



Computer Networks

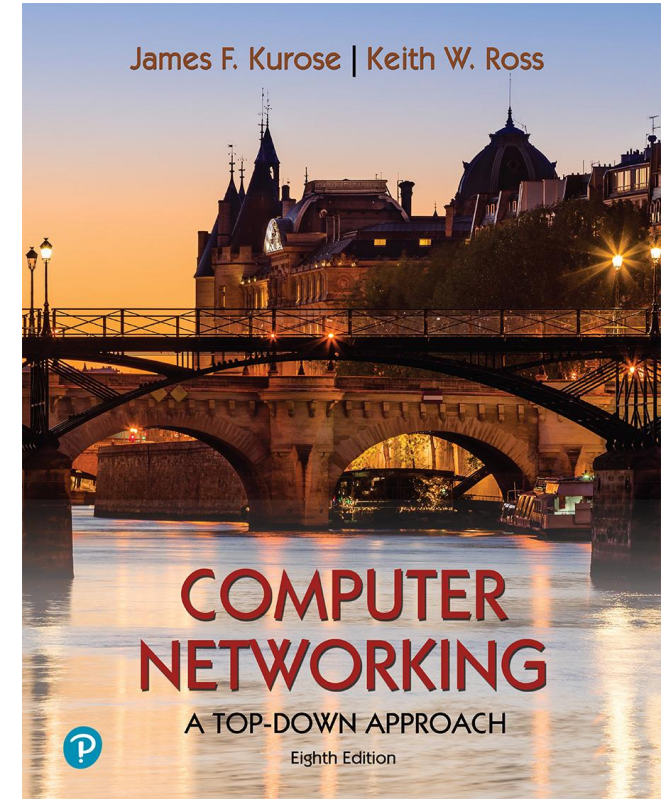
Amir Mahdi Sadeghzadeh, Ph.D.



Chapter 1

Introduction

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Computer Networking: A Top-Down Approach

8th edition

Jim Kurose, Keith Ross
Pearson, 2020

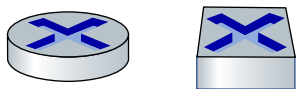


The Internet: a “nuts and bolts” view



Billions of connected computing *devices*:

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



Packet switches: forward packets (chunks of data)

- *routers, switches*

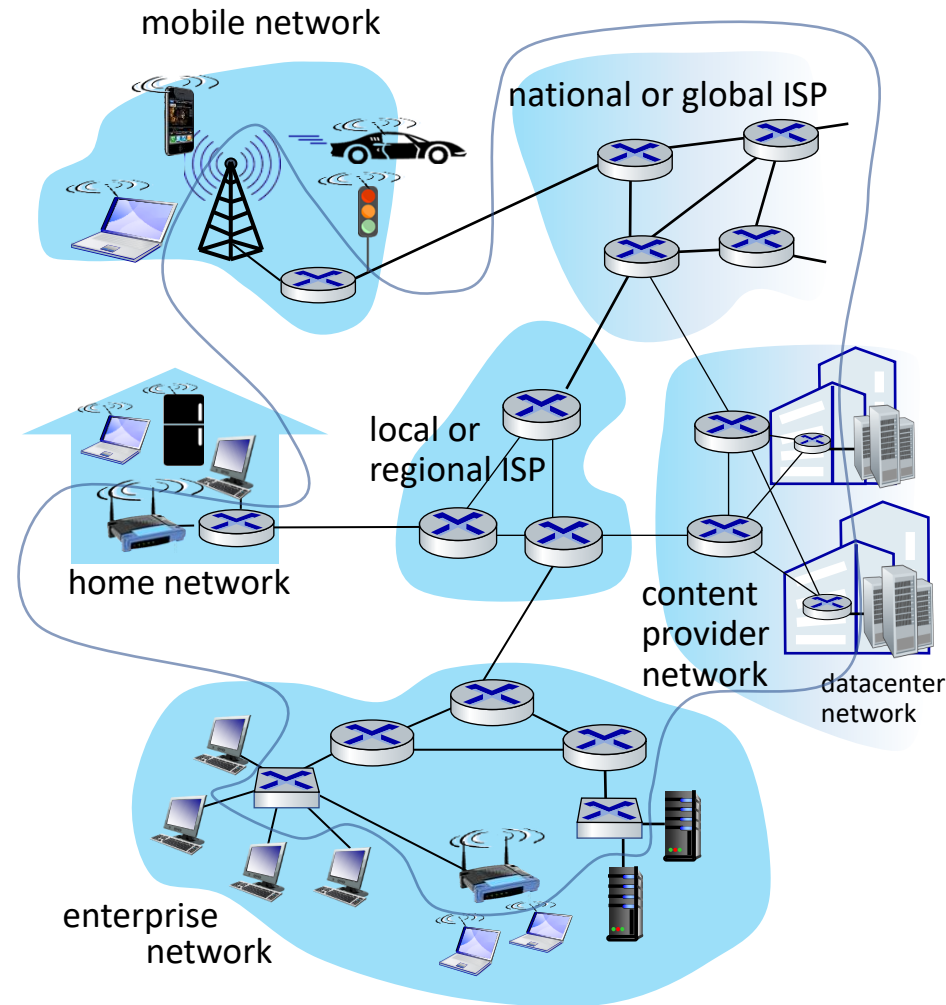


Communication links

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

Networks

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





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

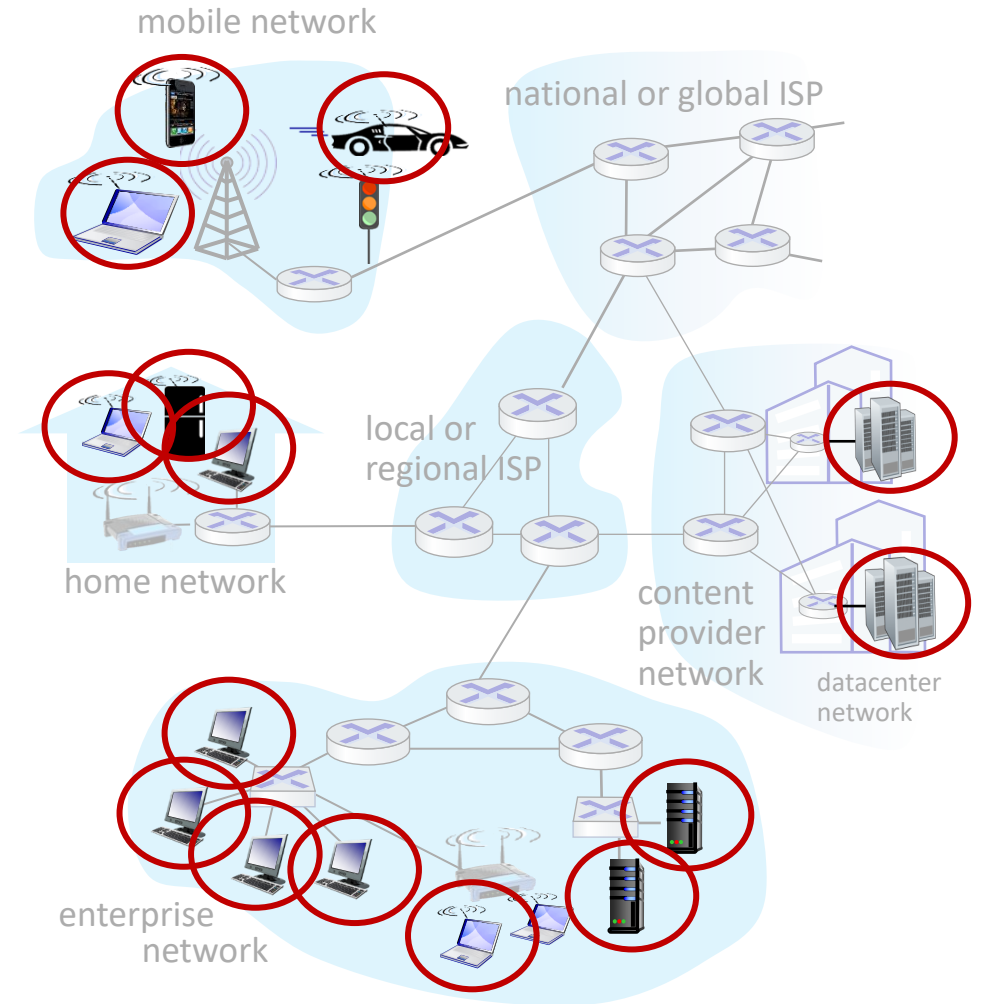




A closer look at Internet structure

Network edge:

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





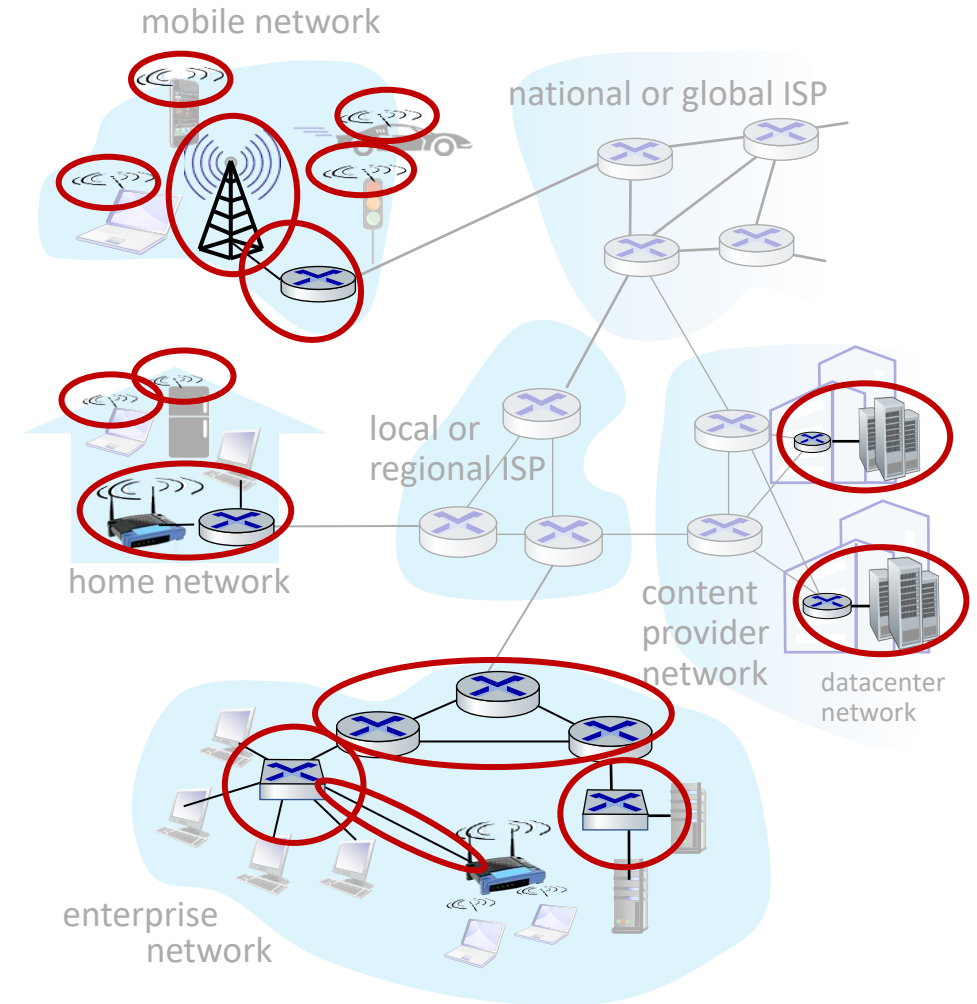
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Network edge:

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Access networks, physical media:

- wired, wireless communication links





A closer look at Internet structure

Network edge:

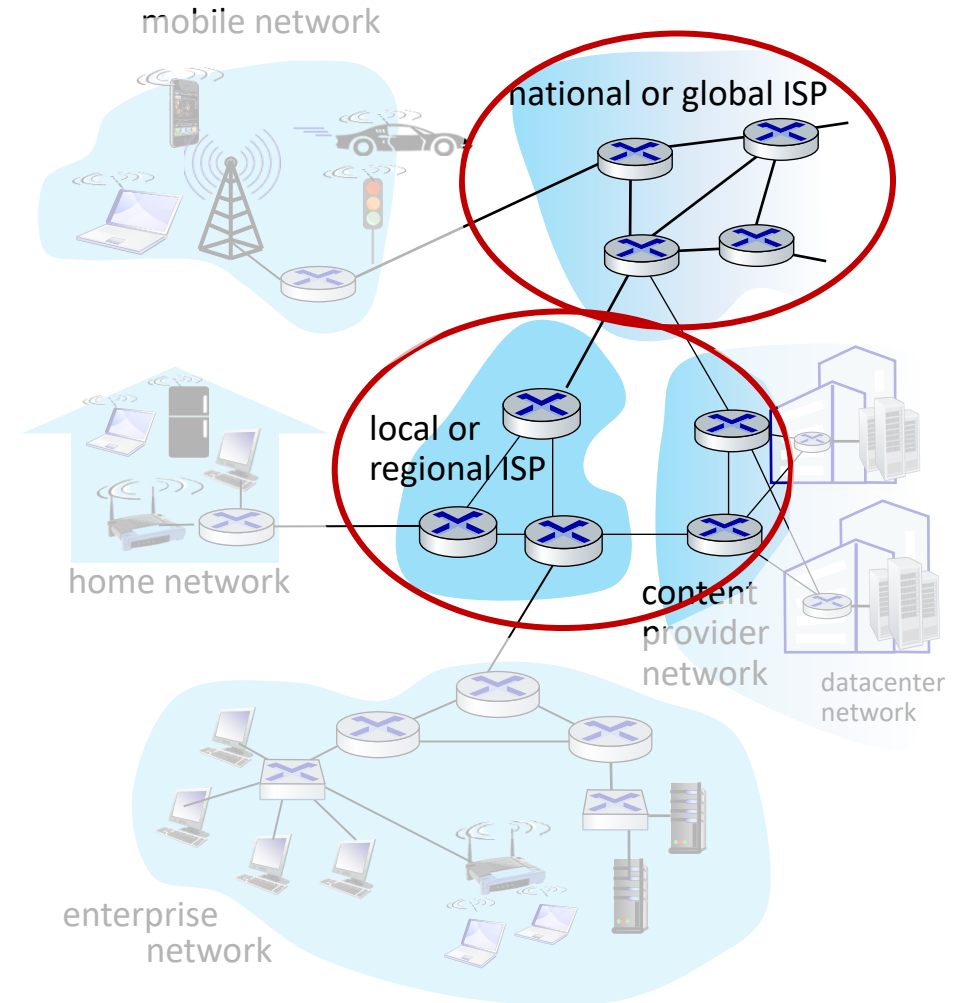
- hosts: clients and servers
- servers often in data centers

Access networks, physical media:

- wired, wireless communication links

Network core:

- interconnected routers
- network of networks

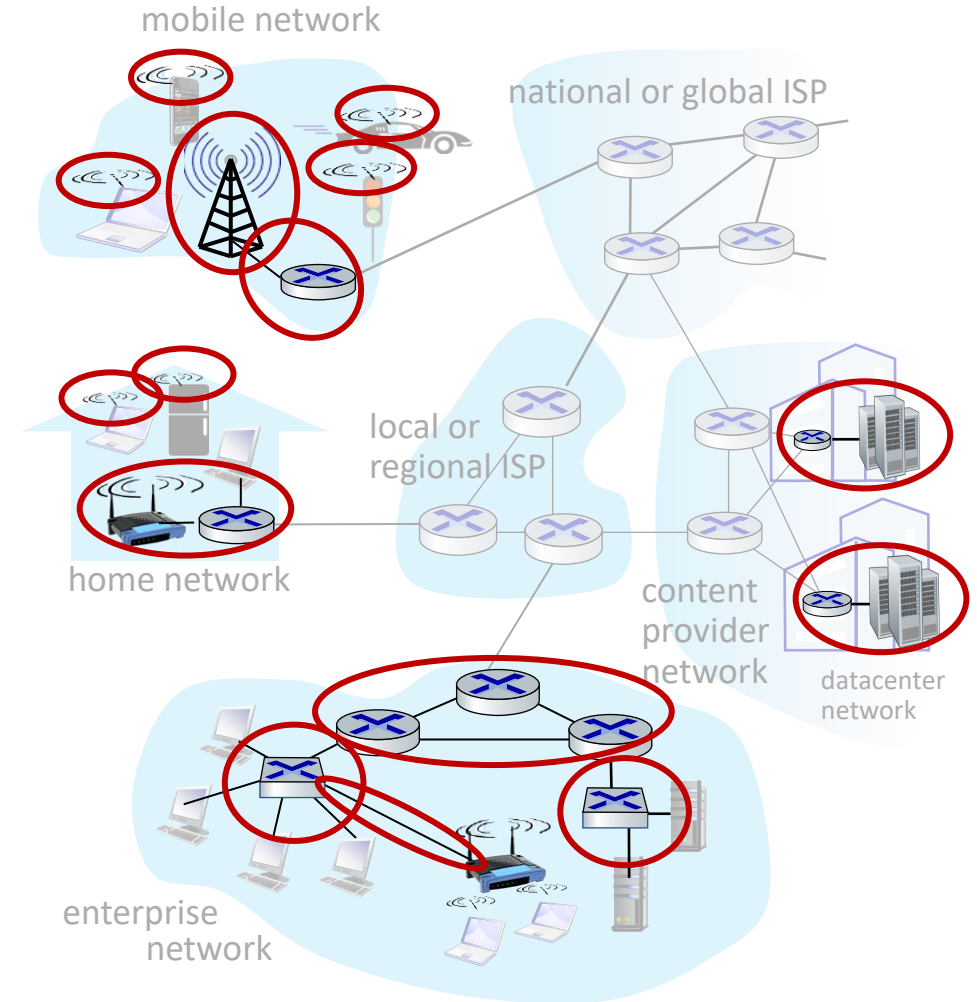




Access networks and physical media

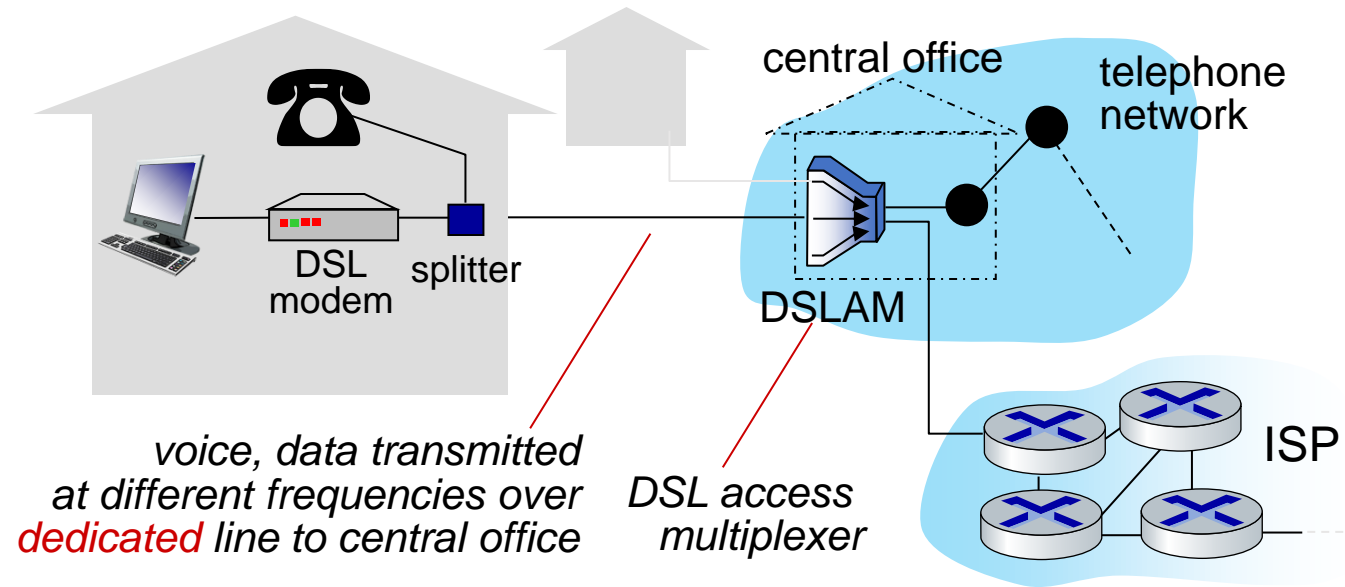
Q: How to connect end systems to edge router?

- residential access nets
- institutional access networks (school, company)
- mobile access networks (WiFi, 4G/5G)





Access networks: digital subscriber line (DSL)

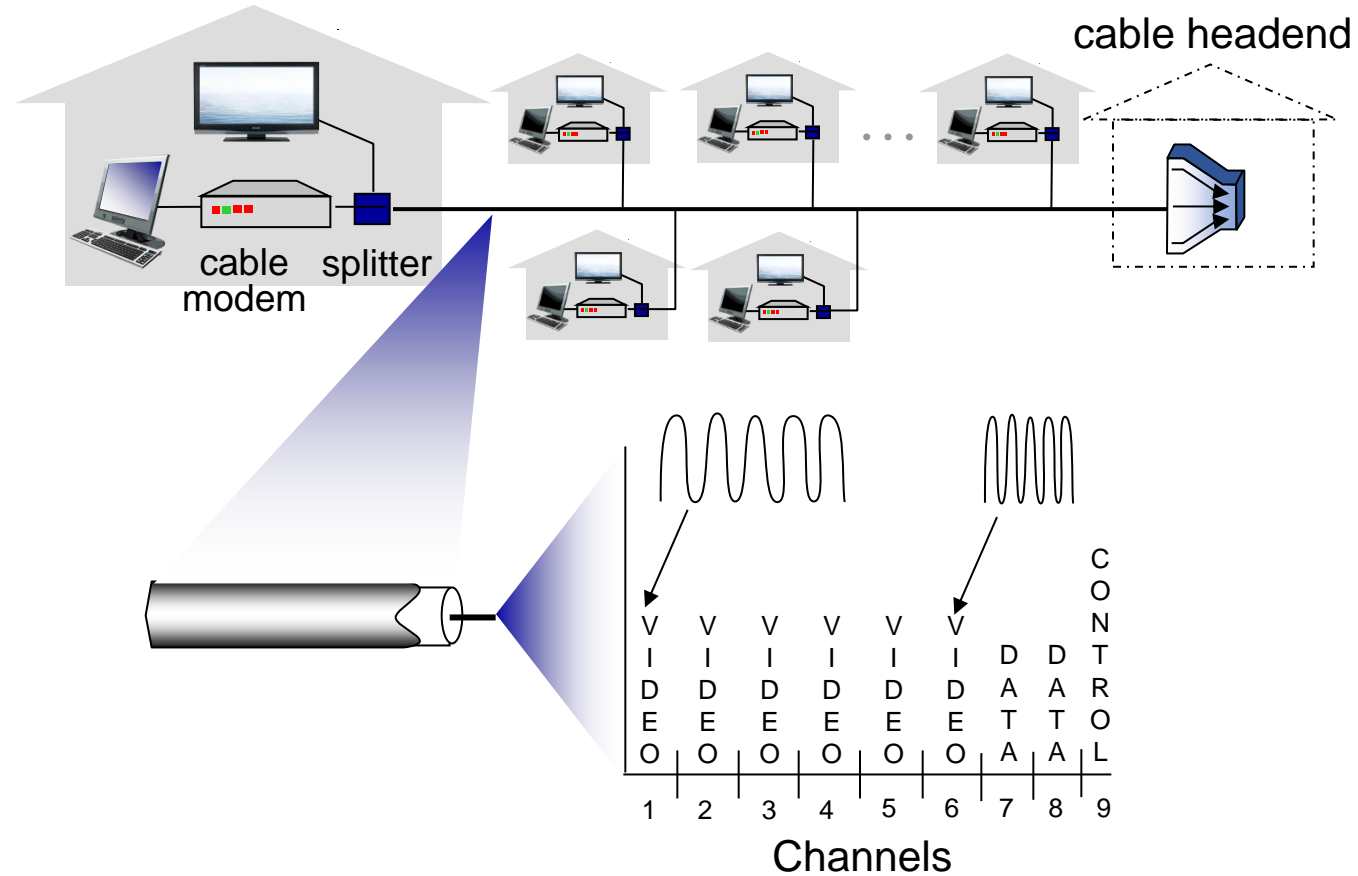


- use *existing* telephone line to central office DSLAM
 - data over DSL phone line goes to Internet
 - voice over DSL phone line goes to telephone net
- 24-52 Mbps dedicated downstream transmission rate
- 3.5-16 Mbps dedicated upstream transmission rate

- Audio frequency range of 0.3KHz to 3.4KHz
- The upper limit can be tens of MHz
- DSL takes advantage of this unused bandwidth
- Usable channels is then split into upstream and downstream traffic



