

Computer Networks

Prof. Xiaoming Fu

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Course Overview

- 19 Oct. 2017 Introduction & Layering
- 26 Oct. 2017 Link Layer I
- 02 Nov. 2017 Link Layer II
- 09 Nov. 2017 Network Layer I
- 16 Nov. 2017 Network Layer II; Routing I
- 23 Nov. 2017 Network Layer III; Routing II; Mobility
- 30 Nov. 2017 Transport Layer I
- 07 Dec. 2017 Transport Layer II
- 14 Dec. 2017 Networked Multimedia
- 21 Dec. 2017 Quality of Service
- 11 Jan. 2018 Network Security I
- 18 Jan. 2018 Network Security II
- 25 Jan. 2018 TBA (probably Q&A session)
- 01 Feb. 2018 Written Examination



Excercises

- Contact e-mail:

obaraka@gwdg.de

- Homework exercises will be handed out regularly after class and are in the wiki.
- Students are encouraged to work on their own and solve the homework exercises to prepare for the final exam.
- Solutions will be presented one week later after class. Thursdays 12:00 – 13:00 in the lecture room.



Grading

- The grading is as follows:

100% Final exam!

- All important information (click on Computer Networks)

wiki.net.informatik.uni-goettingen.de



Chapter 1

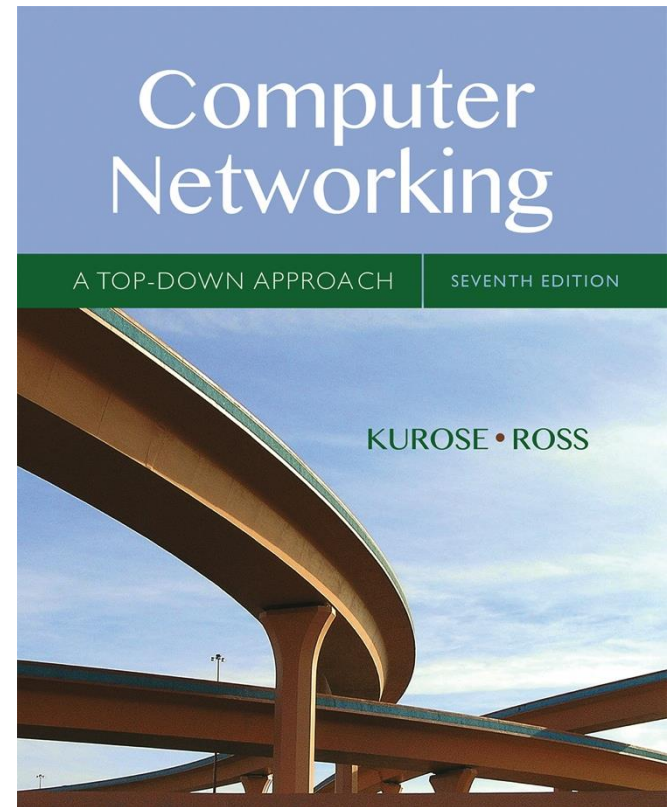
Introduction

This lecture is based on the book:

Computer Networking: A Top Down Approach
7th edition. Jim Kurose, Keith Ross, Pearson, 2018.

Alternative textbook:

- A. Tanenbaum, "Computer Networks", 5th edition, Prentice Hall, 2010
- D. Comer, "Computer Networks and Internets", 5th edition, Prentice Hall, 2008



Chapter 1: 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



Chapter 1: roadmap

1.1 *What is the Internet?*

1.2 Network edge

- end systems, access networks, links

1.3 Network core

- circuit switching, packet switching, network structure

1.4 Delay, loss and throughput in packet-switched networks

1.5 Protocol layers, service models

1.6 History



“Fun” Internet-connected devices



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



sensorized,
bed
mattress

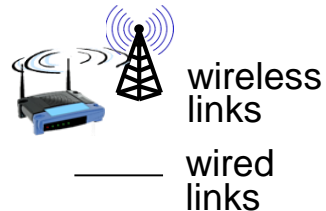


Internet phones

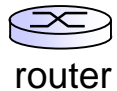
What's the Internet: "nuts and bolts" view



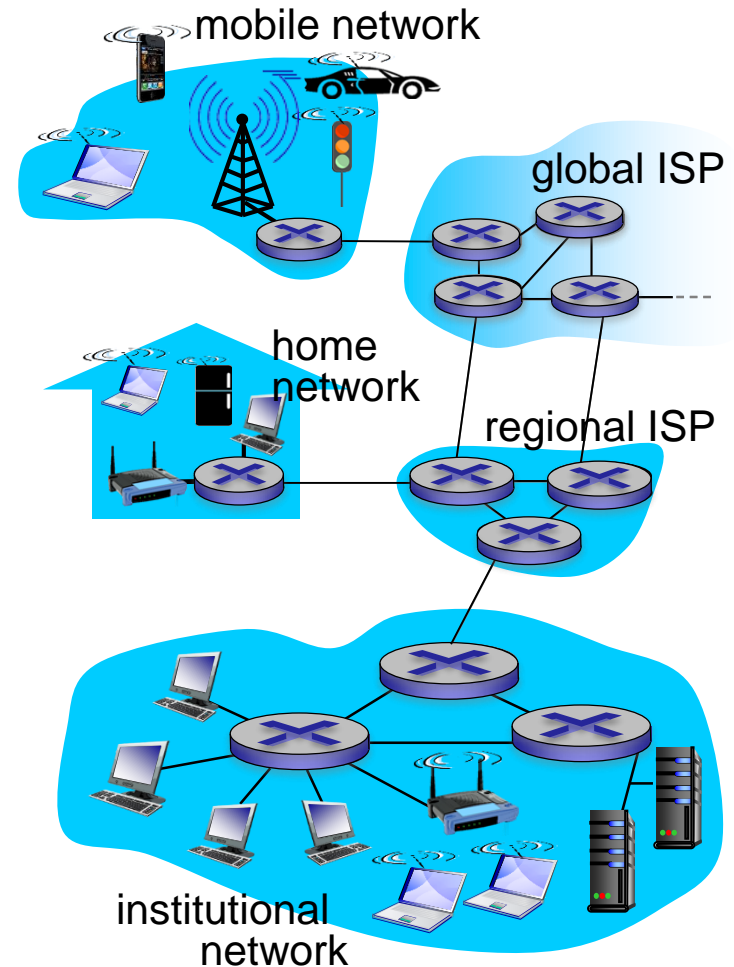
- billions of connected computing devices:
 - hosts* = *end systems*
 - running *network apps*



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

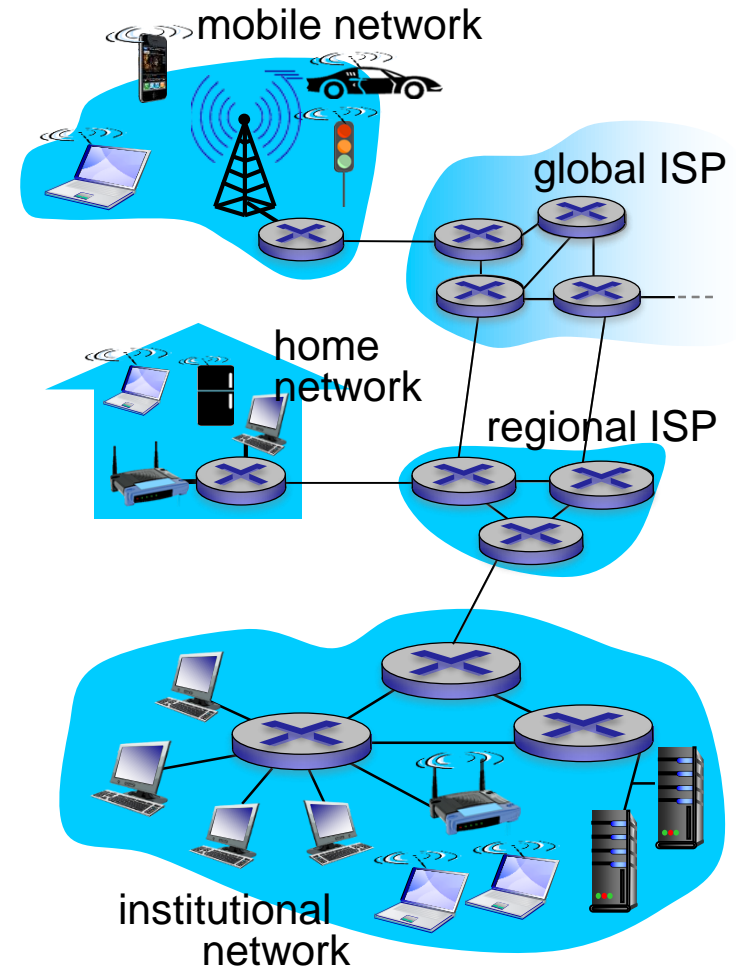


- packet switches*:
 - routers* *switches*



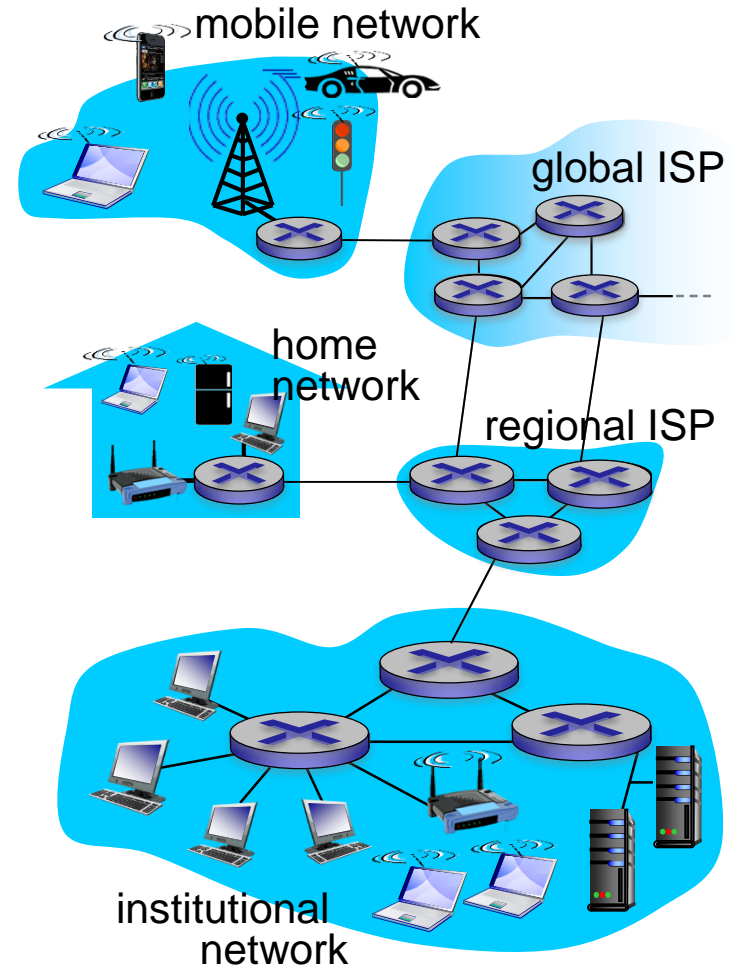
What's the Internet: "nuts and bolts" view

- **Internet: "network of networks"**
 - Interconnected ISPs
- **protocols** control sending, receiving of messages
 - 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 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 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

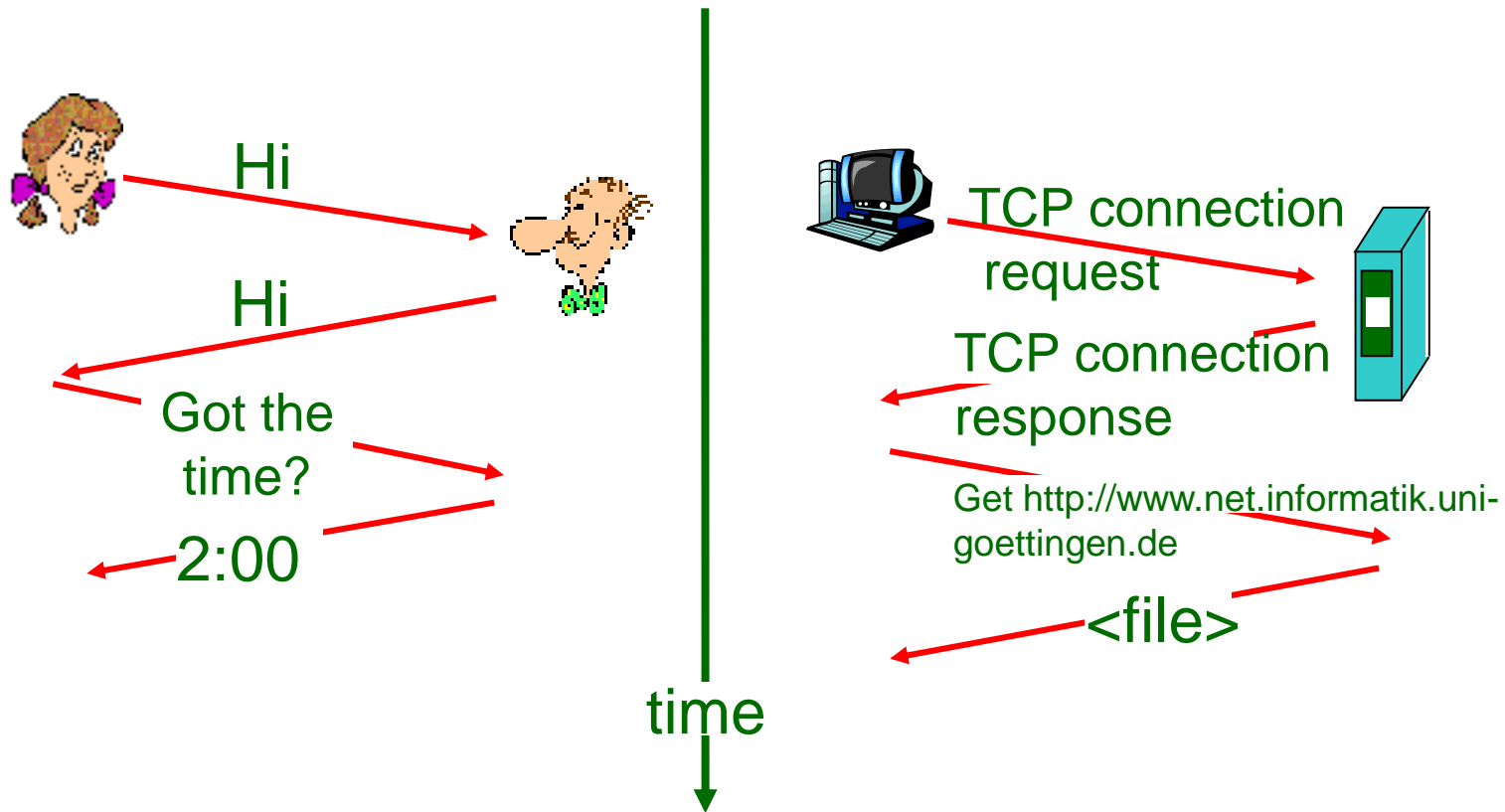
network protocols:

