

# Computer Networks and Applications

COMP 3331/COMP 9331

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?



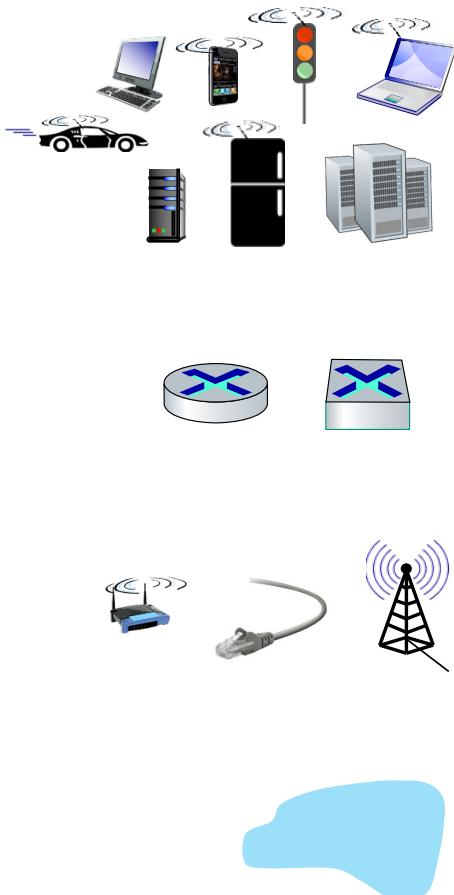
- A. One single homogenous network
- B. An interconnection of different computer networks
- C. An infrastructure that provides services to networked applications
- D. Something else

**Answer: B and C as explained on the next few slides**

Open a browser and type: [pollev.com/salil](https://pollev.com/salil)



# 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)

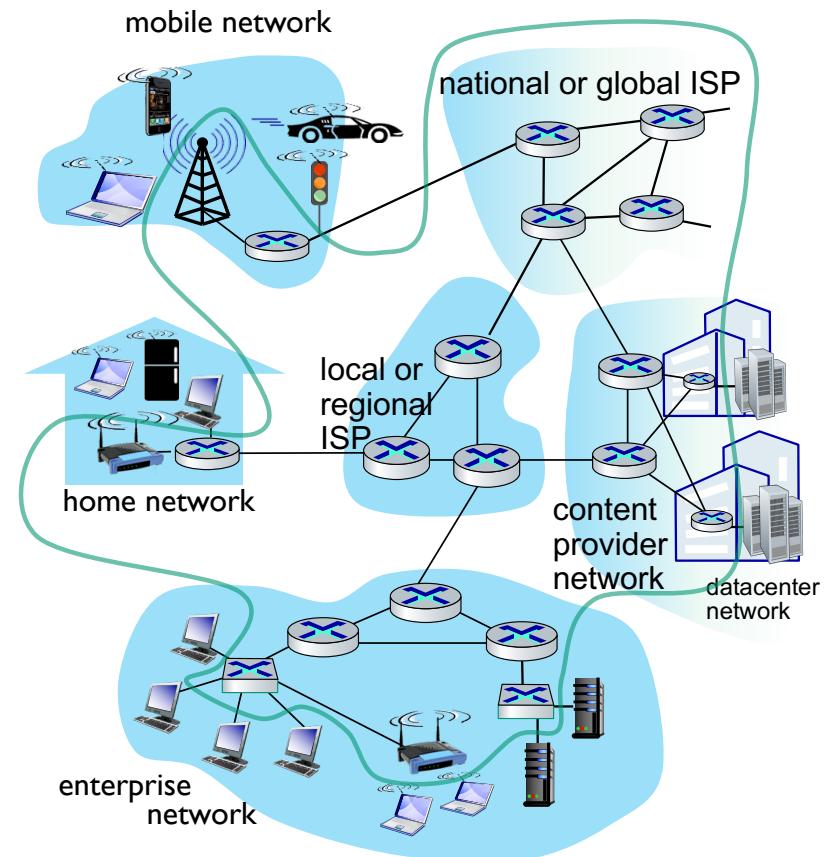
- routers, switches

**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



Amazon Echo



Internet  
refrigerator



Networked TV Set top Boxes



sensorized,  
bed  
mattress



pacemaker



Tweet-a-watt:  
monitor energy use



Fitbit

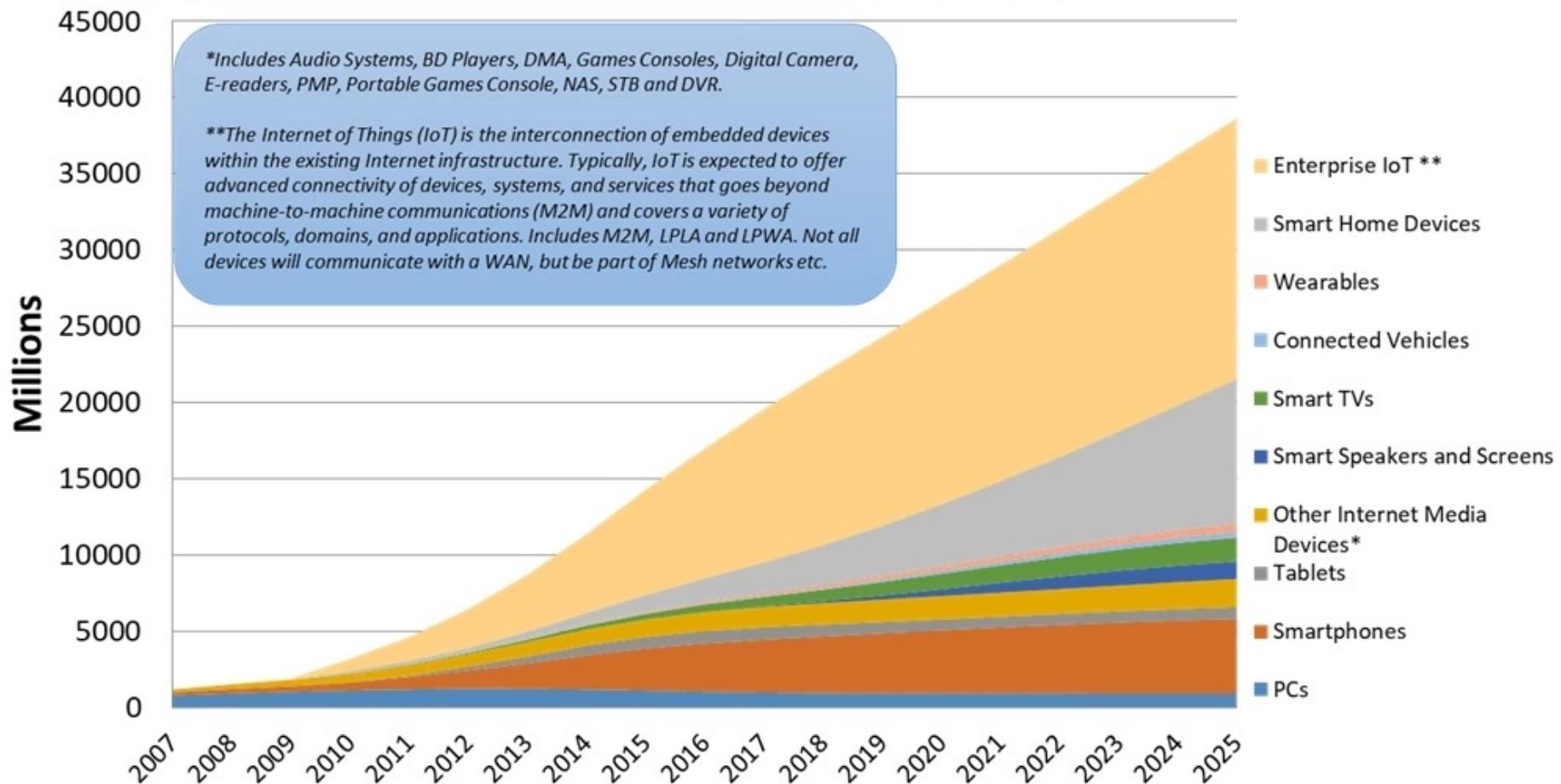


Smart Lightbulbs



AR devices

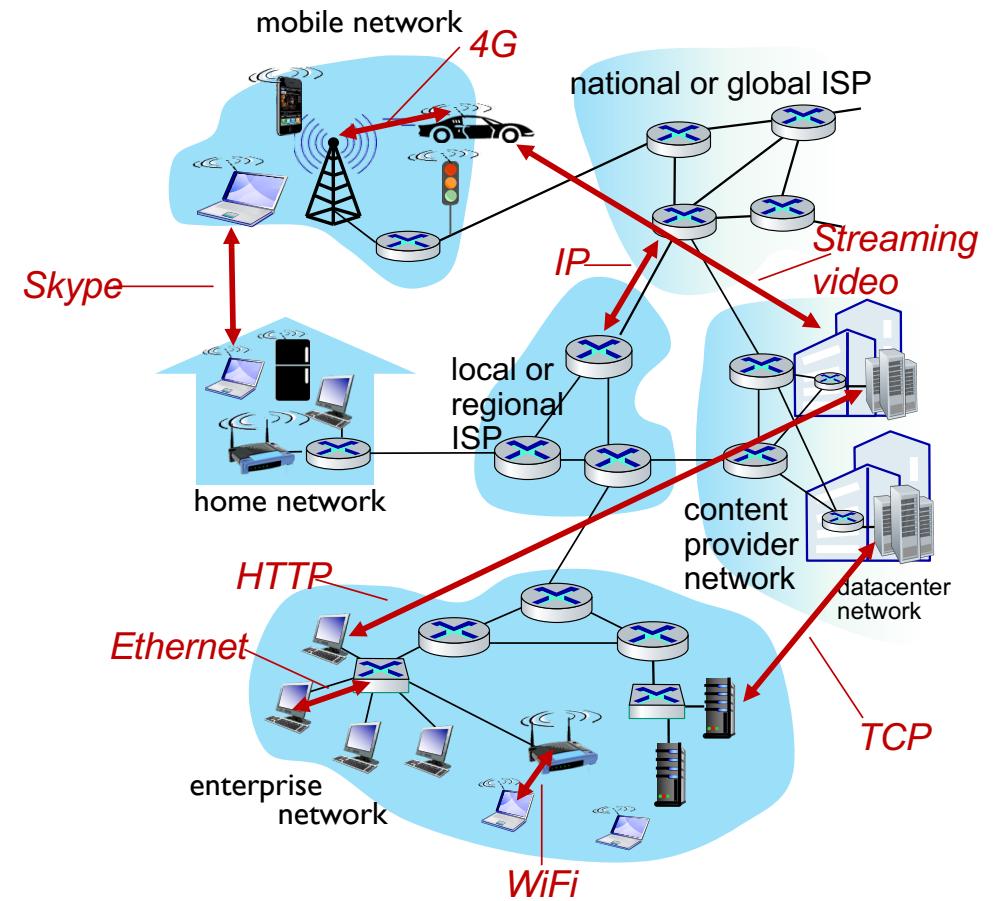
## Global Connected and IoT Device Installed Base Forecast



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

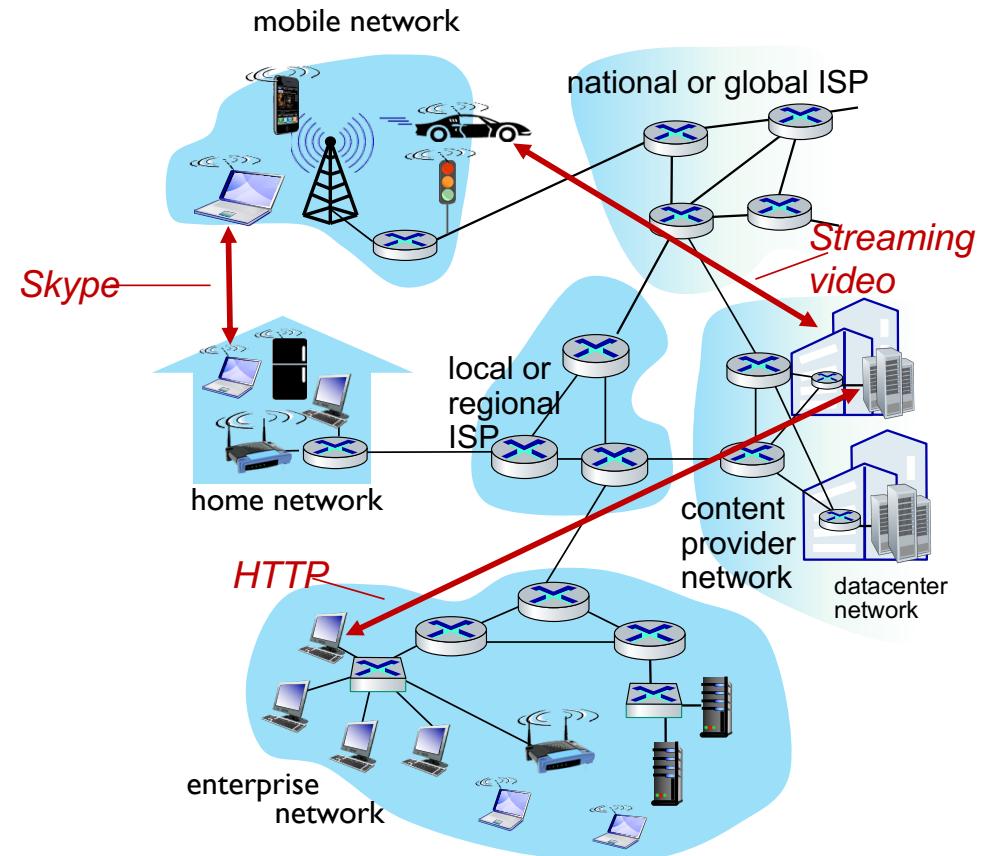
# The Internet: a “nuts and bolts” view

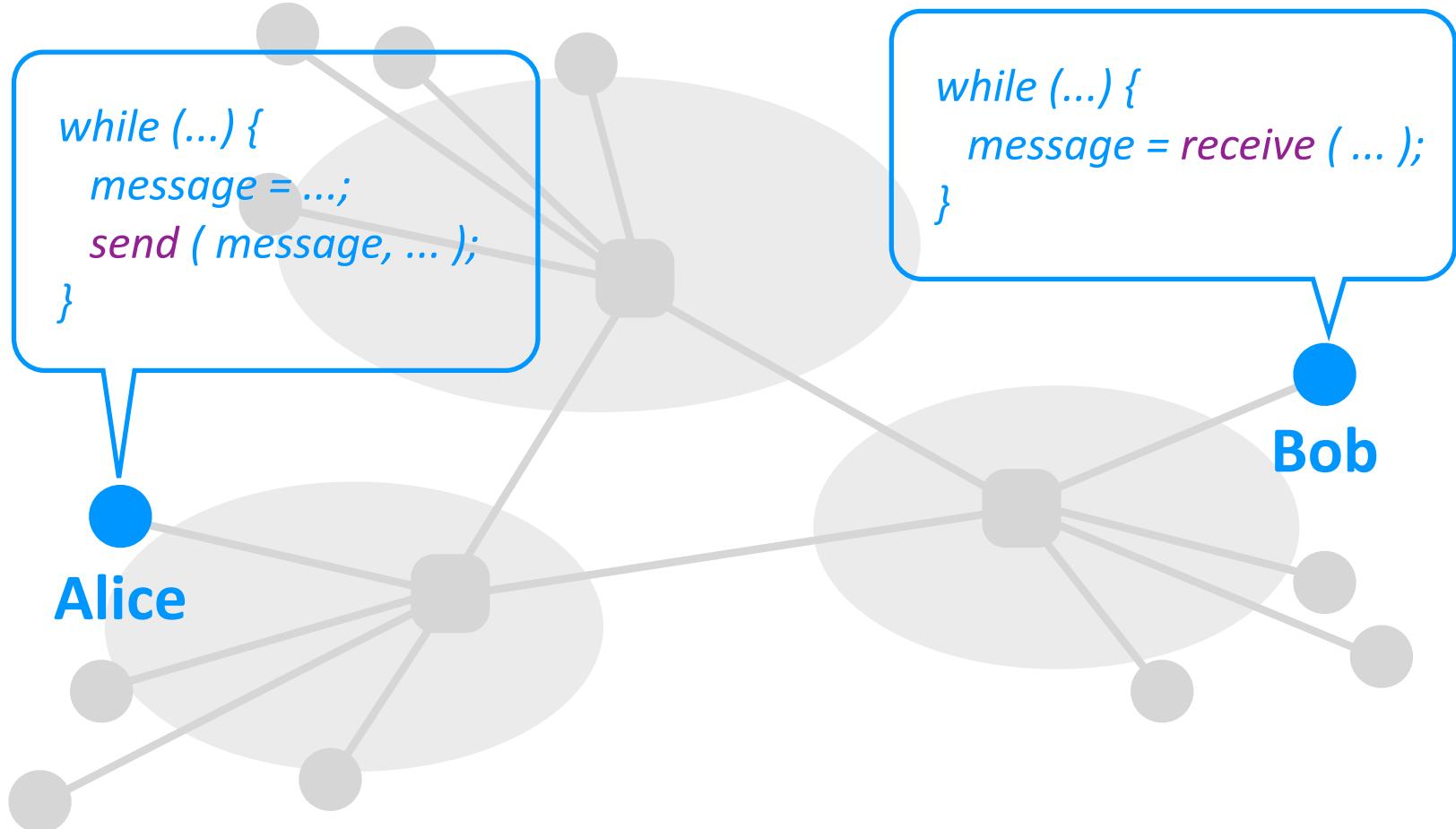
- ❖ *Internet: “network of networks”*
  - Interconnected ISPs
  - *protocols are everywhere*
    - control sending, receiving of messages
    - e.g., HTTP (Web), streaming video, Skype, TCP, IP, WiFi, 4G, Ethernet
  - *Internet standards*
    - RFC: Request for Comments
    - IETF: Internet Engineering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

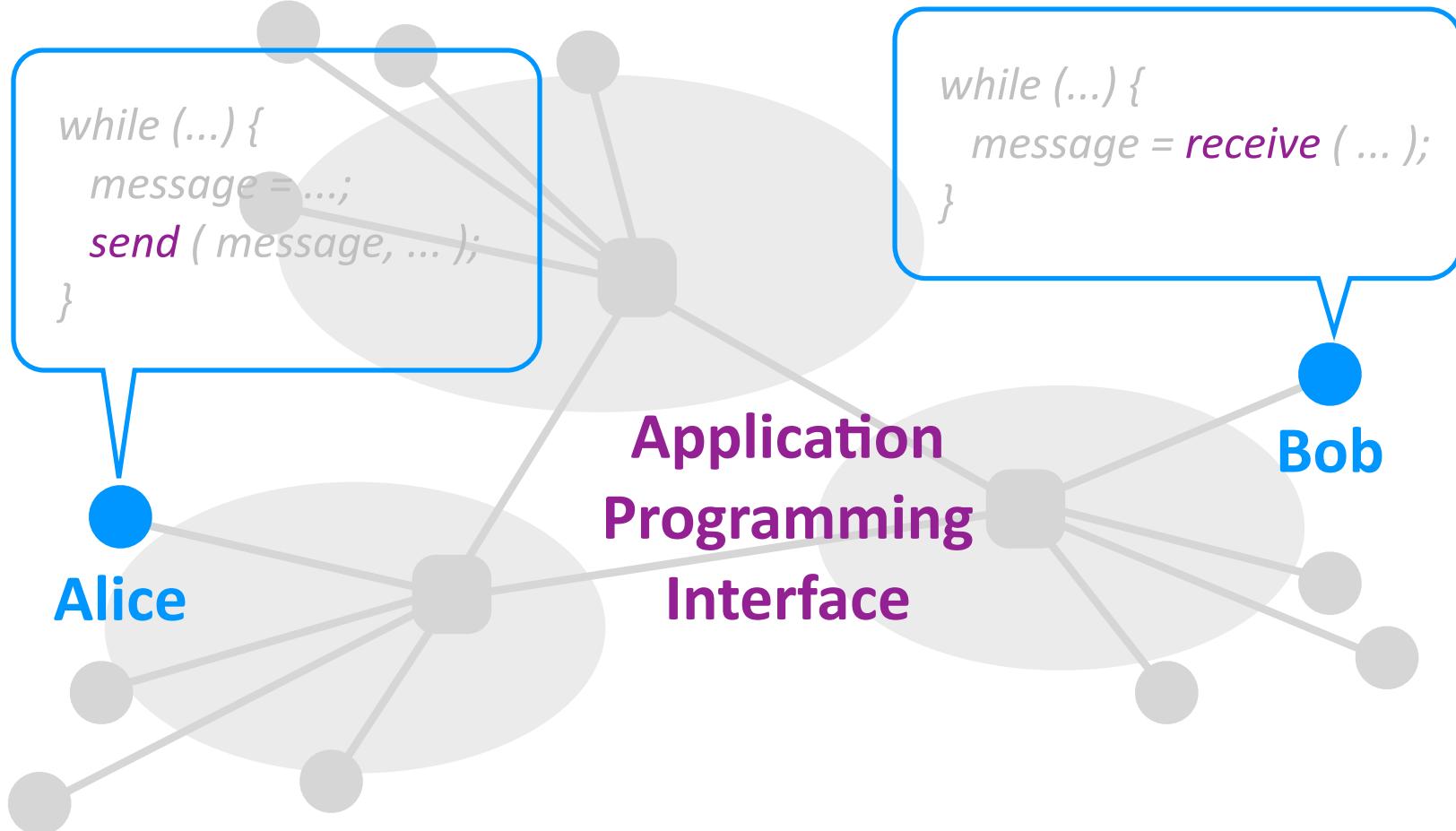


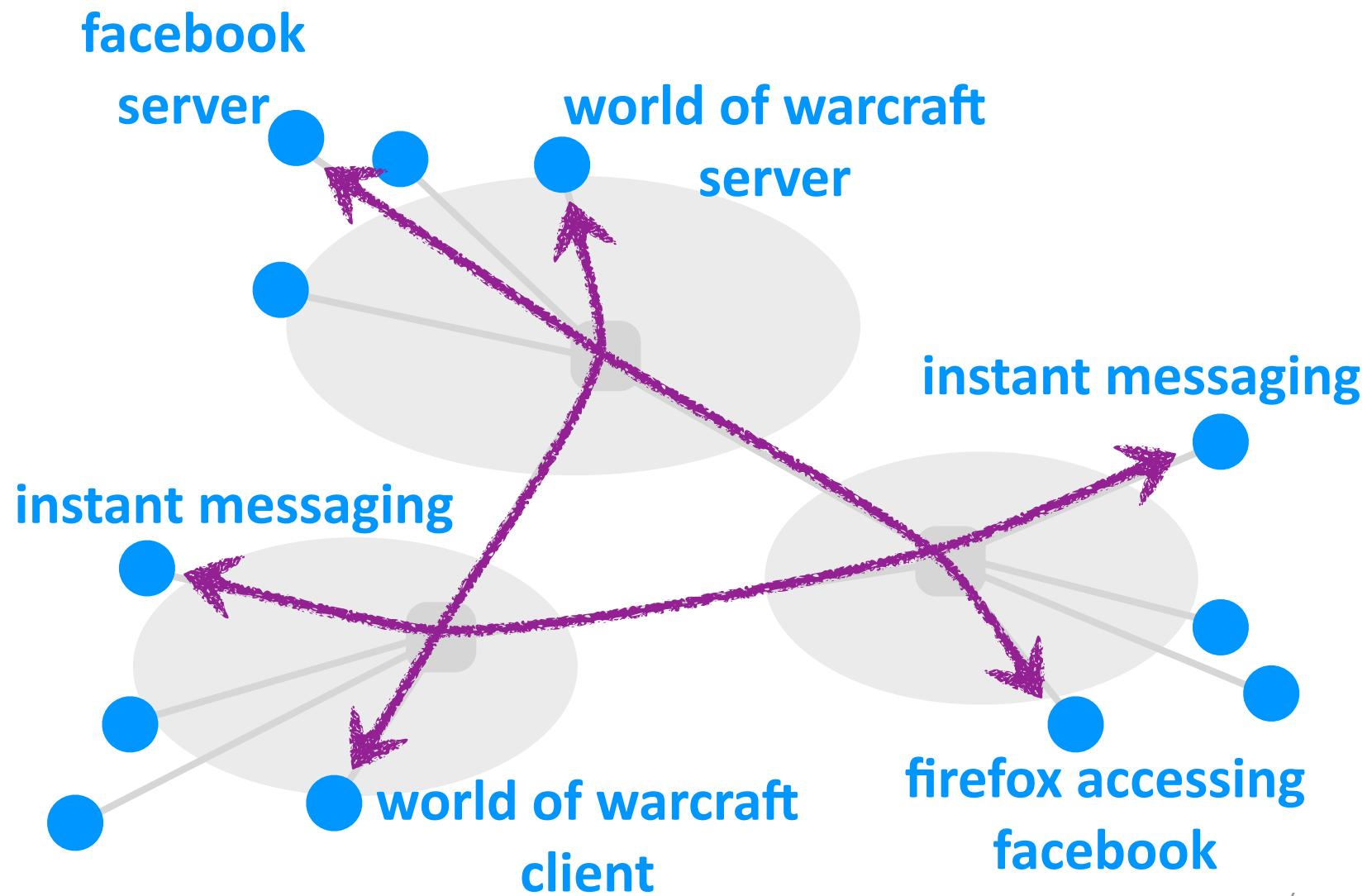
# The Internet: a “service” view

- ❖ **Infrastructure** that provides services to applications:
  - Web, streaming video, multimedia teleconferencing, email, games, e-commerce, social media, interconnected 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

... specific messages sent  
... specific actions taken  
when message received,  
or other events

