COMS 2014A / 2020A

Computer Networks

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Lecture 1

- Networks basics
- What is the internet
  - a network of networks, platform etc
- Network edge
- Network core
- Wireshark
- Slides adapted from prescribed Textbook authors version and some from Prof. A. Mislove

Chapter 1: introduction

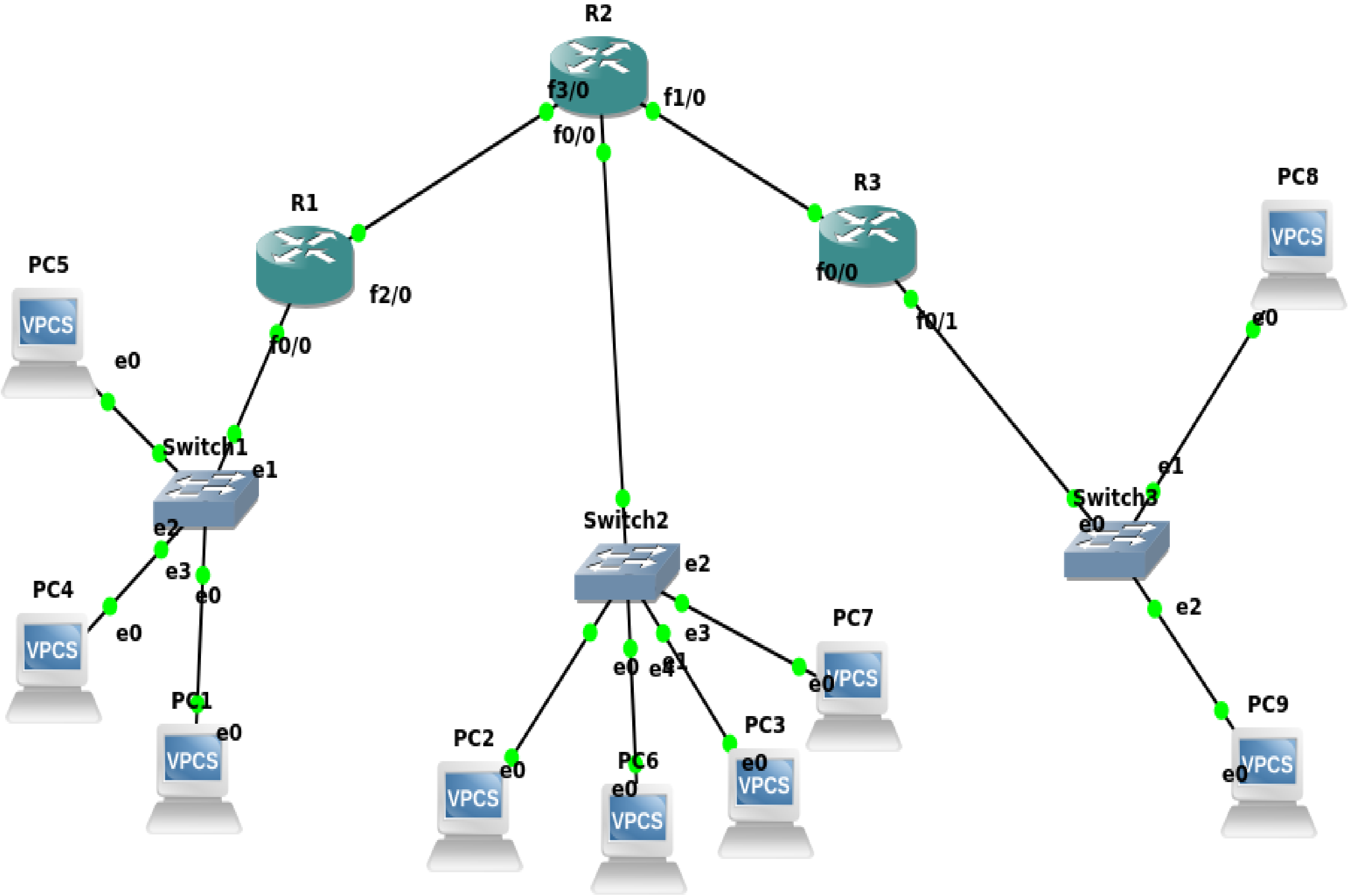
Chapter goal:

- Get "feel," "big picture," introduction to terminology
  - more depth, detail *later* in course

Lectures 1 and 2 roadmap:

- What is a computer network? What *is* the Internet? What *is* a protocol?
- Network edge: hosts, access network, physical media
- Network core: packet/circuit switching, internet structure
- Performance: loss, delay, throughput
- Protocol layers, service models
- Security
- History

What is a Computer network ?



Virtual computer network created using GNS3

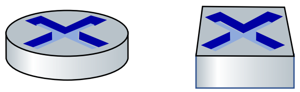
Computer network: nature, character

- **Motivation** for networking devices. Why?
  - Communication
  - Sharing
- **Components** of a network. What?
  - Computing devices
  - Connectors
  - Protocols, standards
- **Design** approaches for networks. How?
  - Star , bus, ring etc
- **Classification** by scale. How?
  - LAN, PAN
  - MAN
  - WAN
  - Internet

The Internet: a "nuts and bolts" view

Billions of connected computing *devices*:

- *hosts = end systems*
- running *network apps* at Internet's "edge"



Packet switches: forward packets (chunks of data)

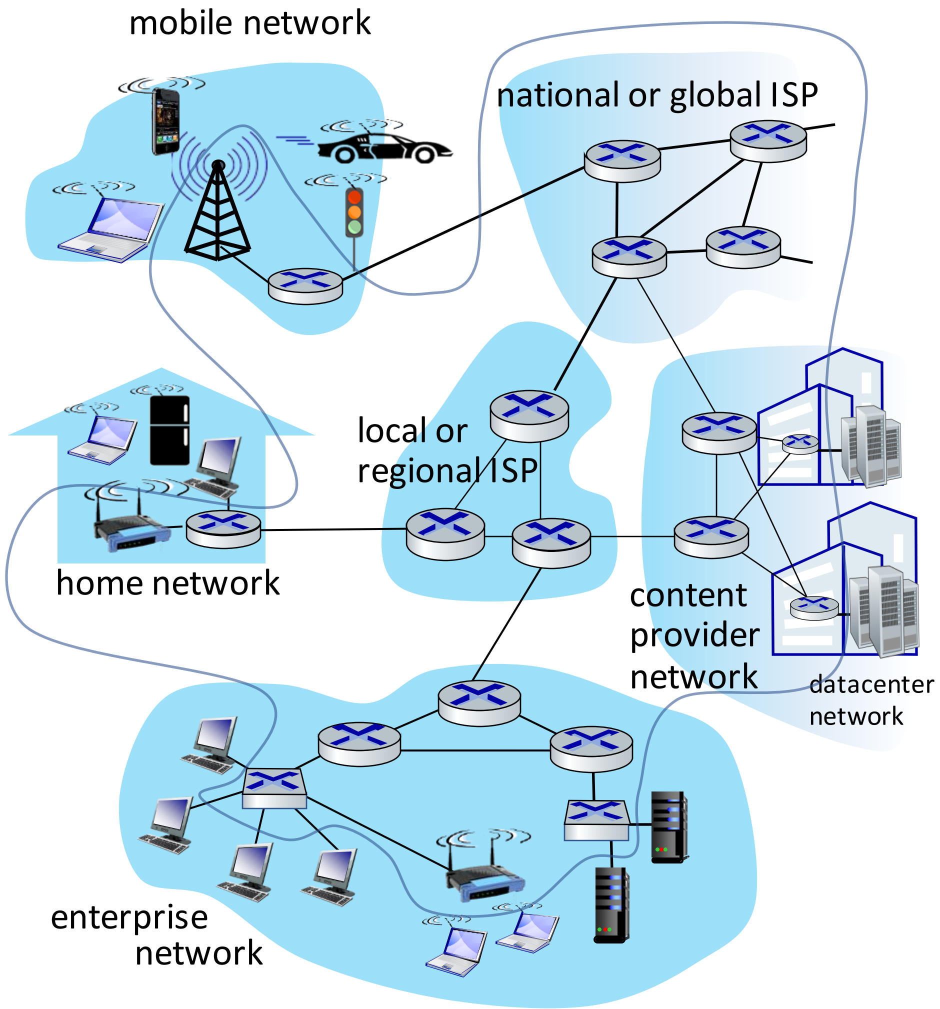
- *routers, switches*

Communication links

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

Networks

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



“Fun” Internet-connected devices


Amazon Echo


Internet refrigerator


IP picture frame

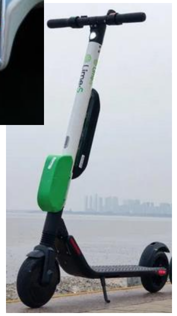

Pacemaker & Monitor


Tweet-a-watt: monitor energy use

bikes



cars


scooters


Web-enabled toaster + weather forecaster

Security Camera


Slingbox: remote control cable TV


AR devices


Internet phones


Gaming devices

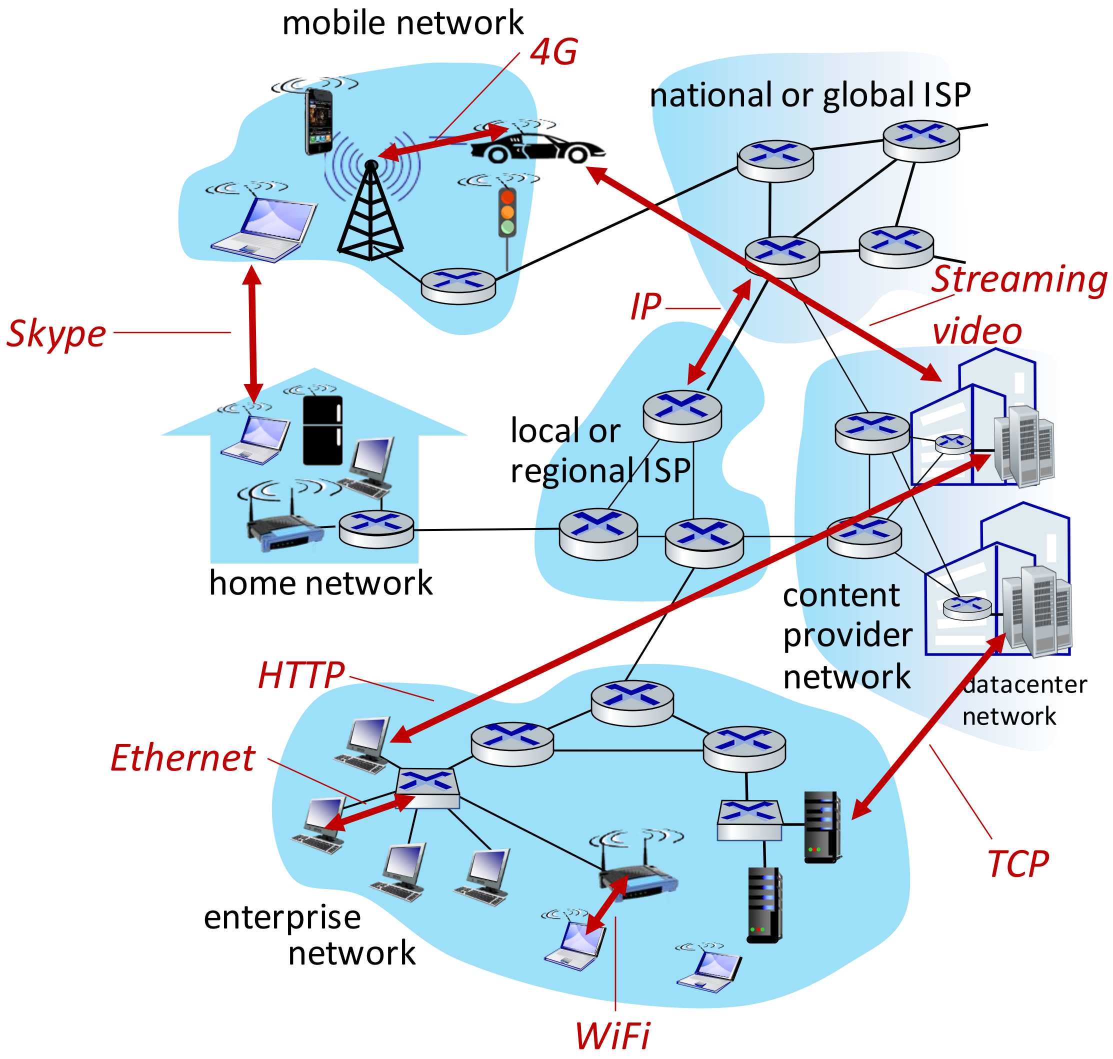

sensorized, bed mattress


Fitbit

Others?

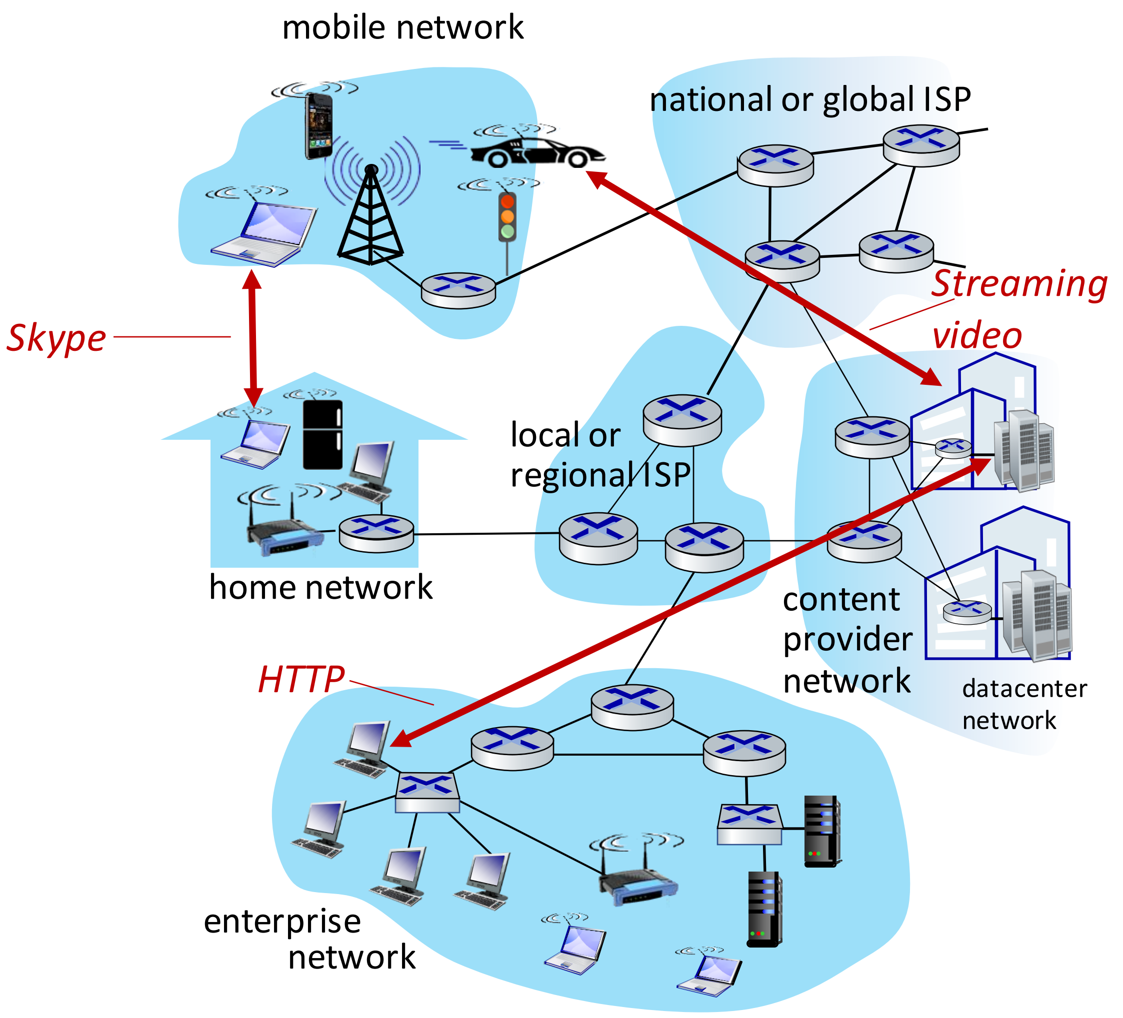
The Internet: a "nuts and bolts" view

- *Internet: "network of networks"*
  - Interconnected ISPs
- *protocols* are *everywhere*
  - control sending, receiving of messages
  - e.g., HTTP (Web), streaming video, Skype, TCP, IP, WiFi, 4G, Ethernet
- *Internet standards*
  - RFC: Request for Comments
  - IETF: Internet Engineering Task Force



The Internet: a "services" view

- *Infrastructure* that provides services to applications:
  - Web, streaming video, multimedia teleconferencing, email, games, e-commerce, social media, inter-connected appliances, …
- provides *programming interface* to distributed applications:
  - "hooks" allowing sending/receiving apps to "connect" to, use Internet transport service
  - provides service options, analogous to postal service



What's a protocol?

