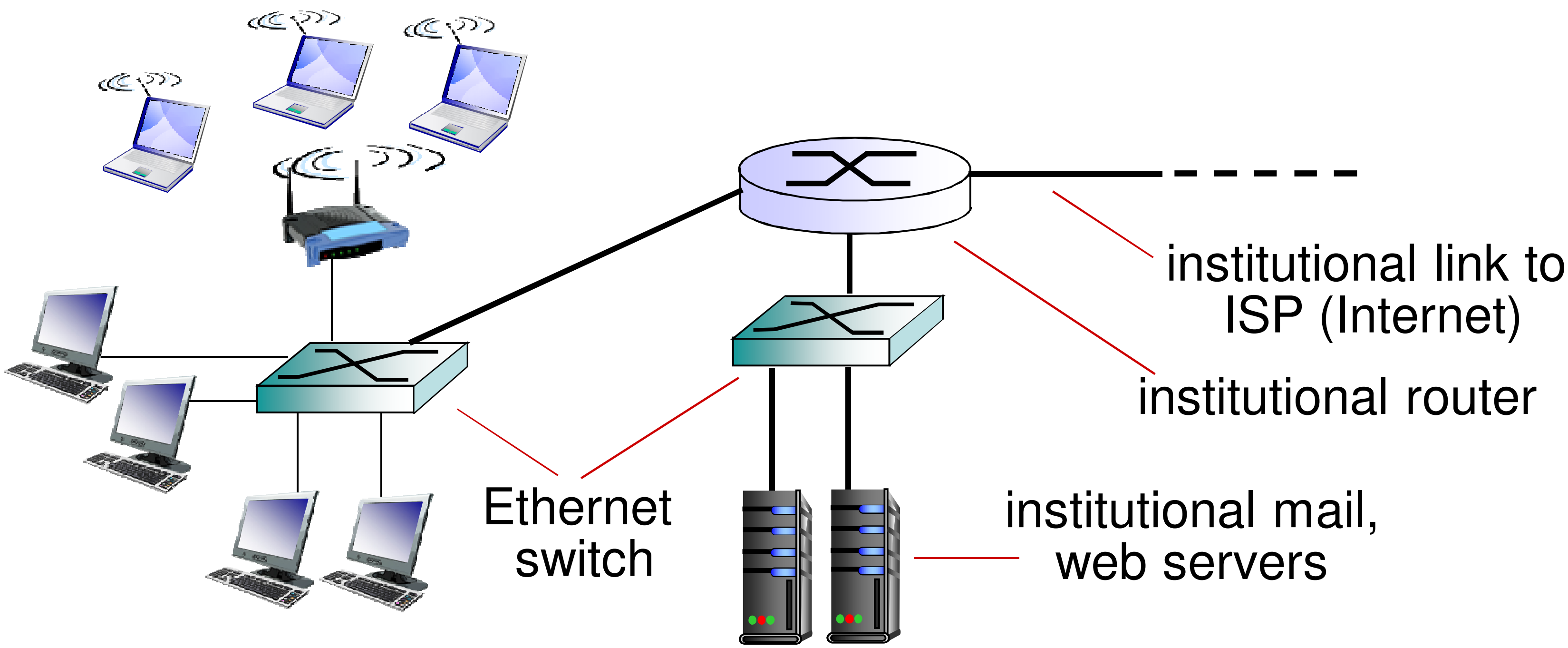


- HFC: hybrid fiber coax
  - asymmetric: up to 30Mbps downstream transmission rate, 2 Mbps upstream transmission rate
- network of cable, fiber attaches homes to ISP router
  - homes *share access network* to cable headend
  - unlike DSL, which has dedicated access to central office

Access net: home network

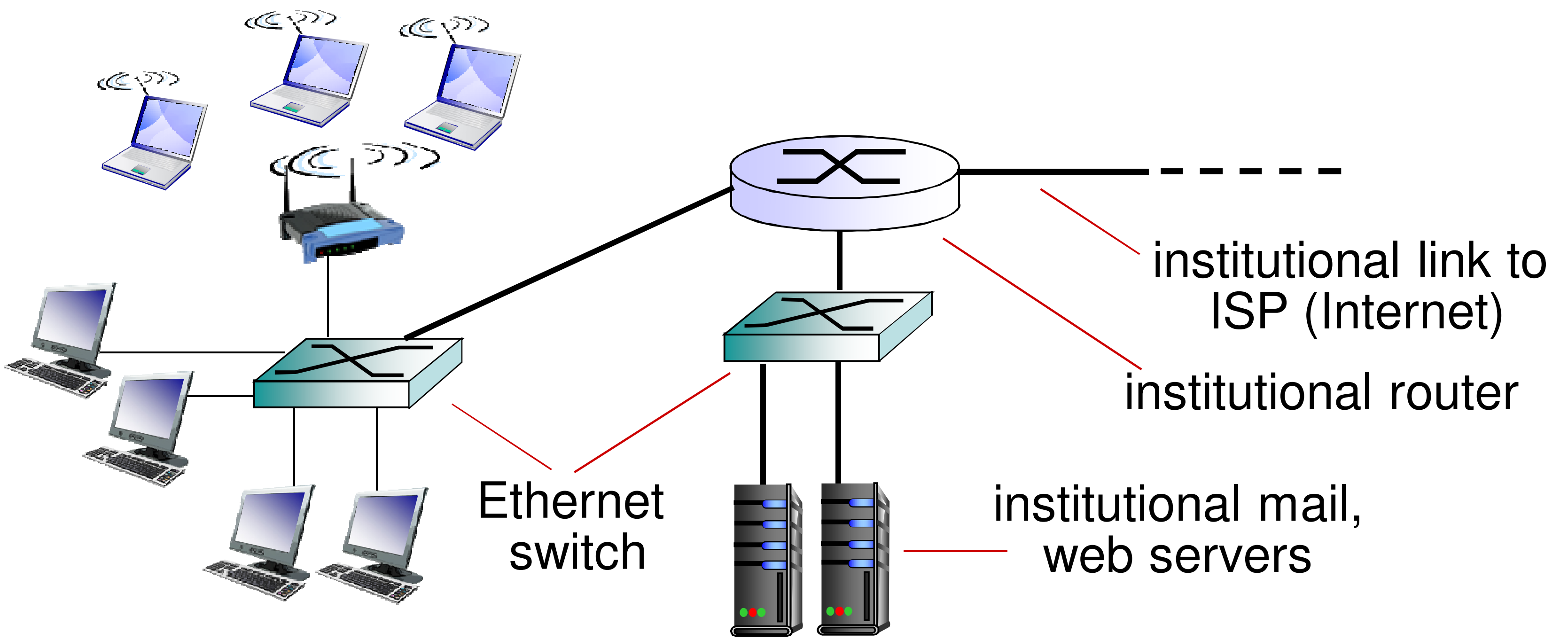


Enterprise access networks (Ethernet)



- typically used in companies, universities, etc
- Ethernet is the most common access technology in corporate, educational and home networks.
- We will discuss Ethernet in detail in coming weeks.

Enterprise access networks (Ethernet)



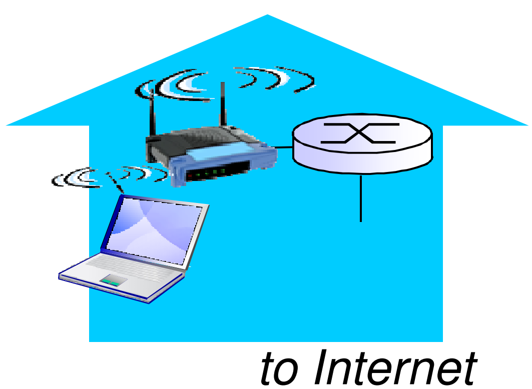
- 10 Mbps, 100Mbps, 1Gbps, 10Gbps transmission rates depending on what your role is in the network!

Wireless access networks

- shared *wireless* access network connects end system to router
  - via base station aka "access point" which is generally "wired" to the enterprise access network

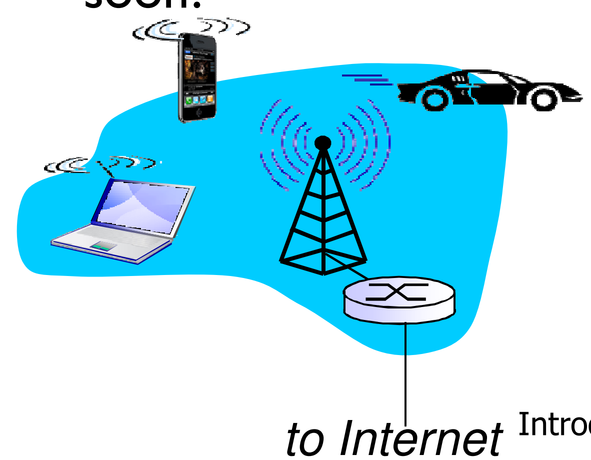
wireless LANs:

- within building (within approx 100 ft of access point)
- 802.11b/g (aka "WiFi"): up to 54 Mbps transmission rate shared



wide-area wireless access

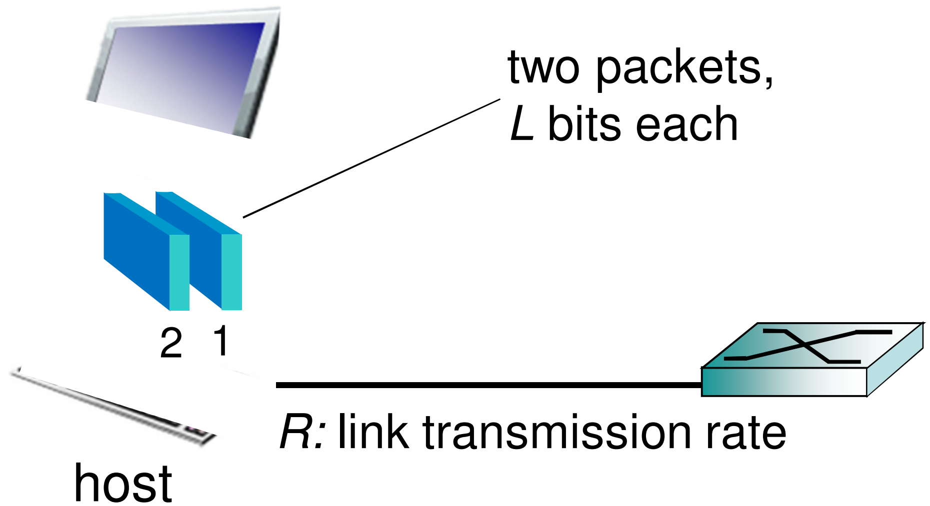
- provided by telecommunications (cellular) operator, 10's km
- between 1 and 10 Mbps
- 3G, 4G: LTE – speed or data rates the driver! – we will cover LTE soon!



Host: sends *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*



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

Physical media

- **Some Terms:**
- 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

Media

twisted pair (TP)

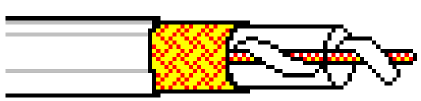
- two insulated copper wires
  - Category 5: 100 Mbps, 1 Gpbs Ethernet
  - Category 6: 10Gbps
  - Cheapest / most common
  - Wires are “twisted” to reduce interference from similar pairs in close vicinity. UTP – common in LAN – no shielding

Physical media: coax, fiber

Media

coaxial cable:

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



Media

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 Gpbs transmission rate)
- low error rate:
  - repeaters spaced far apart
  - immune to electromagnetic noise

Physical media: radio

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

radio link types:

- terrestrial microwave
- LAN (e.g., WiFi)
- wide-area (e.g., cellular)
- satellite

Physical media: radio

radio link types:

- terrestrial radio
  - Weather conditions affect loss
  - Classified into (a) short operation e.g. a few meters (b) local operation – e.g.10 - 100meters (b) wide area operation e.g. tens of km
  - 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
  - LEO, MEO, HEO

Physical media: radio

radio link types:

- satellite
  - Kbps to 45Mbps channel (or multiple smaller channels)
  - 270 msec end-end delay
  - geosynchronous versus low altitude
  - GEO (geo-stationary earth orbit): at about 35,786km above the earth's surface
  - LEO (low-earth orbit): at about 500-1500km above the earth's surface
  - MEO (medium-earth orbit) or ICO (intermediate circular orbit): at about 6000-20,000km above the earth's surface
  - HEO – Highly Elliptical Earth Orbit

  - Varying applications, delays and characteristics

Network Core

1.1 what *is* the Internet?