- 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 msg transmission, receipt

What's a protocol?

a human protocol and a computer network protocol:



Chapter 1: roadmap

1.1 What *is* the Internet?

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- circuit switching, packet switching, network structure

1.4 Delay, loss and throughput in packet-switched networks

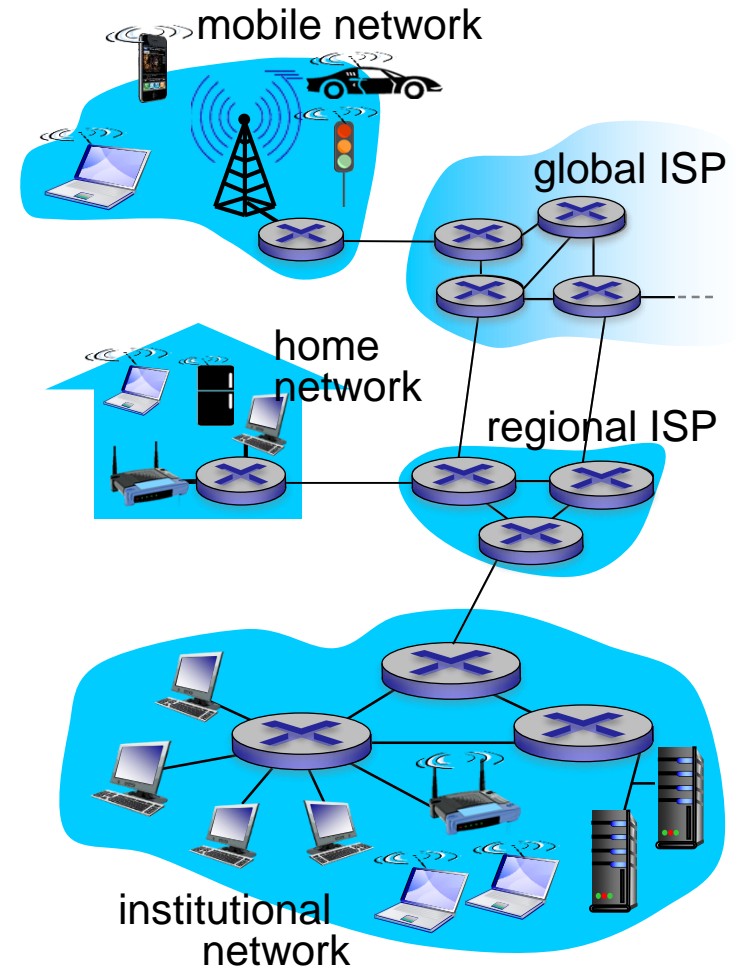
1.5 Protocol layers, service models

1.6 History



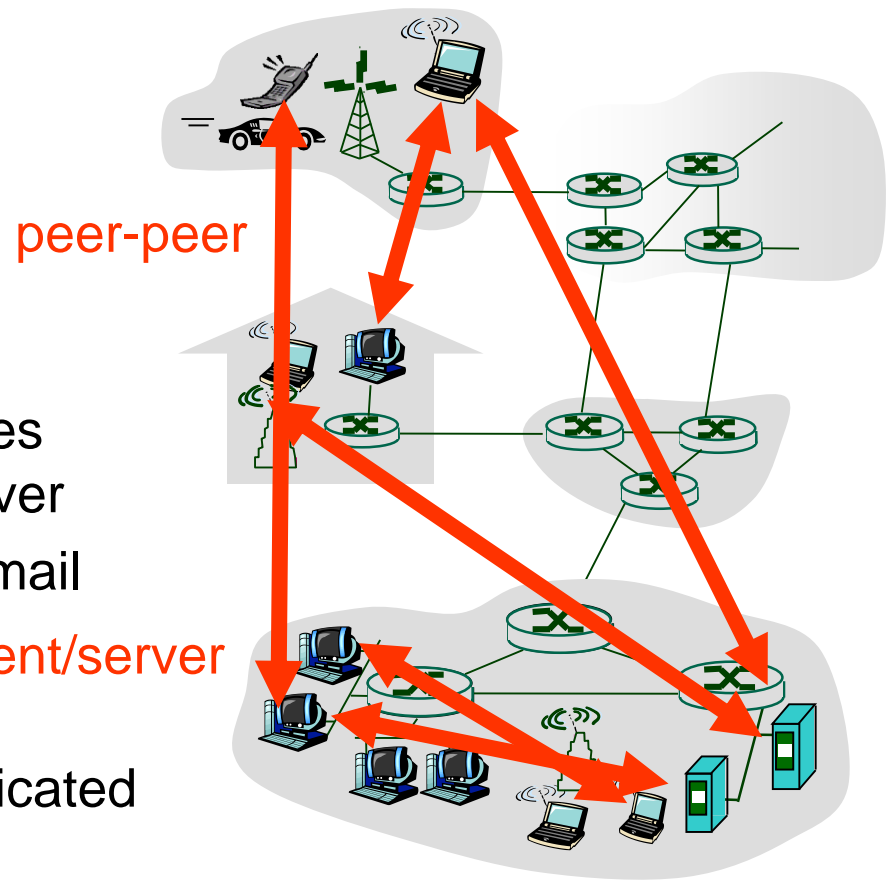
A closer look at network structure:

- **network edge:**
applications and hosts
- **access networks, physical media:**
wired, wireless communication links
- **network core:**
 - interconnected routers
 - network of networks



The network edge:

- **end systems (hosts):**
 - run application programs
 - e.g. web, email
 - at “edge of network”
- **client/server model**
 - client host requests, receives service from always-on server
 - e.g. web browser/server; email client/server
- **peer-peer model:**
 - minimal (or no) use of dedicated servers
 - e.g. Skype, BitTorrent



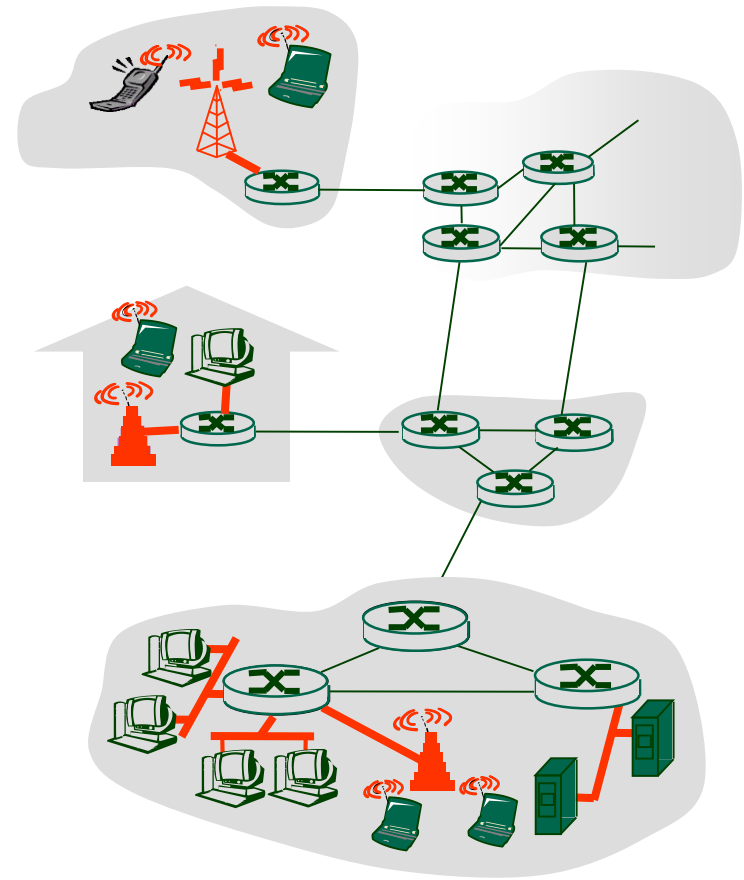
Access networks and physical media

Q: How to connect end systems to edge router?

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

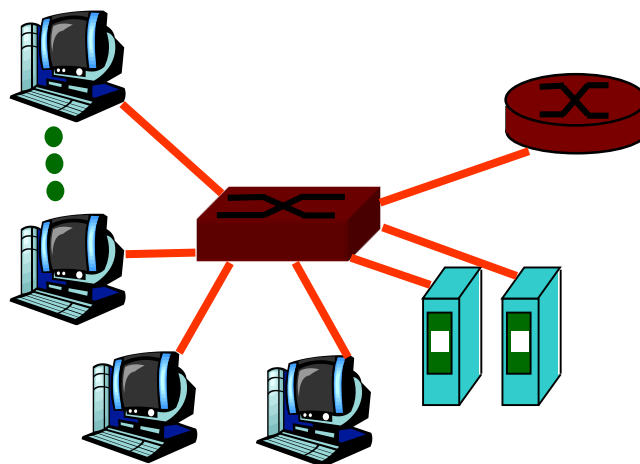
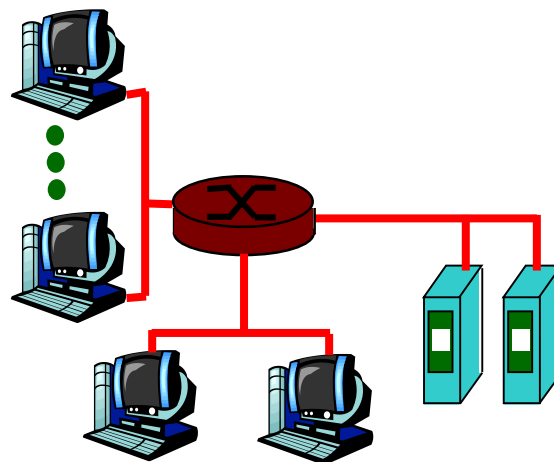
Keep in mind:

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

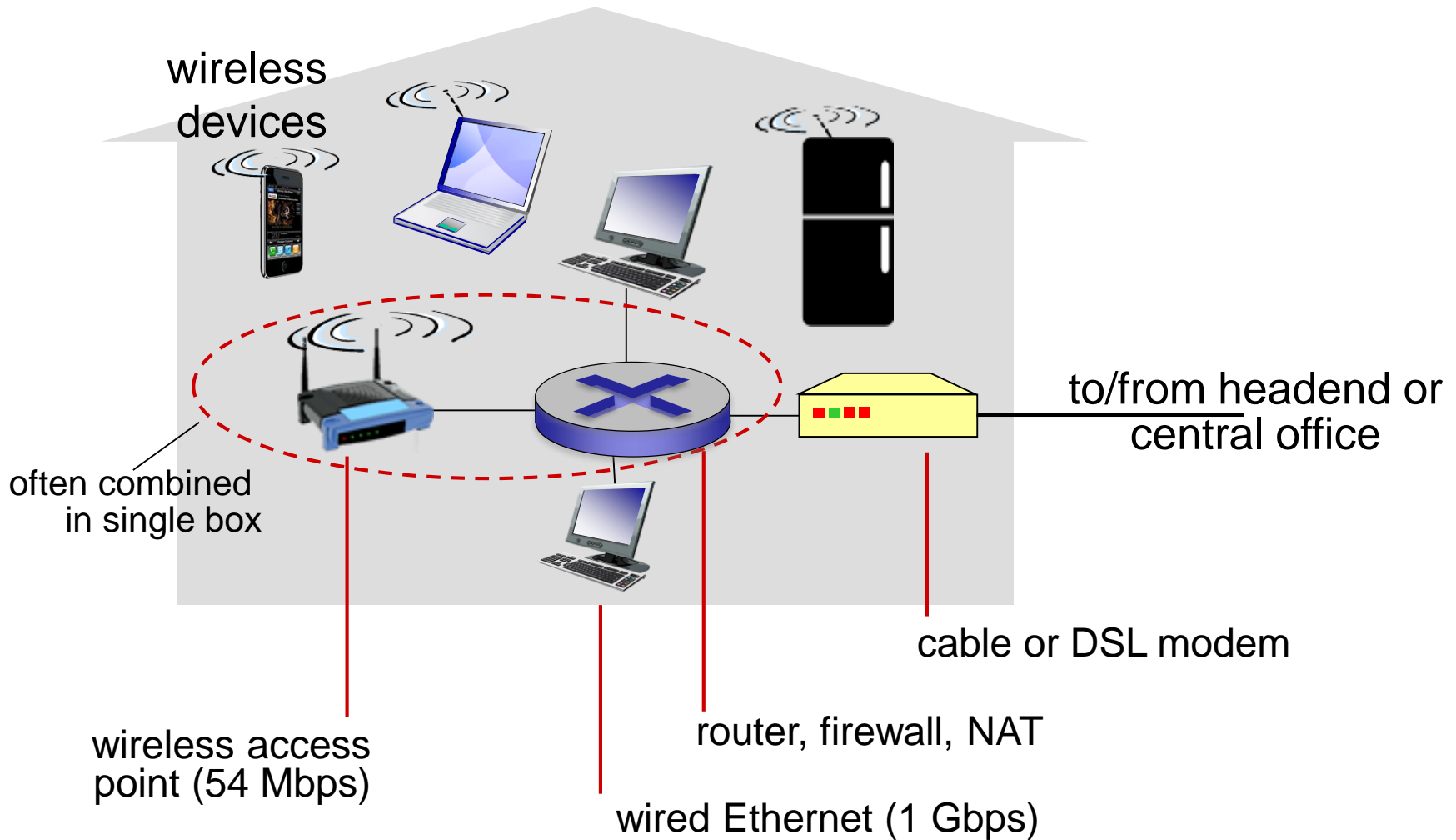


Example: Company access: local area networks

- company/univ **local area network** (LAN) connects end system to edge router (example: our GöNet)
- **Ethernet:**
 - 10 Mbs, 100Mbps, 1Gbps, 10Gbps Ethernet
 - modern configuration: end systems connect into *Ethernet switch*
- LANs: will be discussed in detail throughout this lecture



Access network: home network



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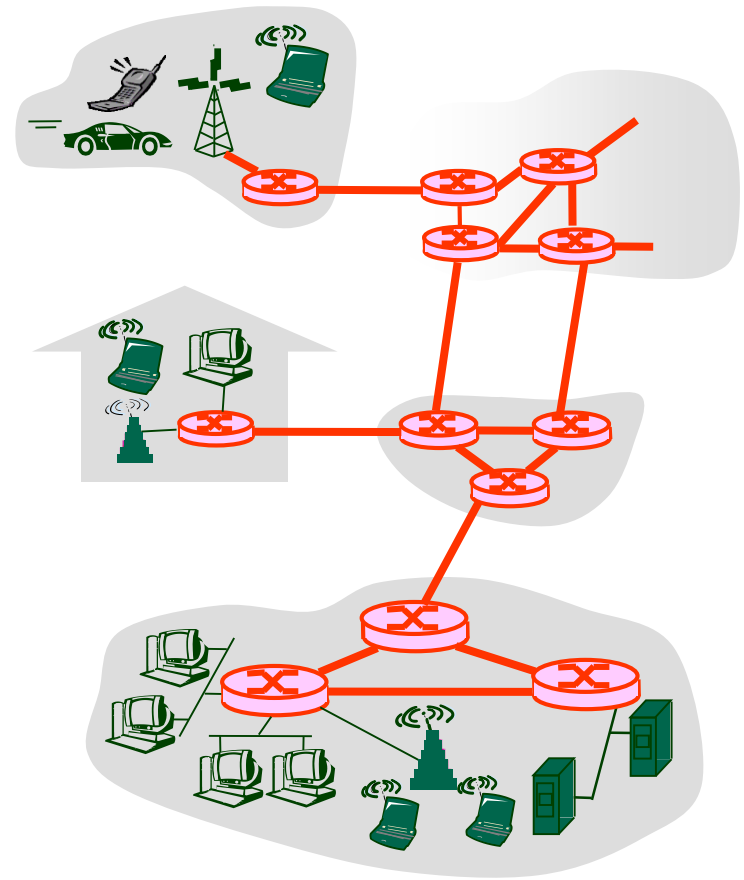
1.5 Protocol layers, service models

1.6 History



The Network Core

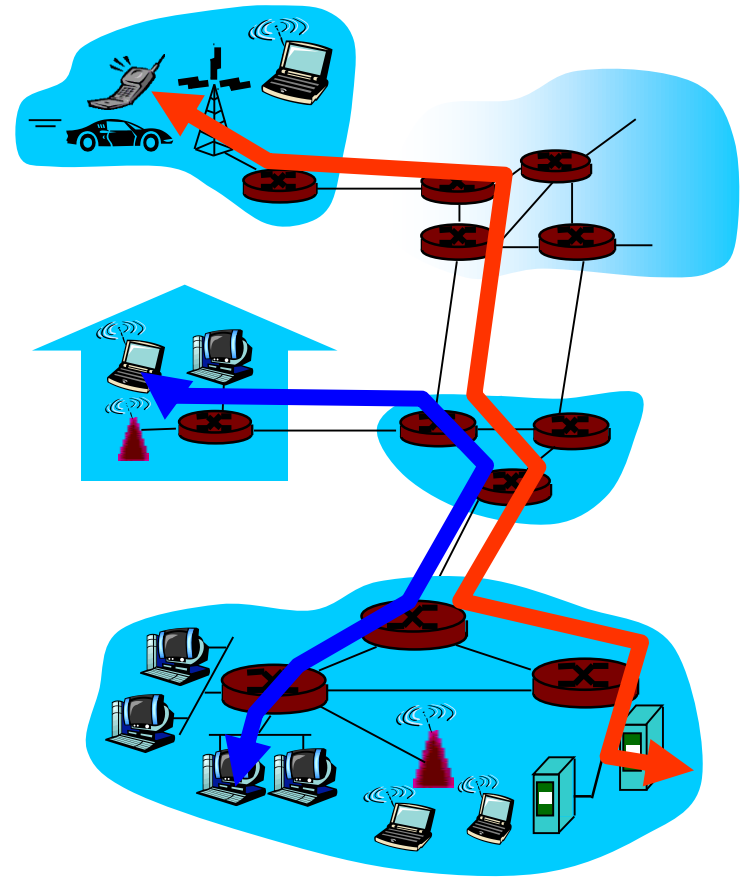
- mesh of interconnected routers
- ***the fundamental question:*** how is data transferred through net?
 - **circuit switching:** dedicated circuit per call: telephone network
 - **packet-switching:** data sent through a network in discrete “chunks”



Network Core: Circuit Switching

End-end resources reserved for “call”

- link bandwidth, switch capacity
- **dedicated resources**: no sharing
- circuit-like (guaranteed) performance
- call setup required



Network Core: Circuit Switching

- network resources (e.g., bandwidth) **divided into “pieces”**
- pieces allocated to calls
 - resource piece *idle* if not used by owning call (*no sharing*)
 - dividing link bandwidth into “pieces”
 - frequency division
 - time division

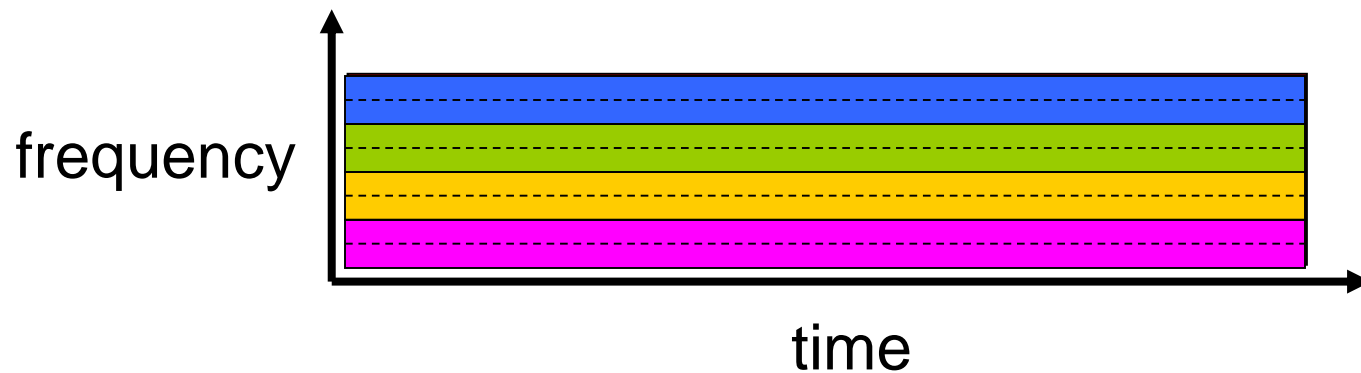


Circuit Switching: FDM and TDM

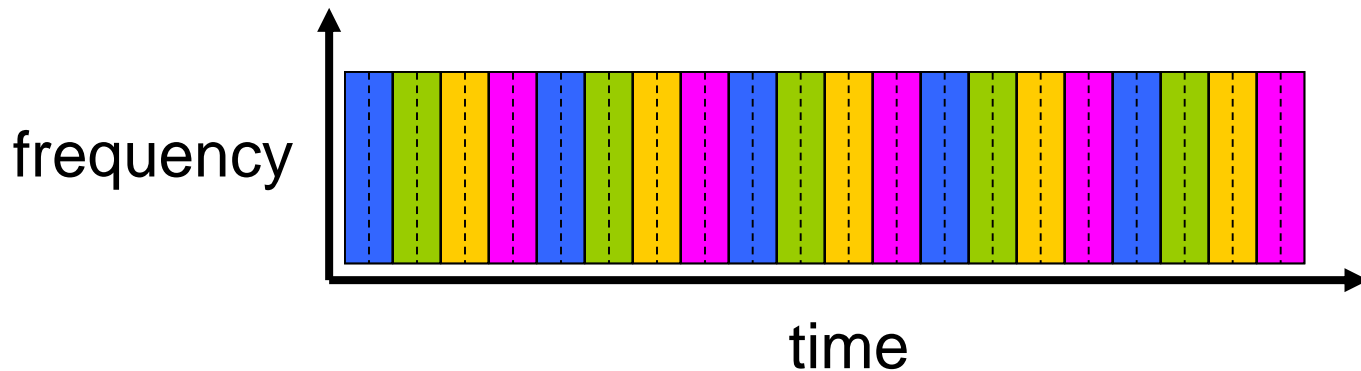
FDM

Example:

4 users



TDM



Numerical example

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



Network Core: Packet Switching

each end-end data stream
divided into *packets*

- user A, B packets *share* network resources
 - Sequence of sending packets does not have fixed pattern → **statistical multiplexing**
- each packet uses full link bandwidth
- resources used *as needed*

Bandwidth division into “pieces”

Dedicated allocation

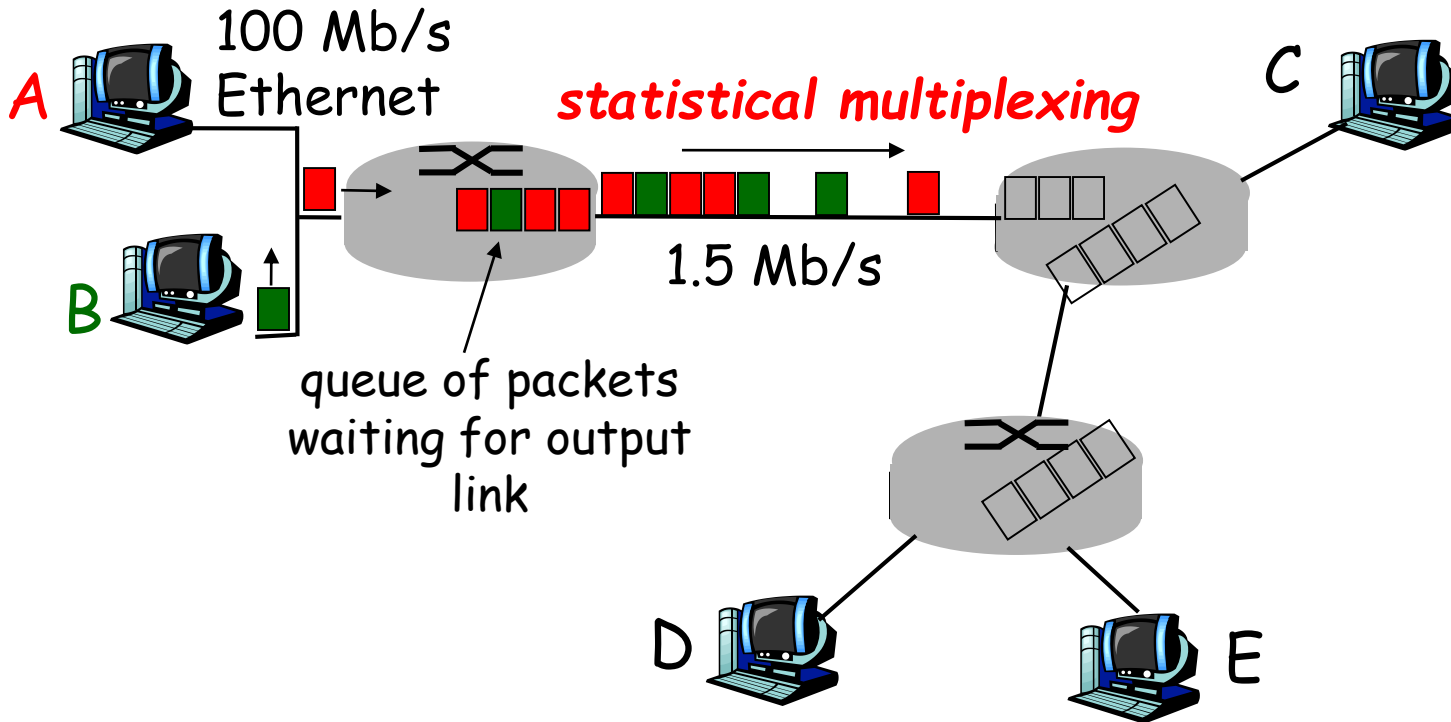
Resource reservation

resource contention:

- aggregate resource demand can exceed amount available
- congestion: packets queue, wait for link use
- store and forward: packets move one hop at a time
 - Node receives complete packet before forwarding



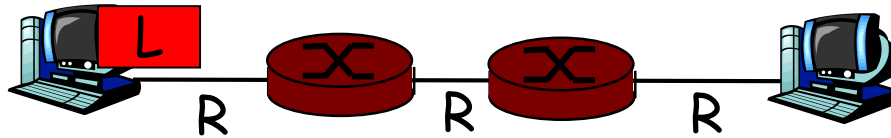
Packet Switching: Statistical Multiplexing



Sequence of A & B packets does not have fixed pattern,
bandwidth shared on demand → **statistical multiplexing**.