Human protocols:

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

Rules for:

… specific messages sent

… specific actions taken when message received, or other events

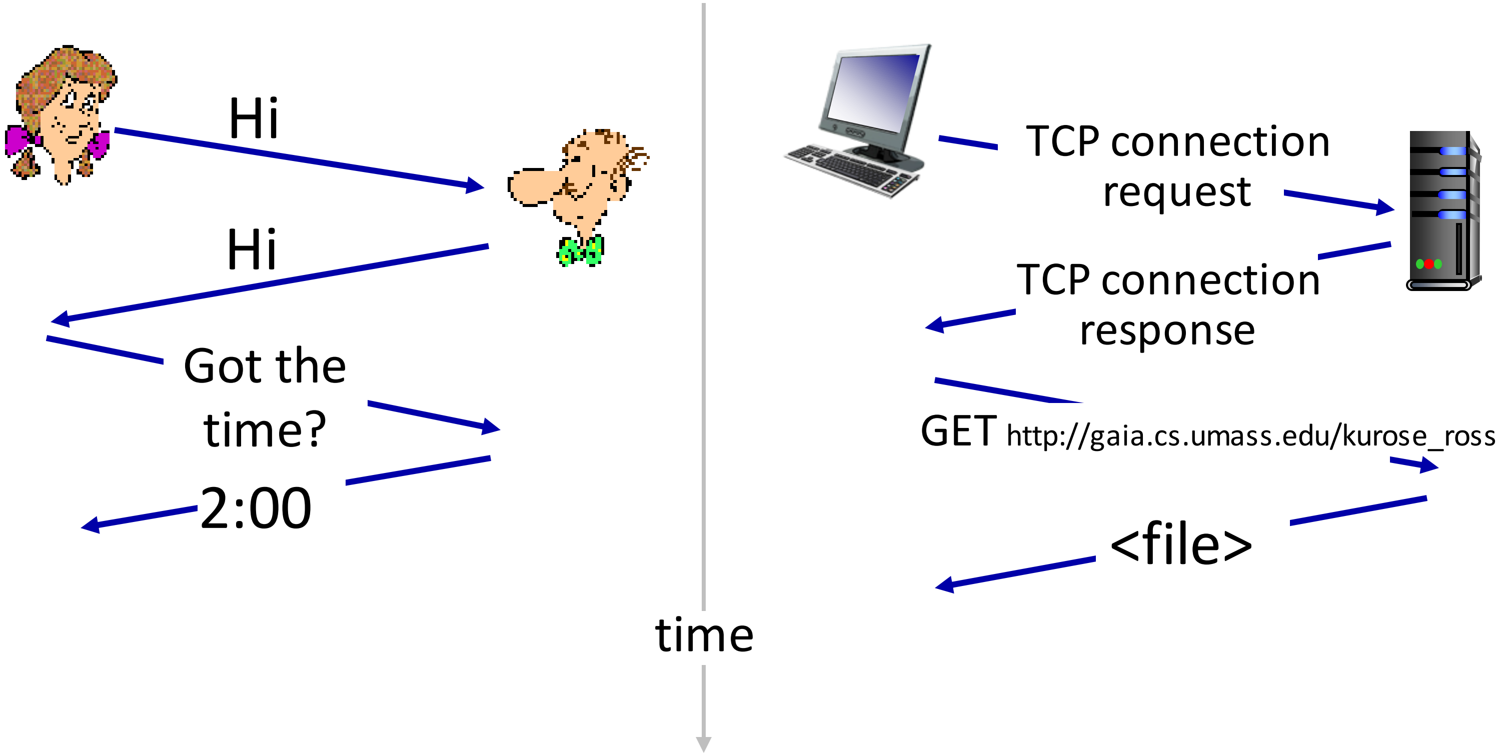
Network protocols:

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

Protocols define the 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:

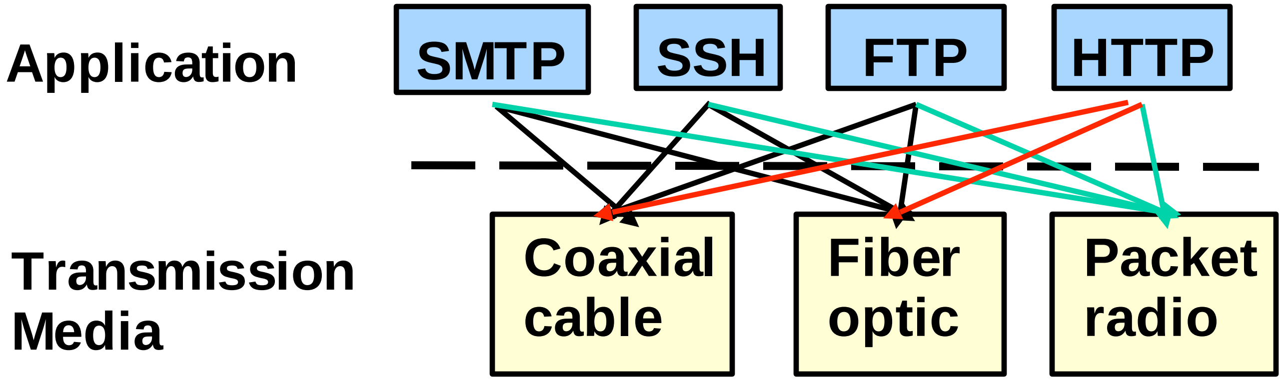


Q: other human protocols?

Protocols: Organizing Network Functionality

- Many kinds of networking **functionality**
  - e.g., encoding, framing, routing, addressing, reliability, etc.
- Many different network styles and **technologies**
  - circuit-switched vs packet-switched, etc.
  - wireless vs wired vs optical, etc.
- Many different **applications**
  - ftp, email, web, P2P, etc.
- Network **architecture**
  - How should different pieces be organized?
  - How should different pieces interact?

Protocols: problem



- new application has to interface to all existing media
  - adding new application requires O(m) work, m = number of media
- new media requires all existing applications be modified
  - adding new media requires O(a) work, a = number of applications

Recall: Software Modularity

Break system into modules:

- Well-defined interfaces gives flexibility
  - can change implementation of modules
  - can extend functionality of system by adding new modules
- Interfaces hide information
  - allows for flexibility
  - but can hurt performance

Network Modularity

Like software modularity, but with a twist:

- Implementation distributed across routers and hosts

- Must decide both:
  - how to break system into modules
  - where modules are implemented

Protocol Layering

- Layering is a particular form of modularization
- The system is broken into a vertical hierarchy of logically distinct entities (layers)
- The service provided by one layer is based solely on the service provided by layer below
- Rigid structure: easy reuse, performance suffers

Layering cencept

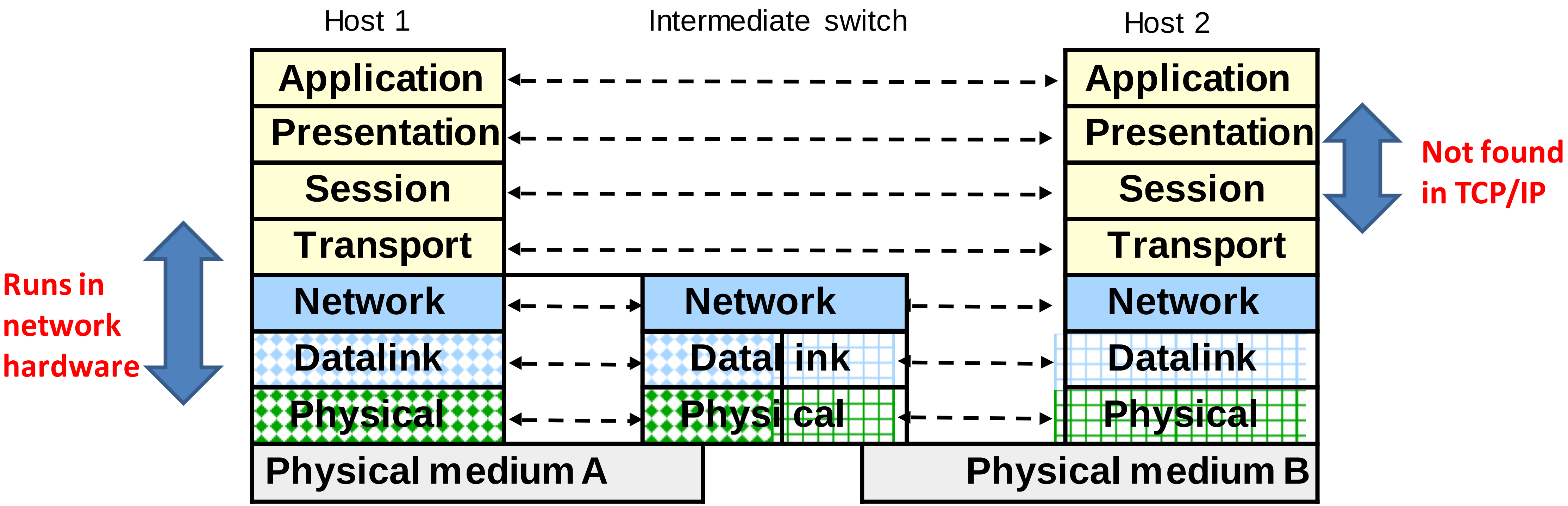
- Layering
  - how to break network functionality into modules
  - Each layer to offer a service to the layer above
- The End-to-End Argument
  - where to implement functionality across the layers from sender to receiver

ISO OSI Reference Model

- ISO – International Standard Organization
- OSI – Open System Interconnection
- Goal: a general open standard
  - allow vendors to enter the market by using their own implementation and protocols
- Not as successful as the TCP/IP protocol stack
- More academic and good as an instruction tool

ISO OSI Reference Model

- Seven layers
  - Lower two layers are peer-to-peer
  - Network layer involves multiple switches
  - Next four layers are end-to-end



Layering Solves Problem

- Application layer doesn't know about anything below the presentation layer, etc.
- Information about network is hidden from higher layers
- This ensures that we only need to implement an application once!

Key Concepts

- Service – says what a layer does
  - Ethernet: unreliable subnet unicast/multicast/broadcast datagram service
  - IP: unreliable end-to-end unicast datagram service
  - TCP: reliable end-to-end bi-directional byte stream service
  - Guaranteed bandwidth/latency unicast service
- Service Interface – says how to access the service
  - E.g. UNIX socket interface
- Protocol – says how is the service implemented
  - a set of rules and formats that govern the communication between two peers

> Internet standards

RFCs

RFC documents contain technical specifications and organizational notes for the Internet.

RFCs produced by the IETF cover many aspects of computer networking. They describe the Internet's technical foundations, such as addressing, routing, and transport technologies. RFCs also specify protocols like TLS 1.3, QUIC, and WebRTC that are used to deliver services used by billions of people every day, such as real-time collaboration, email, and the domain name system.

Only some RFCs are standards. Depending on their maturity level and what they cover, RFCs are labeled with different statuses: Internet Standard, Proposed Standard, Best Current Practice, Experimental, Informational, and Historic.

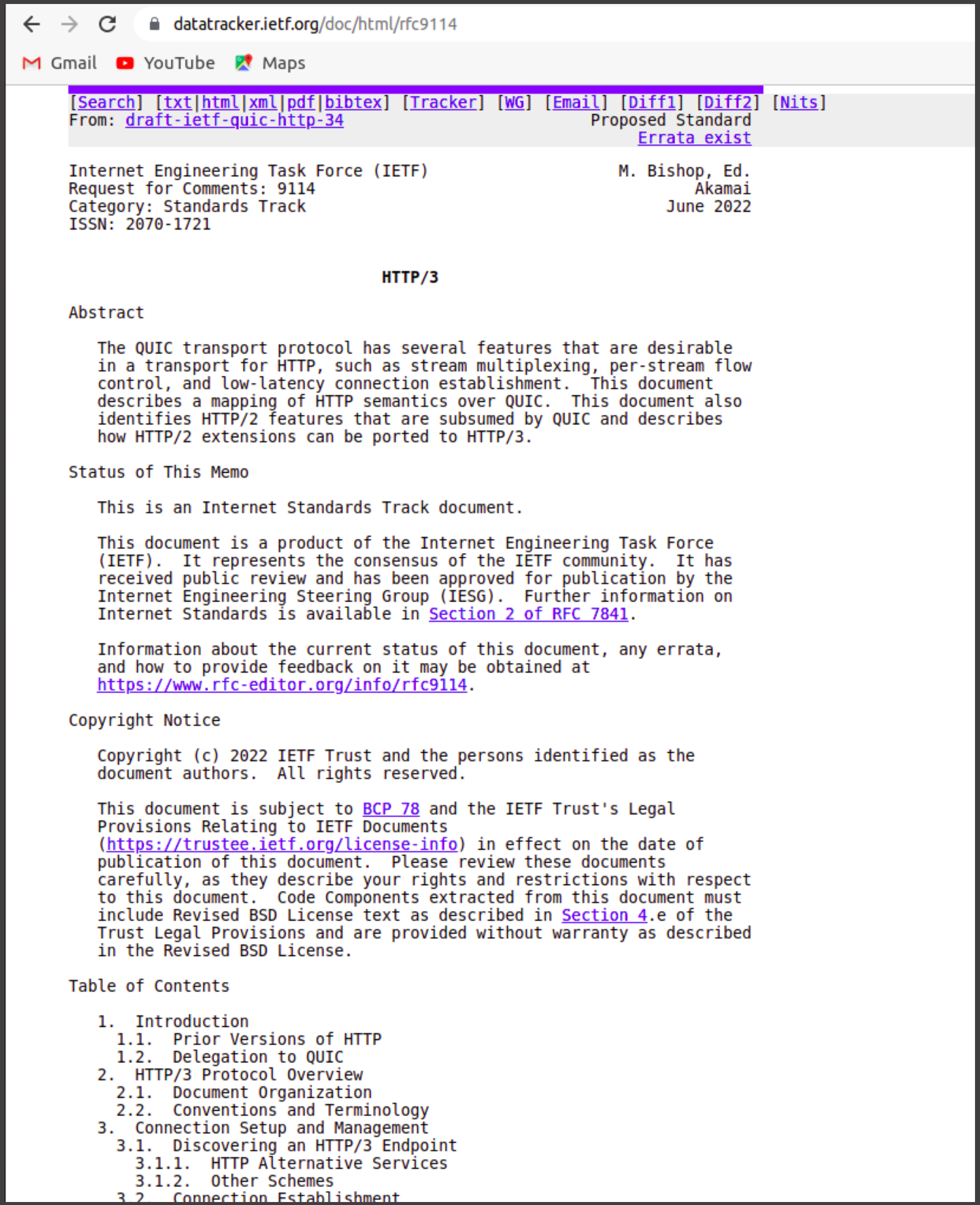
The RFC Series includes documents produced by the IETF, the Internet Architecture Board (IAB), the Internet Research Task Force (IRTF), and independent submitters. All RFCs are published by the RFC Editor, which is the authoritative source for retrieving RFCs.

RFCs usually begin as Internet-Drafts (I-Ds) written by an individual or a small group. In the IETF, these are then usually adopted by a working group, and improved and revised. Less often, I-Ds are considered within the IETF as “individual submissions” sponsored by an Area Director. While not every I-D becomes an RFC, a well-defined set of processes (also documented in RFCs) guides the consideration and progression of a document. When they are published, RFCs are freely available online.

Software developers, hardware manufacturers, and network operators around the world voluntarily implement and adopt the technical specifications described by RFCs.

The IETF recognizes that security vulnerabilities will be discovered in IETF protocols and welcomes their critical evaluation by researchers. The Internet Engineering Steering Group has provided guidance on how to report vulnerabilities believed to be discovered in IETF protocols.

INTERNET STANDARDS
RFCs
Intellectual property rights
Standards process
Publishing and accessing RFCs



datatracker.ietf.org/doc/html/rfc9114

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From: draft-ietf-quic-http-34 Proposed Standard
Errata exist

Internet Engineering Task Force (IETF)
Request for Comments: 9114
Category: Standards Track
ISSN: 2070-1721

M. Bishop, Ed.
Akamai
June 2022

HTTP/3

Abstract

The QUIC transport protocol has several features that are desirable in a transport for HTTP, such as stream multiplexing, per-stream flow control, and low-latency connection establishment. This document describes a mapping of HTTP semantics over QUIC. This document also identifies HTTP/2 features that are subsumed by QUIC and describes how HTTP/2 extensions can be ported to HTTP/3.

Status of This Memo

This is an Internet Standards Track document.

This document is a product of the Internet Engineering Task Force (IETF). It represents the consensus of the IETF community. It has received public review and has been approved for publication by the Internet Engineering Steering Group (IESG). Further information on Internet Standards is available in Section 2 of RFC 7841.

Information about the current status of this document, any errata, and how to provide feedback on it may be obtained at https://www.rfc-editor.org/info/rfc9114.