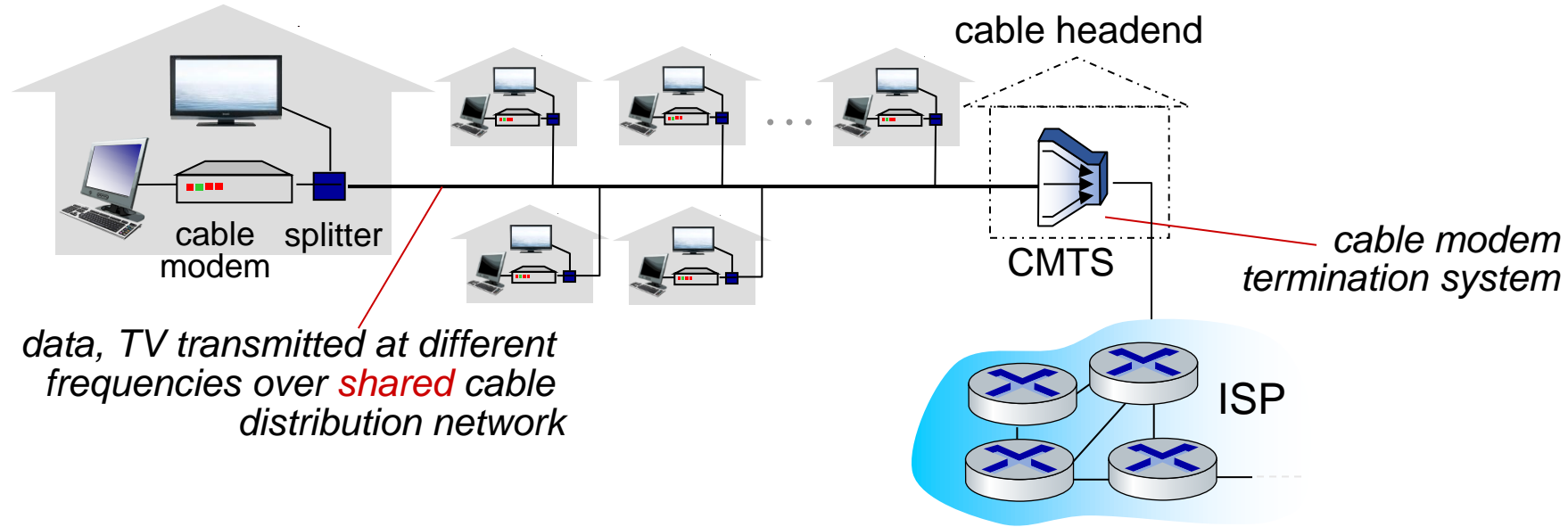
Access networks: cable-based access



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



Access networks: cable-based access



■ HFC: hybrid fiber coax

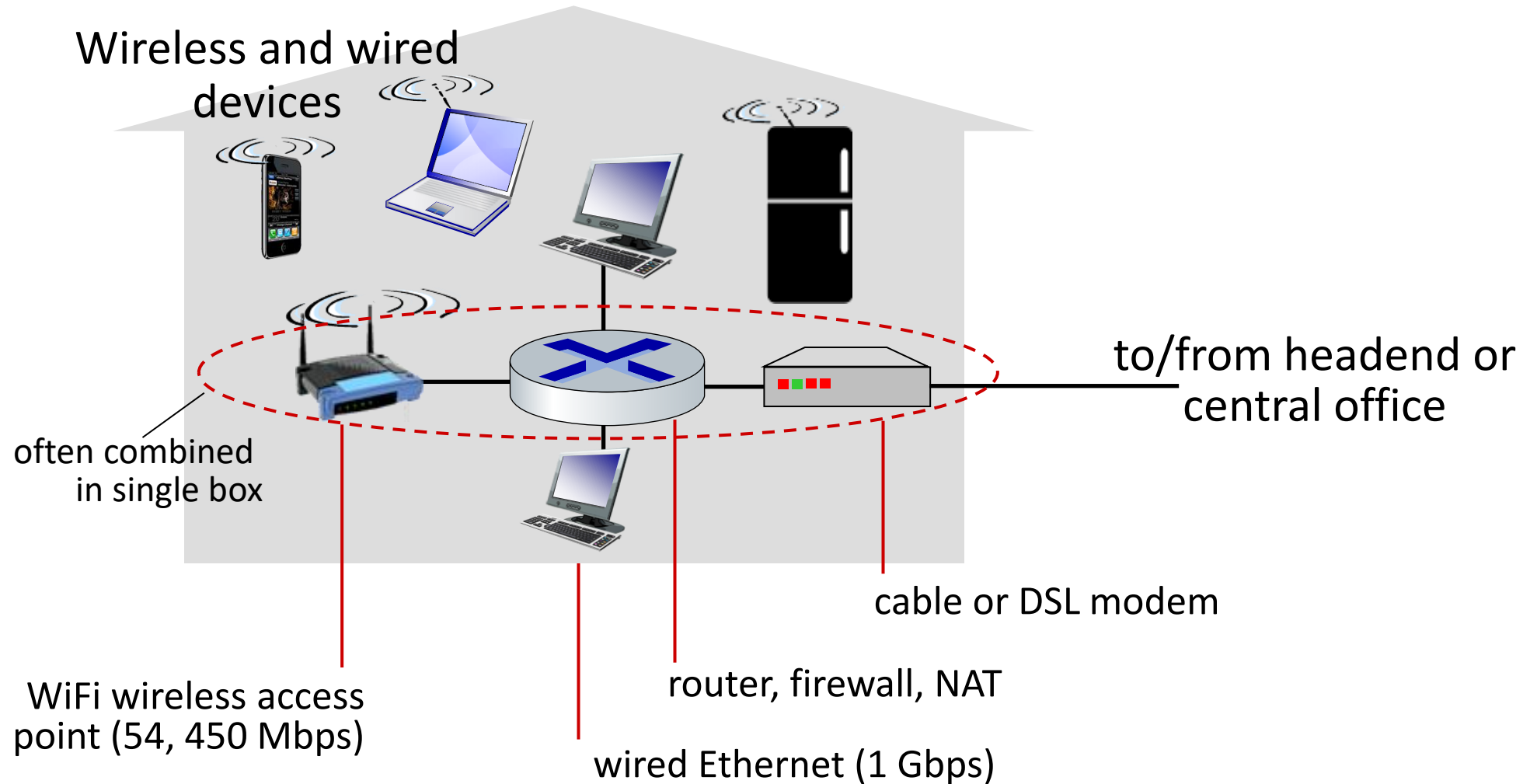
- asymmetric: up to 40 Mbps – 1.2 Gbps downstream transmission rate, 30-100 Mbps upstream transmission rate

■ network of cable, fiber attaches homes to ISP router

- homes *share access network* to cable headend



Access networks: home networks





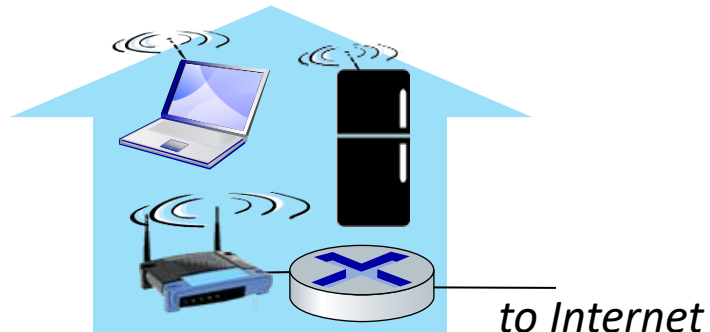
Wireless access networks

Shared *wireless* access network connects end system to router

- via base station aka “access point”

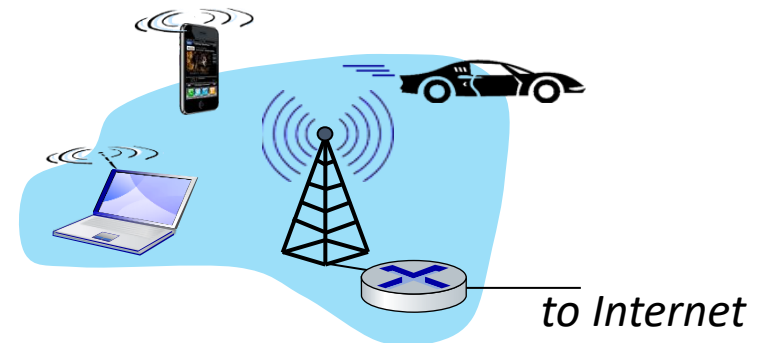
Wireless local area networks (WLANs)

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



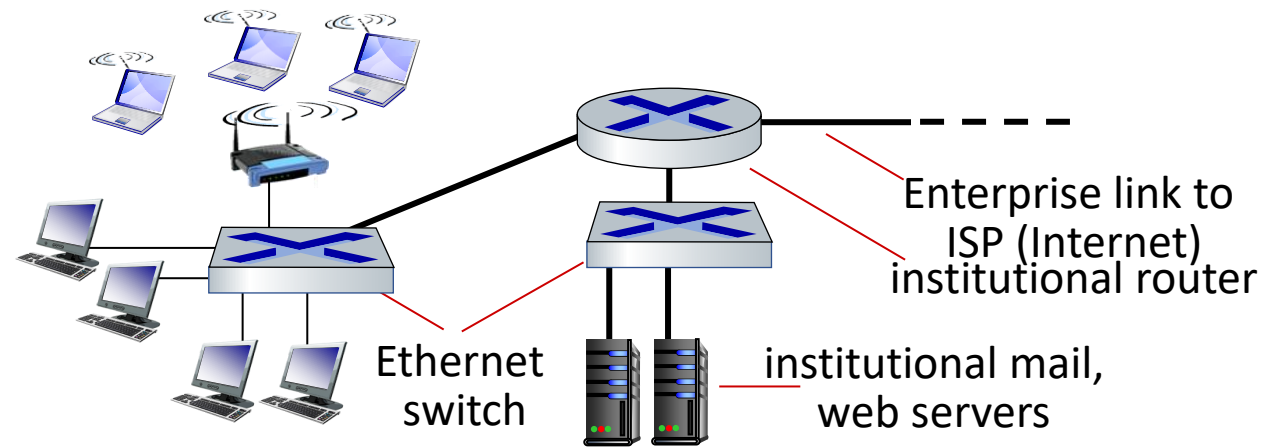
Wide-area cellular access networks

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





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

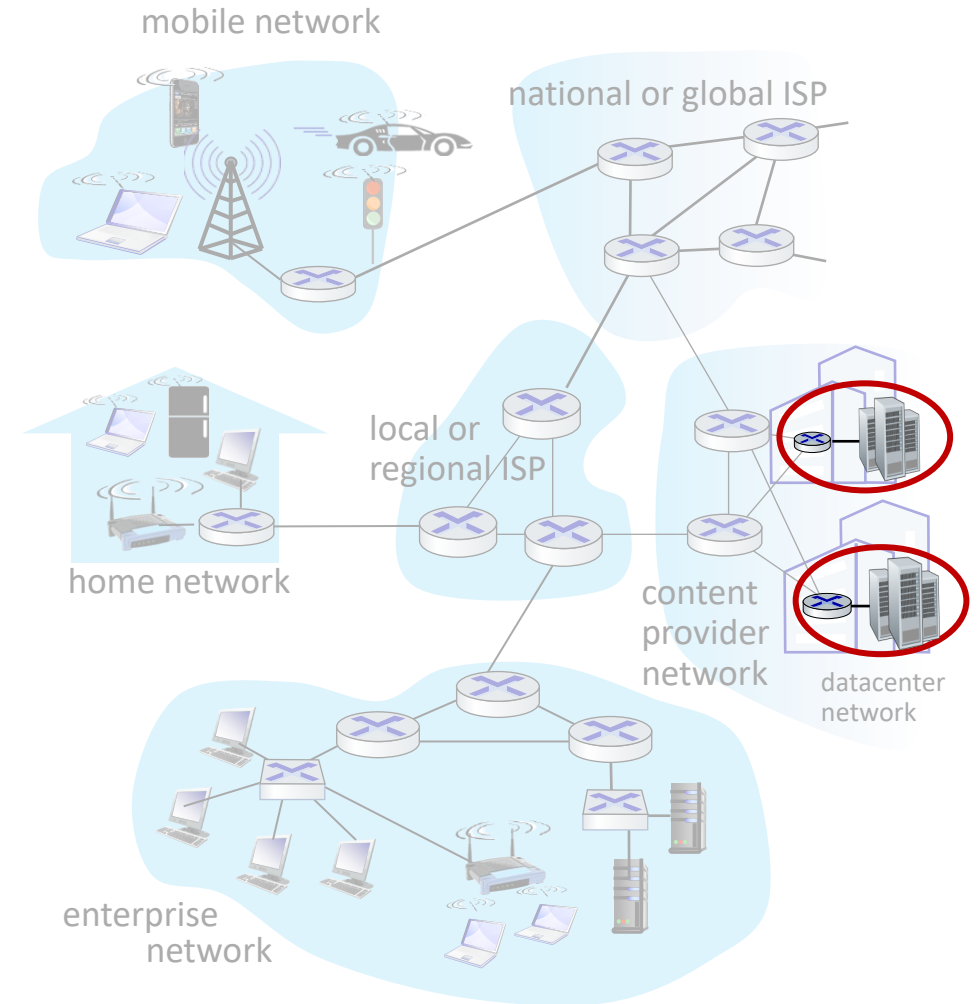


Access networks: data center networks

- 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)

