Computer Networks and Applications

COMP 3331/COMP 9331

Key Topics

- Internet as a network of networks
- The protocol stack and layering principle
- Edge vs. Core
- Loss, delay and throughput
- Packet switching vs. Circuit switching

Week 1

Introduction to Computer Networks

Reading Guide: Chapter 1, Sections 1.1 - 1.4

Acknowledgment

- Majority of lecture slides are from the author's lecture slide set
  - Enhancements + *additional material*

Introduction

Our goal:

- Get “feel,” “big picture,” introduction to terminology
  - more depth, detail *later* in course
- Approach:
  - use Internet as example

Overview/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
- Protocol layers, service models
- Security (self study, not on exam)
- History (self study, not on exam)

Hobbe’s Internet Timeline - http://www.zakon.org/robert/internet/timeline/

Quiz: What is the Internet?

A. One single homogenous network

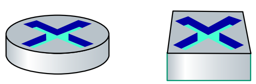
B. An interconnection of different computer networks

C. An infrastructure that provides services to networked applications

D. Something else

The Internet: a "nuts and bolts" view

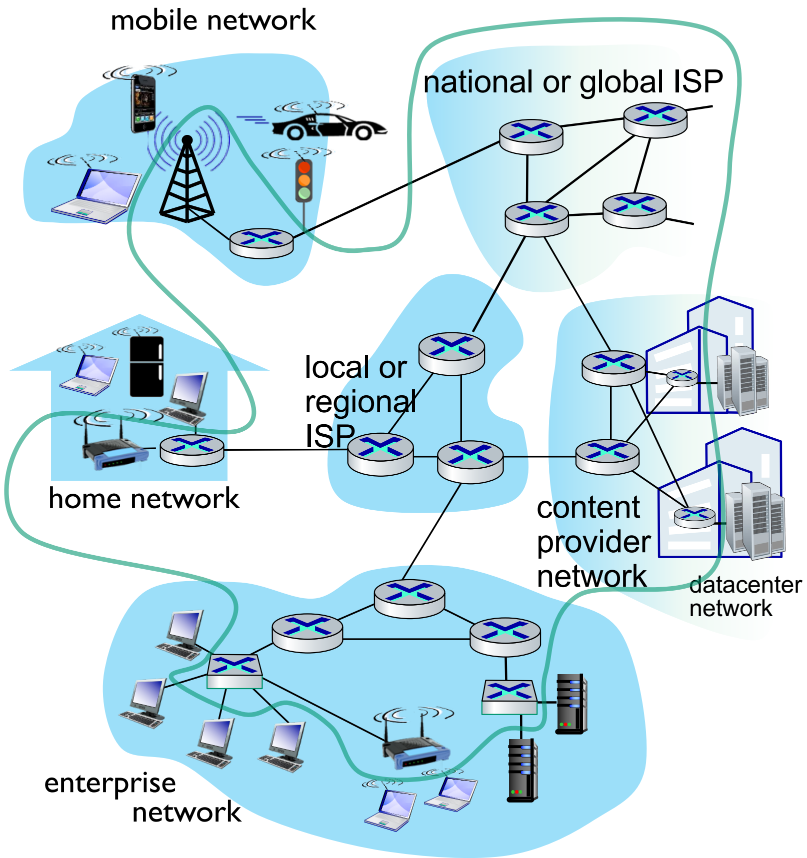
Billions of connected computing *devices*:
- *hosts* = *end systems*
- running *network apps* at Internet's "edge"



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 appliances

Security Camera

Picture frame

Web-enabled toaster +
weather forecaster

car

pacemaker

Tweet-a-watt:
monitor energy use

Fitbit

Networked TV Set top Boxes

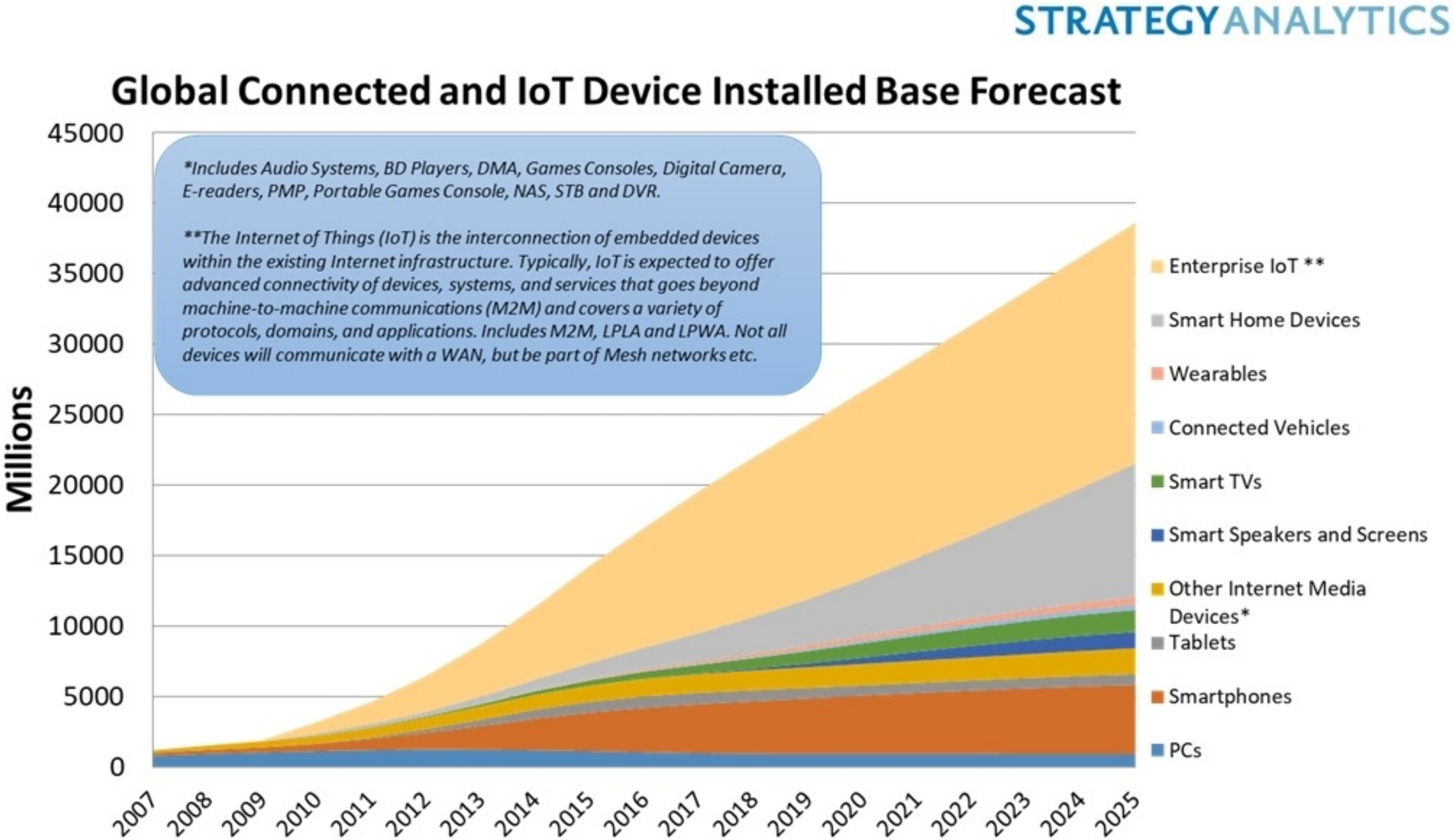
Amazon Echo

Internet
refrigerator

sensorized,
bed
mattress

Smart Lightbulbs

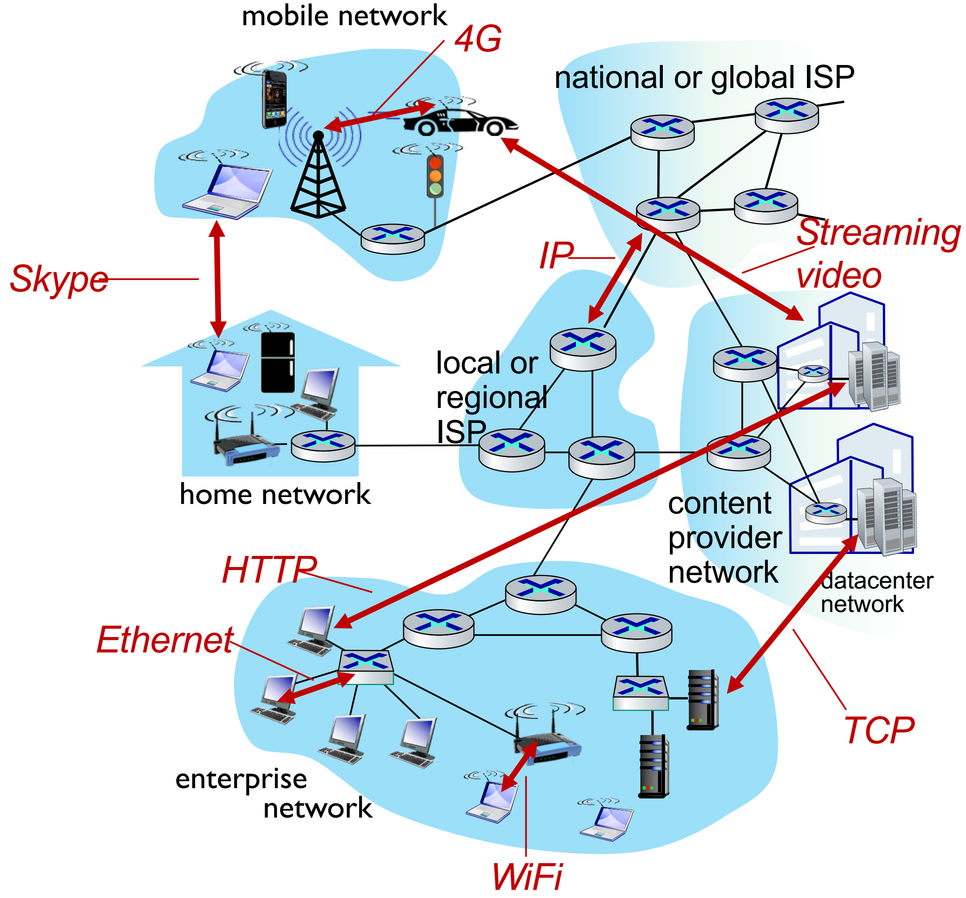
AR devices



Source – Strategy Analytics research services, May 2019: IoT Strategies, Connected Home Devices, Connected Computing Devices, Wireless Smartphone Strategies, Wearable Device Ecosystem, Smart Home Strategies

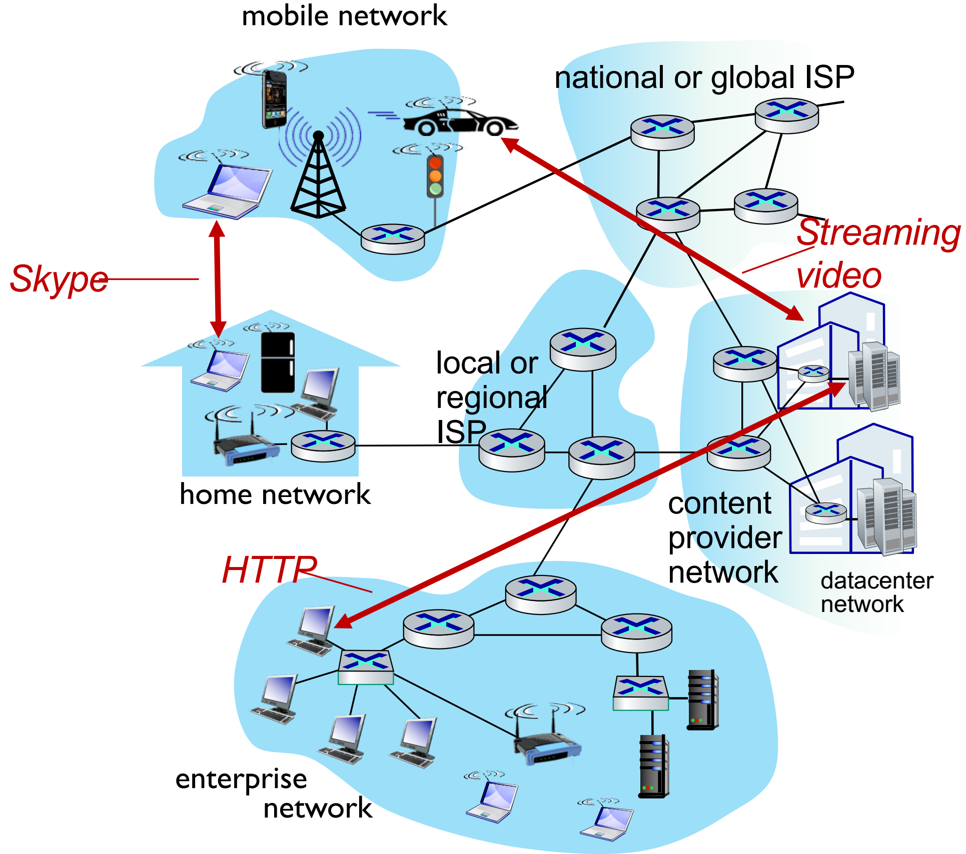
The Internet: a "nuts and bolts" view

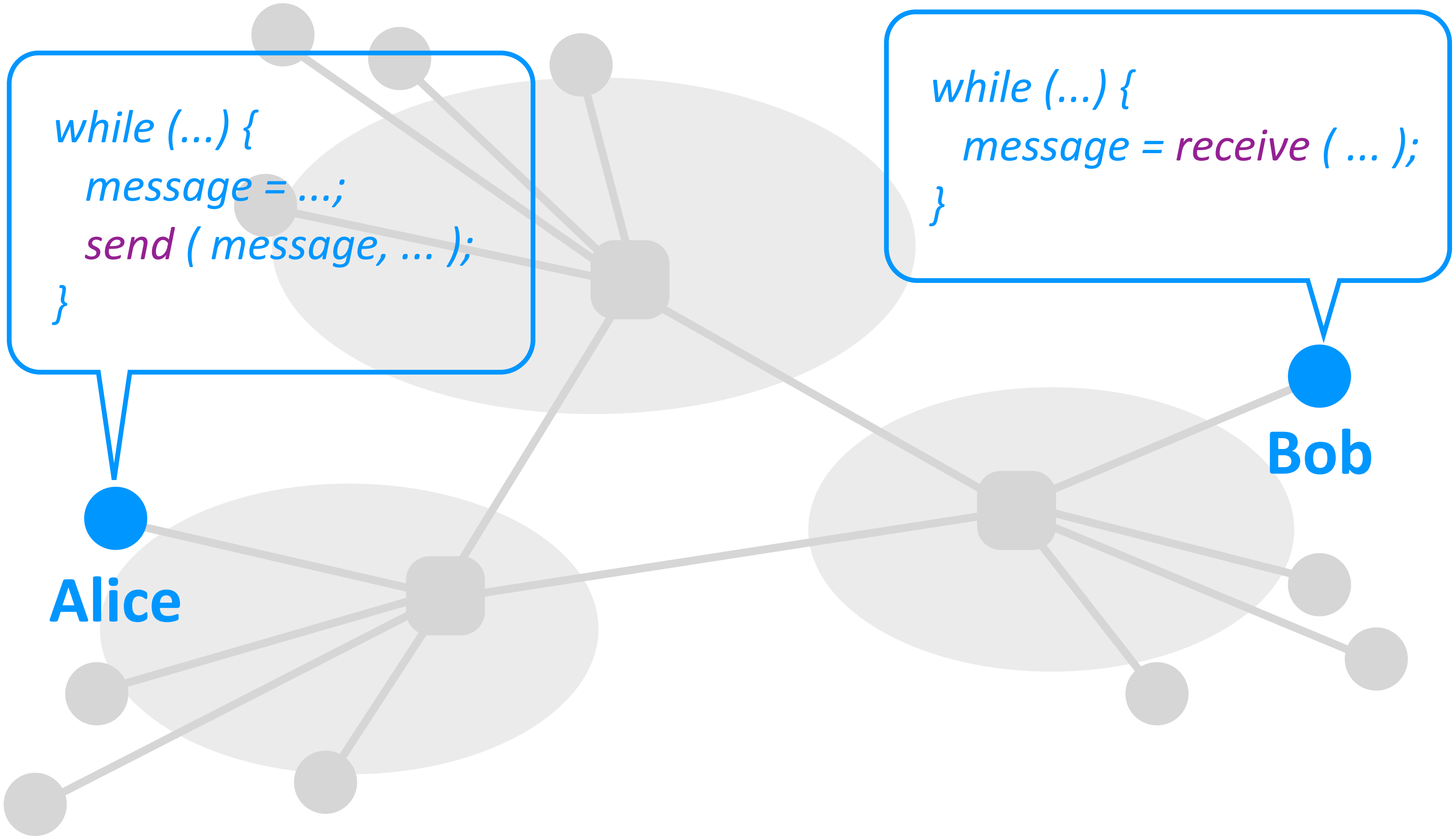
- *Internet: "network of networks"*
  - Interconnected ISPs
- *protocols* are *everywhere*
  - control sending, receiving of messages
  - e.g., HTTP (Web), streaming video, Skype, TCP, IP, WiFi, 4G, Ethernet
- *Internet standards*
  - RFC: Request for Comments
  - IETF: Internet Engineering Task Force

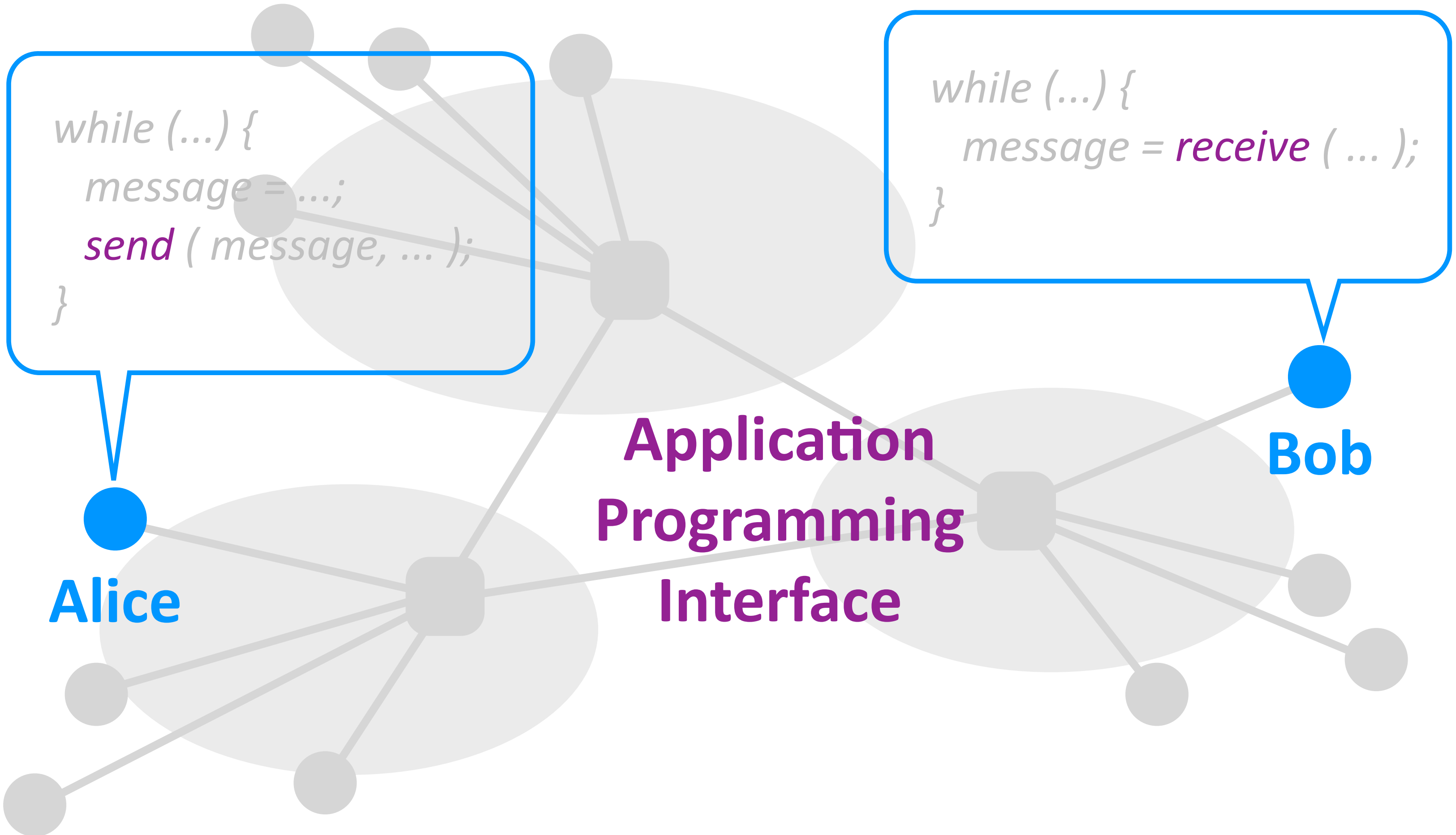


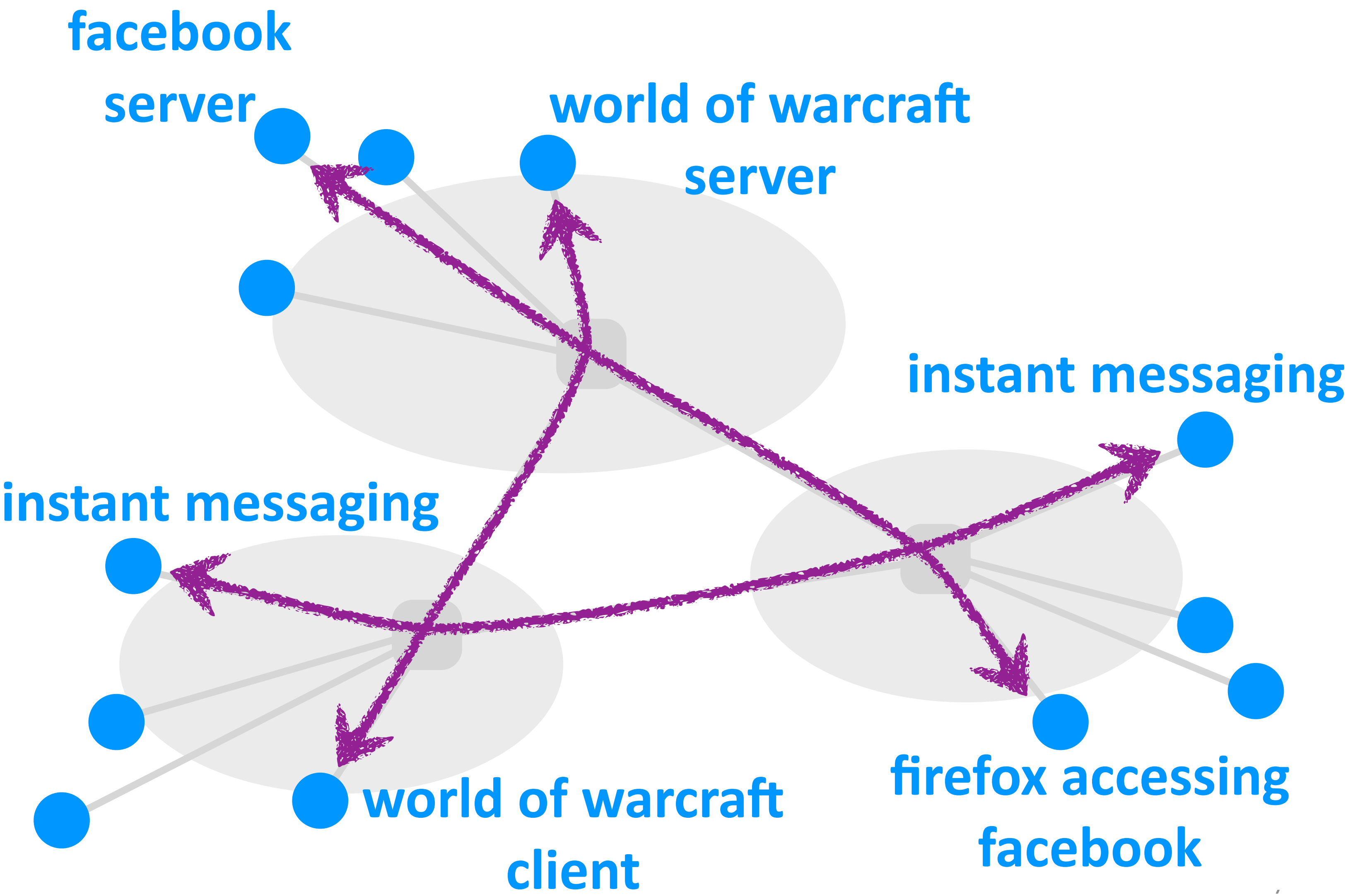
The Internet: a "service" view

- *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




while (...) {
message = ...;
send (message, ...);
}
while (...) {
message = receive (...);
}
Alice
Bob


while (...) {
message = ...;
send (message, ...);
}
while (...) {
message = receive (...);
}
Application
Programming
Interface
Alice
Bob


facebook
server
world of warcraft
server
instant messaging
instant messaging
world of warcraft
client
firefox accessing
facebook

What's a protocol?

Human protocols:

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

… specific messages sent

… specific actions taken when message received, or other events

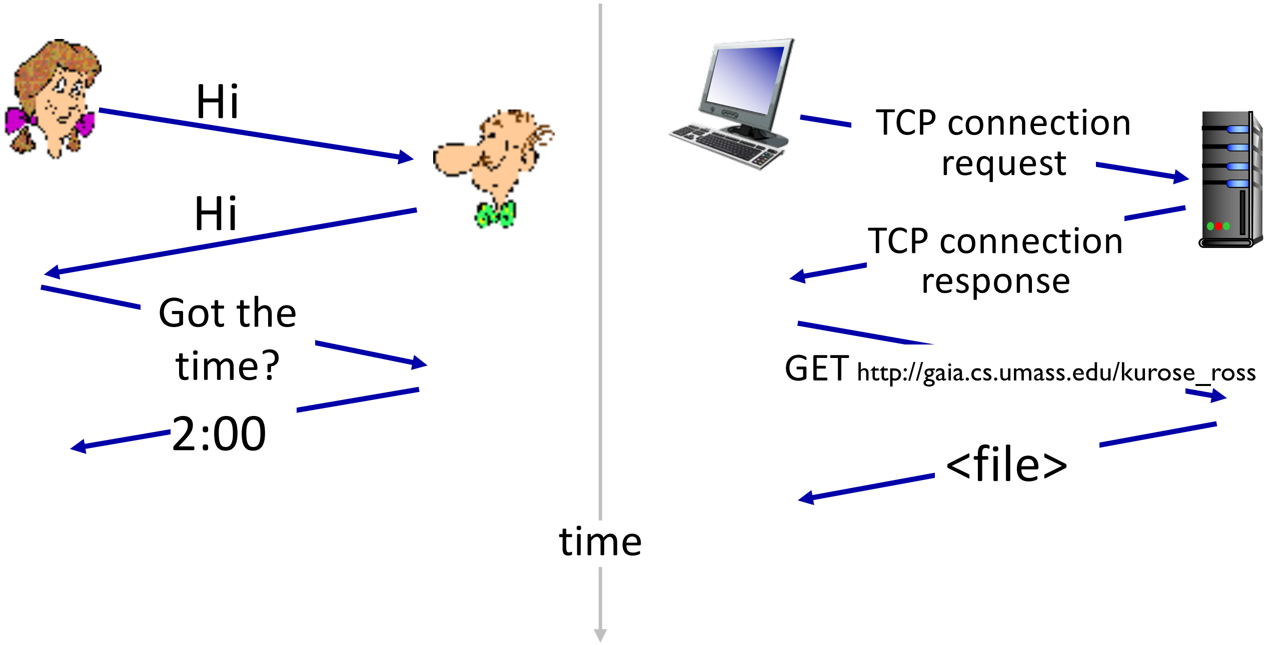
Network protocols:

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

Protocols define the format, order of messages 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:



Q: other human protocols?