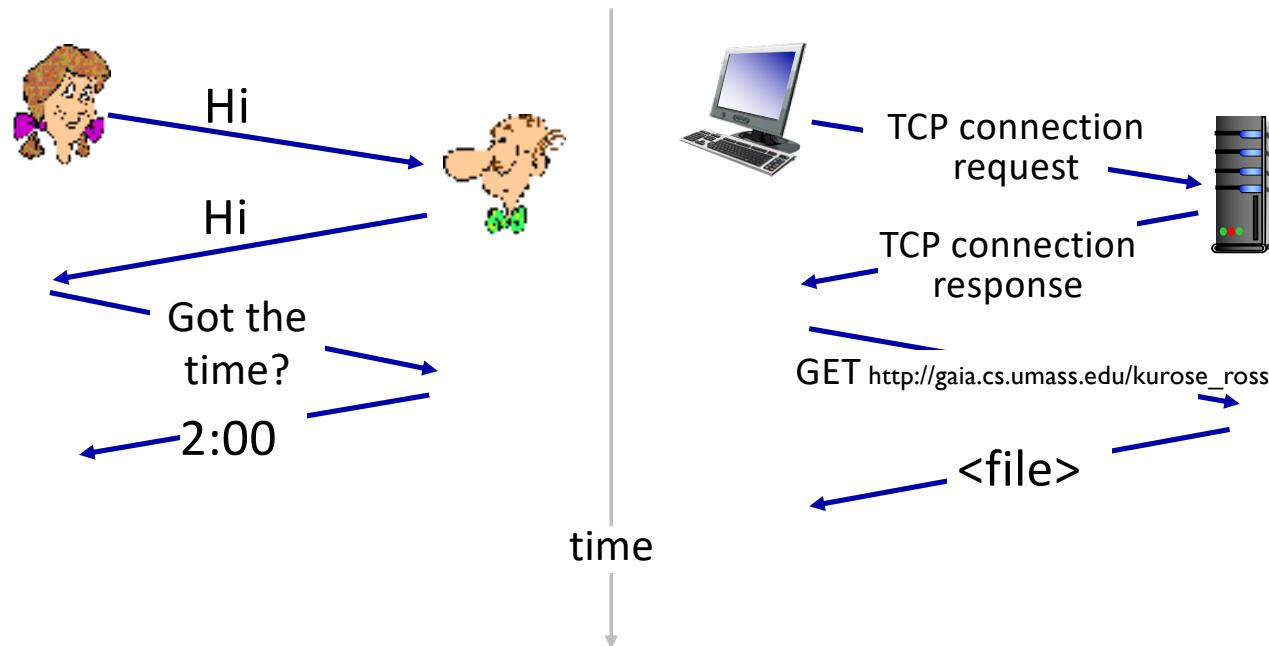
## *Network protocols:*

- 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

**This is a poll for students.  
There is no correct answer**

Open a browser and type: **pollev.com/salil**



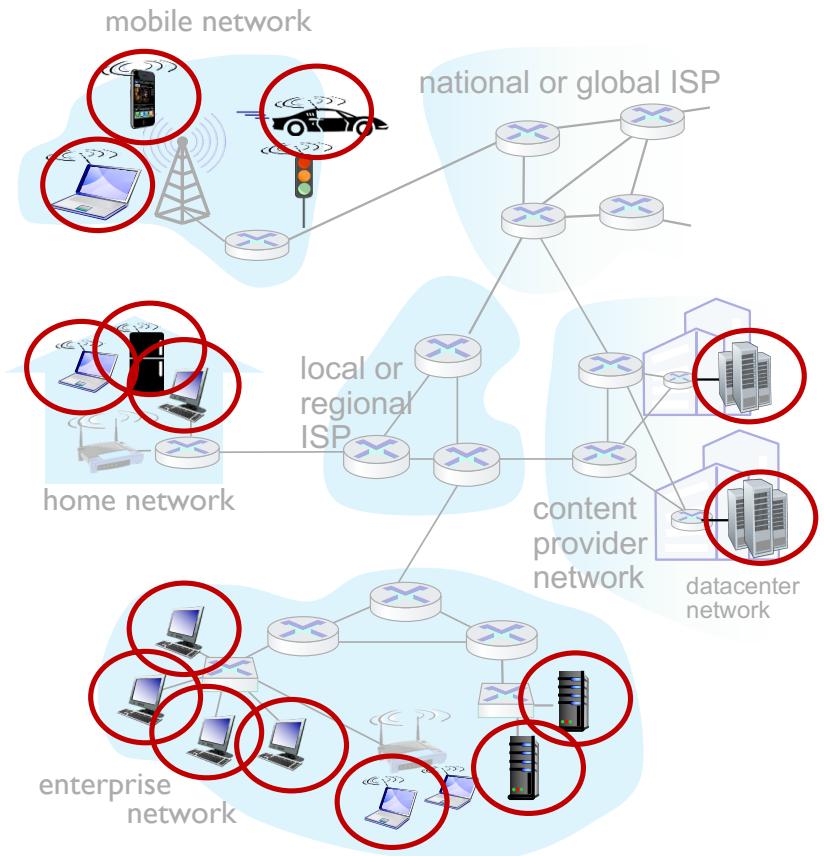
# Introduction: roadmap

- ❖ 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



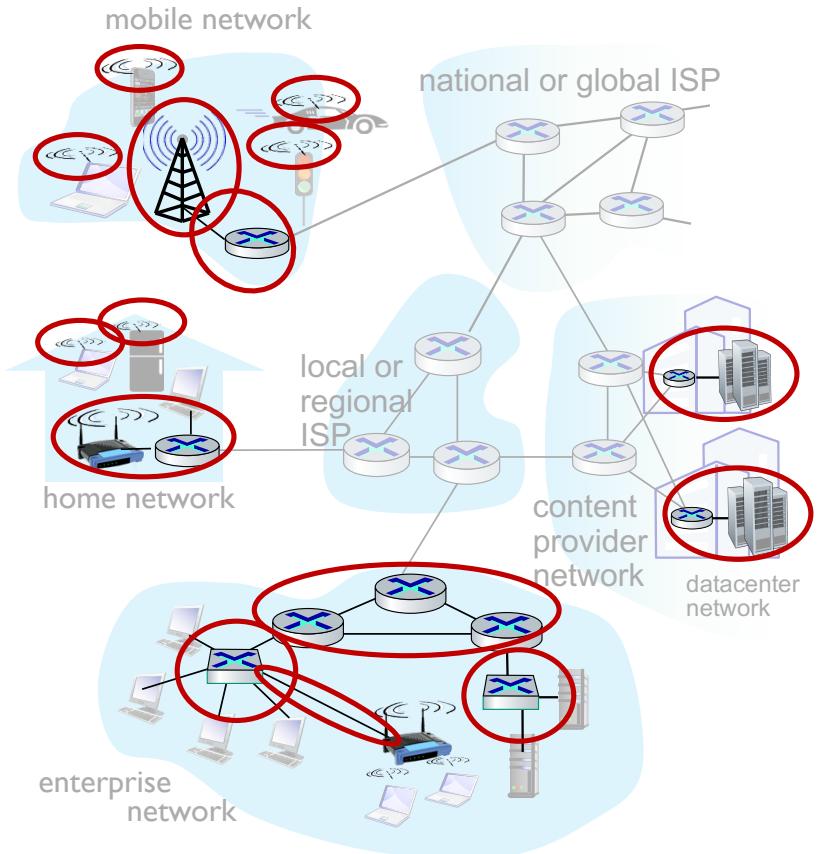
# A closer look at Internet structure

## Network edge:

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## Access networks, physical media:

- ❖ wired, wireless communication links



# A closer look at Internet structure

## Network edge:

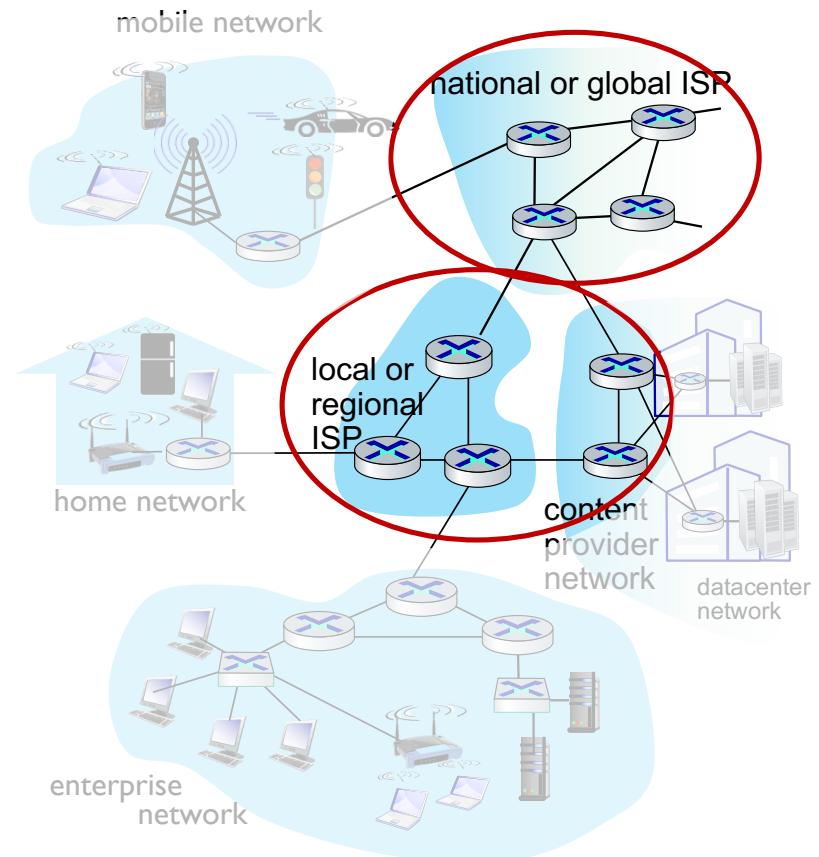
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## Access networks, physical media:

- ❖ wired, wireless communication links

## Network core:

- interconnected routers
- network of networks



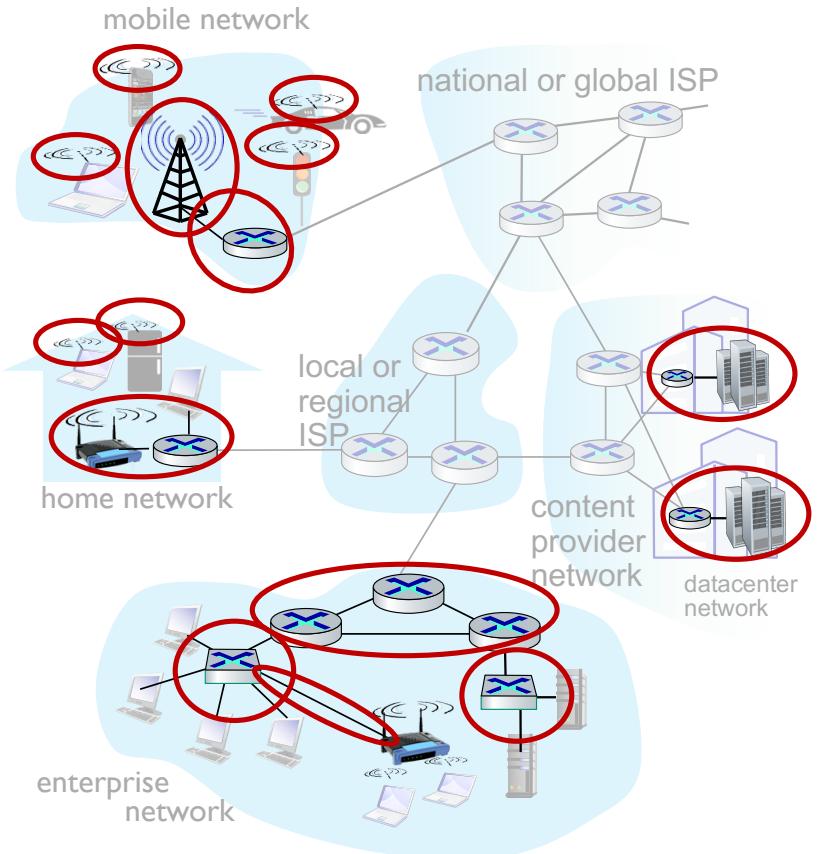
# Access networks and physical media

*Q: How to connect end systems to edge router?*

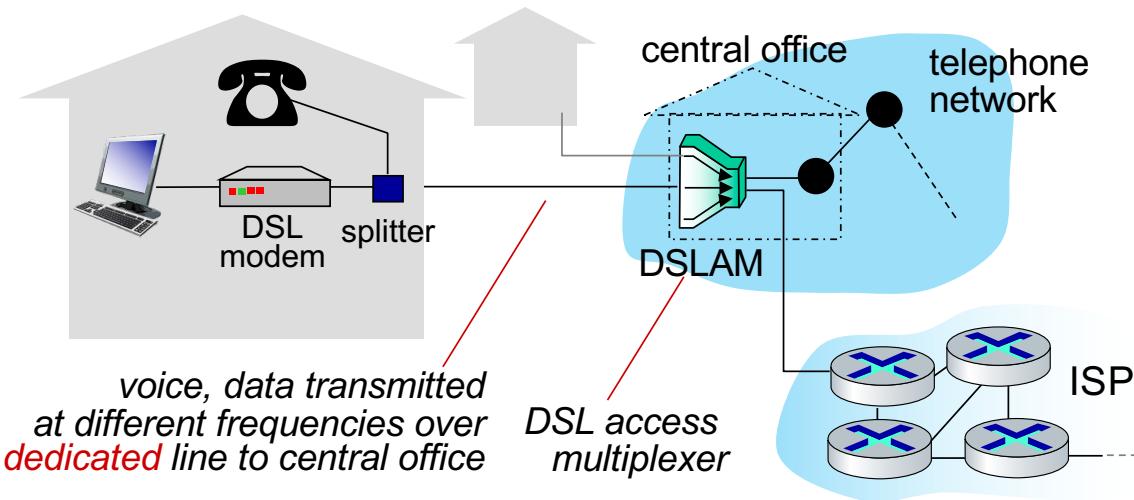
- ❖ residential access nets
- ❖ institutional access networks (school, company)
- ❖ mobile access networks (WiFi, 4G/5G)

*What to look for:*

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

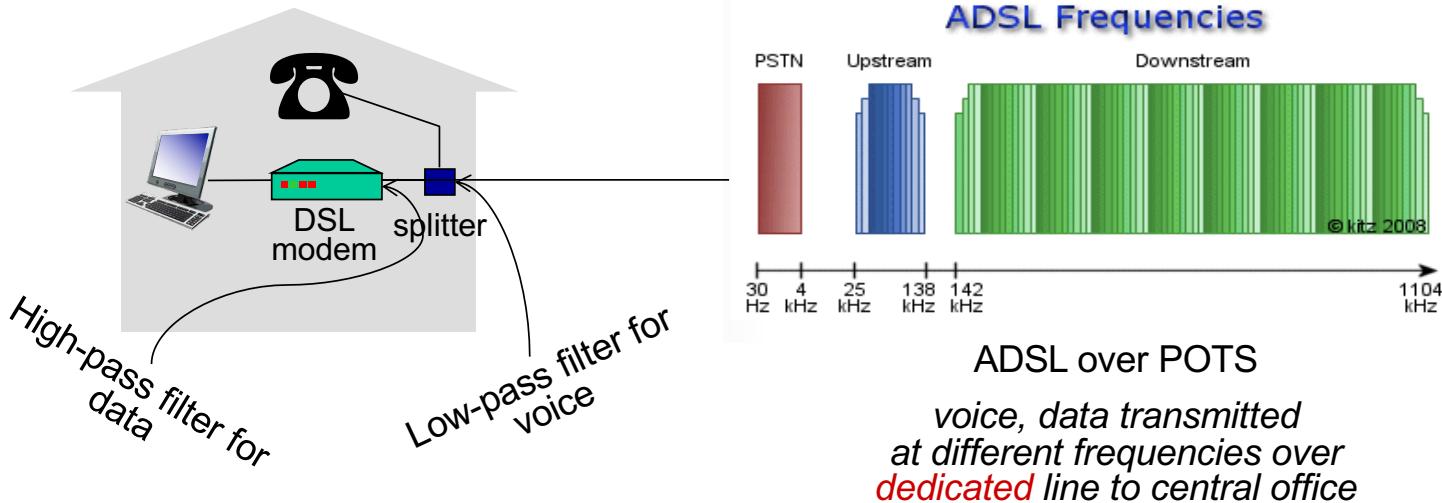


# Access networks: digital subscriber line (DSL)



- 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

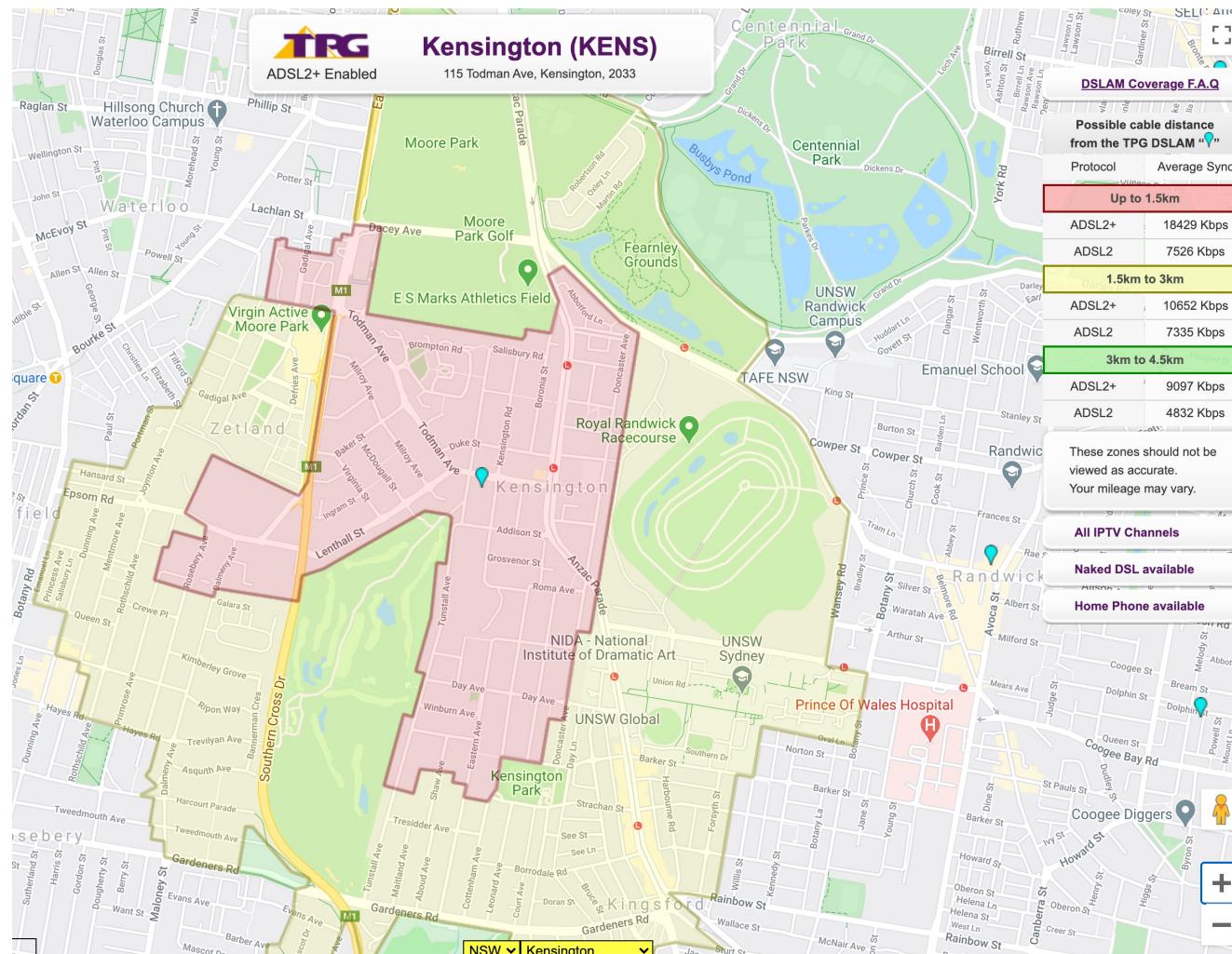
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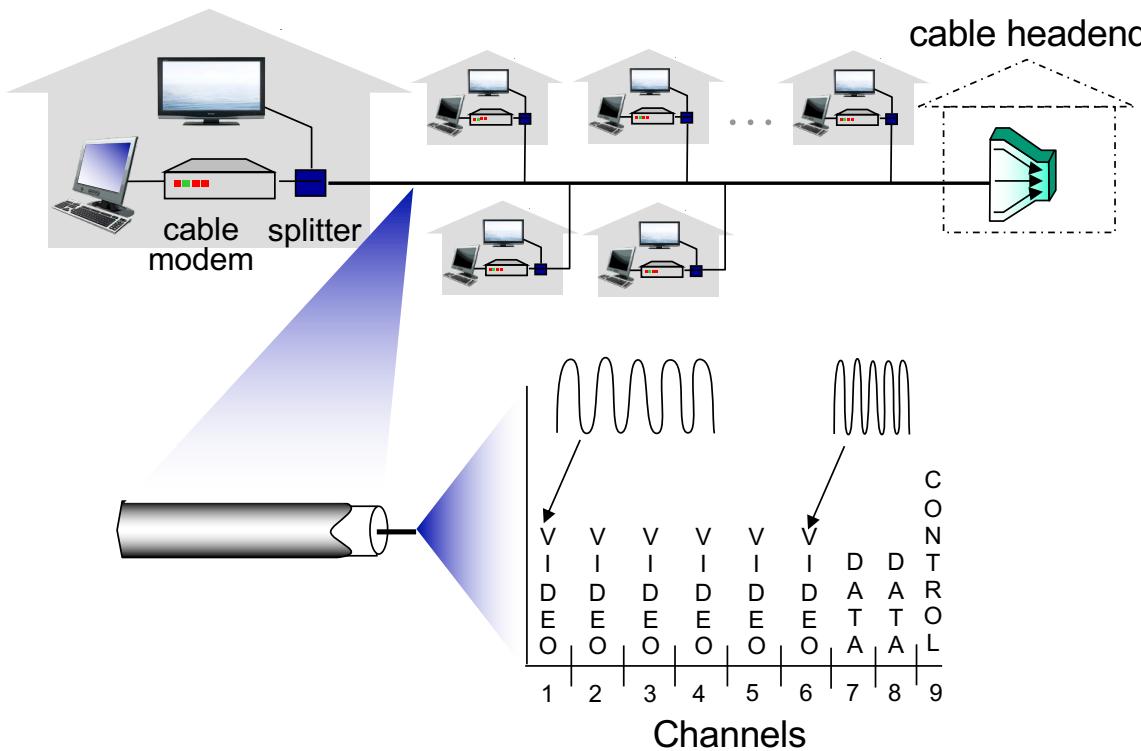
Different data rates for upload and download (ADSL)