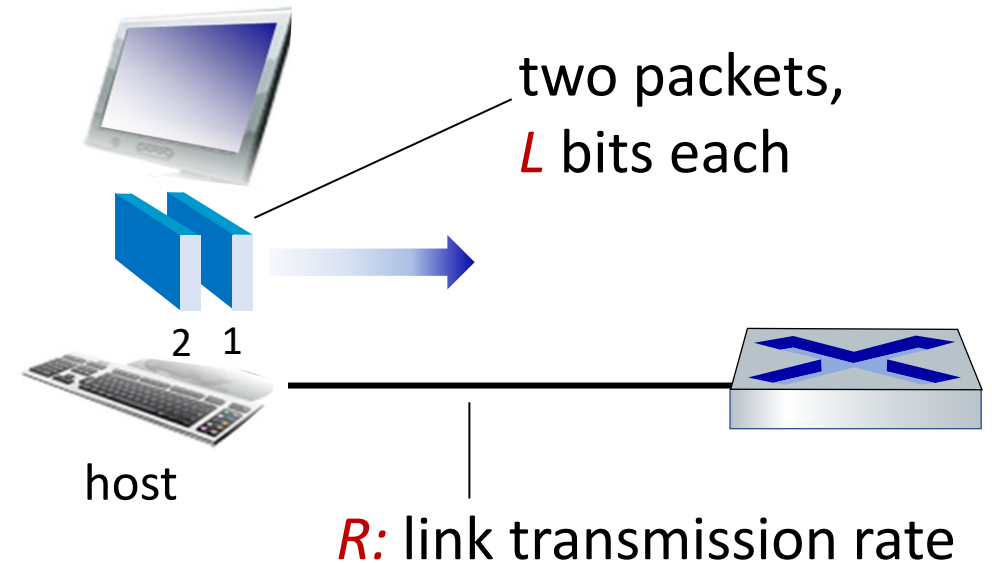




Host: sends *packets* of data

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*



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

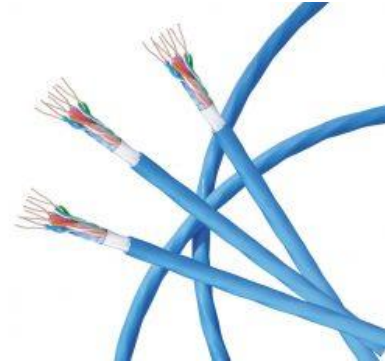


Links: physical media

- **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

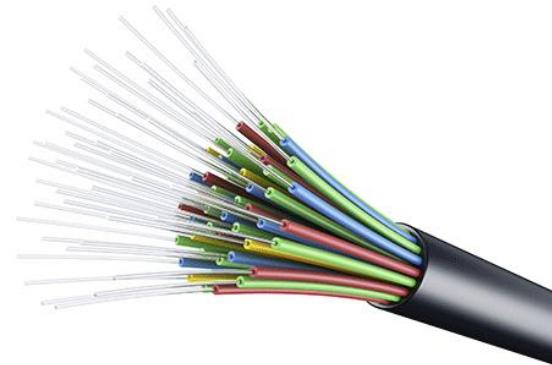
Coaxial cable:

- 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/5G cellular)
 - 10's Mbps (4G) over ~10 Km
- **Bluetooth**: cable replacement
 - short distances, limited rates
- **terrestrial microwave**
 - point-to-point; 45 Mbps channels
- **satellite**
 - up to < 100 Mbps (Starlink) downlink
 - 270 msec end-end delay (geostationary)



Chapter 1: roadmap

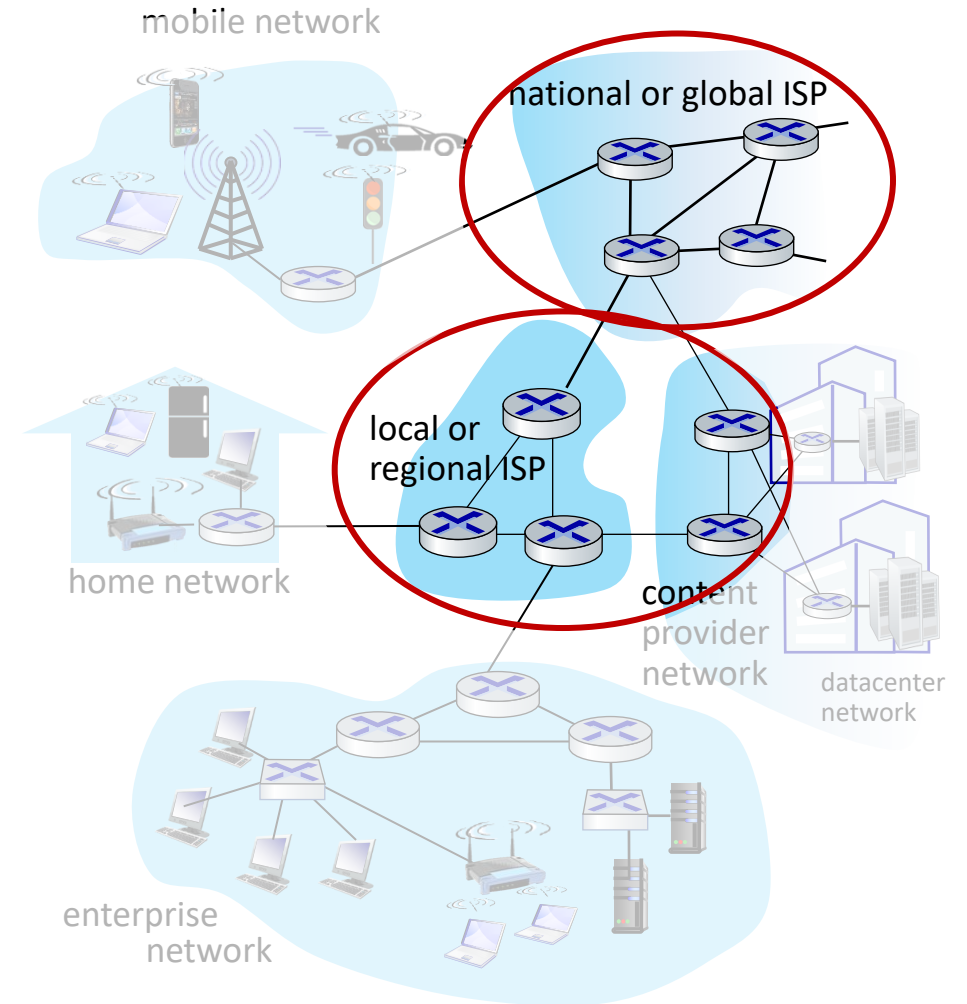
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The network core

- 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**

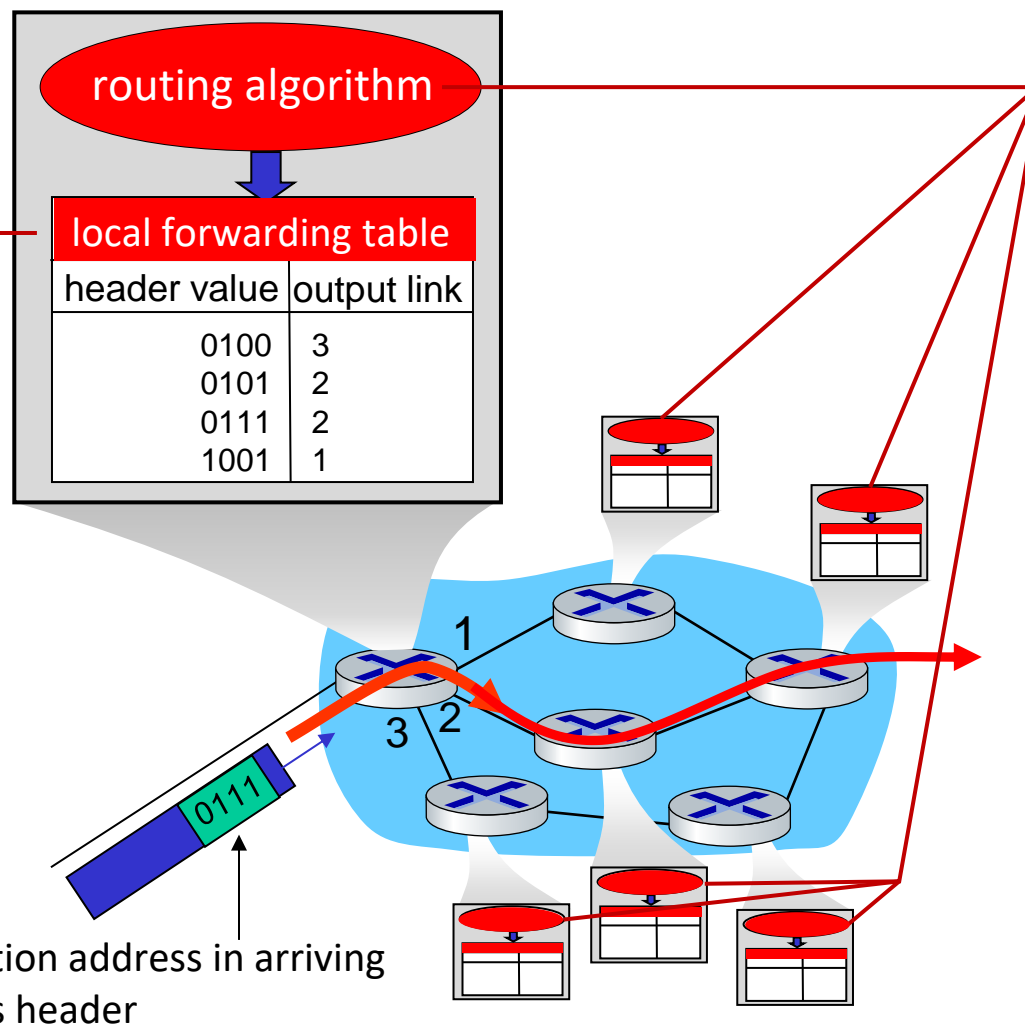




Two key network-core functions

Forwarding:

- aka “switching”
- *local* action: move arriving packets from router’s input link to appropriate router output link



Routing:

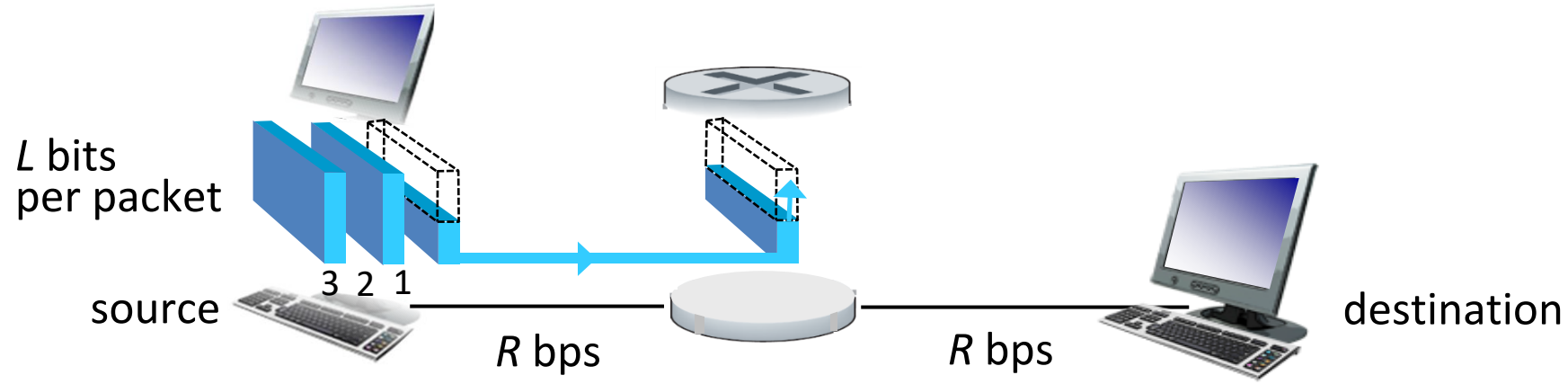
- *global* action: determine source-destination paths taken by packets
- routing algorithms