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HTTP3

Reference For Comments

WIFI

RFCs

ieeexplore.ieee.org/browse/standards/get-program/page/series?id=68

Gmail YouTube Maps

IEEE 802.3: Ethernet

IEEE 802.11: Wireless LANs

802.11ba-2021

802.11ba-2021 - IEEE Standard for Information Technology--Telecommunications and Information Exchange between Systems--Local and Metropolitan Area Networks-Specific Requirements--Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications - Amendment 3: Wake-Up Radio Operation

802.11ay-2021

802.11ay-2021 - IEEE Standard for Information Technology--Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks--Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: Enhanced Throughput for Operation in License-exempt Bands above 45 GHz

802.11ax-2021

802.11ax-2021 - IEEE Standard for Information Technology--Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks--Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 1: Enhancements for High-Efficiency WLAN

802.11-2020

802.11-2020 - IEEE Standard for Information Technology--Telecommunications and Information Exchange between Systems - Local and Metropolitan Area Networks--Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications

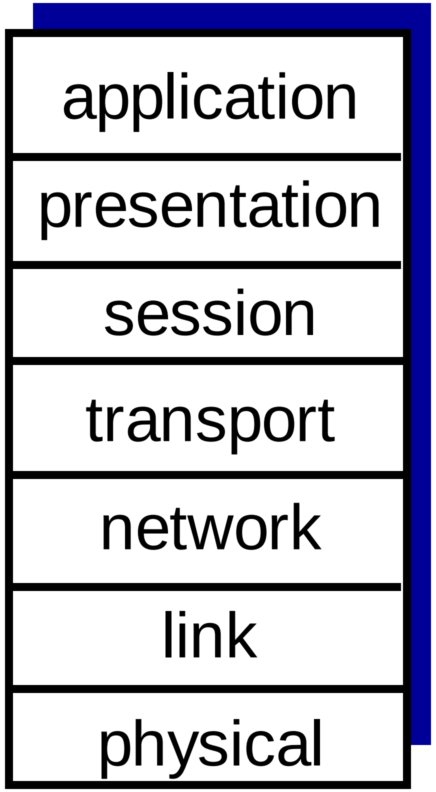
IEEE 802.15: Wireless PANs

IEEE 802.16: Broadband Wireless MANs

ISO/OSI reference model

Two layers not found in Internet protocol stack! (TCP/IP)

- *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?



The seven layer OSI/ISO reference model

Chapter 1: roadmap

- What *is* the Internet?
- What *is* a protocol?
- Network edge: hosts, access network, physical media
- Network core: packet/circuit switching, internet structure
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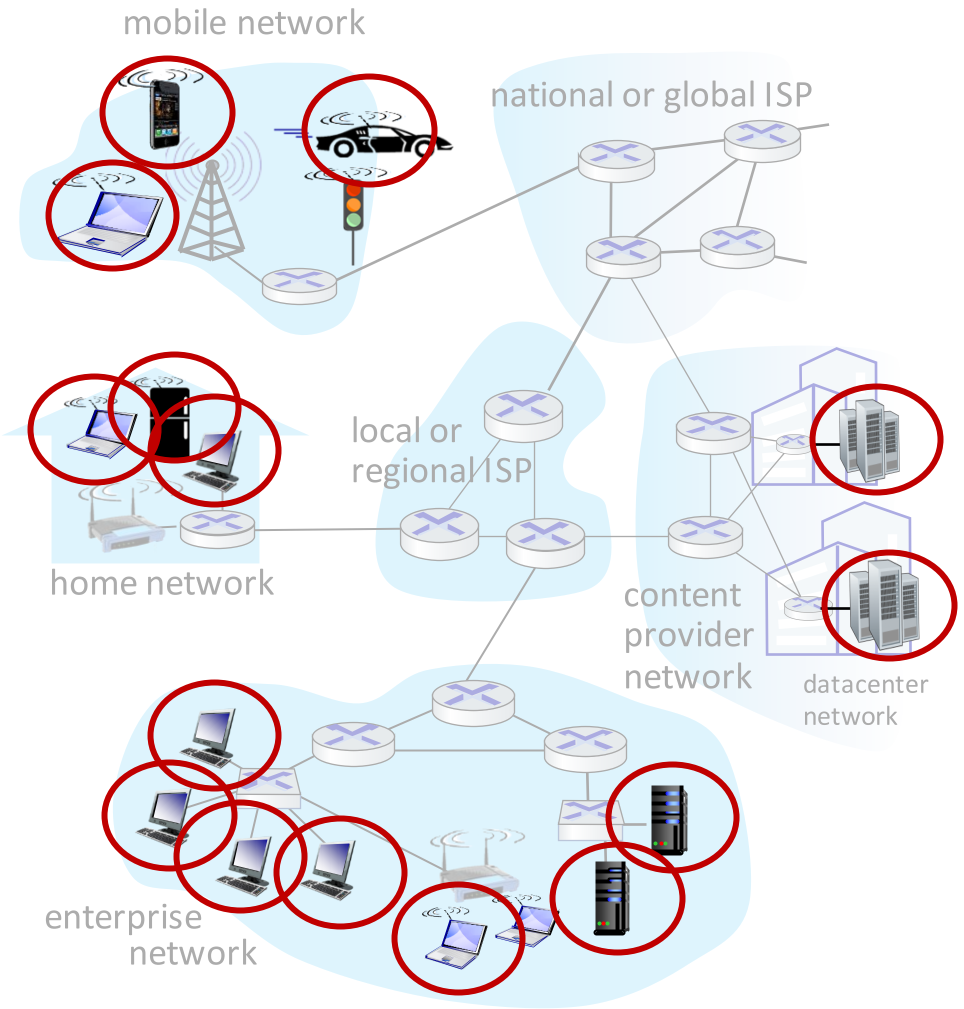
A closer look at Internet structure

Network edge:

- hosts: clients and servers
- servers often in data centers



A closer look at Internet structure

Network edge:

- hosts: clients and servers
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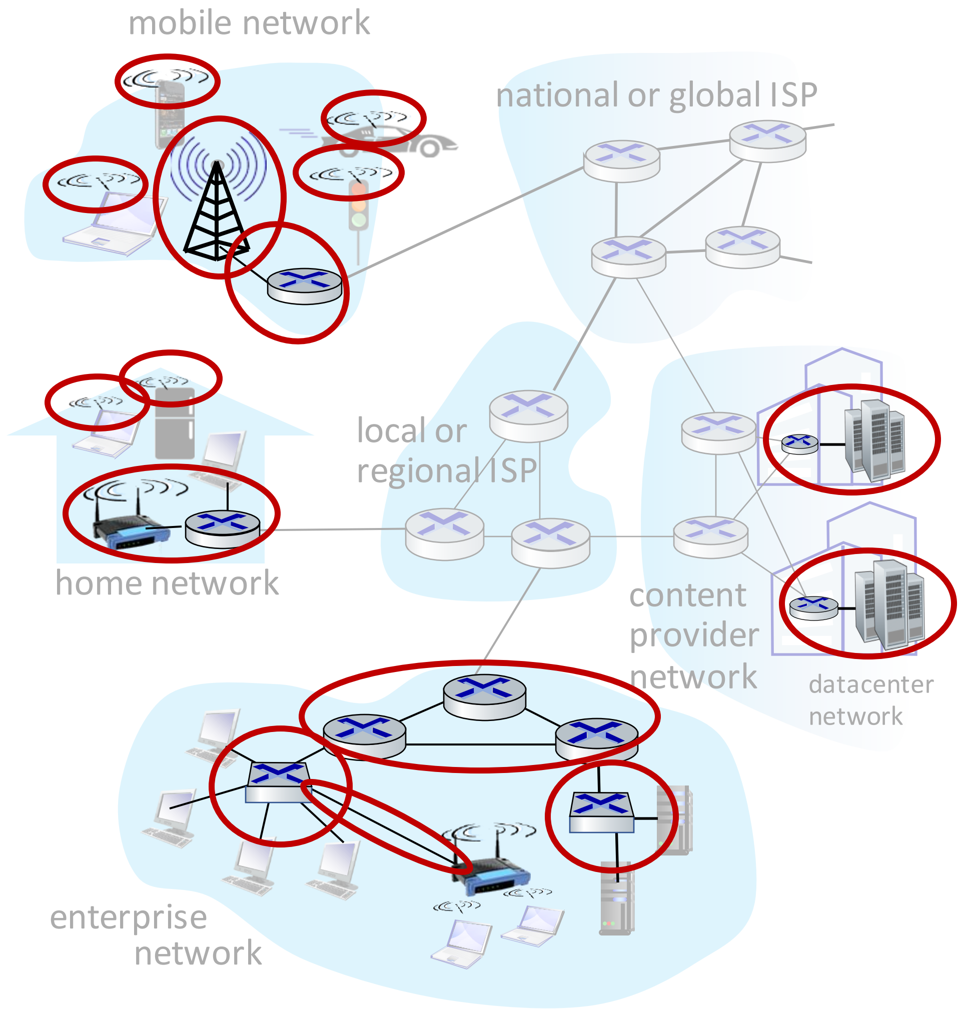
Access networks, physical media:

- wired, wireless communication links

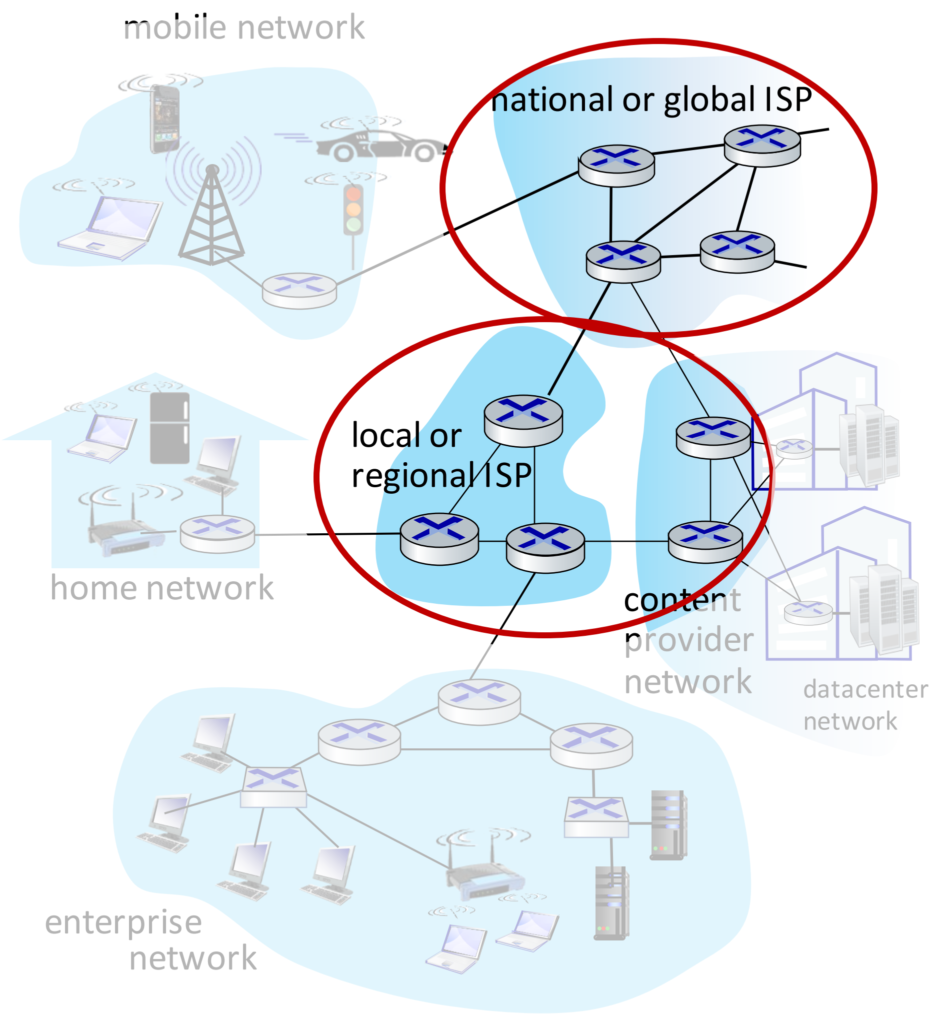


A closer look at Internet structure

Network edge:
- hosts: clients and servers
- servers often in data centers

Access networks, physical media:
- wired, wireless communication links

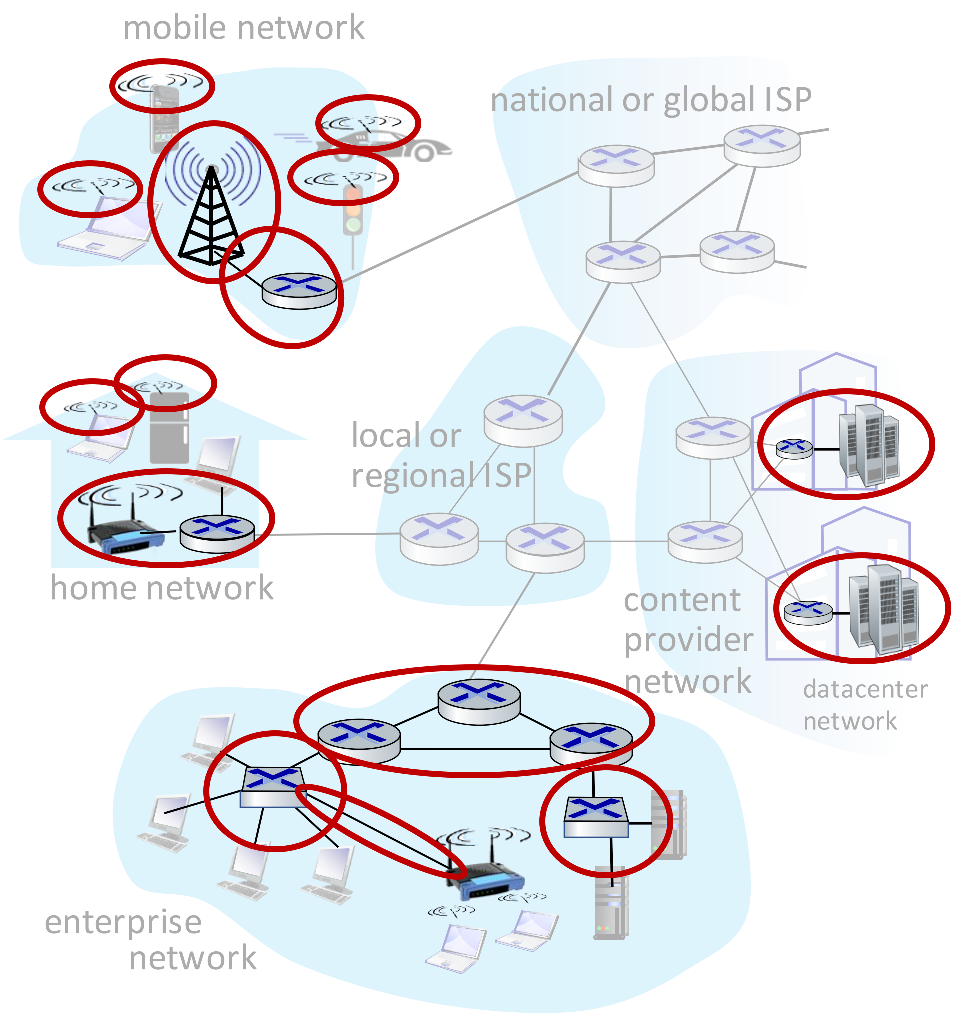
Network core:
- interconnected routers
- network of networks



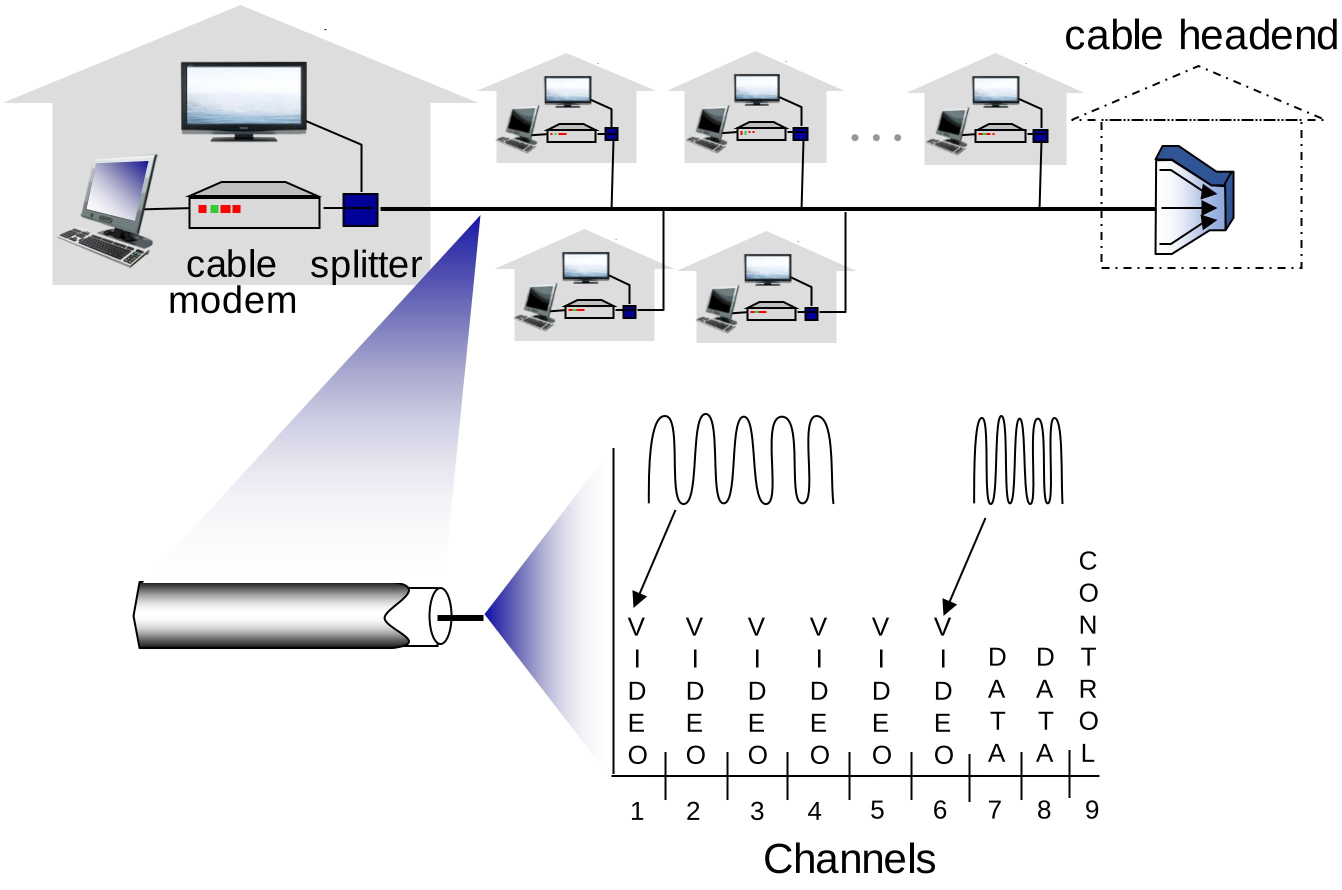
Access networks and physical media

Q: How to connect end systems to edge router?