Quiz: Internet of Things

How many Internet-connected devices do you have in your home (include your computers, phones, tablets)?

A. Less than 10

B. Between 10 to 20

C. Between 20 to 50

D. Between 50 to 100

E. More than 100

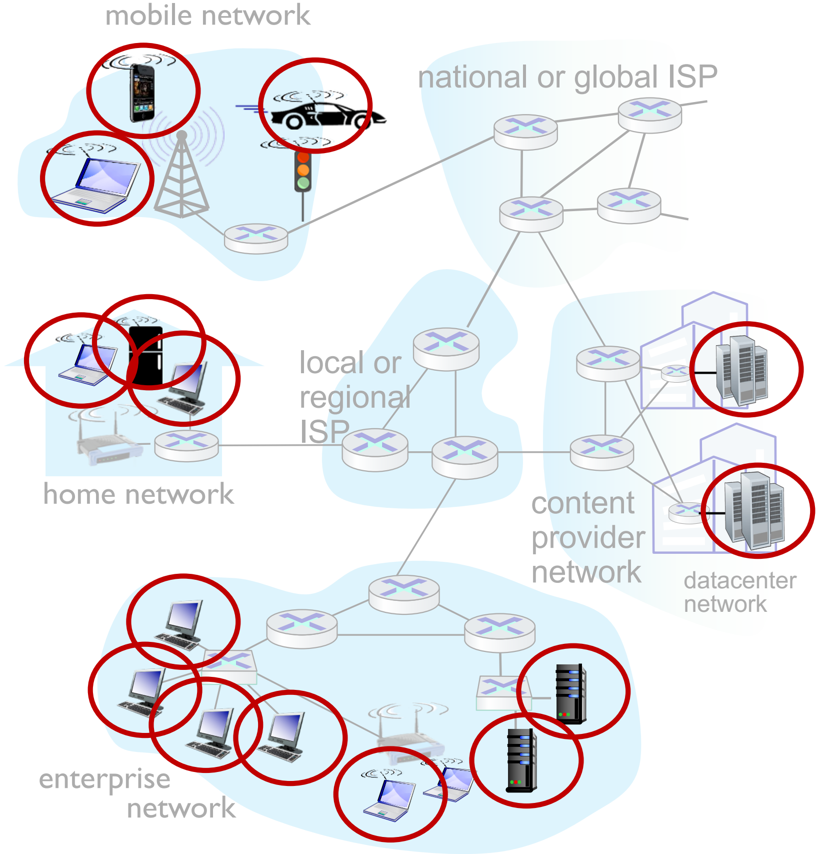
Introduction: roadmap

- 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



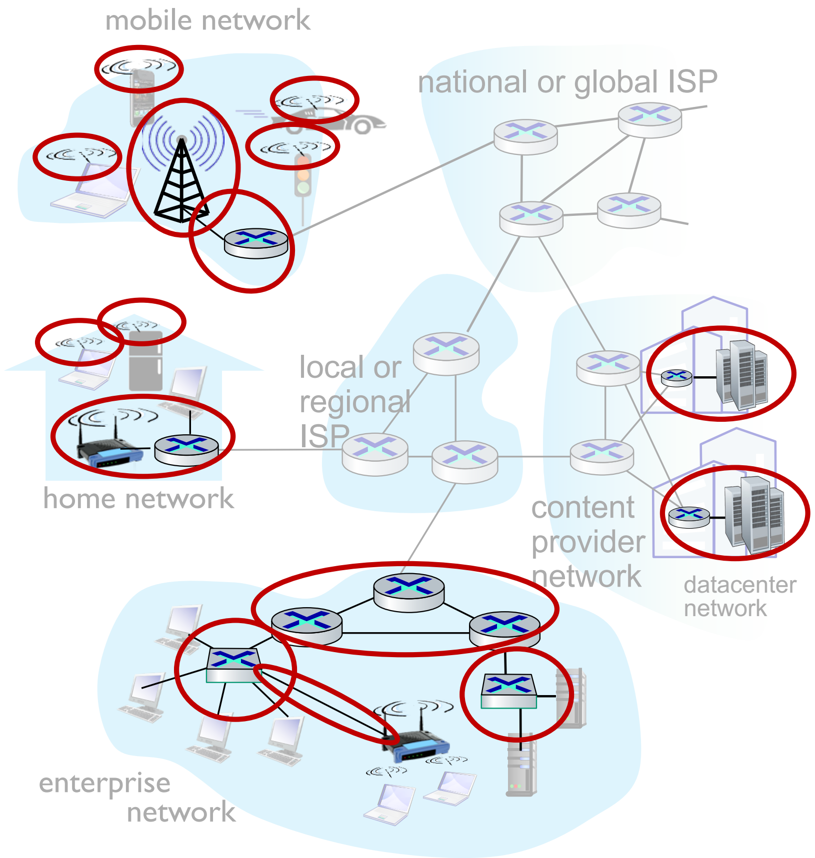
A closer look at Internet structure

Network edge:

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

Access networks, physical media:

- wired, wireless communication links

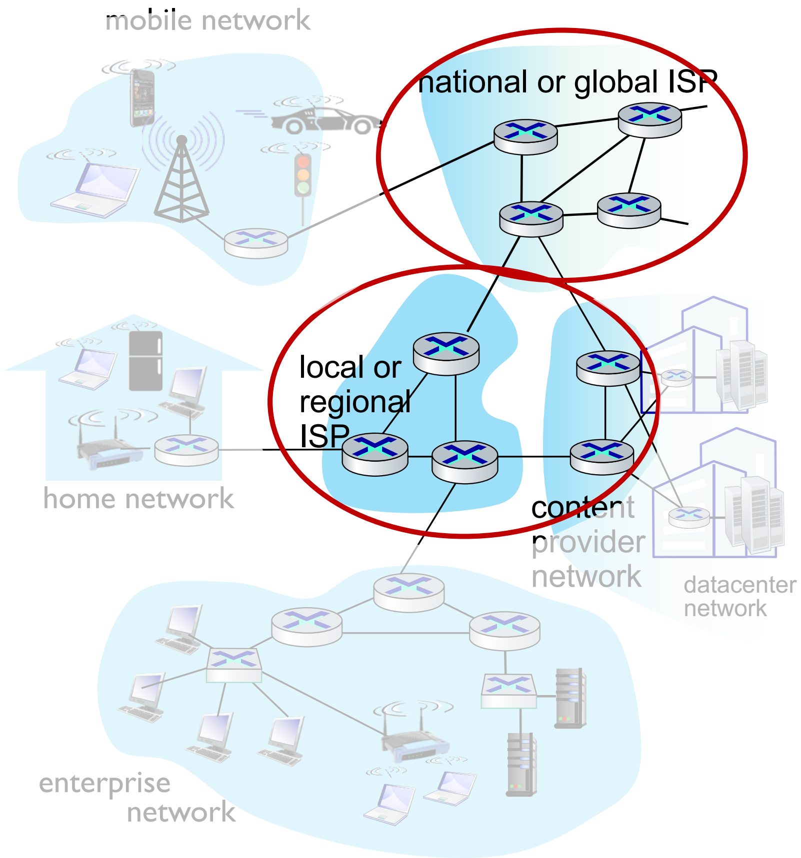


A closer look at Internet structure

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



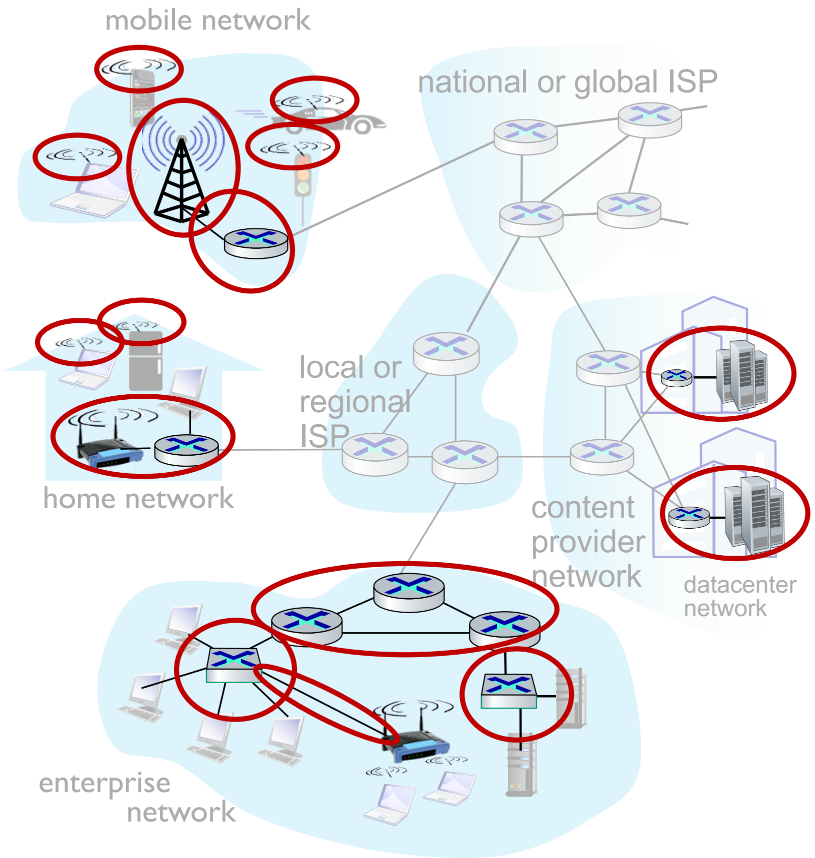
Access networks and physical media

Q: How to connect end systems to edge router?

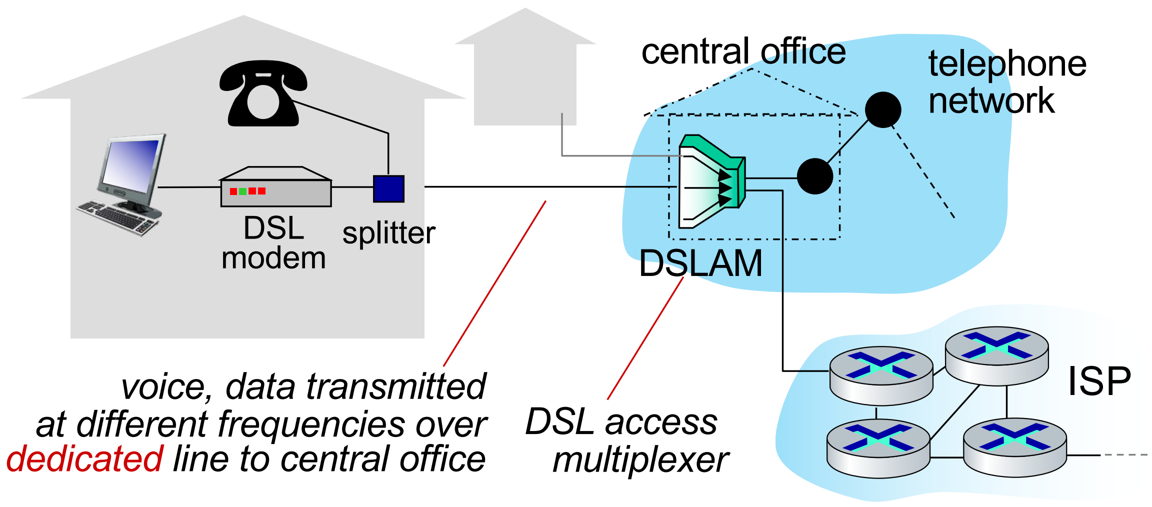
- residential access nets
- institutional access networks (school, company)
- mobile access networks (WiFi, 4G/5G)

What to look for:

- transmission rate (bits per second) of access network?
- shared or dedicated access among users?

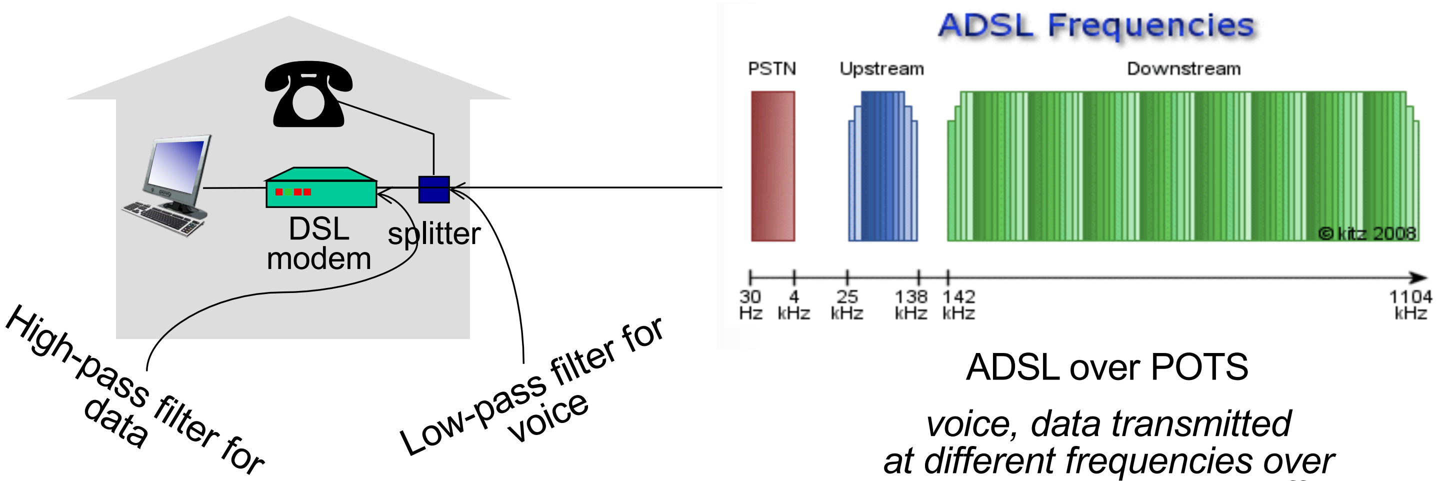


Access networks: digital subscriber line (DSL)



- 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

Access net: digital subscriber line (DSL)



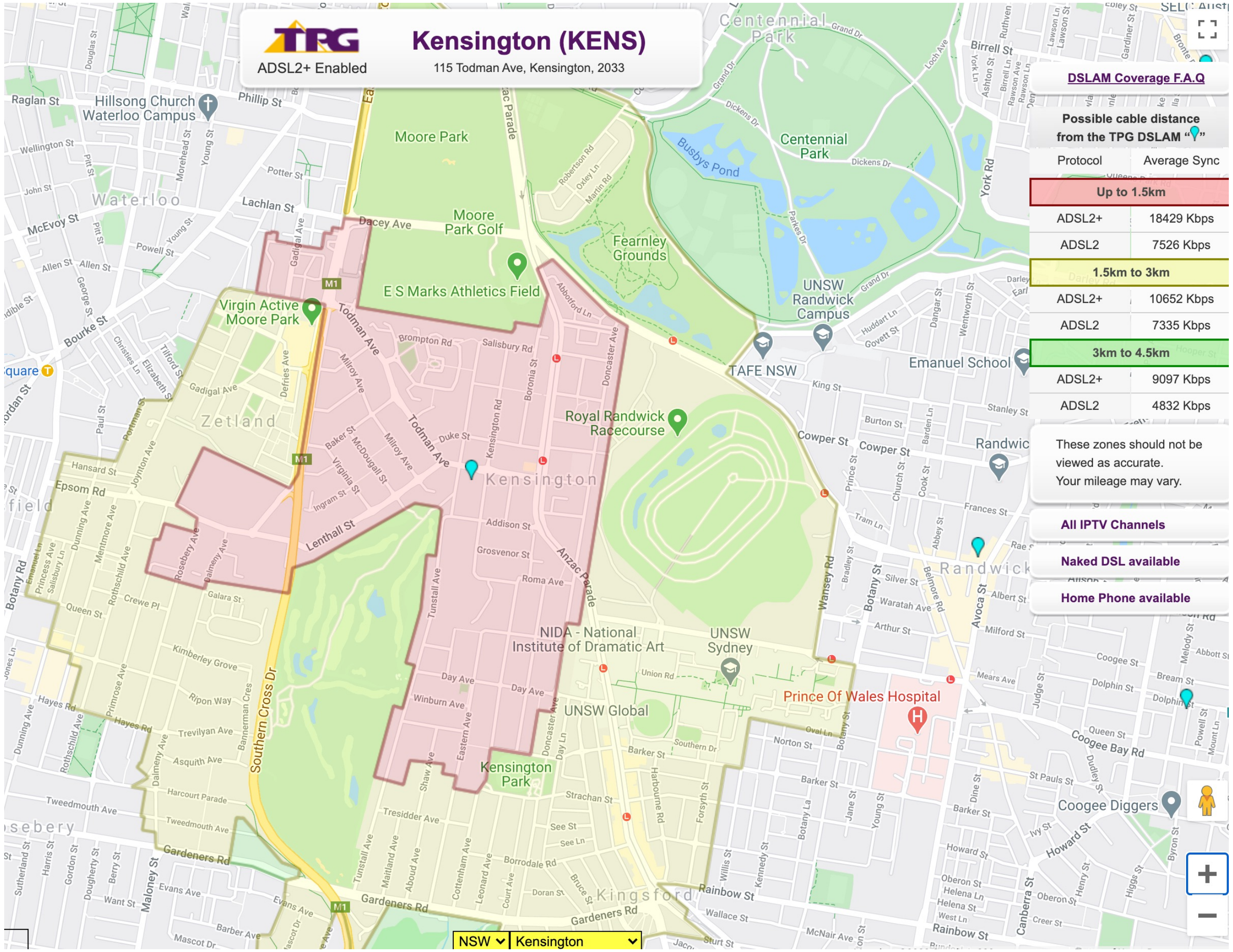
ADSL over POTS

voice, data transmitted at different frequencies over dedicated line to central office

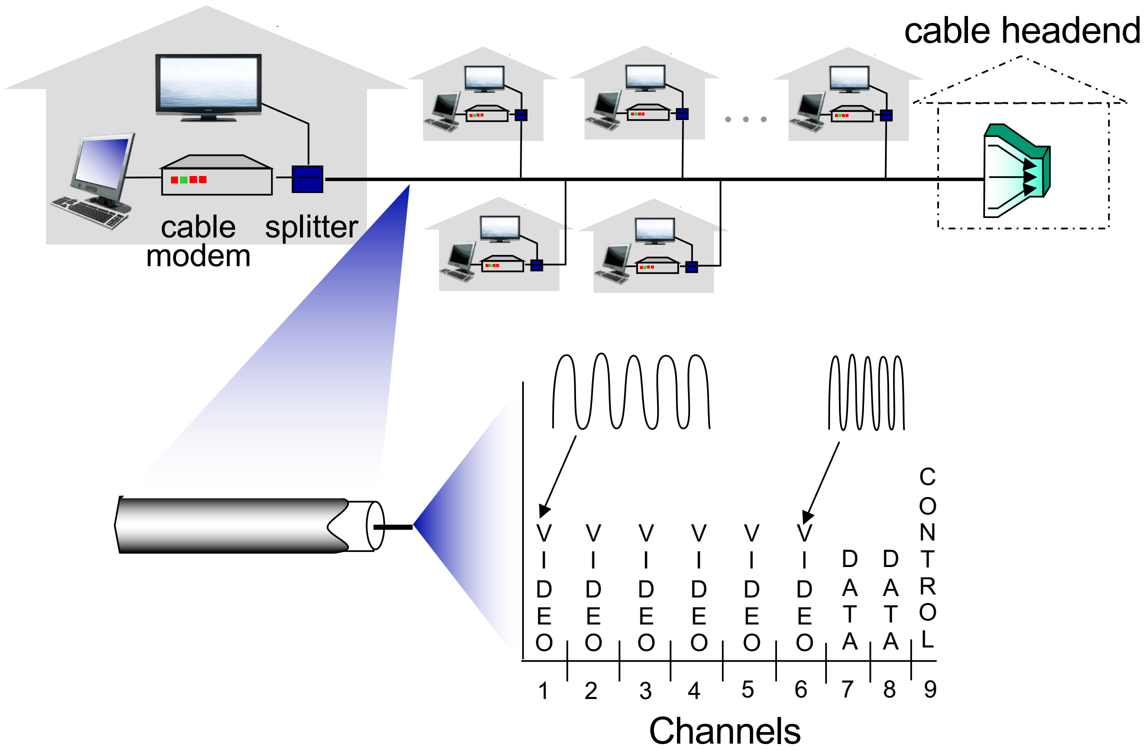
Different data rates for upload and download (ADSL)

- 24-52 Mbps dedicated downstream transmission rate
- 3.5-16 Mbps dedicated upstream transmission rate

Access net: digital subscriber line (DSL)

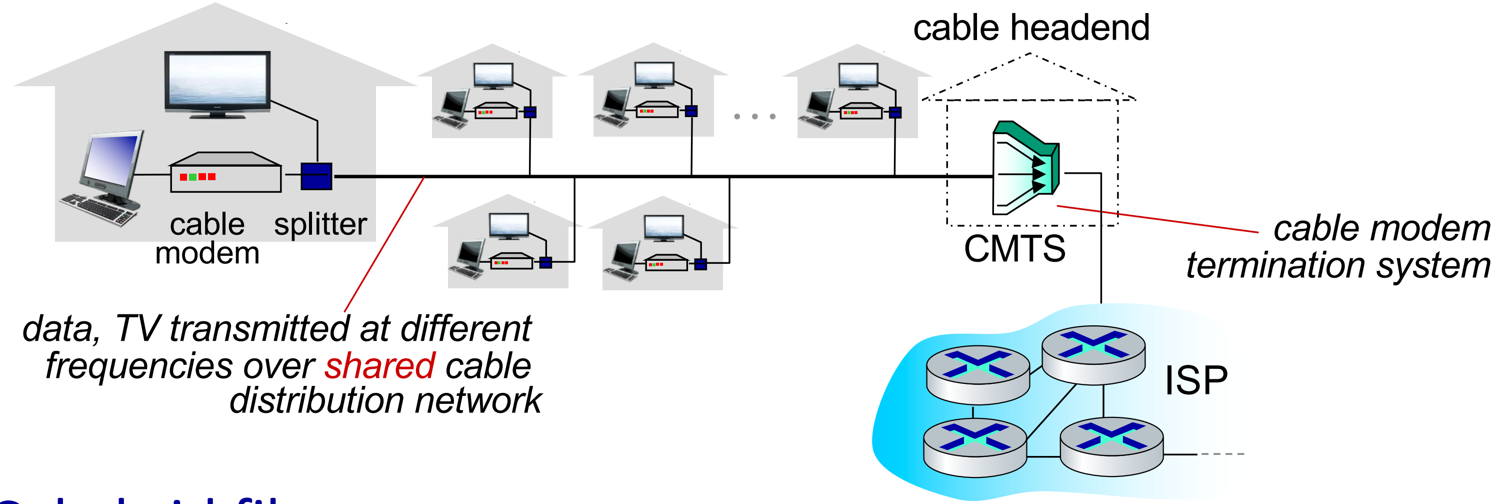


Access networks: cable-based access



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

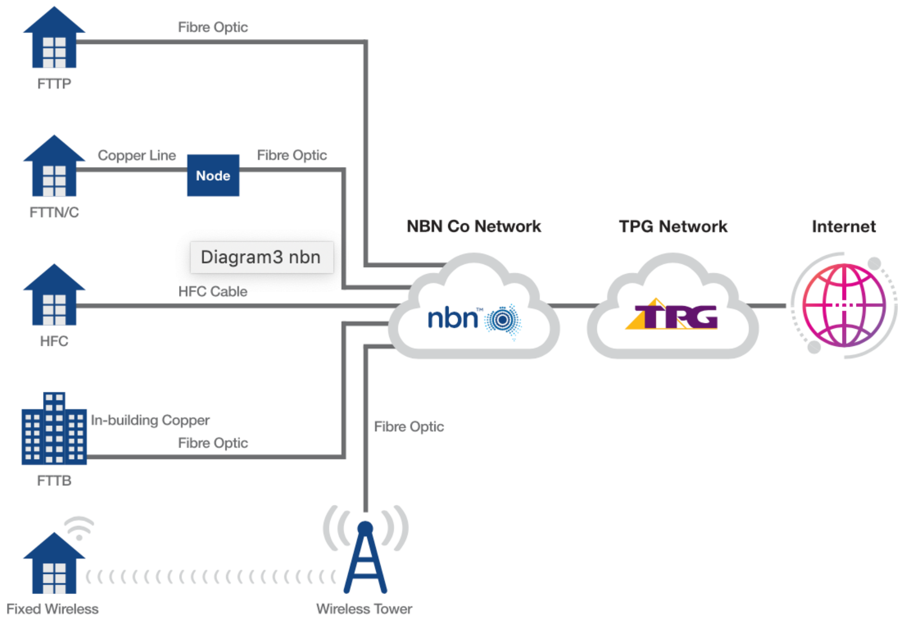
Access networks: cable-based access

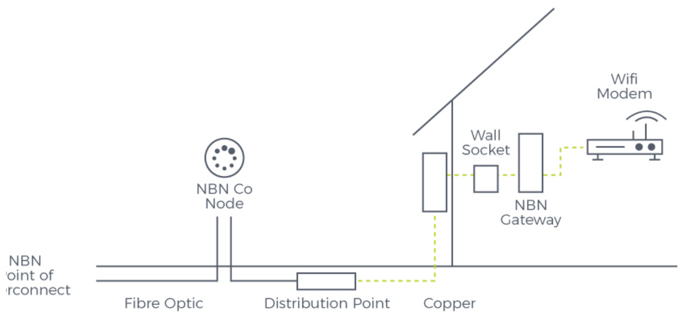


- HFC: hybrid fiber coax
  - asymmetric: up to 40 Mbps – 1.2 Gbs downstream transmission rate, 30-100 Mbps upstream transmission rate
- network of cable, fiber attaches homes to ISP router
  - homes *share access network* to cable headend
  - Unlike DSL, which has dedicated access to central office