Packet-switching: store-and-forward



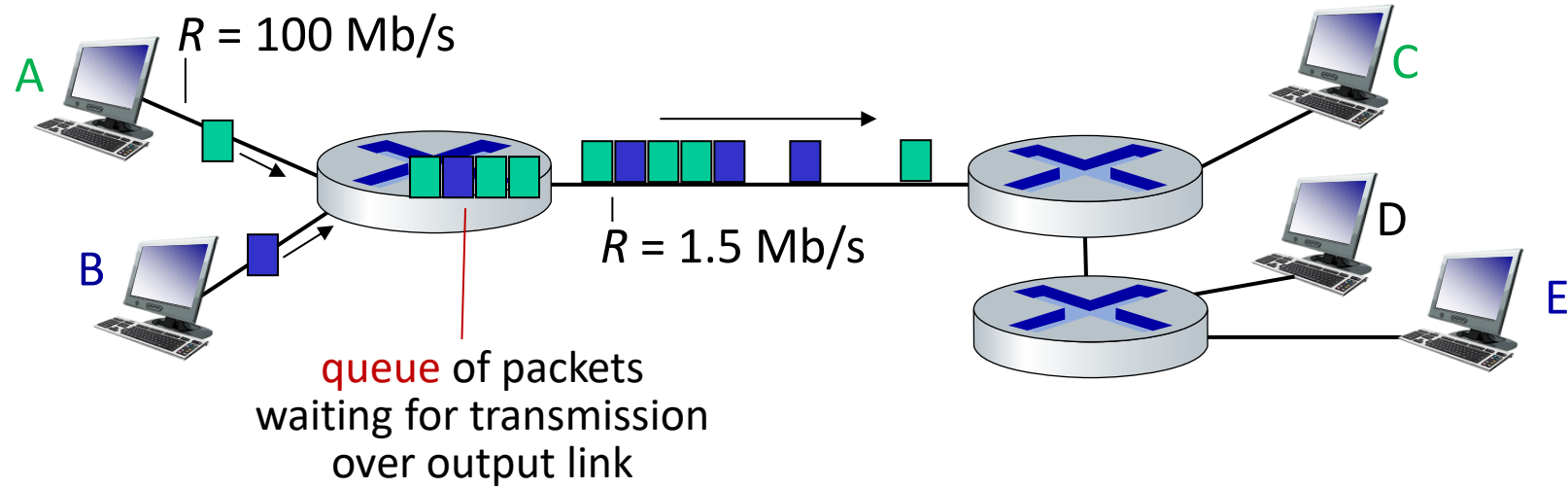
- **packet transmission delay:** takes L/R seconds to transmit (push out) L -bit packet into link at R bps
- **store and forward:** entire packet must arrive at router before it can be transmitted on next link

One-hop numerical example:

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



Packet-switching: queueing

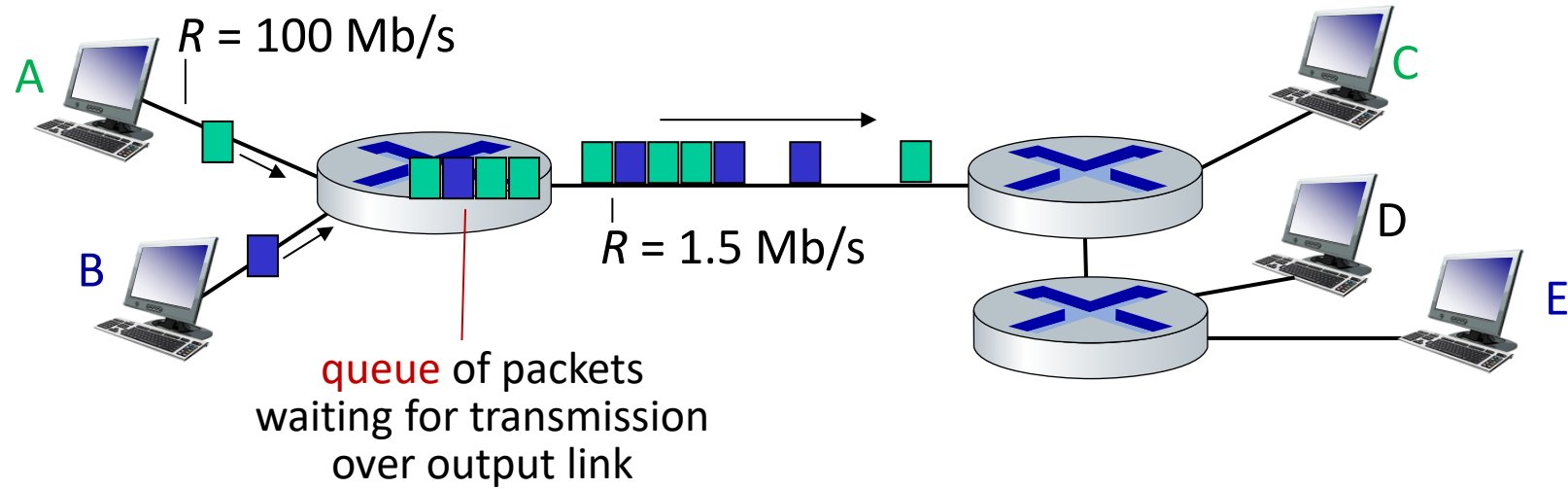


Queueing occurs when work arrives faster than it can be serviced:





Packet-switching: queueing



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

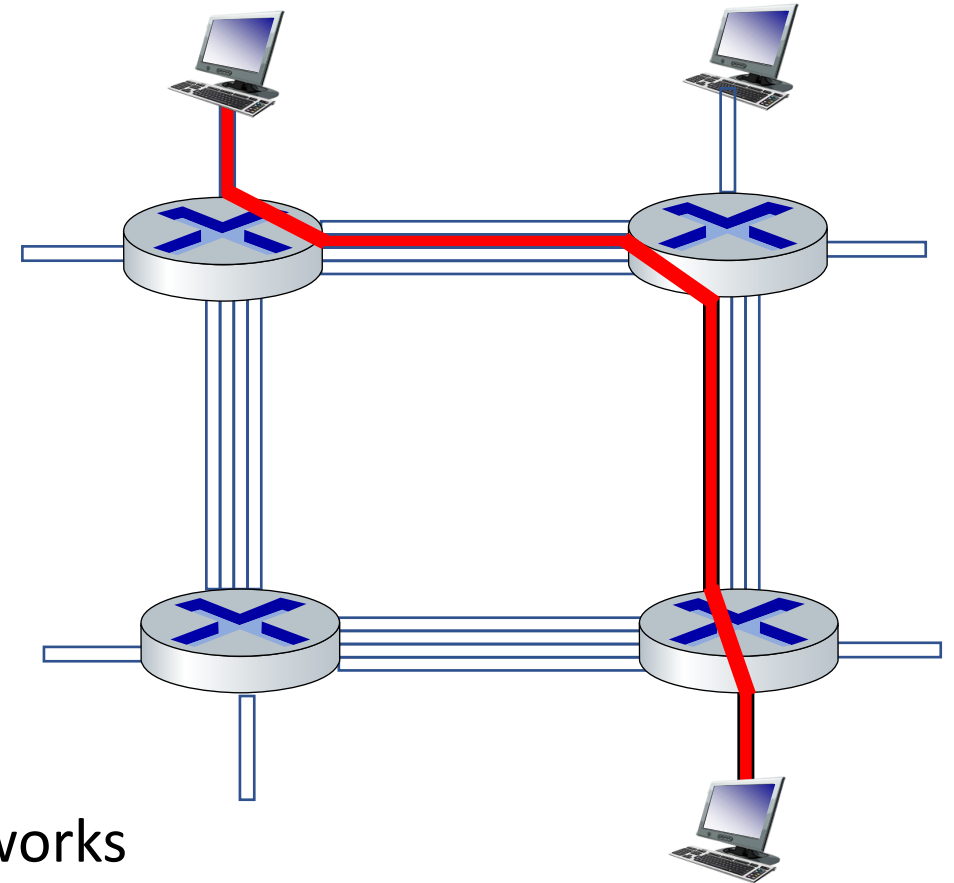
- packets will queue, waiting to be transmitted on output link
- packets can be dropped (lost) if memory (buffer) in router fills up



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

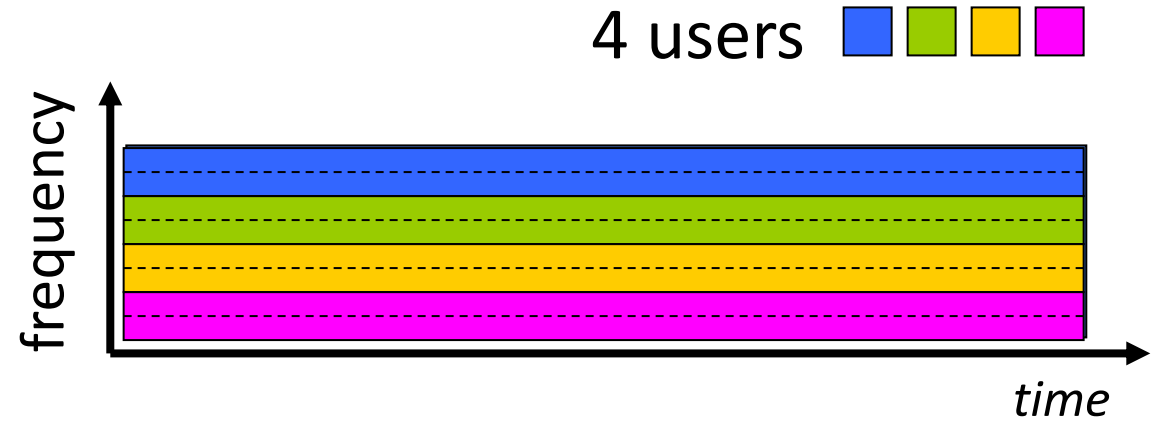




Circuit switching: FDM and TDM

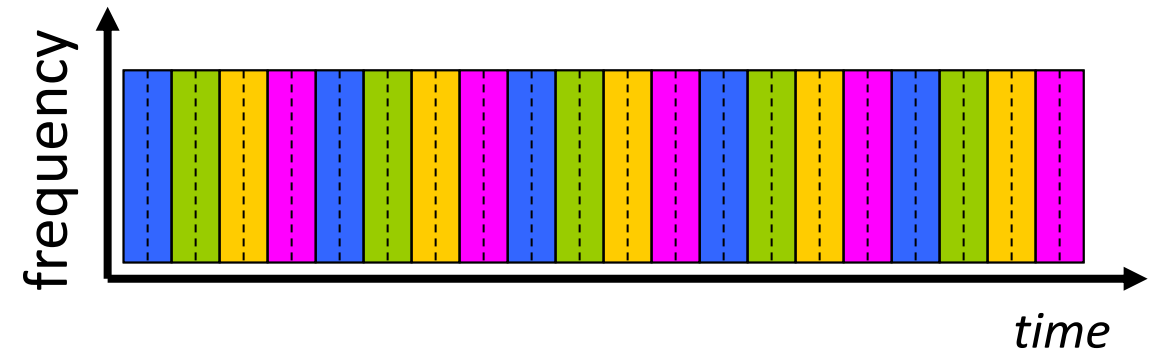
Frequency Division Multiplexing (FDM)

- 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)

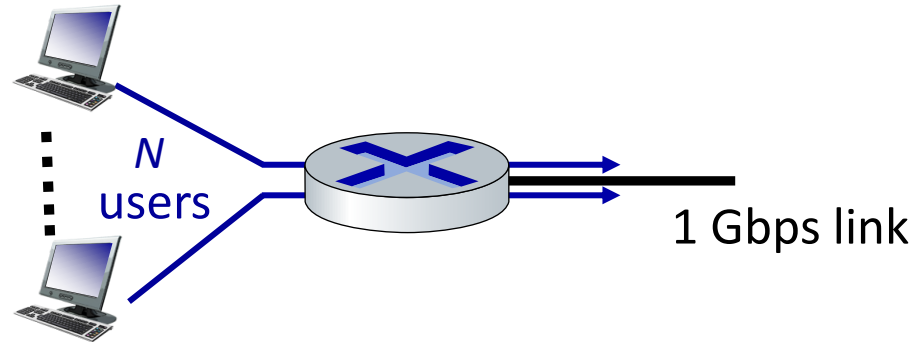




Packet switching versus circuit switching

example:

- 1 Gb/s link
- 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?