- residential access nets i.e internet to the home
- institutional access networks (school, company)
- mobile access networks (WiFi, 4G/5G)

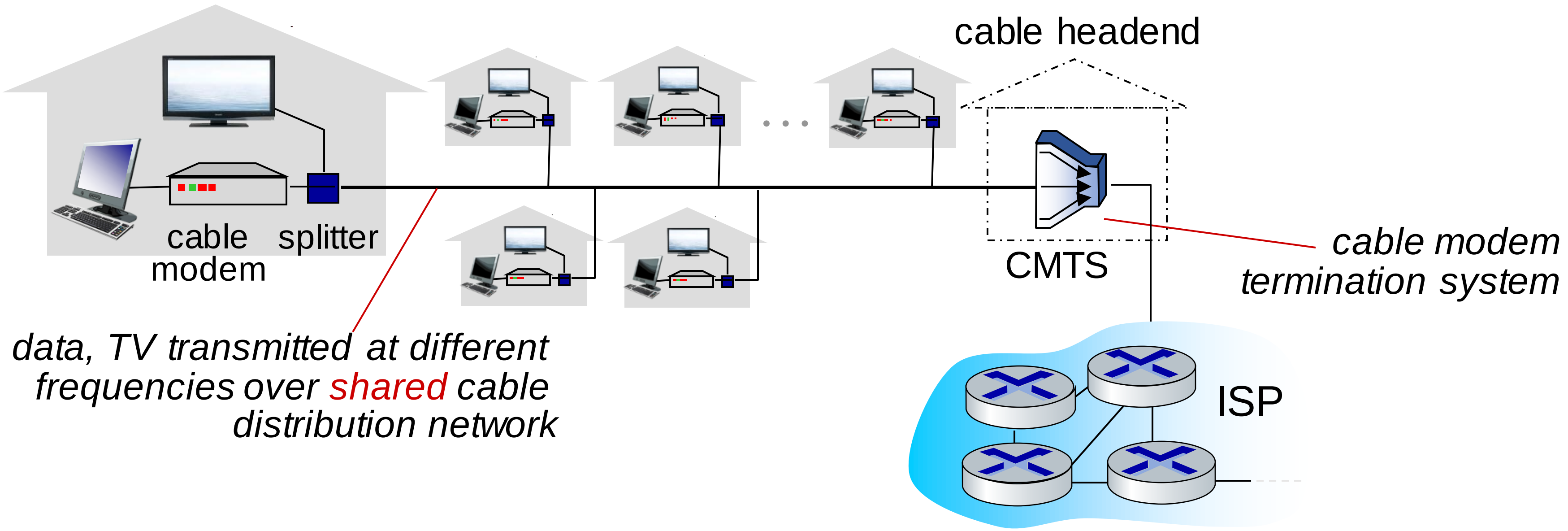


Access networks: cable-based access



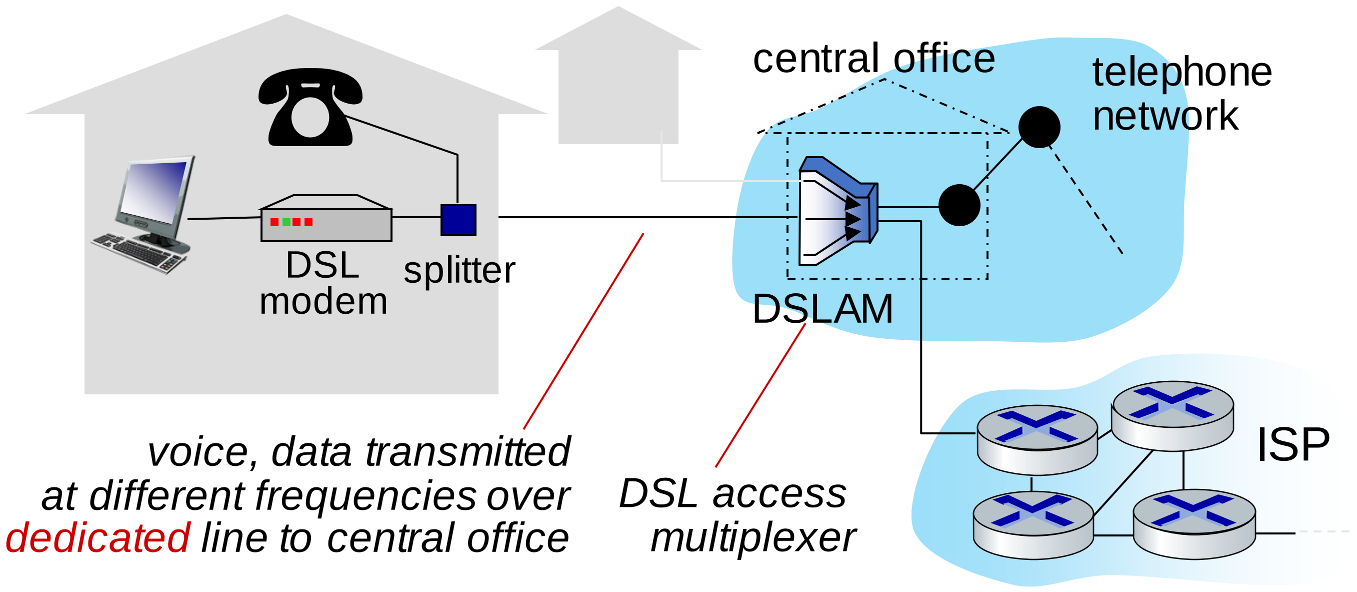
frequency division multiplexing (FDM): different channels transmitted in different frequency bands

Access networks: cable-based access



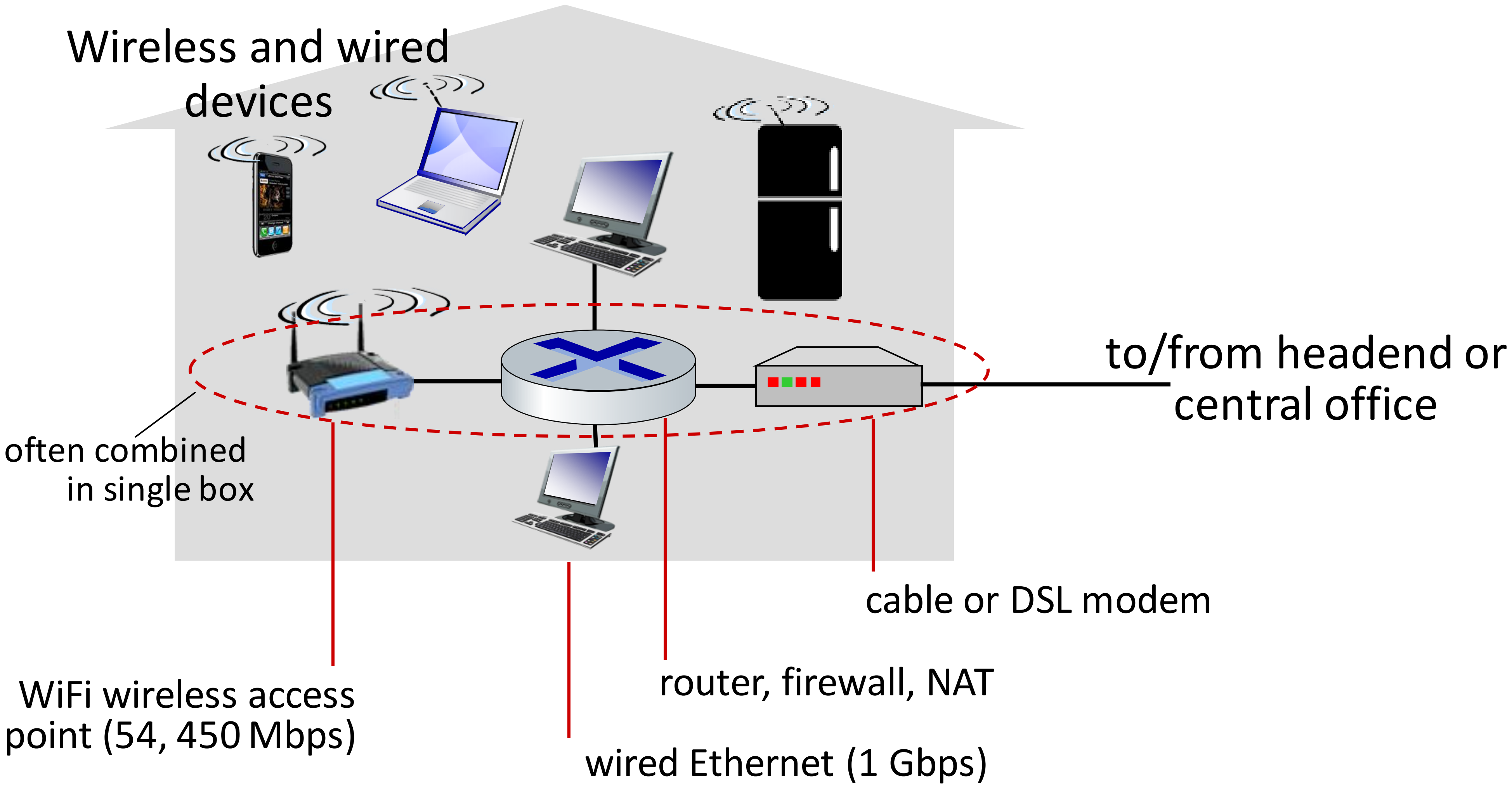
- HFC: hybrid fiber coax
  - asymmetric: up to 40 Mbps – 1.2 Gbps downstream transmission rate, 30-100 Mbps upstream transmission rate
- network of cable, fiber attaches homes to ISP router
  - homes *share access network* to cable headend

Access networks: 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
- 24-52 Mbps dedicated downstream transmission rate
- 3.5-16 Mbps dedicated upstream transmission rate

Access networks: home networks



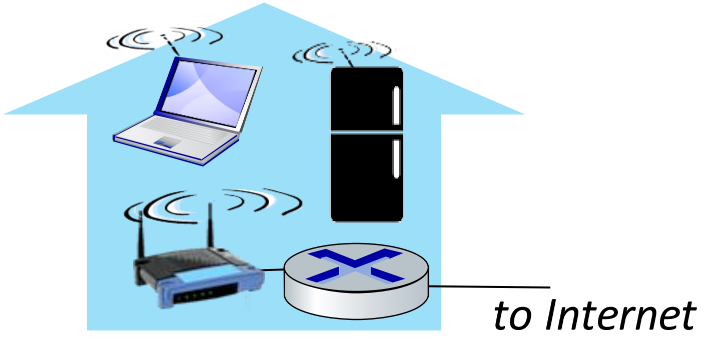
Wireless access networks

Shared *wireless* access network connects end system to router

- via base station aka “access point”

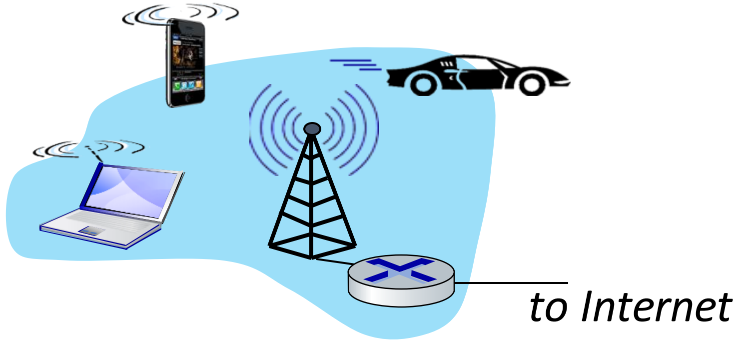
Wireless local area networks (WLANs)

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

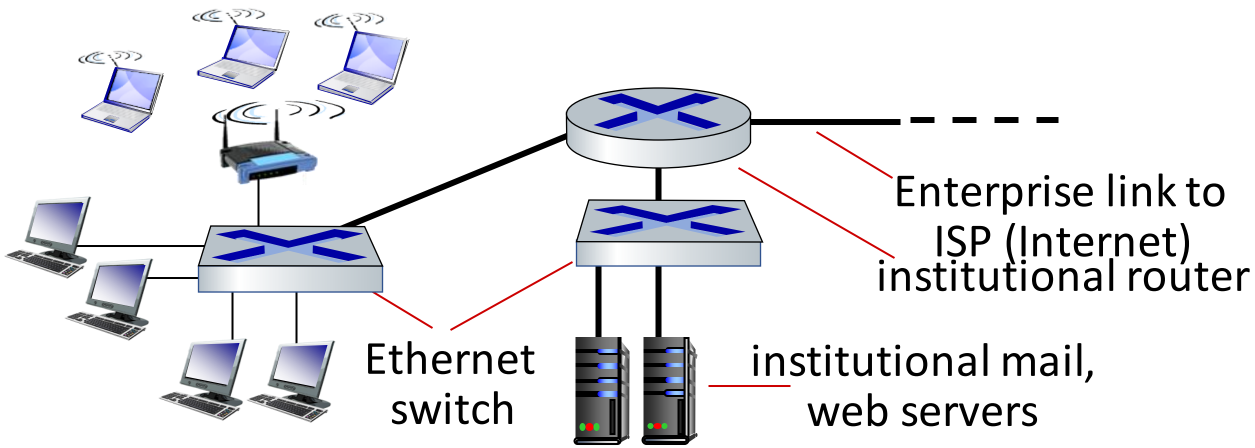


Wide-area cellular access networks

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



Access networks: enterprise networks

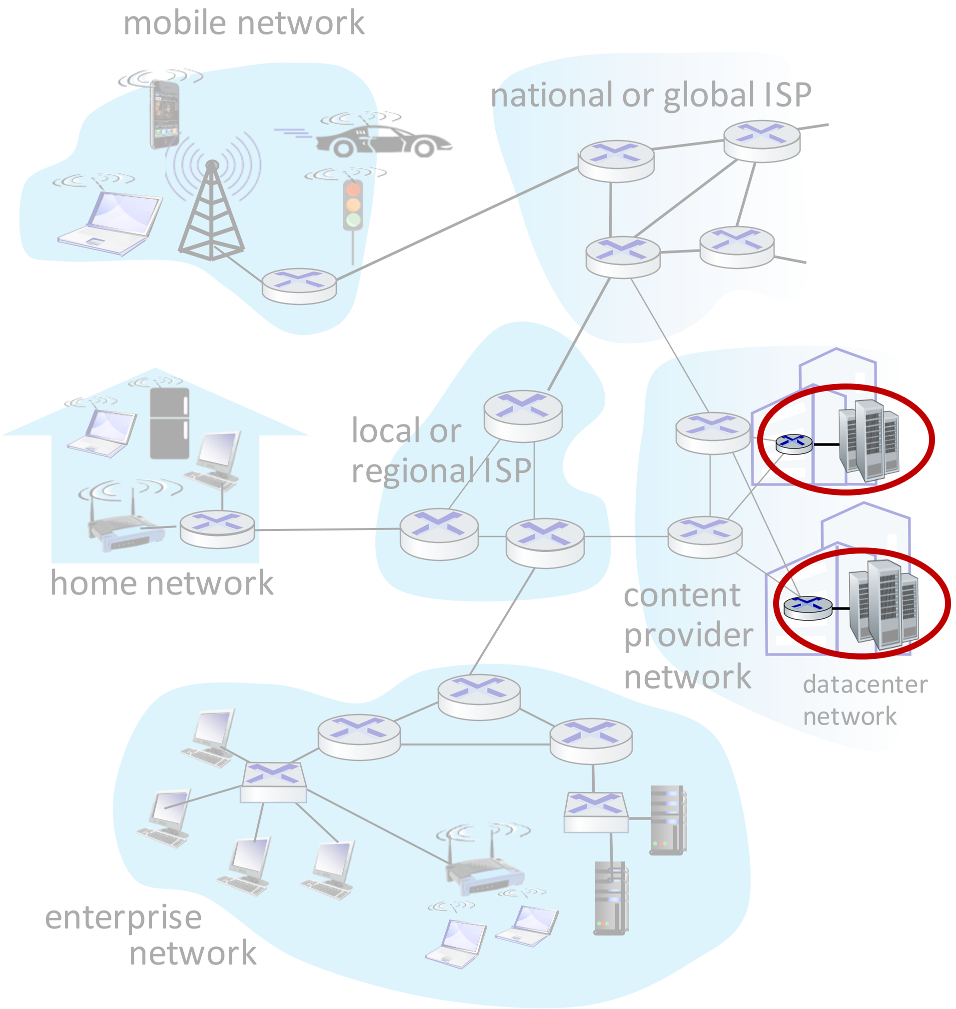


- companies, universities, etc.
- mix of wired, wireless link technologies, connecting a mix of switches and routers (we'll cover differences shortly)
  - Ethernet: wired access at 100Mbps, 1Gbps, 10Gbps
  - WiFi: wireless access points at 11, 54, 450 Mbps