TDM: each host gets same slot in revolving TDM frame.

Packet-switching: store-and-forward



- takes L/R seconds to transmit (push out) packet of L bits on to link at R bps
- **store and forward**: entire packet must arrive at router before it can be transmitted on next link
- **delay** = $3L/R$ (assuming zero propagation delay)

Example:

- $L = 7.5$ Mbits
- $R = 1.5$ Mbps
- transmission delay = 15 sec

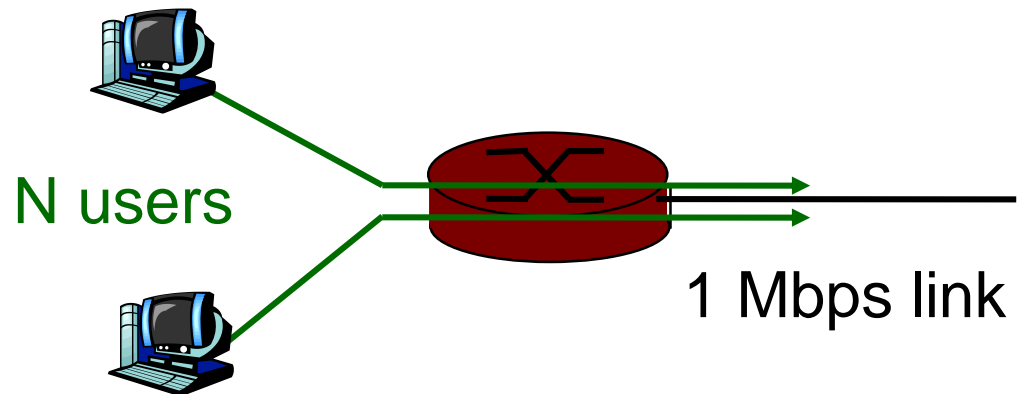
Note:

- In order to be more efficient, large packets are usually segmented into smaller packets

Packet switching versus circuit switching

Packet switching allows more users to use network!

- 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 low



Packet switching versus circuit switching

Is packet switching better than circuit switching?

- great for bursty data
 - resource sharing
 - simpler, no call setup
- **excessive congestion:** 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

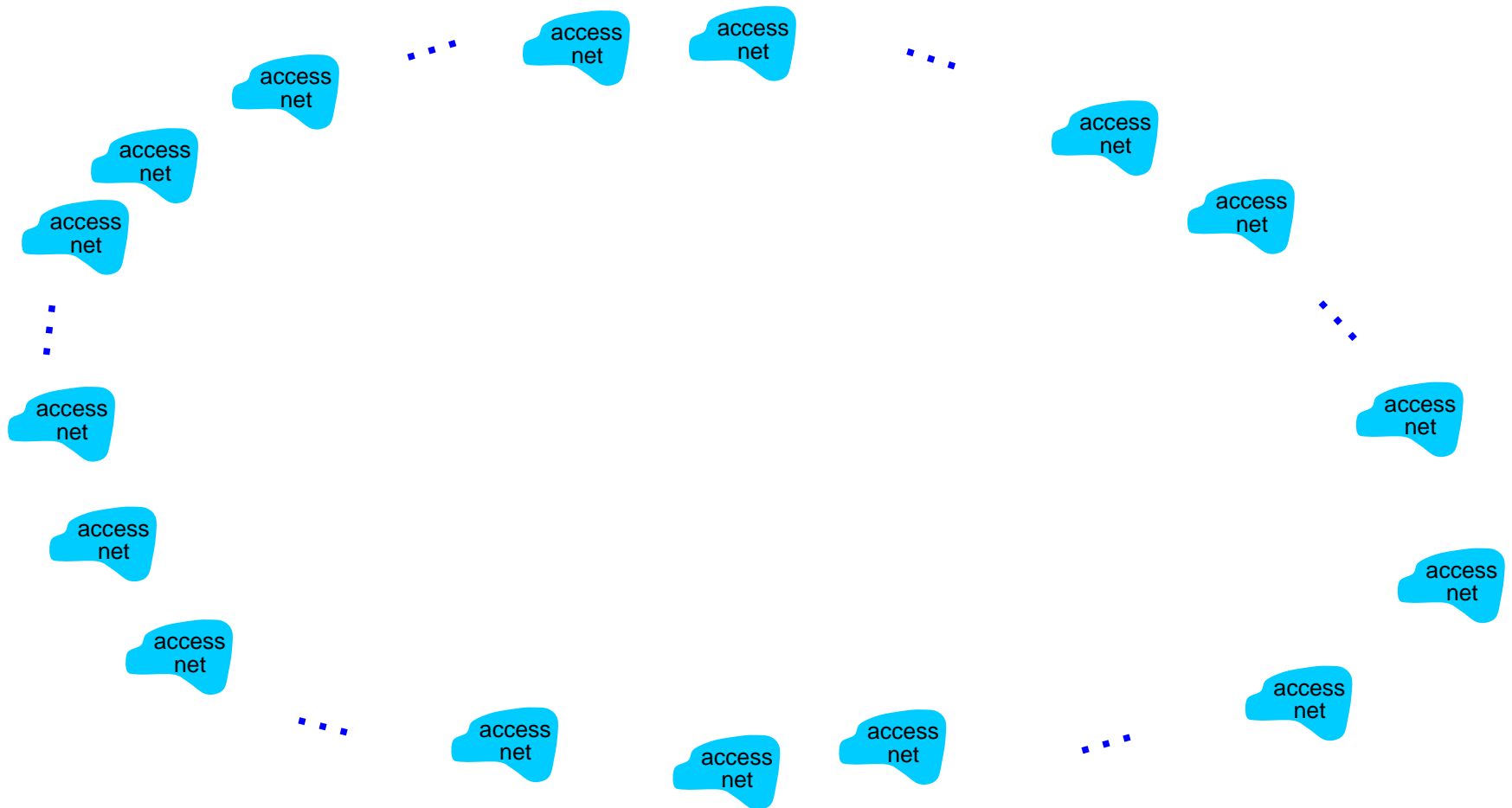


Internet structure: network of networks

- 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

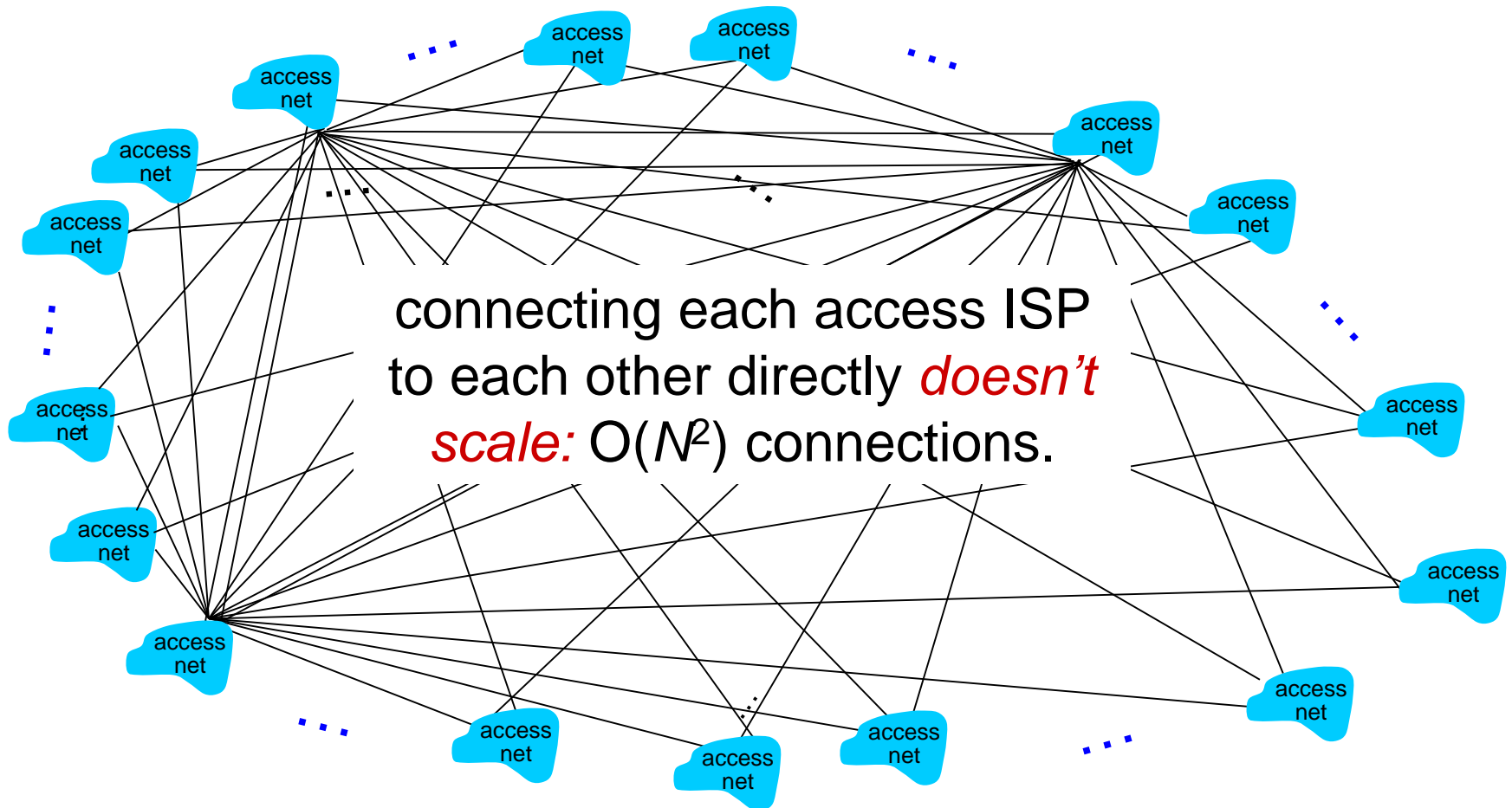
Internet structure: network of networks

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



Internet structure: network of networks

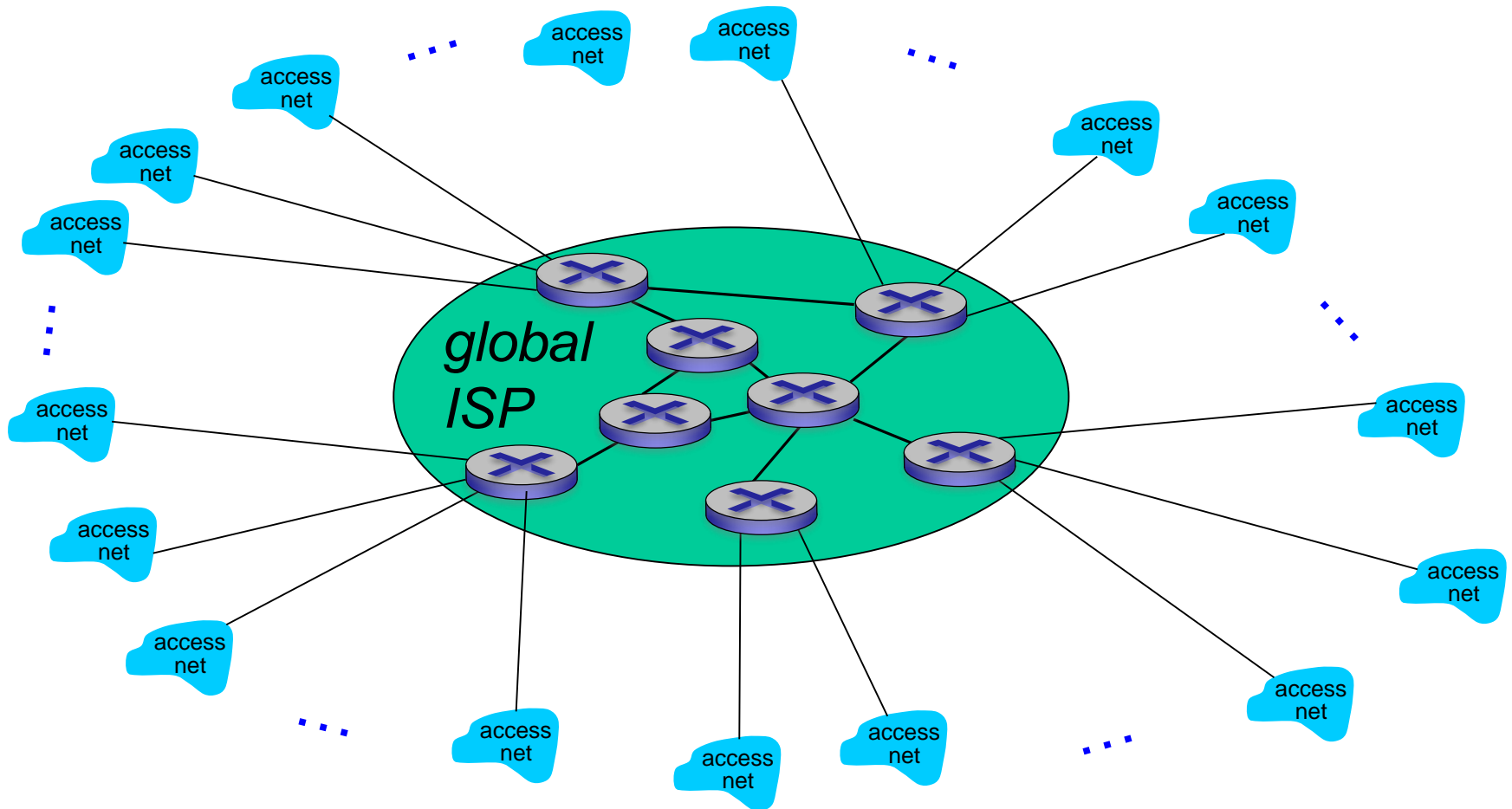
Option: connect each access ISP to every other access ISP?