1.2 network edge

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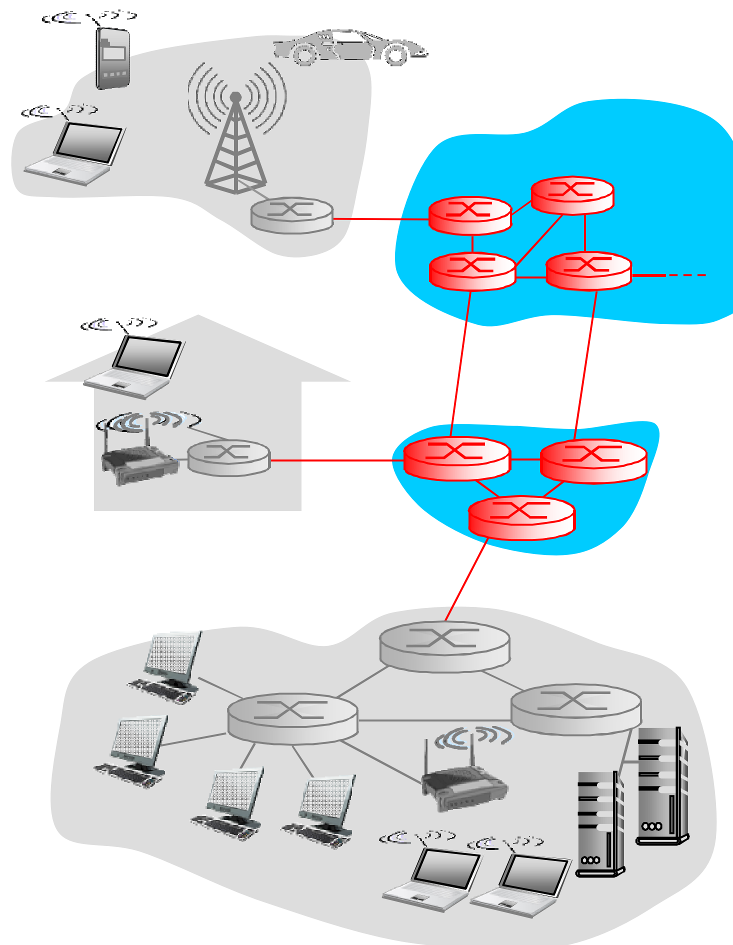
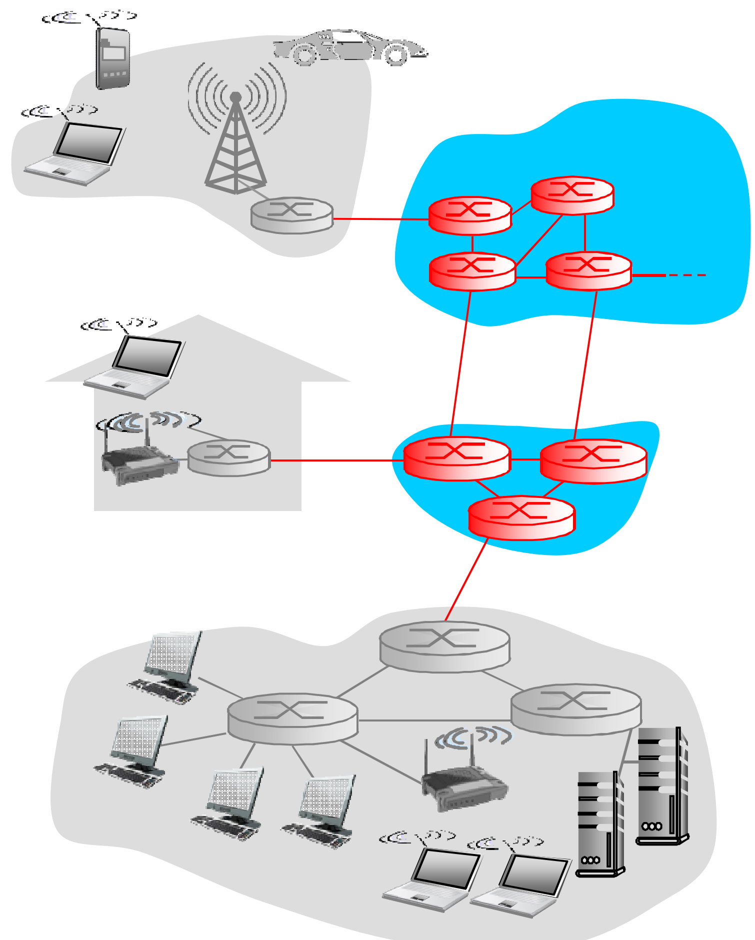
The network core

- The network core is the mesh of packet switches (routers & link layer switches) and links that interconnect the internets end systems.
- End systems exchange “messages” with each other
  - Data
  - Control
- These messages are broken down into “**packets**”



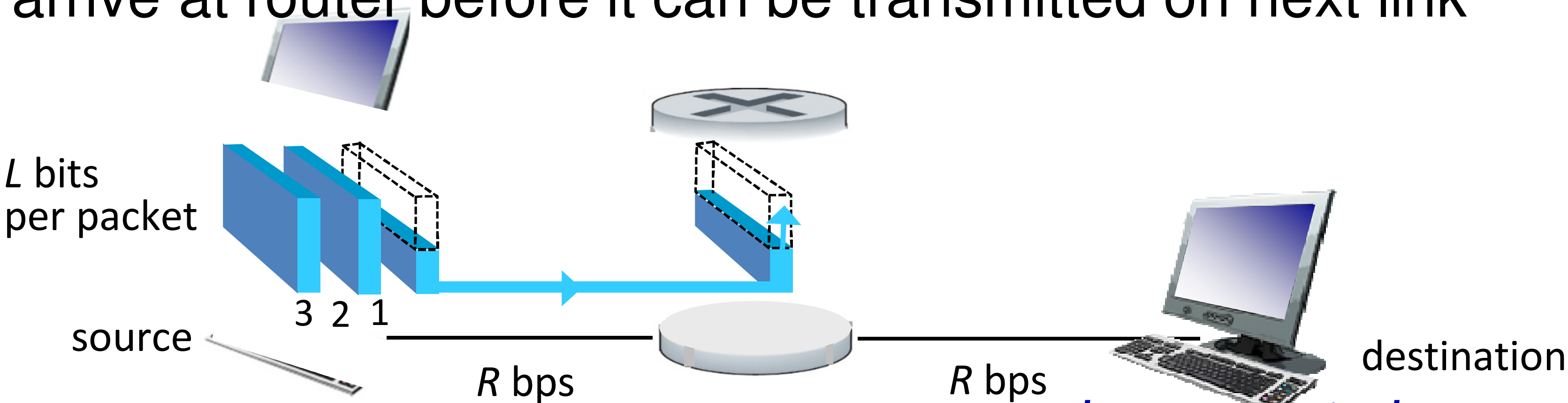
The network core

- packet-switching: hosts break application-layer messages into *packets*
  - route packets from one router to the next, across links on path from source to destination
  - each packet transmitted at full link capacity
  - Internet is packet switched!



Packet-switching: store-and-forward

❖ *Key point of store and forward:* entire packet must arrive at router before it can be transmitted on next link



one-hop numerical example:

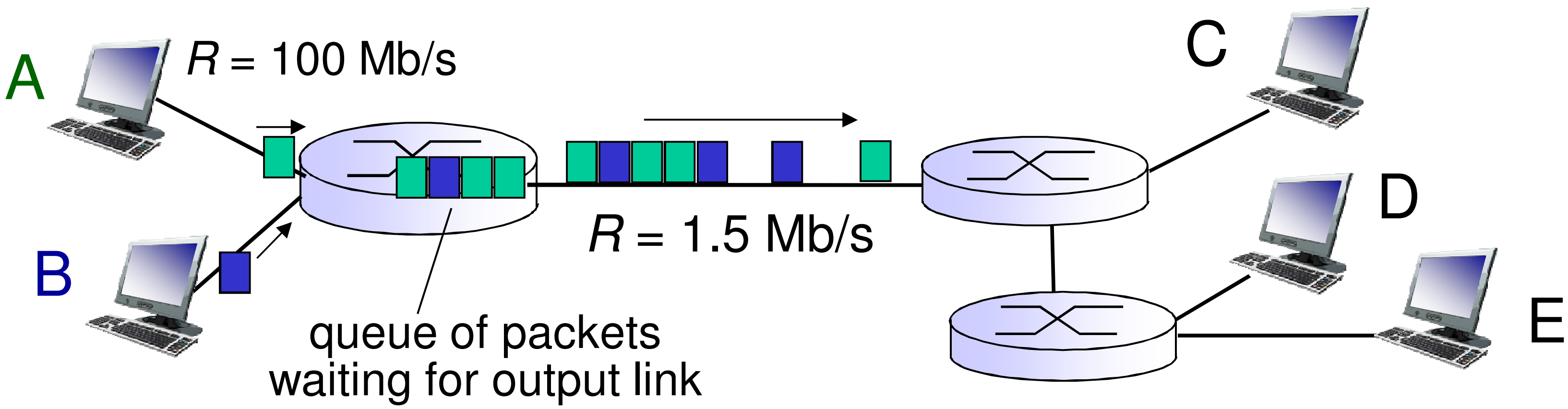
- *L* = 7.5 Mbits
- *R* = 1.5 Mbps
- one-hop transmission delay = 5 sec

❖ In this example: 3 packets, each *L* bits, some of 1st bit txed!

❖ takes *L*/*R* seconds to transmit (push out) *L*-bit packet into link at *R* bps, router wont tx until all packet is rxed – it buffers i.e. waits

❖ end-end delay = 2*L*/*R* (assuming zero propagation delay)

Packet Switching: queueing delay, loss



queuing and loss:

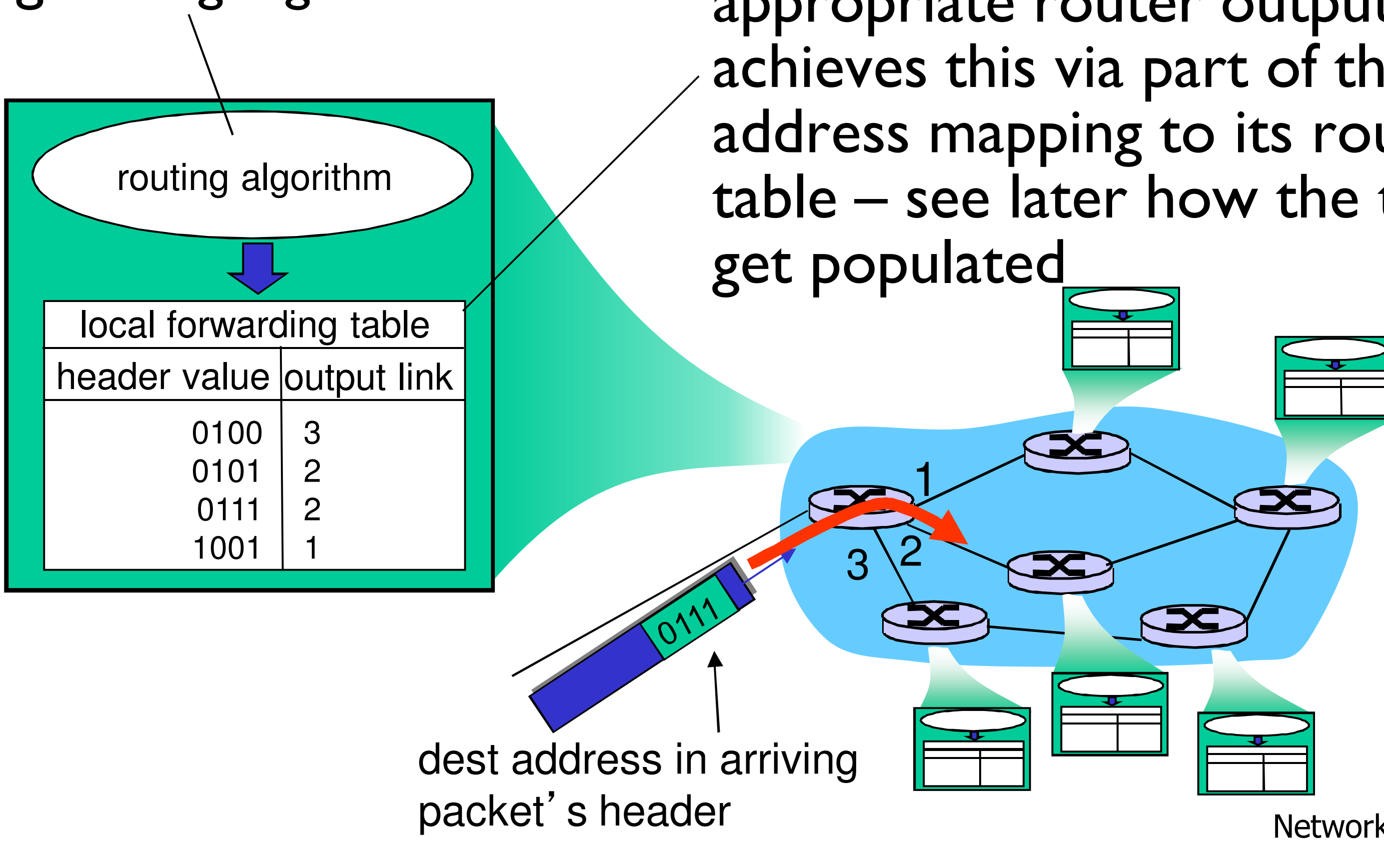
- If arrival rate (in bits) to link exceeds transmission rate of link for a period of time:
  - packets will queue, wait to be transmitted on link
  - packets can be dropped (lost) if memory (buffer) fills up

Two key network-core functions

Routing protocols: determines source-destination route taken by packets, i.e. sets routing table via using *routing algorithms*

Forwarding tables:

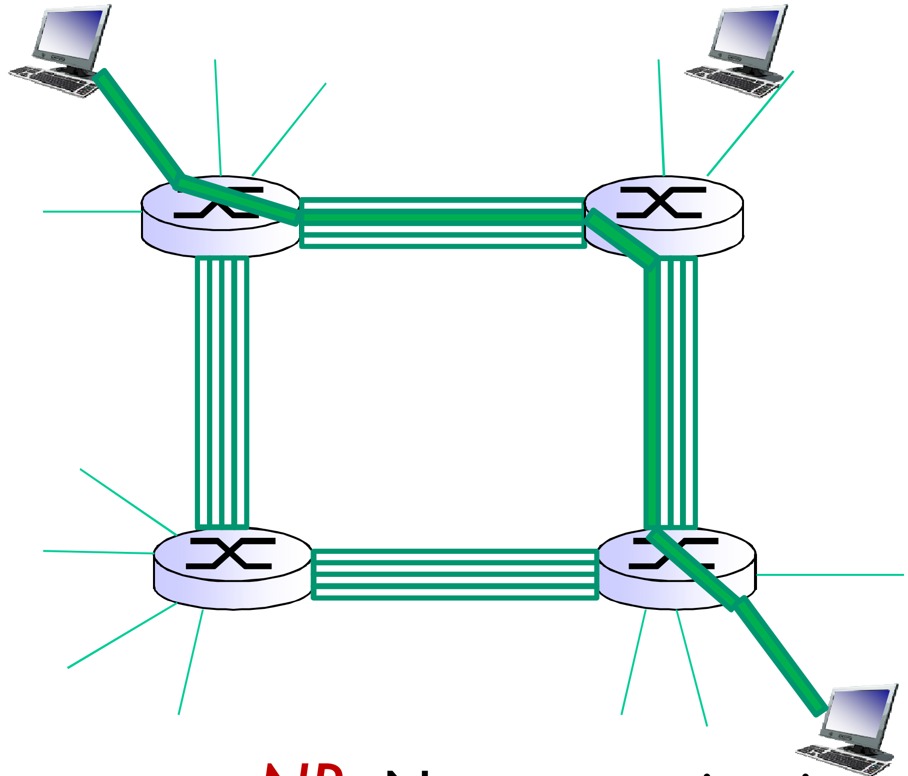
Determines which output link to send the packets, and moves packets from router's input to appropriate router output – achieves this via part of the IP address mapping to its routing table – see later how the tables get populated



Circuit switching

end-end resources allocated to, **reserved** for "call" between source & dest:

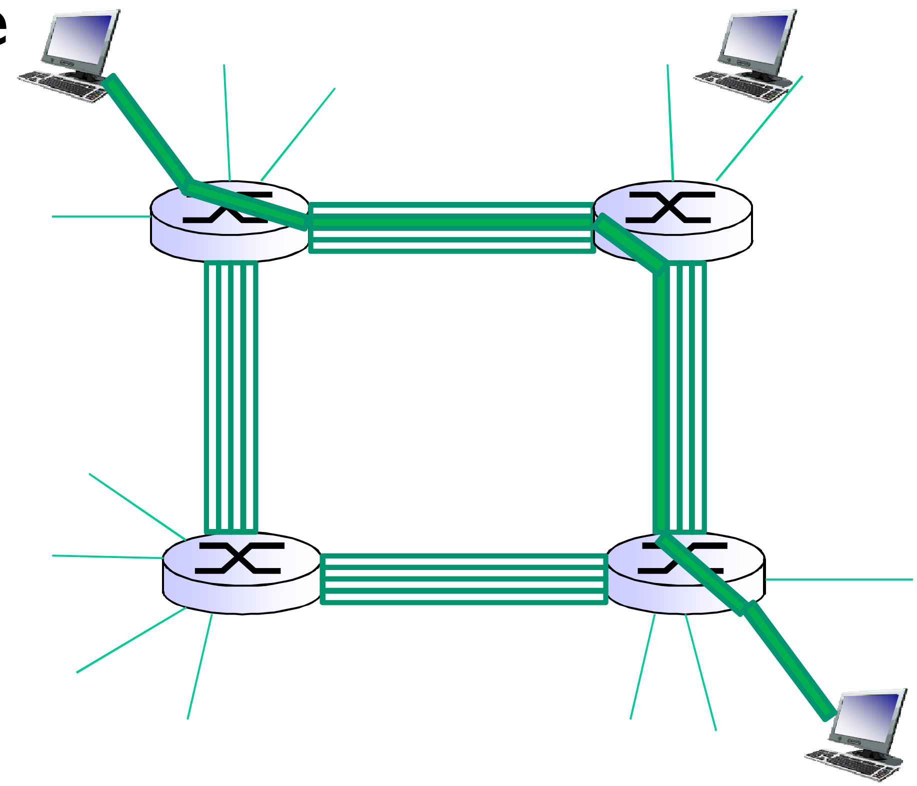
- In diagram, each link has four circuits.
  - call gets 2nd circuit in top link and 1st circuit in right link.
- dedicated resources: no sharing
  - circuit-like (guaranteed) performance
- circuit segment idle if not used by call *(no sharing)*
- Commonly used in traditional telephone networks



NB: No reservation in packet switching!

Circuit switching

- It is called “circuit” because this is the name given to the established and reserved path between the source and the destination.
- Since its reserved – the data transfer rate is guaranteed!



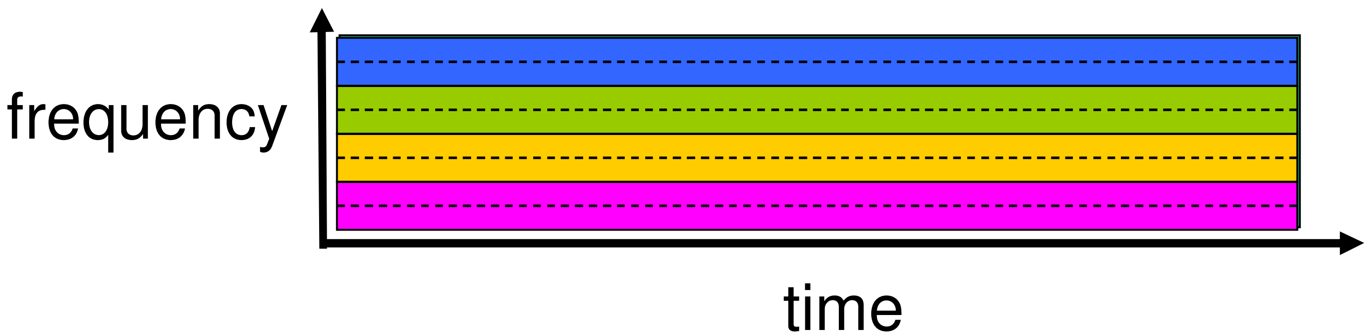
Multiplexing Circuit switching

A circuit switch is either multiplexed via frequency or time!

Example:

4 users

FDM - frequency spectrum of the link is divided between connections across the link



FDM - The portion a connection gets is called its "bandwidth"

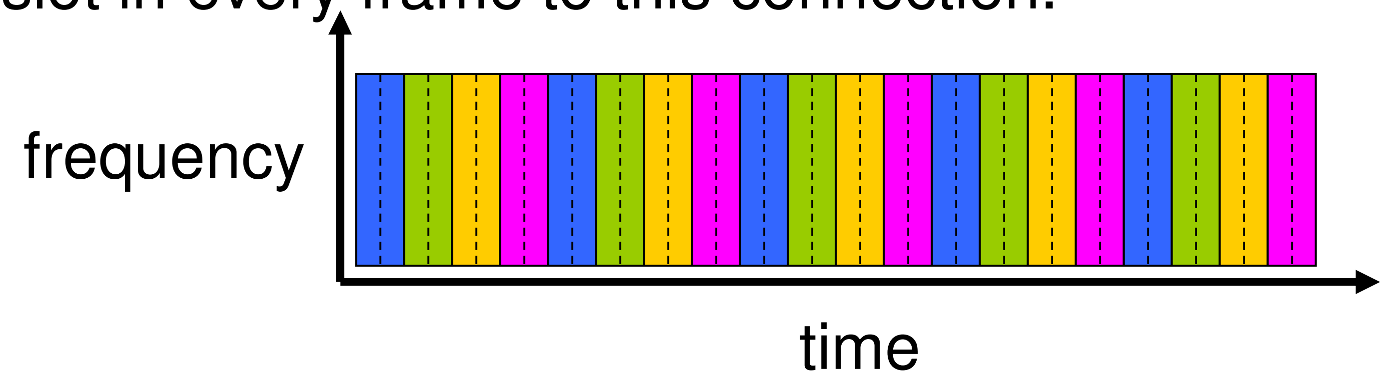
Multiplexing Circuit switching

A circuit switch is either multiplexed via frequency or time!

Example:

4 users

TDM – time is divided into frames of fixed duration and each frame is divided into a fixed number of time slots.
When connection is established, the network dedicates one time slot in every frame to this connection.