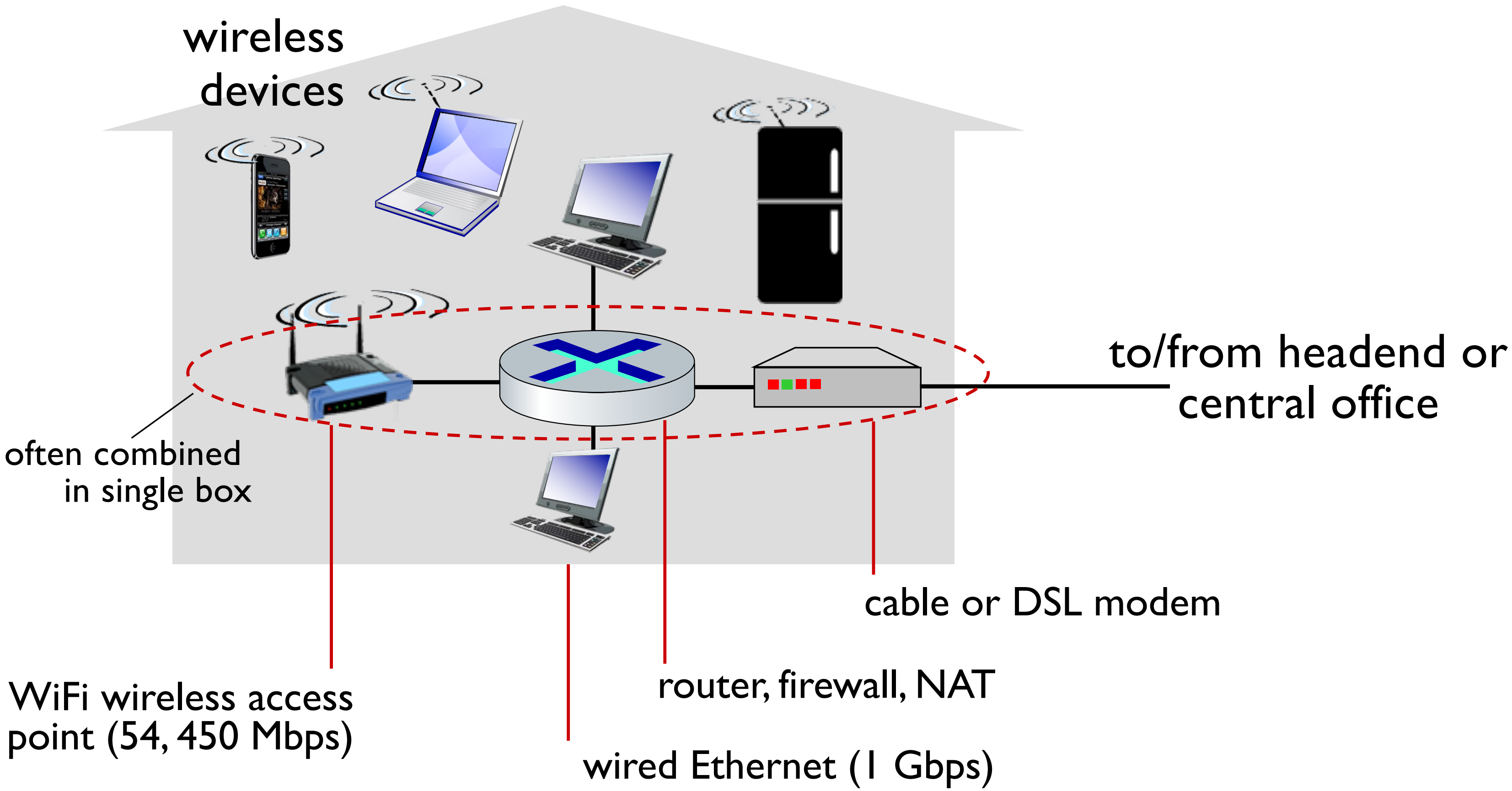
Fiber to the home/premise/curb

- Fully optical fiber path all the way to the home (or premise or curb)
  - e.g., NBN, Google, Verizon FIOS
  - ~30 Mbps to 1Gbps





Access networks: home networks



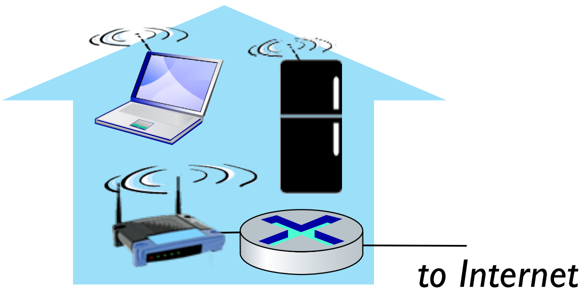
Wireless access networks

Shared *wireless* access network connects end system to router

- via base station aka "access point"

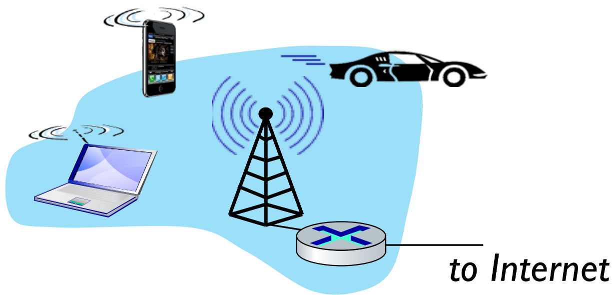
Wireless local area networks (WLANs)

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

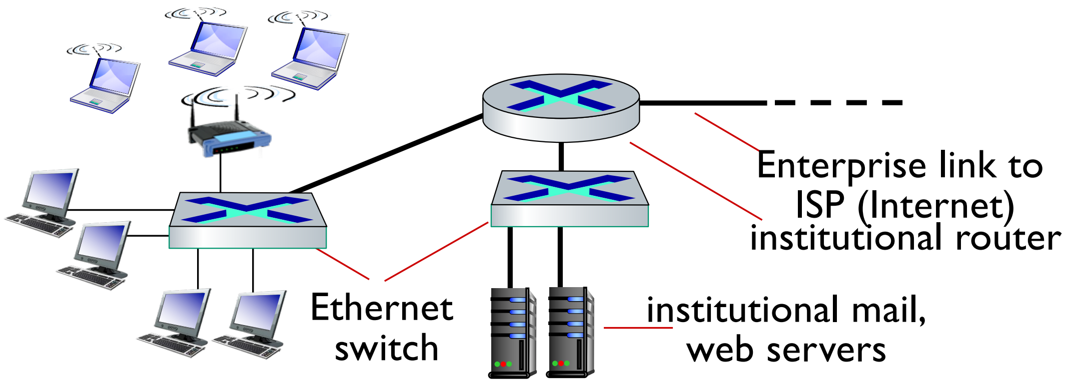


Wide-area cellular access networks

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



Access networks: enterprise networks

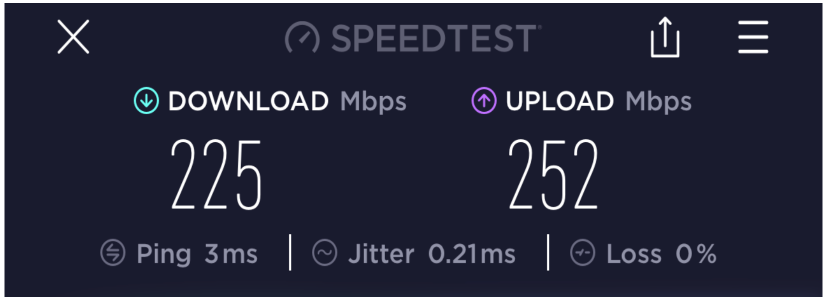


- companies, universities, etc.
- mix of wired, wireless link technologies, connecting a mix of switches and routers (we'll cover differences shortly)
  - Ethernet: wired access at 100Mbps, 1Gbps, 10Gbps
  - WiFi: wireless access points at 11, 54, 450 Mbps

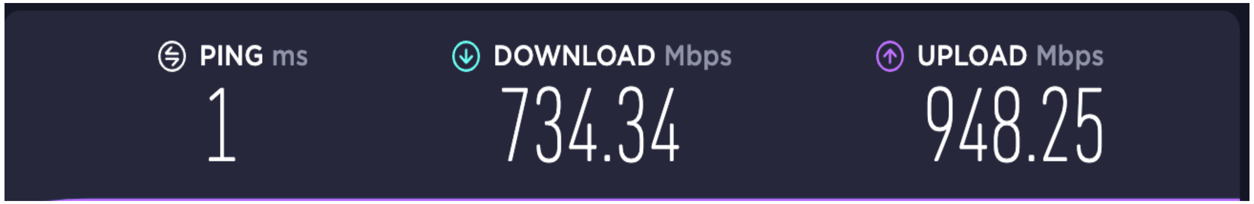
Sample results

Can you explain the differences?

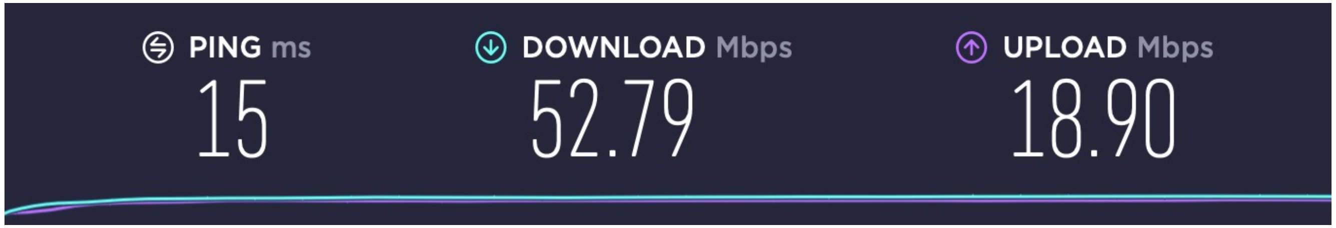
Uniwide



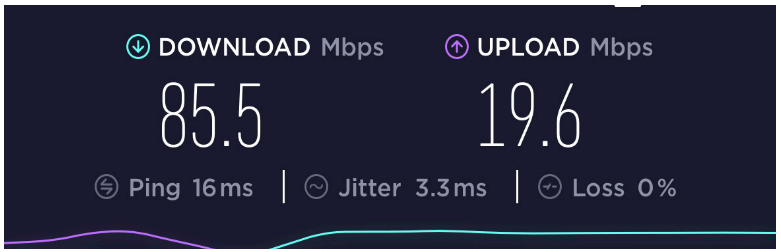
Wired Network @ CSE



FTTC + Cable + WiFi @ my home



4G Network



Quiz: Your access network

Your residential ISP provides connectivity using the following technology:

A. DSL

B. Cable

C. Fiber to the home/premise/curb

D. Mobile (3G/4G/5G)

E. Satellite

F. Something Else

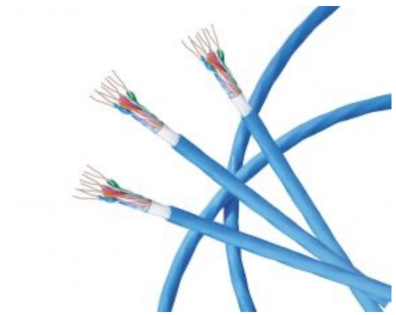
Links: physical media

SELF STUDY
NOT ON EXAM

- 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

SELF STUDY
NOT ON EXAM

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

SELF STUDY
NOT ON EXAM

Wireless radio

- signal carried in electromagnetic spectrum
- no physical "wire"
- broadcast and "half-duplex" (sender to receiver)
- propagation environment effects:
  - reflection
  - obstruction by objects
  - interference

Radio link types:

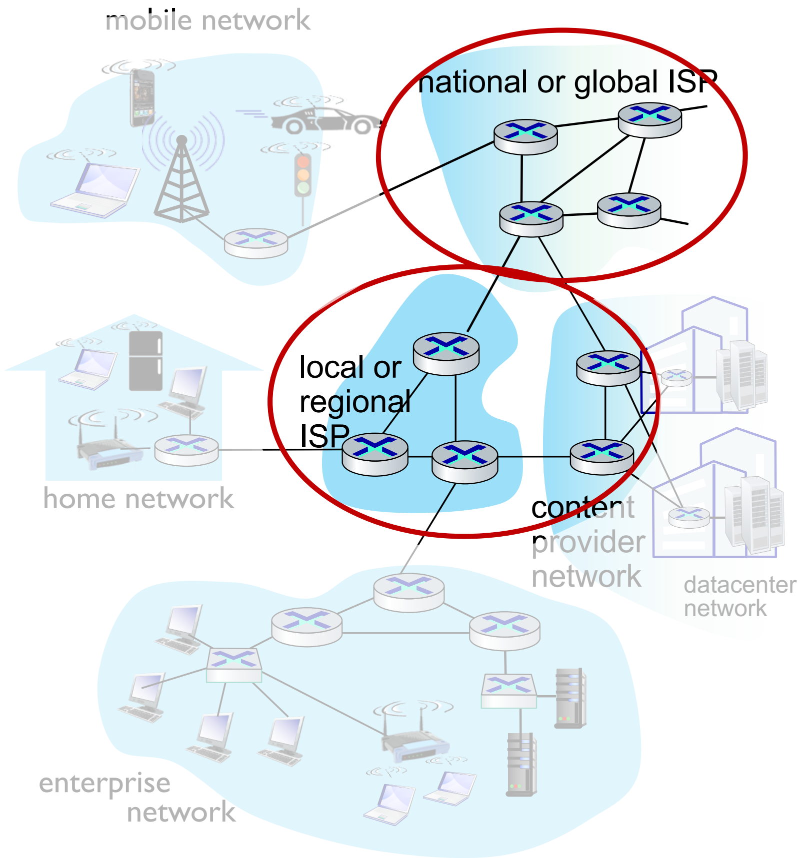
- terrestrial microwave
  - up to 45 Mbps channels
- Wireless LAN (WiFi)
  - Up to 100's Mbps
- wide-area (e.g., cellular)
  - 4G cellular: ~ 10's Mbps
- satellite
  - up to 45 Mbps per channel
  - 270 msec end-end delay
  - geosynchronous versus low-earth-orbit

Introduction: 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

The network core

- mesh of interconnected routers
- packet-switching: hosts break application-layer messages into *packets*
  - forward packets from one router to the next, across links on path from source to destination
  - each packet transmitted at full link capacity
  - **Is used in the Internet**

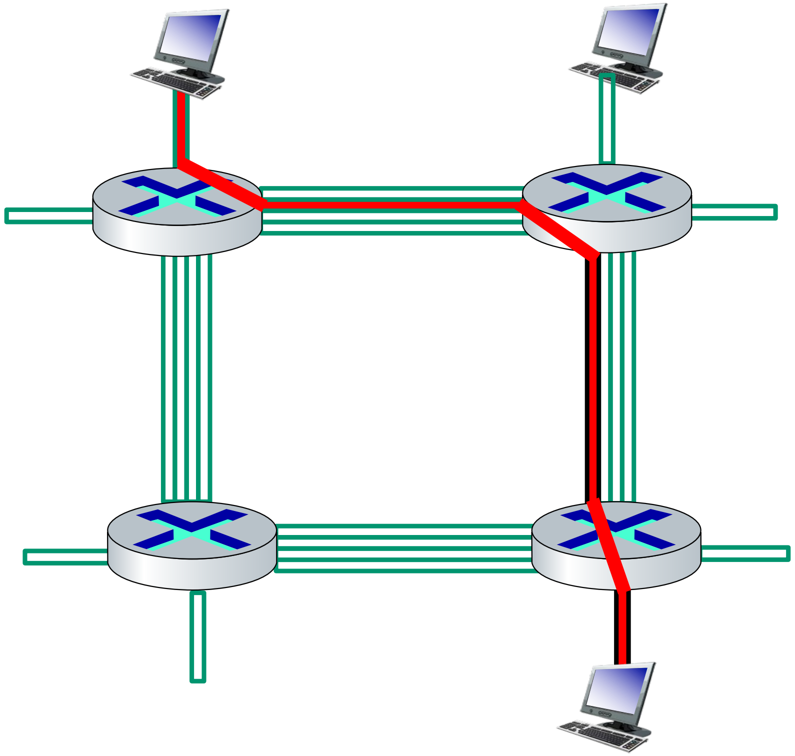


- circuit-switching: an alternative used in legacy telephone networks which was considered during the design of the Internet

Alternative to packet switching: circuit switching

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

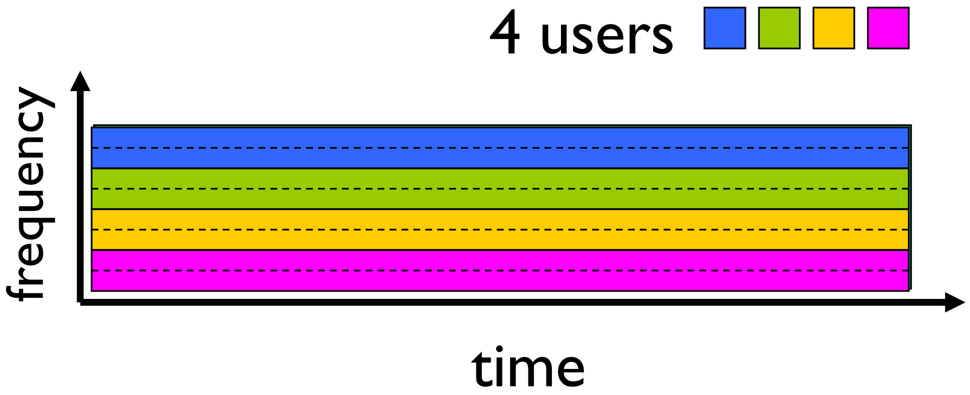
- in diagram, each link has four circuits.
  - call gets 2nd circuit in top link and 1st circuit in right link.
- dedicated resources: no sharing
  - circuit-like (guaranteed) performance
- circuit segment idle if not used by call (no sharing)
- commonly used in traditional telephone networks



Circuit switching: FDM and TDM

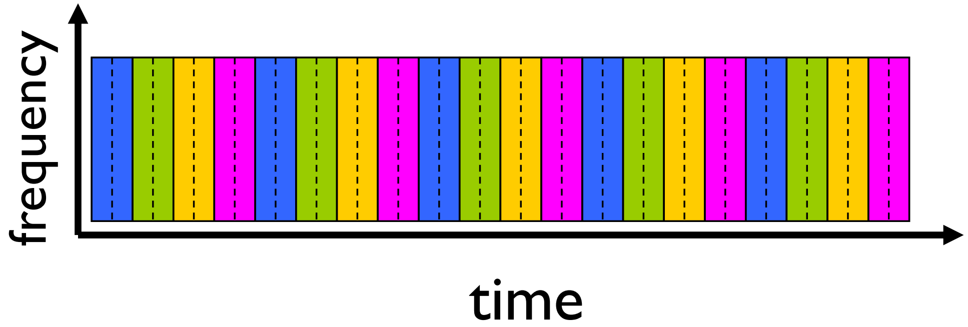
Frequency Division Multiplexing (FDM)

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

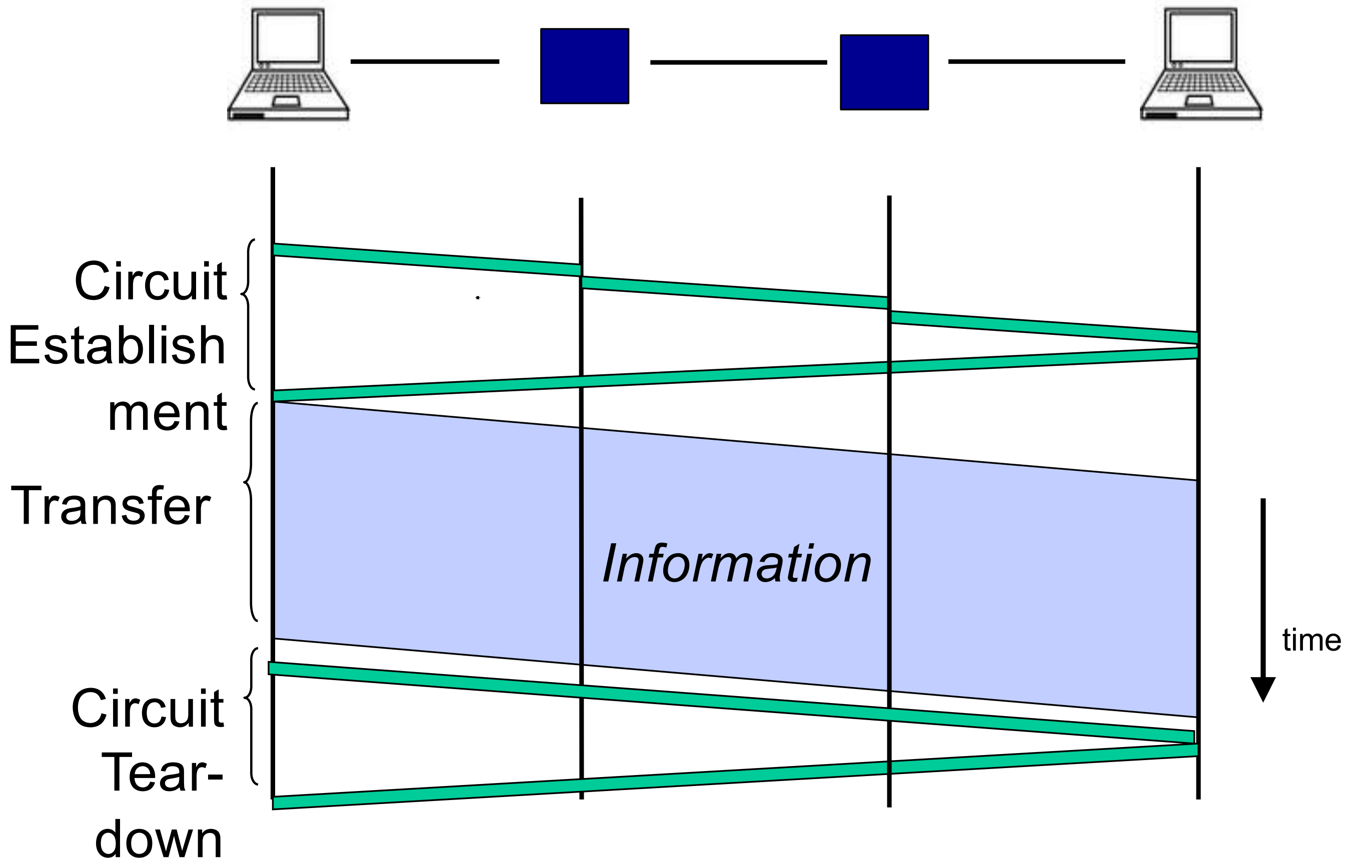


Time Division Multiplexing (TDM)

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



Timing in Circuit Switching

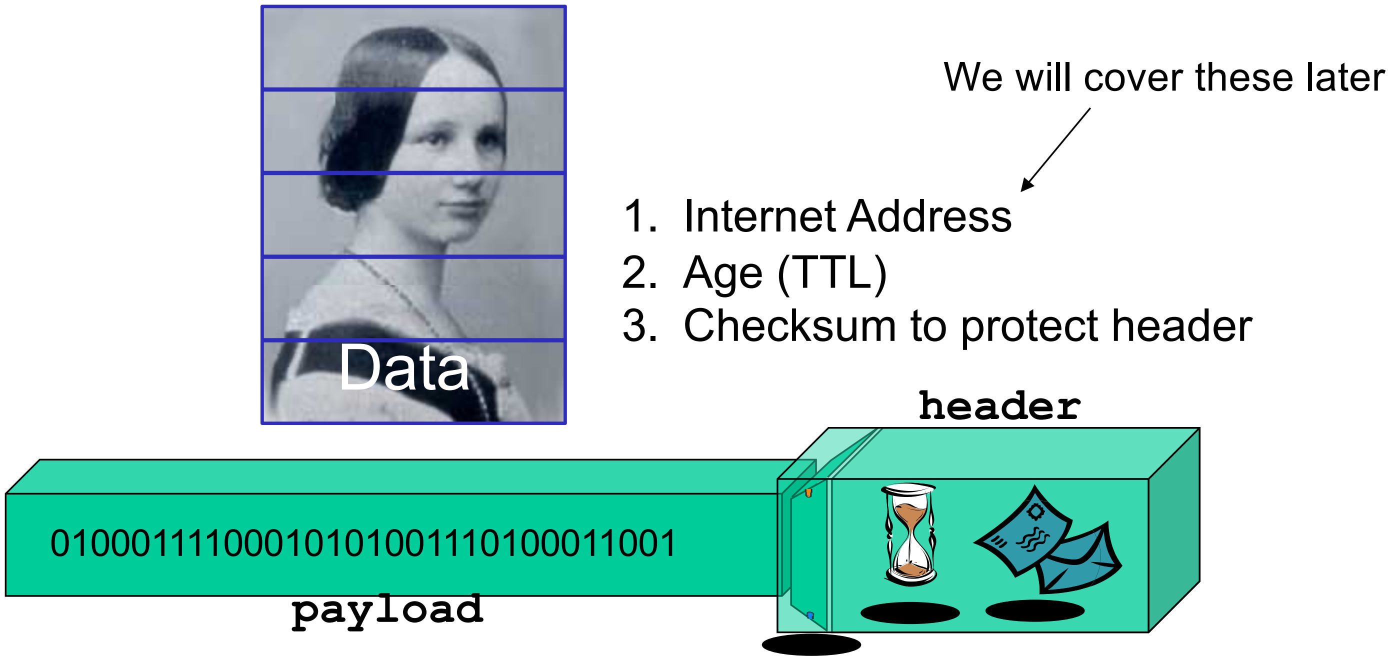


Why circuit switching is not feasible?