Internet structure: network of networks

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

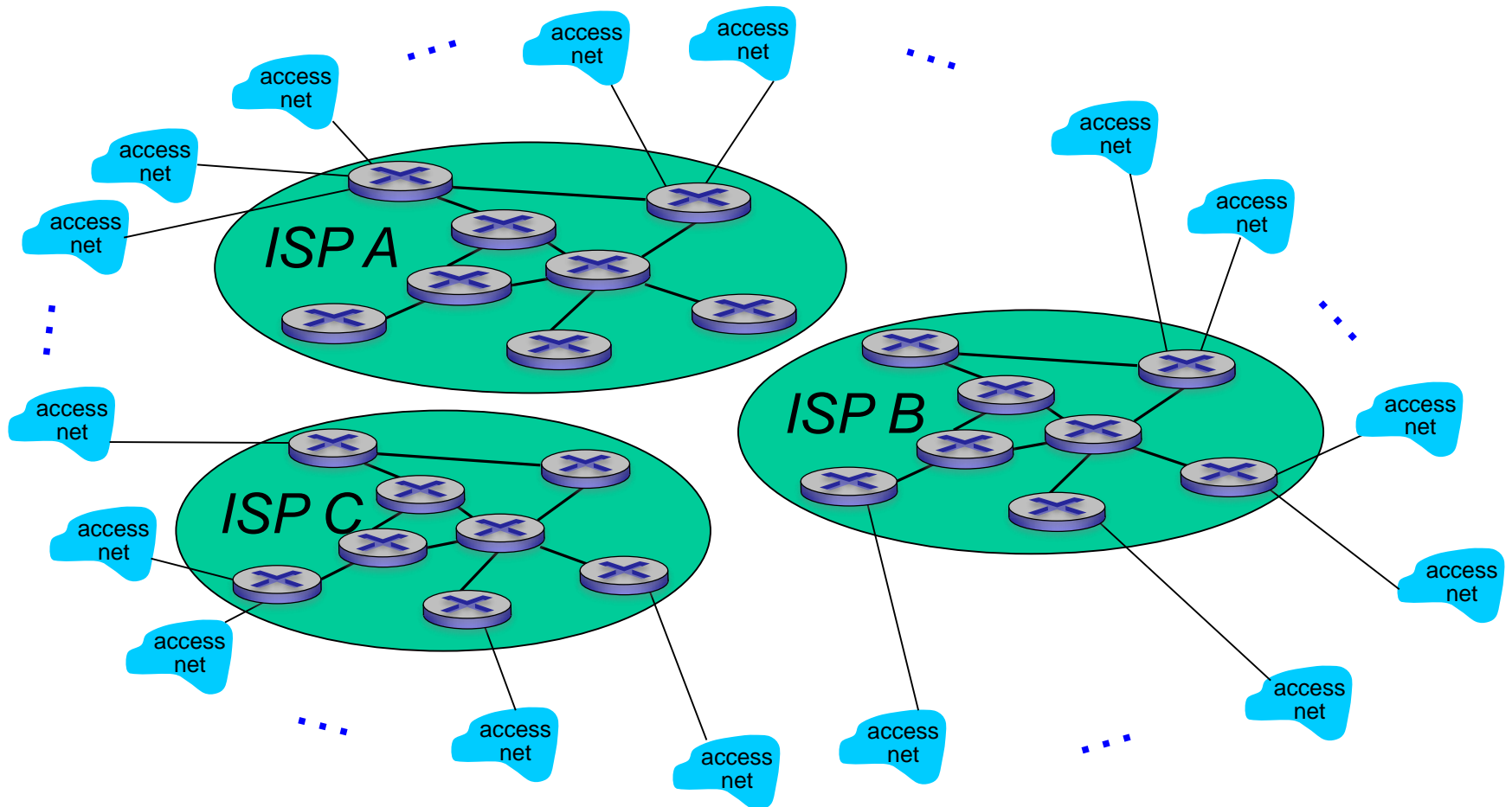
Customer and *provider* ISPs have economic agreement.



Internet structure: network of networks

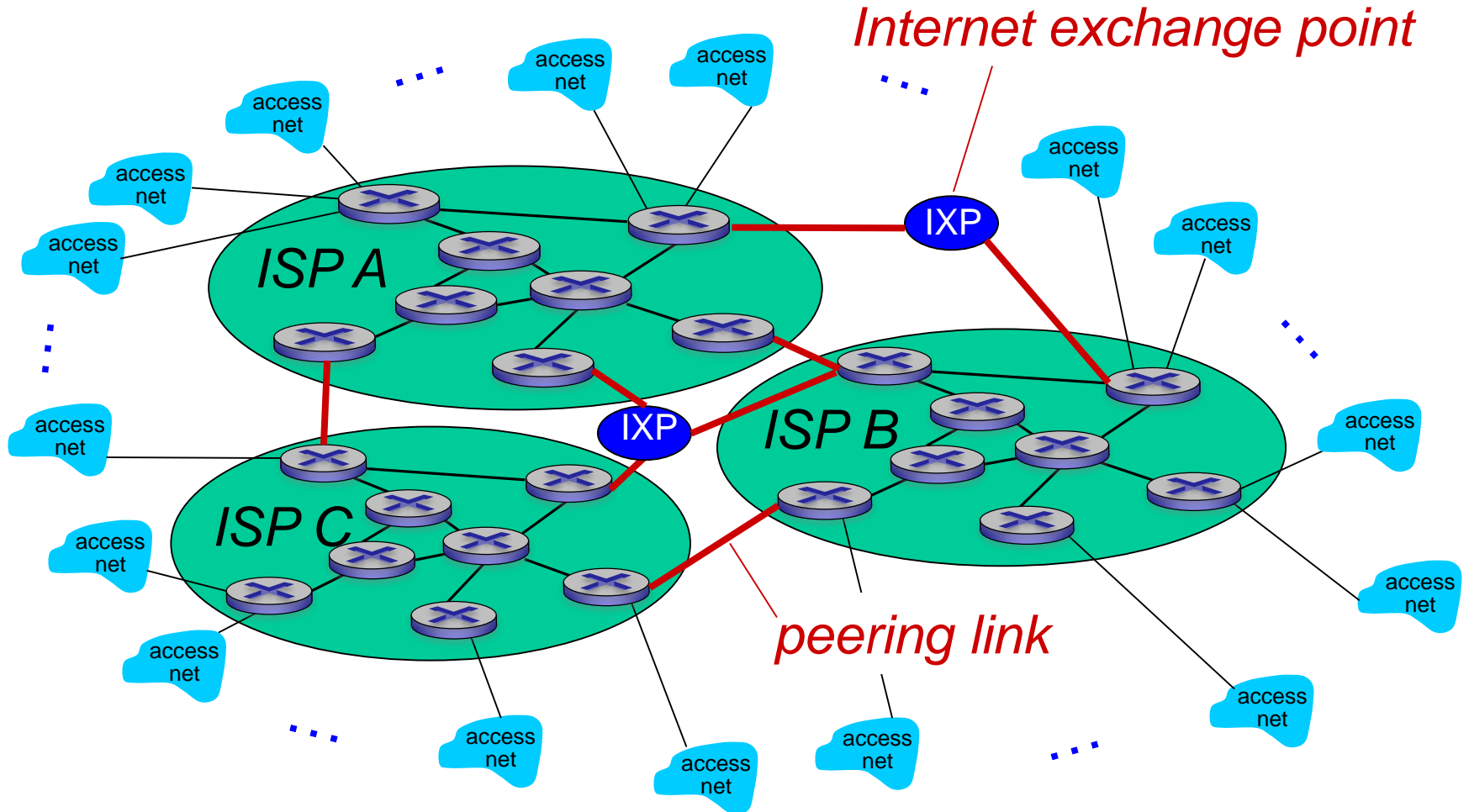
But if one global ISP is viable business, there will be competitors

....