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

# Access net: digital subscriber line (DSL)

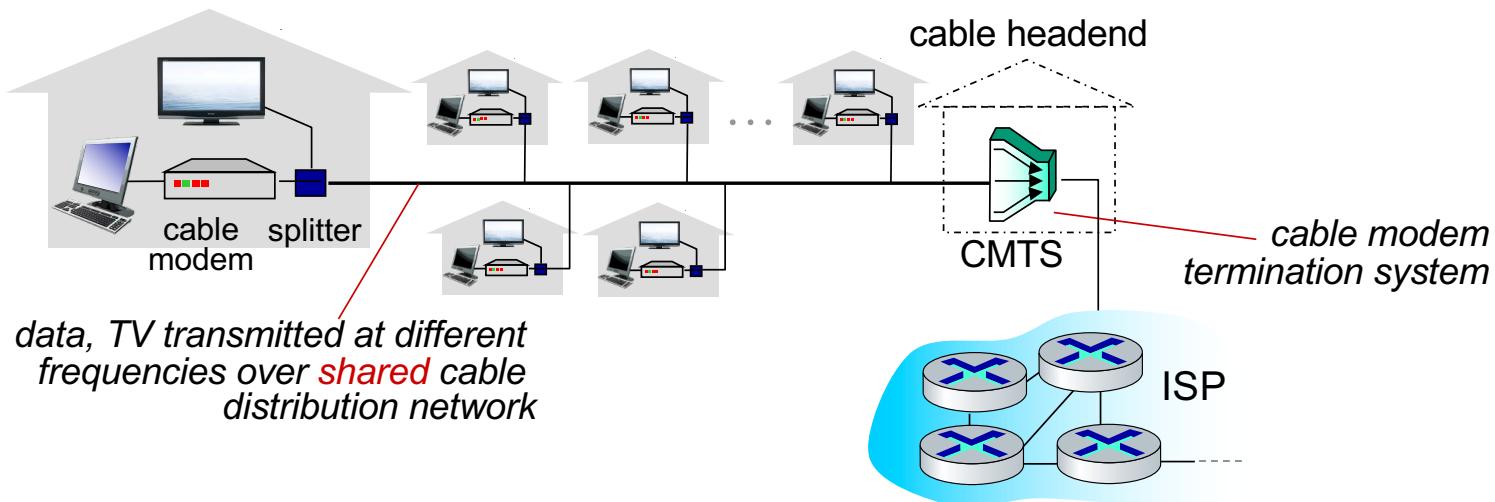


# Access networks: cable-based access



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

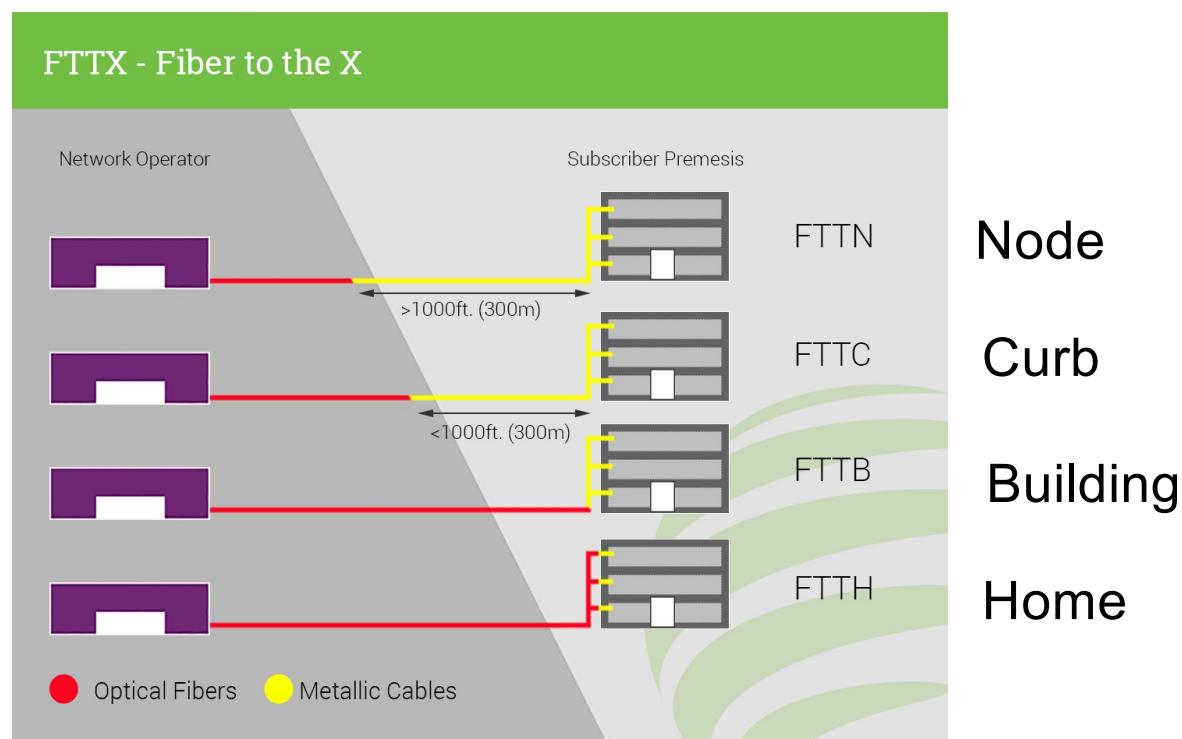
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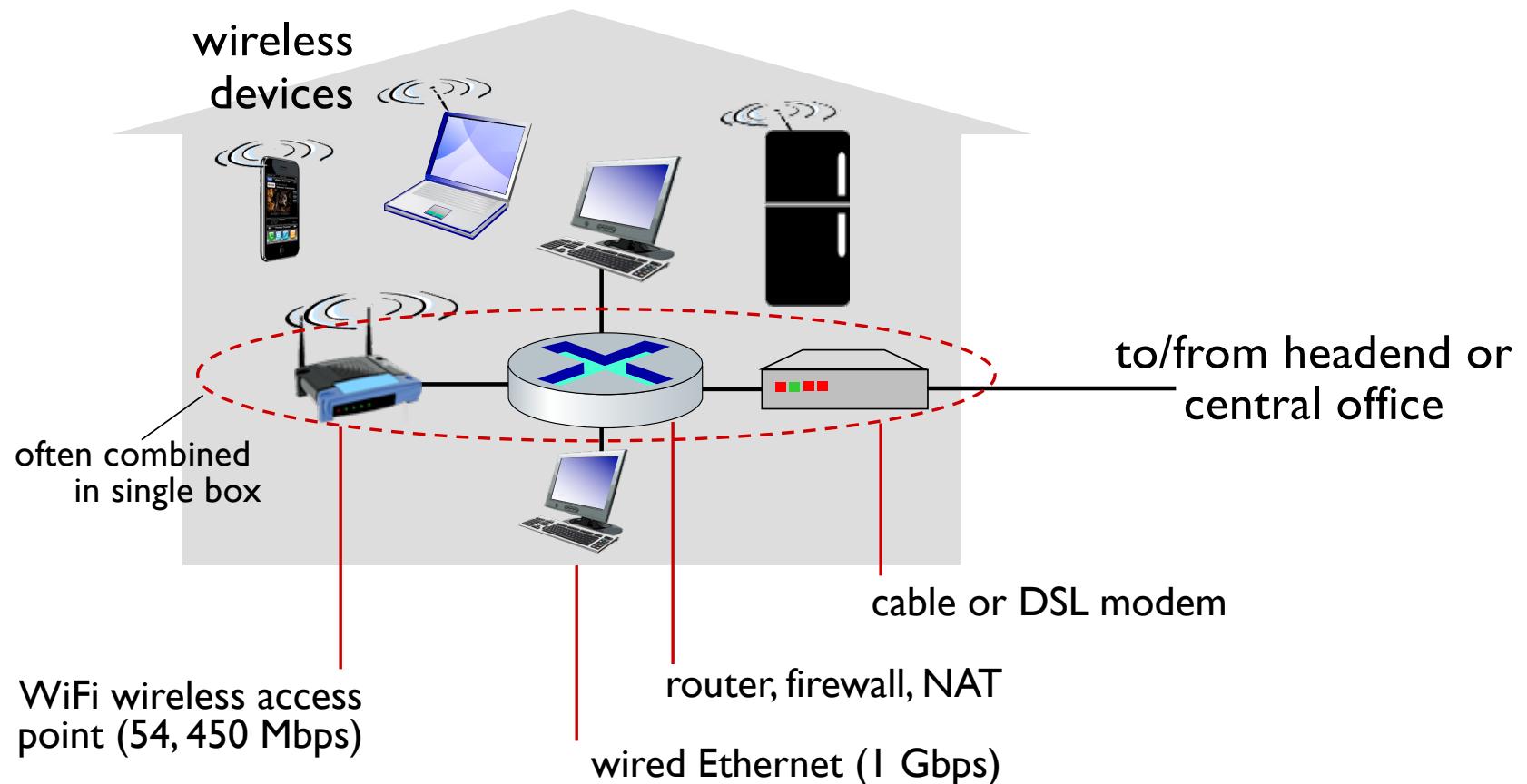
- HFC: hybrid fiber coax
  - asymmetric: up to 40 Mbps – 1.2 Gbs downstream transmission rate, 30-100 Mbps upstream transmission rate
- **network** of cable, fiber attaches homes to ISP router
  - homes **share access network** to cable headend
  - Unlike DSL, which has dedicated access to central office

# 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 1 Gbps



# Access networks: home networks



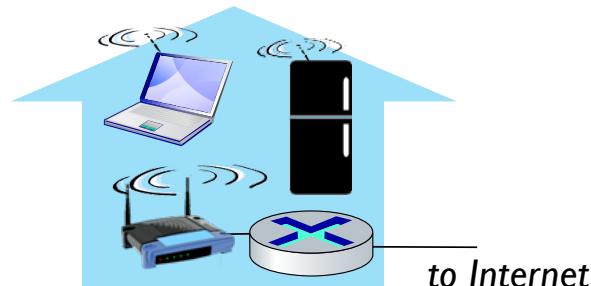
# Wireless access networks

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

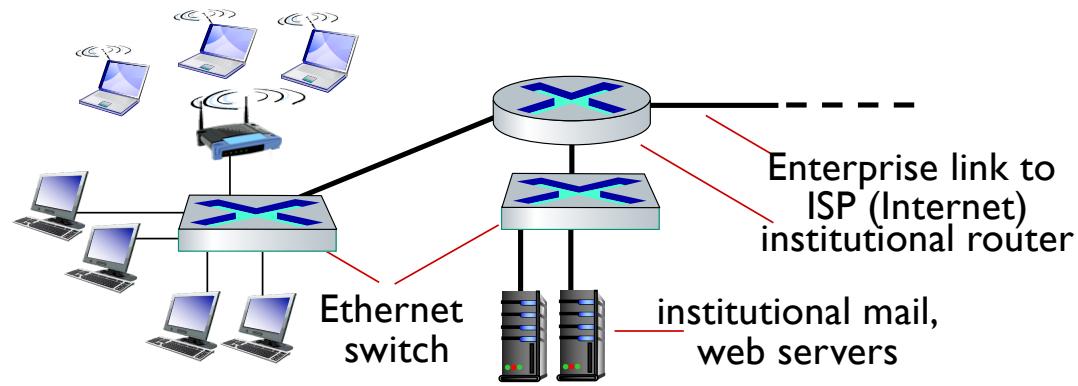


## Wide-area cellular access networks

- 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

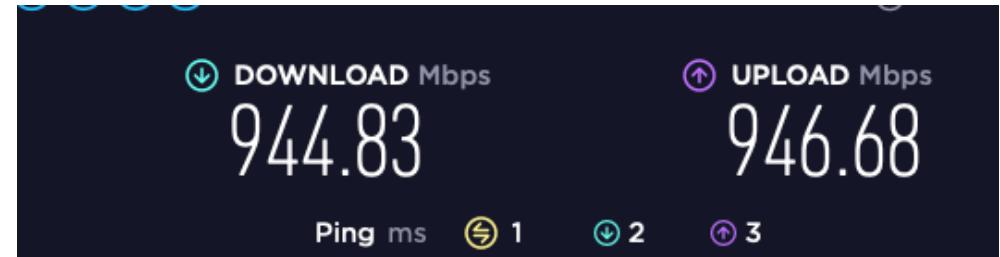
# Sample results

Can you explain the differences?

Uniwide @ CSE



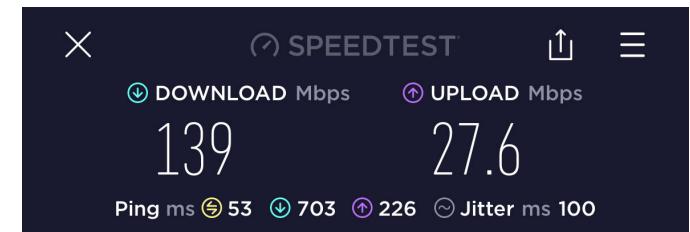
Wired Network @ CSE



FTTB + WiFi @ my home



Optus 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. Campus WiFi (e.g., Uniwide)
- G. Something Else

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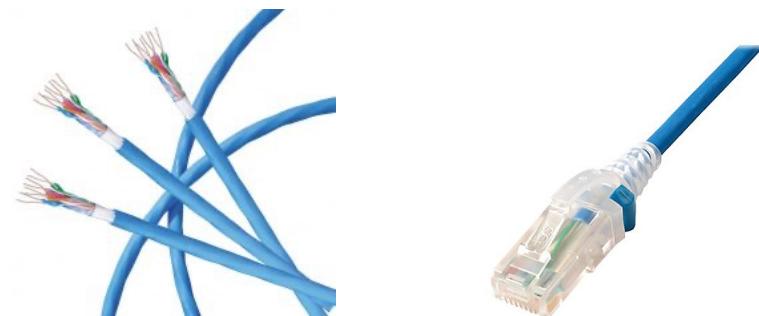
# Links: physical media

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

## Coaxial cable:

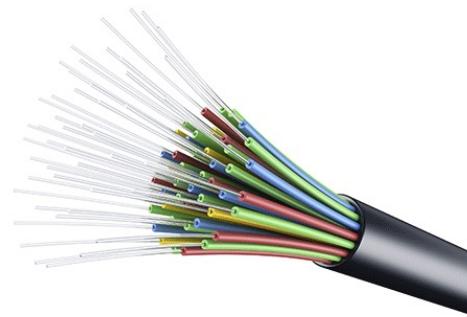
- two concentric copper conductors
- bidirectional
- broadband:
  - multiple frequency channels on cable
  - 100's Mbps per channel



SELF STUDY  
NOT ON EXAM

## 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:

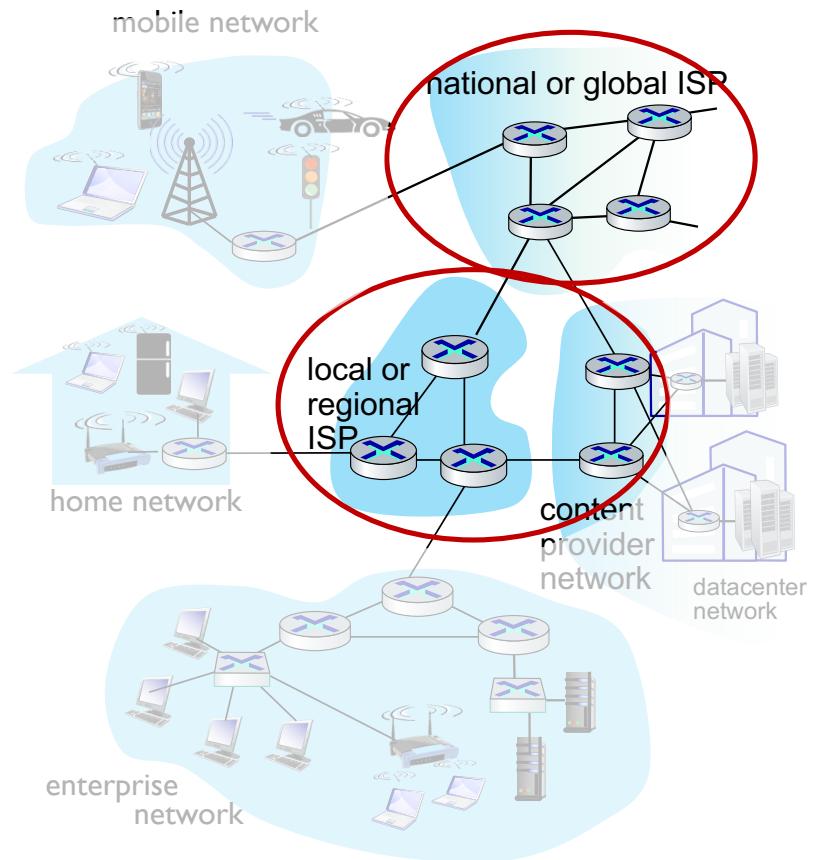
- terrestrial microwave
  - up to 45 Mbps channels
- Wireless LAN (WiFi)
  - Up to 100's Mbps
- wide-area (e.g., cellular)
  - 4G cellular: ~ 10's Mbps
- satellite
  - up to 45 Mbps per channel
  - 270 msec end-end delay
  - geosynchronous versus low-earth-orbit

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# The network core

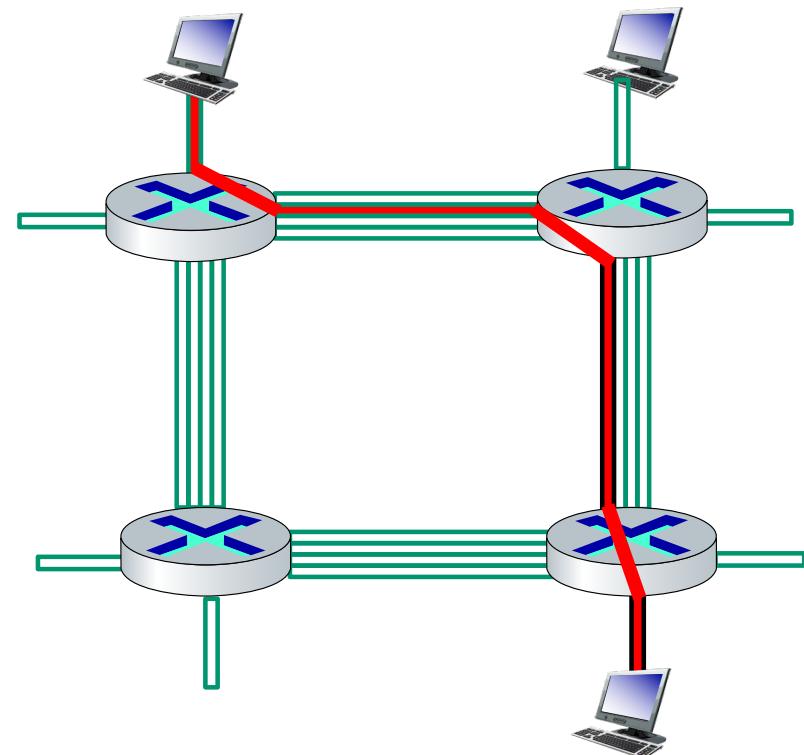
- ❖ mesh of interconnected routers
- ❖ **packet-switching:** hosts break application-layer messages into **packets**
  - forward packets from one router to the next, across links on path from source to destination
  - each packet transmitted at full link capacity
  - **Is used in the Internet**
- ❖ **circuit-switching:**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

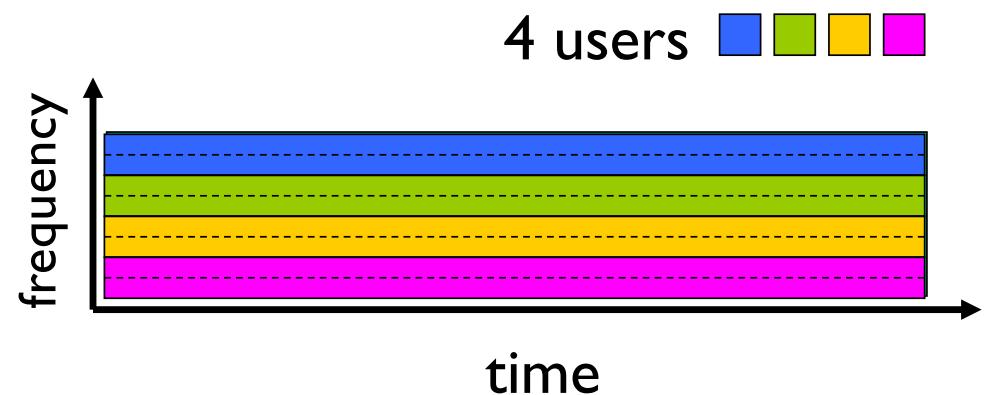
- ❖ in diagram, each link has four circuits.
  - call gets 2<sup>nd</sup> circuit in top link and 1<sup>st</sup> circuit in right link.
- ❖ dedicated resources: no sharing
  - circuit-like (guaranteed) performance
- ❖ circuit segment idle if not used by call (no sharing)
- ❖ commonly used in traditional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



# Circuit switching: FDM and TDM

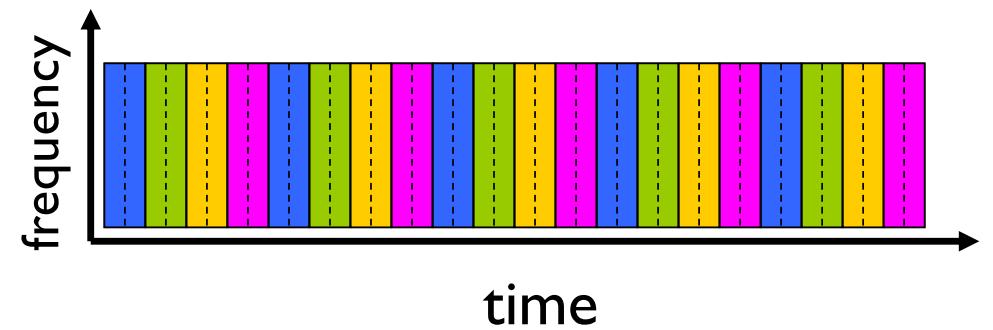
## Frequency Division Multiplexing (FDM)

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

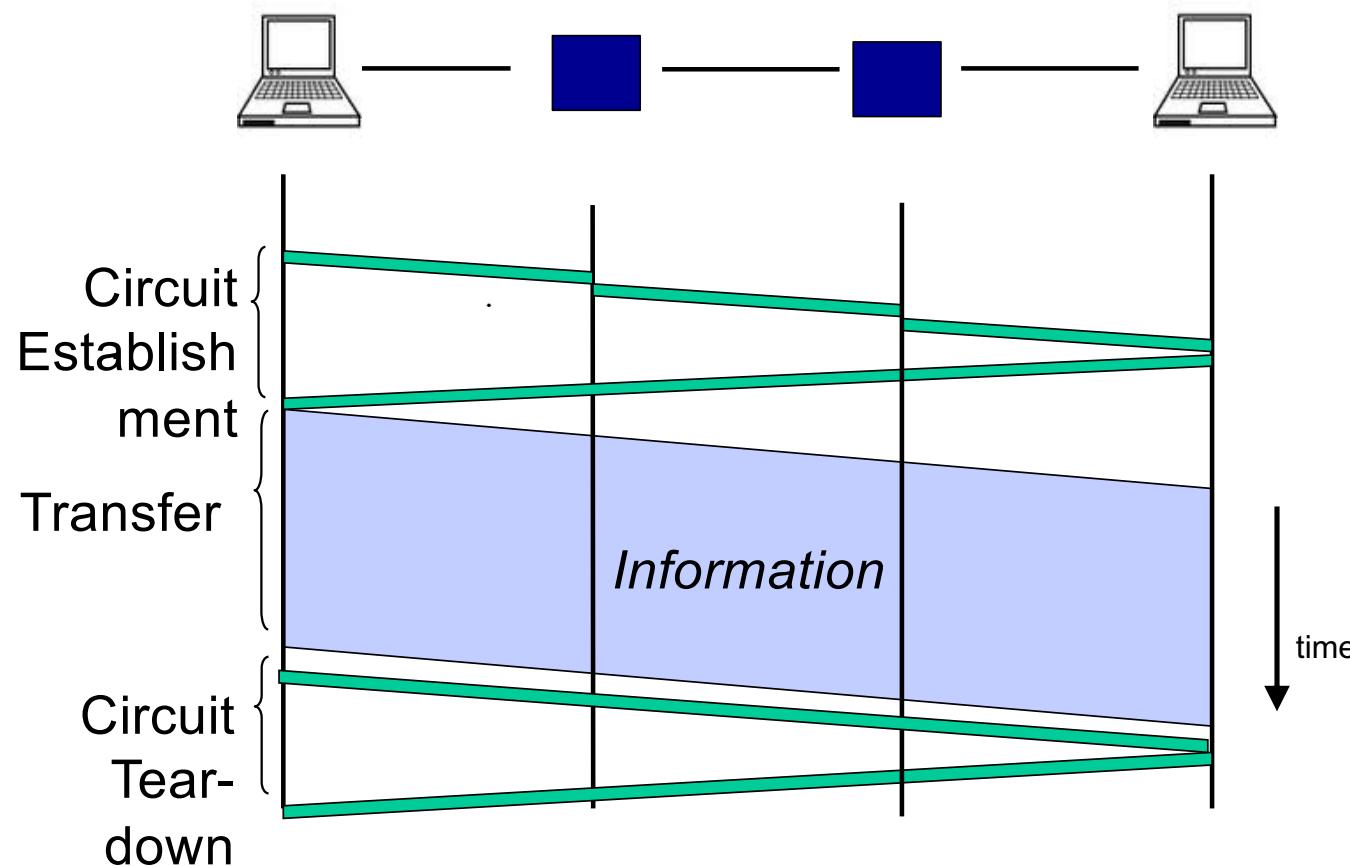


## Time Division Multiplexing (TDM)

- 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

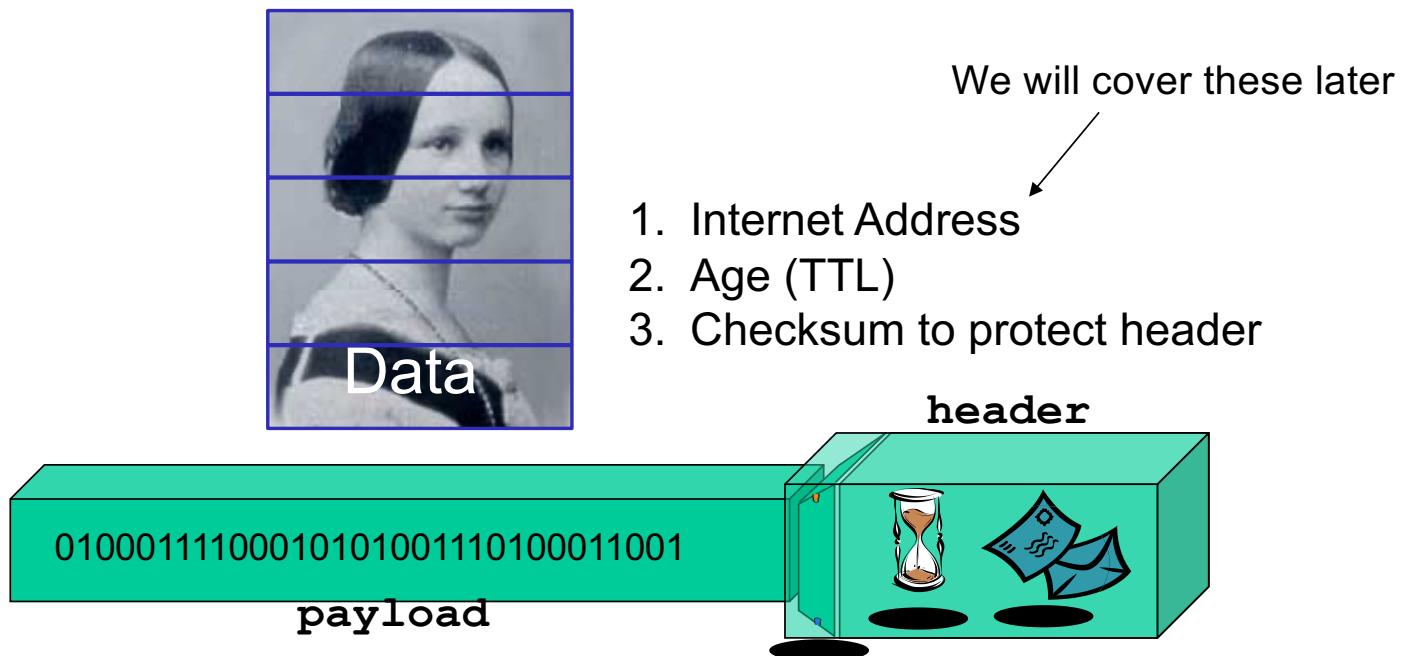
- Computers communicate at very diverse rates. For example, viewing a video vs using telnet or web browsing
- Fixed data rate is not useful