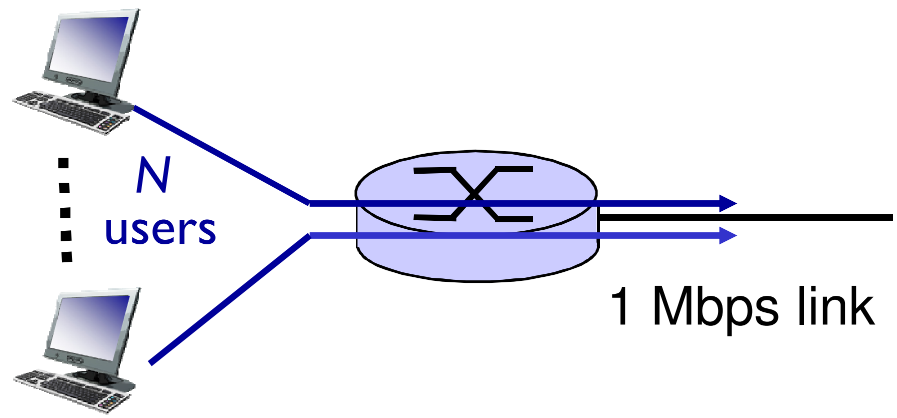


Packet switching versus circuit switching

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

Packet switching versus circuit switching

Packet switching

- great for bursty data
  - resource sharing
  - simpler, no call setup
- 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 (researchers working at this, we will discuss later in more detail)

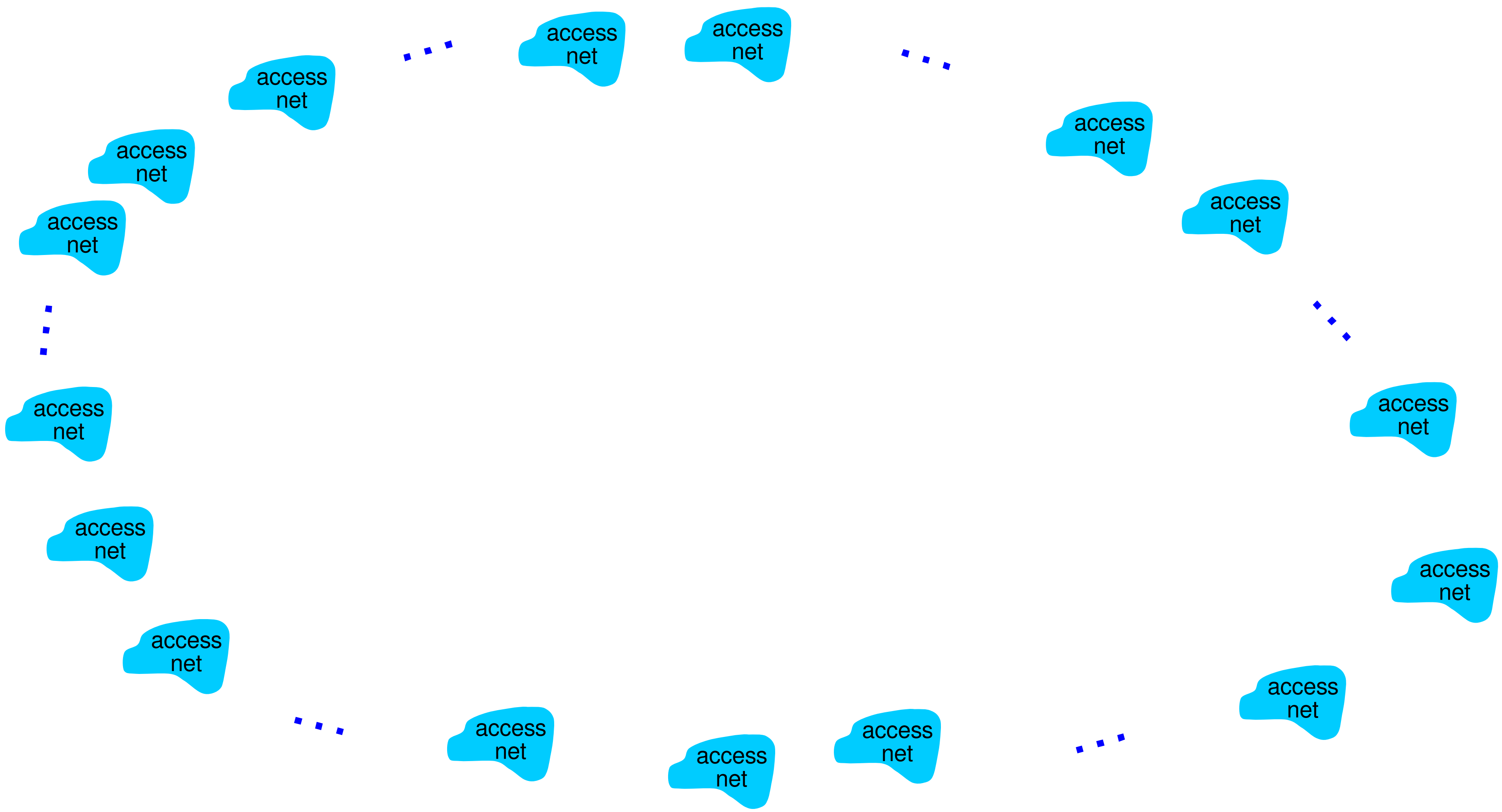
Packet switching Vs Circuit switching – each one is better in certain conditions – can you think of any? –there is a migration towards packet switching networks even from circuit based telephony now!

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

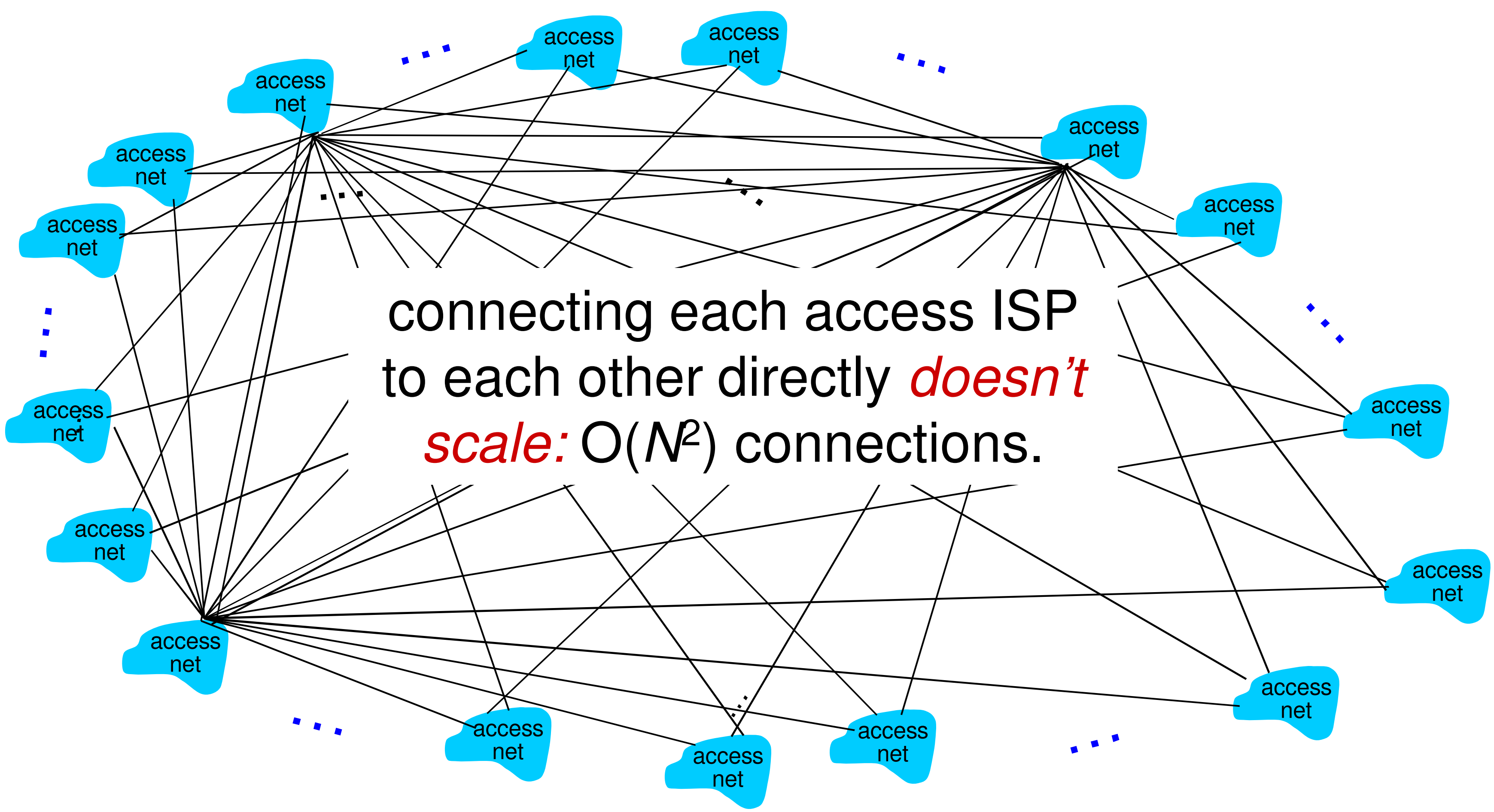
Internet structure: network of networks

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



Internet structure: network of networks

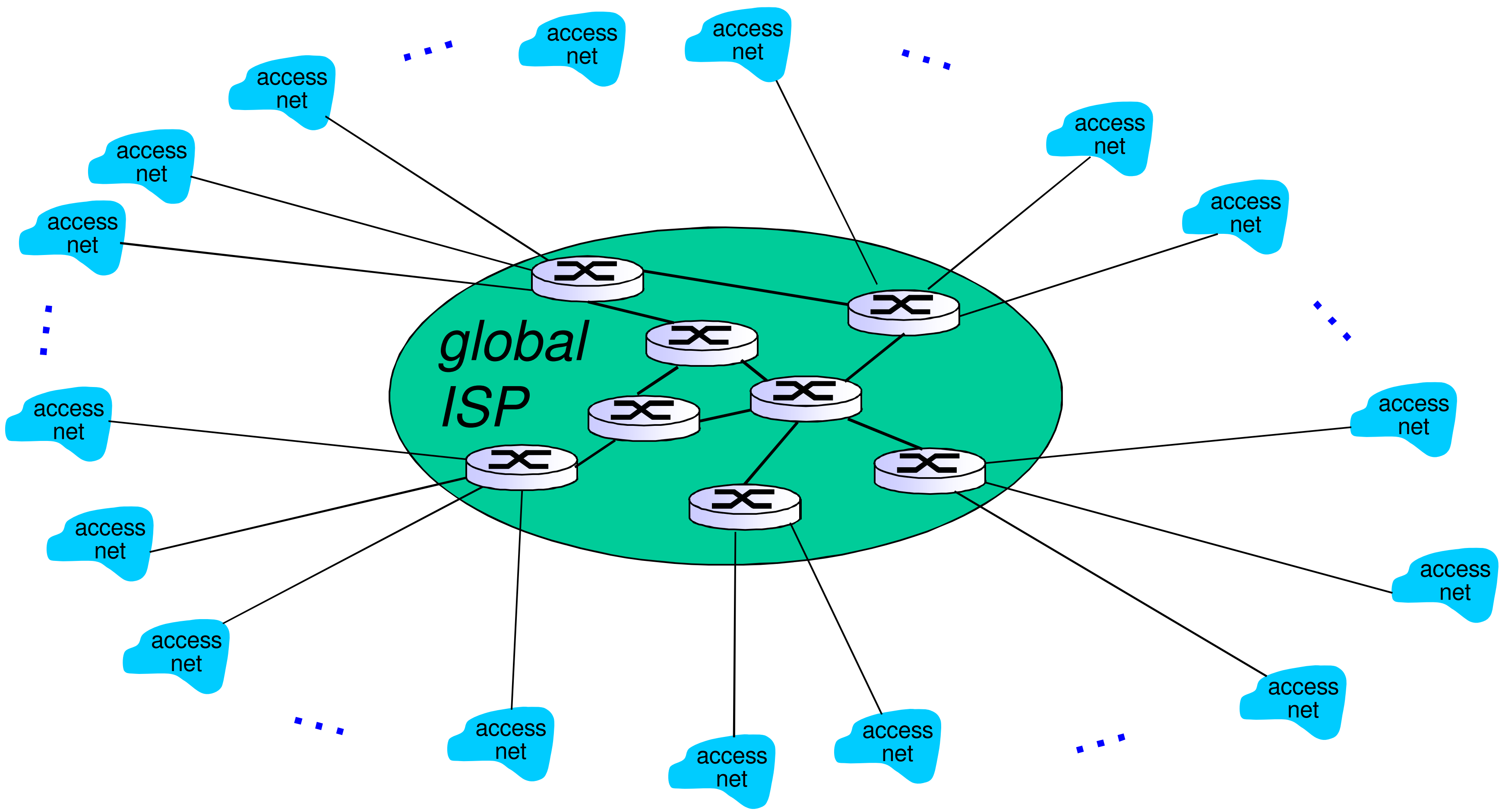
Option: connect each access ISP to every other access ISP?