- Inefficient
  - Computer communications tends to be very bursty. For example, viewing a sequence of web pages
  - Dedicated circuit cannot be used or shared in periods of silence
  - Cannot adapt to network dynamics
- Fixed data rate
  - Computers communicate at very diverse rates. For example, viewing a video vs using telnet or web browsing
  - Fixed data rate is not useful
- Connection state maintenance
  - Requires per communication state to be maintained that is a considerable overhead
  - Not scalable

Packet Switching

- Data is sent as chunks of formatted bits (Packets)
- Packets consist of a "header" and "payload"



Packet Switching

- Data is sent as chunks of formatted bits (Packets)
- Packets consist of a "header" and "payload"
  - payload is the data being carried
  - header holds instructions to the network for how to handle packet (think of the header as an API)

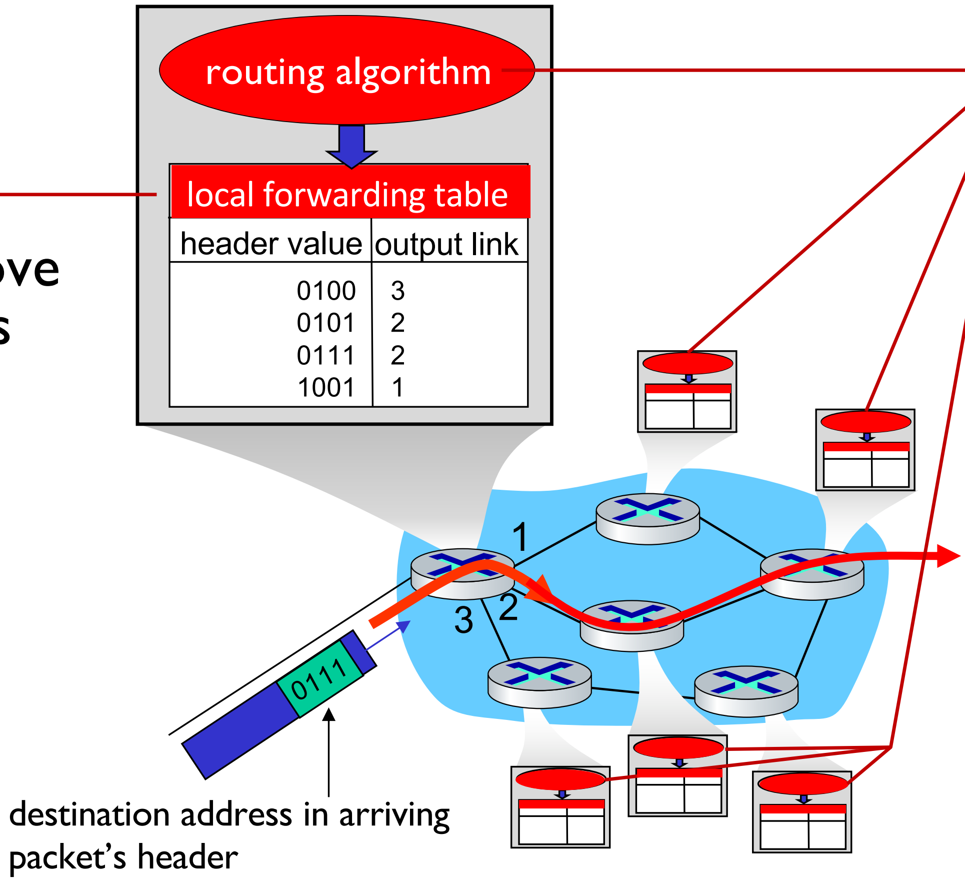
Packet Switching

- Data is sent as chunks of formatted bits (Packets)
- Packets consist of a "header" and "payload"
- Switches "forward" packets based on their headers

Peek ahead: Two key network-core functions

Forwarding:

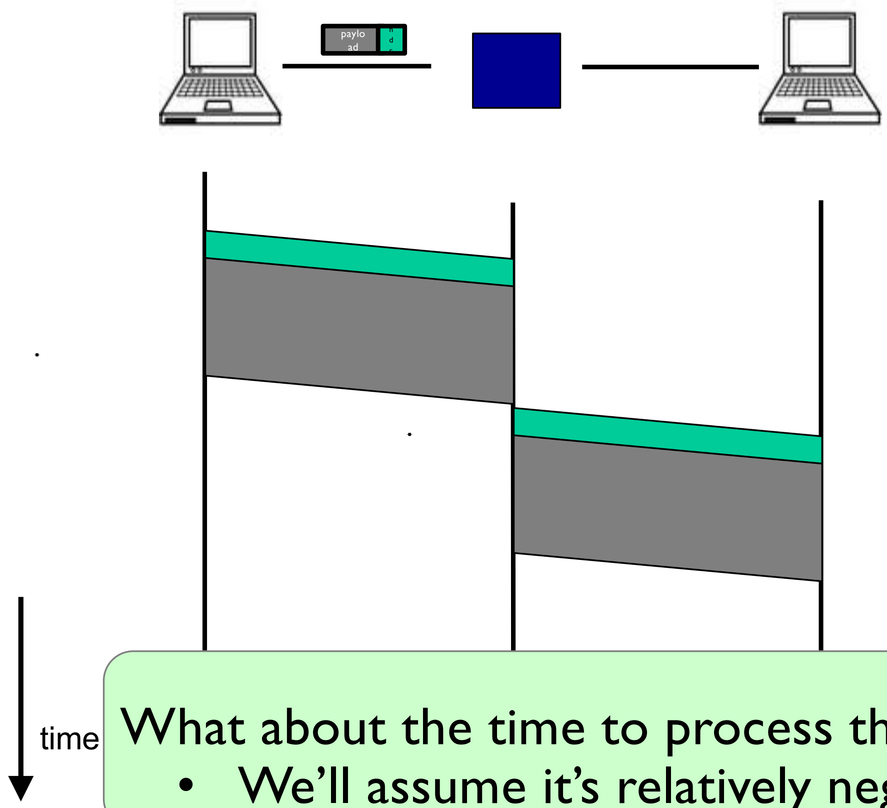
- *local* action: move arriving packets from router's input link to appropriate router output link



Routing:

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

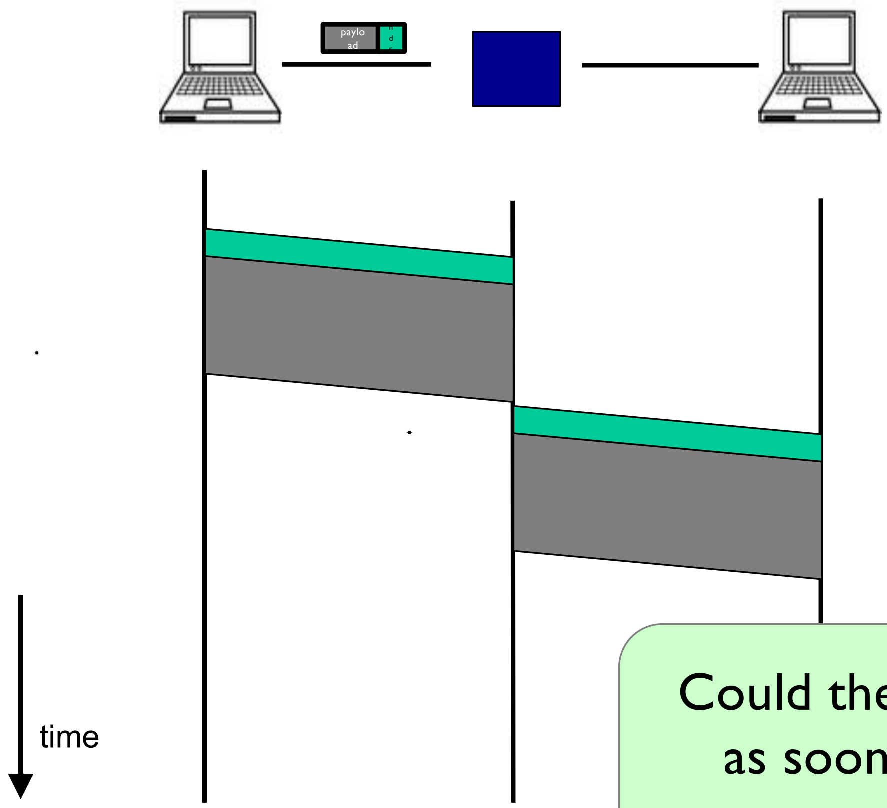
Timing in Packet Switching



What about the time to process the packet at the switch?

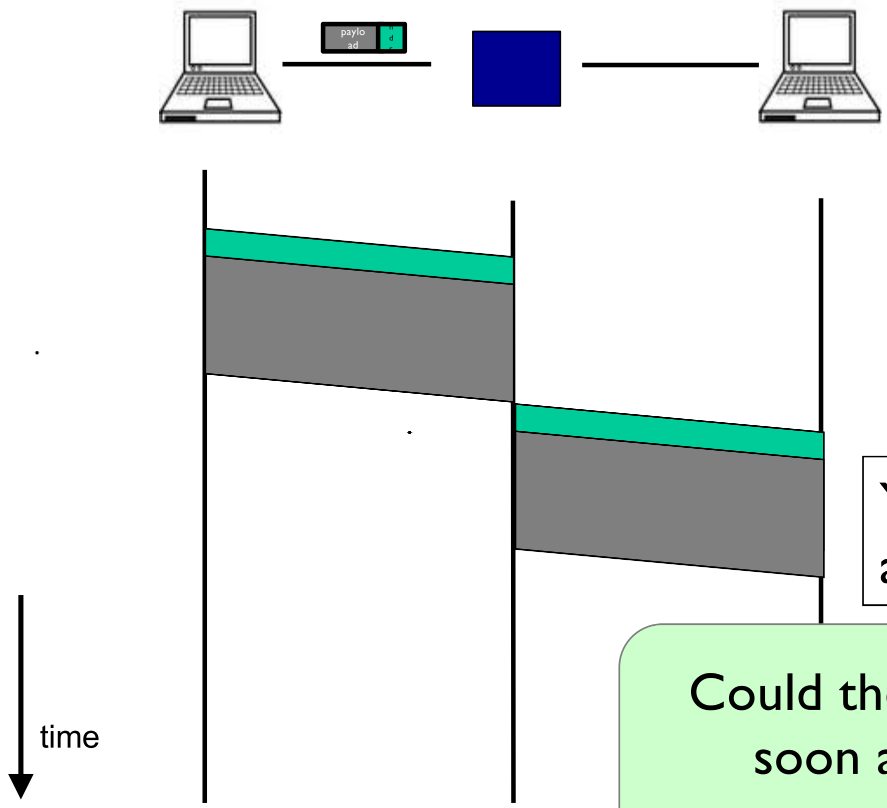
- We'll assume it's relatively negligible (mostly true)

Timing in Packet Switching



Could the switch start transmitting as soon as it has processed the header?

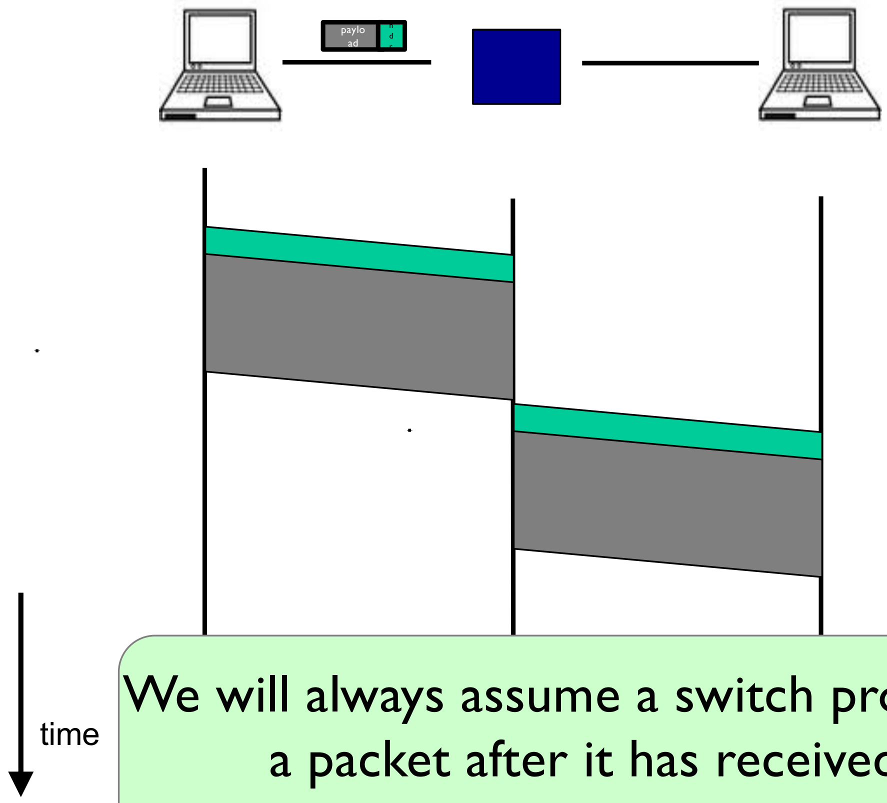
Timing in Packet Switching



Yes! This would be called a “cut through” switch

Could the switch start transmit as soon as it has processed the header?

Timing in Packet Switching



We will always assume a switch processes/forwards a packet after it has received it entirely.
This is called "store and forward" switching

Packet Switching

- Data is sent as chunks of formatted bits (Packets)
- Packets consist of a "header" and "payload"
- Switches "forward" packets based on their headers

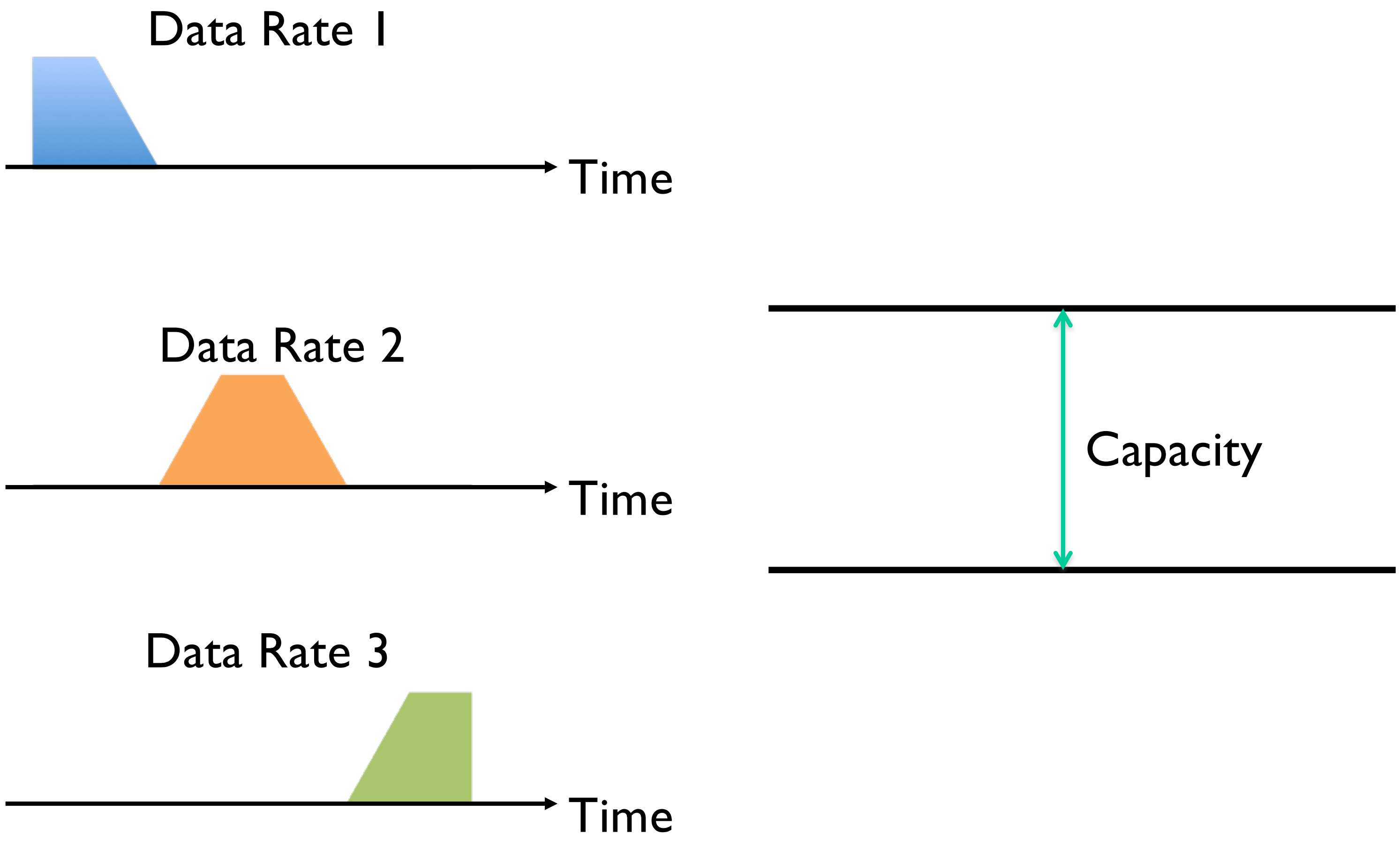
Packet Switching

- Data is sent as chunks of formatted bits (Packets)
- Packets consist of a “header” and “payload”
- Switches “forward” packets based on their headers
- Each packet travels independently
  - no notion of packets belonging to a “circuit”

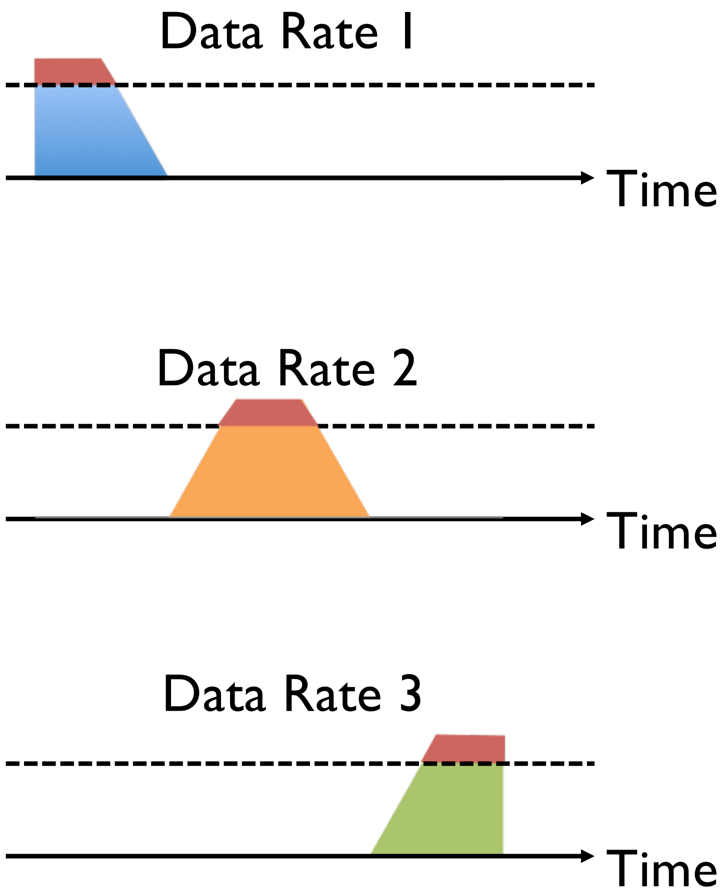
Packet Switching

- Data is sent as chunks of formatted bits (Packets)
- Packets consist of a "header" and "payload"
- Switches "forward" packets based on their headers
- Each packet travels independently
- No link resources are reserved. Instead, packet switching leverages statistical multiplexing

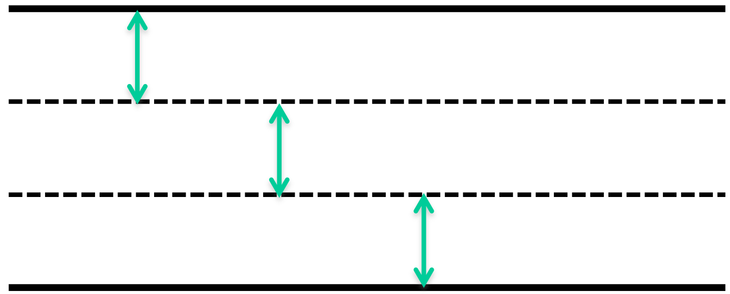
Three Flows with Bursty Traffic



When Each Flow Gets 1/3rd of Capacity

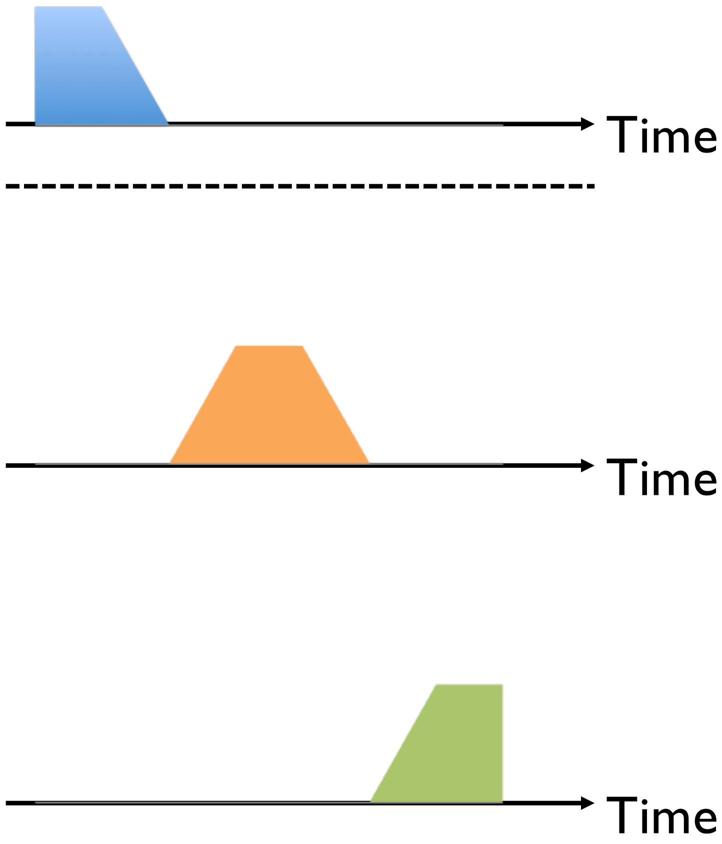


like circuit switching



Overloaded

When Flows Share Total Capacity



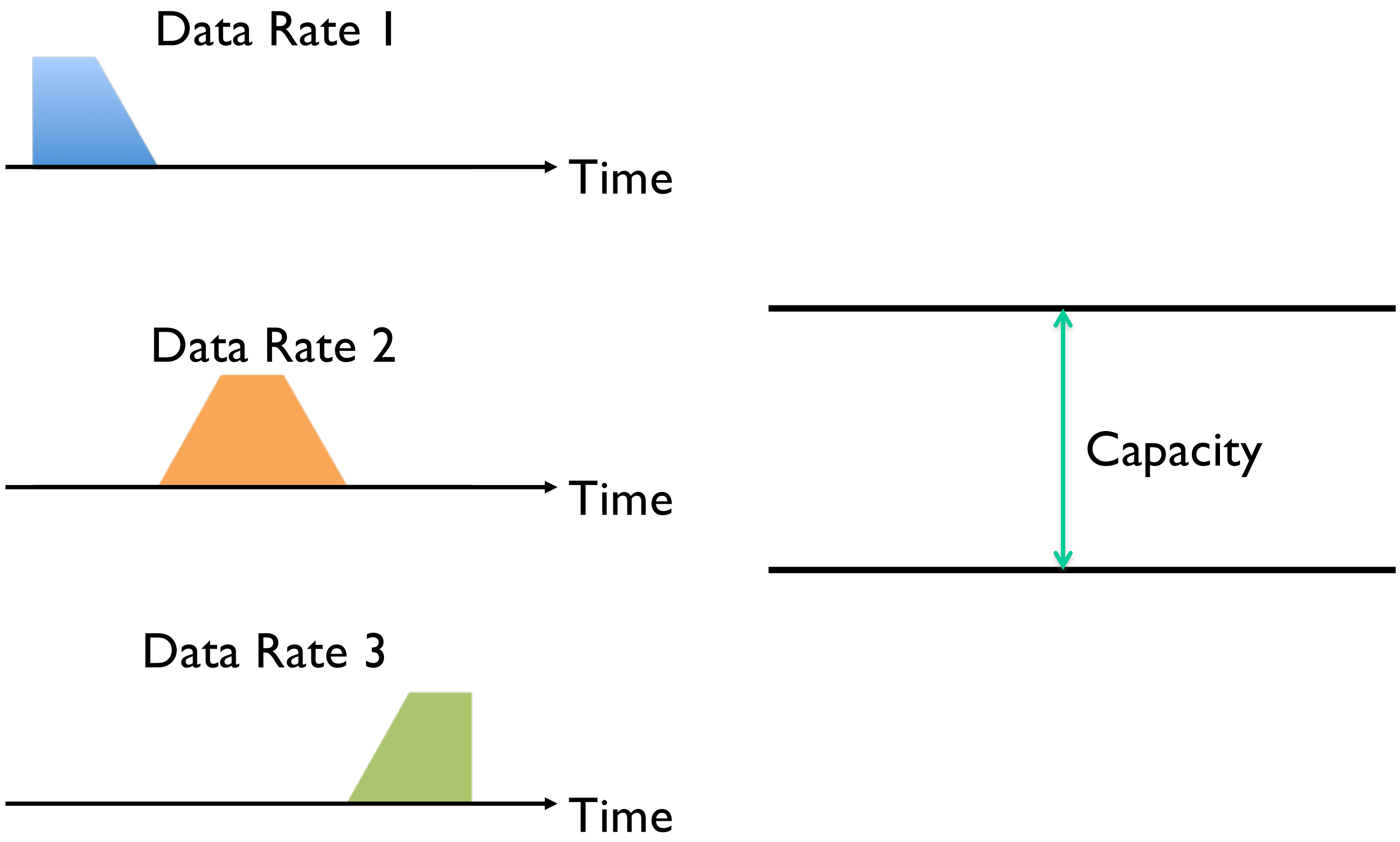
packet switching

No Overloading

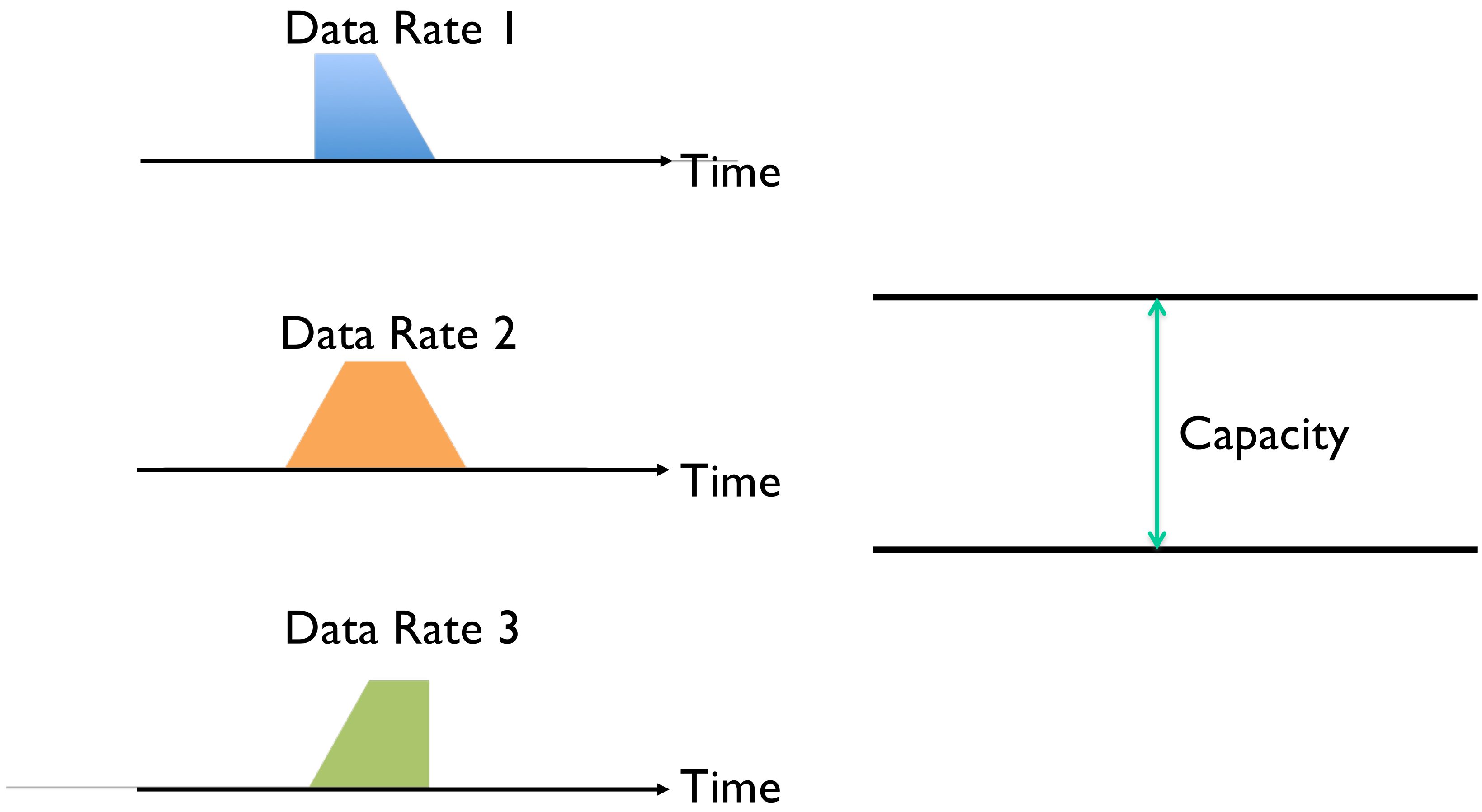
Statistical multiplexing relies on the assumption that not all flows burst at the same time