## ➤ 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)

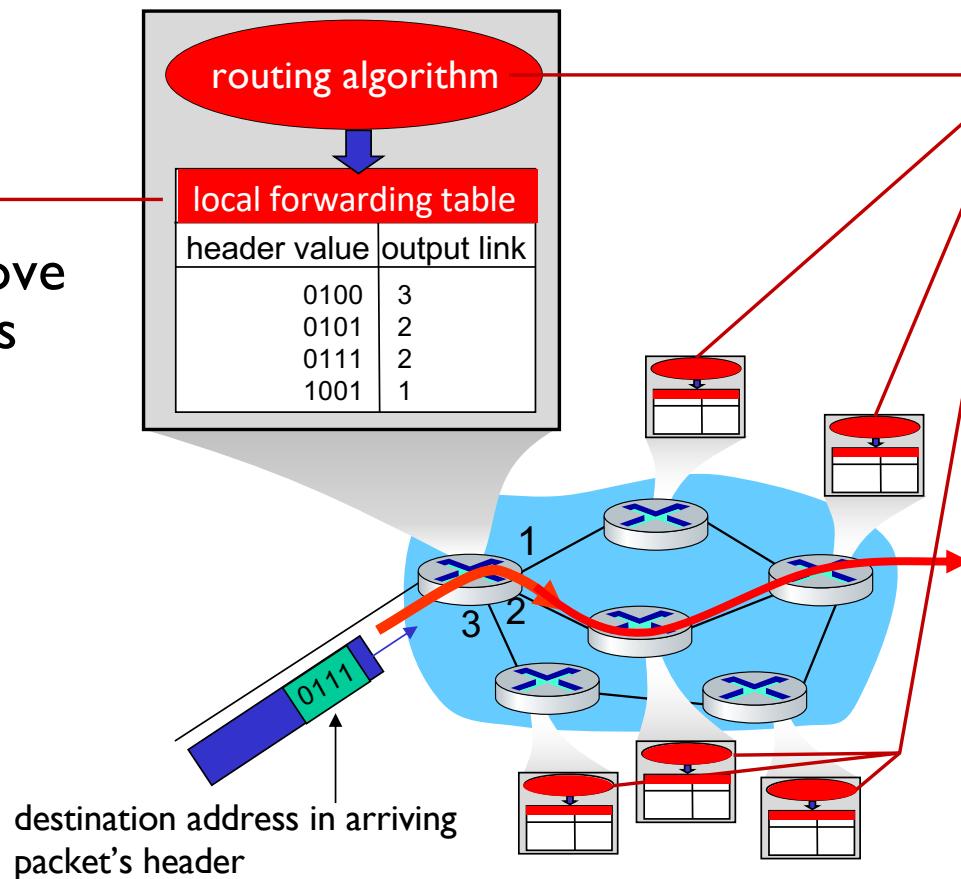
# Packet Switching

- ❖ 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:

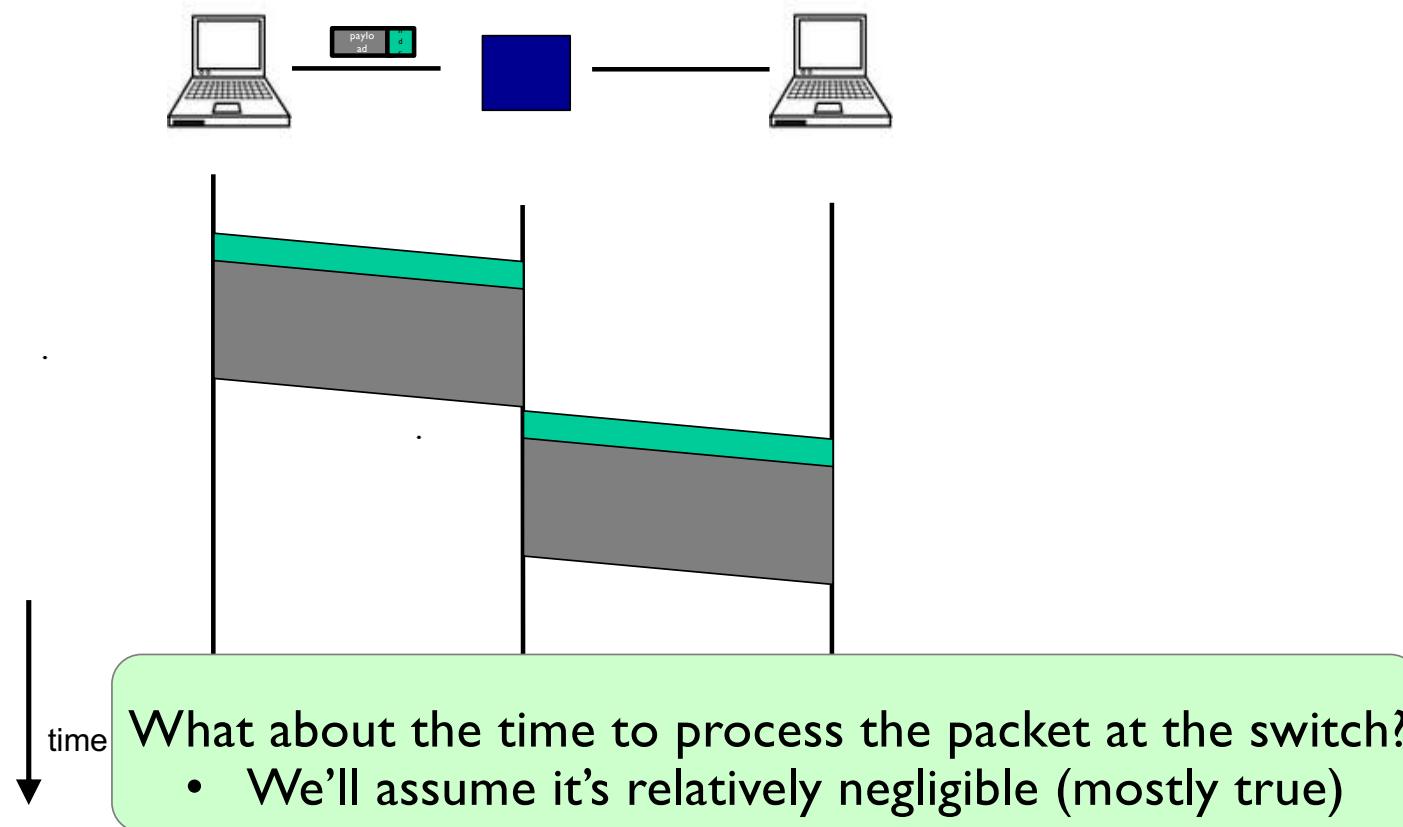
- ❖ *local* action: move arriving packets from router's input link to appropriate router output link



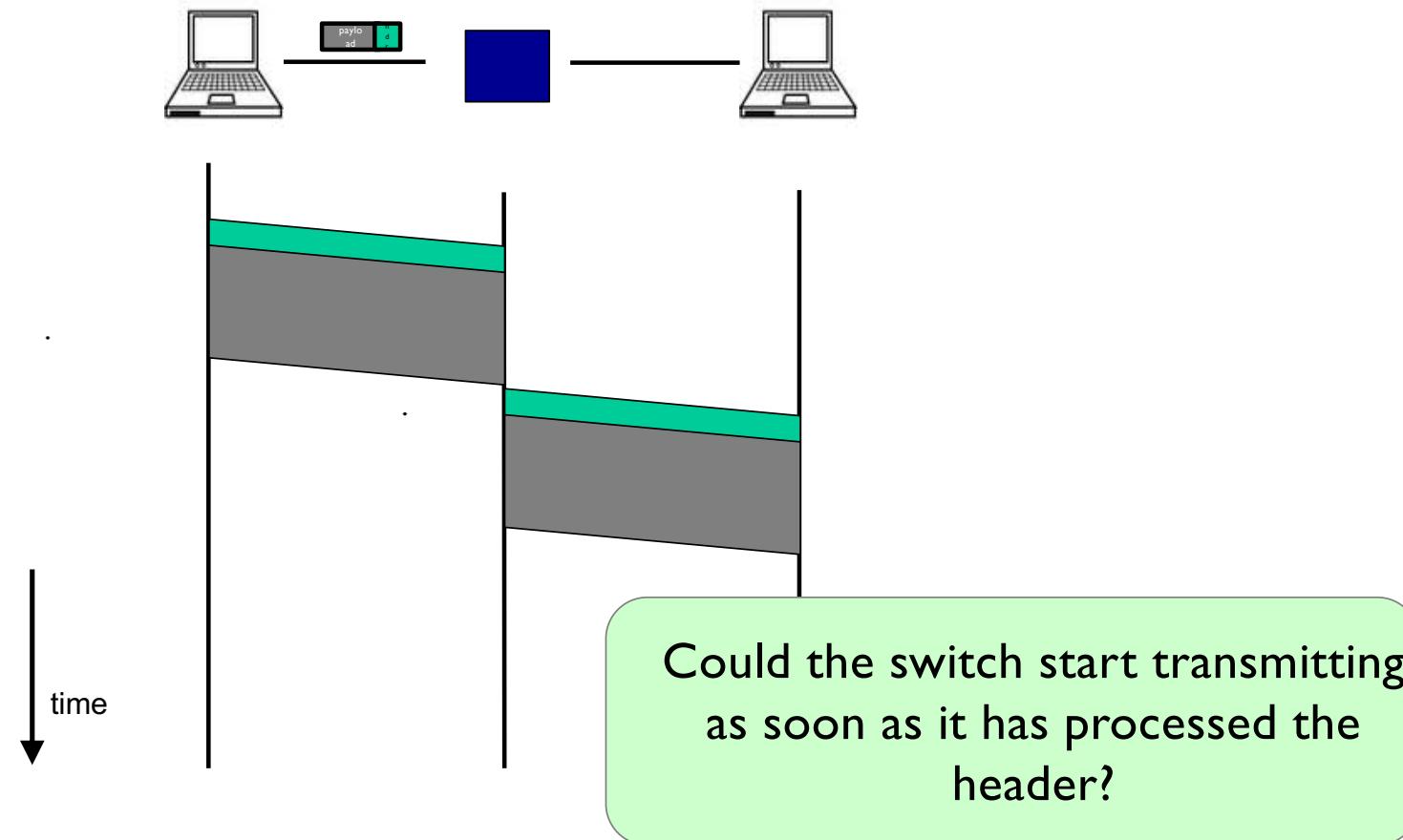
## Routing:

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

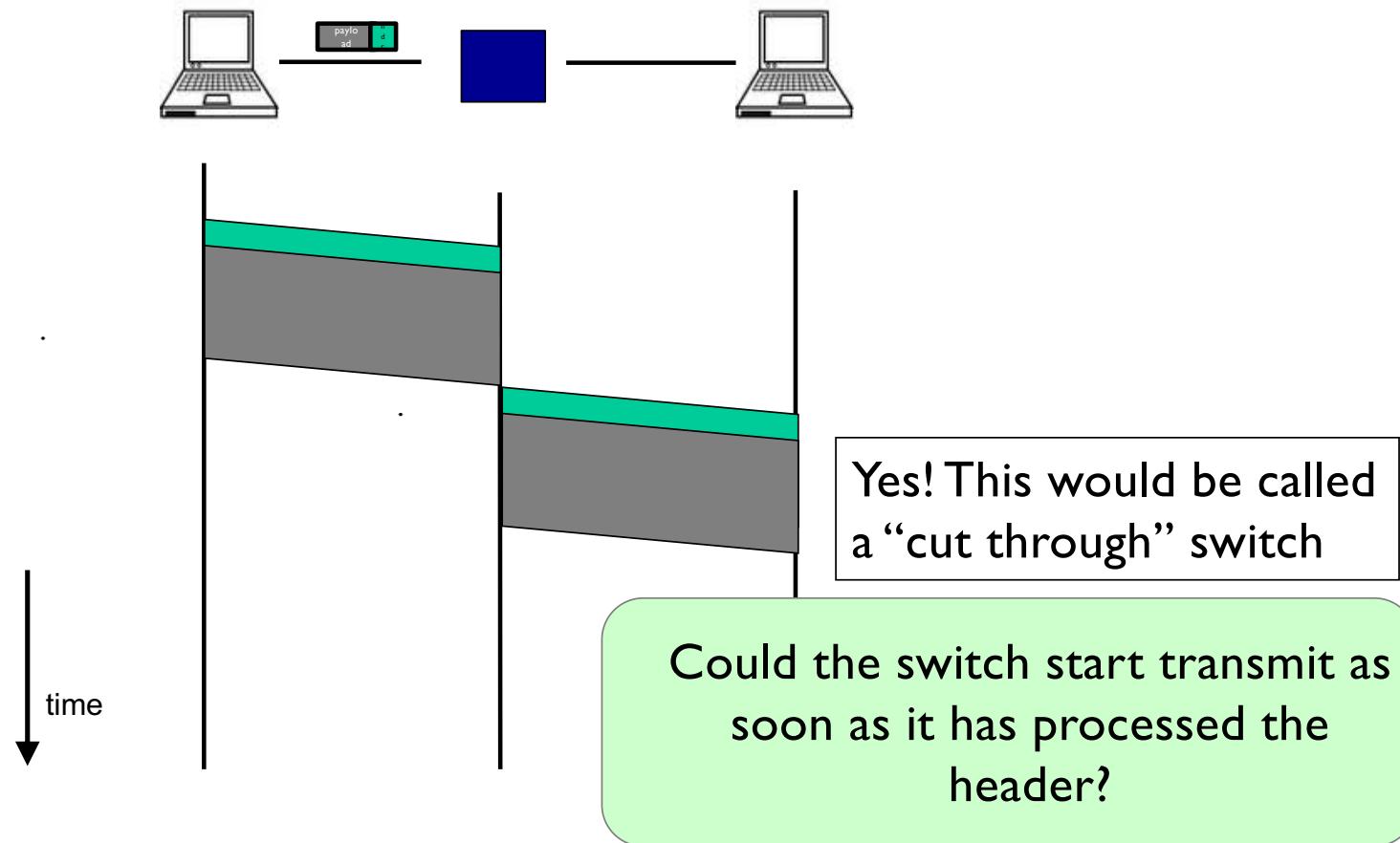
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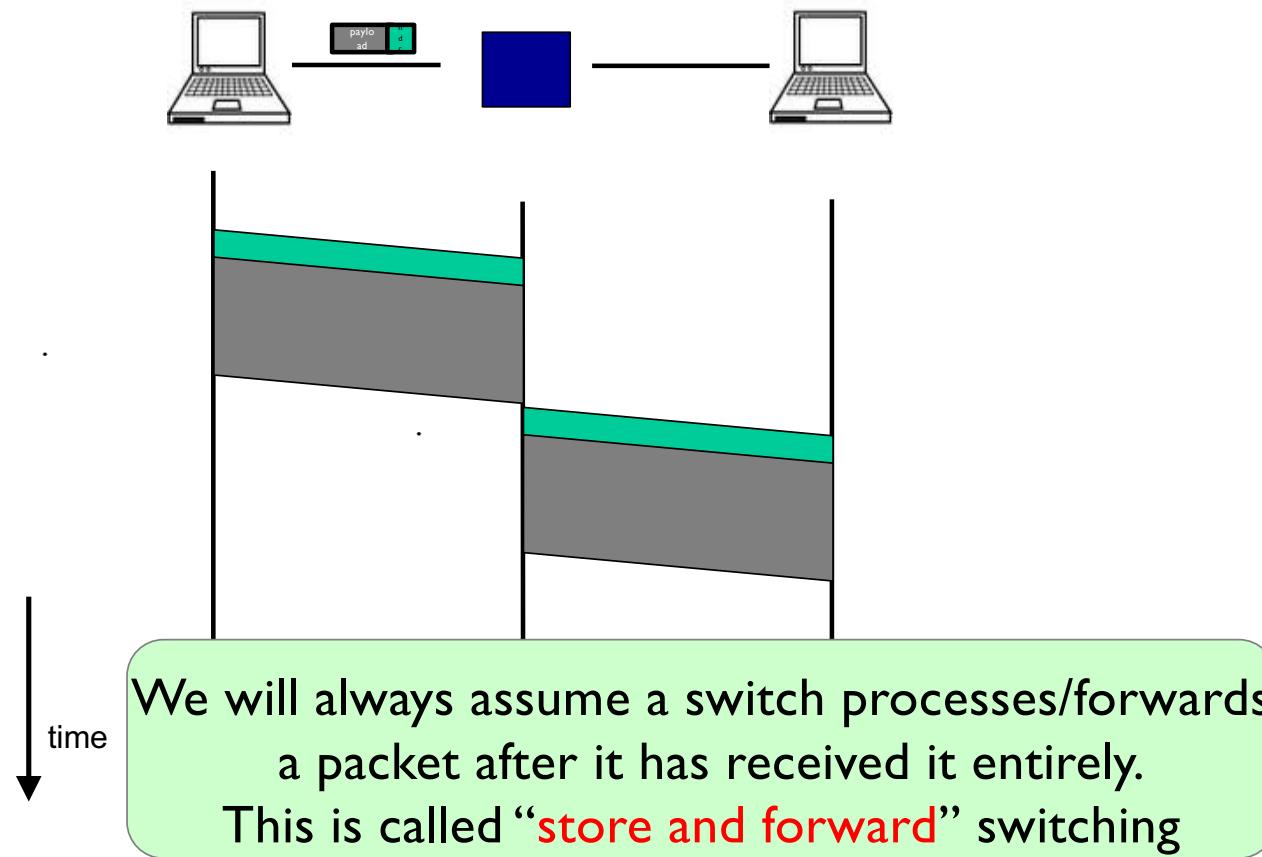
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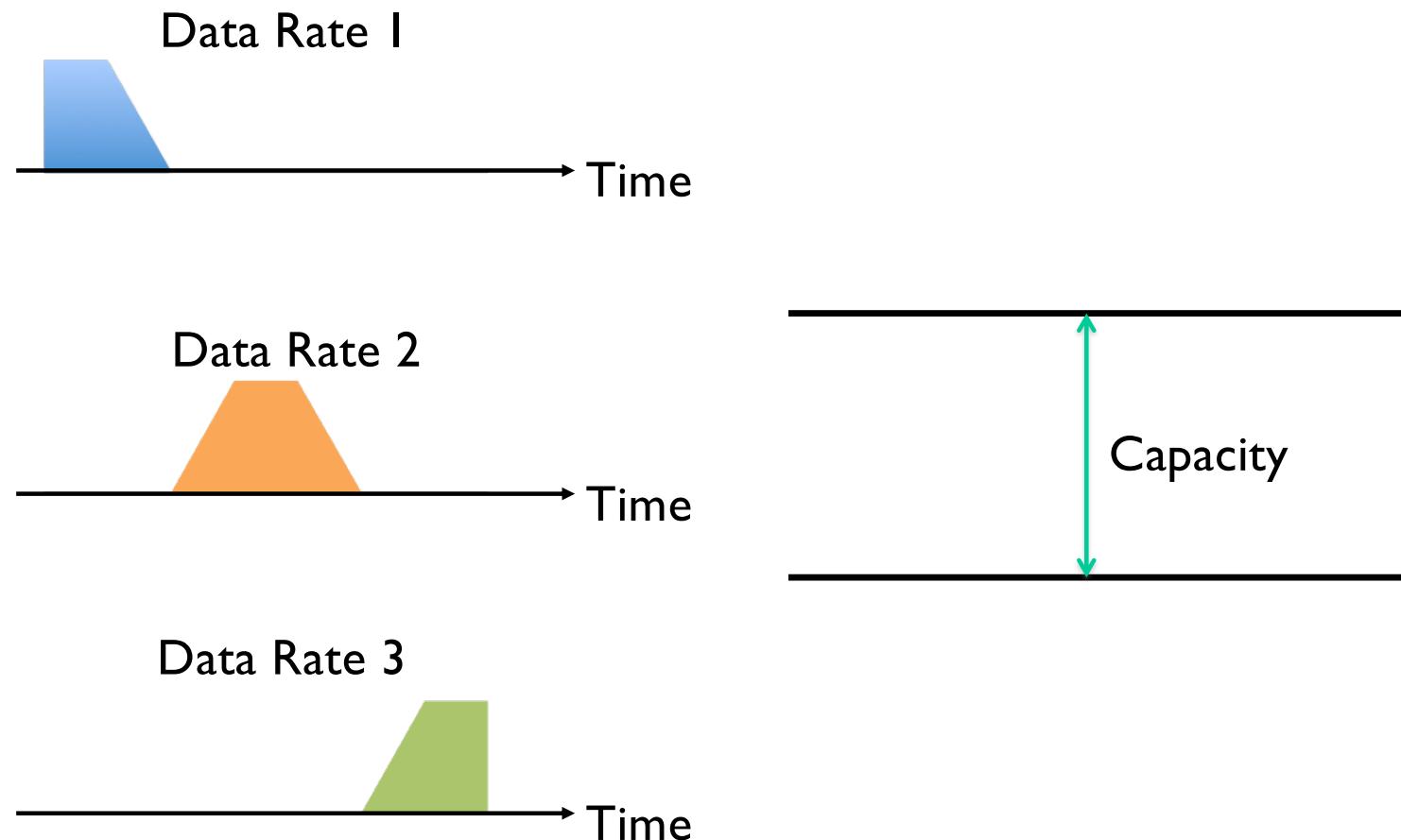
# Packet Switching

- ❖ 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”

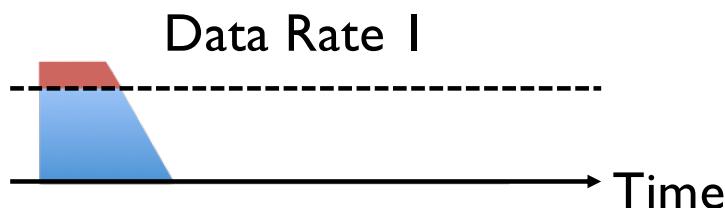
# Packet Switching

- ❖ 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**

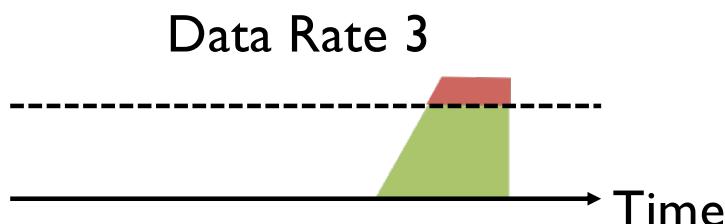
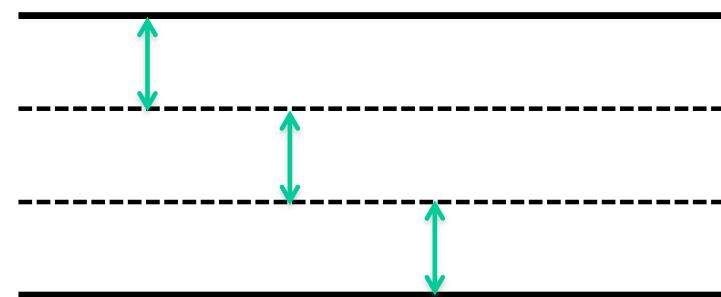
# Three Flows with Bursty Traffic