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

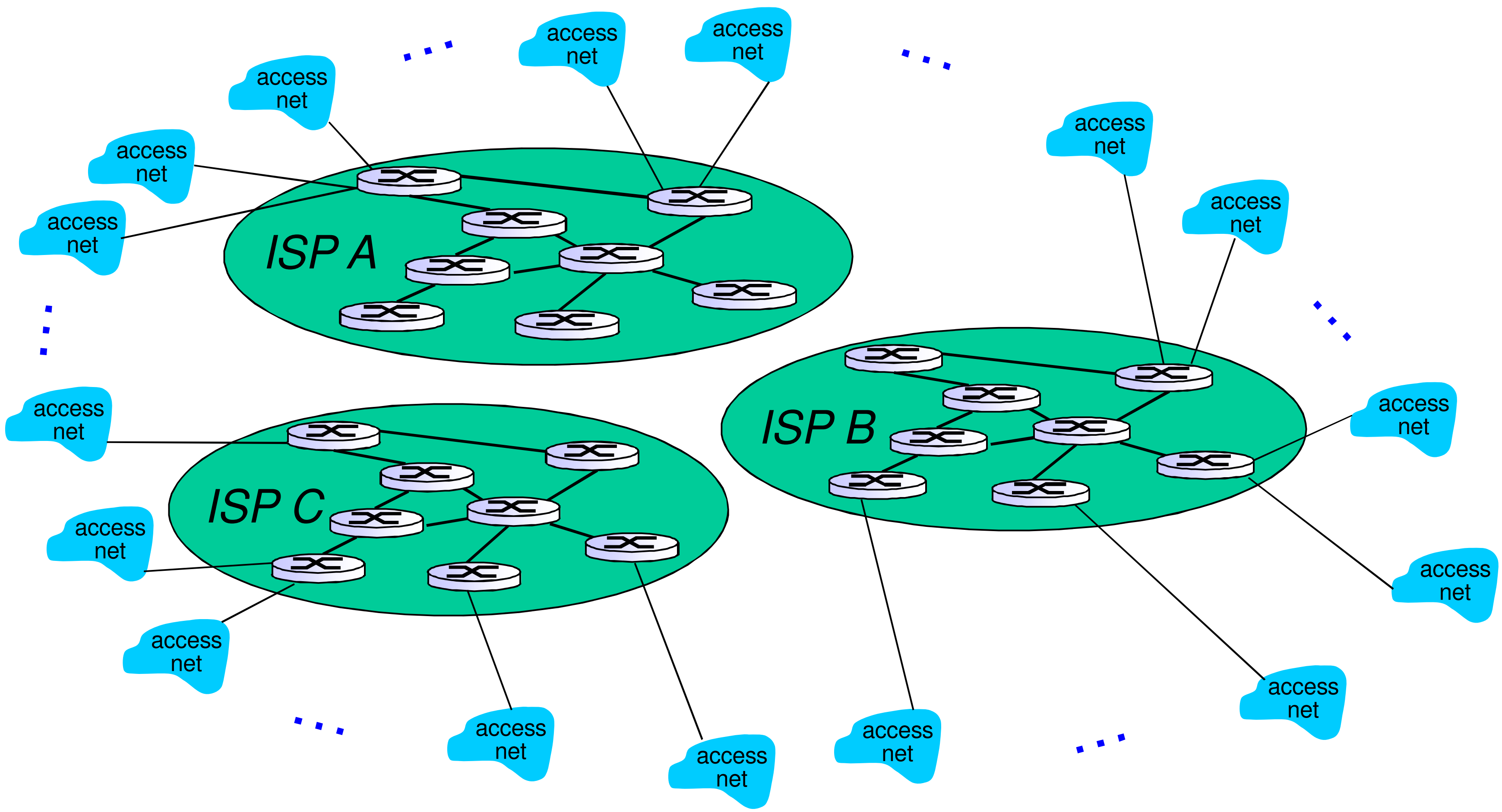
Internet structure: network of networks

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



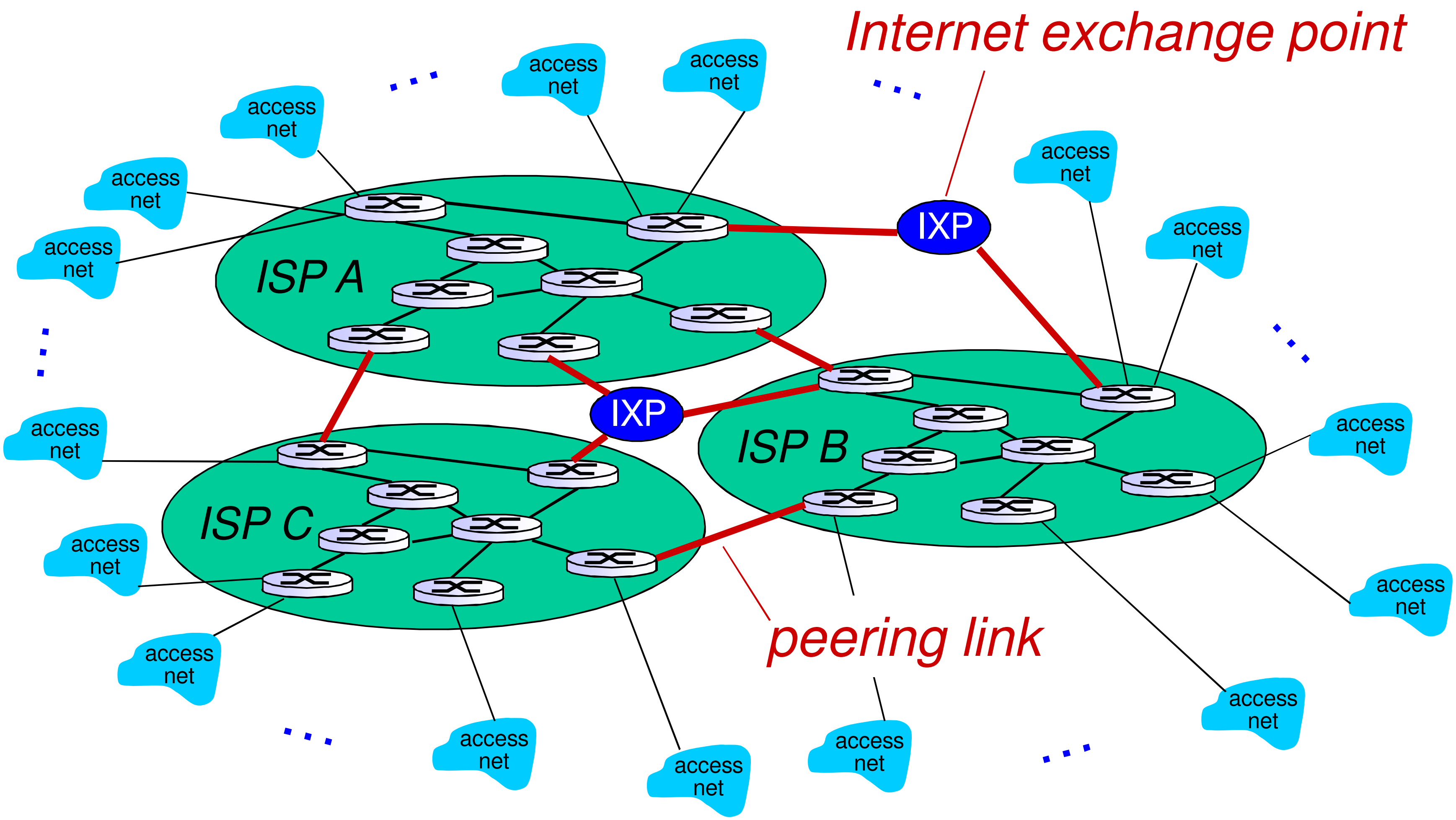
Internet structure: network of networks

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



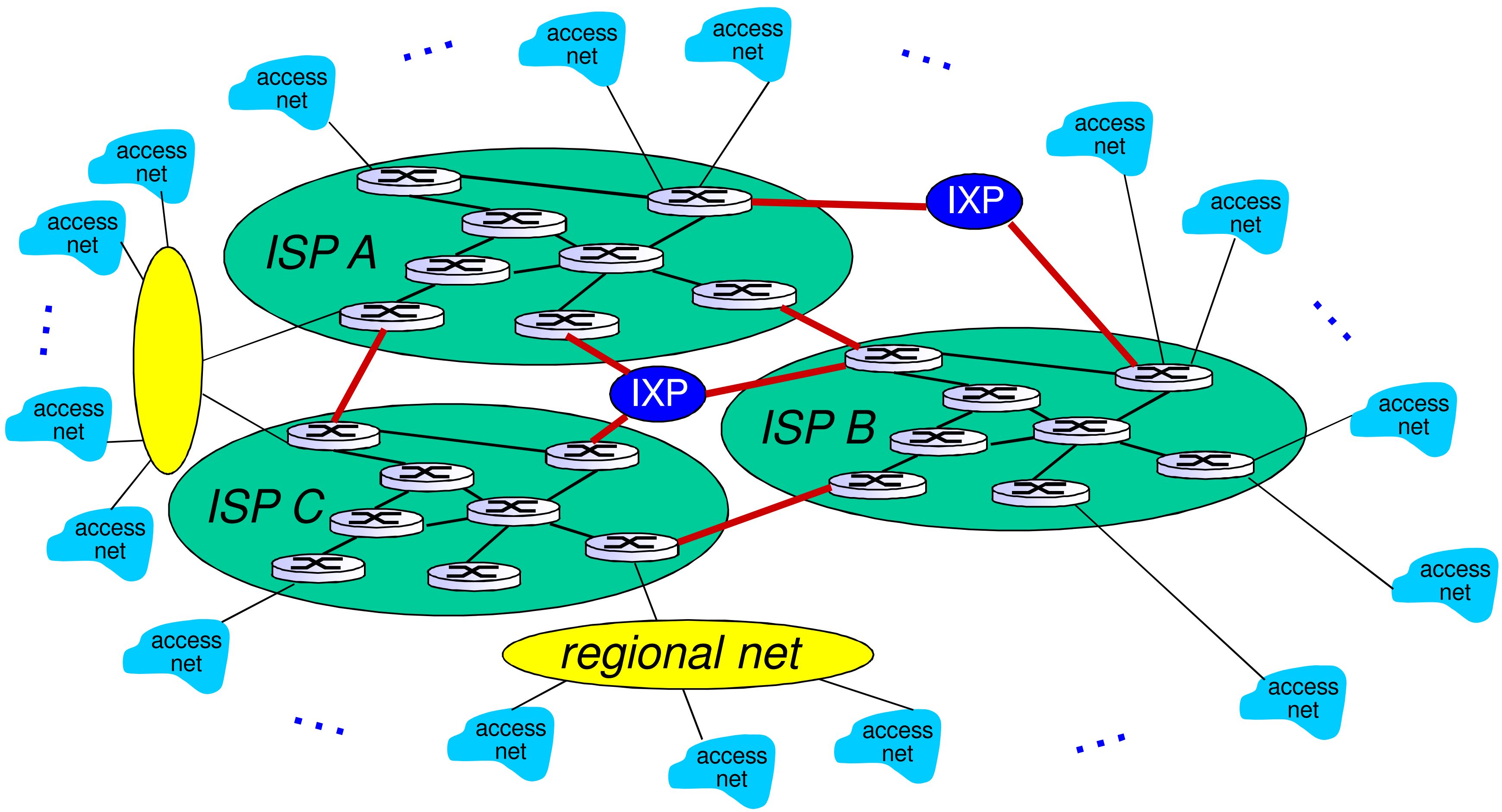
Internet structure: network of networks

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