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



Binomial Probability Distribution

- A fixed number of observations (trials), n
 - e.g., 20 tosses of a coin

- Binary random variable
 - e.g., Head or tail in coin toss
 - Often called as success or failure
 - Prob of success is p , and prob of failure is $1-p$

- Constant probability for each observation



Binomial distribution

- If you have only two possible outcomes (call them 1/0 or yes/no or success/failure) in n independent trials, then the probability of exactly X “successes”

The diagram shows the binomial distribution formula $\binom{n}{X} p^X (1-p)^{n-X}$ enclosed in a purple box. Four arrows point from descriptive text to parts of the formula: one from ' n ' to ' $n = \text{number of trials}$ ', one from ' X ' to ' $X = \# \text{ successes out of } n \text{ trials}$ ', one from ' p ' to ' $p = \text{probability of success}$ ', and one from ' $1-p$ ' to ' $1-p = \text{probability of failure}$ '.

$$\binom{n}{X} p^X (1-p)^{n-X}$$

$n = \text{number of trials}$

$X = \#$
successes
out of n
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success

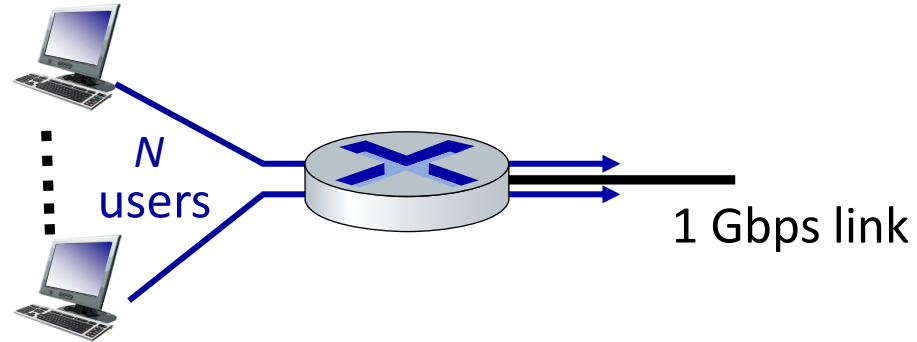
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Packet switching versus circuit switching

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Q: how did we get value 0.0004?

A:

$$\sum_{n=11}^{35} \binom{35}{n} p^n (1-p)^{35-n} \leq 0.0004$$

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Packet switching versus circuit switching

Is packet switching a “slam dunk winner”?

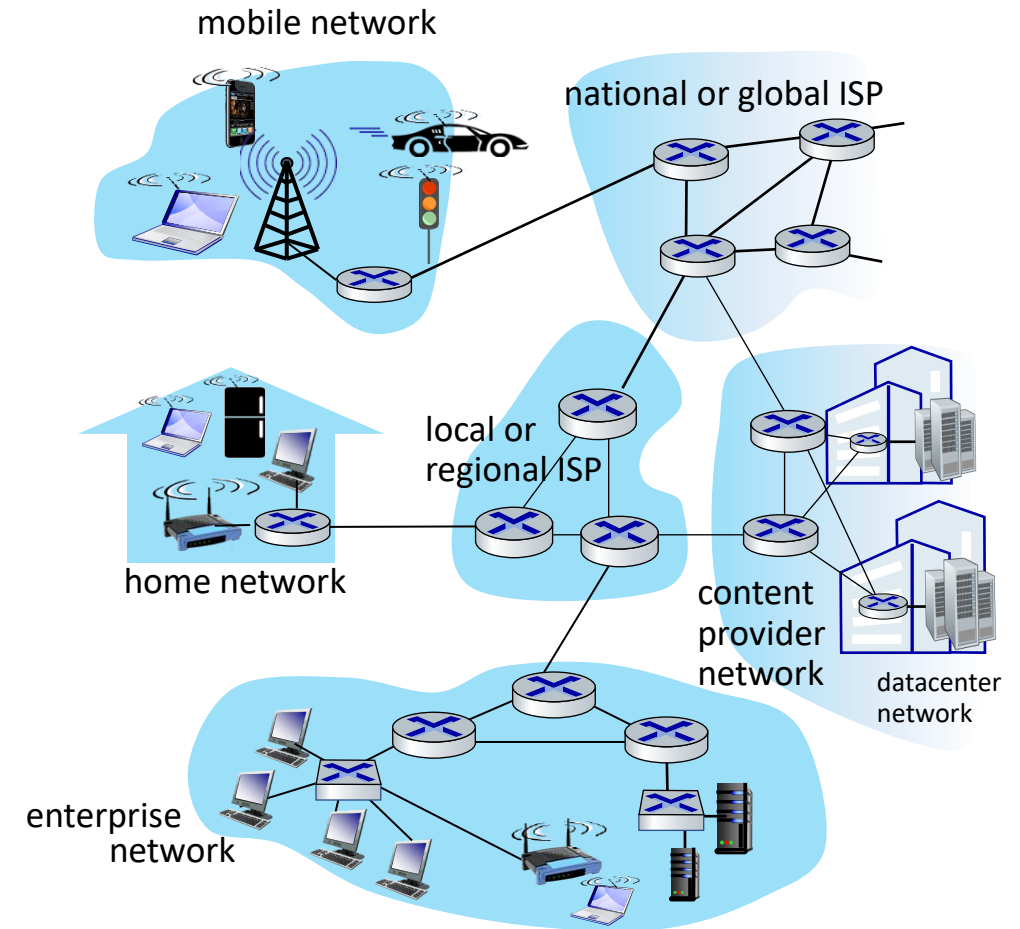
- great for “bursty” data – sometimes has data to send, but at other times not
 - resource sharing
 - simpler, no call setup
- **excessive congestion possible:** packet delay and loss due to buffer overflow
 - protocols needed for reliable data transfer, congestion control
- **Q: How to provide circuit-like 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**

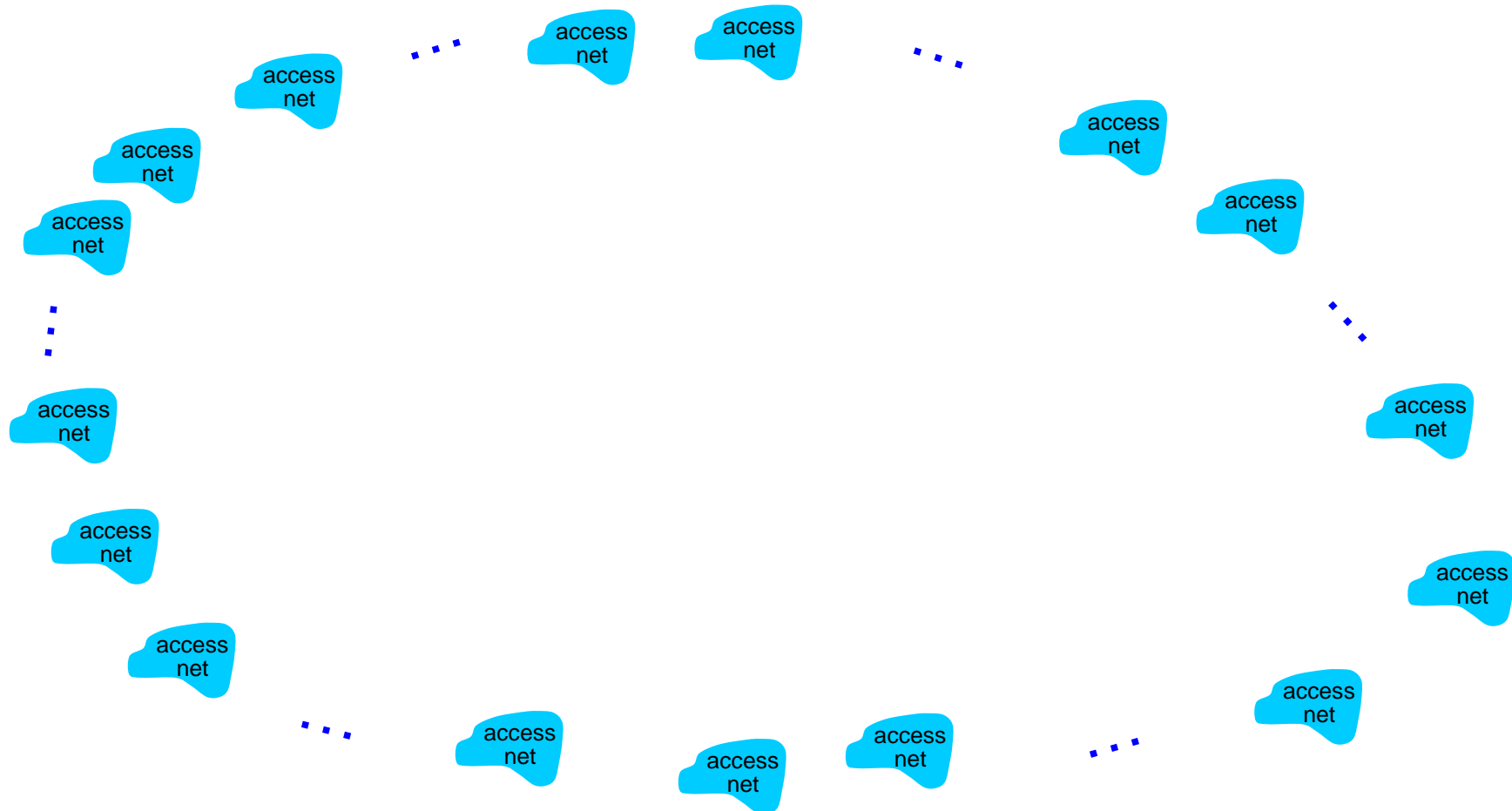


Let's take a stepwise approach to describe current Internet structure



Internet structure: a “network of networks”

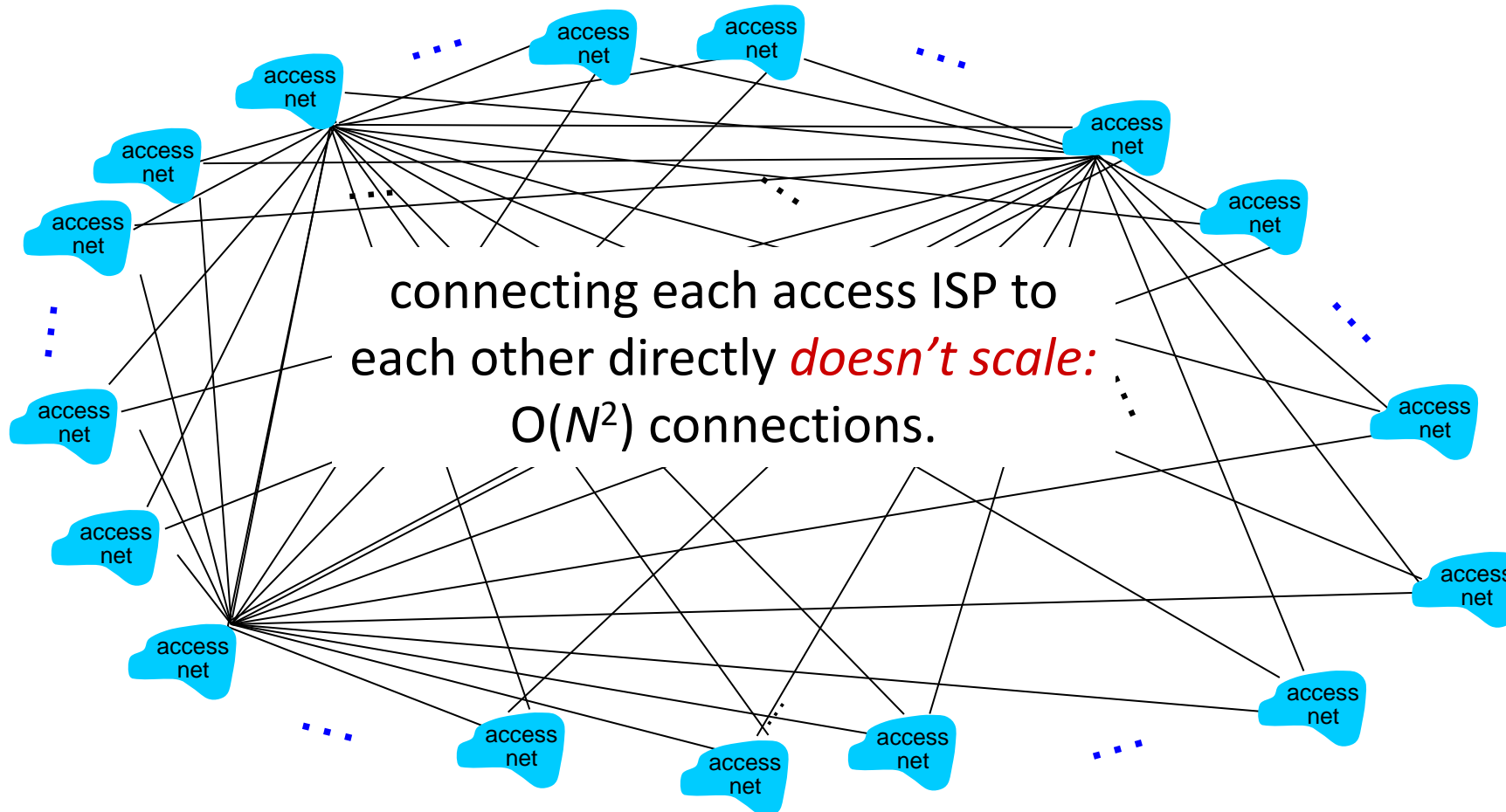
Question: given *millions* of access ISPs, how to connect them together?