# When Each Flow Gets 1/3<sup>rd</sup> of Capacity

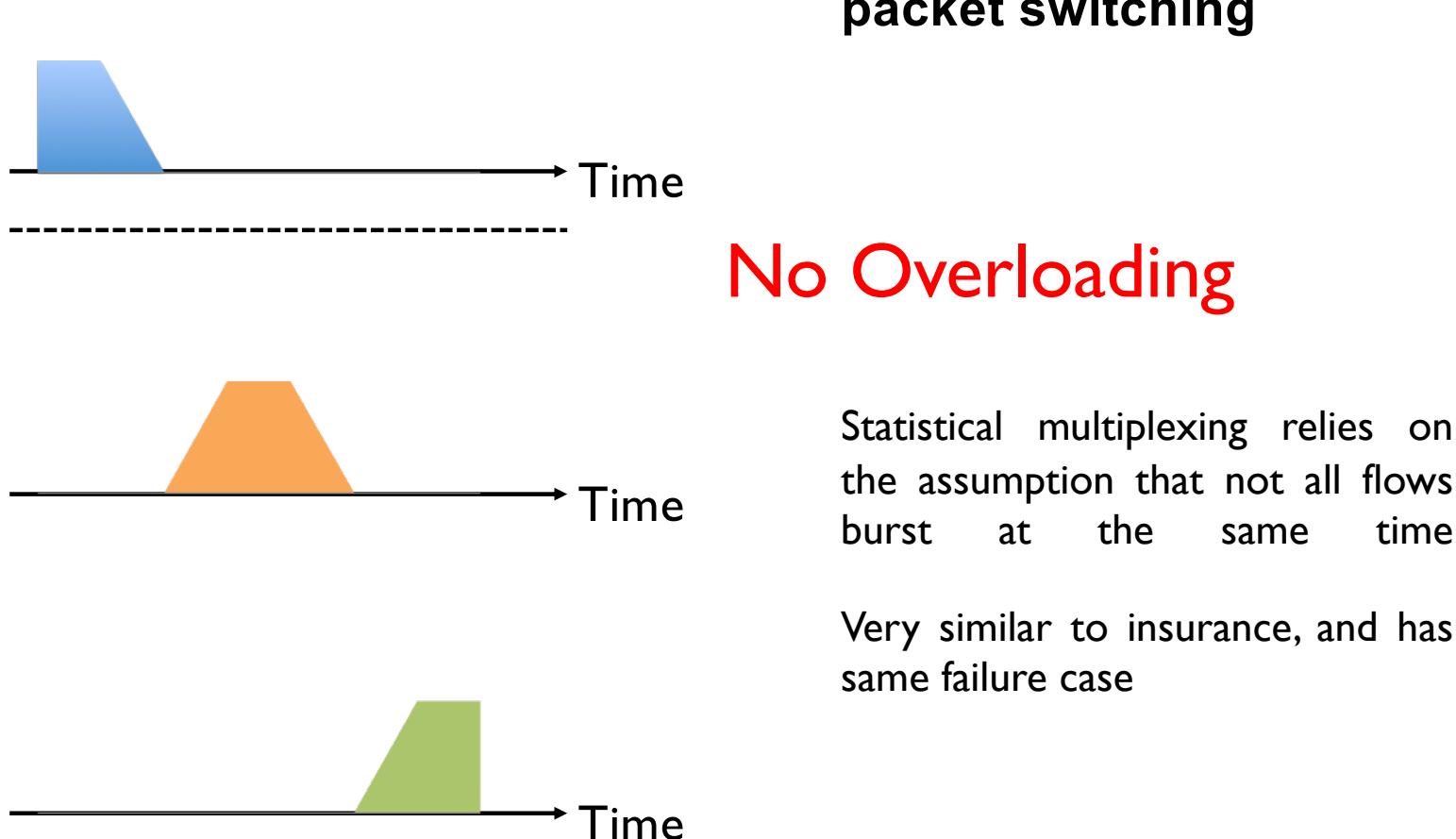


like circuit switching

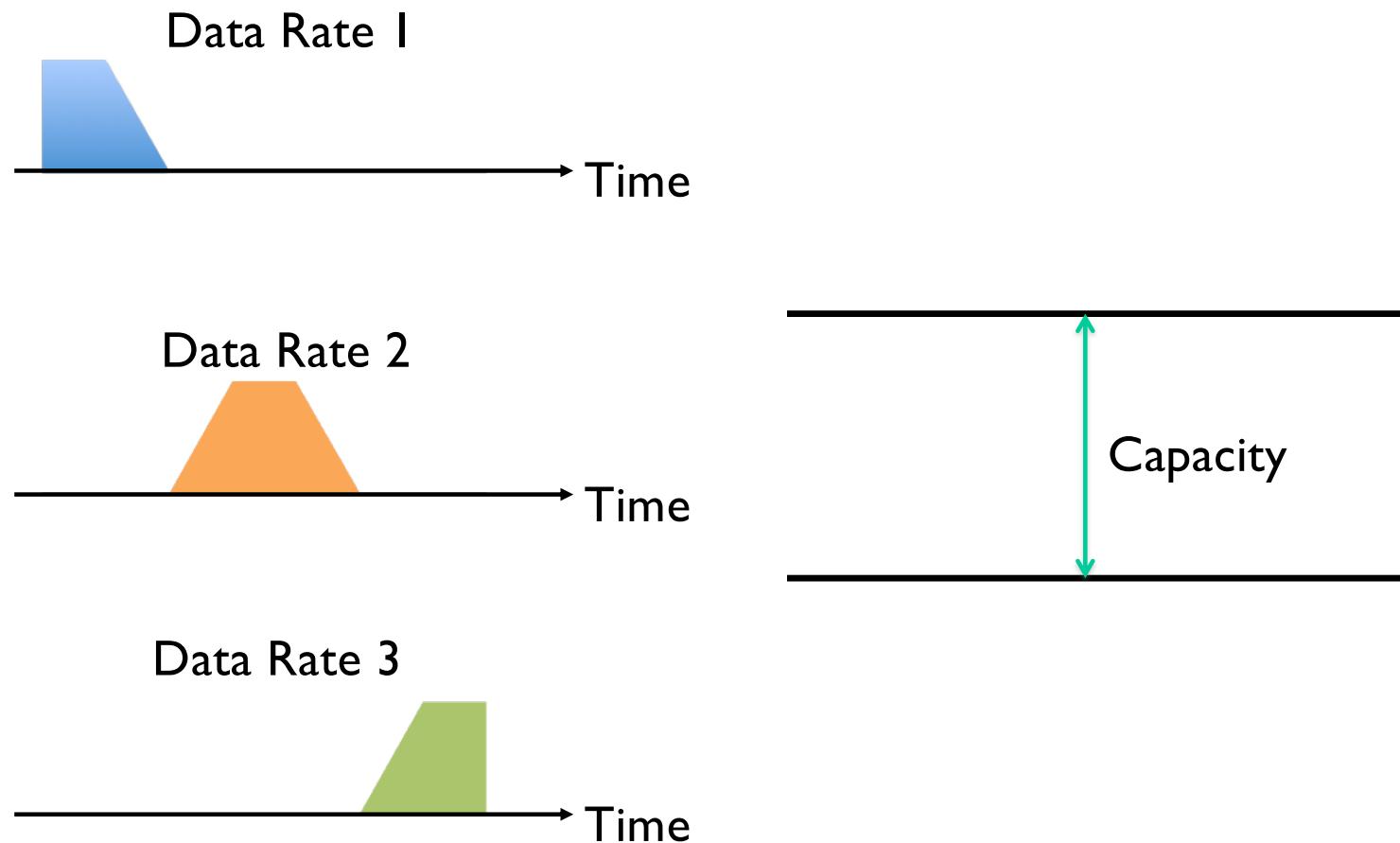


Overloaded

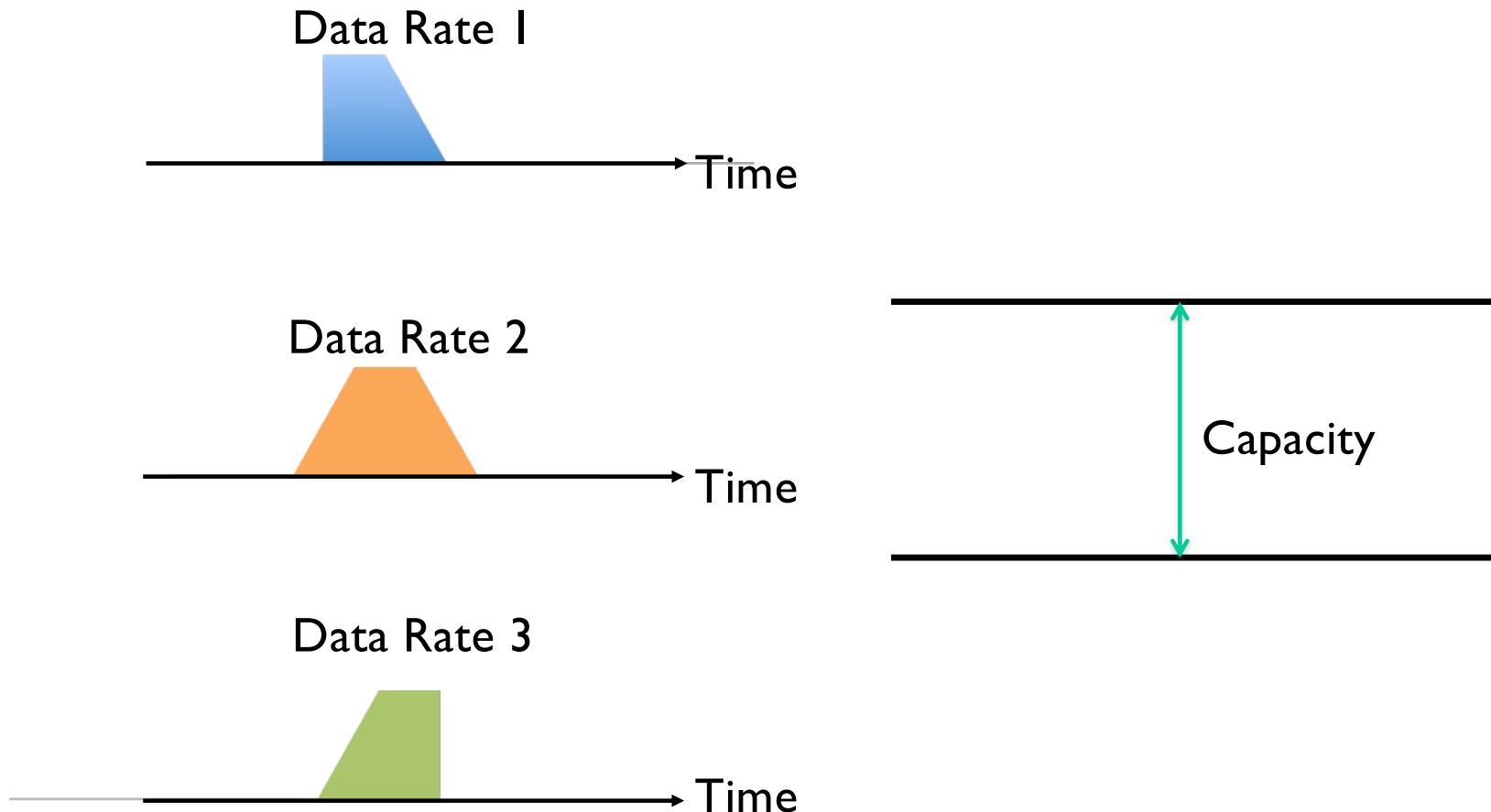
# When Flows Share Total Capacity



# Three Flows with Bursty Traffic

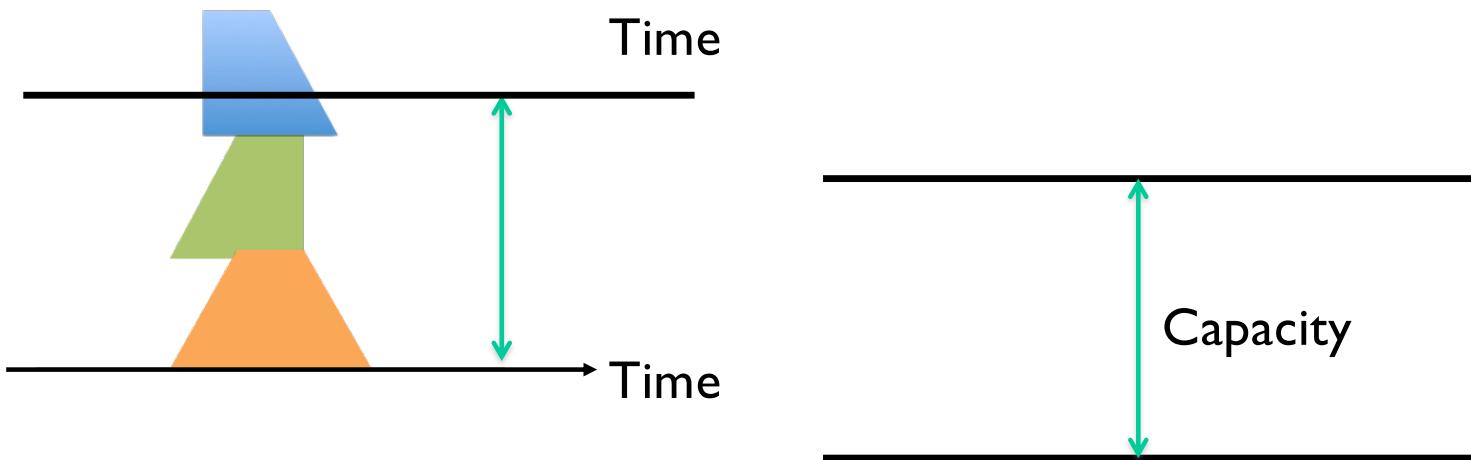


# Three Flows with Bursty Traffic



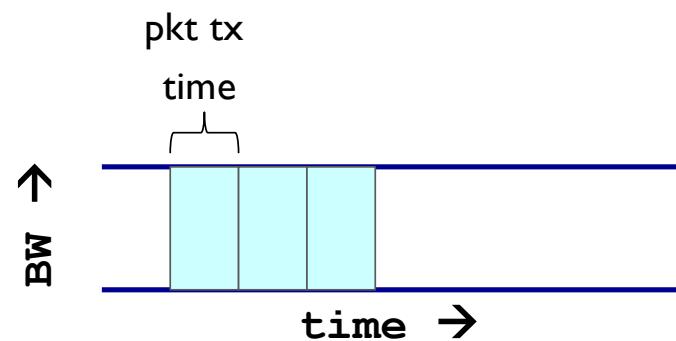
# Three Flows with Bursty Traffic

Data Rate 1+2+3 >> Capacity

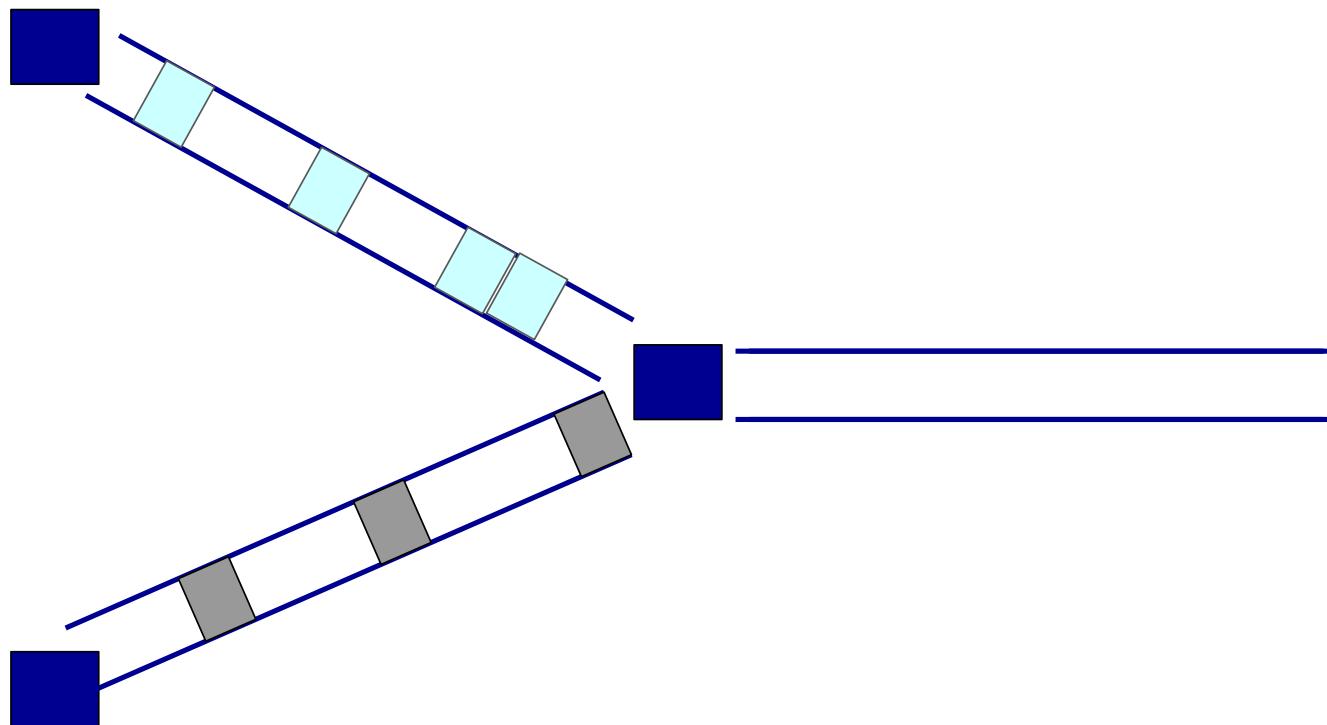


What do we do under overload?

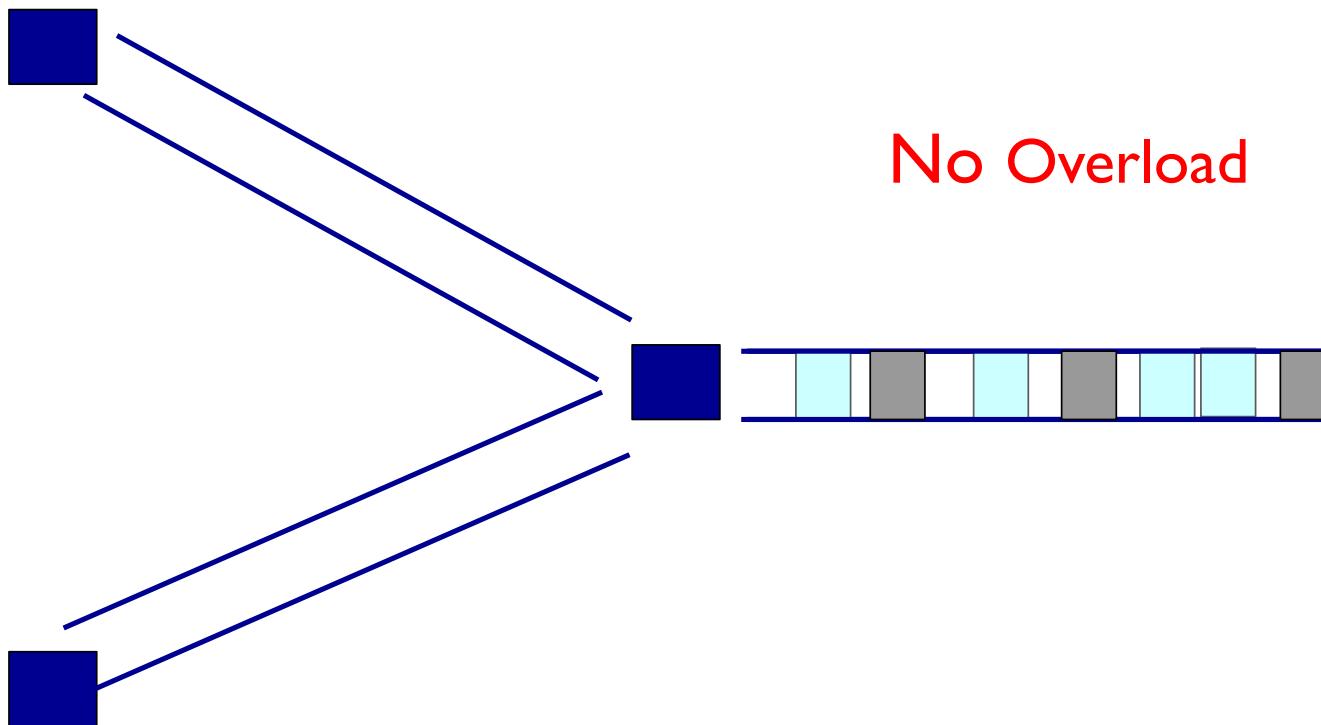
# Statistical multiplexing: pipe view



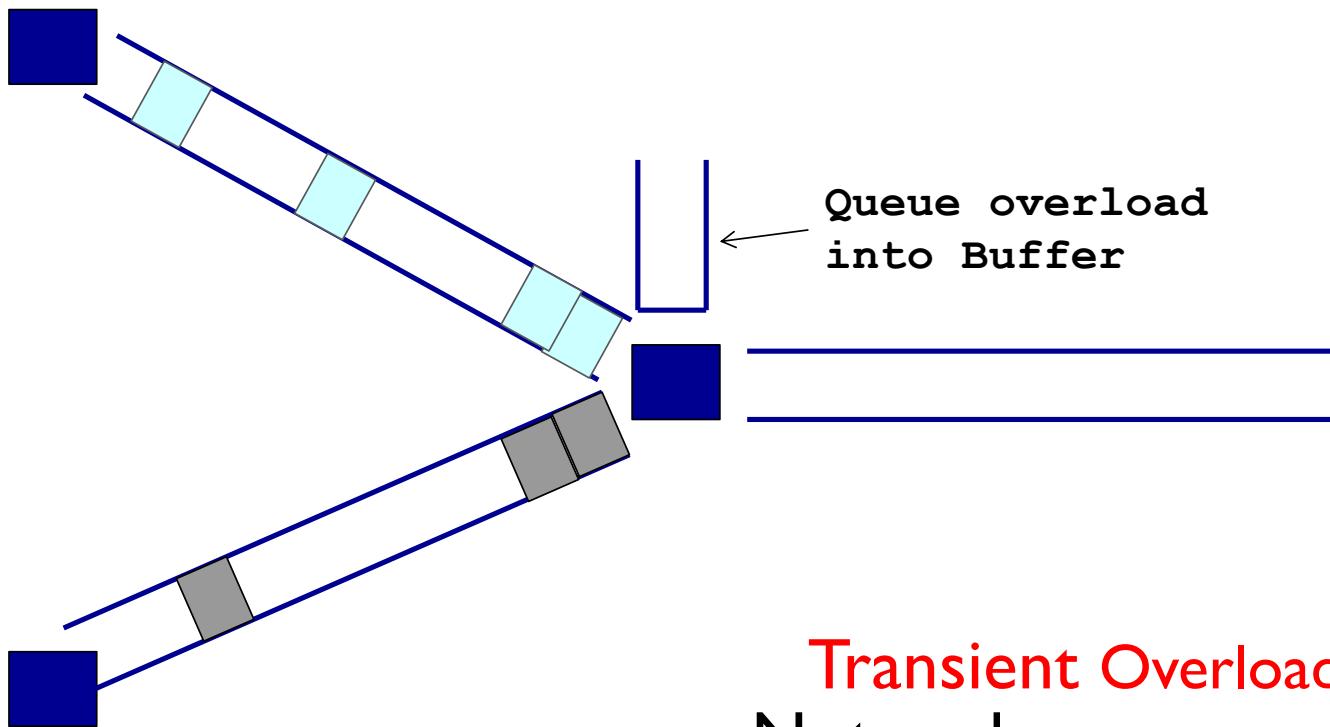
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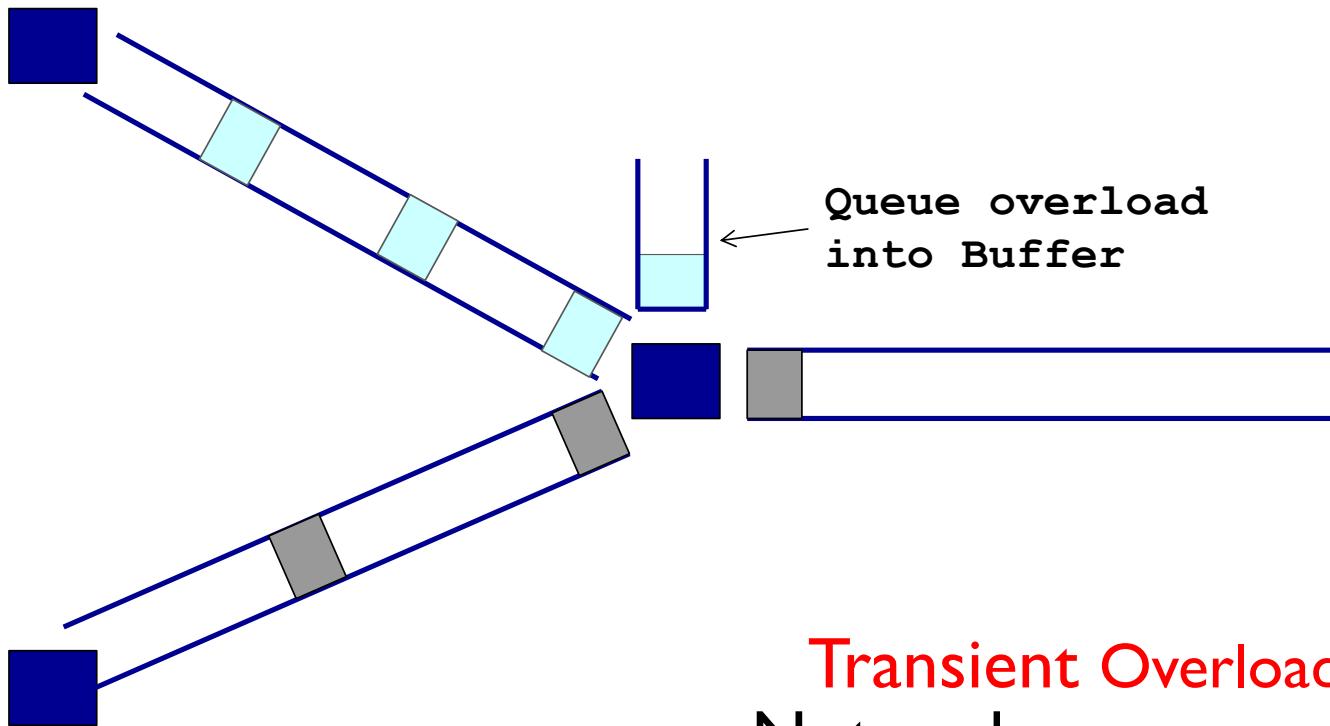
# Statistical multiplexing: pipe view