Access networks: data center networks

- high-bandwidth links (10s to 100s Gbps) connect hundreds to thousands of servers together, and to Internet

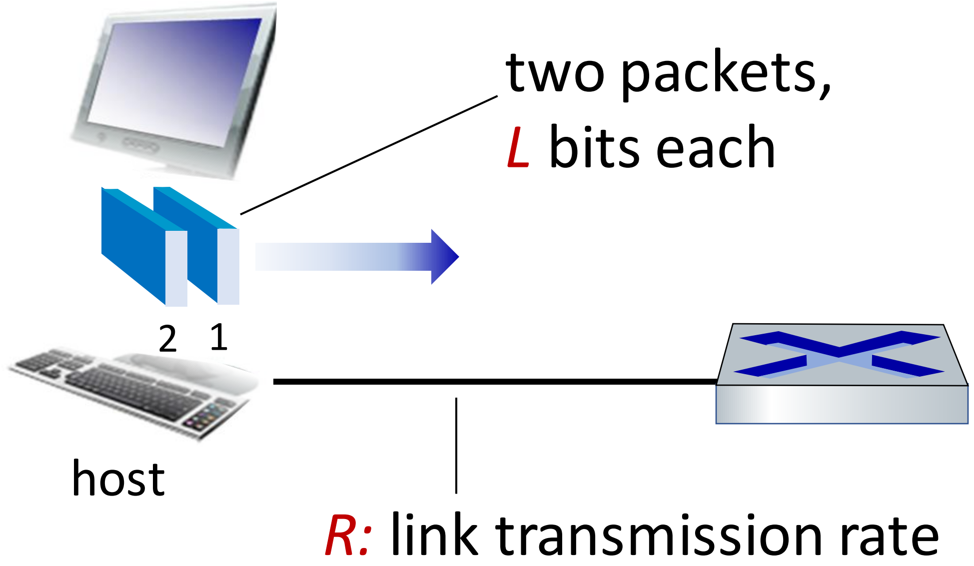
Courtesy: Massachusetts Green High Performance Computing Center (mghpcc.org)



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*



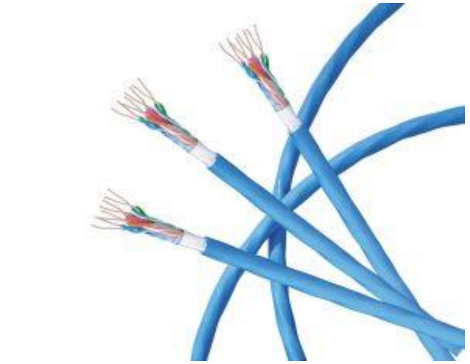
$$\text{packet transmission delay} = \text{time needed to transmit } L\text{-bit packet into link} = \frac{L \text{ (bits)}}{R \text{ (bits/sec)}}$$

Links: physical media

- bit: propagates between transmitter/receiver pairs
- physical link: what lies between transmitter & receiver
- guided media:
  - signals propagate in solid media: copper, fiber, coax
- unguided media:
  - signals propagate freely, e.g., radio

Twisted pair (TP)

- two insulated copper wires
  - Category 5: 100 Mbps, 1 Gbps Ethernet
  - Category 6: 10Gbps Ethernet



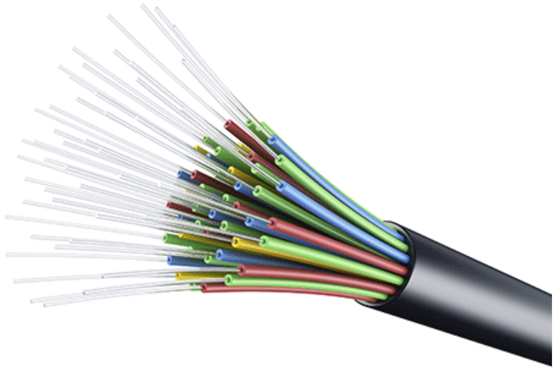
Links: physical media

Coaxial cable:

- two concentric copper conductors
- bidirectional
- broadband:
  - multiple frequency channels on cable
  - 100's Mbps per channel

Fiber optic cable:

- glass fiber carrying light pulses, each pulse a bit
- high-speed operation:
  - high-speed point-to-point transmission (10's-100's Gbps)
- low error rate:
  - repeaters spaced far apart
  - immune to electromagnetic noise



Links: physical media

Wireless radio

- signal carried in various “bands” in electromagnetic spectrum
- no physical “wire”
- broadcast, “half-duplex” (sender to receiver)
- propagation environment effects:
  - reflection
  - obstruction by objects
  - Interference/noise

Radio link types:

- Wireless LAN (WiFi)
  - 10-100’s Mbps; 10’s of meters
- wide-area (e.g., 4G cellular)
  - 10’s Mbps over ~10 Km
- Bluetooth: cable replacement
  - short distances, limited rates
- terrestrial microwave
  - point-to-point; 45 Mbps channels
- satellite
  - up to 45 Mbps per channel
  - 270 msec end-end delay

Chapter 1: roadmap

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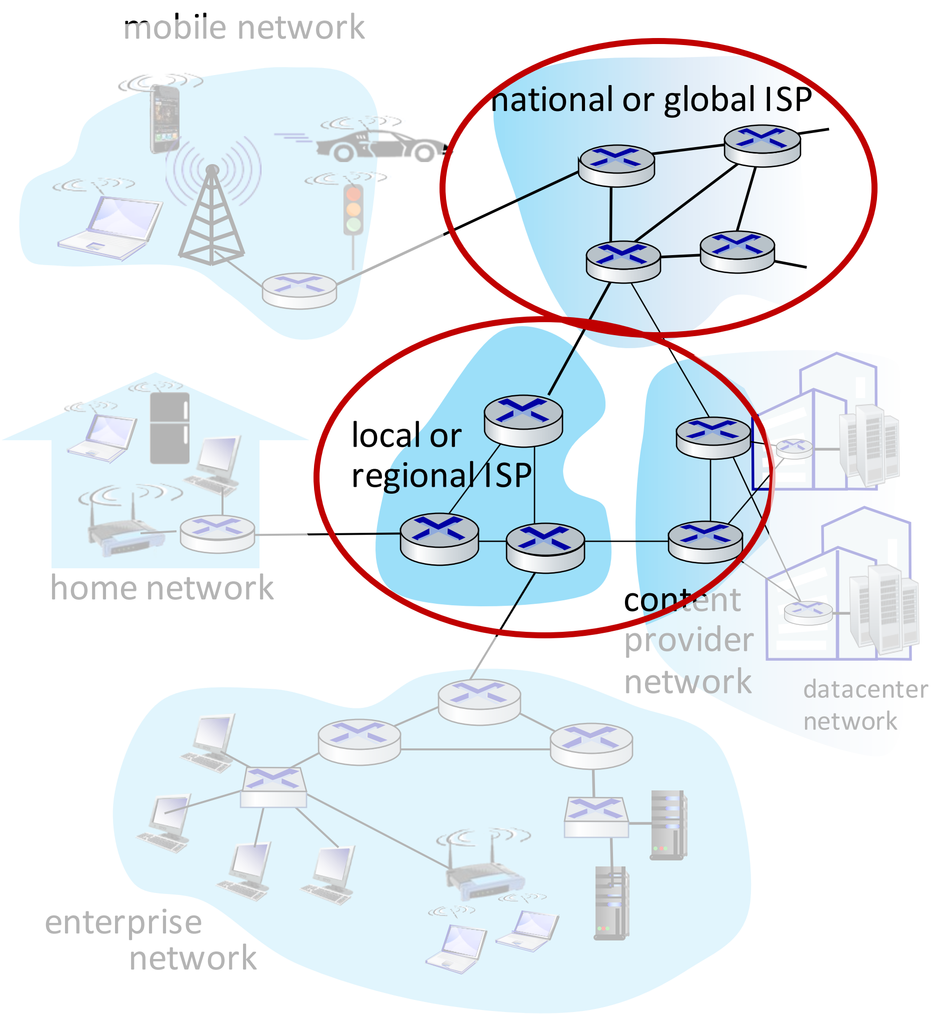
The network core

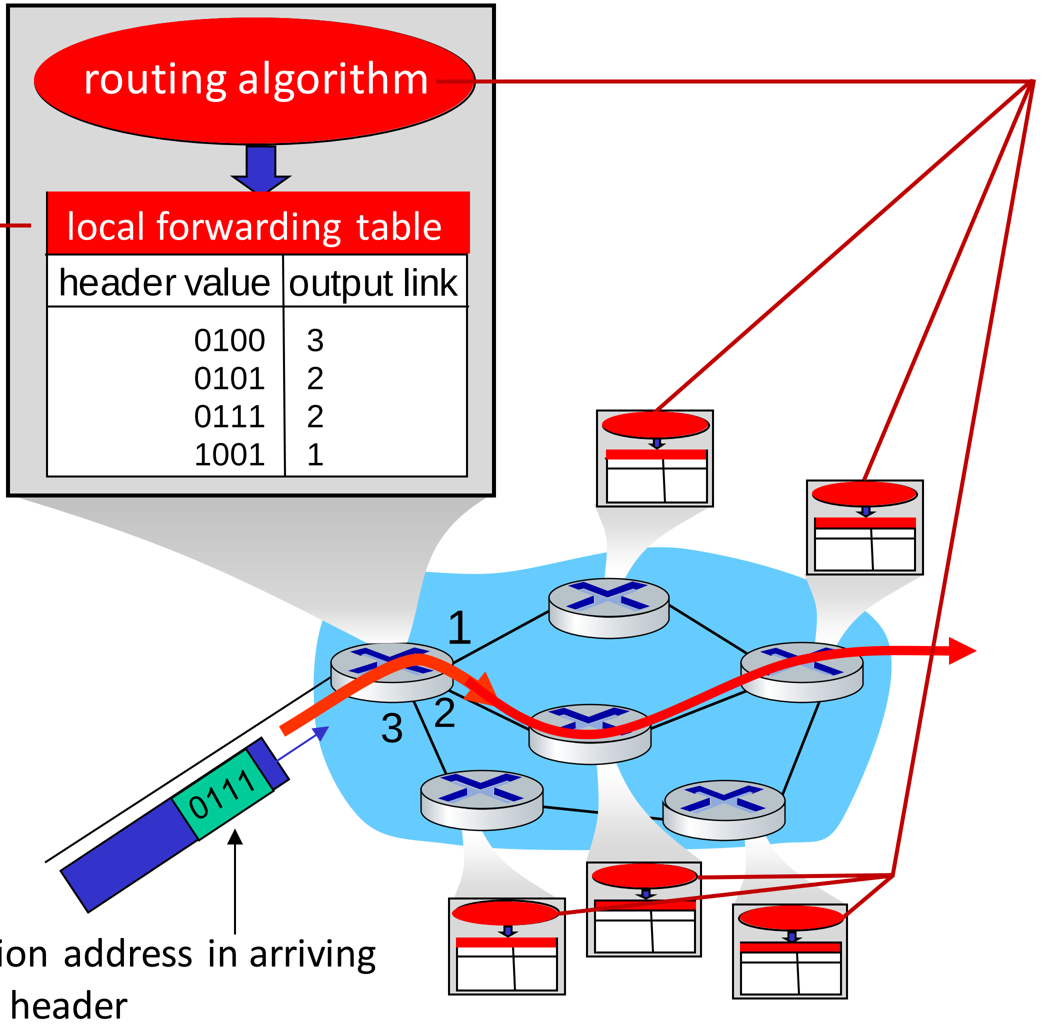
- mesh of interconnected routers
- packet-switching: hosts break application-layer messages into *packets*
  - network forwards packets from one router to the next, across links on path from source to destination



Two key network-core functions

Forwarding:

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



Routing:

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


45 h
3,053 miles
48 h
3,309 miles
routing
United States
San Jose
Northampton
Victoria
Seattle
WASHINGTON
MONTANA
NORTH DAKOTA
MINNESOTA
Portland
Minneapolis
SOUTH DAKOTA
WISCONSIN
OREGON
IDAHO
WYOMING
MICHIGAN
Toronto
Quebec City
Montreal
Ottawa
MAINE
VERMONT
NEW HAMPSHIRE
Detroit
Chicago
IOWA
NEVADA
UTAH
COLORADO
Kansas City
ILLINOIS
INDIANA
OHIO
PENNSYLVANIA
New York
Philadelphia
Indianapolis
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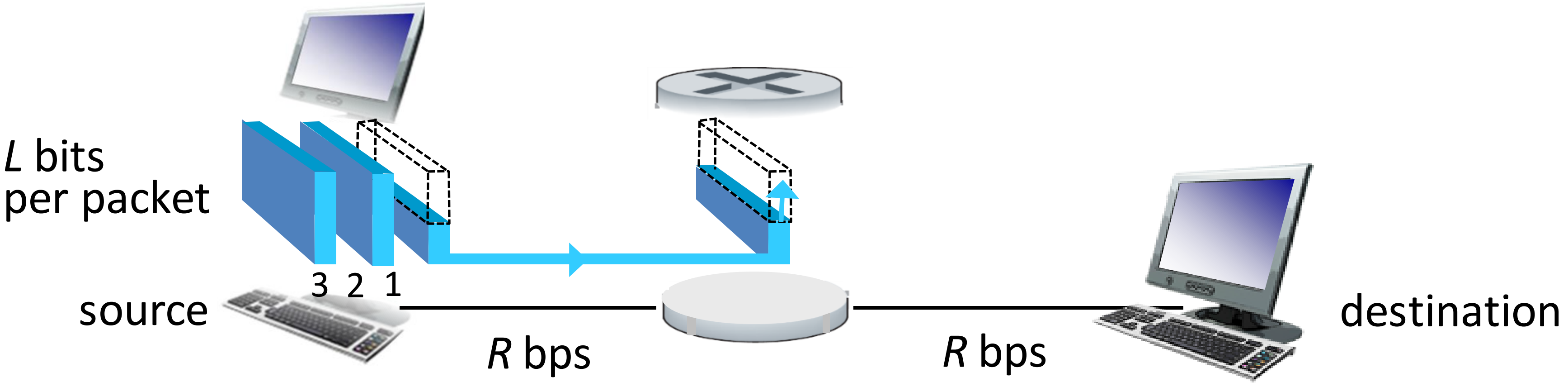
ARKANSAS
Los Angeles
ARIZONA
NEW MEXICO
Atlanta
SOUTH CAROLINA
MISSISSIPPI
ALABAMA
GEORGIA
San Diego
Phoenix
Dallas
Tucson
El Paso
TEXAS
BAJA CALIFORNIA
SONORA
Austin
Houston
LOUISIANA
New Orleans
Jacksonville
CHIHUAHUA
San Antonio
COAHUILA
Orlando
Tampa
FLORIDA


forwarding
forwarding
45 h
3,053 miles
48 h
3,309 miles
United States
San Jose
Northampton
Sacramento
Cleveland