Very similar to insurance, and has same failure case

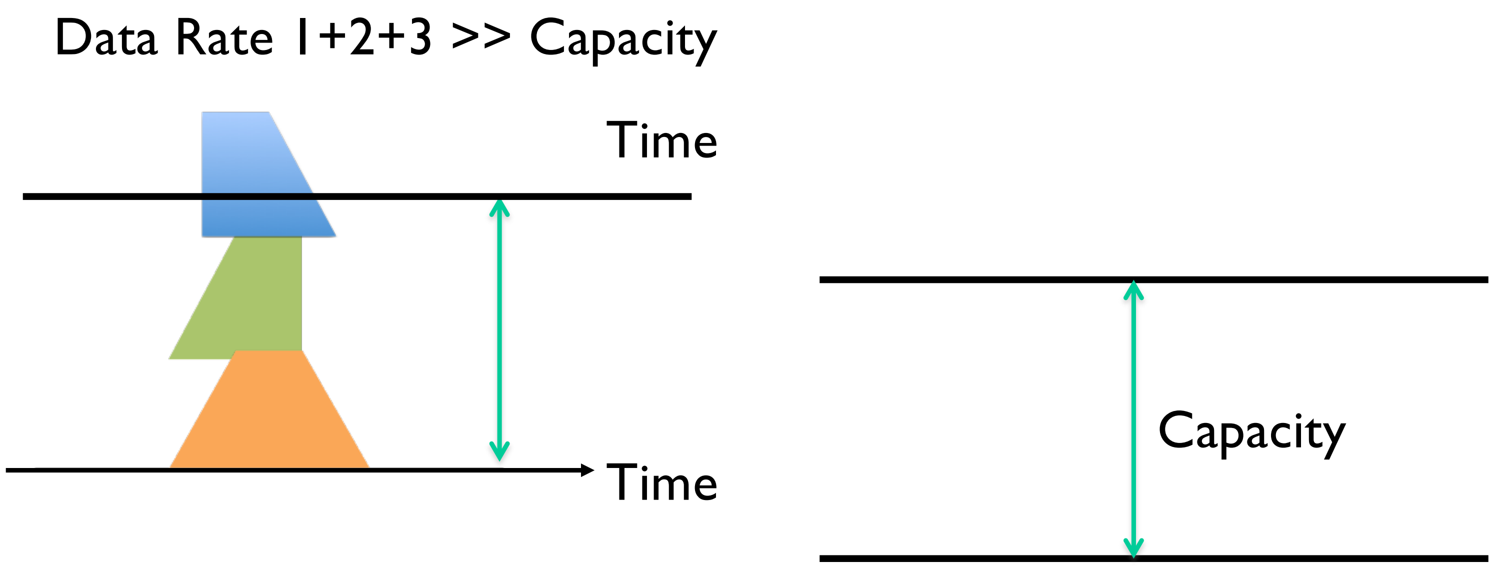
Three Flows with Bursty Traffic



Three Flows with Bursty Traffic

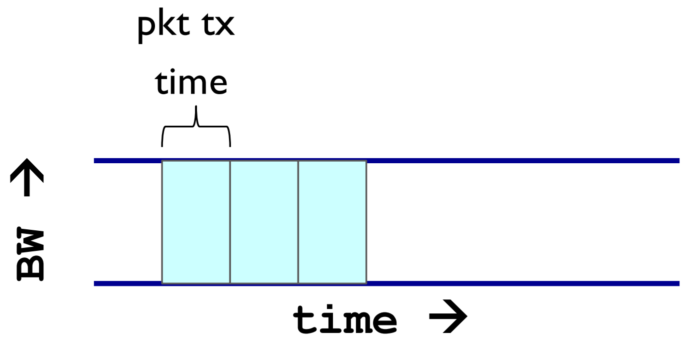


Three Flows with Bursty Traffic

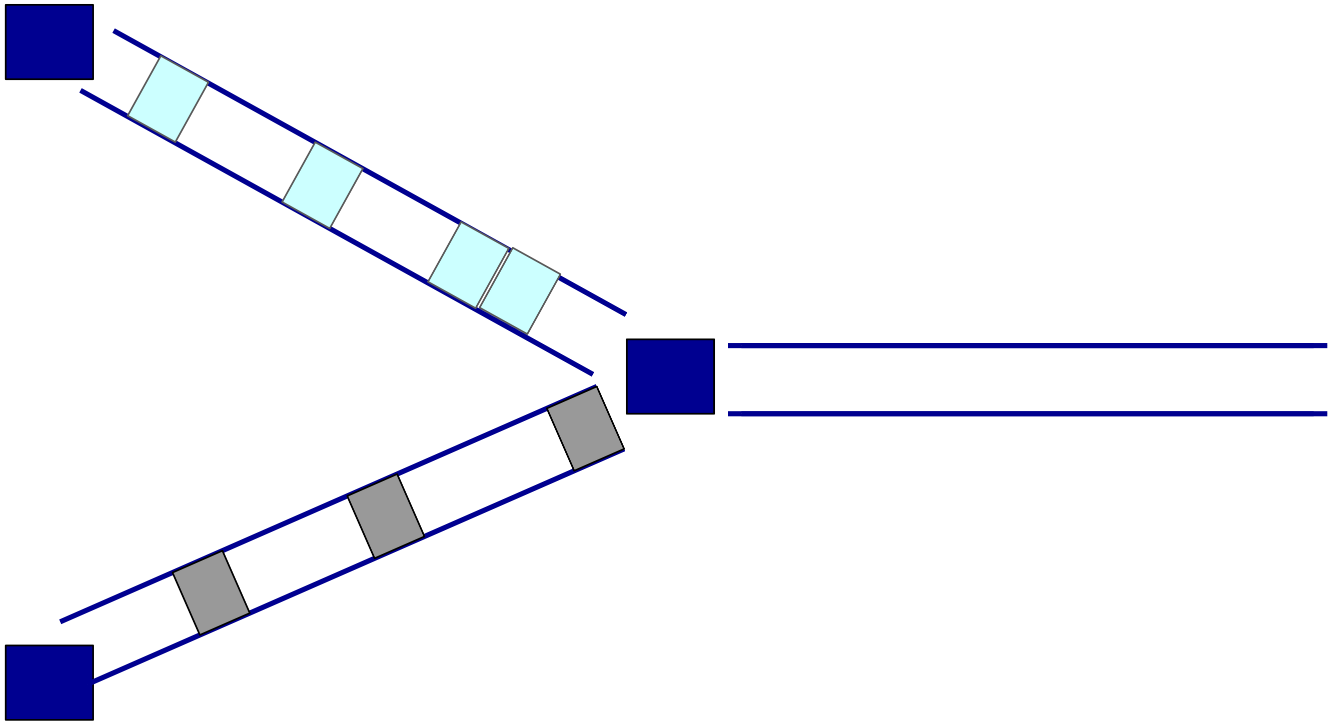


What do we do under overload?

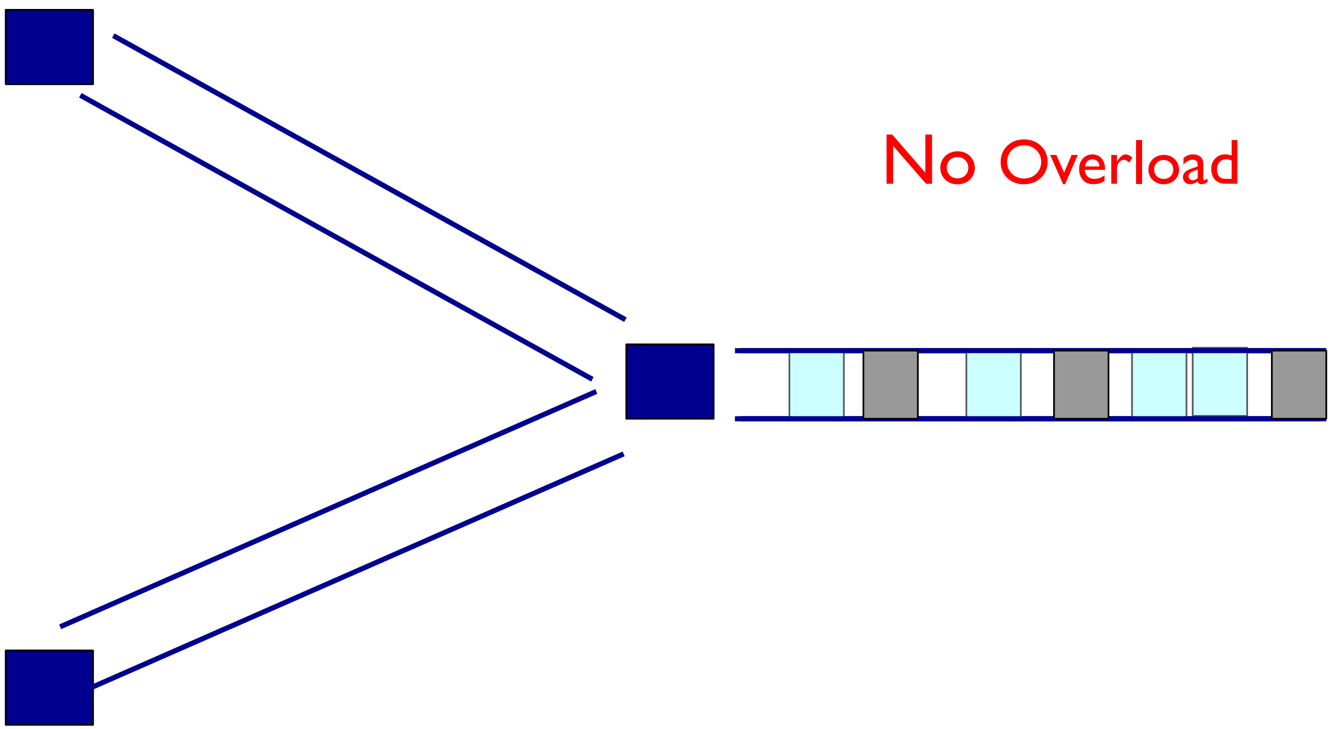
Statistical multiplexing: pipe view



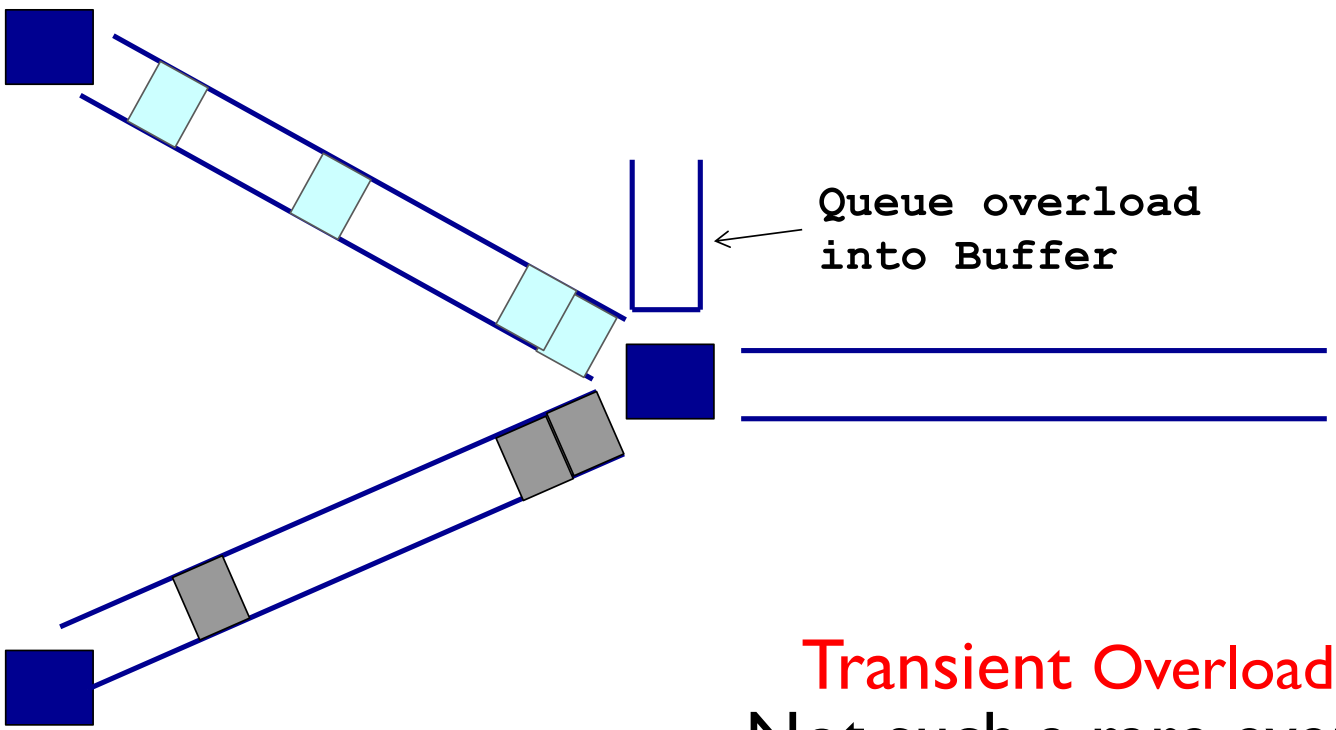
Statistical multiplexing: pipe view



Statistical multiplexing: pipe view

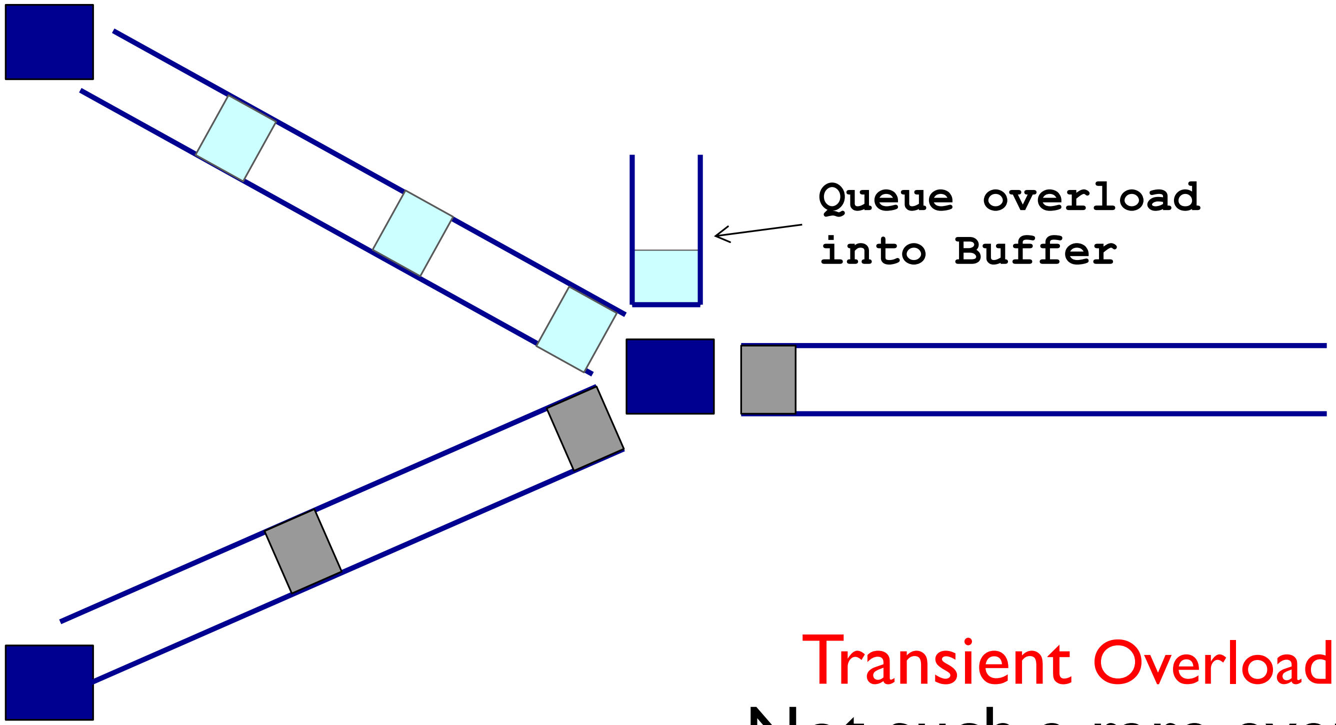


Statistical multiplexing: pipe view



Transient Overload
Not such a rare event

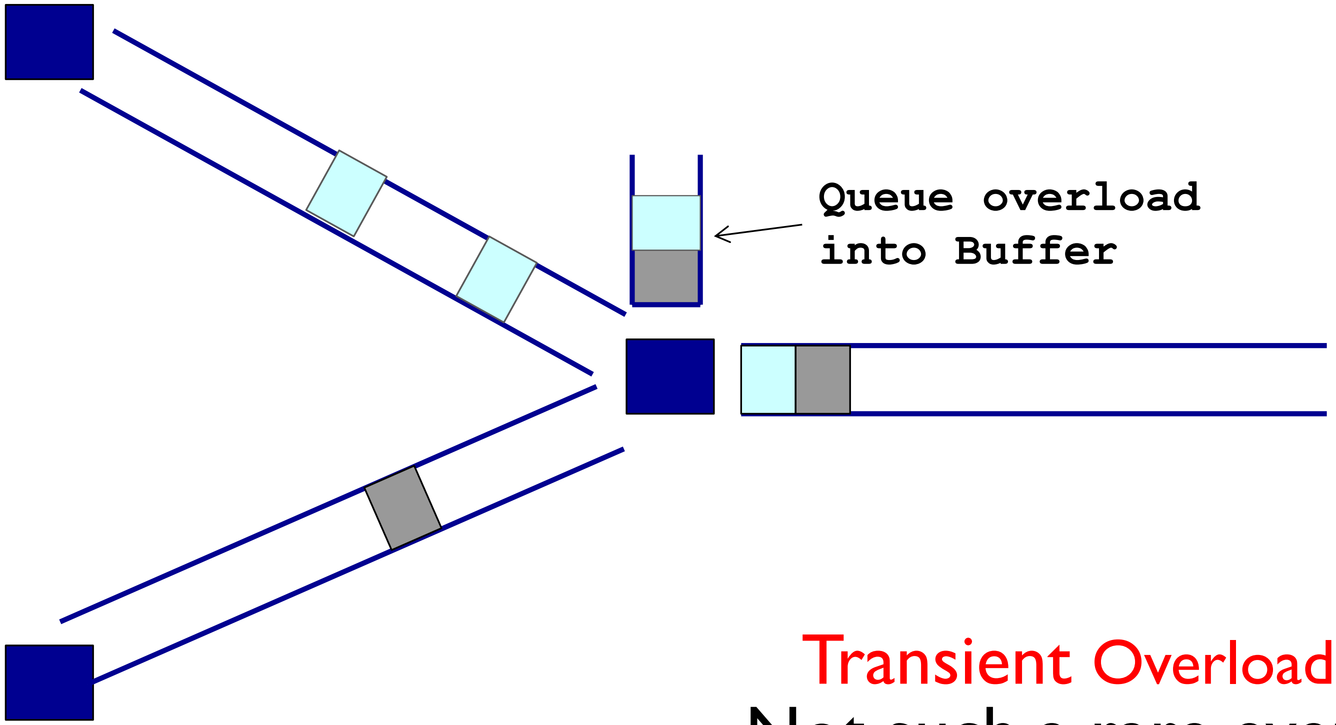
Statistical multiplexing: pipe view



Transient Overload

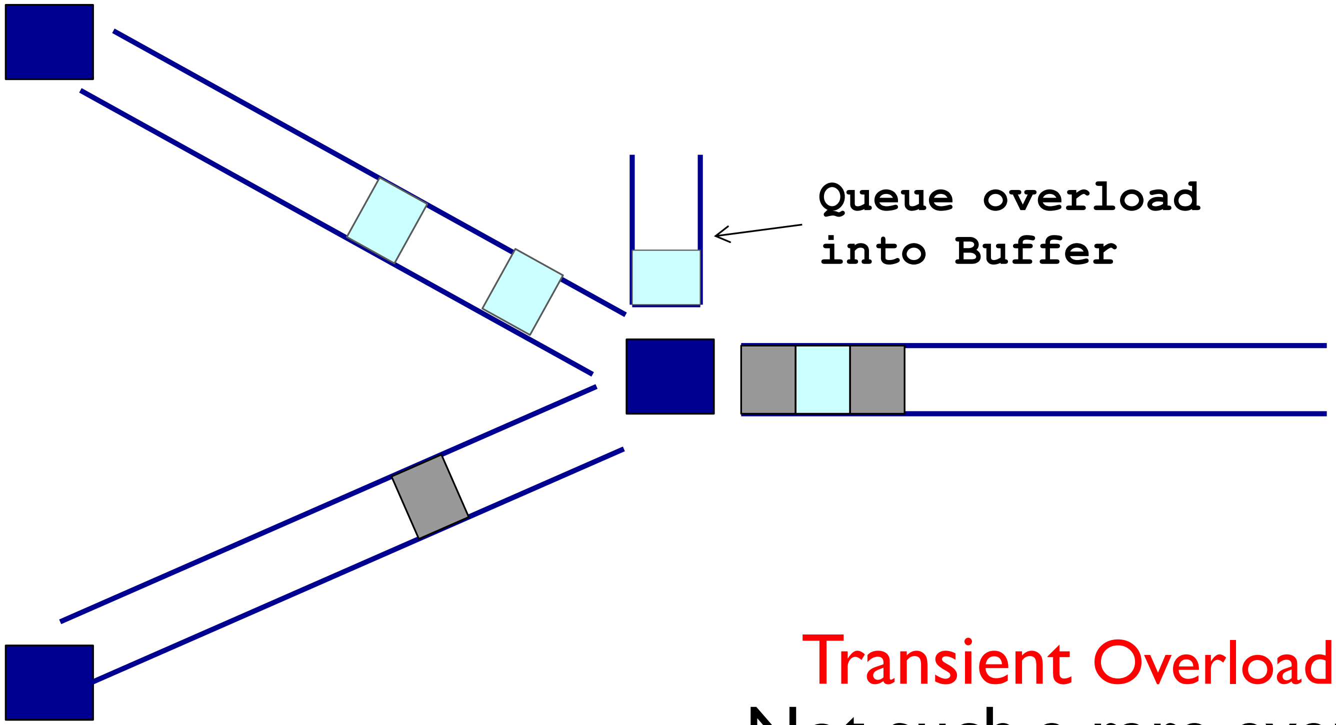
Not such a rare event

Statistical multiplexing: pipe view



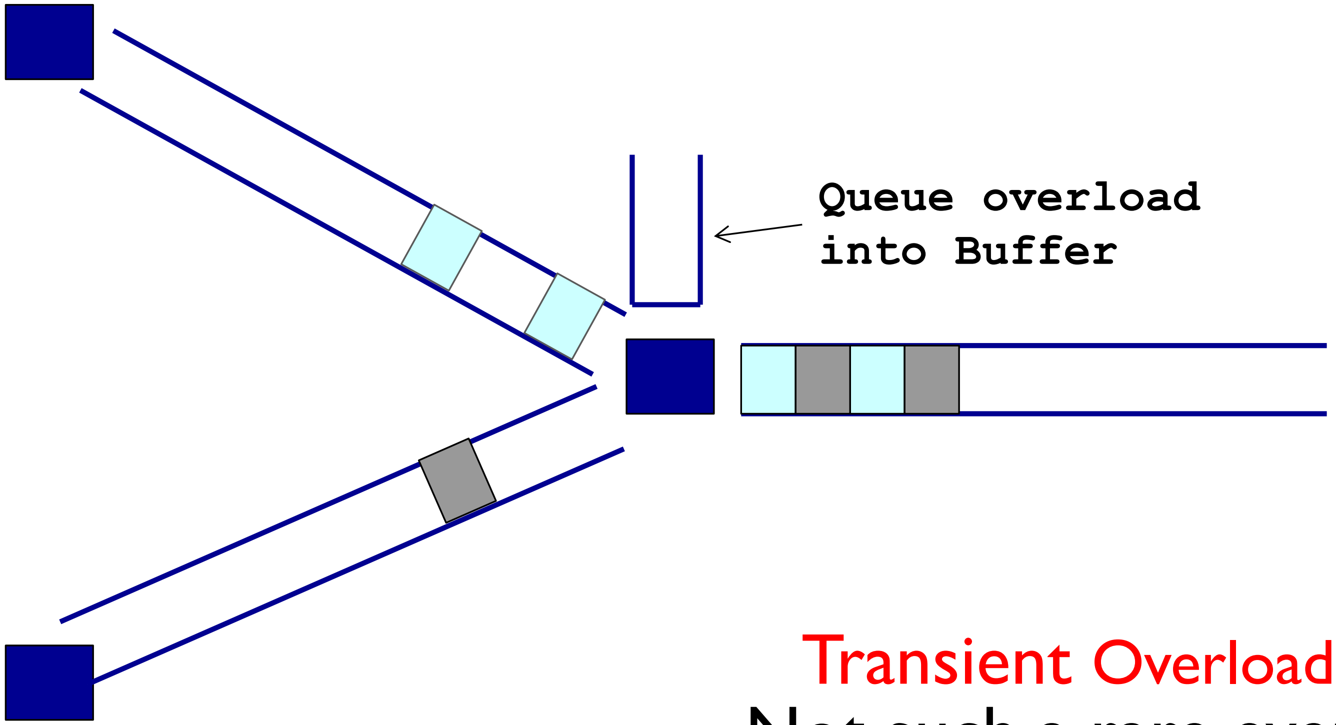
Transient Overload
Not such a rare event