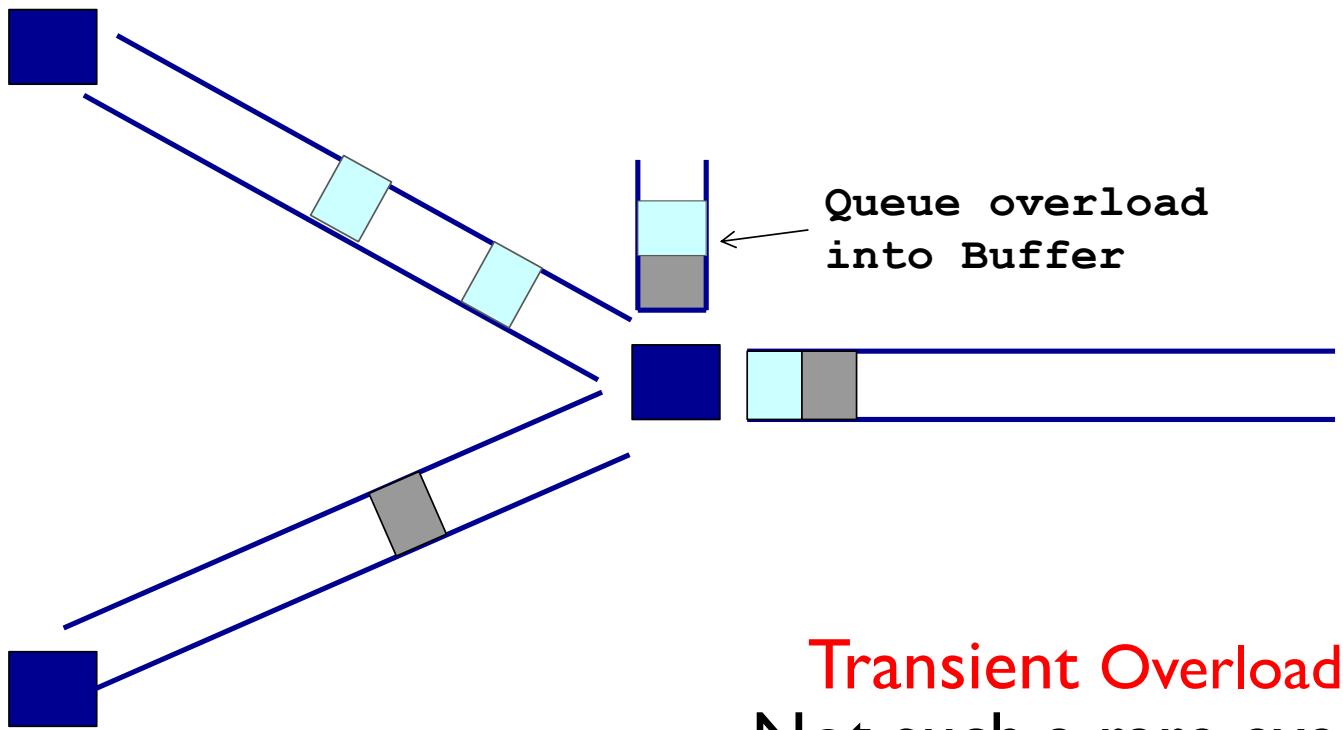
# Statistical multiplexing: pipe view



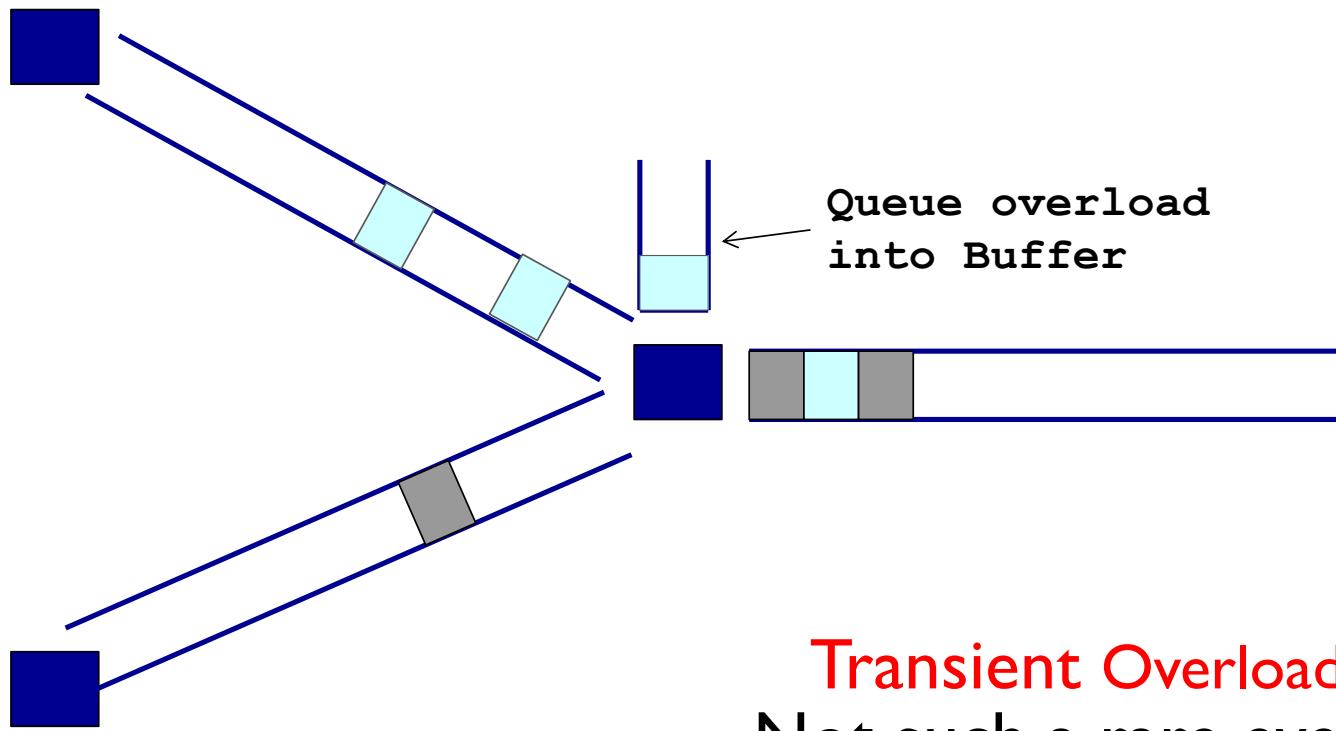
# Statistical multiplexing: pipe view



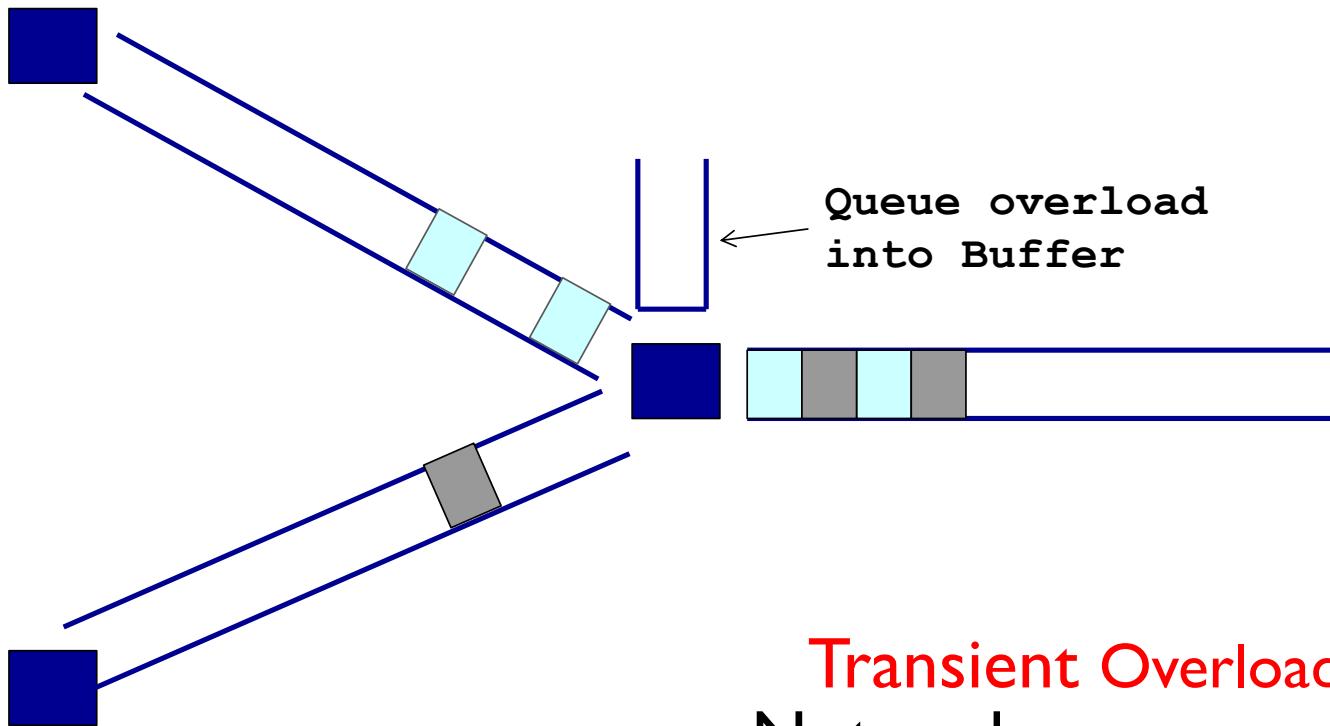
# Statistical multiplexing: pipe view



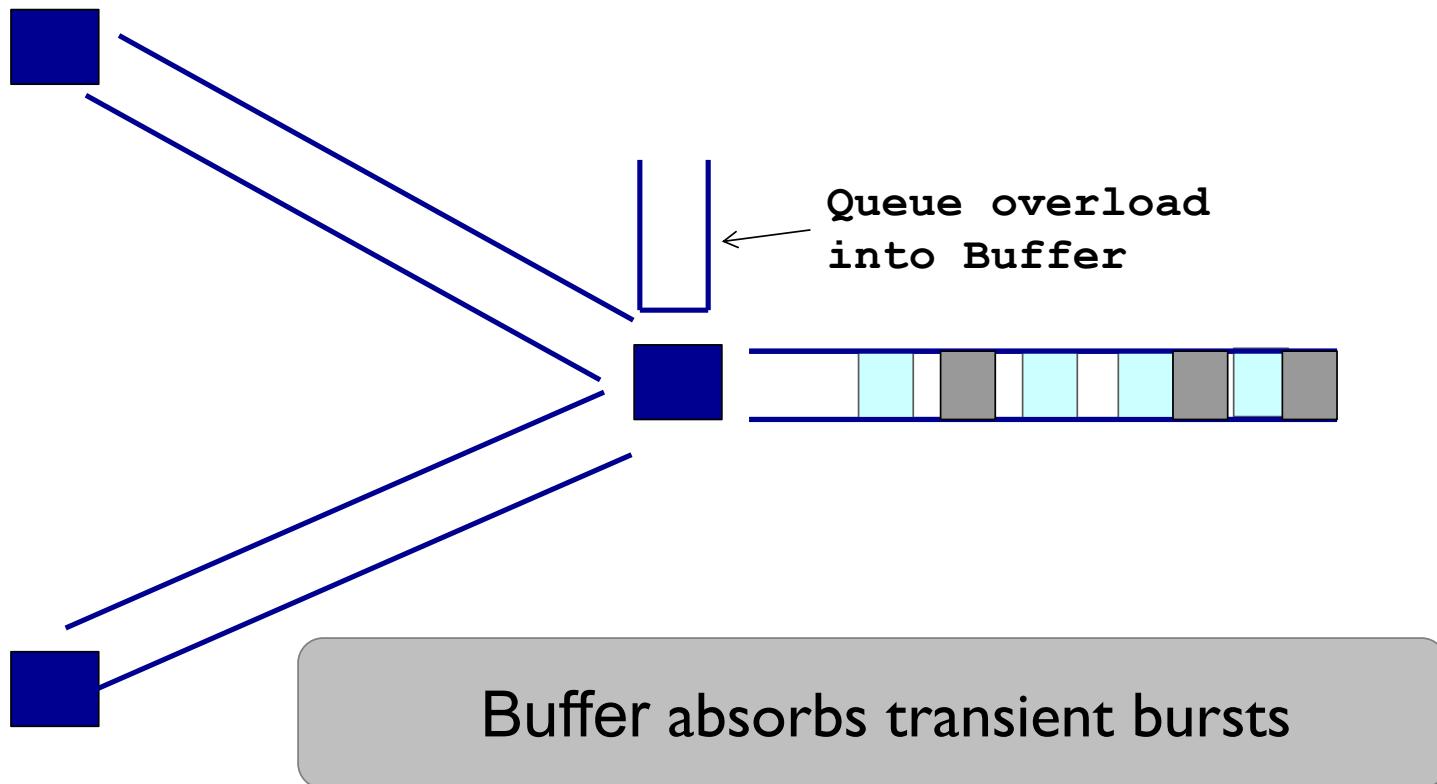
# Statistical multiplexing: pipe view



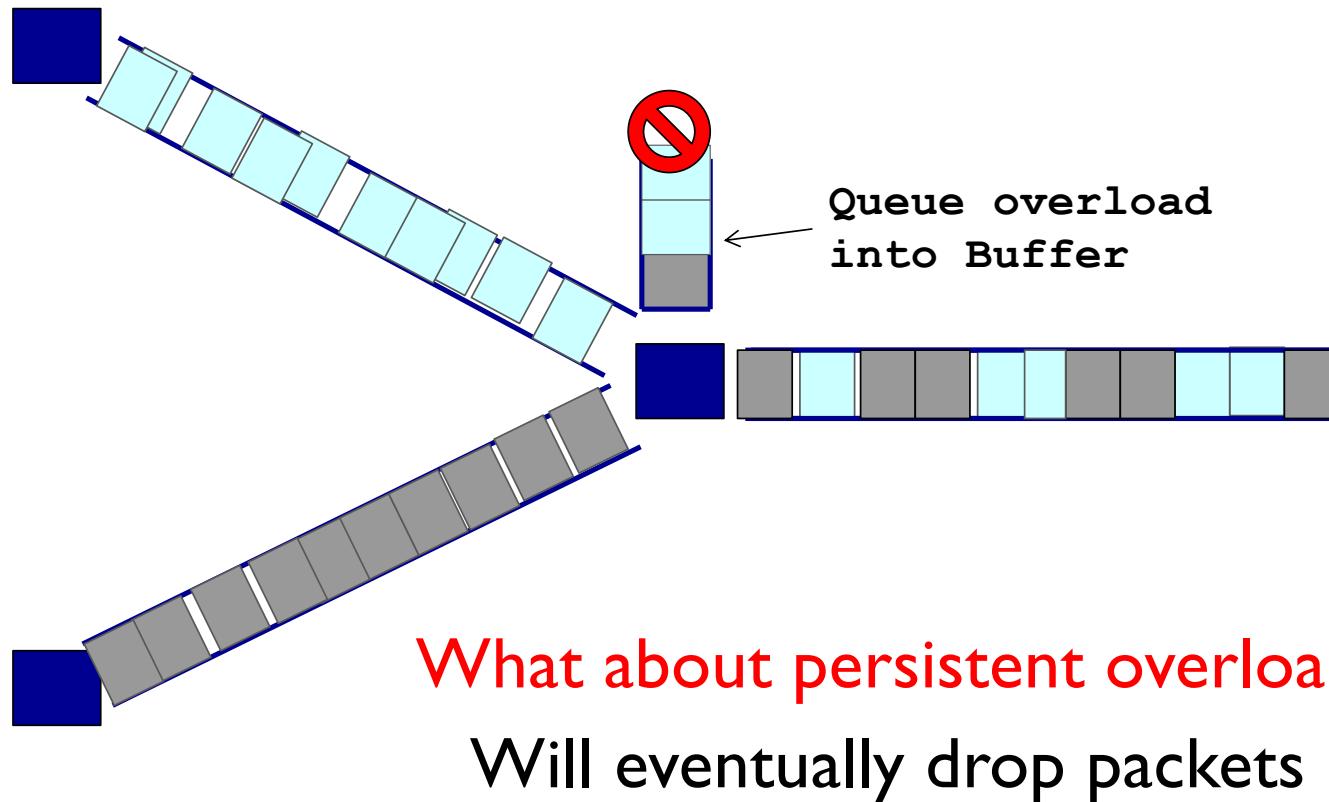
# Statistical multiplexing: pipe view



## Statistical multiplexing: pipe view



## Statistical multiplexing: pipe view



# Packet switching versus circuit switching

*packet switching allows more users to use network!*

example:

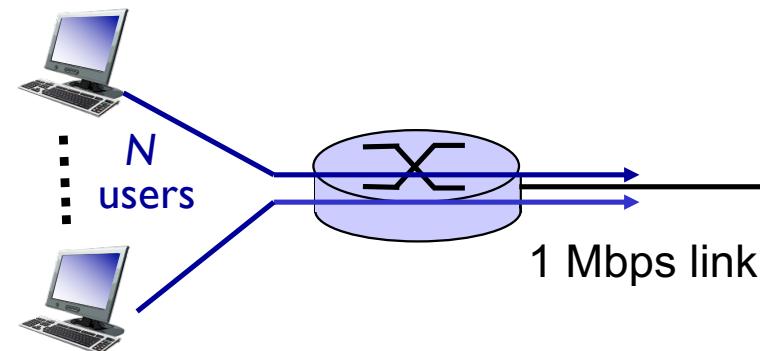
- 1 Mb/s link
- each user:
  - 100 kb/s when “active”
  - active 10% of time

❖ *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 =  $(1/2) \times (1/2) \times (1/2) \times (1-1/2) \times (1-1/2)$   
 $= (1/2)^5$
  - Another way to get exactly 3 heads is: THHHT
  - Probability of this sequence occurring =  $(1-1/2) \times (1/2) \times (1/2) \times (1/2) \times (1-1/2)$   
 $= (1/2)^5$
  - How many such unique combinations exist?

# Binomial Distribution: Example

Outcome	Probability
THHHT	$(1/2)^3 \times (1/2)^2$
HHHTT	$(1/2)^3 \times (1/2)^2$
TTHHH	$(1/2)^3 \times (1/2)^2$
HTTHH	$(1/2)^3 \times (1/2)^2$
HHTTH	$(1/2)^3 \times (1/2)^2$
THTHH	$(1/2)^3 \times (1/2)^2$
HTHTH	$(1/2)^3 \times (1/2)^2$
HHTHT	$(1/2)^3 \times (1/2)^2$
THHTH	$(1/2)^3 \times (1/2)^2$
<u>HTHHT</u>	<u><math>(1/2)^3 \times (1/2)^2</math></u>
10 arrangements $\times (1/2)^3 \times (1/2)^2$	

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

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

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

$$P(3 \text{ heads and 2 tails}) = 10 \times (1/2)^5 = 0.3125$$

# 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” =

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

$n$  = number of trials  
 $X$  = # successes out of  $n$  trials  
 $p$  = probability of success  
 $1-p$  = probability of failure

## Packet switching versus circuit switching

- ❖ Let's revisit the earlier problem
- ❖  $N = 35$  users
- ❖  $\text{Prob } (\# \text{ active users} > 10) = 1 - \underbrace{\text{Prob } (\# \text{ active} = 10)}_{\begin{aligned} &- \text{Prob } (\# \text{ active} = 9) \\ &- \text{Prob } (\# \text{ active} = 8) \\ &\dots \\ &- \text{Prob } (\# \text{ active} = 0) \end{aligned}}$

where  $\text{Prob } (\# \text{ active} = 10)$  =  $C(35, 10) \times 0.1^{10} \times 0.9^{25}$

- ❖  $\text{Prob } (\# \text{ active users} > 10) = 0.0004$  (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

In \_\_\_\_\_ resources are allocated as required without explicit reservations

- A. Packet switching
- B. Circuit switching
- C. Both
- D. None

**Answer: A**

Open a browser and type: **pollev.com/salil**





## Quiz: Switching

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 typically the same
- B. is independent
- C. is always different from

**Answer: A**

Open a browser and type: **pollev.com/salil**

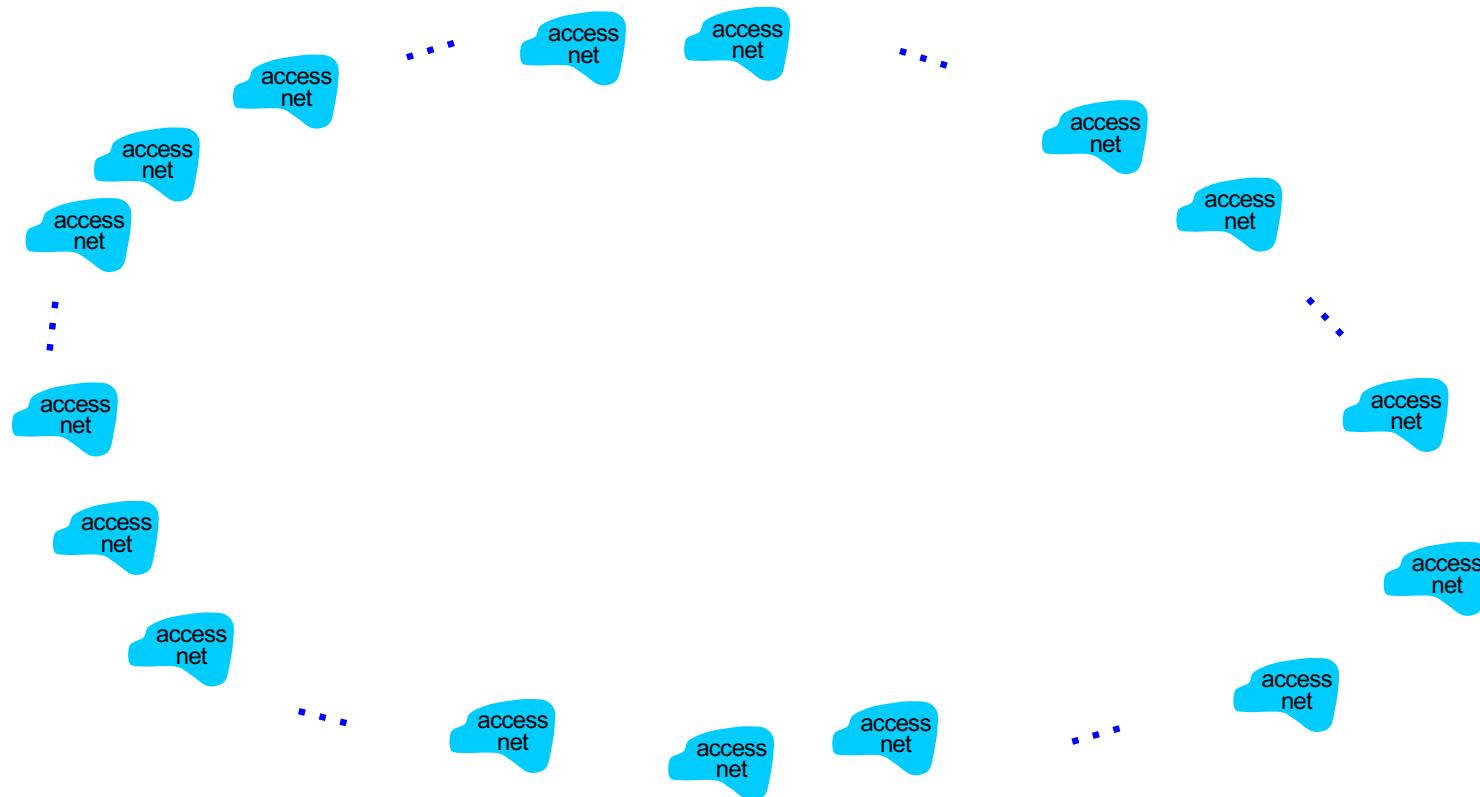


# Internet structure: a “network of networks”

- ❖ 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

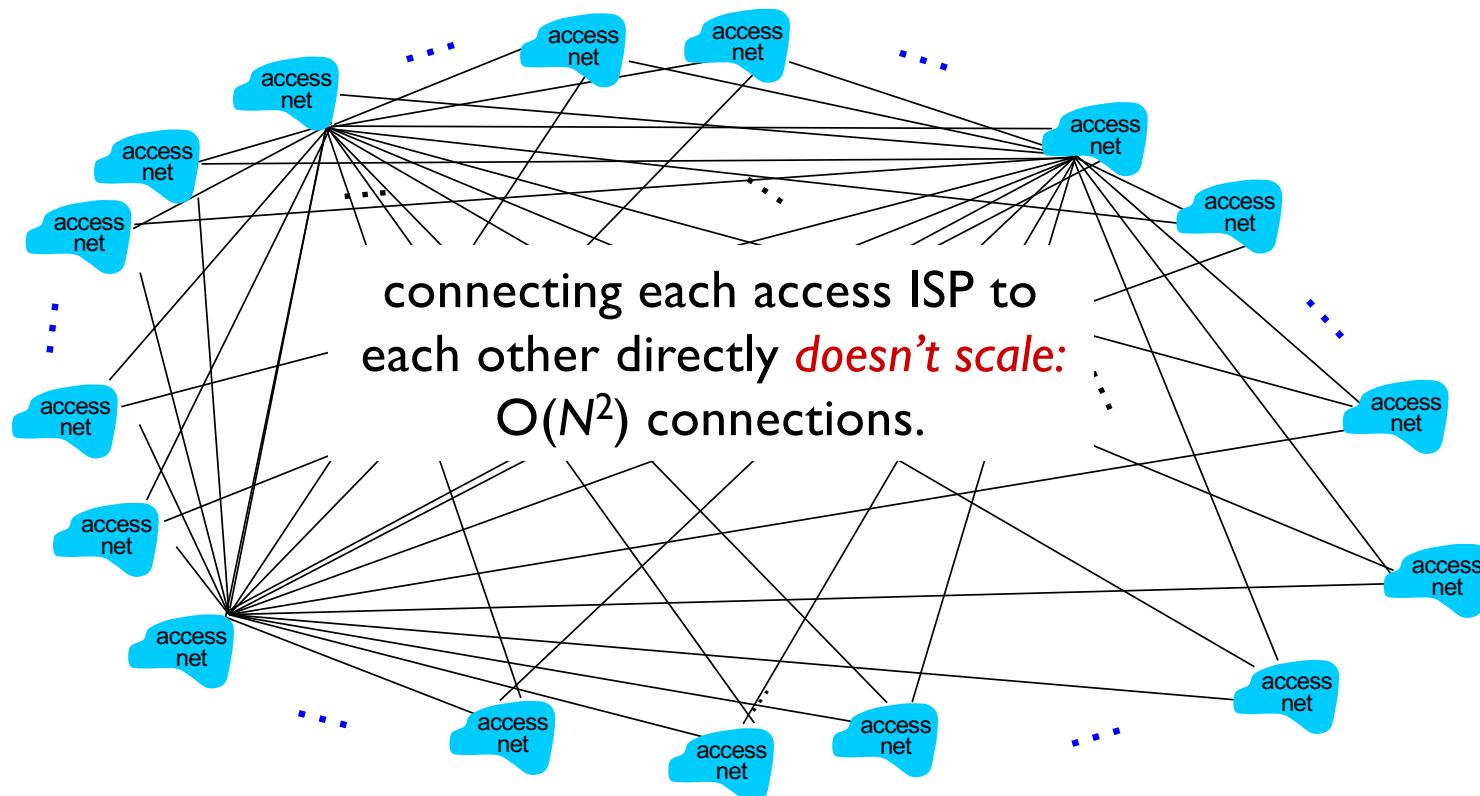
# Internet structure: a “network of networks”

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



# Internet structure: a “network of networks”

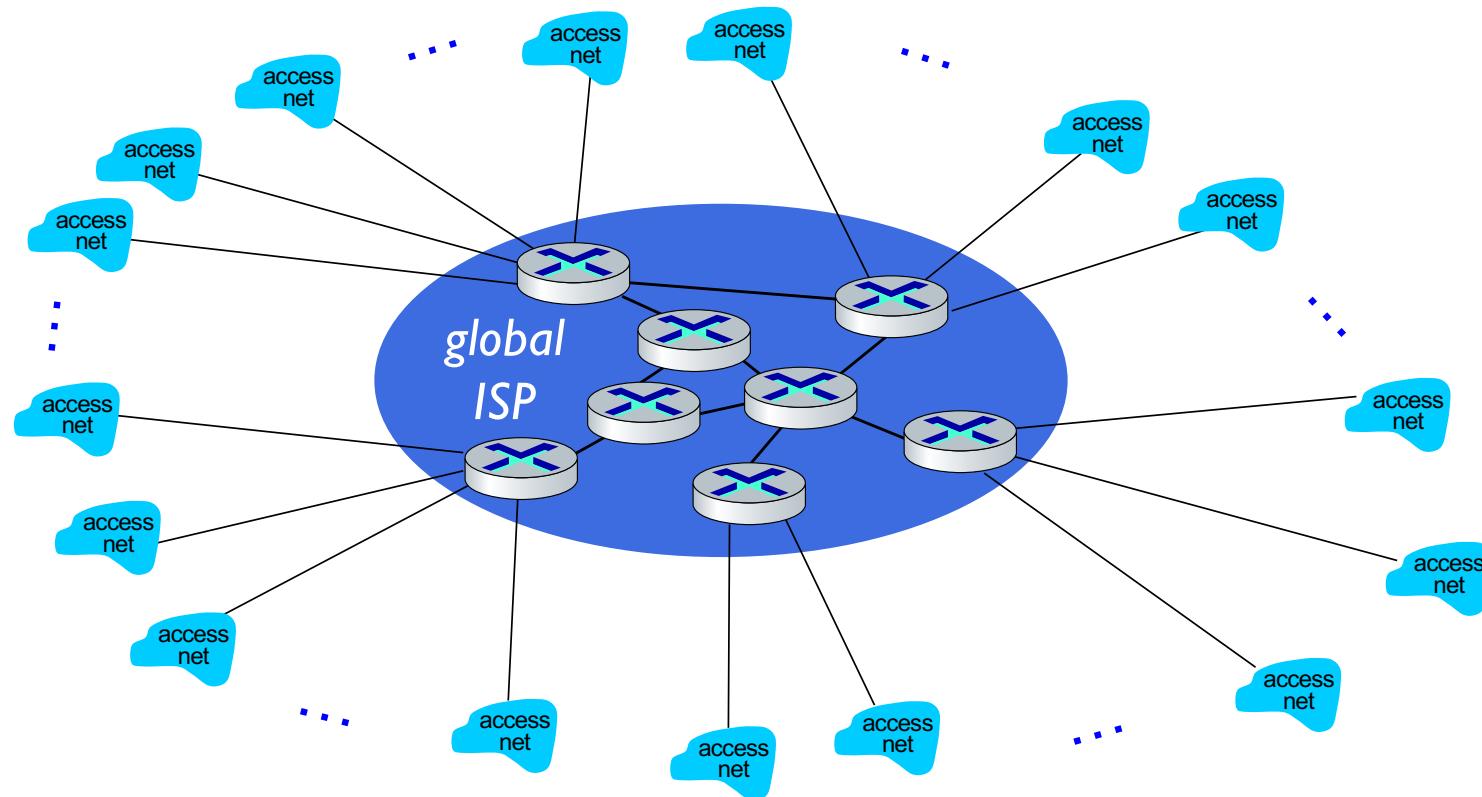
**Question:** given *millions* of access ISPs, how to connect them together?