Internet structure: a “network of networks”

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

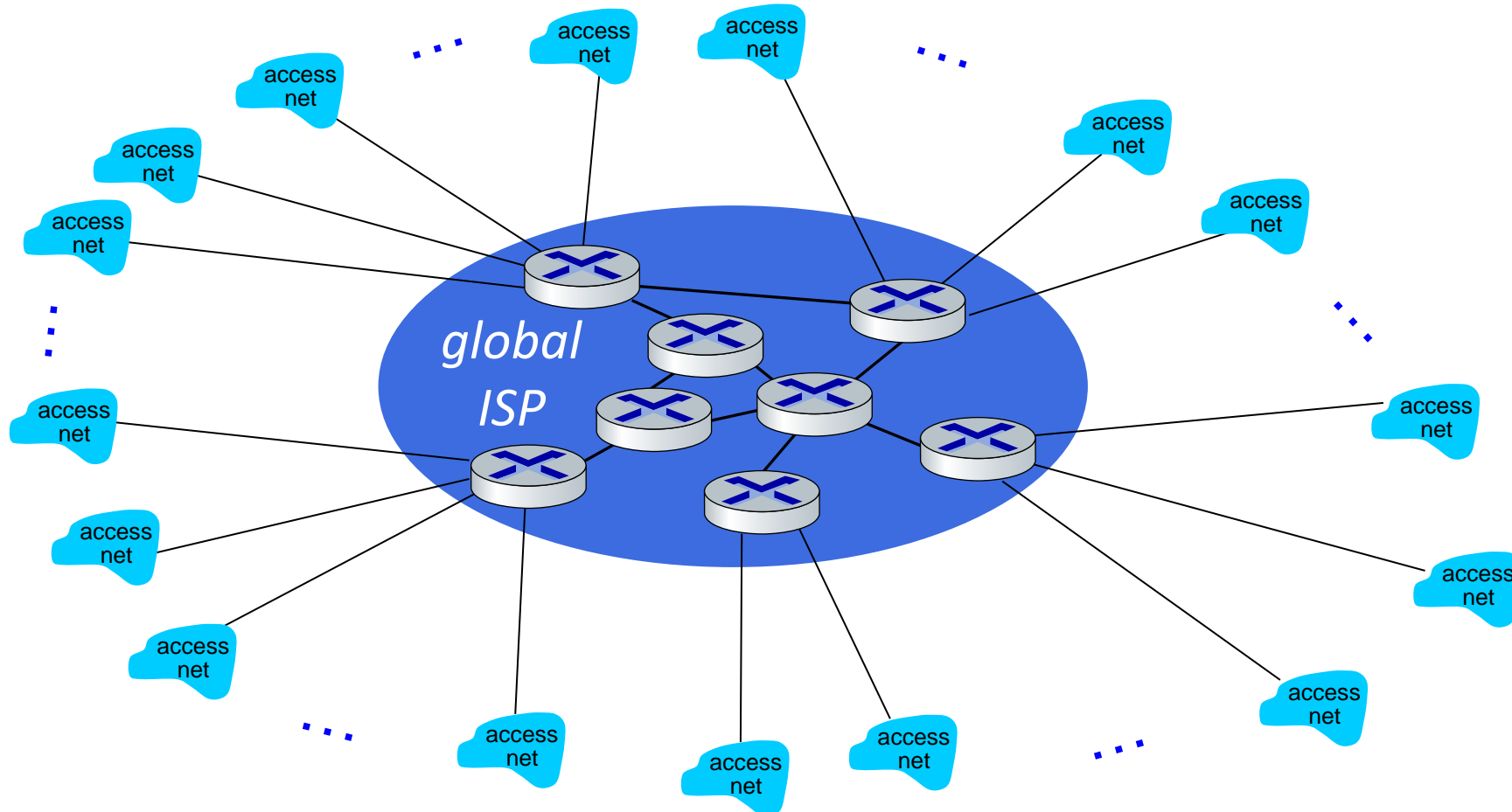




Internet structure: a “network of networks”

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

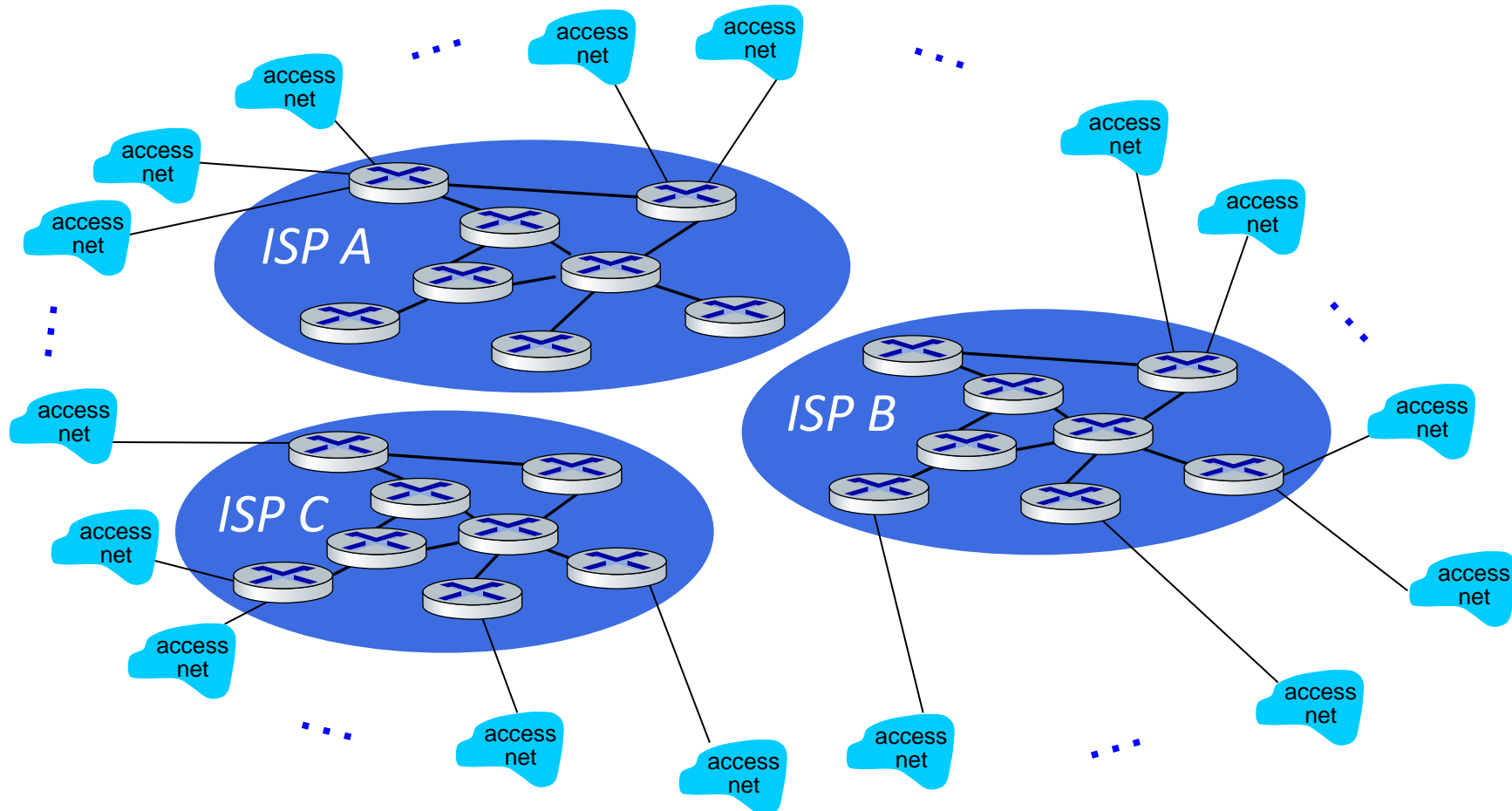
Customer and provider ISPs have economic agreement.





Internet structure: a “network of networks”

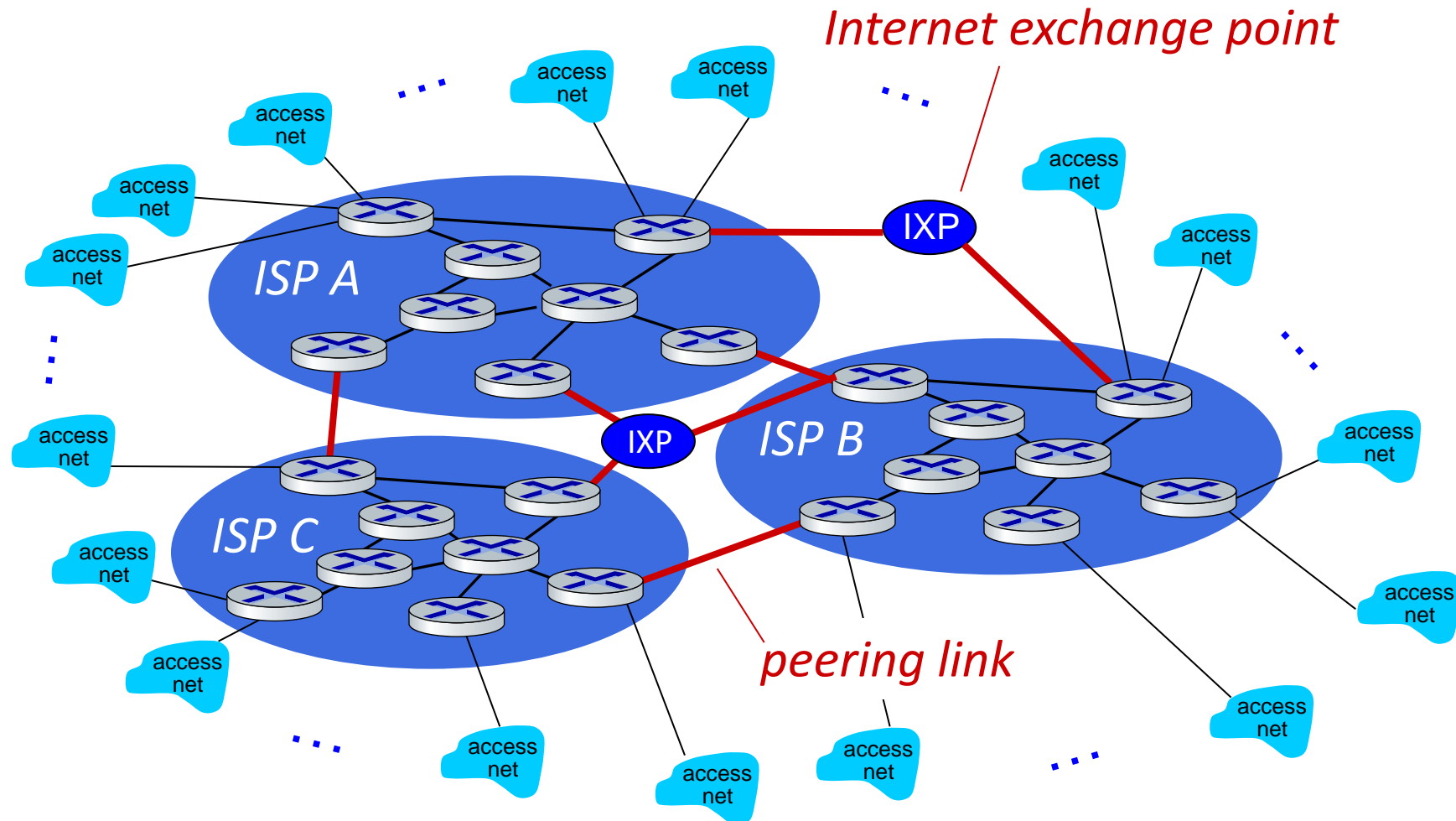
But if one global ISP is viable business, there will be competitors