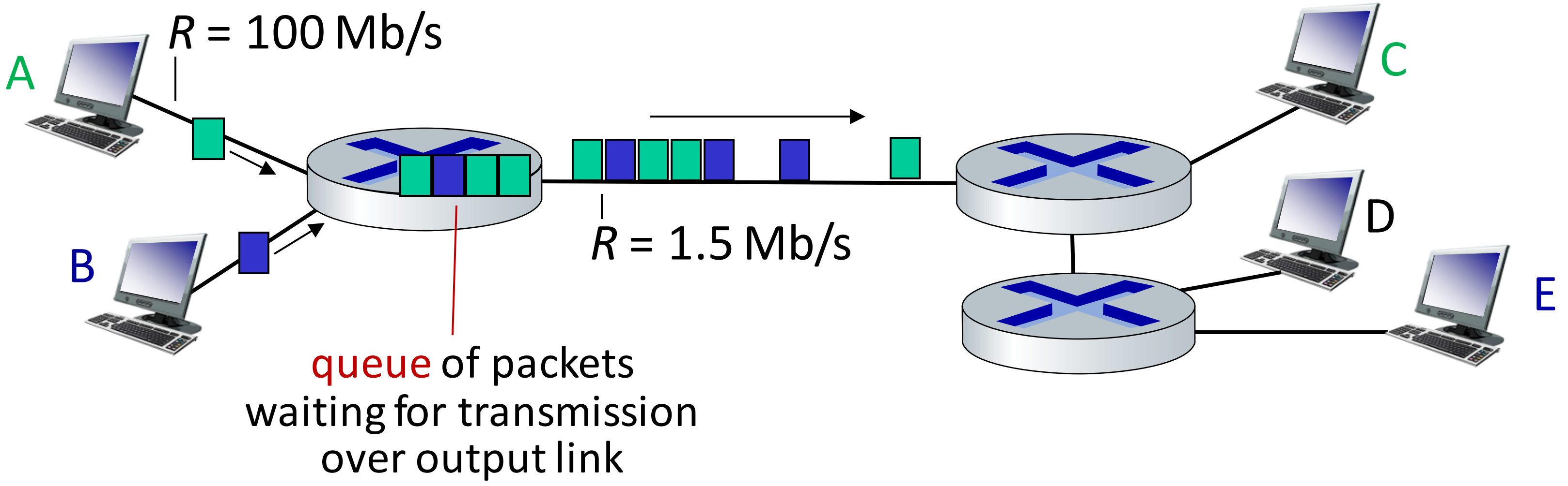
Packet-switching: store-and-forward



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

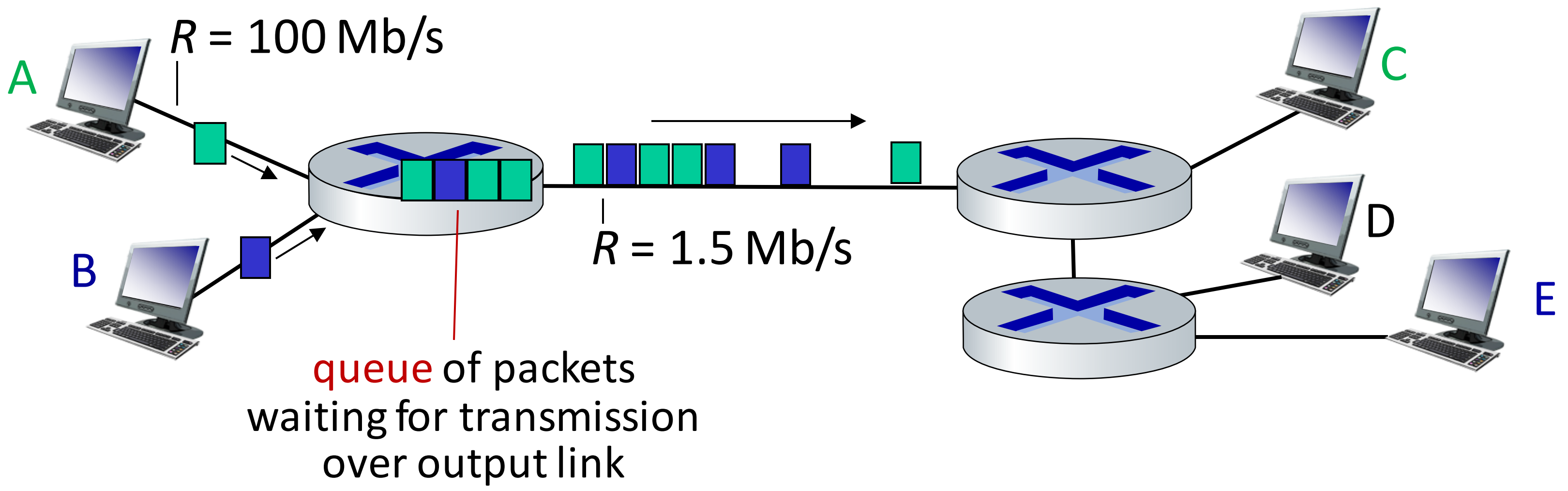
One-hop numerical example:
- L = 10 Kbits
- R = 100 Mbps
- one-hop transmission delay = 0.1 msec

Packet-switching: queueing



Queueing occurs when work arrives faster than it can be serviced:

Packet-switching: queueing



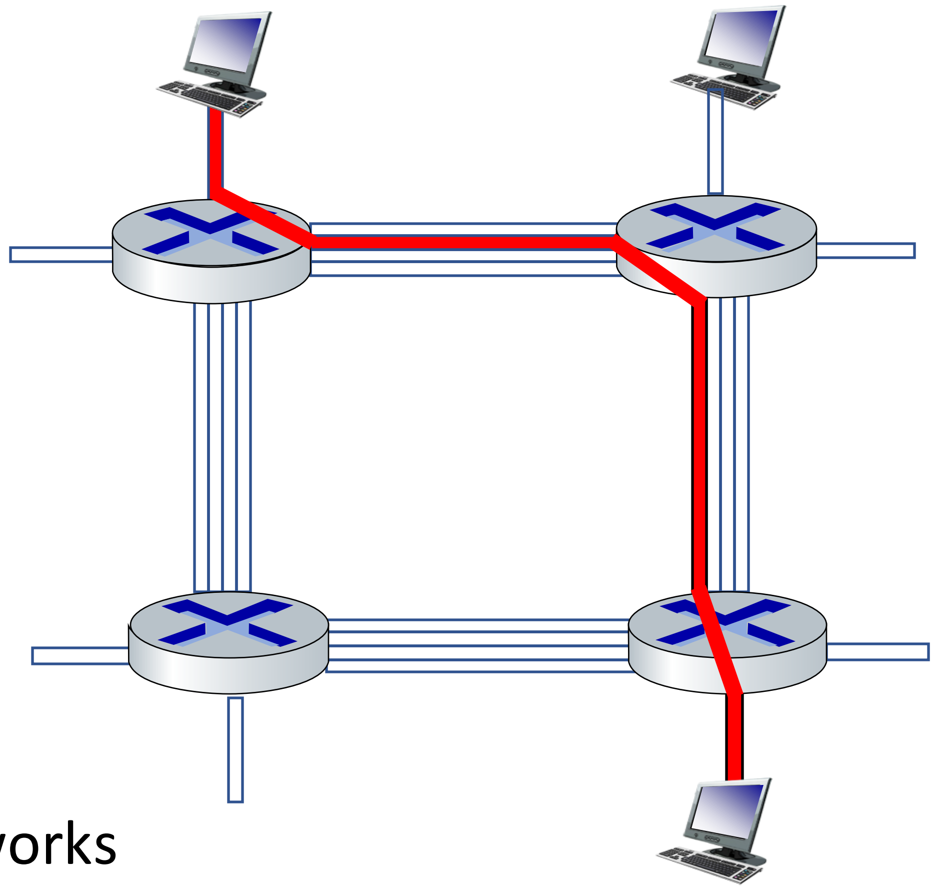
Packet queuing and loss: if arrival rate (in bps) to link exceeds transmission rate (bps) of link for some period of time:

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

Alternative to packet switching: circuit switching

end-end resources allocated to, reserved for “call” between source and destination

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

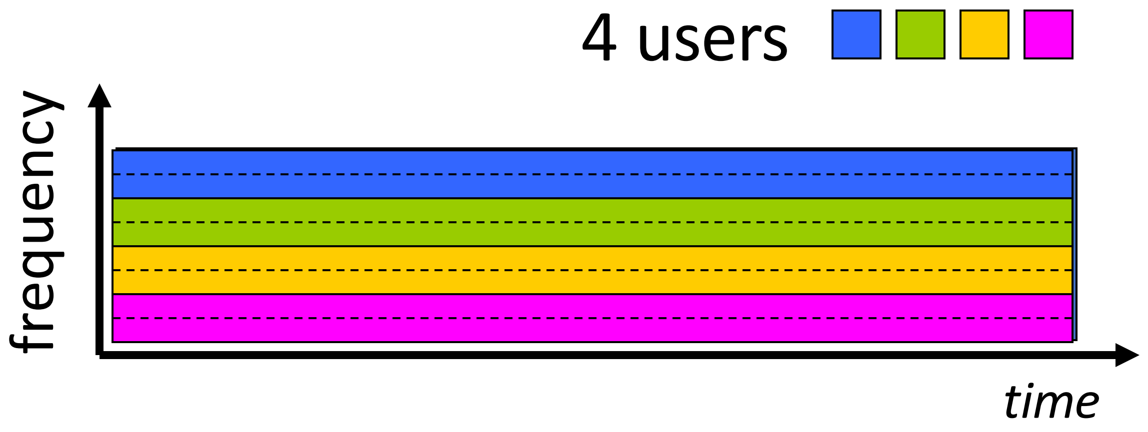


* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/interactive

Circuit switching: FDM and TDM

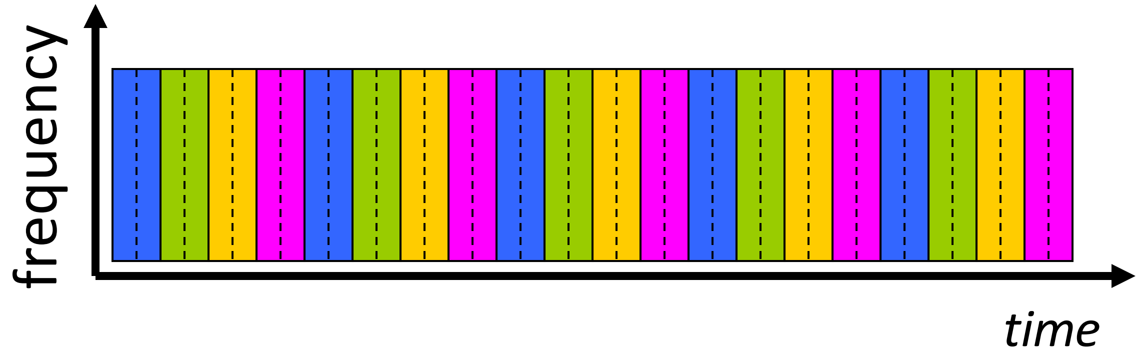
Frequency Division Multiplexing (FDM)

- optical, electromagnetic frequencies divided into (narrow) frequency bands
- each call allocated its own band, can transmit at max rate of that narrow band



Time Division Multiplexing (TDM)

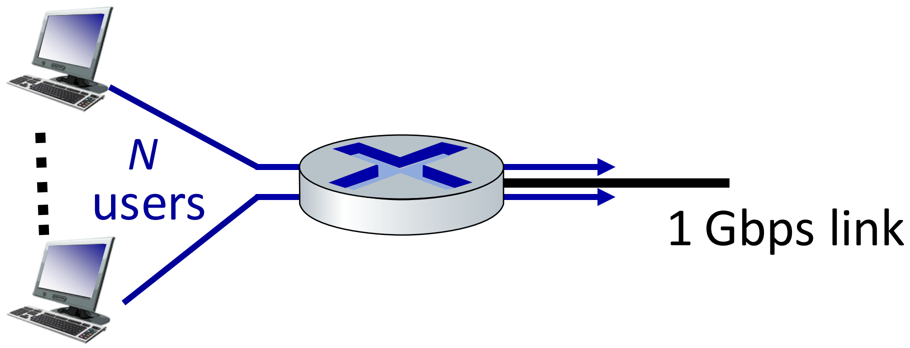
- time divided into slots
- each call allocated periodic slot(s), can transmit at maximum rate of (wider) frequency band (only) during its time slot(s)



Packet switching versus circuit switching

example:

- 1 Gb/s link
  - (1 Gb/s =1000Mbps)
- each user:
  - 100 Mb/s when "active"
  - active 10% of time



Q: how many users can use this network under circuit-switching and packet switching?

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

Q: how did we get value 0.0004?

A: HW problem (for those with course in probability only)

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

Packet switching versus circuit switching

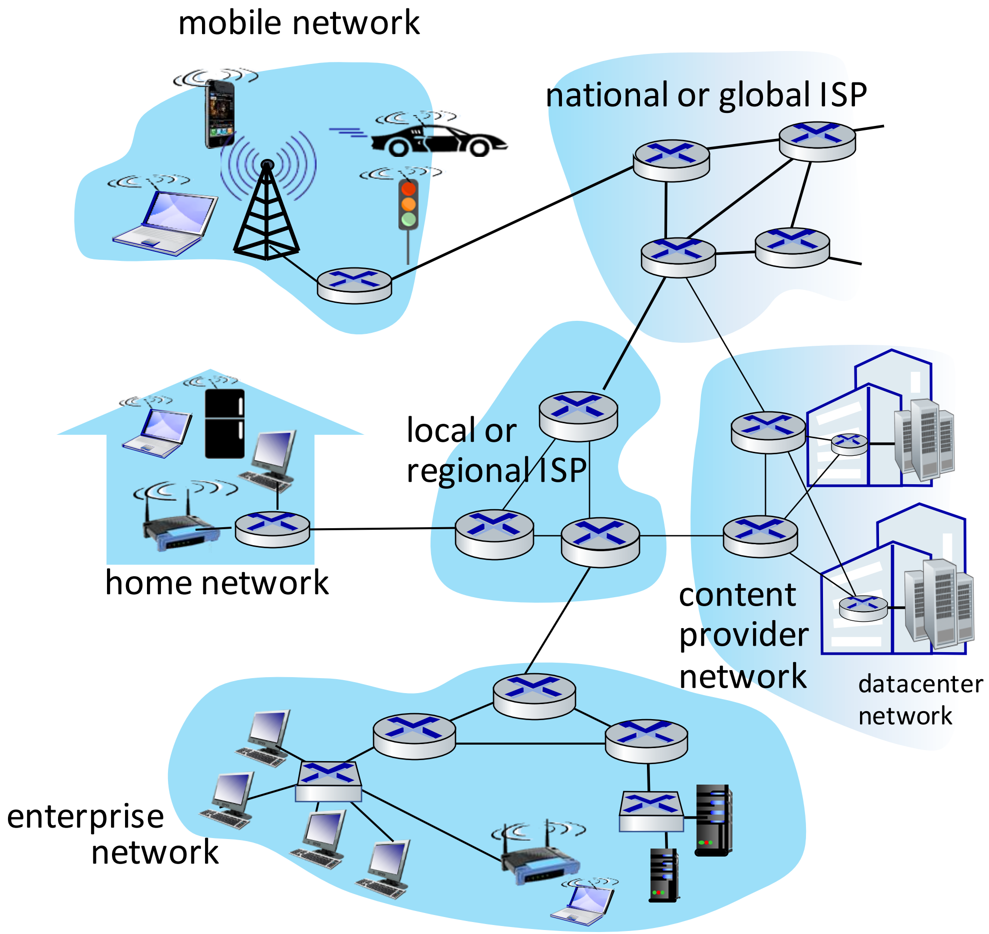
Is packet switching a "slam dunk winner"?

- great for "bursty" data – sometimes has data to send, but at other times not
  - resource sharing
  - simpler, no call setup
- excessive congestion possible: packet delay and loss due to buffer overflow
  - protocols needed for reliable data transfer, congestion control
- *Q:* How to provide circuit-like behavior with packet-switching?
  - "It's complicated." We'll study various techniques that try to make packet switching as "circuit-like" as possible.