# Internet structure: a “network of networks”

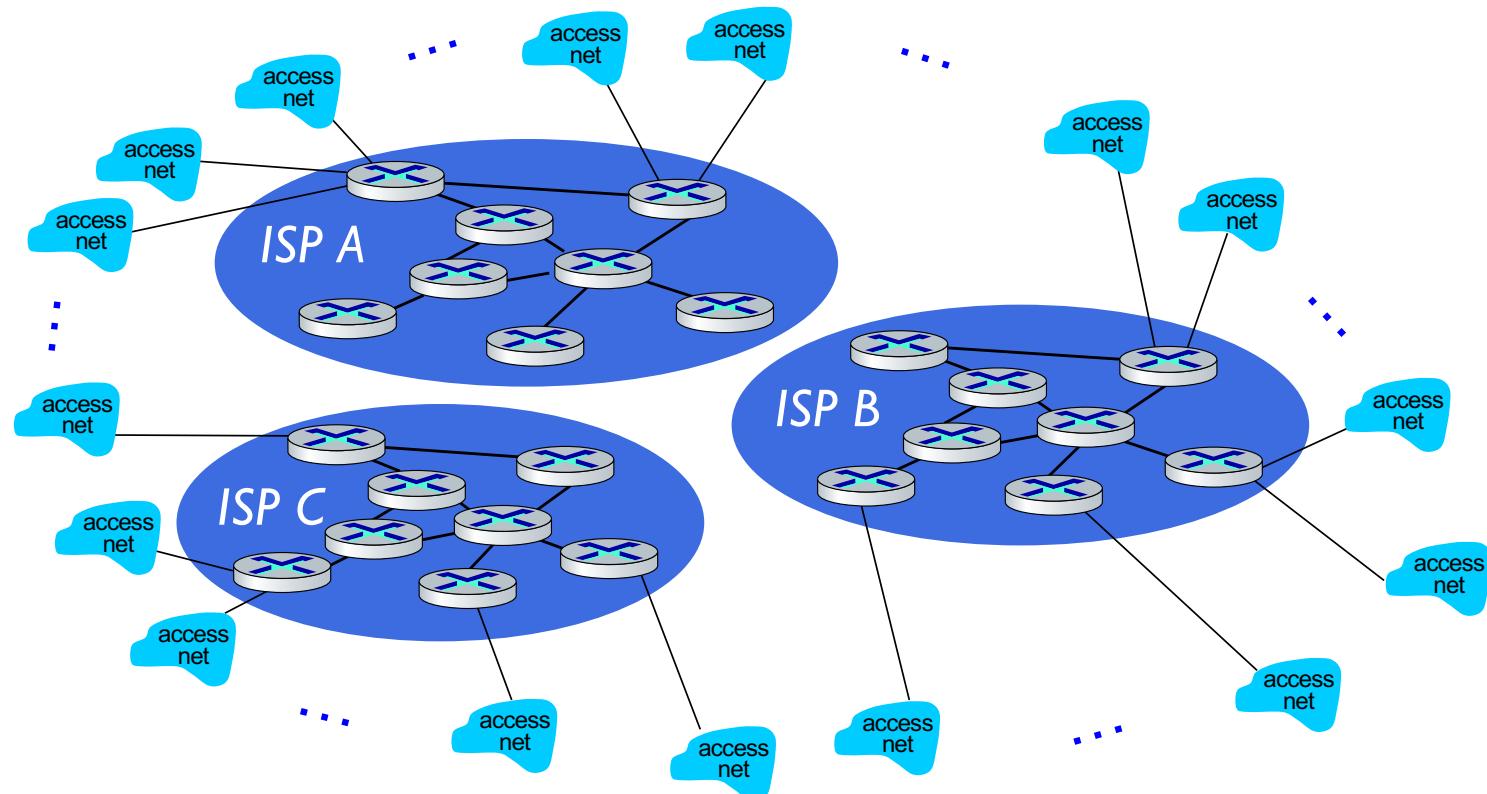
*Option:* connect each access ISP to one global transit ISP?

*Customer and provider ISPs have economic agreement.*



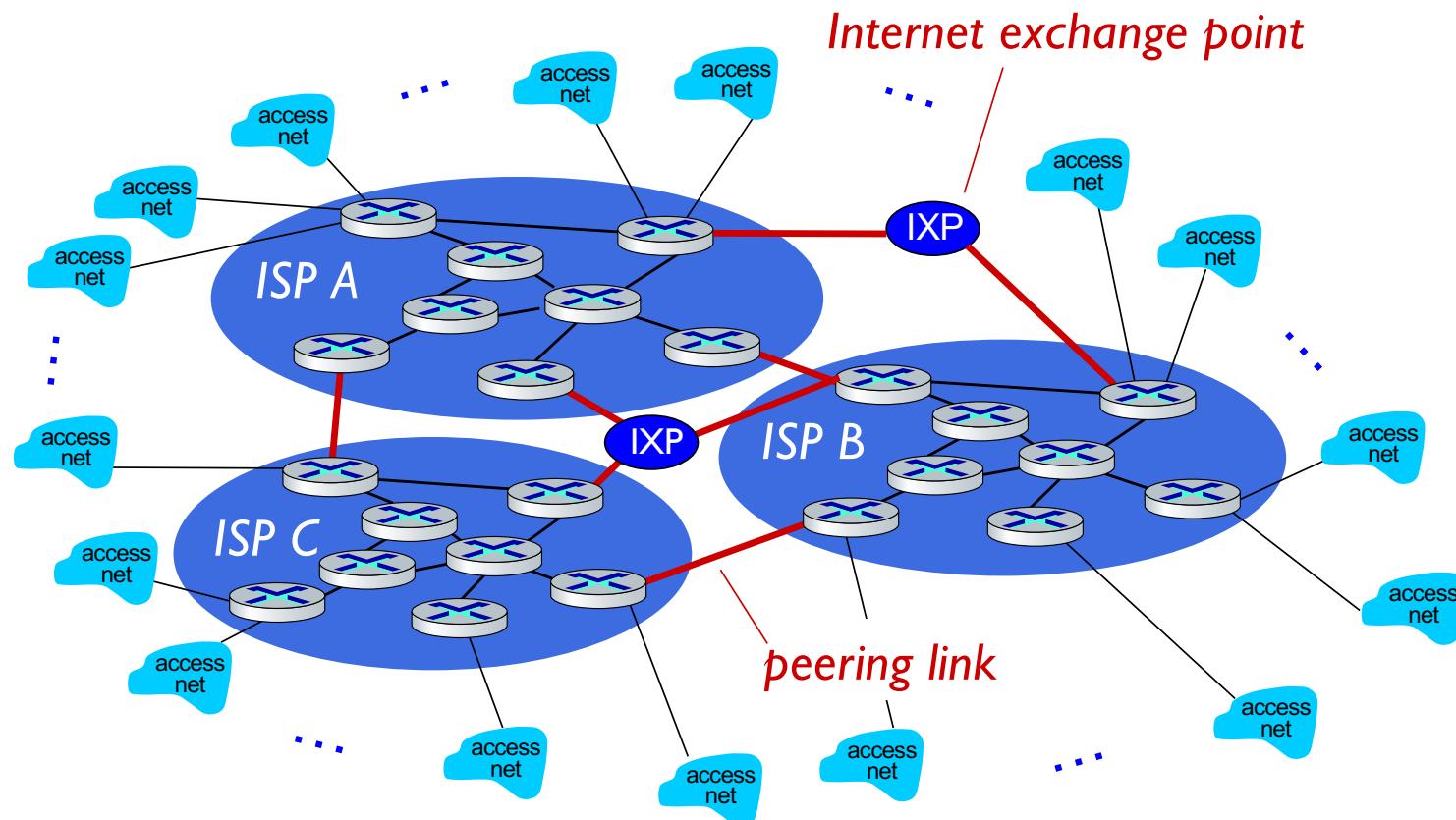
# Internet structure: a “network of networks”

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



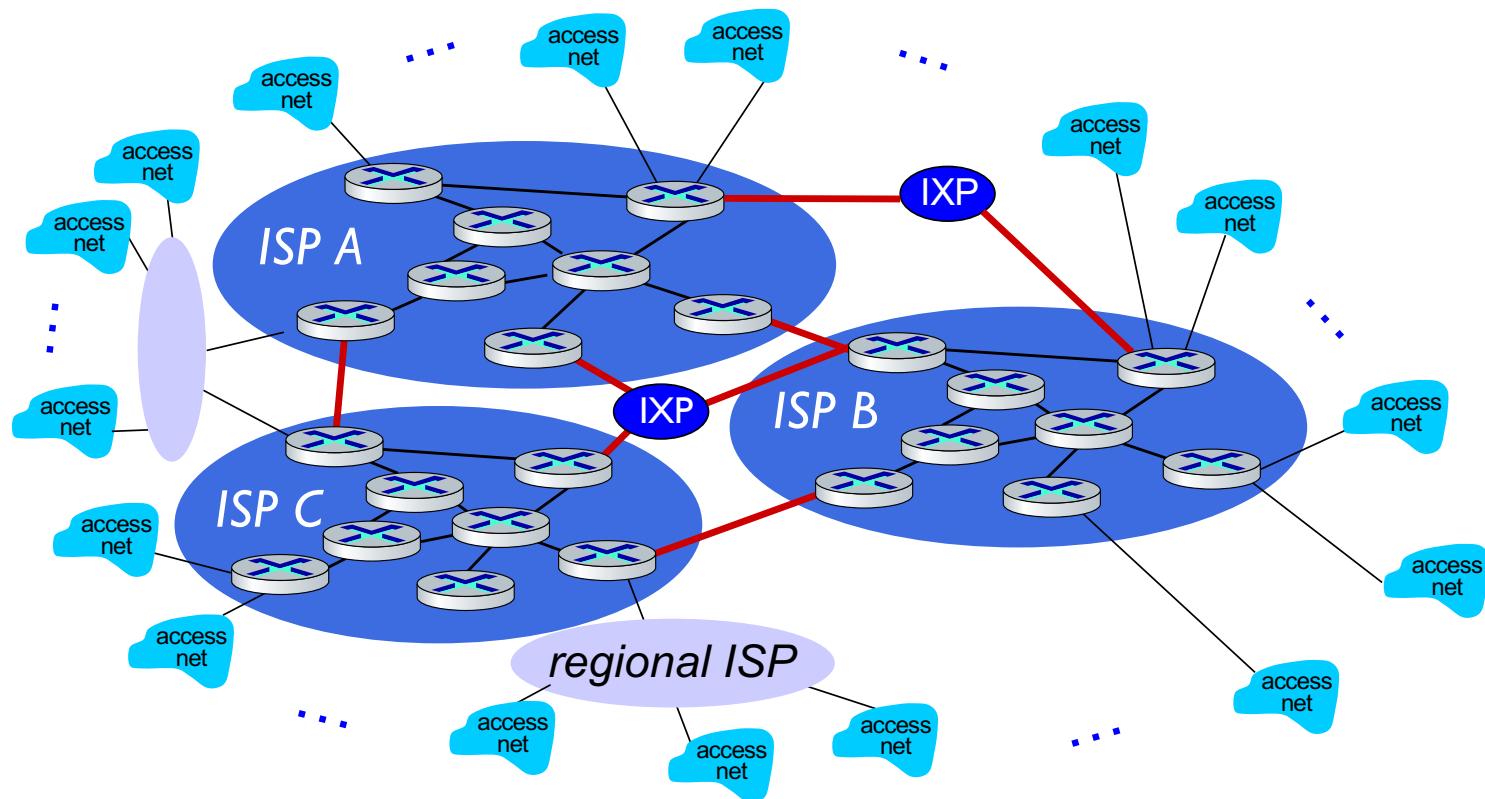
# Internet structure: a “network of networks”

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



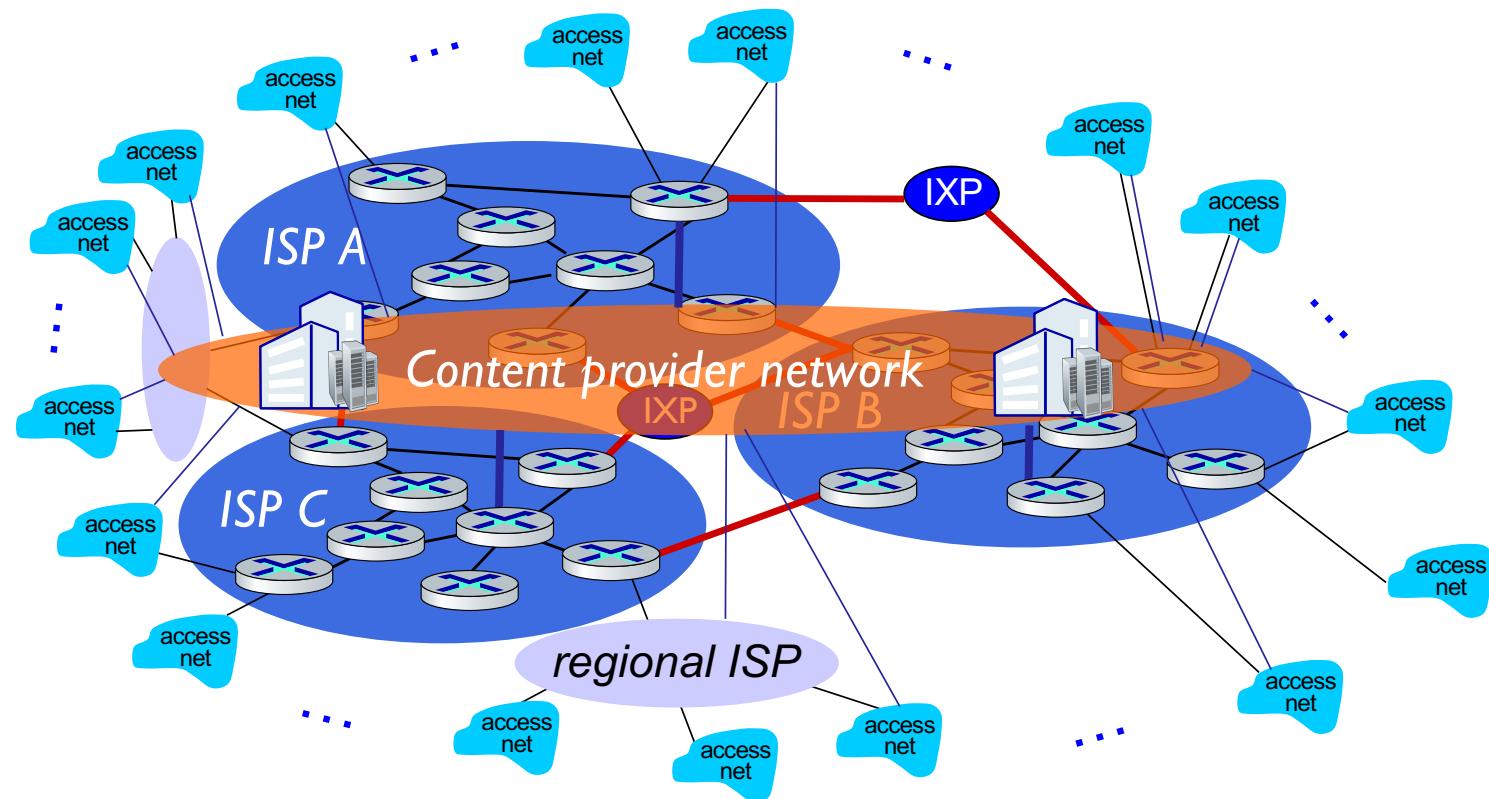
# Internet structure: a “network of networks”

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

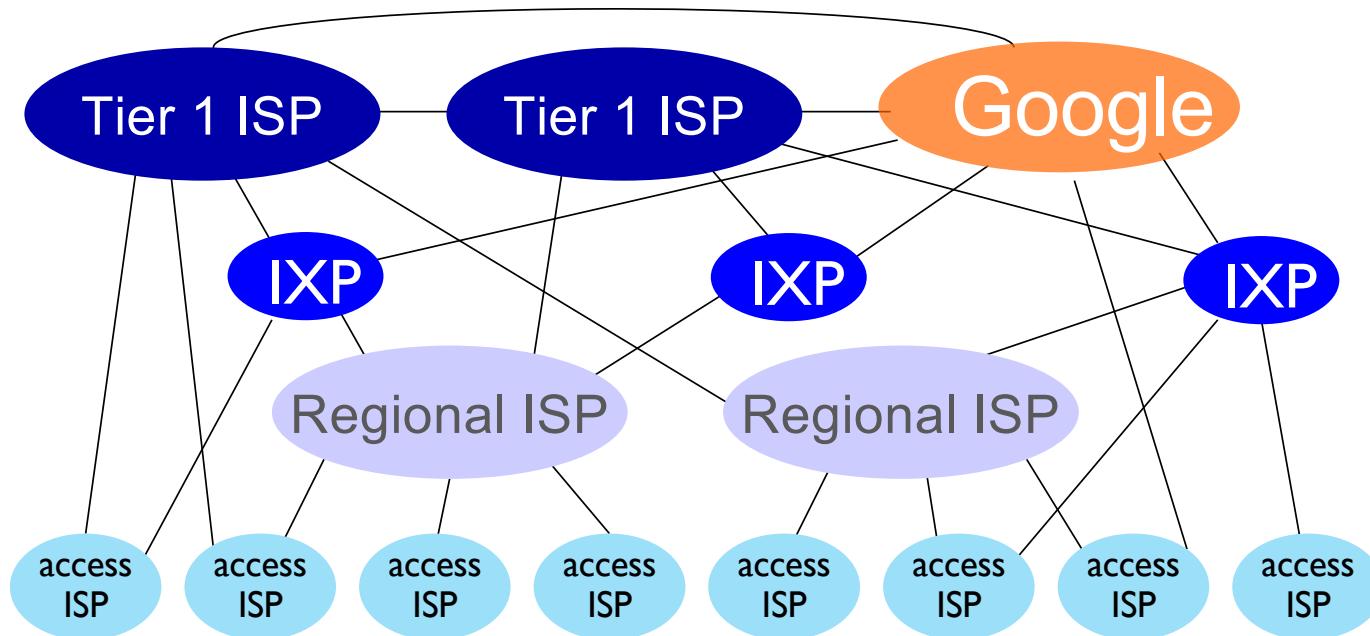


# Internet structure: a “network of networks”

... 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

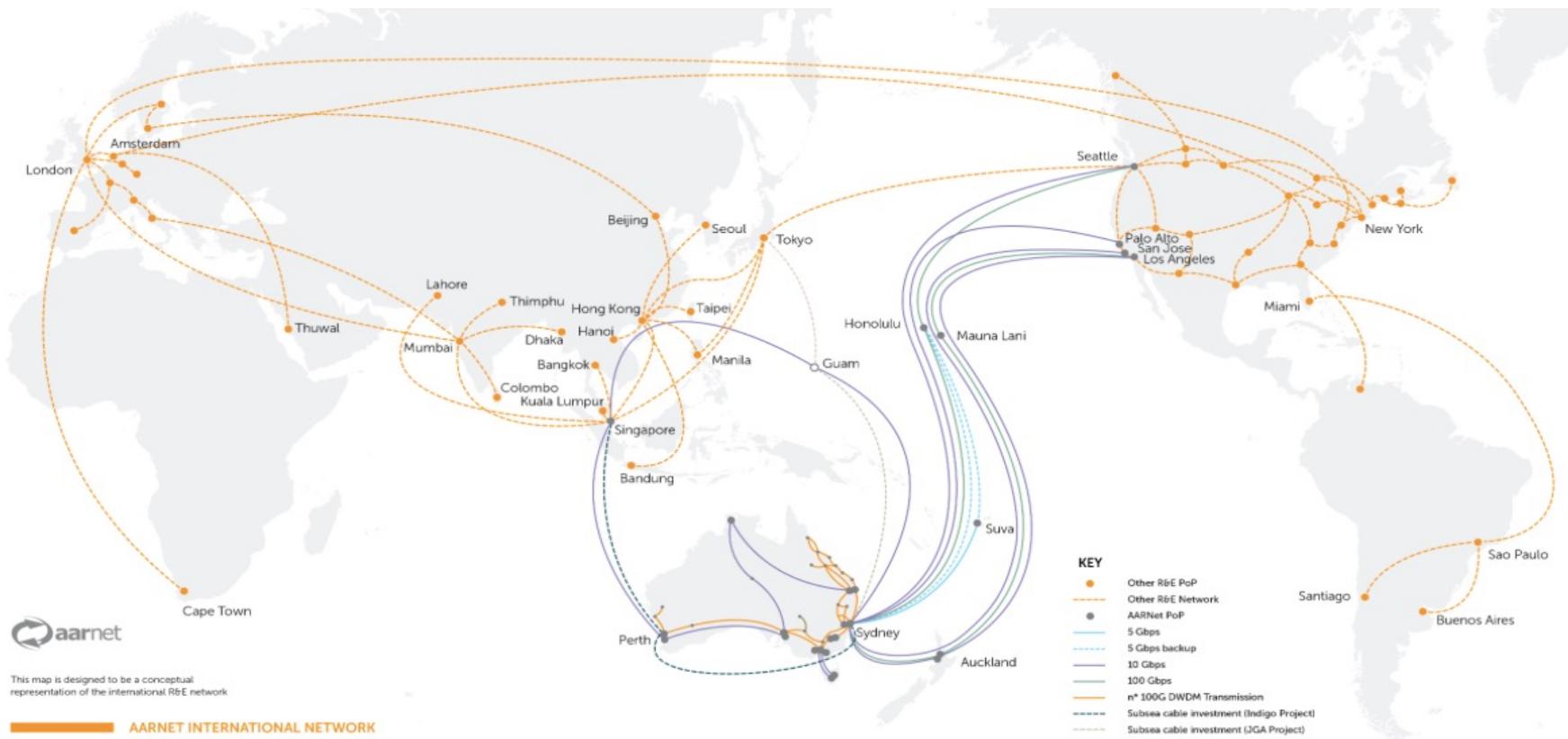
# Tier-I ISP Network map: Sprint (2019)



# AARNET: Australia's Academic and Research Network

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

<https://www.submarinecablemap.com>



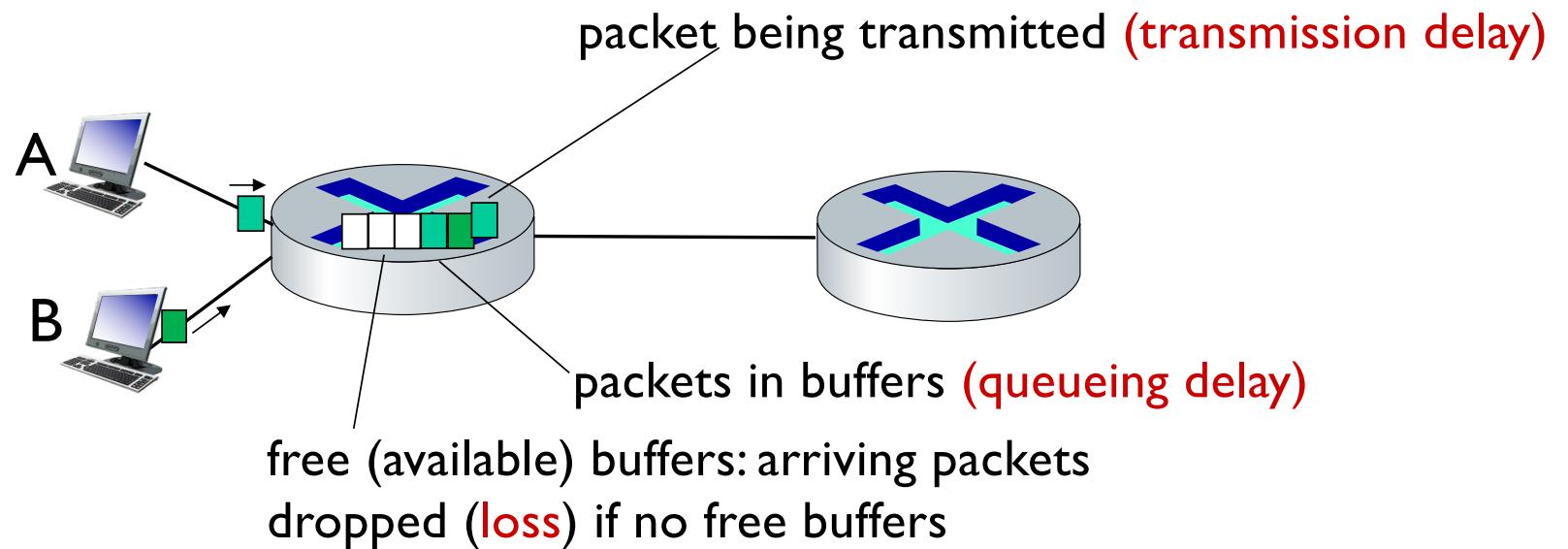
# Introduction: roadmap

- ❖ 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

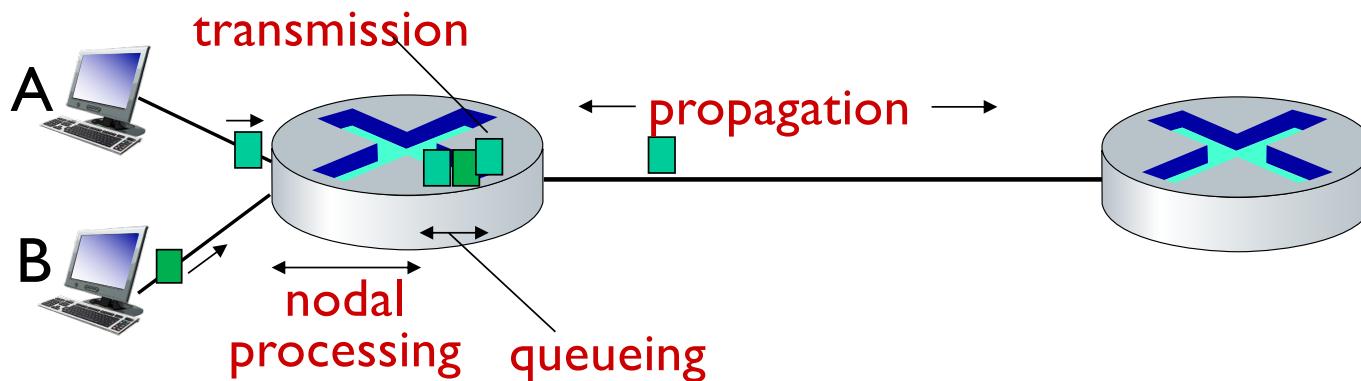
# How do packet loss and delay occur?