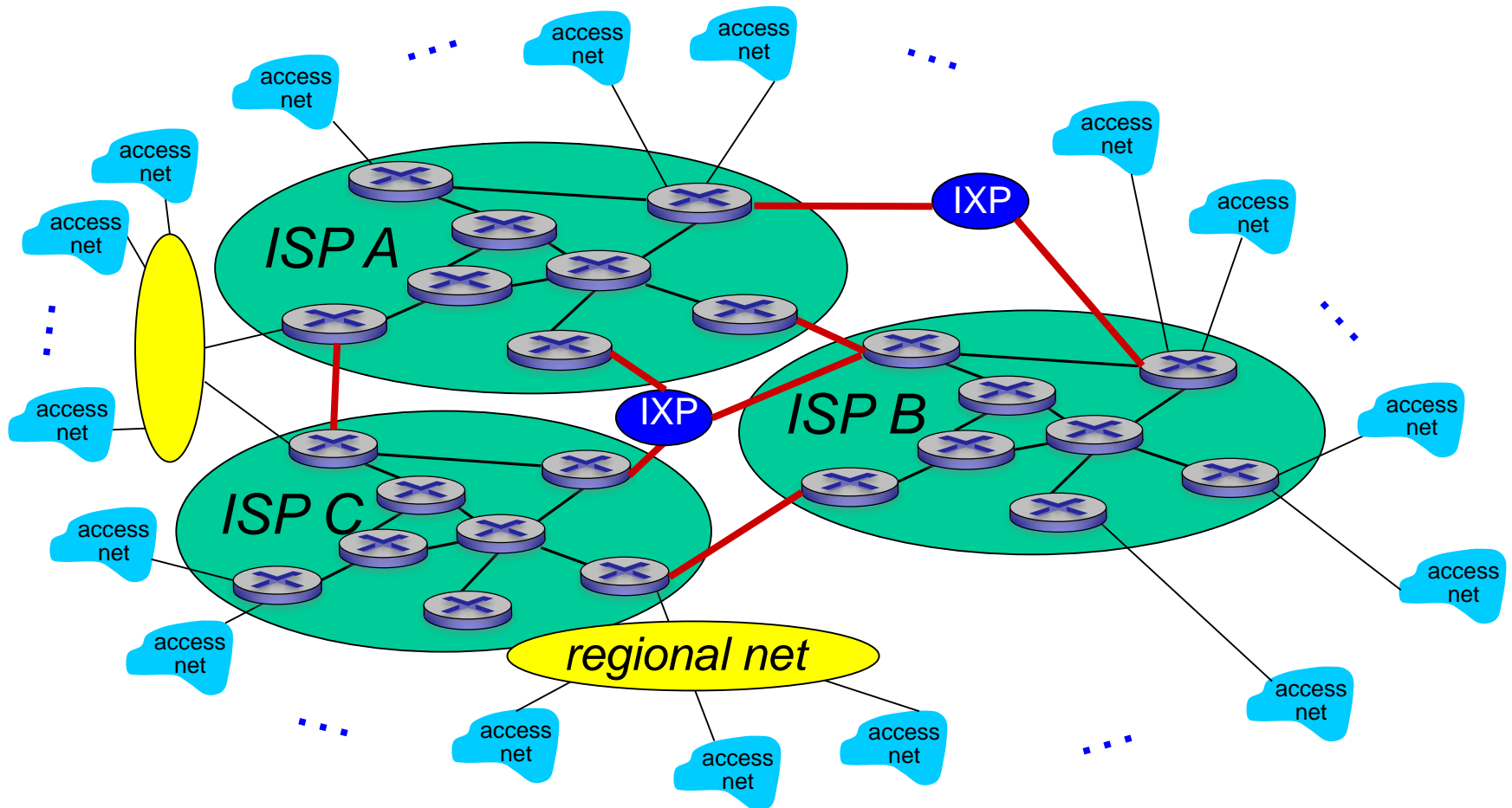
Internet structure: network of networks

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



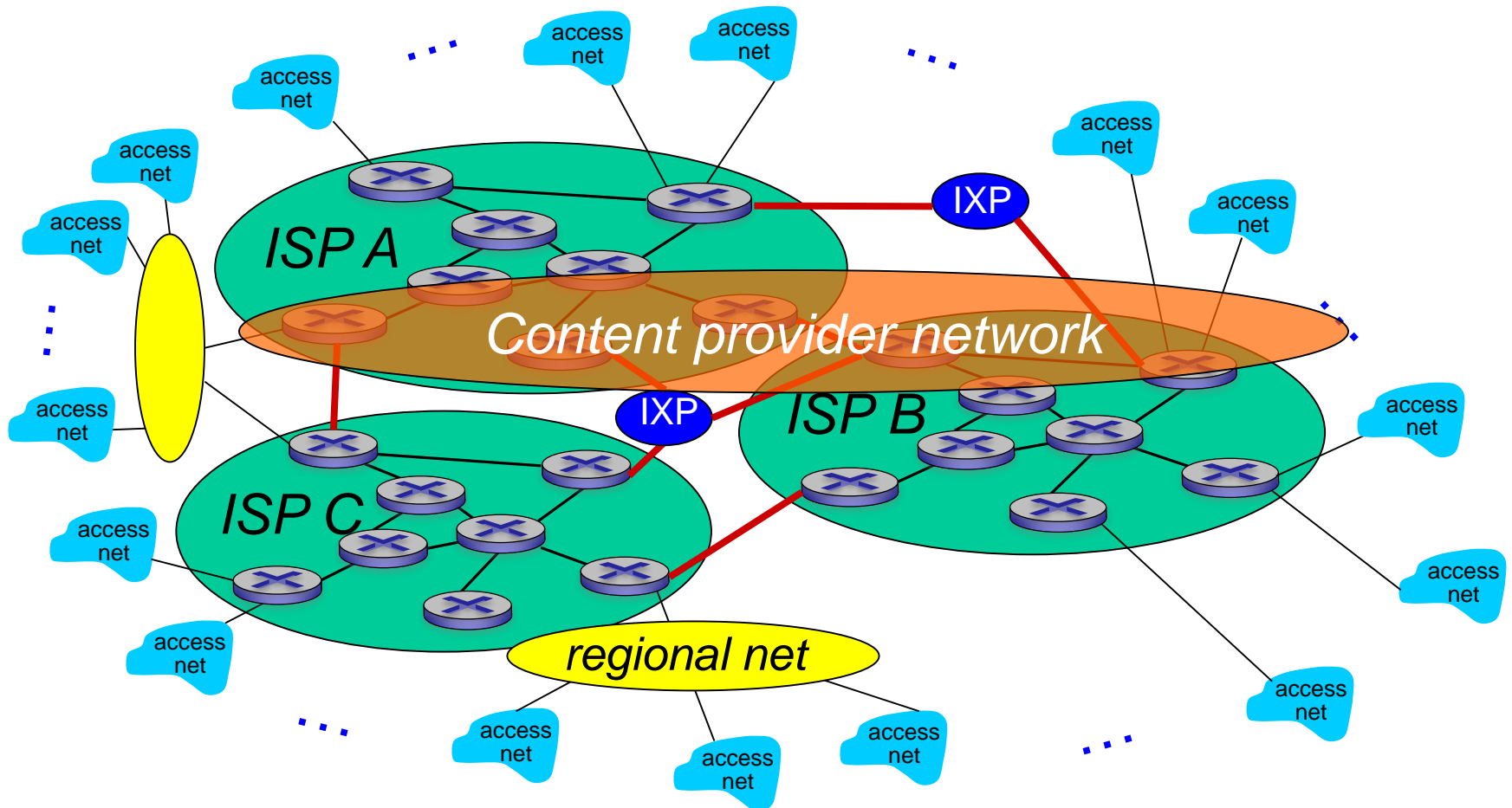
Internet structure: network of networks

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

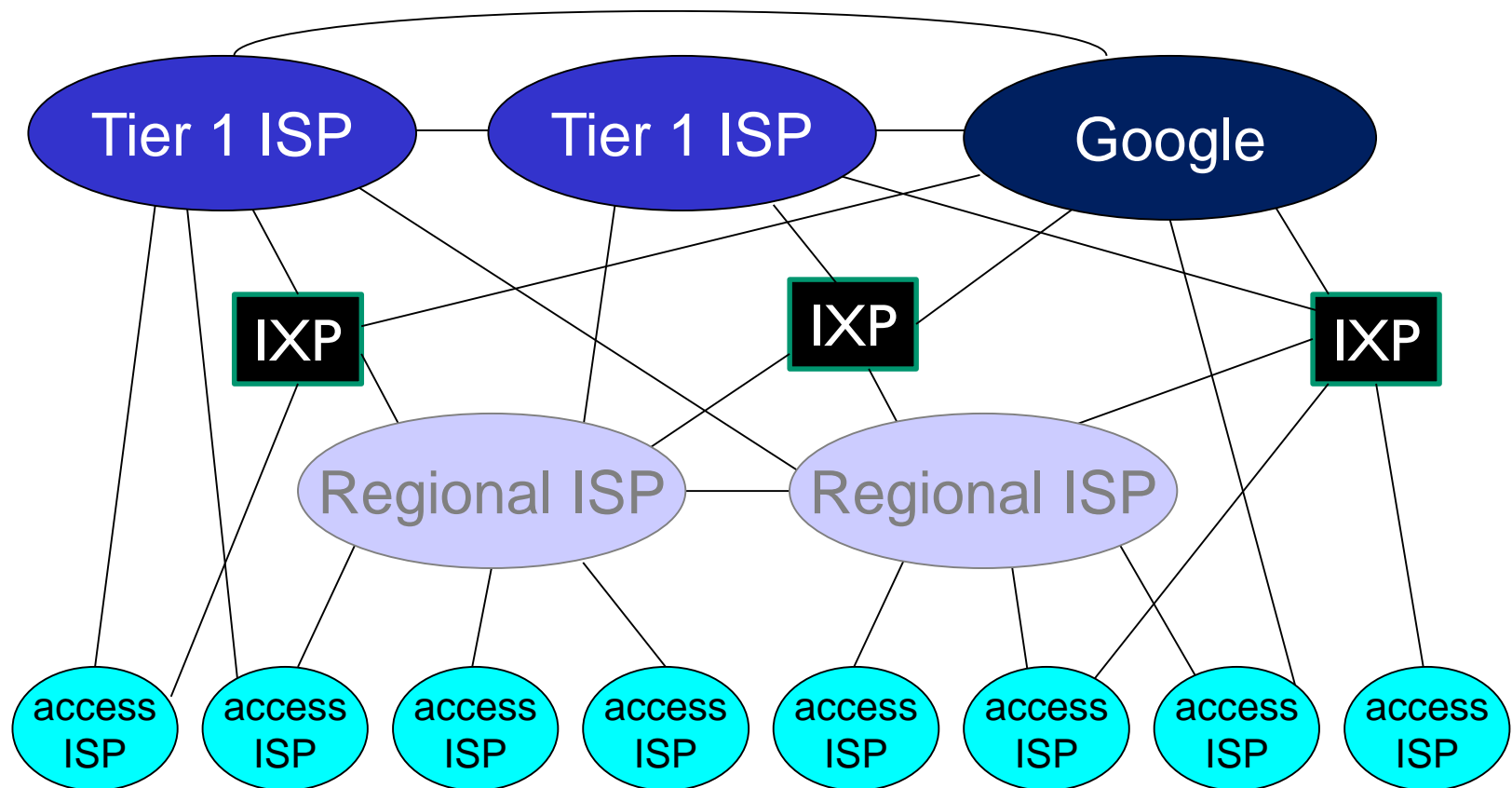


Internet structure: network of networks

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

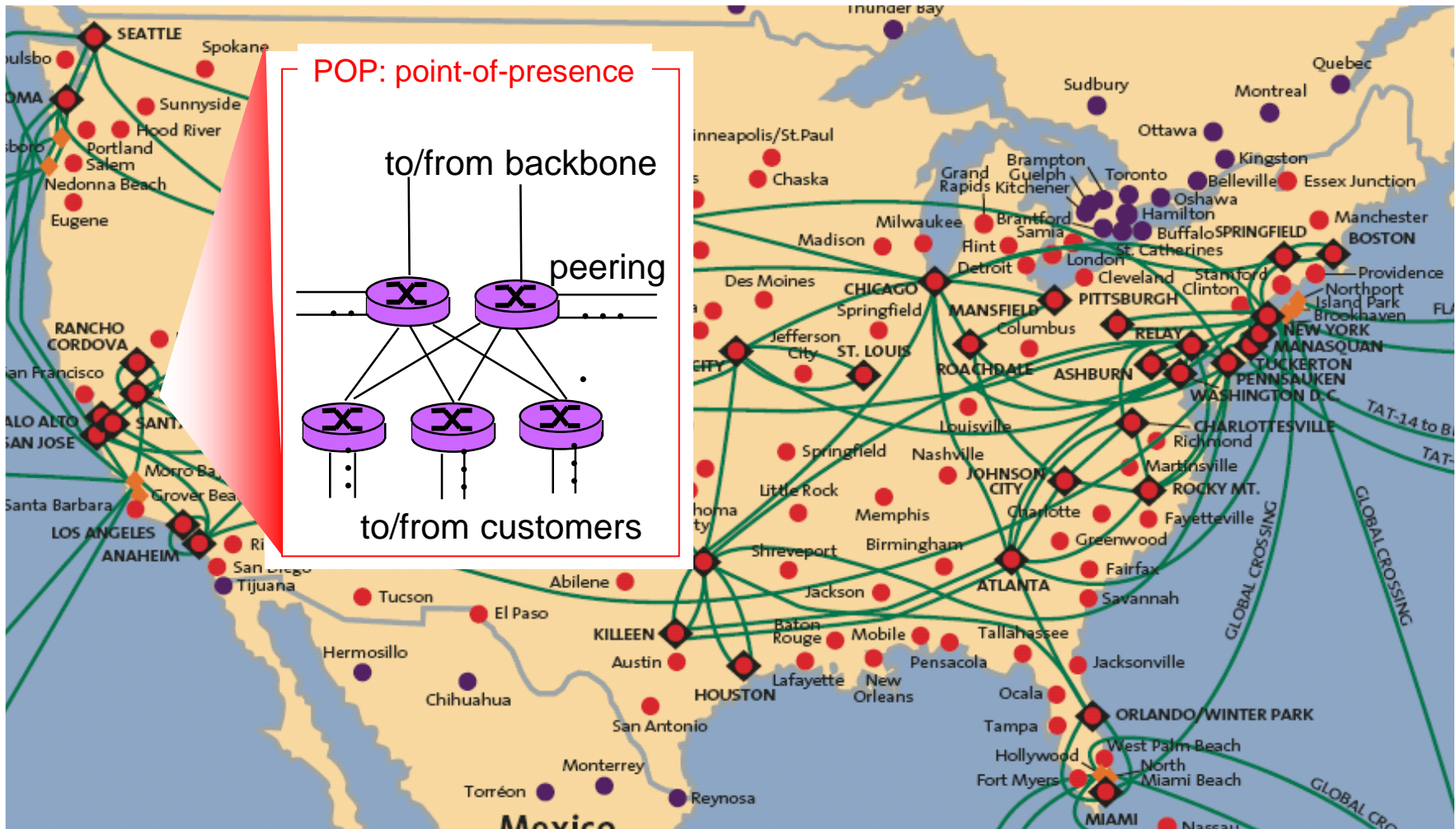


Internet structure: network of networks



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

Tier-1 ISP: e.g., Sprint



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1.5 Protocol layers, service models

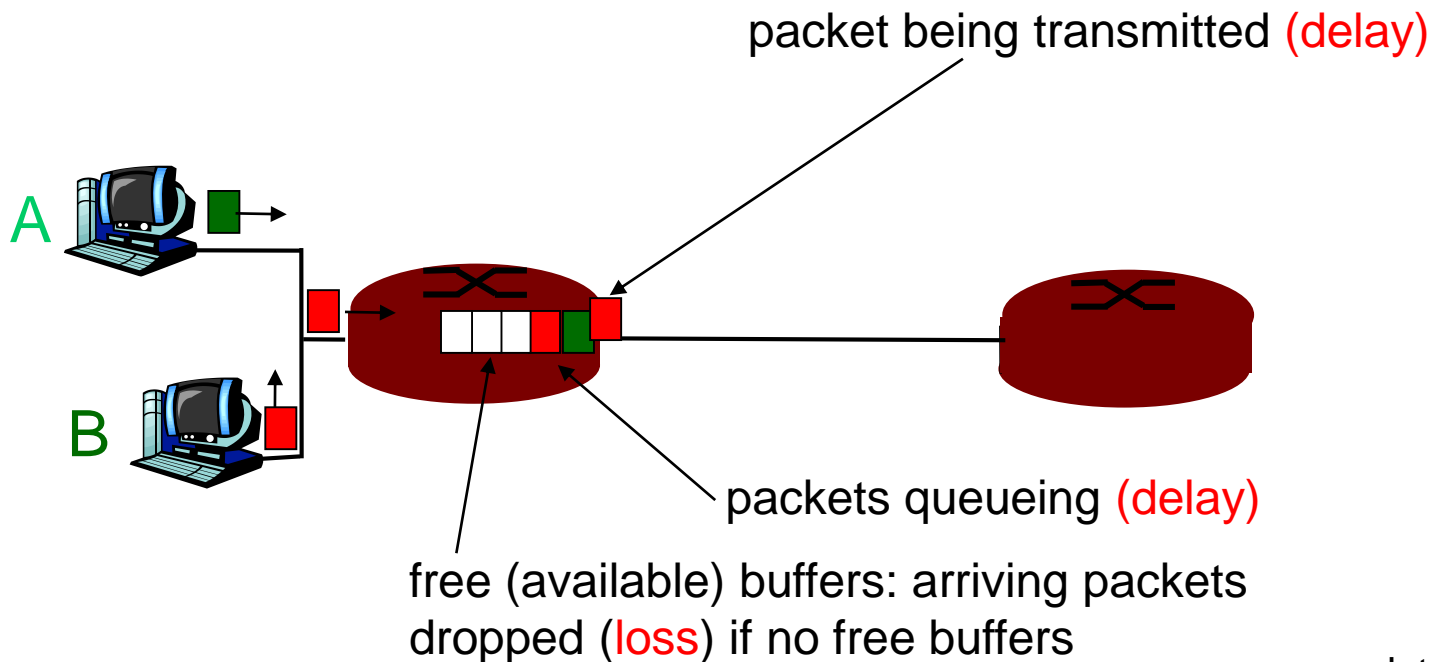
1.6 History



How do loss and delay occur?