Statistical multiplexing: pipe view



Transient Overload
Not such a rare event

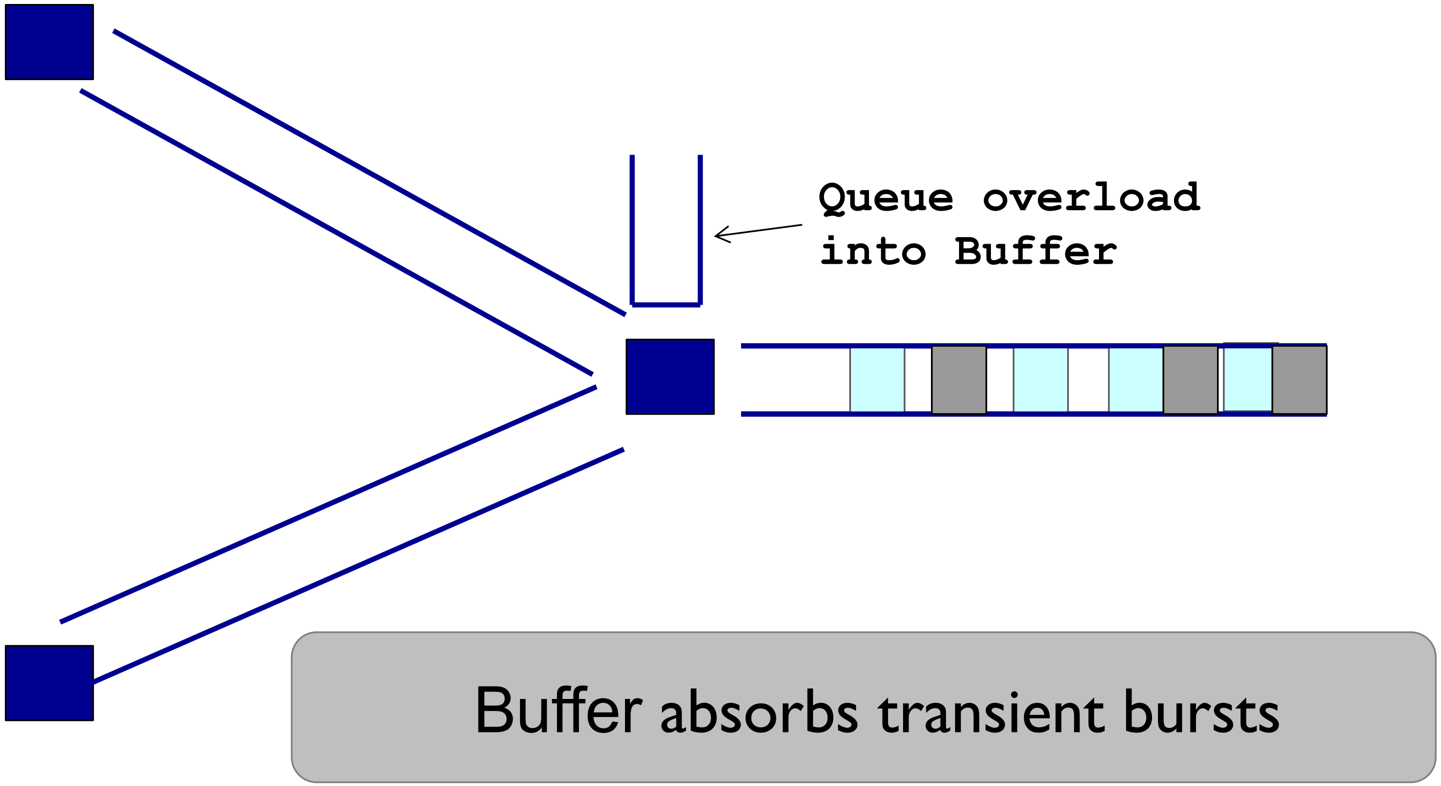
Statistical multiplexing: pipe view



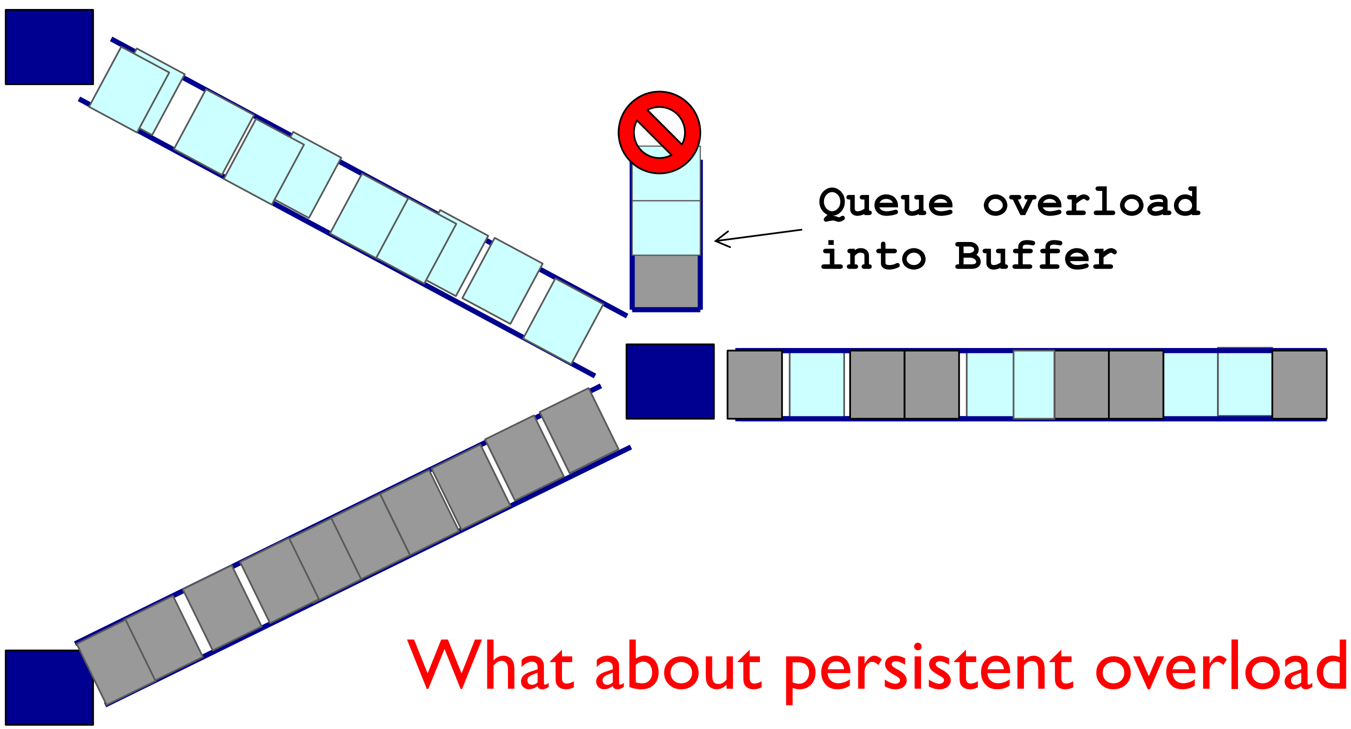
Transient Overload

Not such a rare event

Statistical multiplexing: pipe view



Statistical multiplexing: pipe view



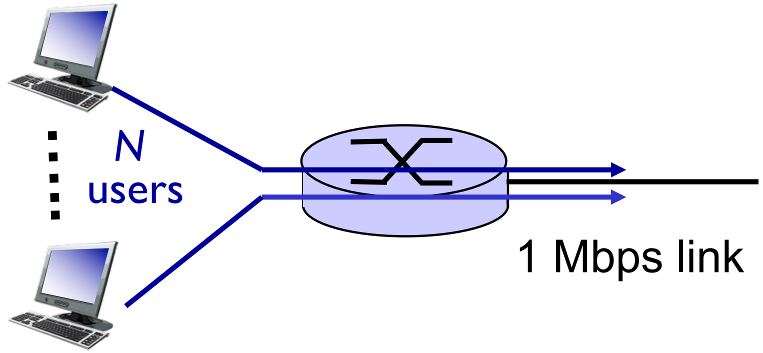
What about persistent overload?

Will eventually drop packets

Packet switching versus circuit switching

packet switching allows more users to use network!

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



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

Q: how did we get value 0.0004?

Q: what happens if > 35 users say 70?

Hint: Bernoulli Trials and Binomial Distribution

Binomial Probability Distribution

- A fixed number of observations (trials), n
  - E.g., 5 tosses of a coin
- Binary random variable
  - E.g., head or tail in a coin toss
  - Often called as success or failure
  - Probability of success is p and failure is (1-p)
- Constant probability for each observation

Binomial Distribution: Example

- Q: What is the probability of observing exactly 3 heads in a sequence of 5 coin tosses
- A:
  - One way to get exactly 3 heads is: HHHTT
  - Probability of this sequence occurring = (1/2) x (1/2) x (1/2) x (1-1/2) x (1-1/2) = $(1/2)^5$
  - Another way to get exactly 3 heads is: THHHT
  - Probability of this sequence occurring = (1-1/2) x (1/2) x (1/2) x (1/2) x (1-1/2) = $(1/2)^5$
  - How many such unique combinations exist?

Binomial Distribution: Example

$\binom{5}{3}$ ways to arrange 3 heads in 5 trials

$^5C_3 = 5!/3!2! = 10$

Outcome	Probability
THHHT	$(1/2)^3\ x\ (1/2)^2$
HHHTT	$(1/2)^3\ x\ (1/2)^2$
TTHHH	$(1/2)^3\ x\ (1/2)^2$
HTTHH	$(1/2)^3\ x\ (1/2)^2$
HHTTH	$(1/2)^3\ x\ (1/2)^2$
THTHH	$(1/2)^3\ x\ (1/2)^2$
HTHTH	$(1/2)^3\ x\ (1/2)^2$
HHTHT	$(1/2)^3\ x\ (1/2)^2$
THHTH	$(1/2)^3\ x\ (1/2)^2$
HTHHT	$(1/2)^3\ x\ (1/2)^2$

10 arrangements $x\ (1/2)^3\ x\ (1/2)^2$

The probability of each unique outcome (note: they are all equal)

P (3 heads and 2 tails) = 10 x $(1/2)^5$ = 0.3125

Binomial Distribution

Note the general pattern emerging → 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"=

n = number of trials

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

1-p = probability of failure

X = # successes out of *n* trials

p = probability of success

Packet switching versus circuit switching

- Let's revisit the earlier problem
- N = 35 users
- Prob (# active users > 10)= 1– Prob (# active = 10)
  – Prob (# active = 9)
  – Prob (# active = 8)
  ...
  – Prob (# active = 0)

where Prob (# active = 10) = C(35,10) x 0.1^{10} x 0.9^{25}

- Prob (# active users > 10) = 0.0004 (approx)

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?
  - bandwidth guarantees traditionally used for audio/video applications

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

Quiz: Switching-1

In _____________ resources are allocated on demand

A. Packet switching

B. Circuit switching

C. Both

D. None

Quiz: Switching-2

A message from device A to B consists of packet X and packet Y. In a circuit switched network, packet Y's path ____________________ packet X's path

A. is the same

B. is independent

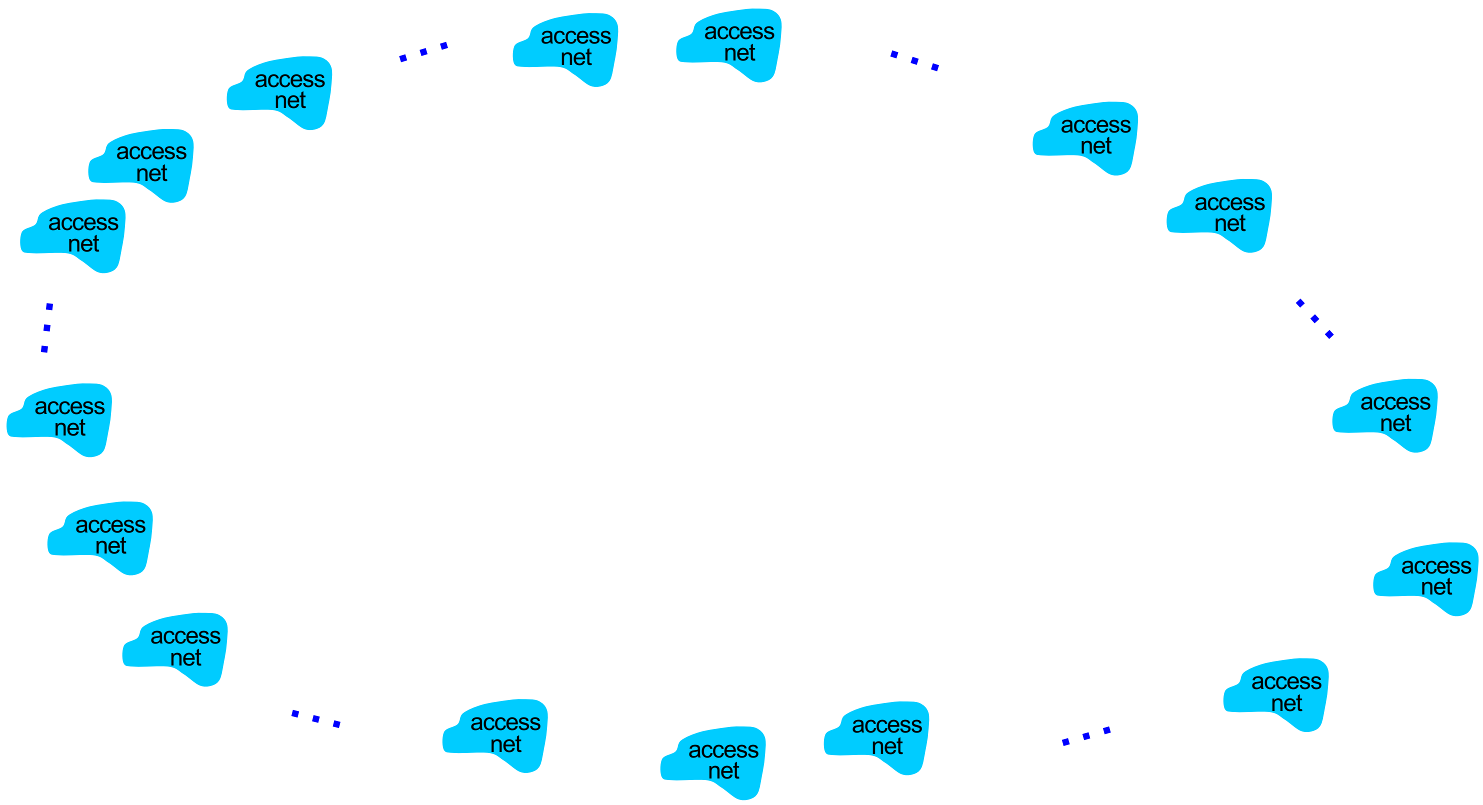
C. is always different from

Internet structure: a "network of networks"

- Hosts connect to Internet via access Internet Service Providers (ISPs)
  - residential, enterprise (company, university, commercial) 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

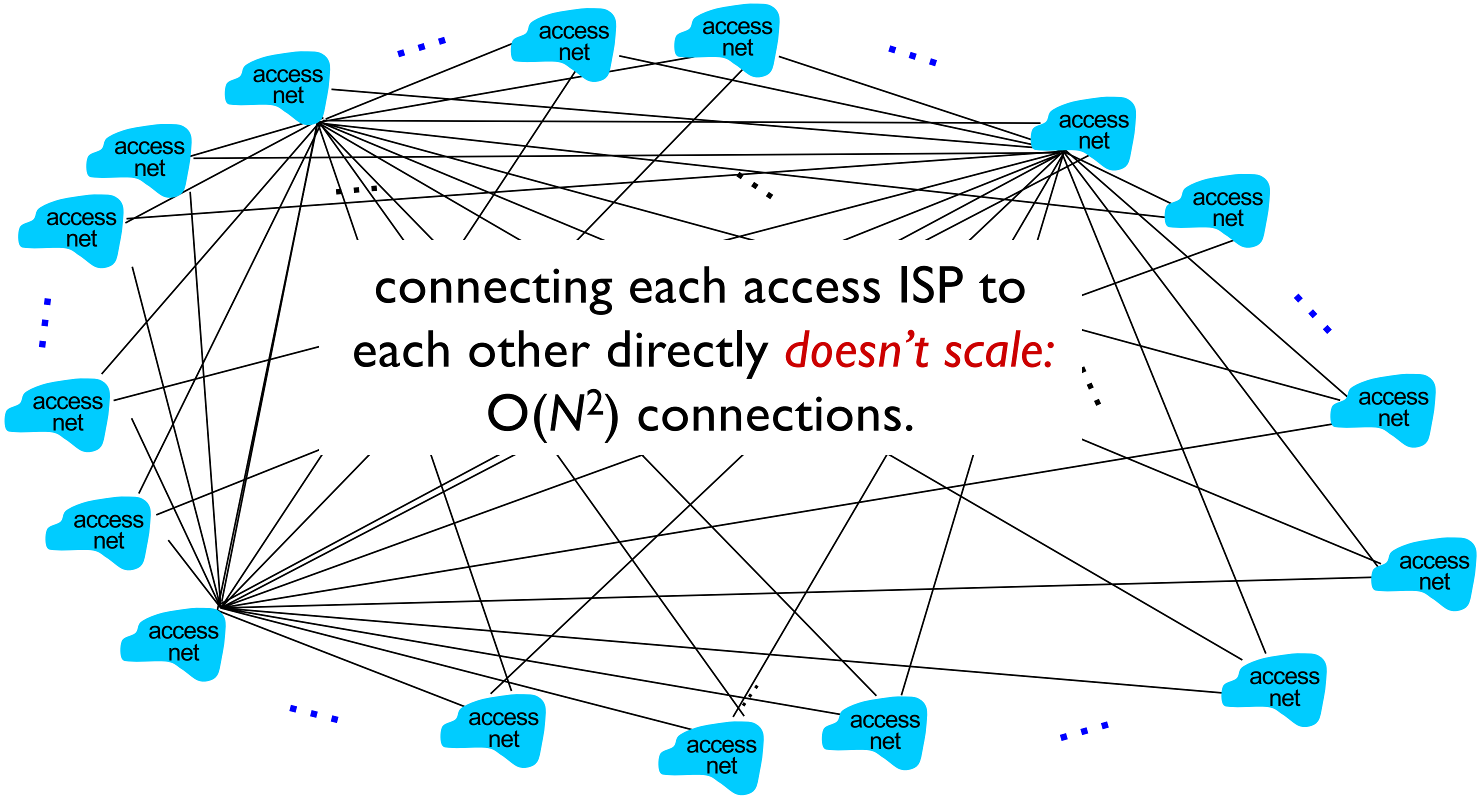
Internet structure: a "network of networks"

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



Internet structure: a "network of networks"

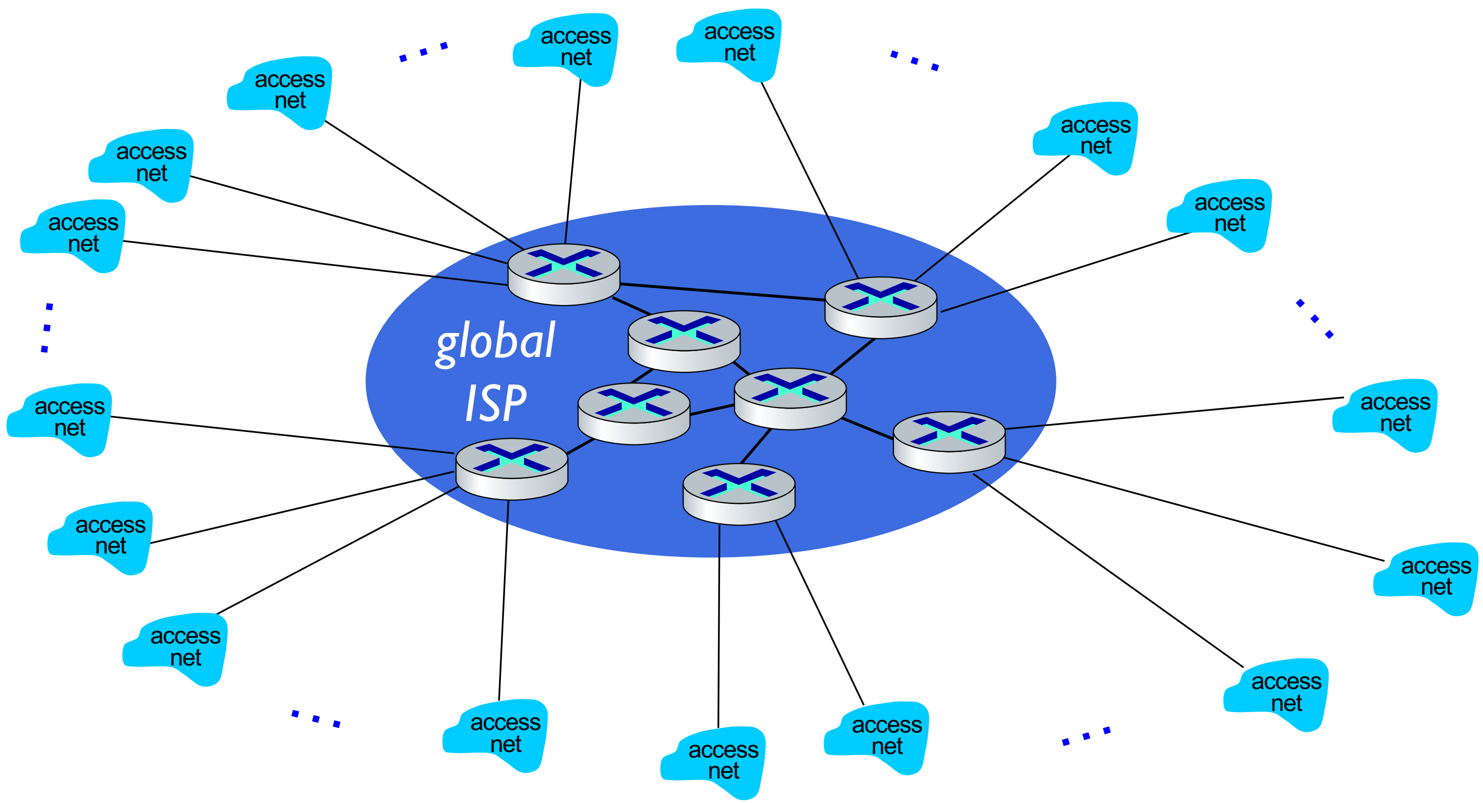
Question: given *millions* of access ISPs, how to connect them together?



Internet structure: a "network of networks"

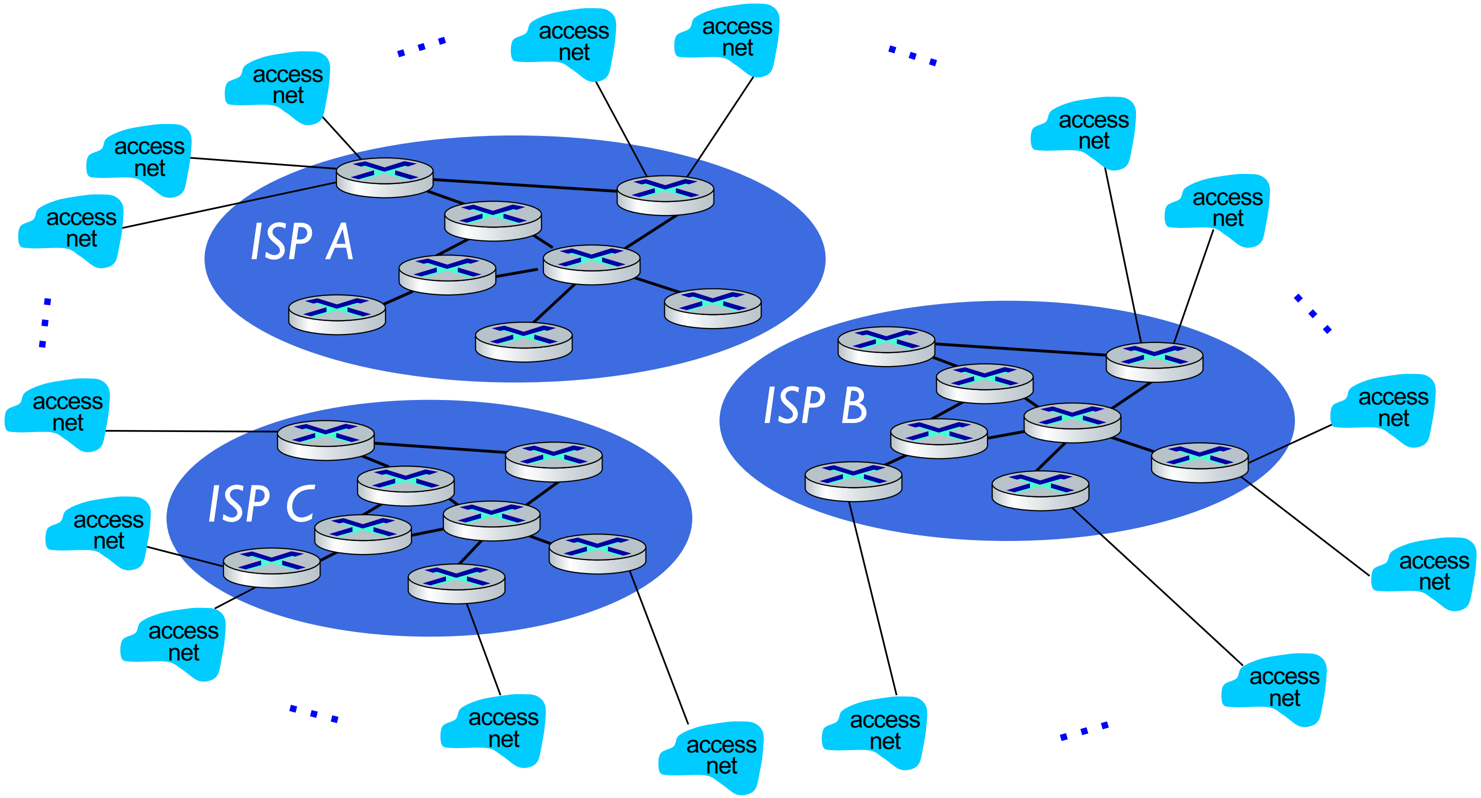
Option: connect each access ISP to one global transit ISP?