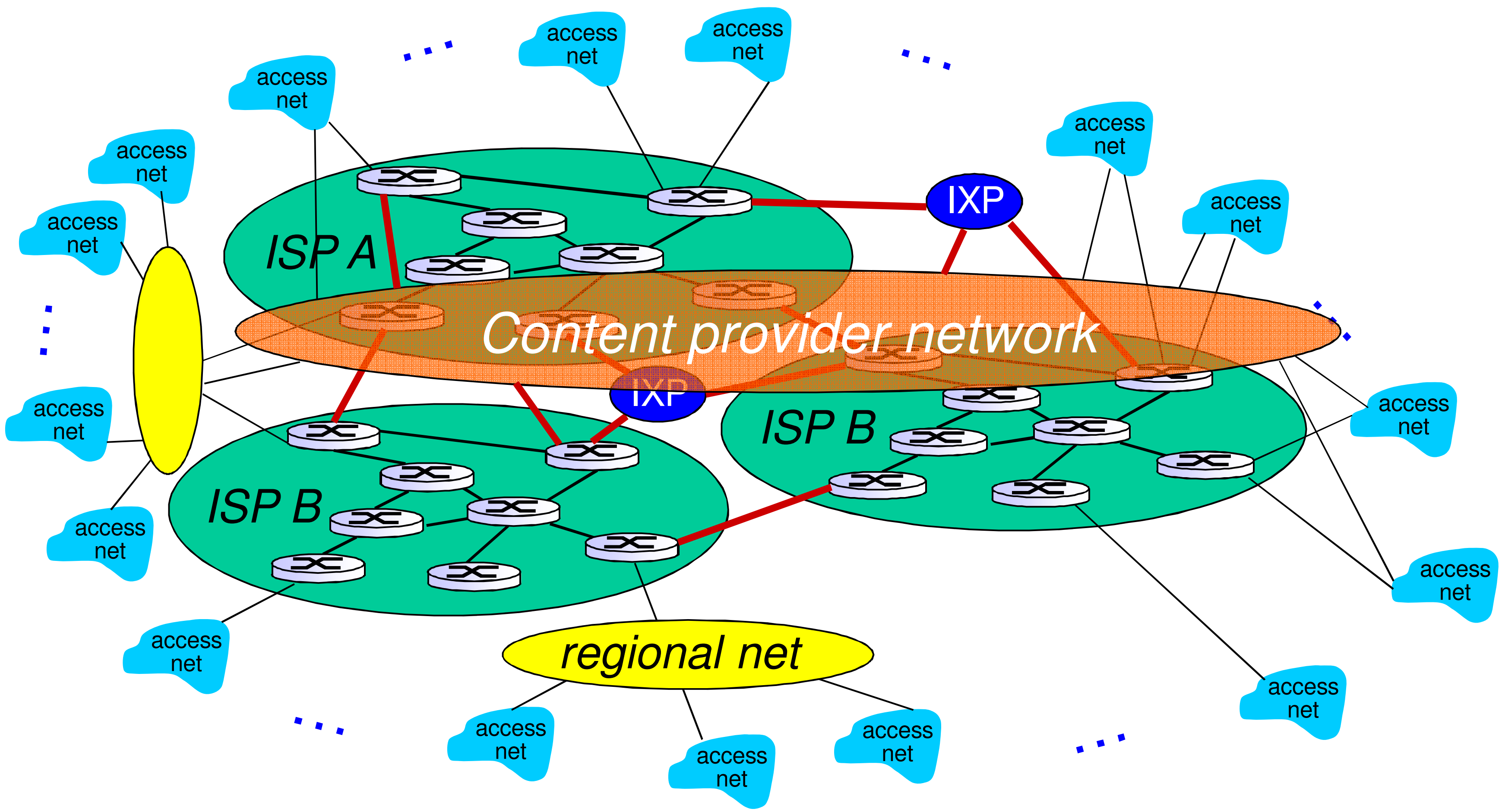
Internet structure: network of networks

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

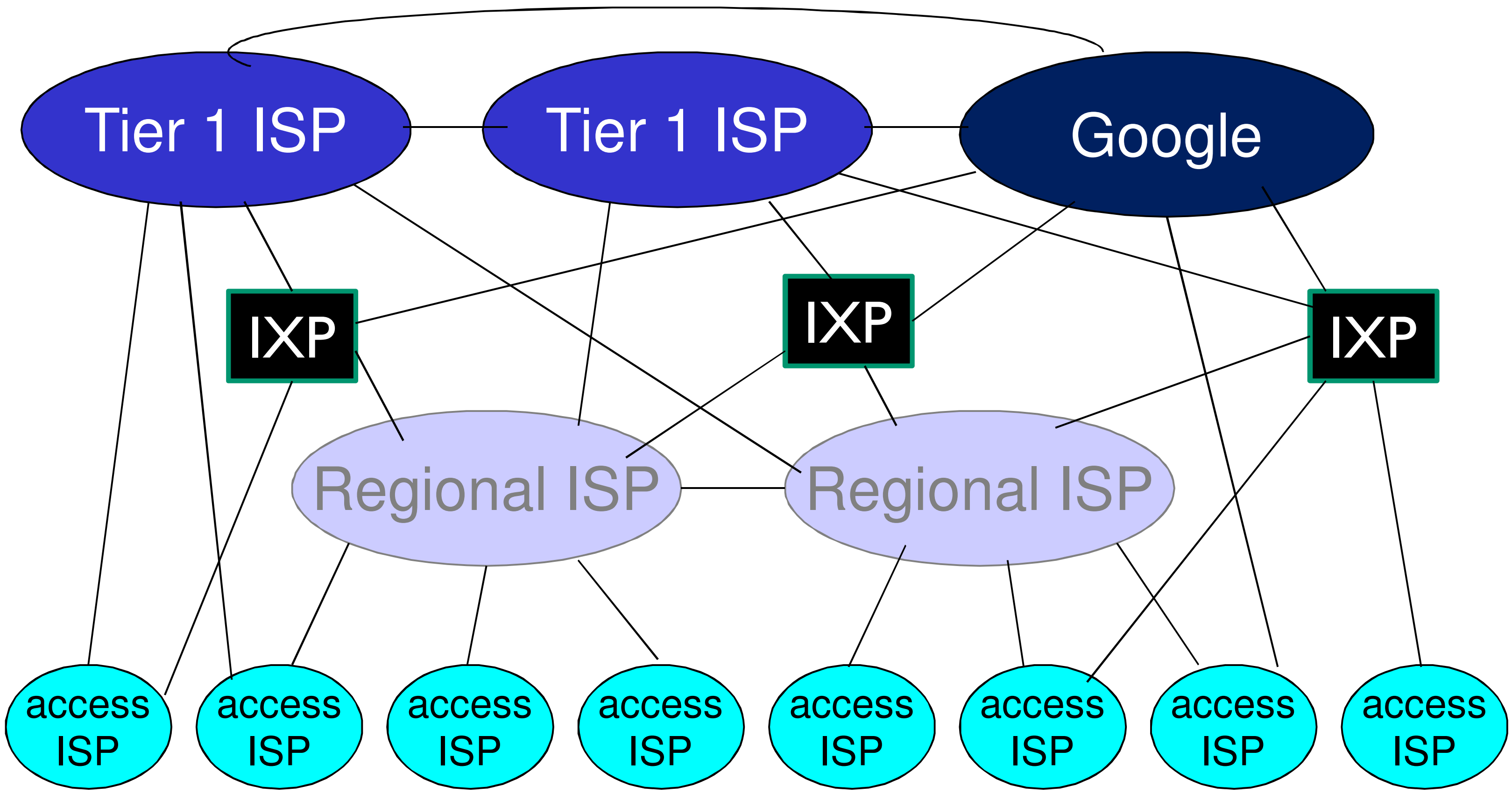


Internet structure: network of networks

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

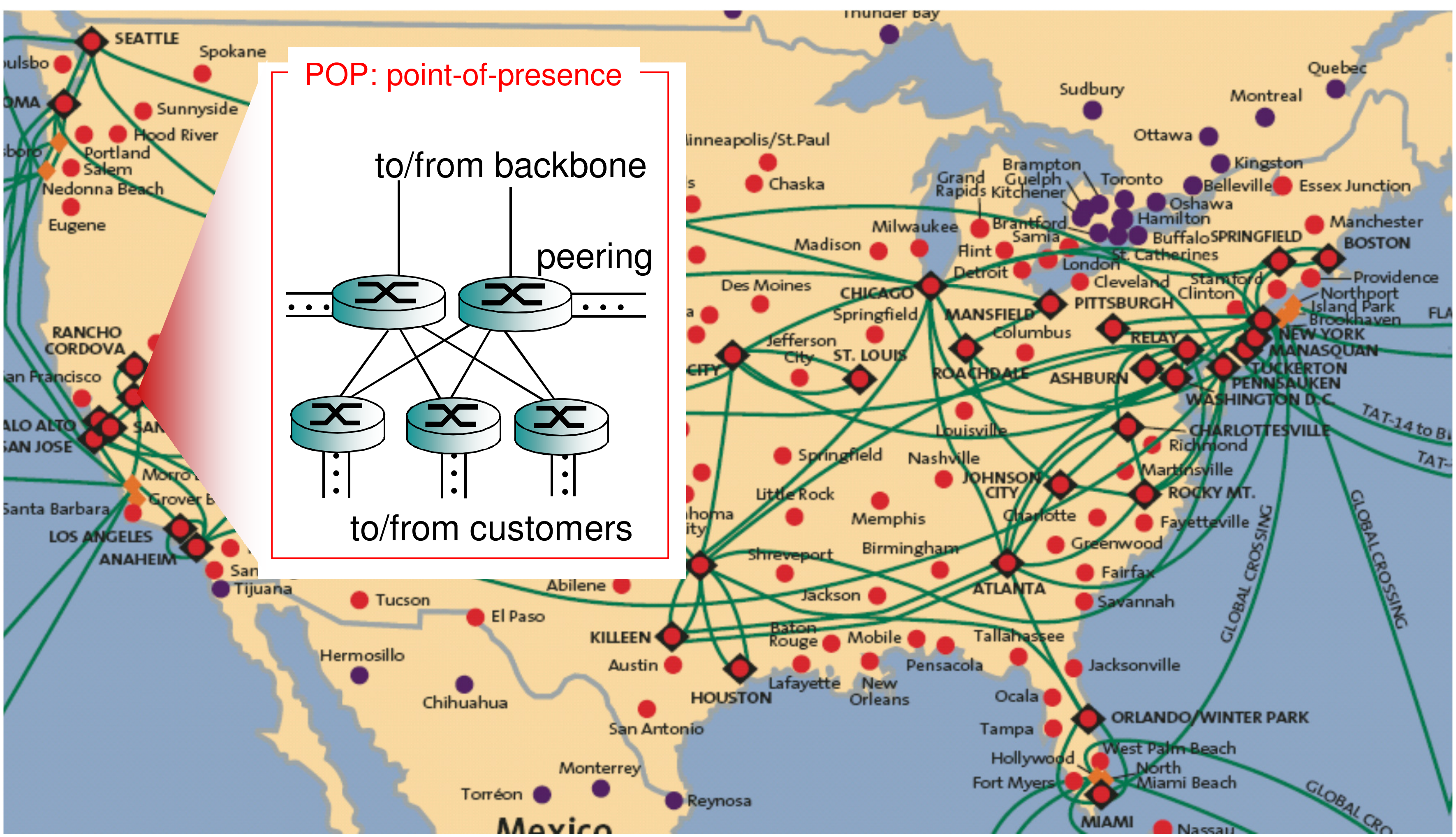


Internet structure: network of networks



- 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's data centers to Internet, often bypassing tier-1, regional ISPs