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

Internet structure: a "network of networks"

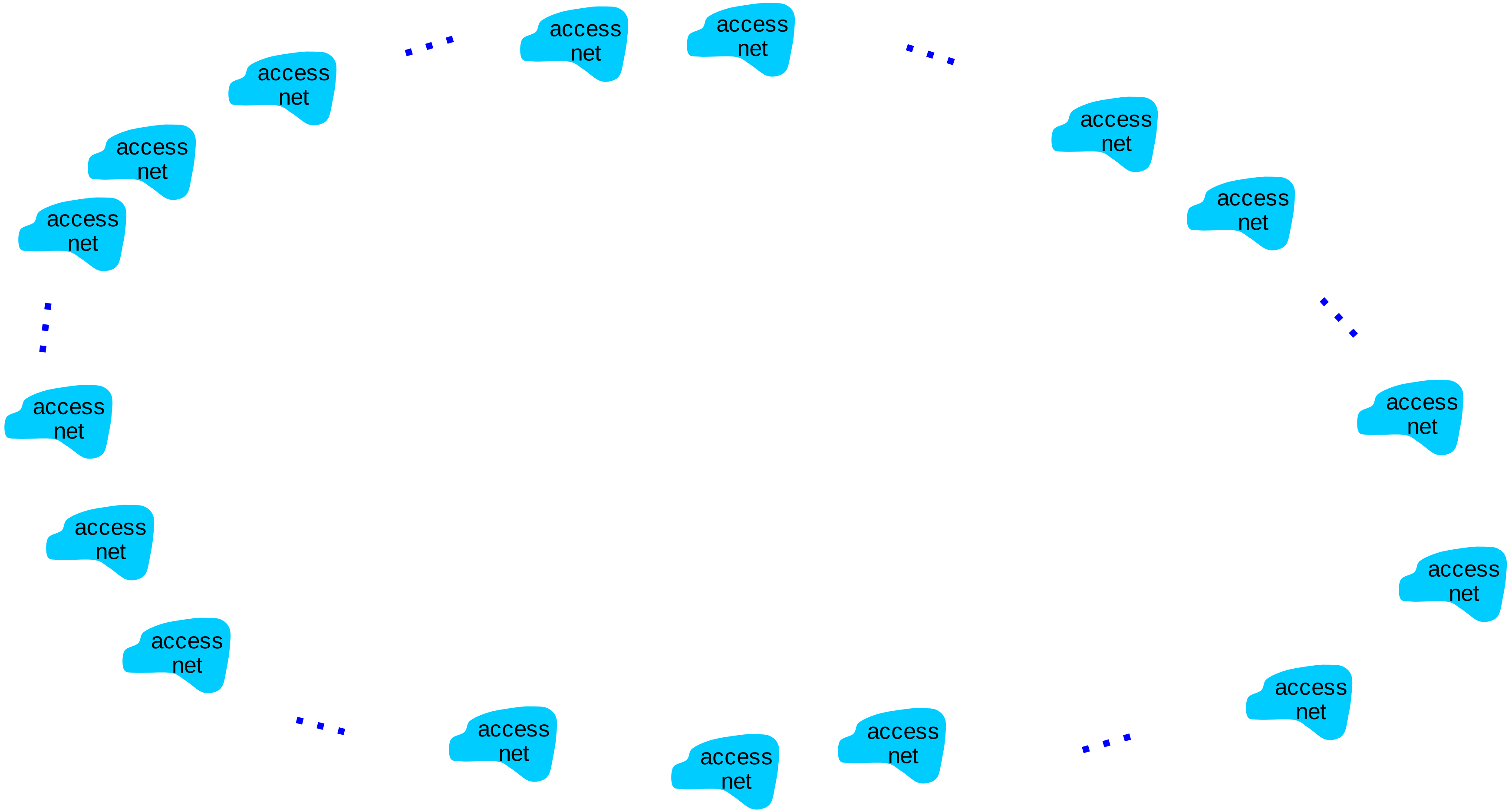
- hosts connect to Internet via access Internet Service Providers (ISPs)
- access ISPs in turn must be interconnected
  - so that *any* two hosts *(anywhere!)* can send packets to each other
- resulting network of networks is very complex
  - evolution driven by economics, national policies



Let's take a stepwise approach to describe current Internet structure

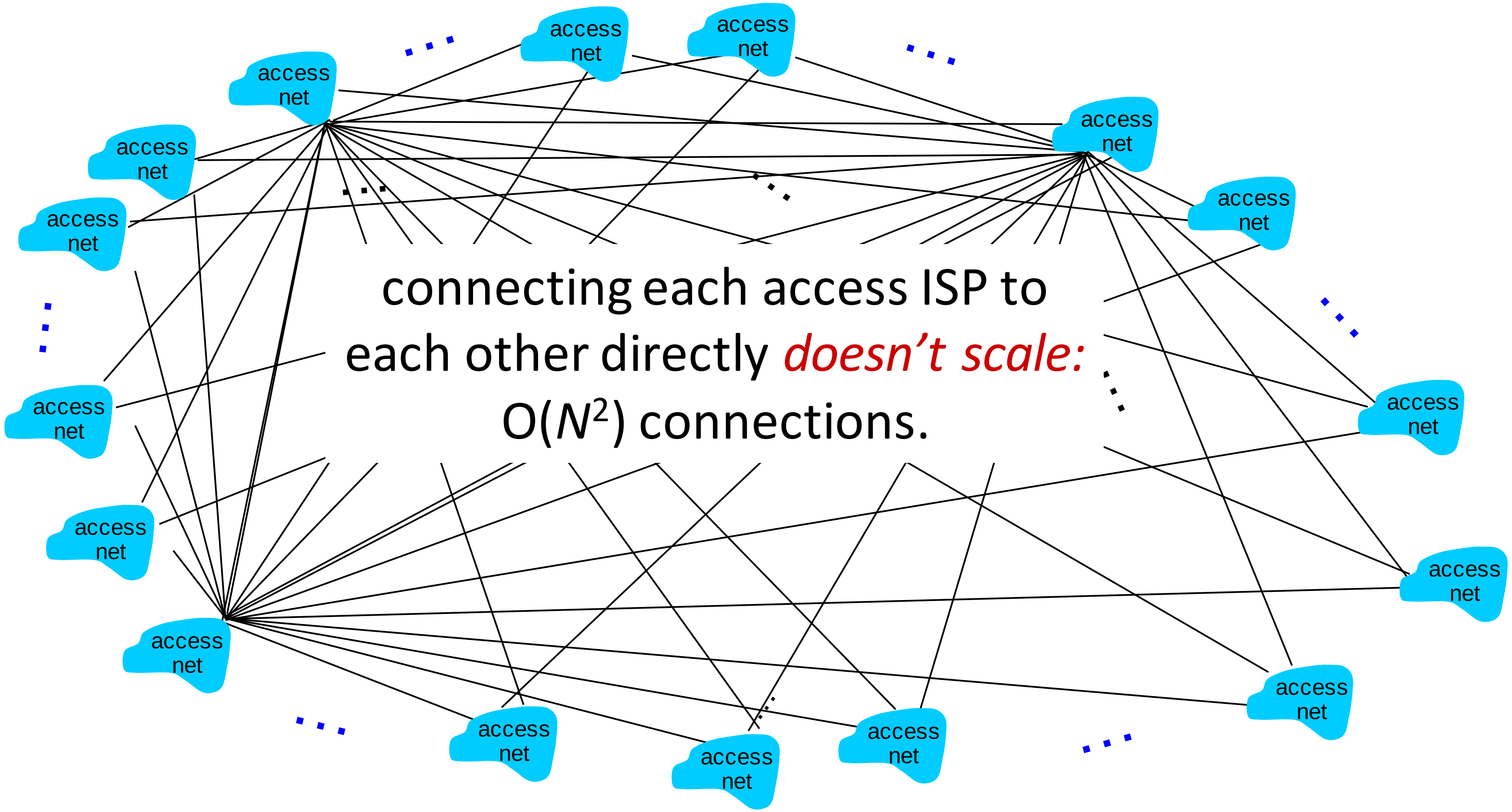
Internet structure: a "network of networks"

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



Internet structure: a "network of networks"

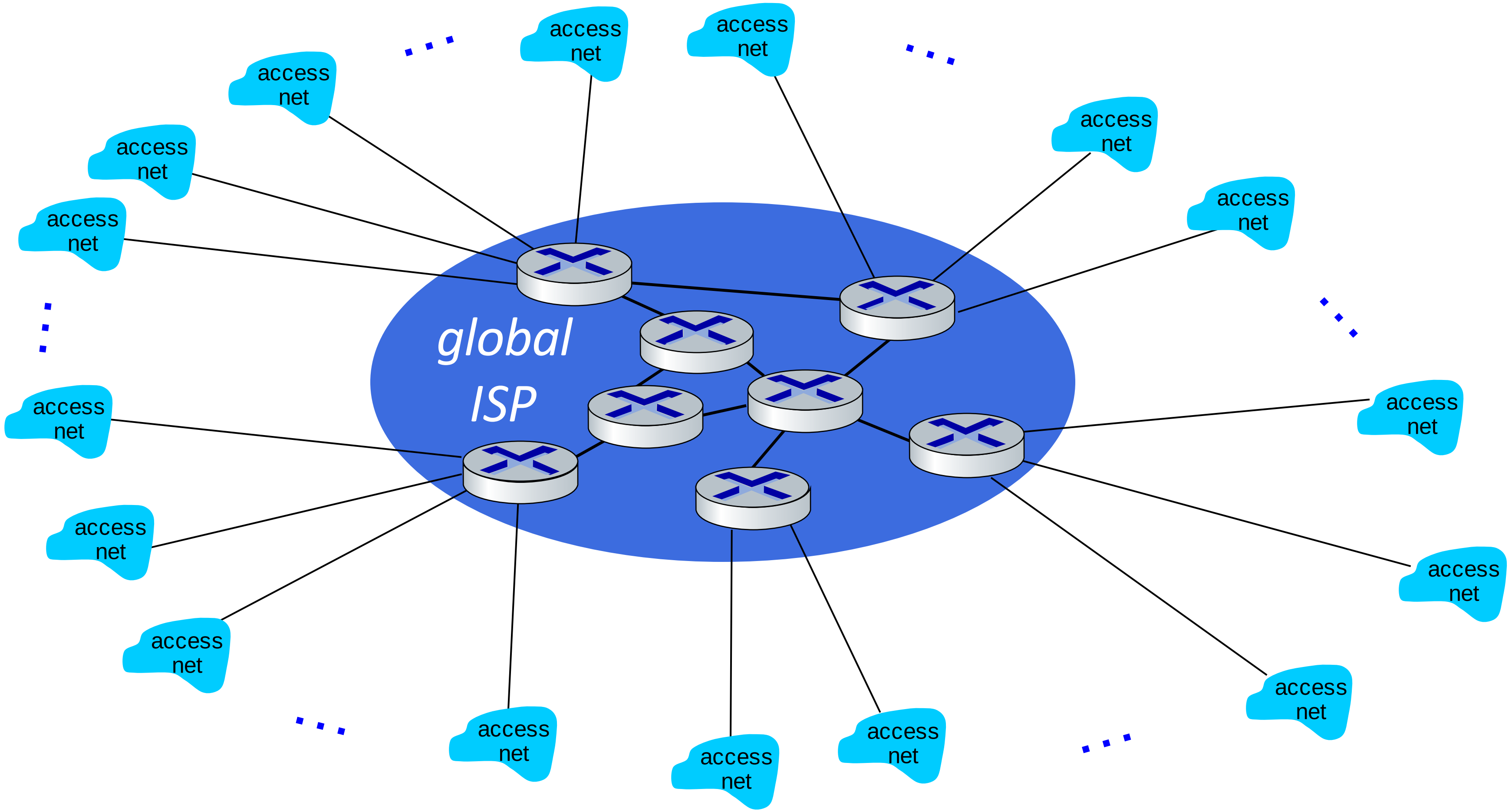
Question: given *millions* of access ISPs, how to connect them together?



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

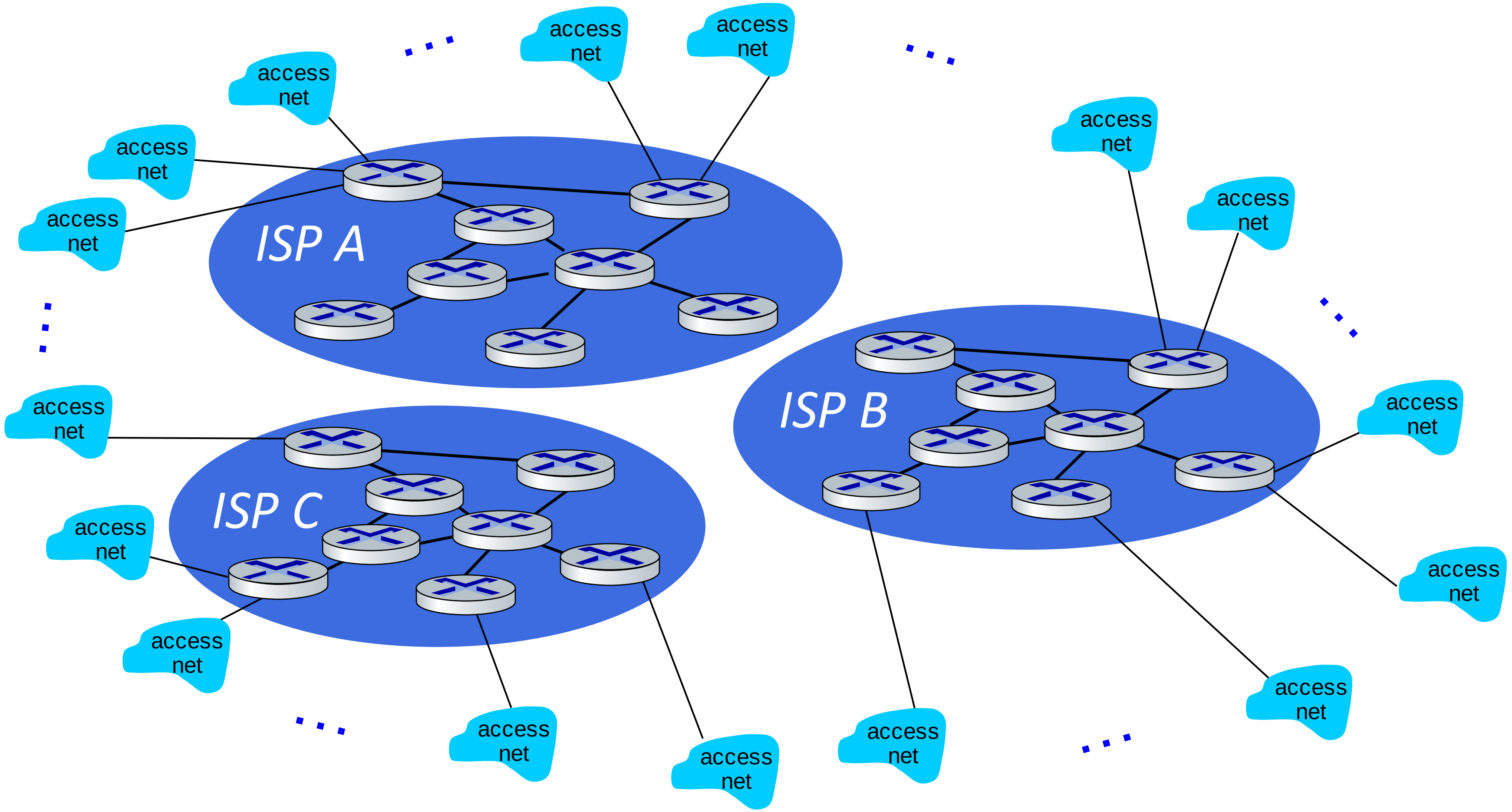
Internet structure: a "network of networks"

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



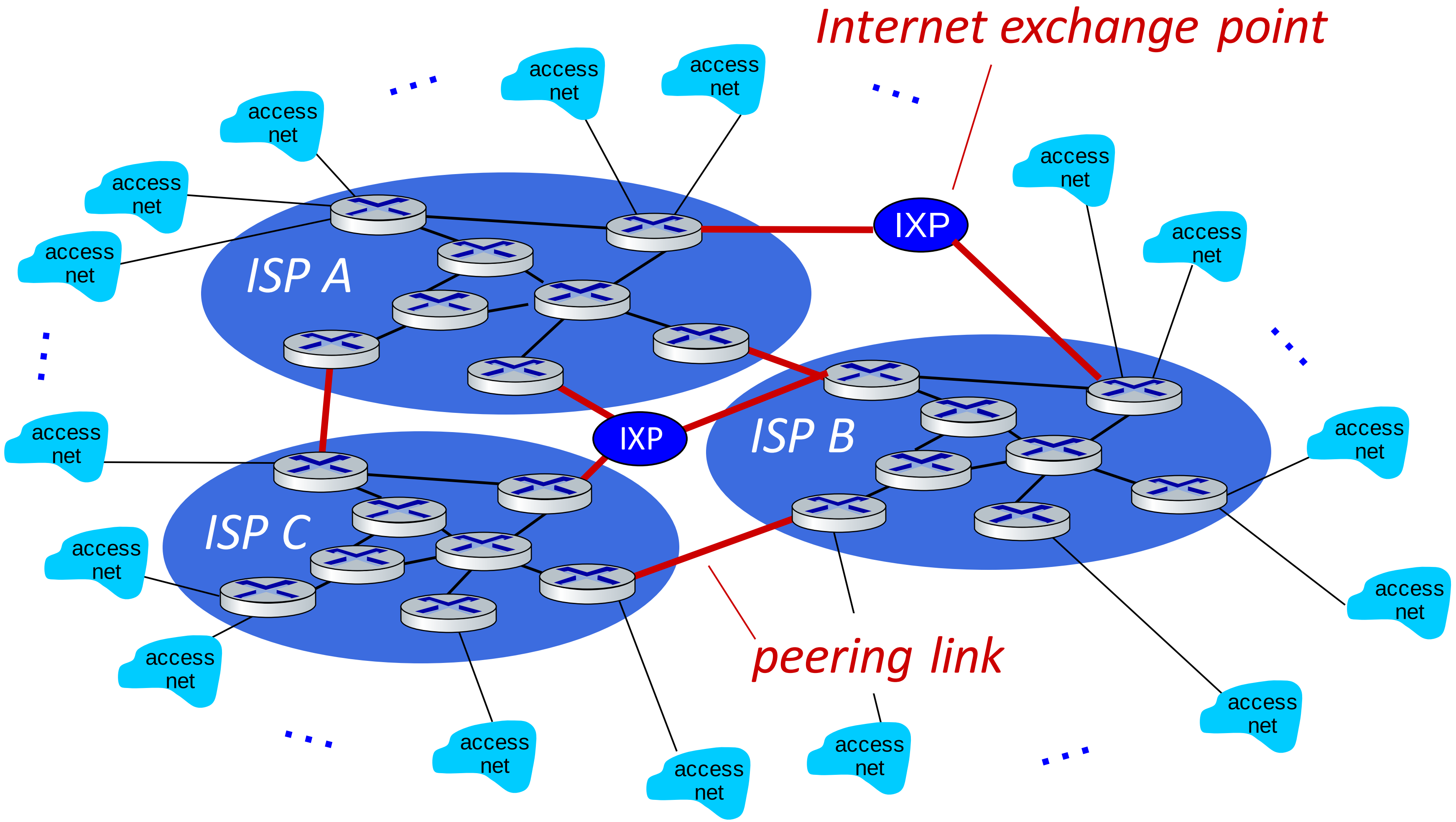
Internet structure: a "network of networks"