Customer and provider ISPs have economic agreement.



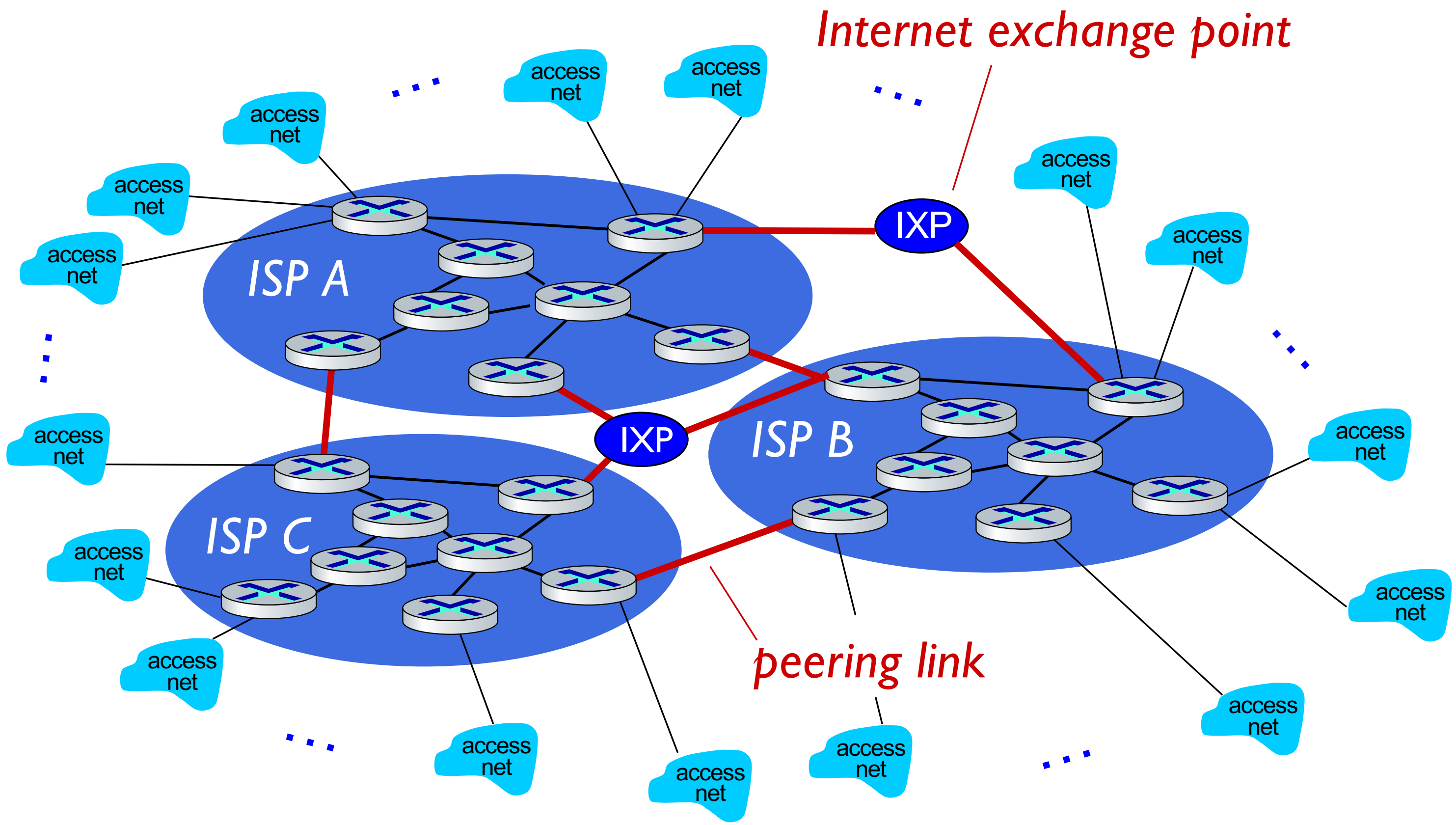
Internet structure: a "network of networks"

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



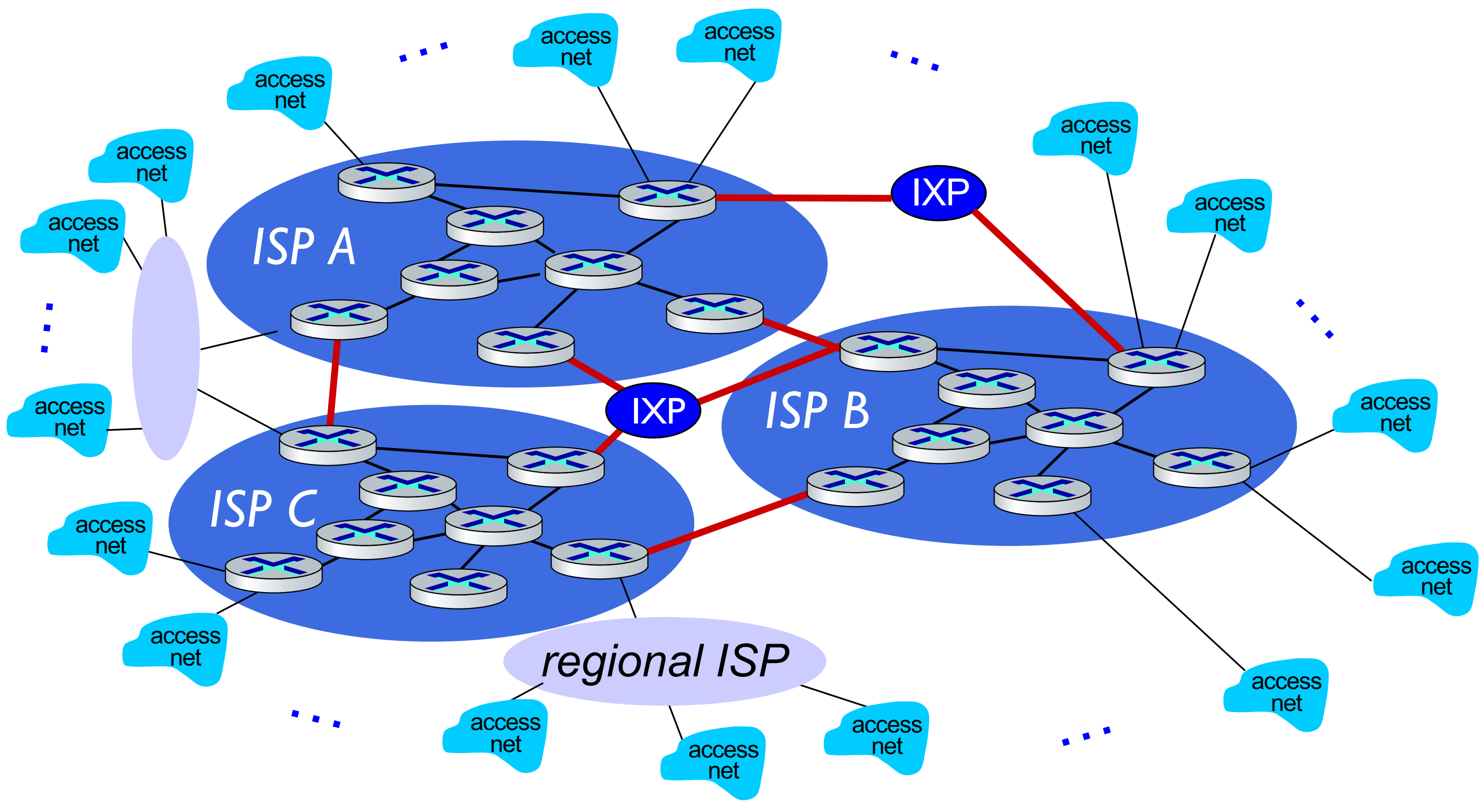
Internet structure: a "network of networks"

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



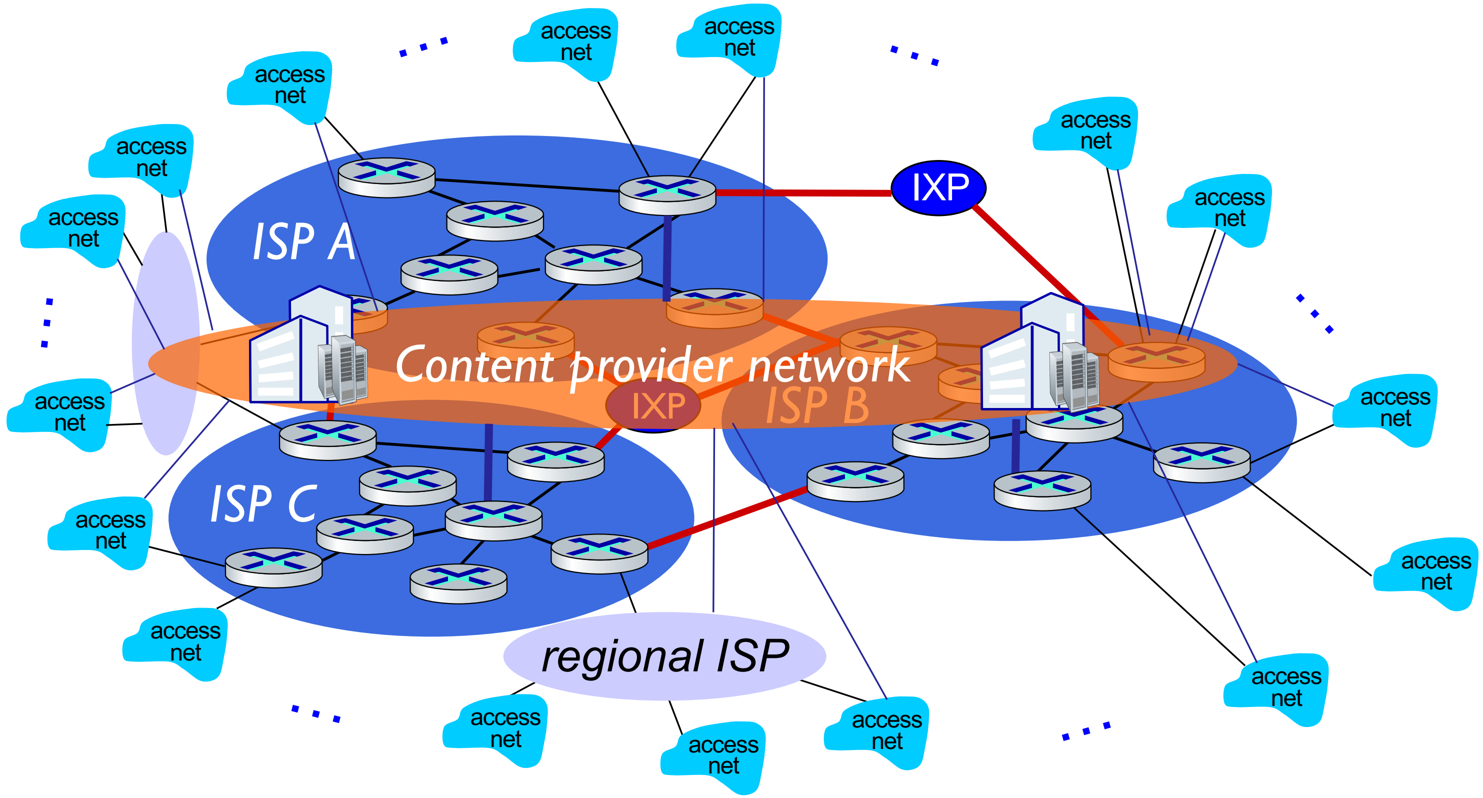
Internet structure: a "network of networks"

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

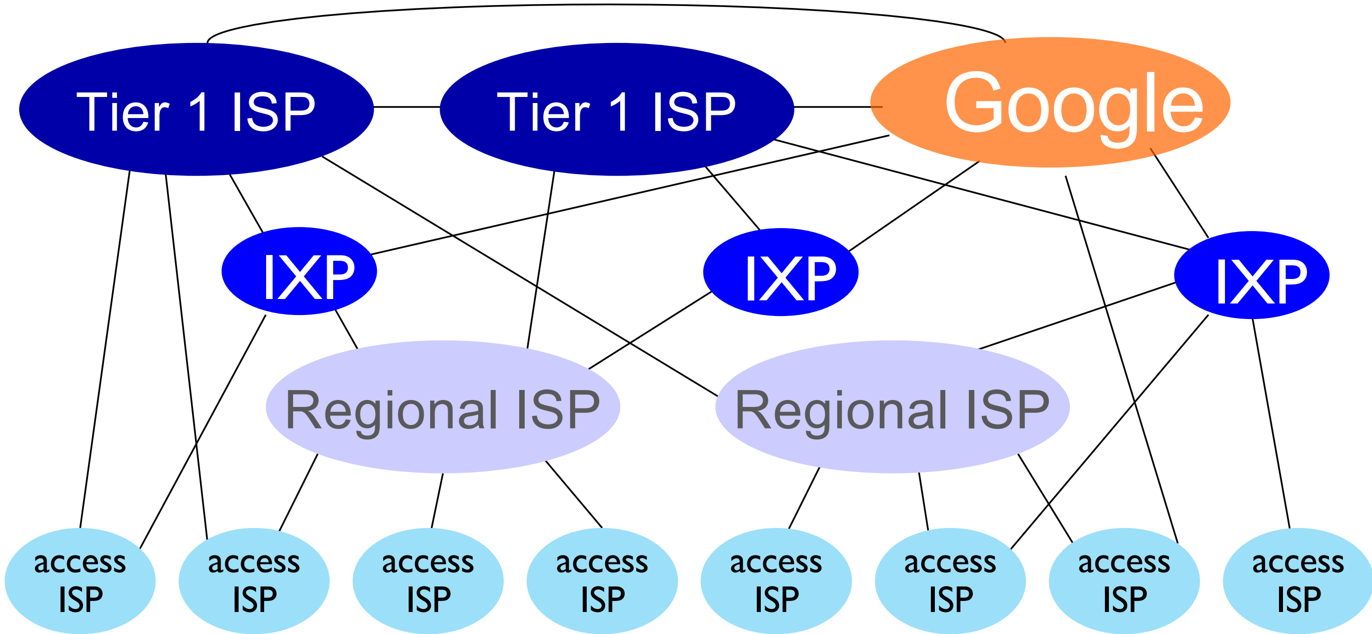


Internet structure: a "network of networks"

… 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

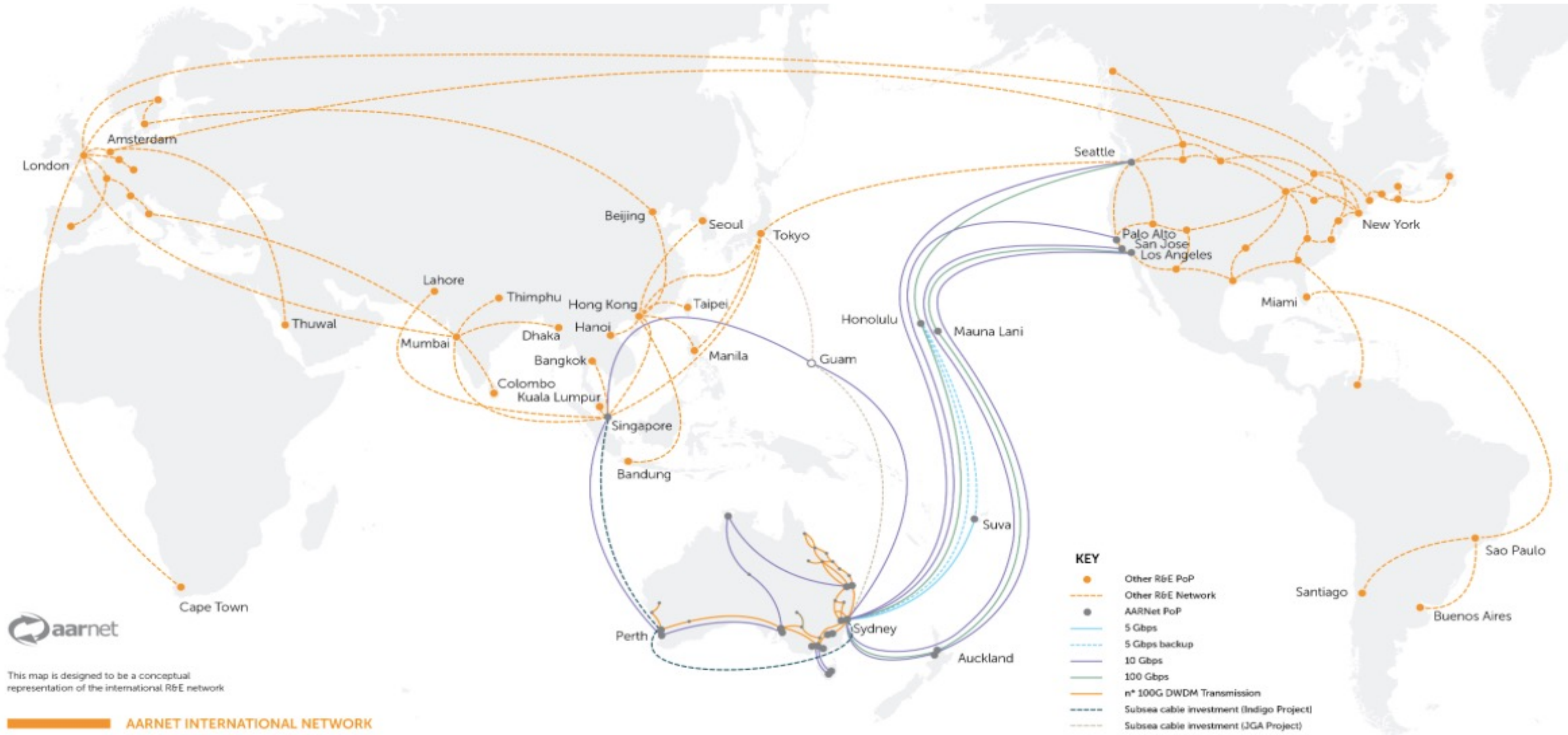
- "tier-1" commercial ISPs (e.g., Level 3, Sprint, AT&T, NTT), national & international coverage
- content provider networks (e.g., Google, Facebook): private network that connects its data centers to Internet, often bypassing tier-1, regional ISPs

Tier-1 ISP Network map: Sprint (2019)

AARNET: Australia's Academic and Research Network

https://www.aarnet.edu.au/

https://www.submarinecablemap.com



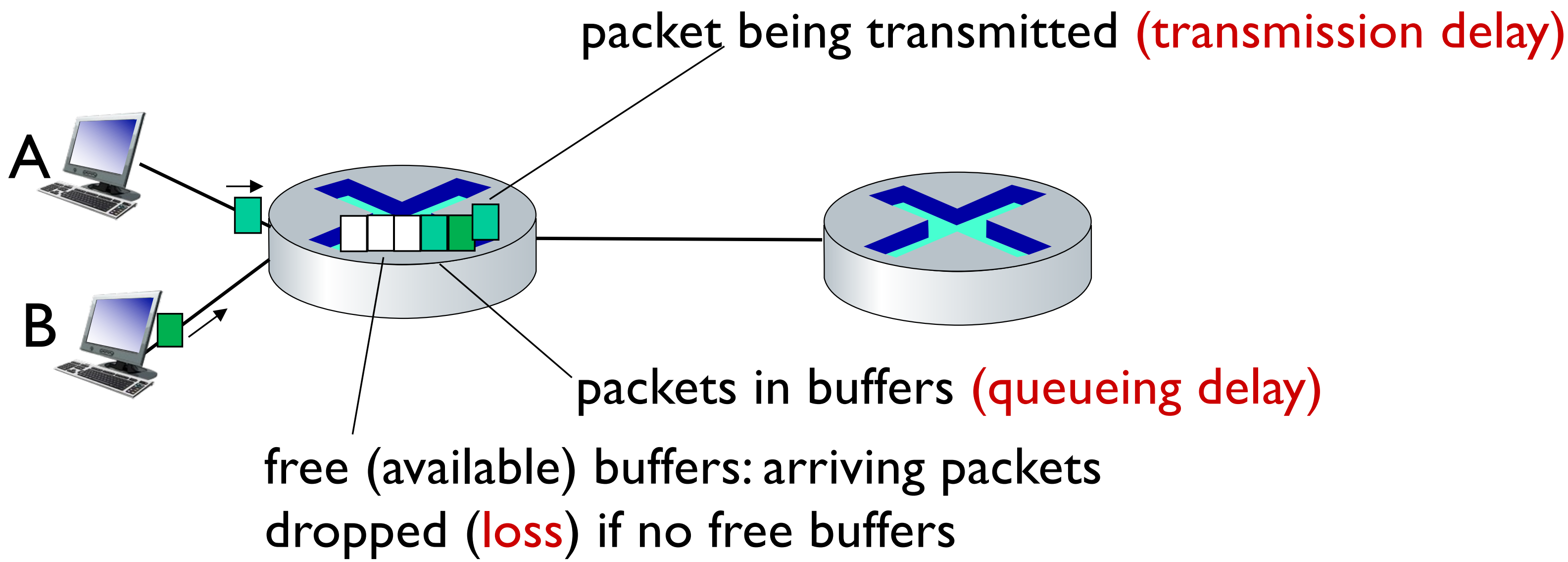
Introduction: roadmap

- 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

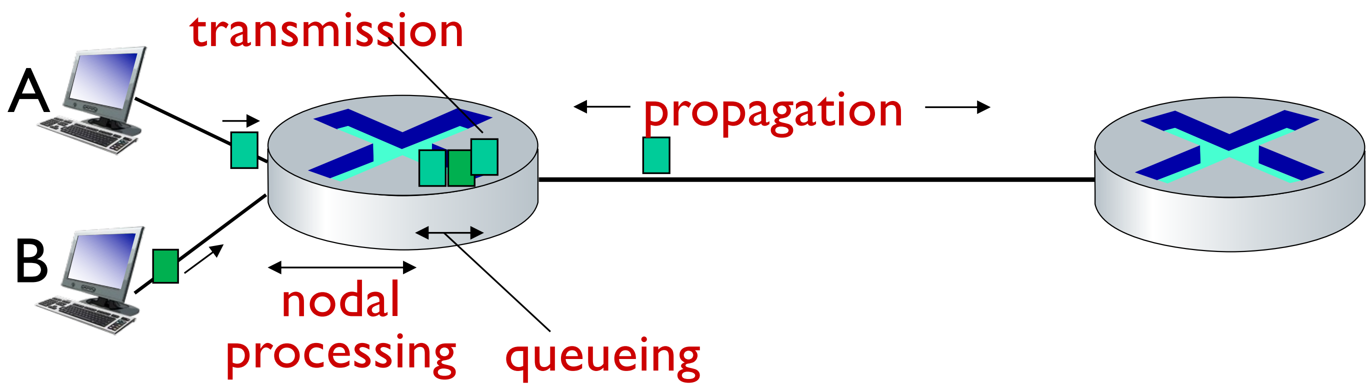
How do packet loss and delay occur?

packets *queue* in router buffers

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



Packet delay: four sources



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

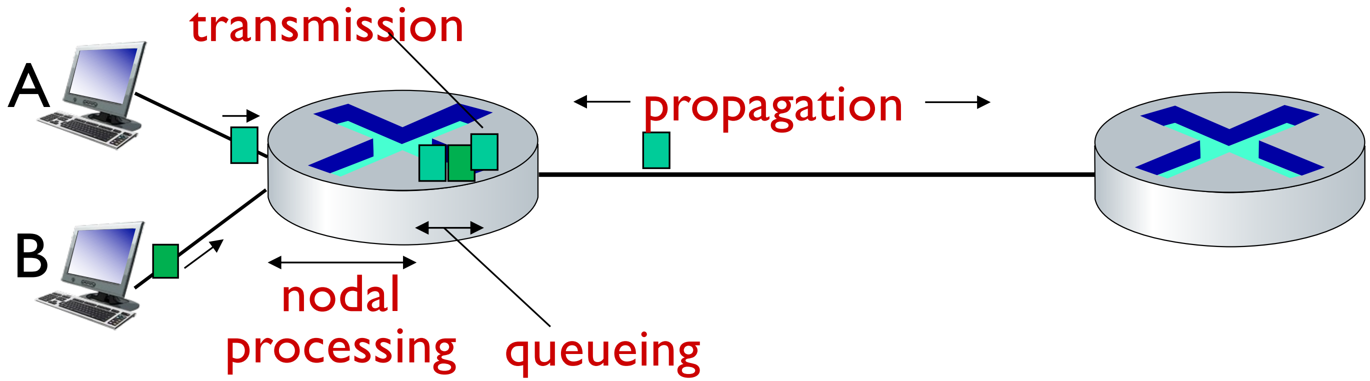
d_{proc}: nodal processing

- 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

Packet delay: four sources



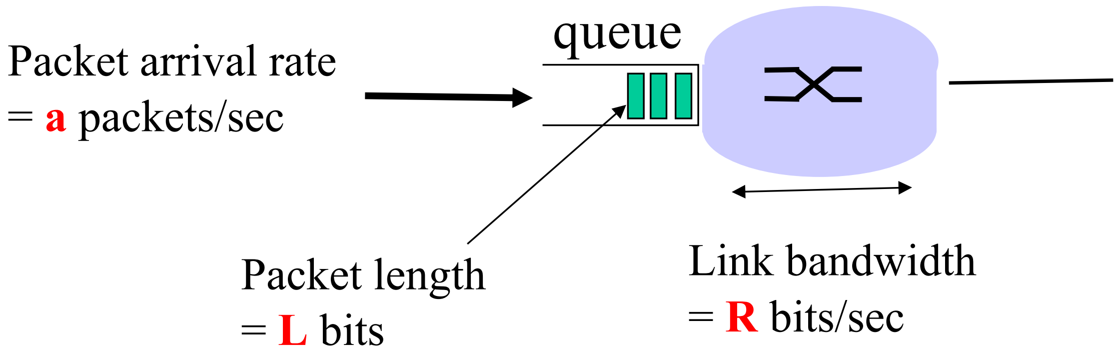
$$d_{\mathrm{nodal}} = d_{\mathrm{proc}} + d_{\mathrm{queue}} + d_{\mathrm{trans}} + d_{\mathrm{prop}}$$

d_{trans}: transmission delay:
- L: packet length (bits)
- R: link *transmission rate (bps)*
- $d_{trans} = L/R$

d_{prop}: propagation delay:
- d: length of physical link
- s: propagation speed (~2×10^8 m/sec)
- $d_{prop} = d/s$

d_{trans} and d_{prop}
very different

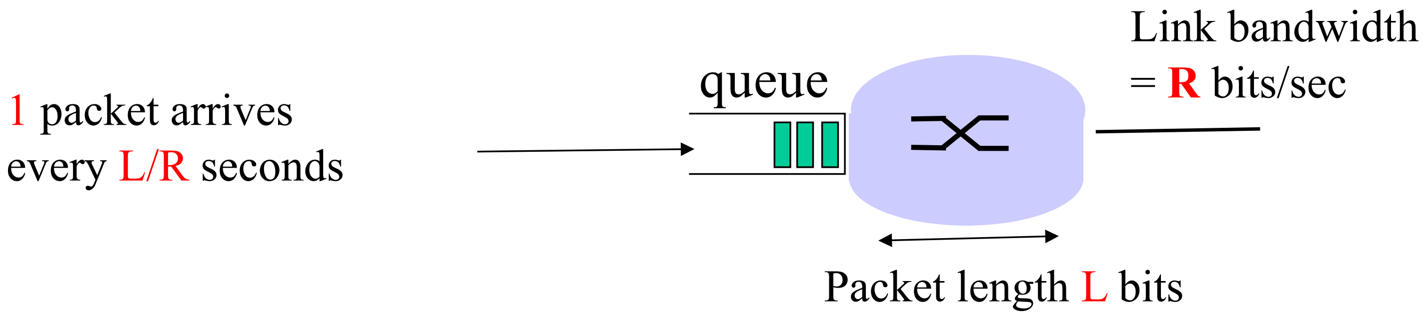
Queueing delay (more insight)