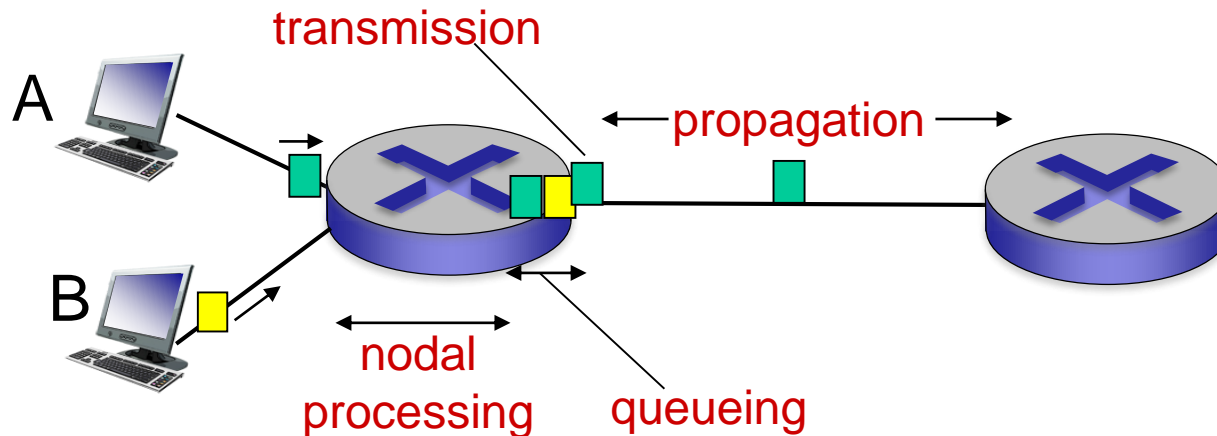
packets *queue* in router buffers

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



Four sources of packet delay

- 1. nodal processing:
 - check bit errors
 - determine output link
- 2. queueing
 - time waiting at output link for transmission
 - depends on congestion level of router



Delay in packet-switched networks

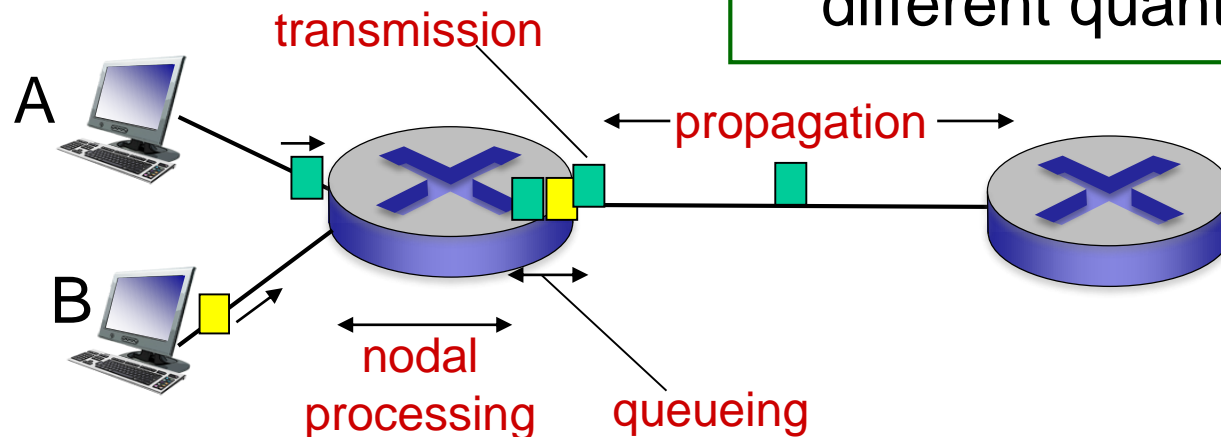
3. Transmission delay:

- R = link bandwidth (bps)
- L = packet length (bits)
- time to send bits into link = L/R

4. Propagation delay:

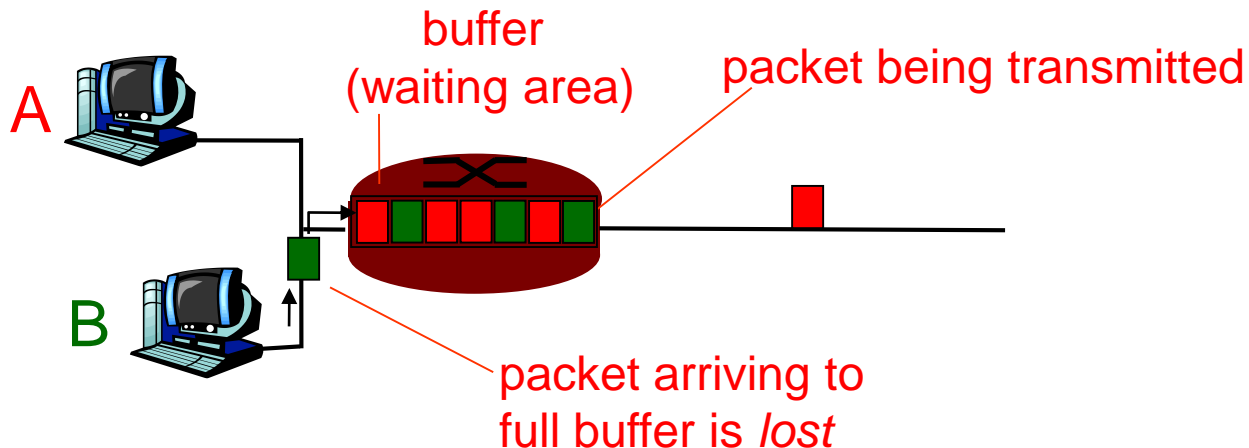
- d = length of physical link
- s = propagation speed in medium ($\sim 2 \times 10^8$ m/sec)
- propagation delay = d/s

Note: s and R are very different quantities!



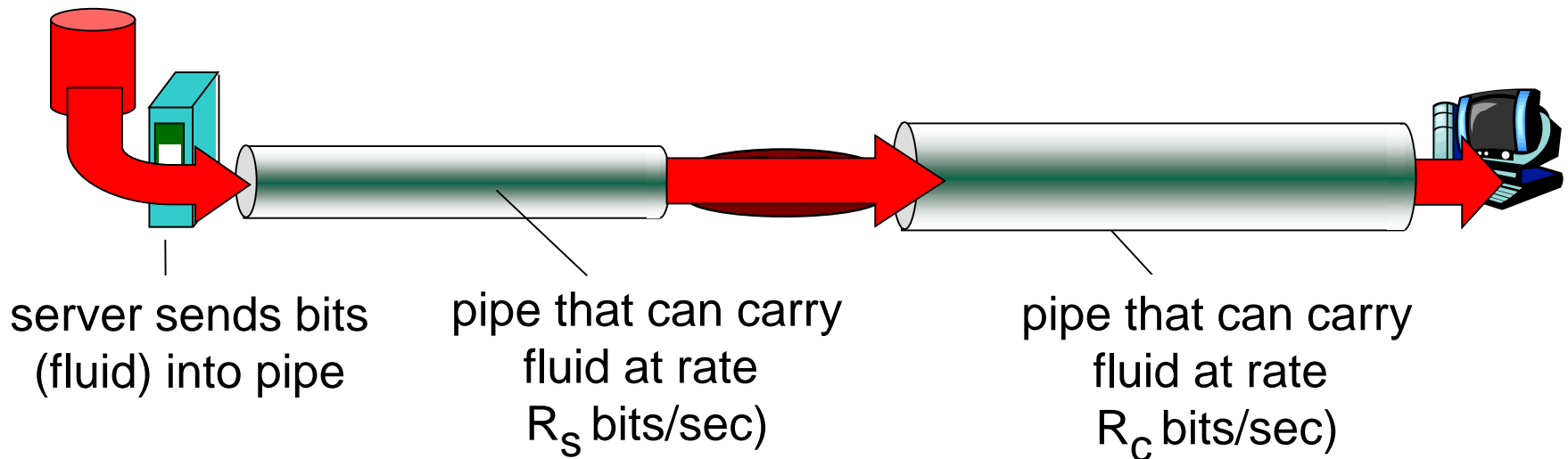
Packet loss

- 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



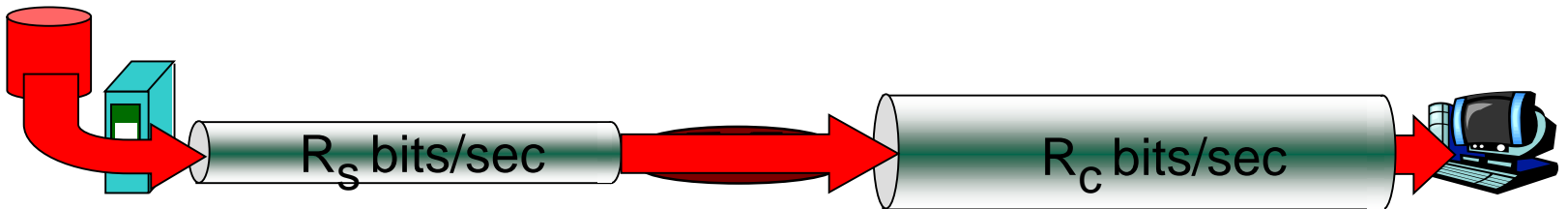
Throughput

- *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

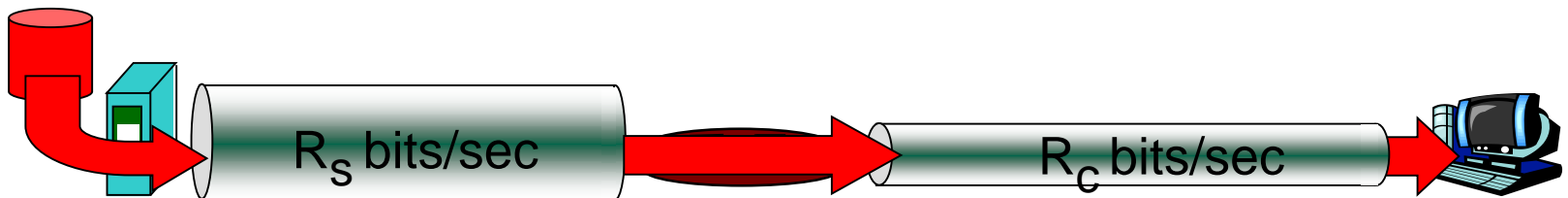


Throughput (more)

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



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

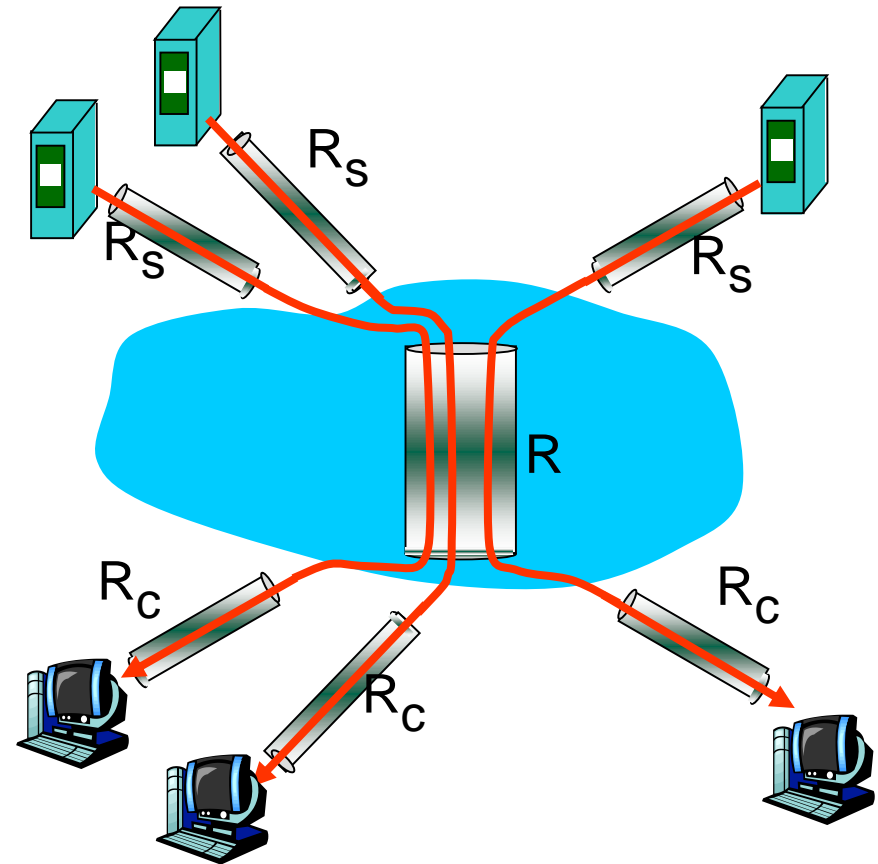


bottleneck link

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

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Protocol “Layers”

Networks are complex!