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



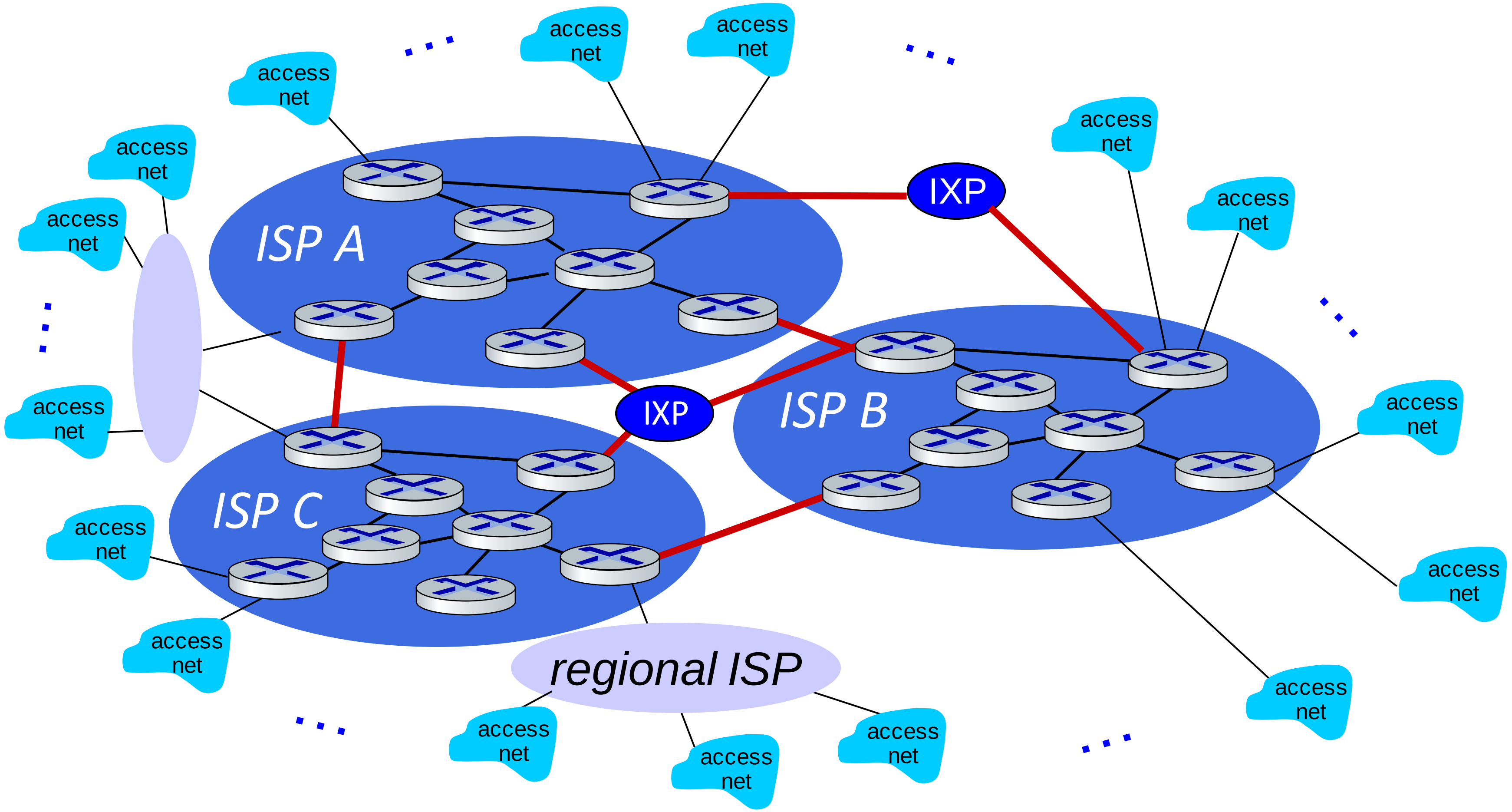
Internet structure: a "network of networks"

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



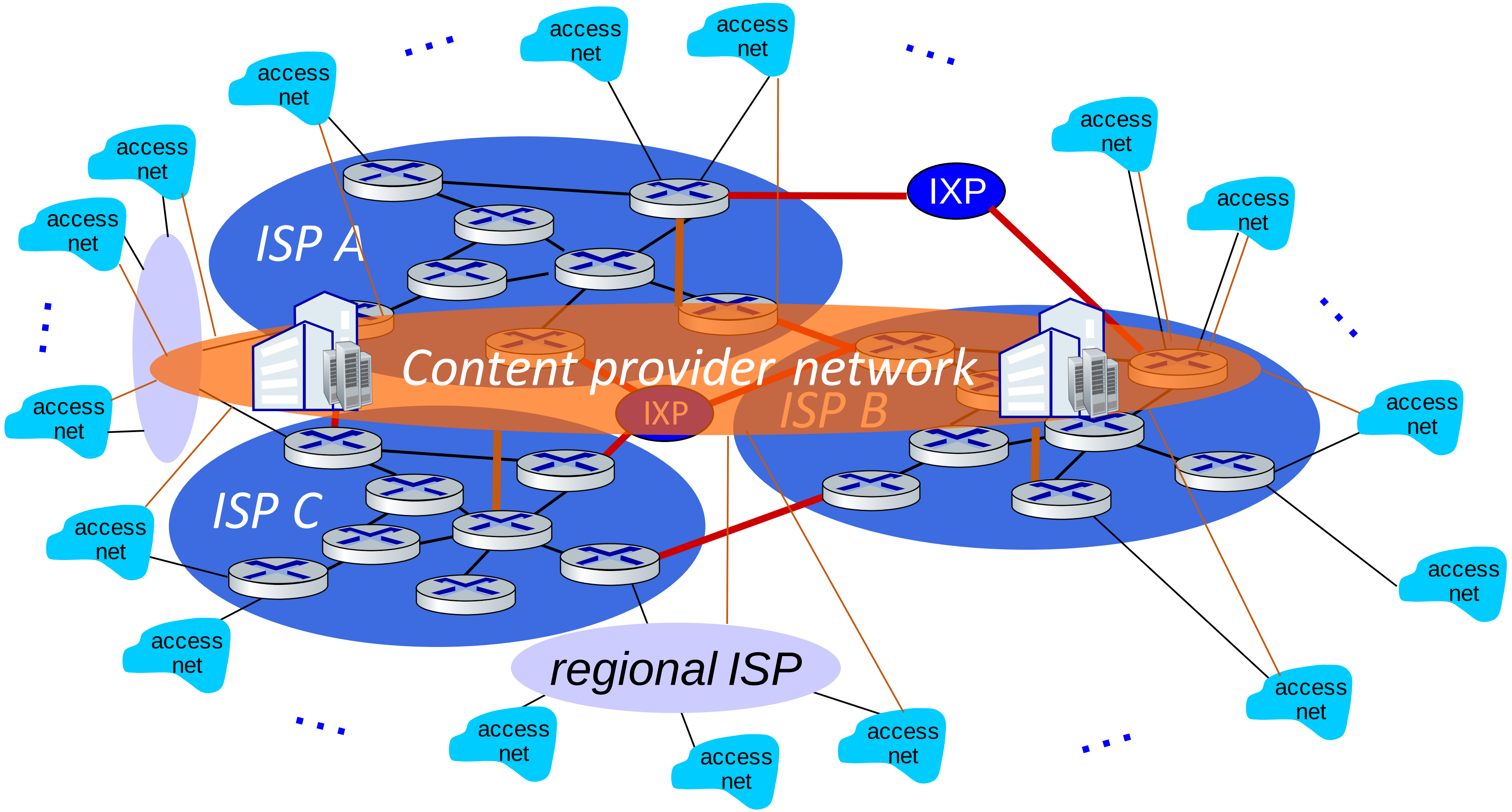
Internet structure: a “network of networks”

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

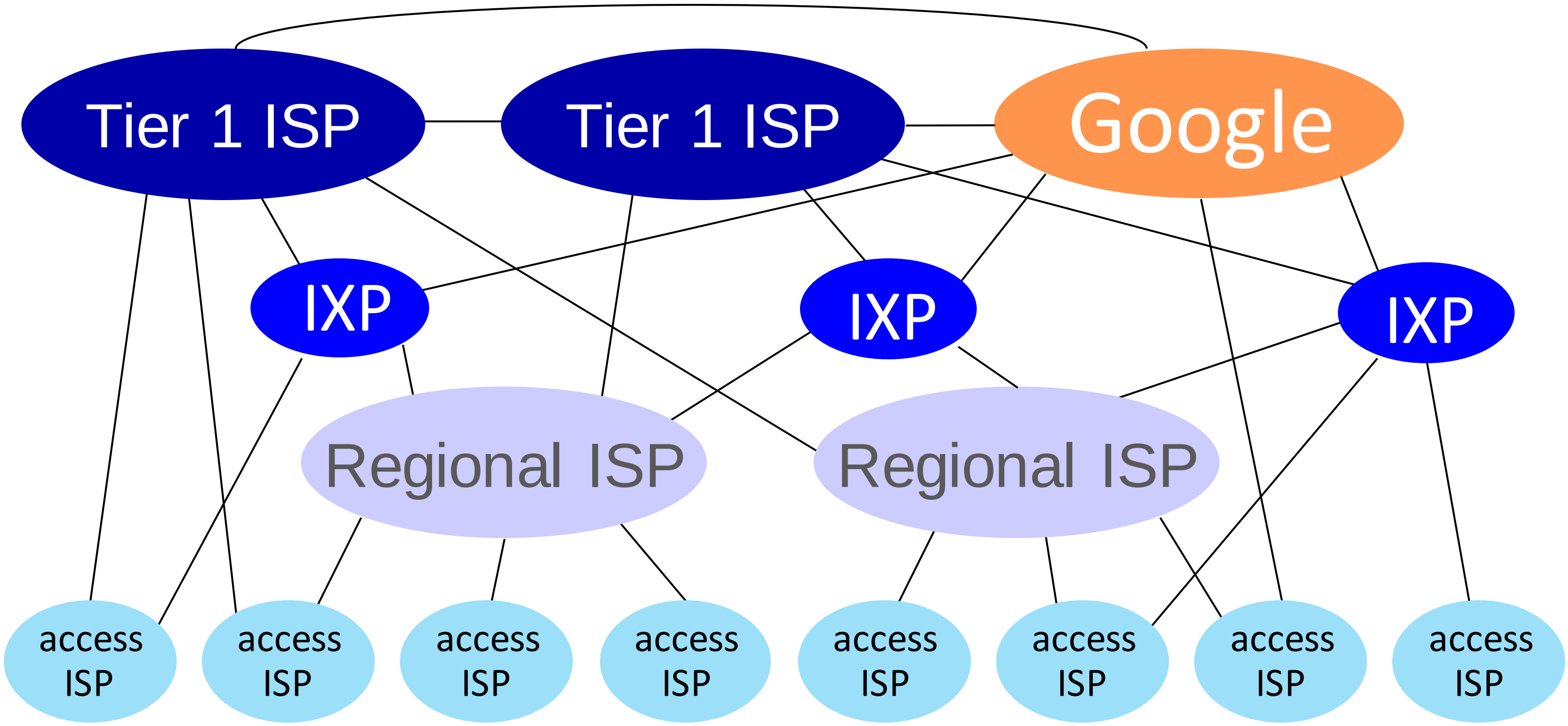


Internet structure: a "network of networks"

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



Internet structure: a "network of networks"

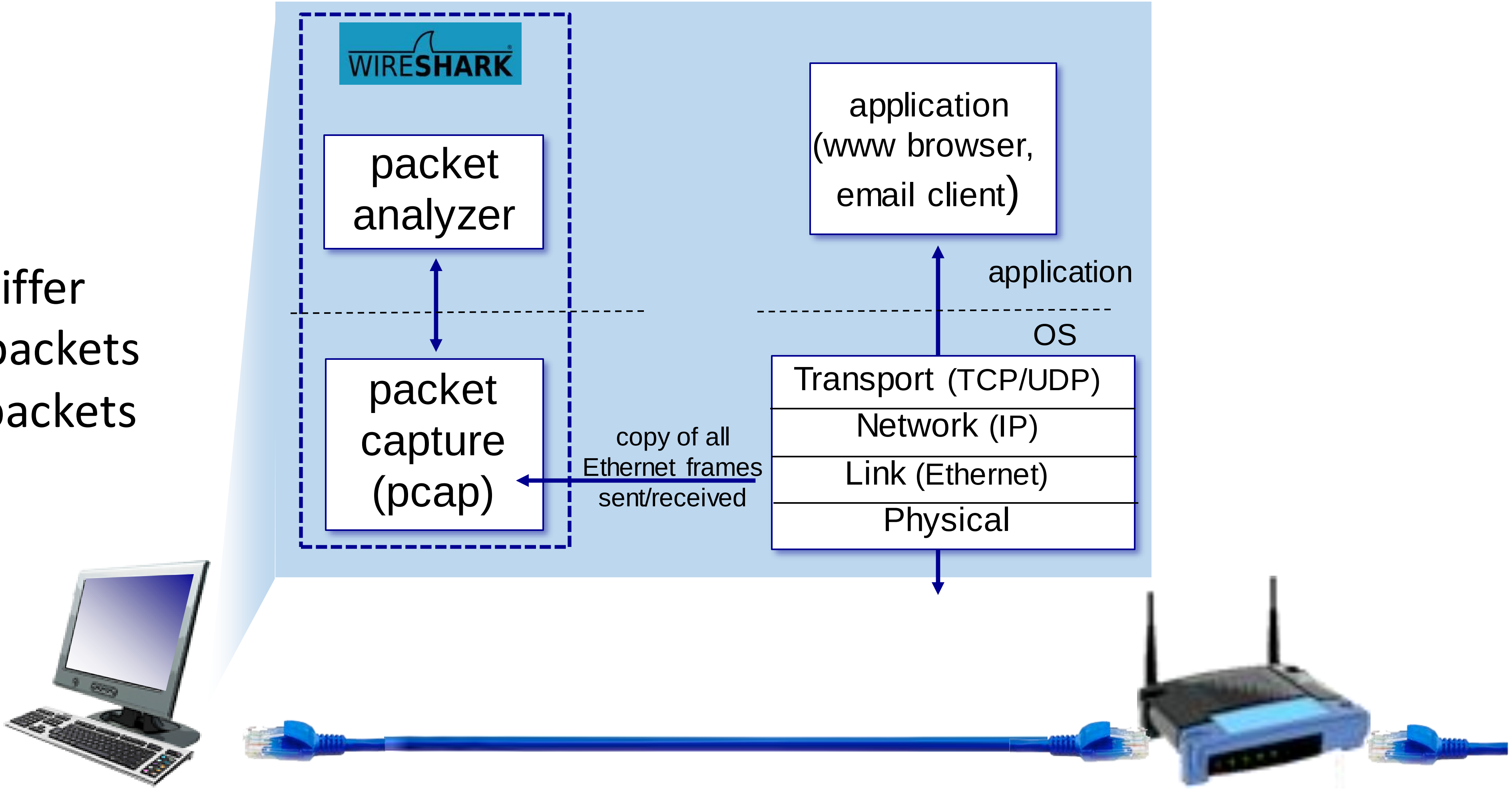


At "center": small # of well-connected large networks

- "tier-1" commercial ISPs (e.g., Level 3, Sprint, AT&T, NTT), national & international coverage
- content provider networks (e.g., Google, Facebook): private network that connects its data centers to Internet, often bypassing tier-1, regional ISPs

Wireshark: Labs

- Packet sniffer
- Capture packets
- Analyse packets



See you in lecture 2

Chapter 1: roadmap

- What *is* the Internet?
- What *is* a protocol?
- Network edge: hosts, access network, physical media
- Network core: packet/circuit switching, internet structure
- Performance: loss, delay, throughput
- Security
- Protocol layers, service models
- History