Tier-1 ISP: e.g., Sprint



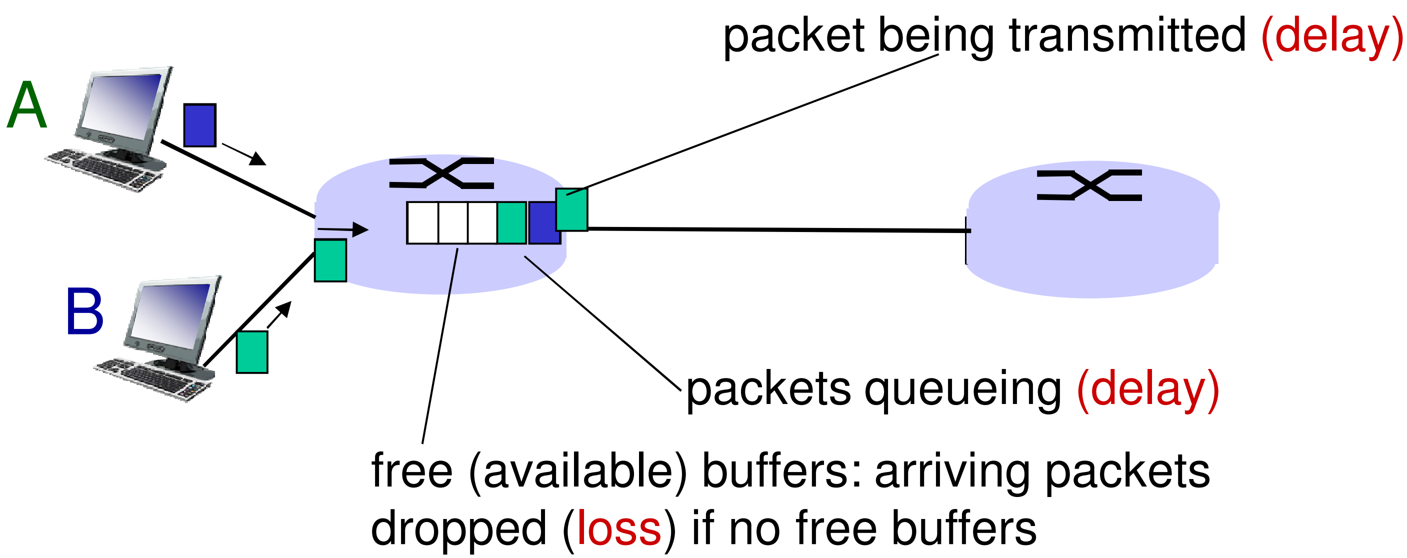
Delay, loss and throughput

How do loss and delay occur?

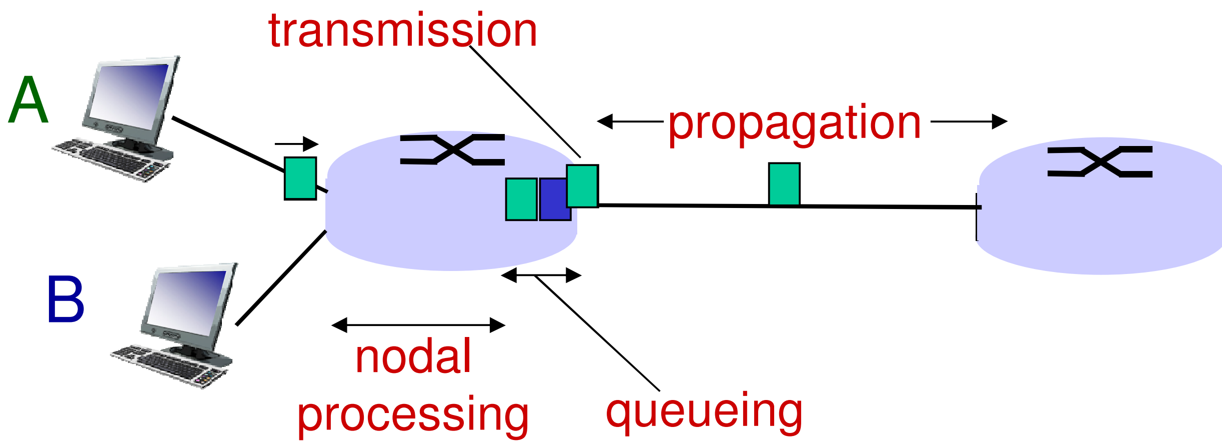
Packet starts at source, travels through routers to destination – as it travels, its suffers delay!

packets *queue* in router buffers

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



Four sources of packet delay



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

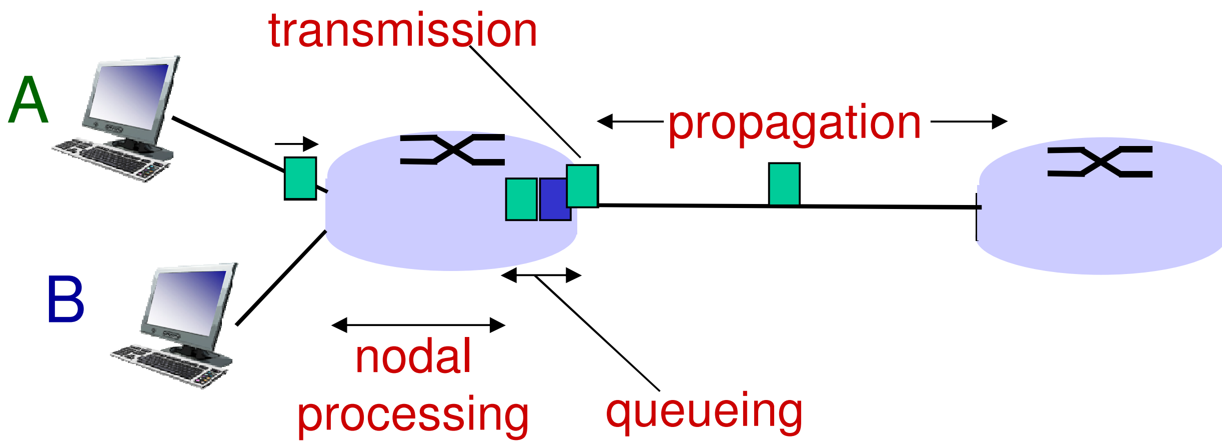
d_{proc}: nodal processing

- 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

Four sources of packet delay



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

d_{trans}: transmission delay (F:

- L: packet length (bits)
- R: link *bandwidth (bps)*
- $d_{trans} = L/R$
- *FIFO model in*

Queue at the router!

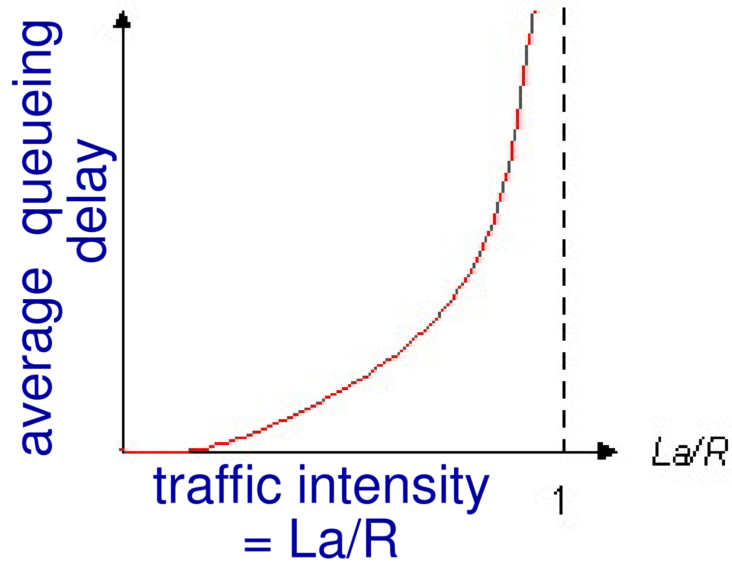
d_{trans} and d_{prop} *very* different

d_{prop}: propagation delay:

- d: length of physical link
- s: propagation speed in medium (~2×10^8 m/sec)
- $d_{prop} = d/s$
- *Delay travelling the distance from router A to router B!*

Queueing delay (revisited)

- *Huge area of research!*
- *Vary from packet to packet – how long will each packet queue for if 10 arrive at same time?*
- *R:* link bandwidth (bps)
- *L:* packet length (i.e. # of bits)
- a: average packet arrival rate => La bits per sec = rate at which bits arrive on the queue



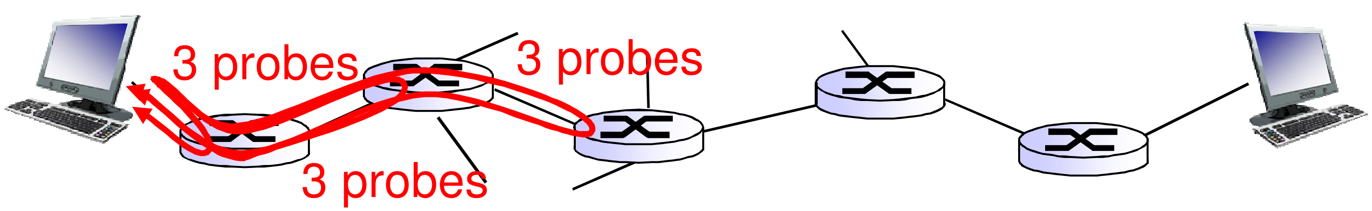
- *La/R* ~ 0: avg. queueing delay small
- *La/R* -> 1: avg. queueing delay large
- *La/R* > 1: more "work" arriving than can be serviced, average delay infinite!

La/R ~ 0

La/R -> 1

“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
  - router *i* will return packets to sender
  - sender times interval between transmission and reply.



"Real" Internet delays, 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

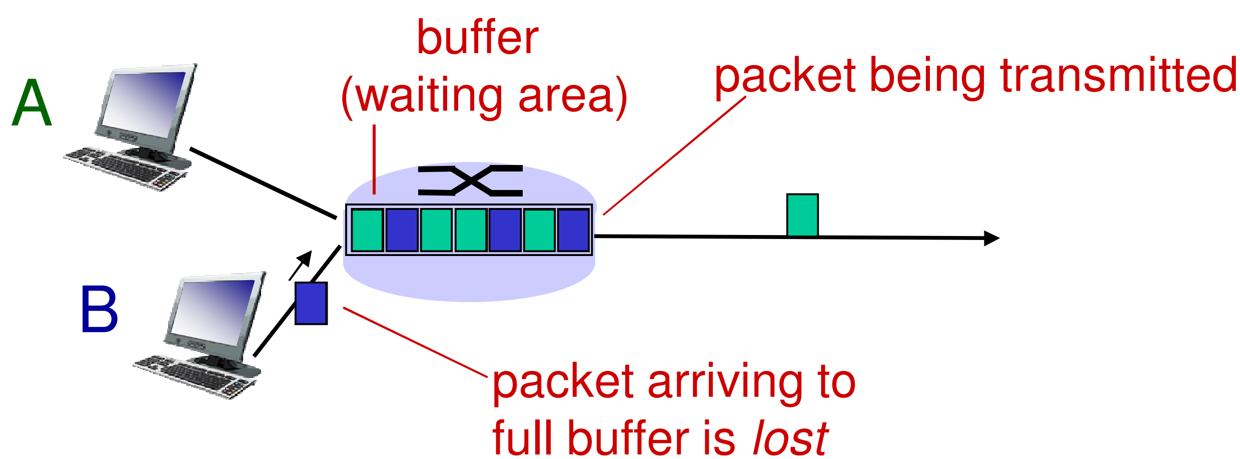
trans-oceanic link

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

NB: In your own time, execute some traceroute commands.