Internet structure: a “network of networks”

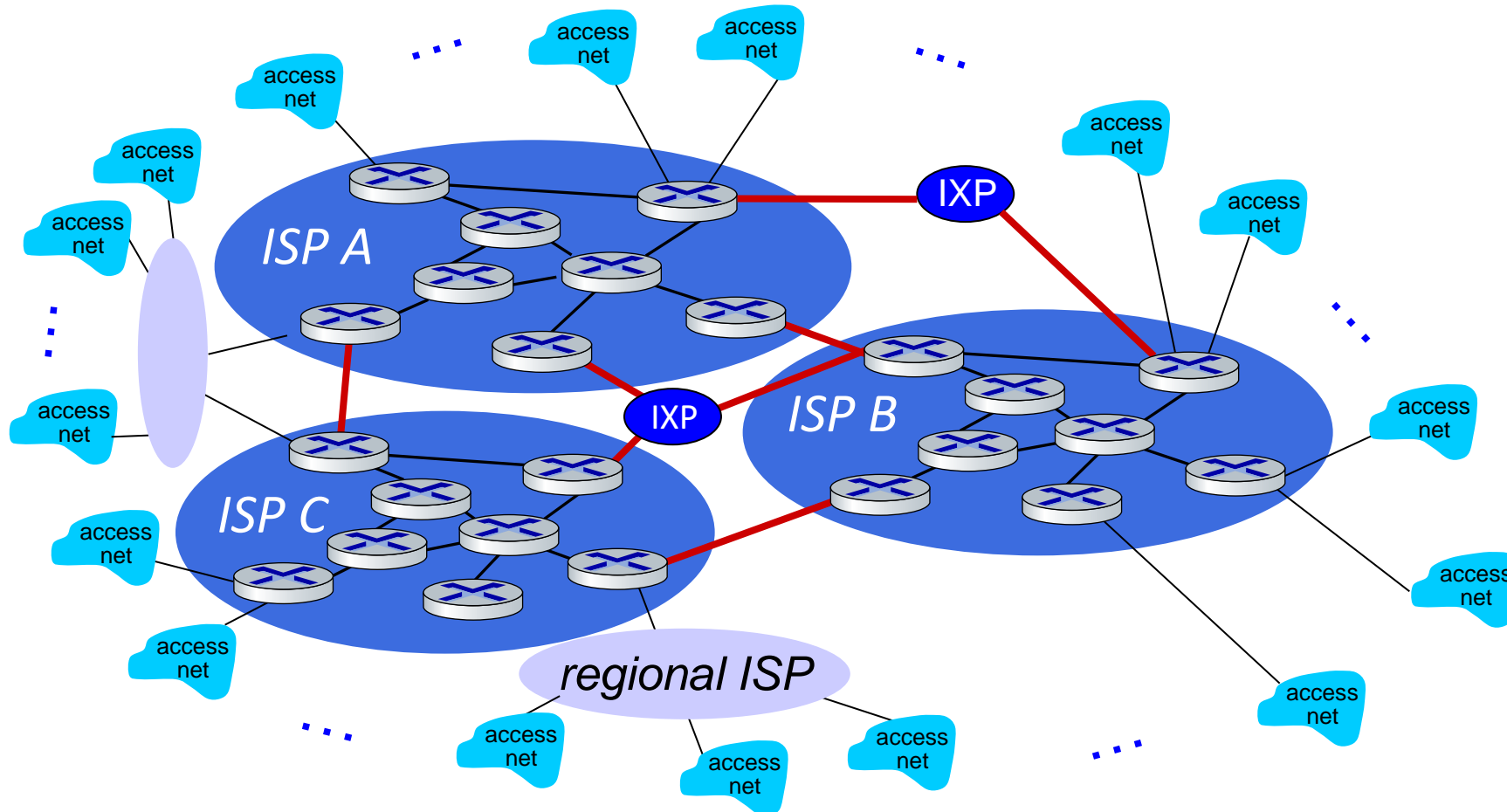
But if one global ISP is viable business, there will be competitors who will want to be connected





Internet structure: a “network of networks”

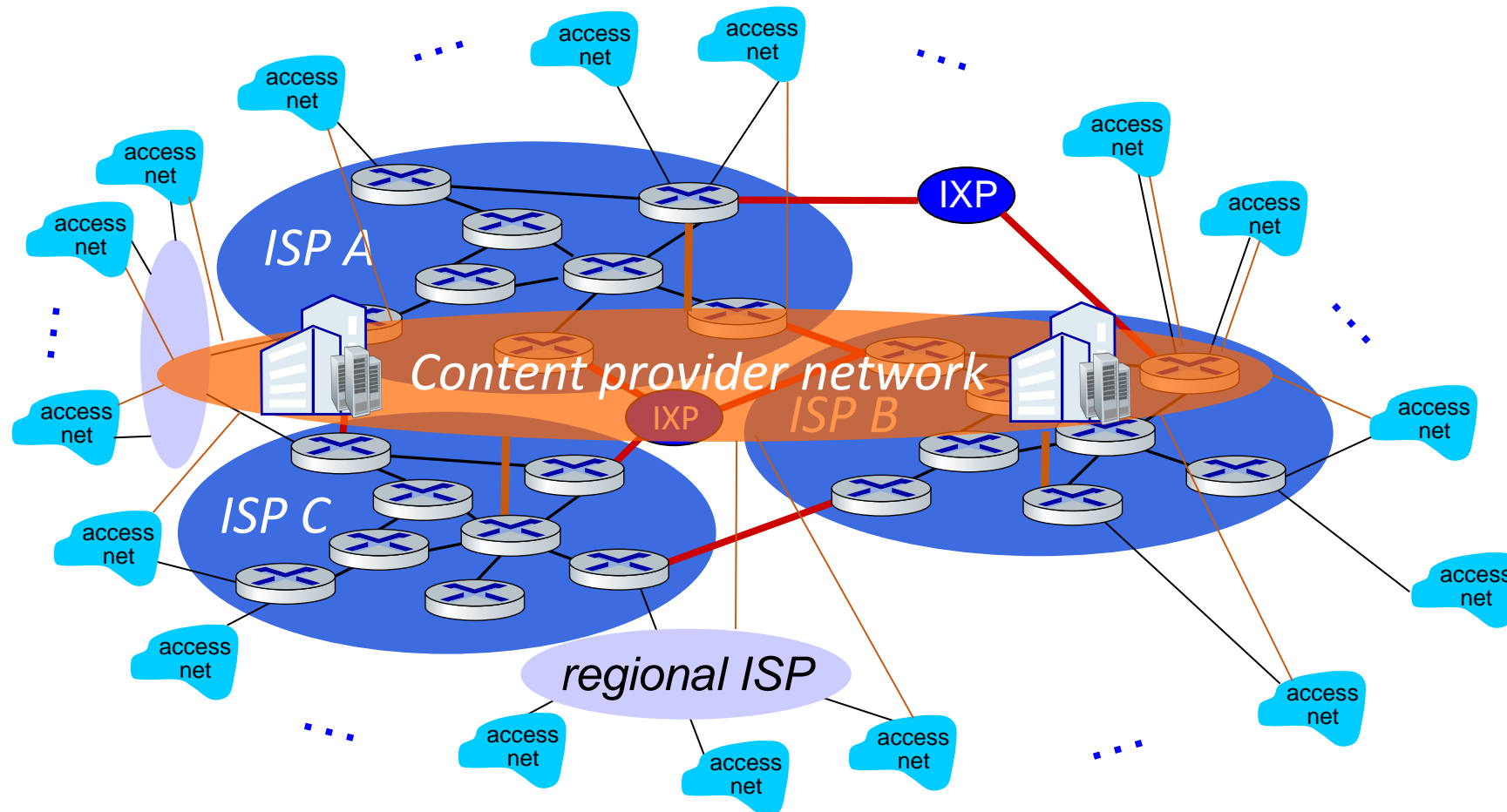
... and regional networks may arise to connect access nets to ISPs





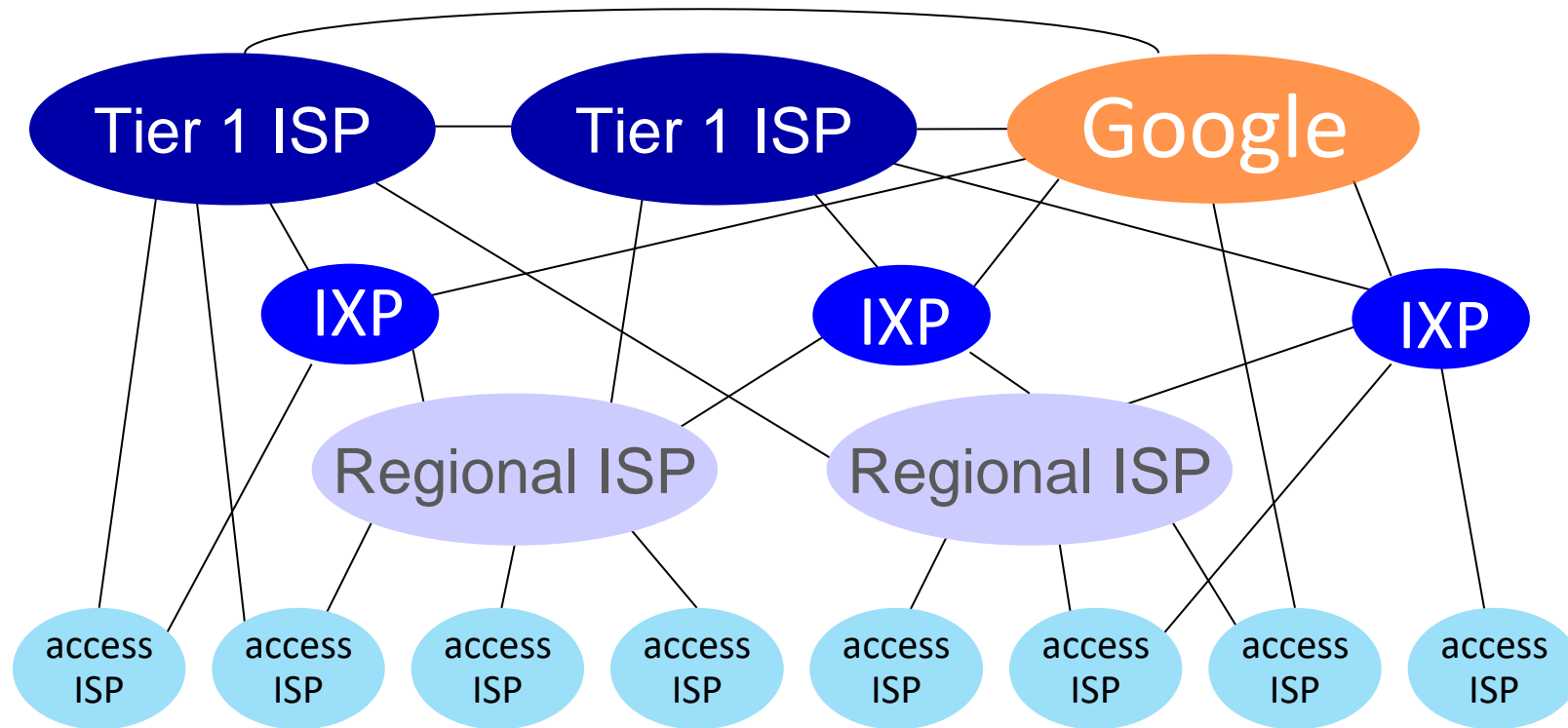
Internet structure: a “network of networks”

... 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