- Every second: aL bits arrive to queue
- Every second: R bits leave the router
- Question: what happens if aL > R ?
- Answer: queue will fill up, and packets will get dropped!!

aL/R is called traffic intensity

Queueing delay: One Scenario

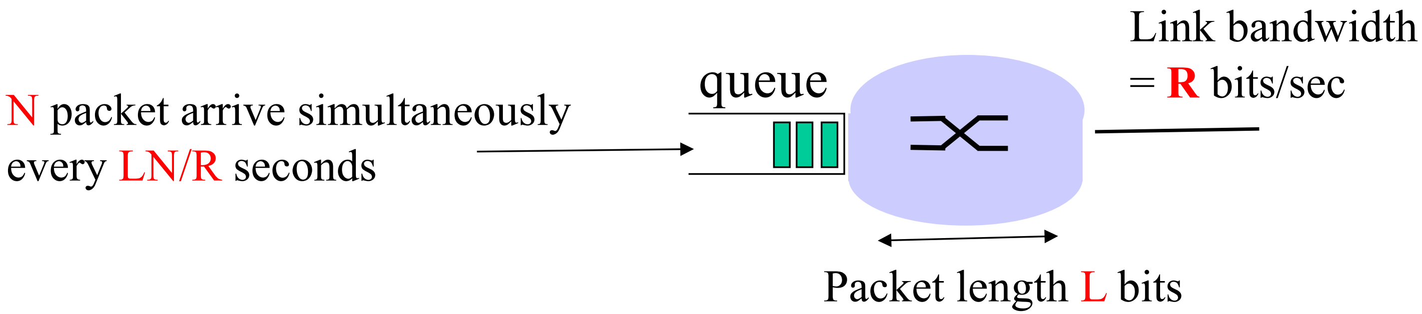


Arrival rate: a = 1/(L/R) = R/L (packet/second)

Traffic intensity = aL/R = (R/L) (L/R) = 1

Average queueing delay = 0
(queue is initially empty)

Queueing delay: Another Scenario



Arrival rate: a = N/(LN/R) = R/L packet/second

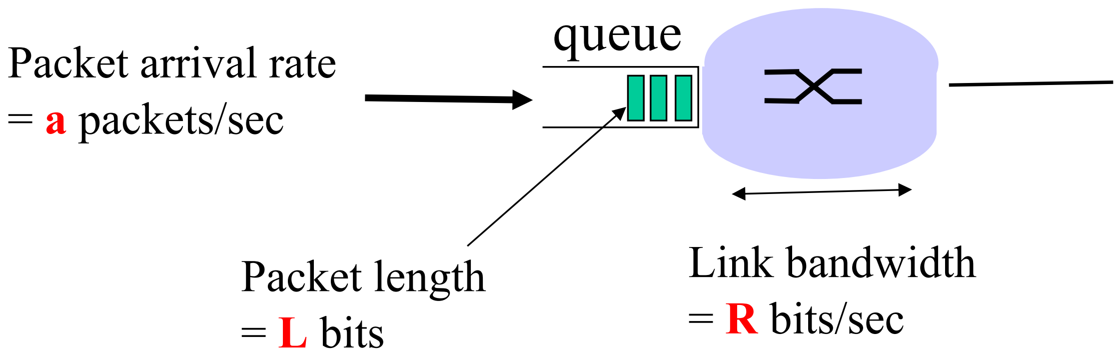
Traffic intensity = aL/R = (R/L) (L/R) = 1

Average queueing delay (queue is empty at time 0) ?

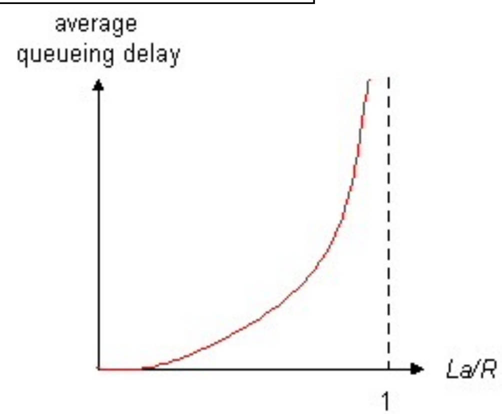
{0 + L/R + 2L/R + … + (N-1)L/R}/N = L/(RN){1+2+…+(N-1)} =L(N-1)/(2R)

Note: traffic intensity is same as previous scenario, but queueing delay is different

Queueing delay: typical behaviour

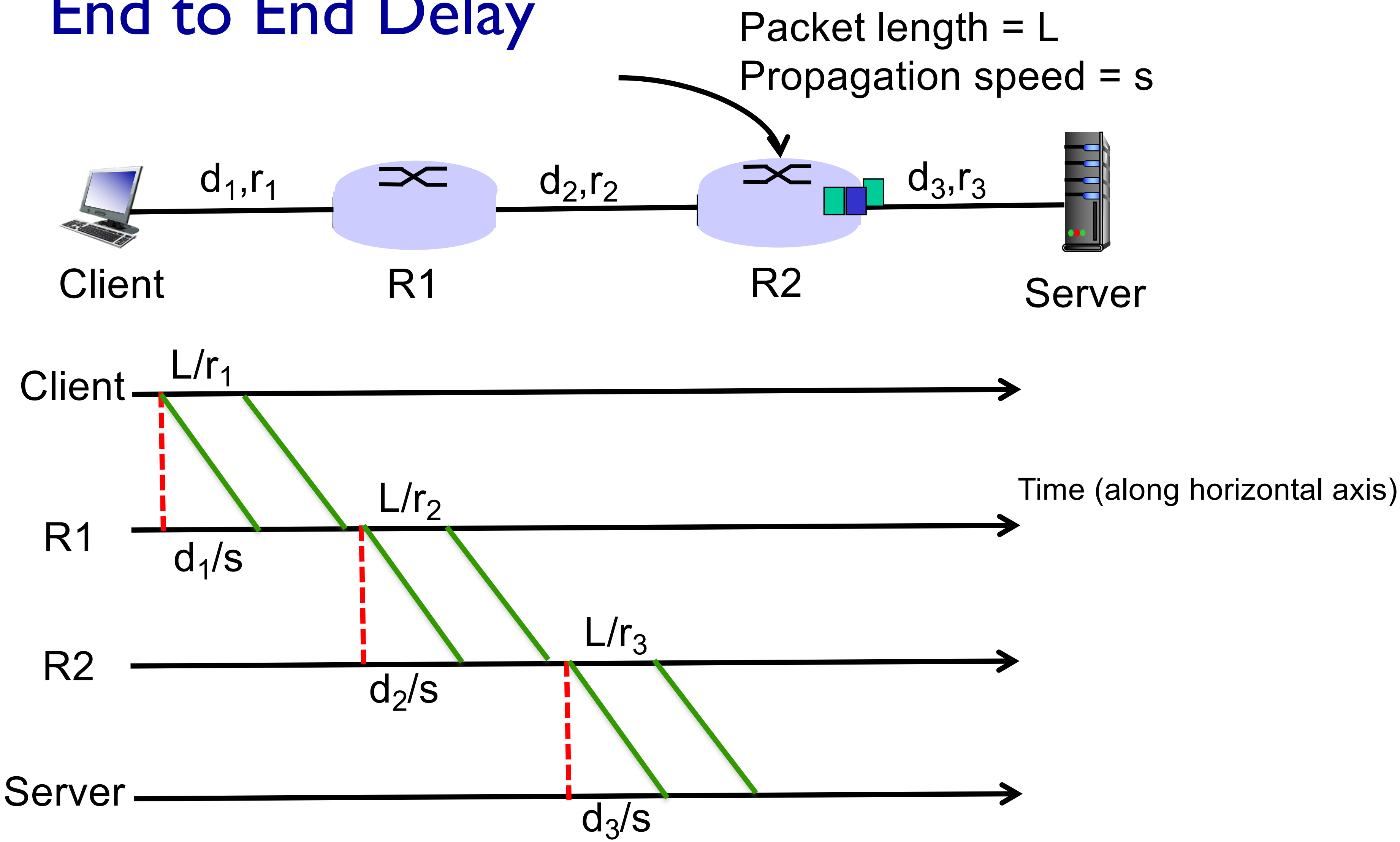


Interactive Java Applet:
http://computerscience.unicam.it/marcantoni/reti/applet/QueuingAndLossInteractive/1.html



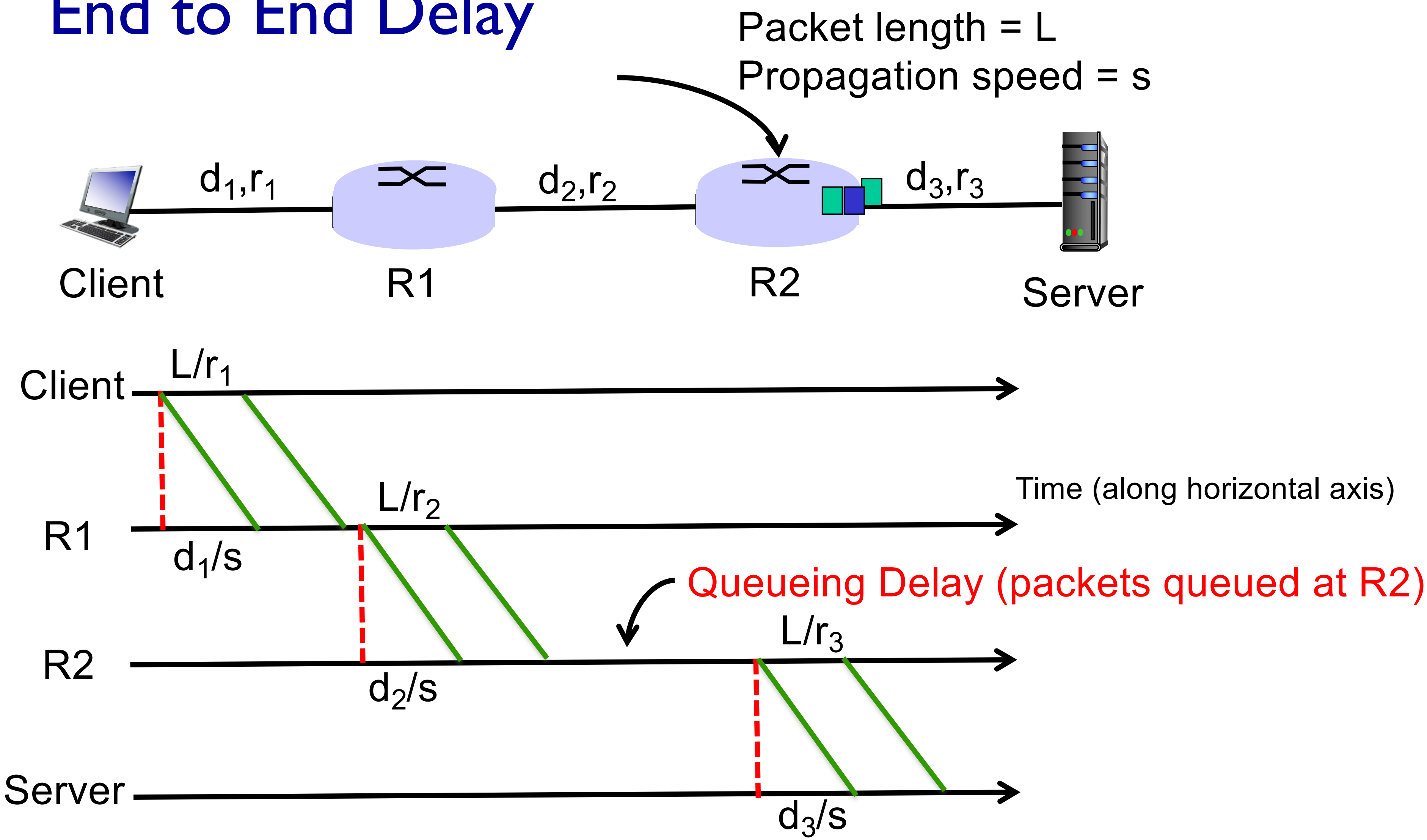
- La/R ~ 0: avg. queueing delay small
- La/R -> 1: delays become large
- La/R > 1: more "work" than can be serviced, average delay infinite!
  (this is when a is random!)

End to End Delay



In the picture, $r_1 = r_2 = r_3$, you may wish to consider what happens when this is not the case

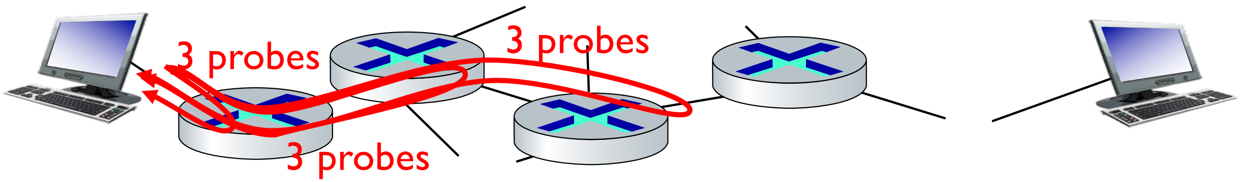
End to End Delay



In the picture, $r_1 = r_2 = r_3$, you may wish to consider what happens when this is not the case

“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 (with time-to-live field value of *i*)
  - router *i* will return packets to sender
  - sender measures time interval between transmission and reply



Real Internet delays and 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
```

3 delay measurements
to border1-rt-fa5-1-0.gw.umass.edu

trans-oceanic link

looks like delays
decrease! Why?

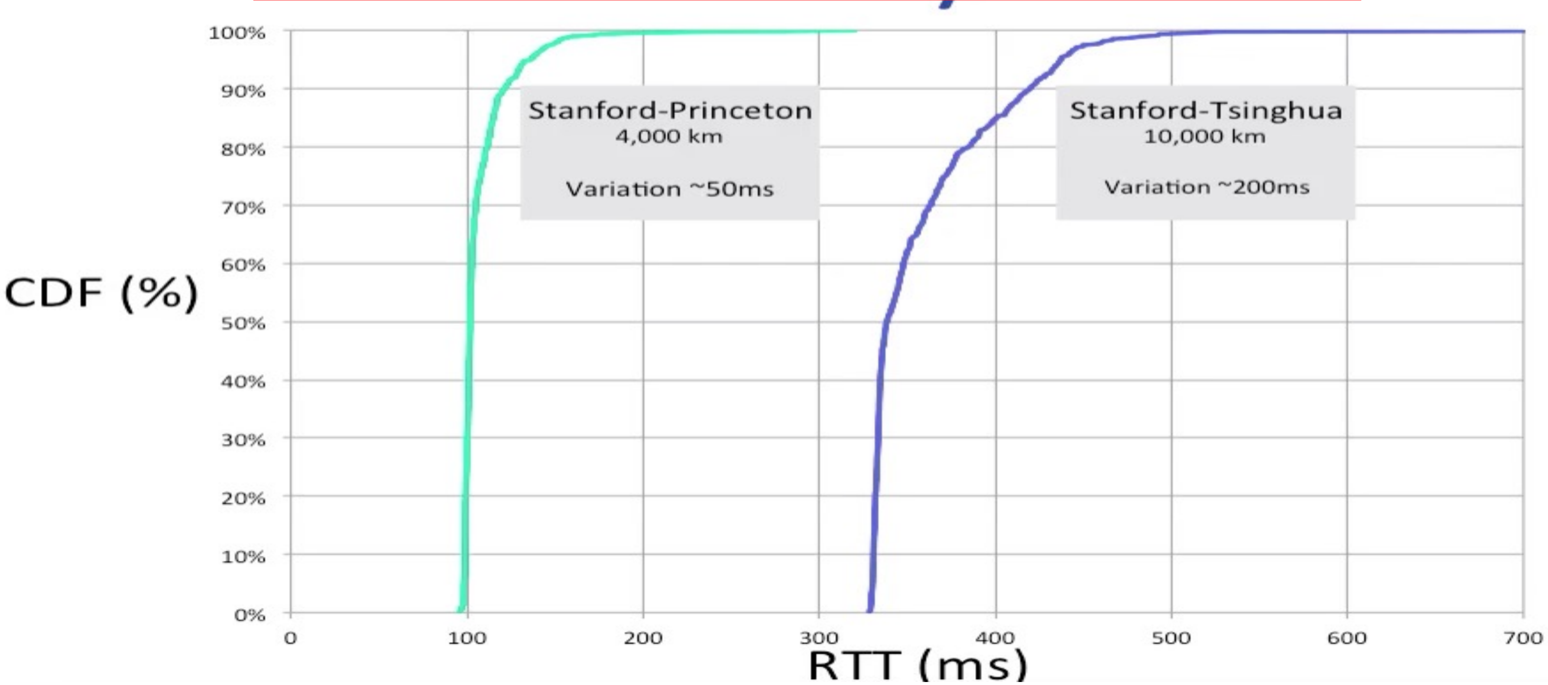
* means no response (probe lost, router not replying)

* Do some traceroutes from exotic countries at www.traceroute.org

“Real” delay variations

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

End-to-end delay = sum of all d_{nodal} along the path



Quiz: Propagation Delay

Propagation delay depends on the size of the packet

A. True

B. False

Quiz: Oh these delays

Consider a packet that has just arrived at a router. What is the correct order of the delays encountered by the packet until it reaches the next-hop router?

A. Transmission, processing, propagation, queuing

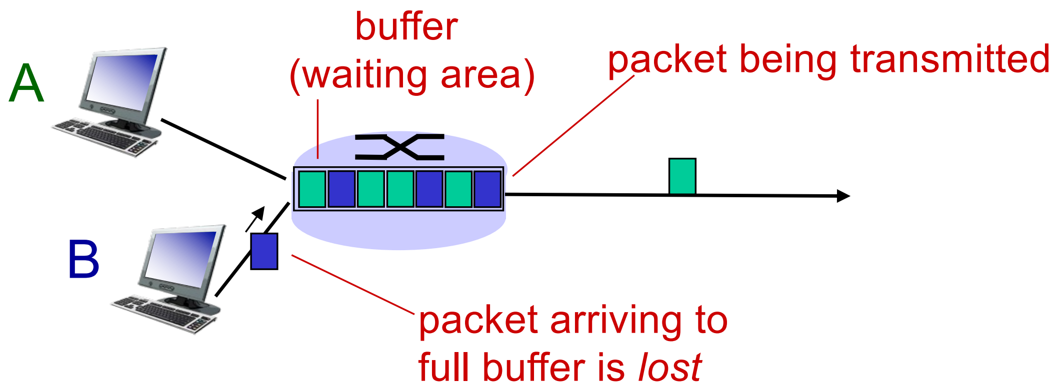
B. Propagation, processing, transmission, queuing

C. Processing, queuing, transmission, propagation

D. Queuing, processing, propagation, transmission

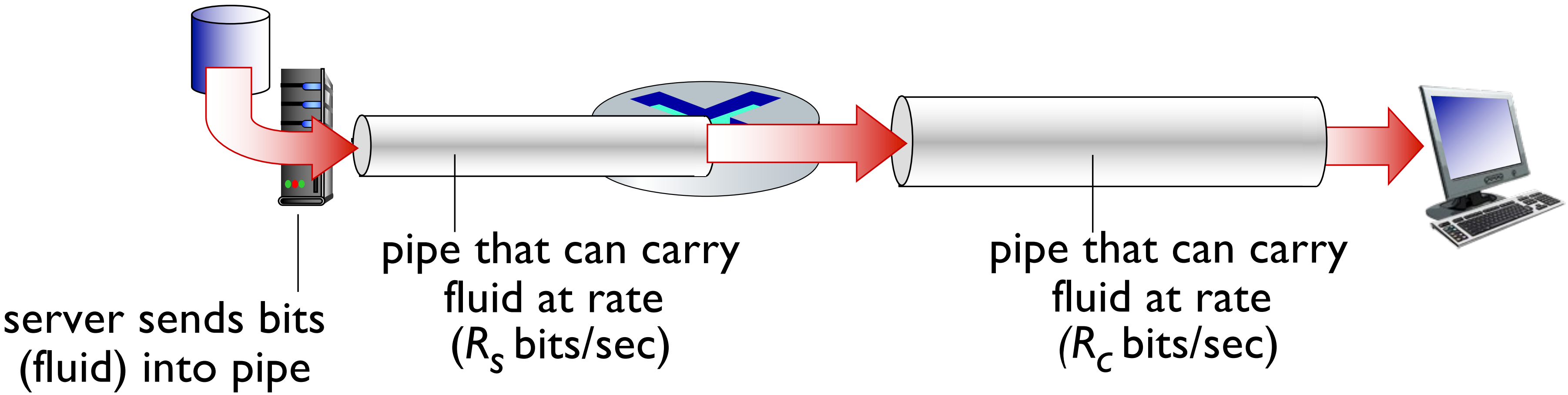
Packet loss

- 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, source end system, or not at all



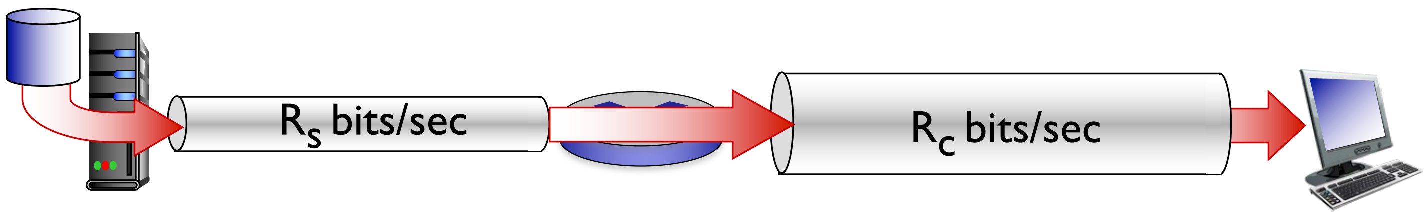
Throughput

- *throughput:* rate (bits/time unit) at which bits are being sent from sender to receiver
  - *instantaneous:* rate at given point in time
  - *average:* rate over longer period of time

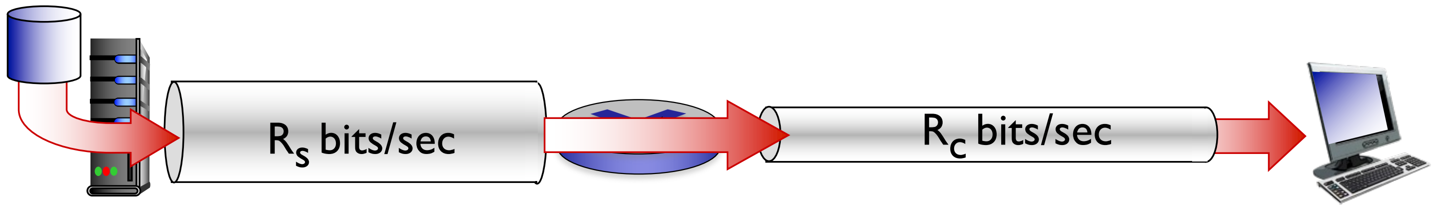


Throughput

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



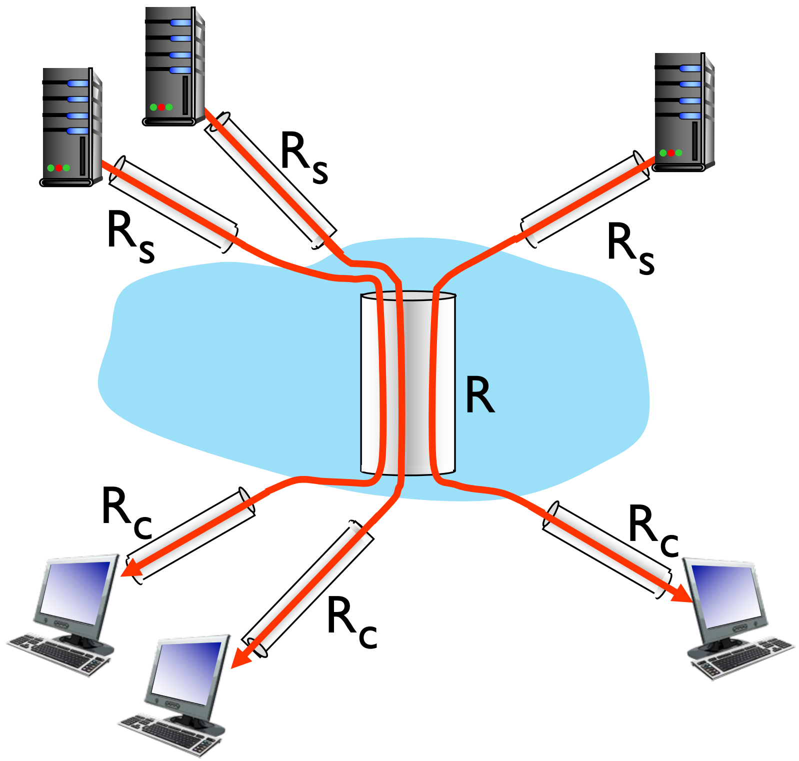
$R_s > R_c$ What is average end-end throughput?



bottleneck link

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

Throughput: network scenario



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

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

Introduction: summary

covered a "ton" of material!

- Internet overview
- what's a protocol?
- network edge, core, access network
  - packet-switching versus circuit-switching
  - Internet structure
- performance: loss, delay, throughput
- Next Week
  - Protocol layers, service models
  - Application Layer

End of Week 1