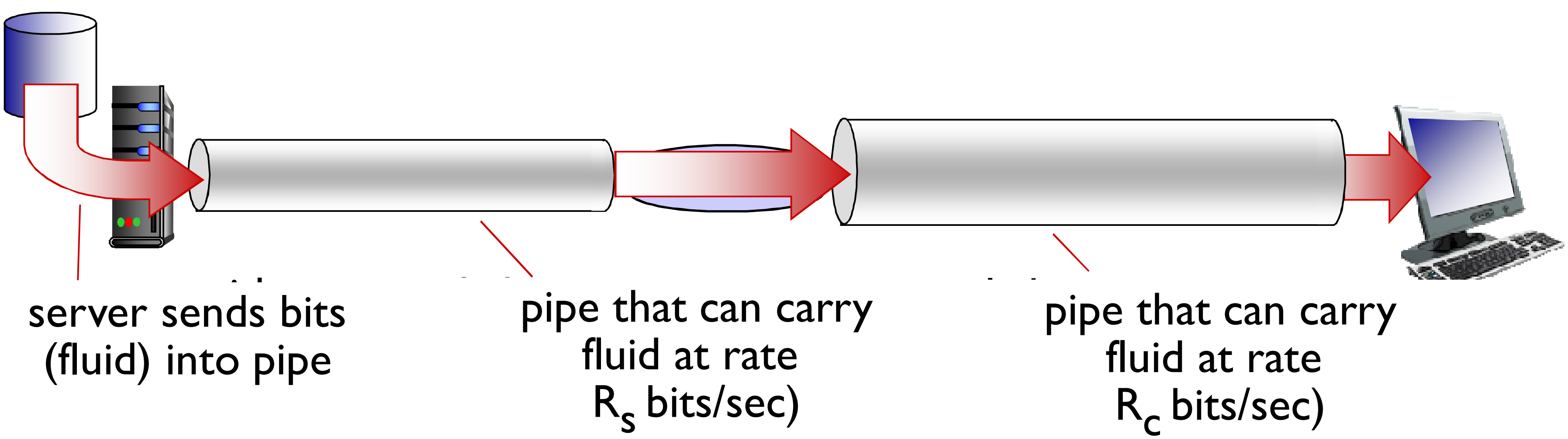
Packet loss

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

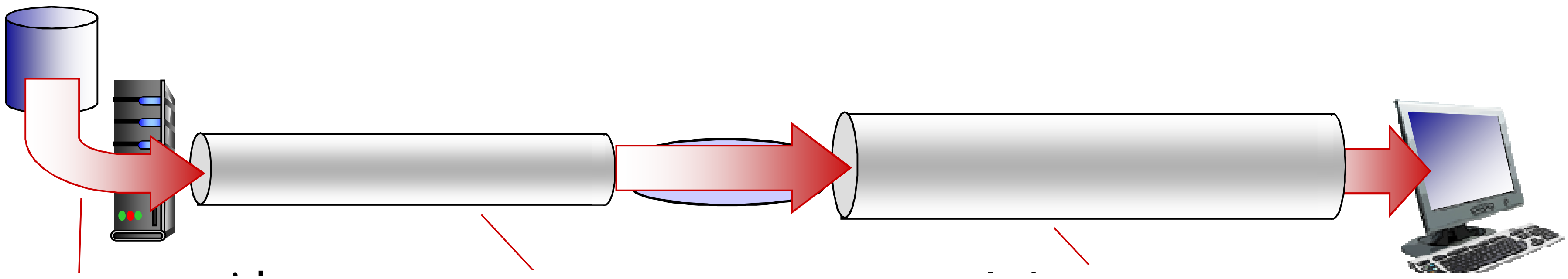


Throughput

- *throughput:* rate (bits/time unit) at which bits transferred between sender/receiver
  - *instantaneous:* rate at given point in time
  - *average:* rate over longer period of time



Throughput



server sends bits (fluid) into pipe

pipe that can carry fluid at rate R_s bits/sec)

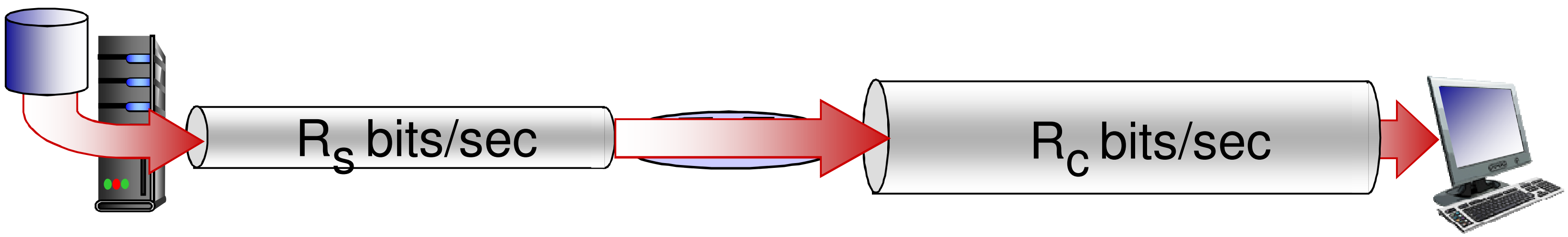
pipe that can carry fluid at rate R_c bits/sec)

a) Server cannot pump fluid through link > Rs bits per sec
b) Router cannot forward bits at a faster rate than Rc bits per sec

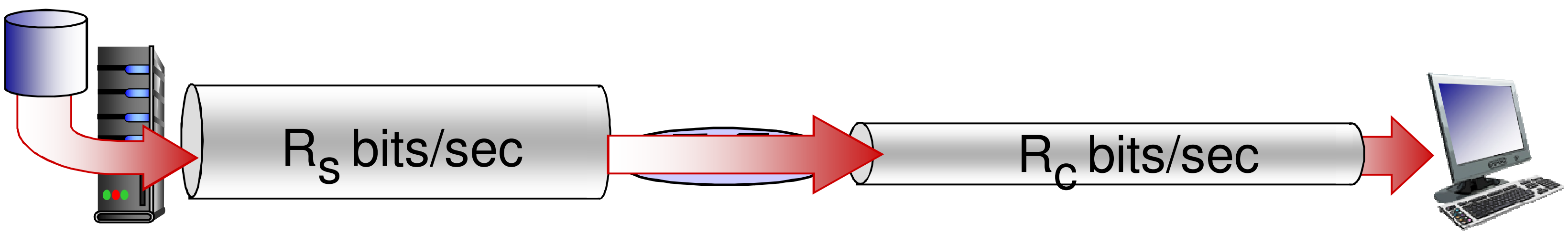
So Consider:

Throughput (more)

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



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

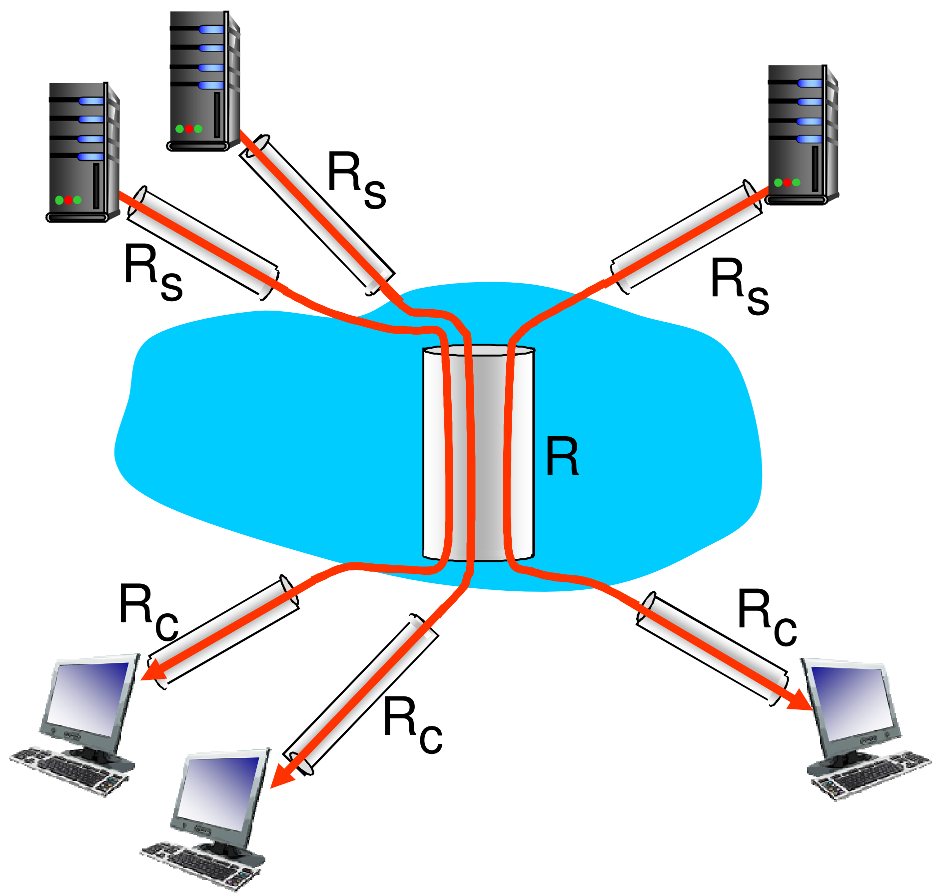


bottleneck link

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

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

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

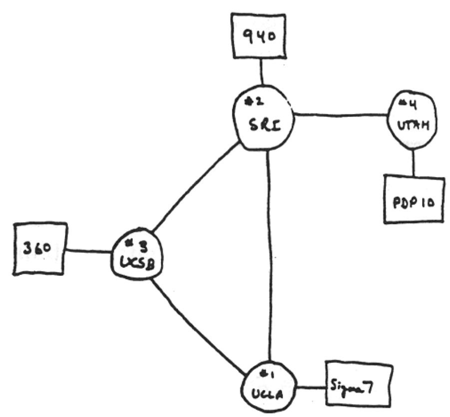
1.4 delay, loss, throughput in networks
1.5 history

Internet history

1961-1972: Early packet-switching principles

- 1961: Kleinrock - queueing theory shows effectiveness of packet-switching
- 1964: Baran - packet-switching in military nets
- 1967: ARPAnet conceived by Advanced Research Projects Agency
- 1969: first ARPAnet node operational

- 1972:
  - ARPAnet public demo
  - NCP (Network Control Protocol) first host-host protocol
  - first e-mail program
  - ARPAnet has 15 nodes



THE ARPA NETWORK

Internet history

1972-1980: Internetworking, new and proprietary nets

- 1970: ALOHAnet satellite network in Hawaii
- 1974: Cerf and Kahn - architecture for interconnecting networks
- 1976: Ethernet at Xerox PARC
- late70's: proprietary architectures: DECnet, SNA, XNA
- late 70's: switching fixed length packets (ATM precursor)
- 1979: ARPAnet has 200 nodes

Cerf and Kahn's internetworking principles:

- minimalism, autonomy - no internal changes required to interconnect networks
- best effort service model
- stateless routers
- decentralized control

define today's Internet architecture

Internet history

1980-1990: new protocols, a proliferation of networks

- 1983: deployment of TCP/IP
- 1982: smtp e-mail protocol defined
- 1983: DNS defined for name-to-IP-address translation
- 1985: ftp protocol defined
- 1988: TCP congestion control

- new national networks: Csnet, BITnet, NSFnet, Minitel
- 100,000 hosts connected to confederation of networks

Internet history

1990, 2000's: commercialization, the Web, new apps

- early 1990's: ARPAnet decommissioned
- 1991: NSF lifts restrictions on commercial use of NSFnet (decommissioned, 1995)
- early 1990s: Web
  - hypertext [Bush 1945, Nelson 1960's]
  - HTML, HTTP: Berners-Lee
  - 1994: Mosaic, later Netscape
  - late 1990's: commercialization of the Web

late 1990's – 2000's:

- more killer apps: instant messaging, P2P file sharing
- network security to forefront
- est. 50 million host, 100 million+ users
- backbone links running at Gbps

Internet history

2005-present

- ~750 million hosts
  - Smartphones and tablets
- Aggressive deployment of broadband access
- Increasing ubiquity of high-speed wireless access
- Emergence of online social networks:
  - Facebook: soon one billion users
- Service providers (Google, Microsoft) create their own networks
  - Bypass Internet, providing "instantaneous" access to search, email, etc.
- E-commerce, universities, enterprises running their services in "cloud" (eg, Amazon EC2)

Questions?