- many “pieces”:
 - hosts
 - routers
 - links of various media
 - applications
 - protocols
 - hardware, software

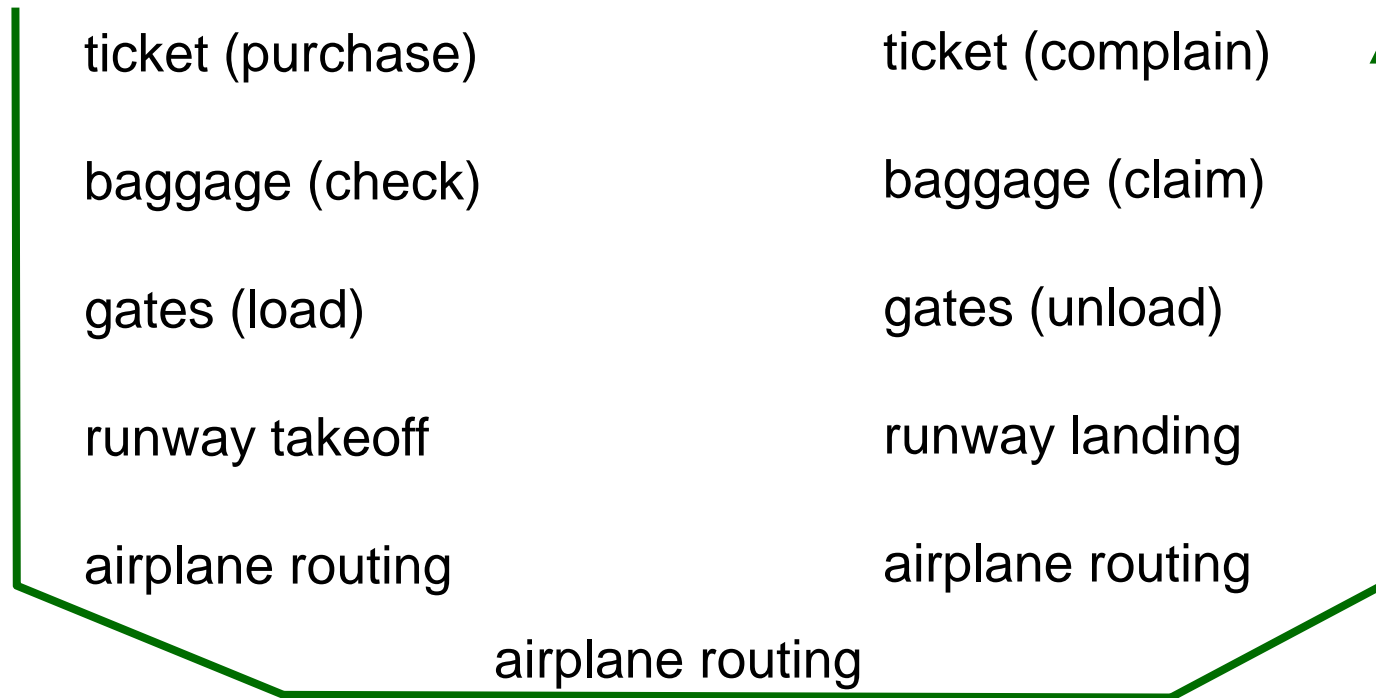
Question:

Is there any hope of
organizing structure of
network?

Or at least our discussion
of networks?



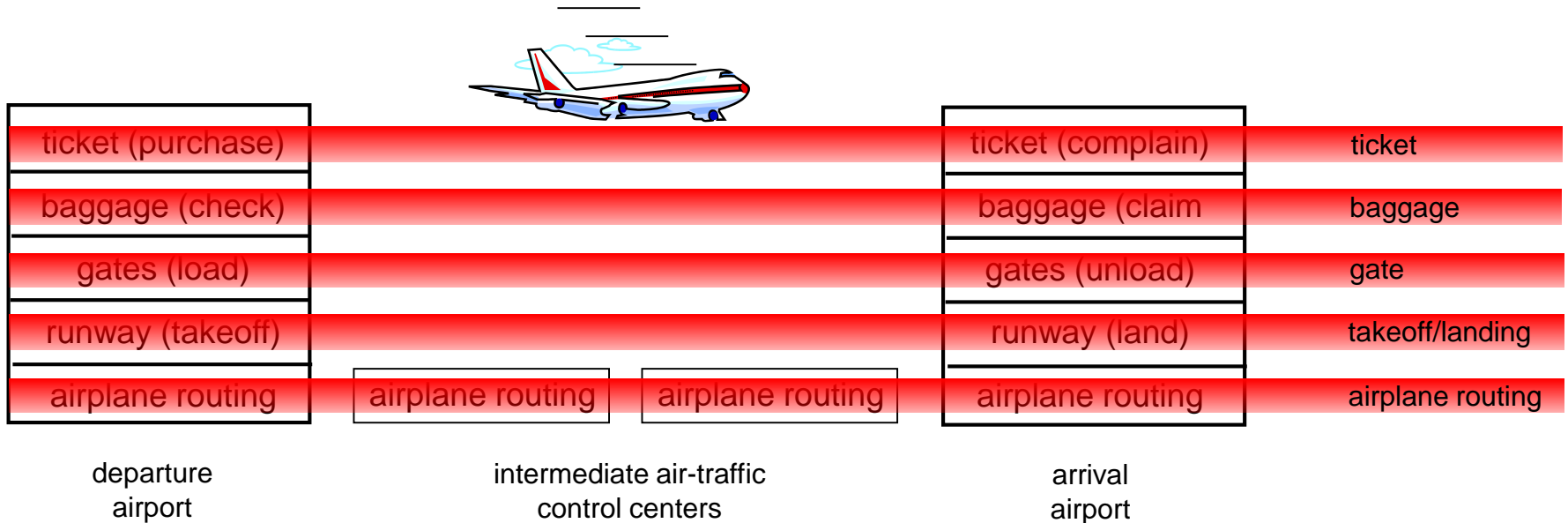
Organization of air travel



- a series of steps



Layering of airline functionality



Layers: each layer implements a service

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



Why layering?

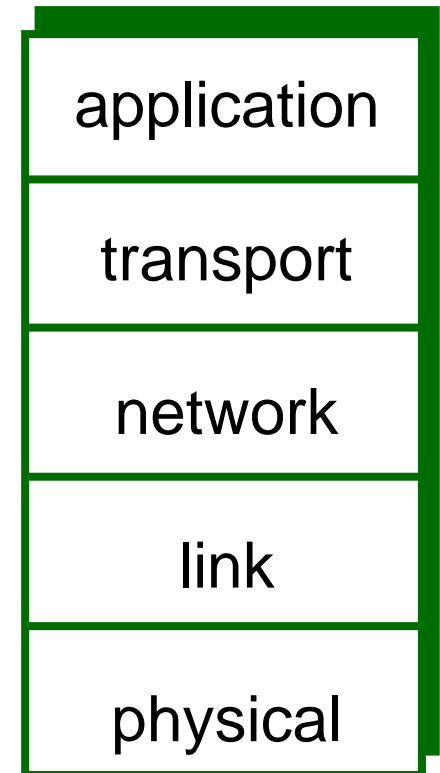
Dealing with complex systems:

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



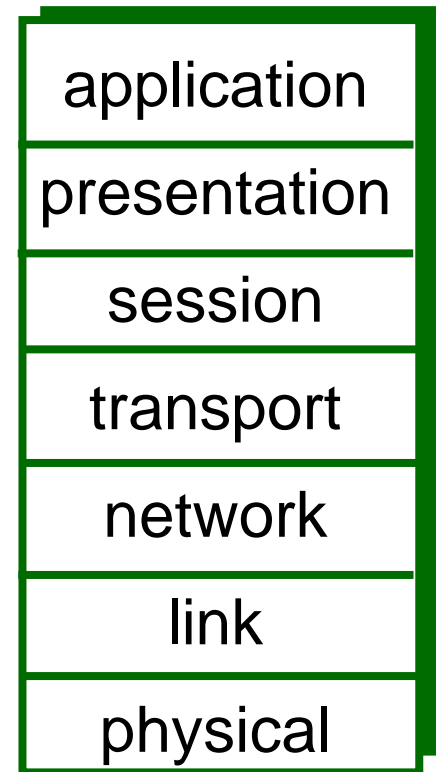
Internet protocol stack

- **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
 - PPP, Ethernet
- **physical:** bits “on the wire”

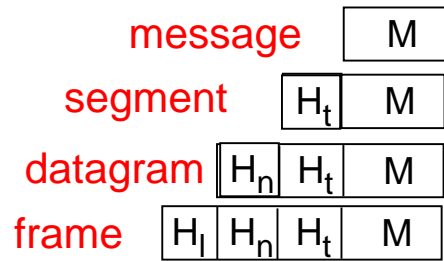


ISO/OSI reference model

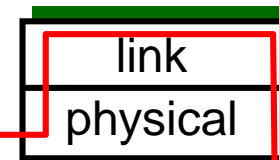
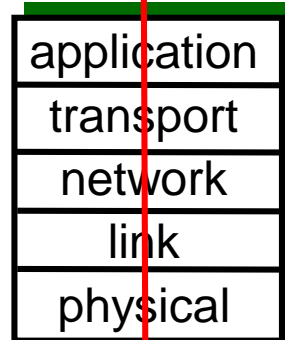
- **presentation**: allow applications to interpret meaning of data, e.g., encryption, compression, machine-specific conventions
- **session**: synchronization, checkpointing, recovery of data exchange
- Internet stack “missing” these layers!
 - these services, *if needed*, must be implemented in application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



Encapsulation

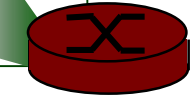
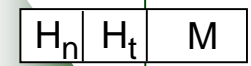
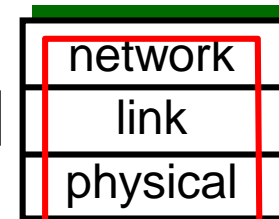
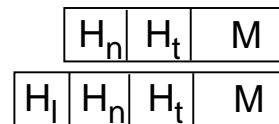
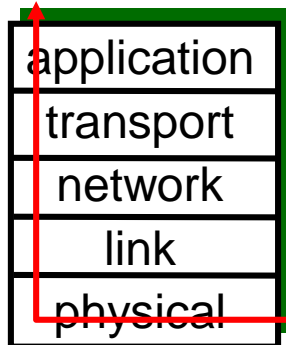
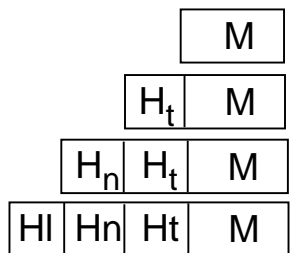


source



switch

destination



router

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1.4 Delay, loss and throughput in packet-switched networks

1.5 Protocol layers, service models

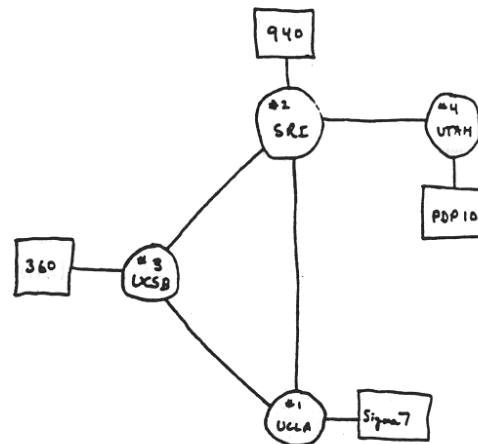
1.6 History



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 demonstration
 - NCP (Network Control Protocol) first host-host protocol
 - first e-mail program
 - ARPAnet has 15 nodes



THE ARPA NETWORK

Internet History

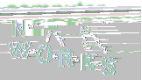
1972-1980: Internetworking, new and proprietary nets

- **1970:** ALOHAnet satellite network in Hawaii
- **1974:** Cerf and Kahn - architecture for interconnecting networks
- **1976:** Ethernet at Xerox PARC
- **late 70'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

2015:

- 40% of world population has access to Internet
- 1 billion websites online
- Largest traffic creators: YouTube, NetFlix, etc.
- Moved to wireless network, mobility
- 1,200 billion search requests towards Google



Introduction: Summary

Covered a “ton” of material!

- Internet overview
 - Incl. Internet / ISP structure
- what’s a protocol?
- network edge, core, access network
 - packet-switching versus circuit-switching
 - Internet structure
- performance: loss, delay, throughput
- layering, service models
- history

You (should ;) now have:

- context, overview, “feel” of networking
- more depth, detail *to follow!*