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



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

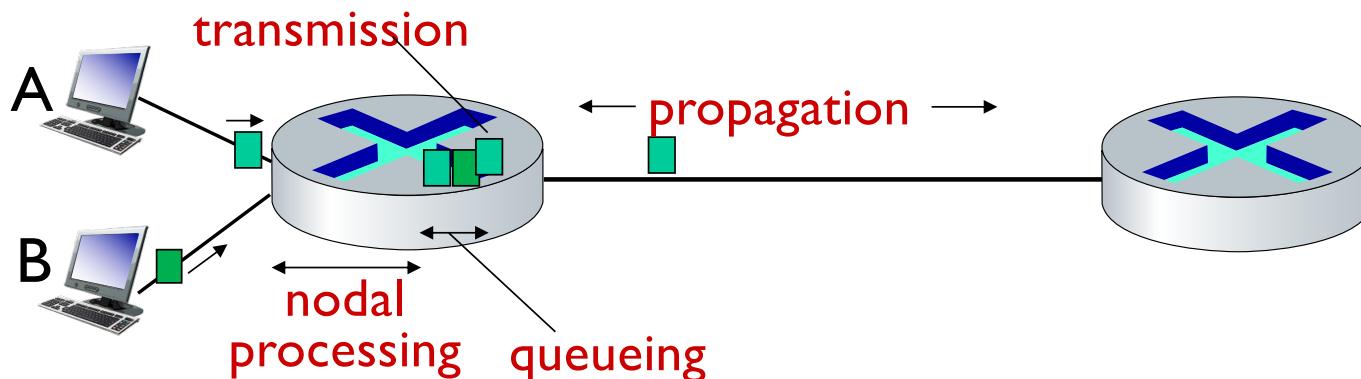
$d_{\text{proc}}$ : nodal processing

- check bit errors
- determine output link
- typically < msec

$d_{\text{queue}}$ : queueing delay

- time waiting at output link for transmission
- depends on congestion level of router

# Packet delay: four sources



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

$d_{\text{trans}}$ : transmission delay:

- $L$ : packet length (bits)
- $R$ : link transmission rate (bps)

$$\boxed{d_{\text{trans}} = L/R}$$

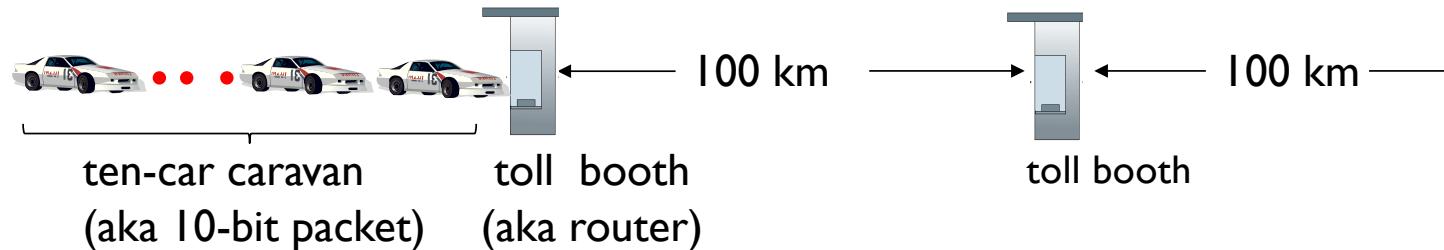
$d_{\text{prop}}$ : propagation delay:

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

$$\boxed{d_{\text{prop}} = d/s}$$

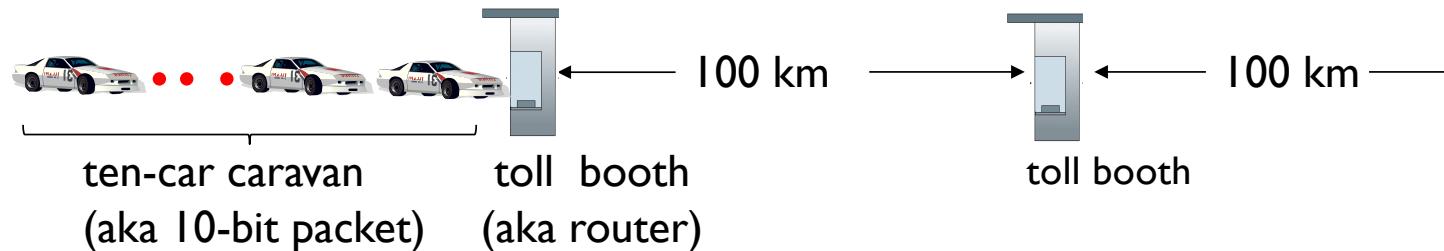
$d_{\text{trans}}$  and  $d_{\text{prop}}$   
very different

# Caravan analogy



- cars “propagate” at 100 km/hr
- toll booth takes 12 sec to service car (bit transmission time)
- car ~ bit; caravan ~ packet
- Q: How long until caravan is lined up before 2nd toll booth?
- time to “push” entire caravan through toll booth onto highway =  $12 \times 10 = 120$  sec
- time for last car to propagate from 1st to 2nd toll both:  $100\text{km}/(100\text{km/hr}) = 1$  hr
- A: 62 minutes

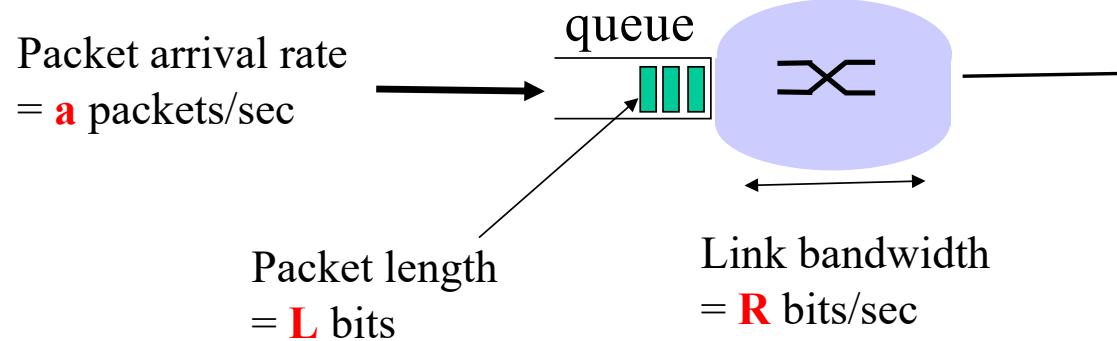
# Caravan analogy



- suppose cars now “propagate” at 1000 km/hr
  - and suppose toll booth now takes one min to service a car
  - **Q: Will cars arrive to 2nd booth before all cars serviced at first booth?**
- A: Yes!** after 7 min, first car arrives at second booth; three cars still at first booth

Interactive Java Applet – Propagation vs transmission delay  
<https://www2.tkn.tu-berlin.de/teaching/rn/animations/propagation/>

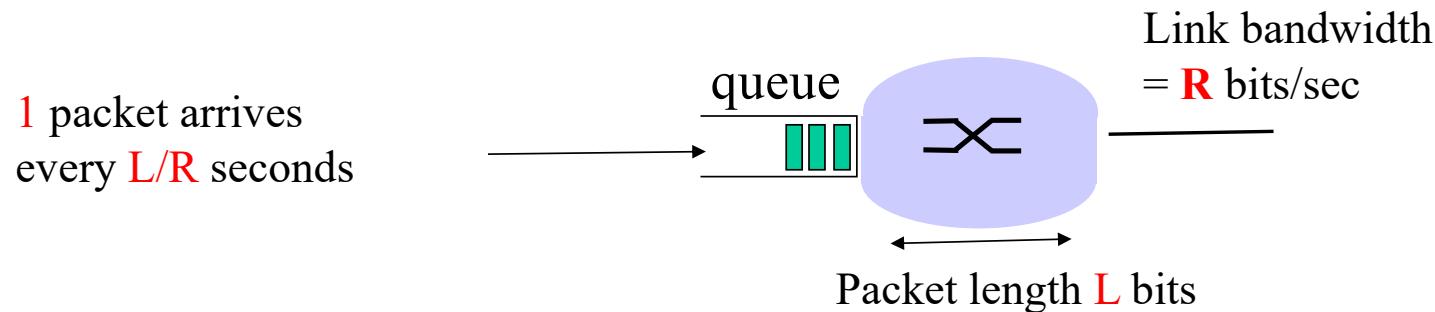
# Queueing delay (more insight)



- ❖ 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)

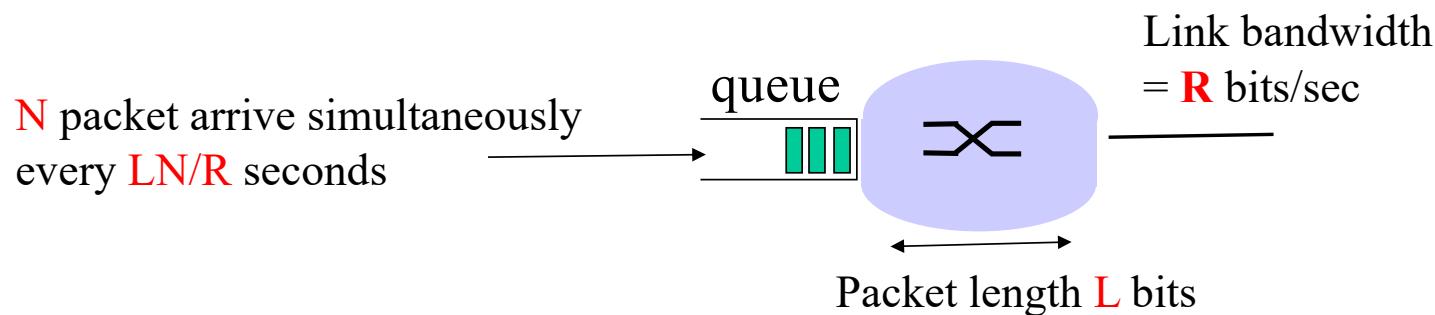


Traffic intensity =  $aL/R = (R/L)(L/R) = 1$

Average queueing delay = 0

(queue is initially empty)

# Queueing delay: Another Scenario



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

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

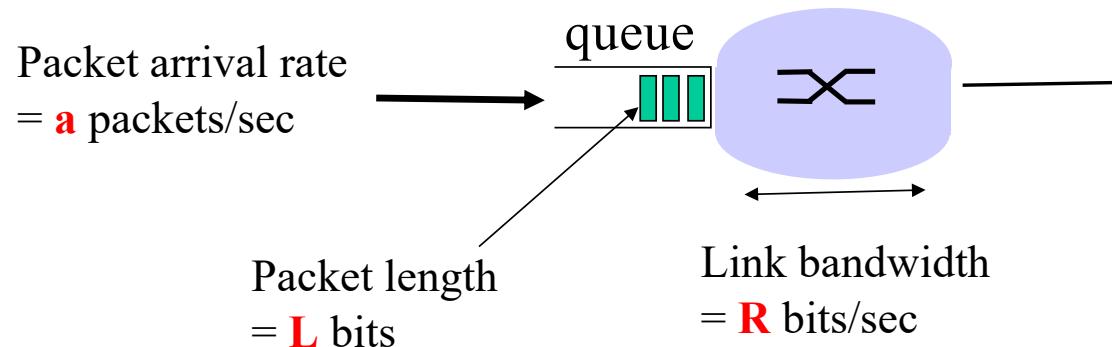


Average queueing delay (queue is empty at time 0) ?

$$\{0 + L/R + 2L/R + \dots + (N-1)L/R\}/N = L/(RN)\{1+2+\dots+(N-1)\} = L(N-1)/(2R)$$

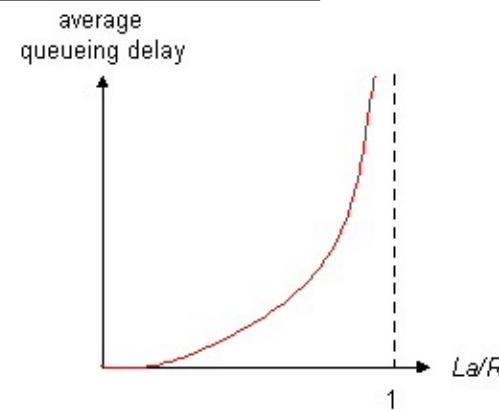
Note: traffic intensity is same as previous scenario, but queueing delay is different

# Queueing delay: typical behaviour



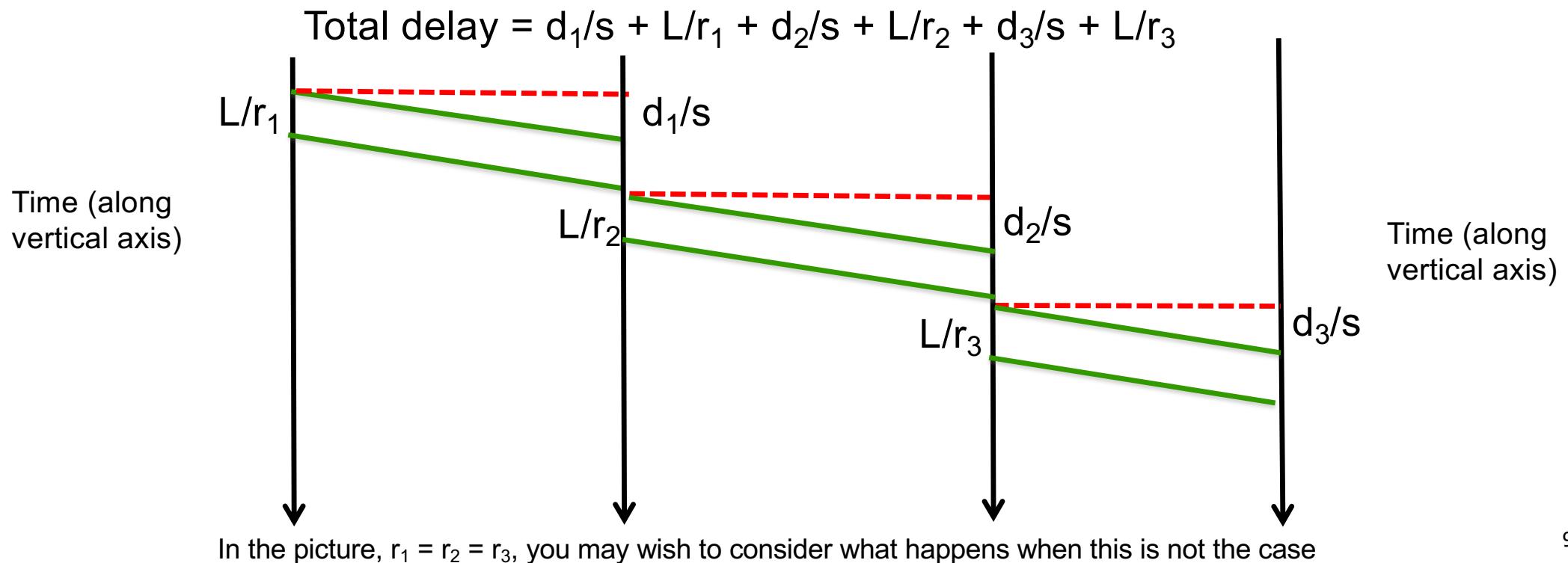
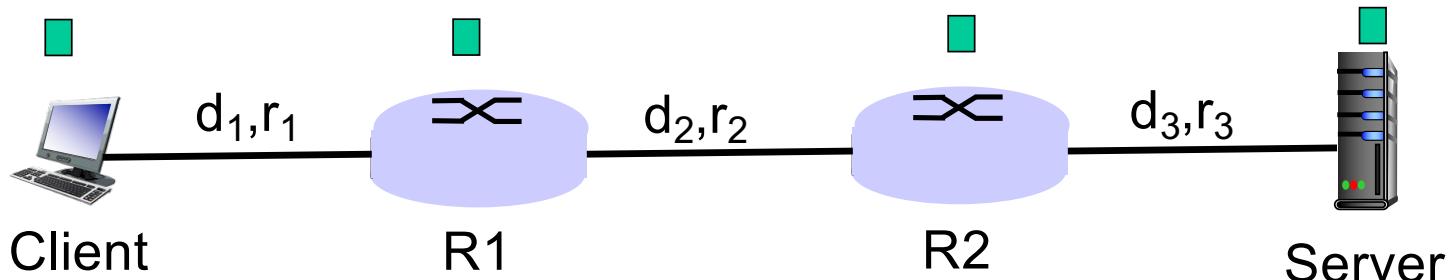
Interactive Java Applet:  
<http://computerscience.unicam.it/marcantoni/reti/applet/QueuingAndLossInteractive/1.html>

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



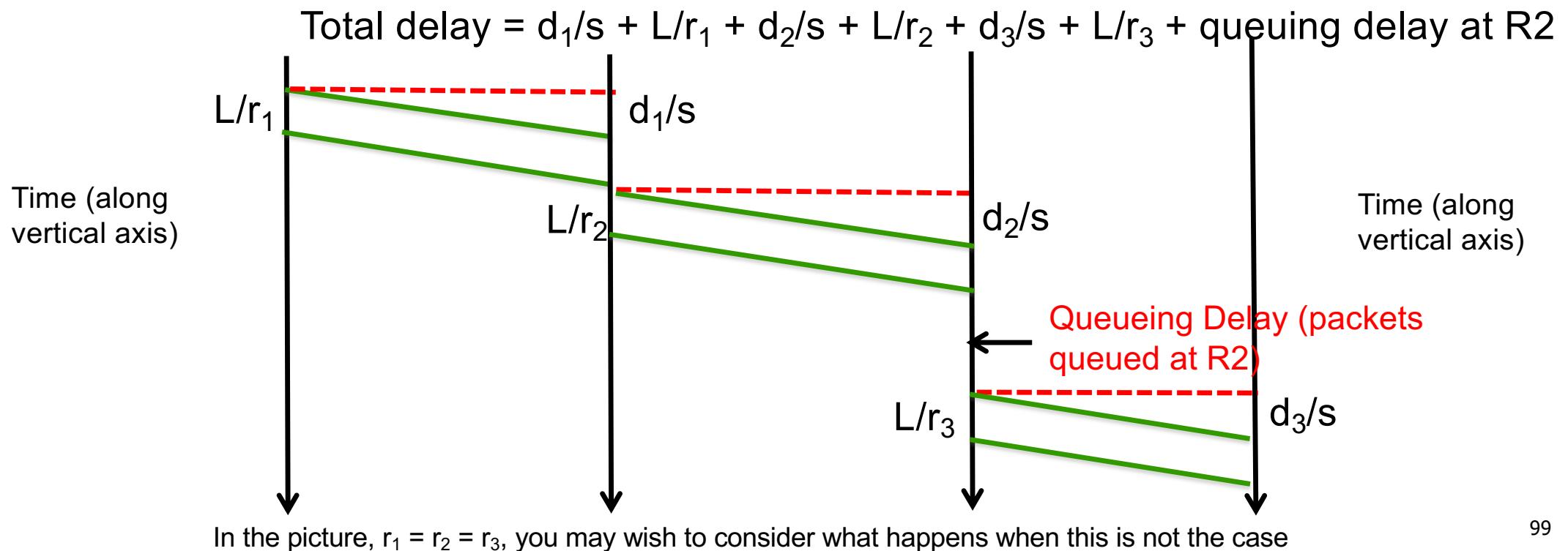
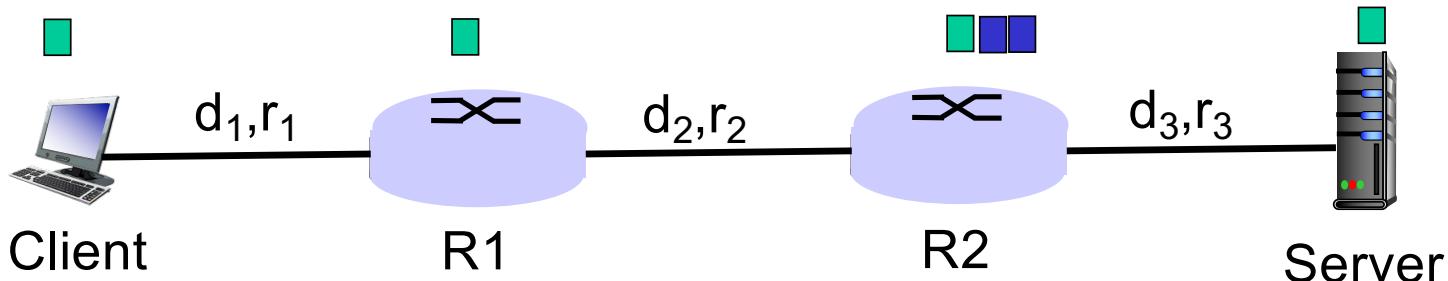
# End to End Delay

Packet length =  $L$   
Propagation speed =  $s$



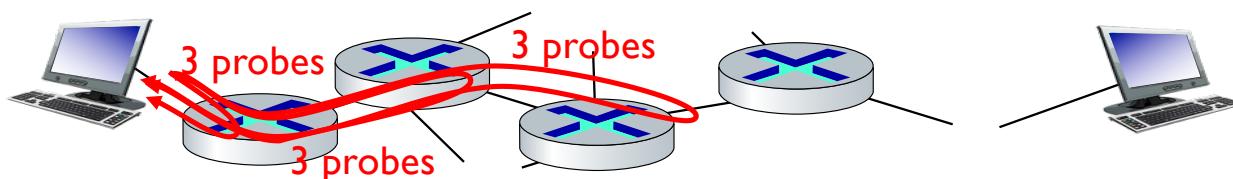
# End to End Delay

Packet length = L  
Propagation speed = s



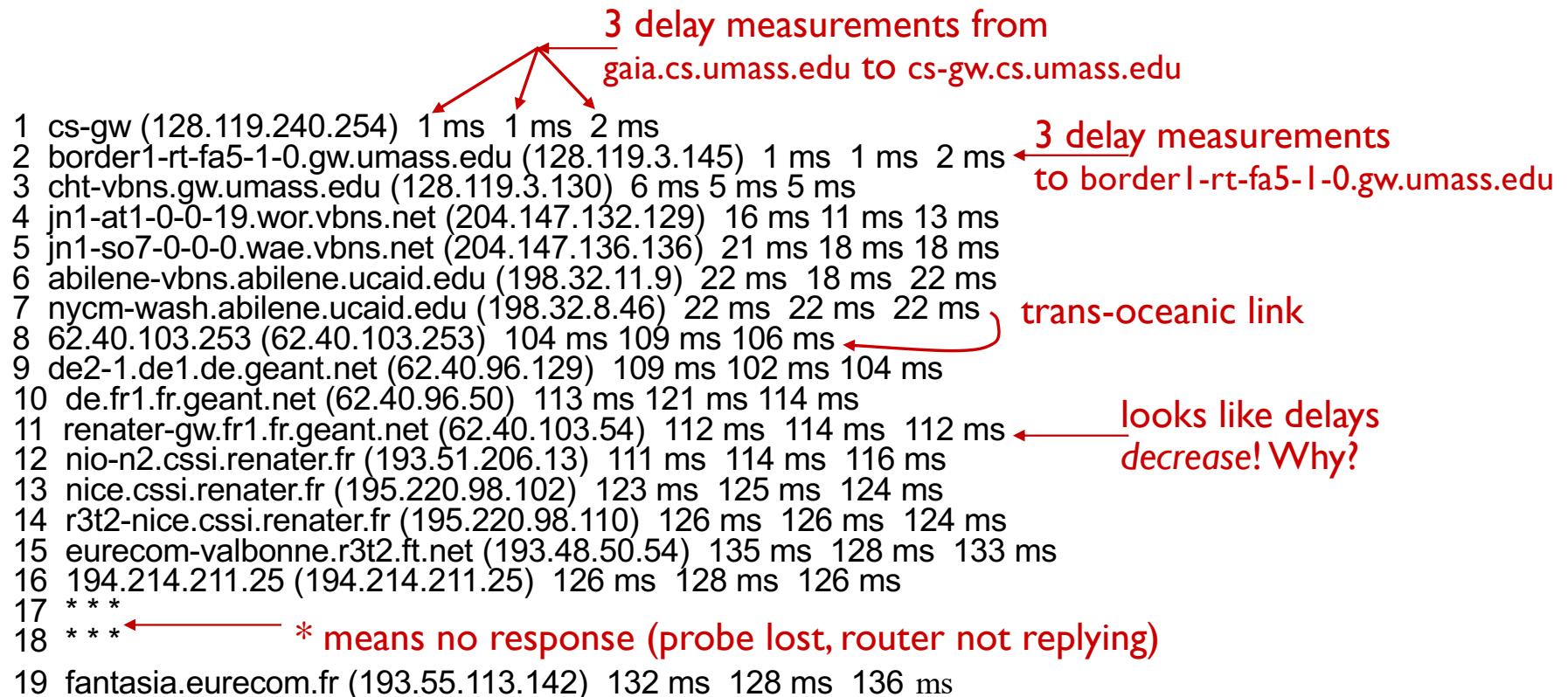
# “Real” Internet delays and routes

- 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

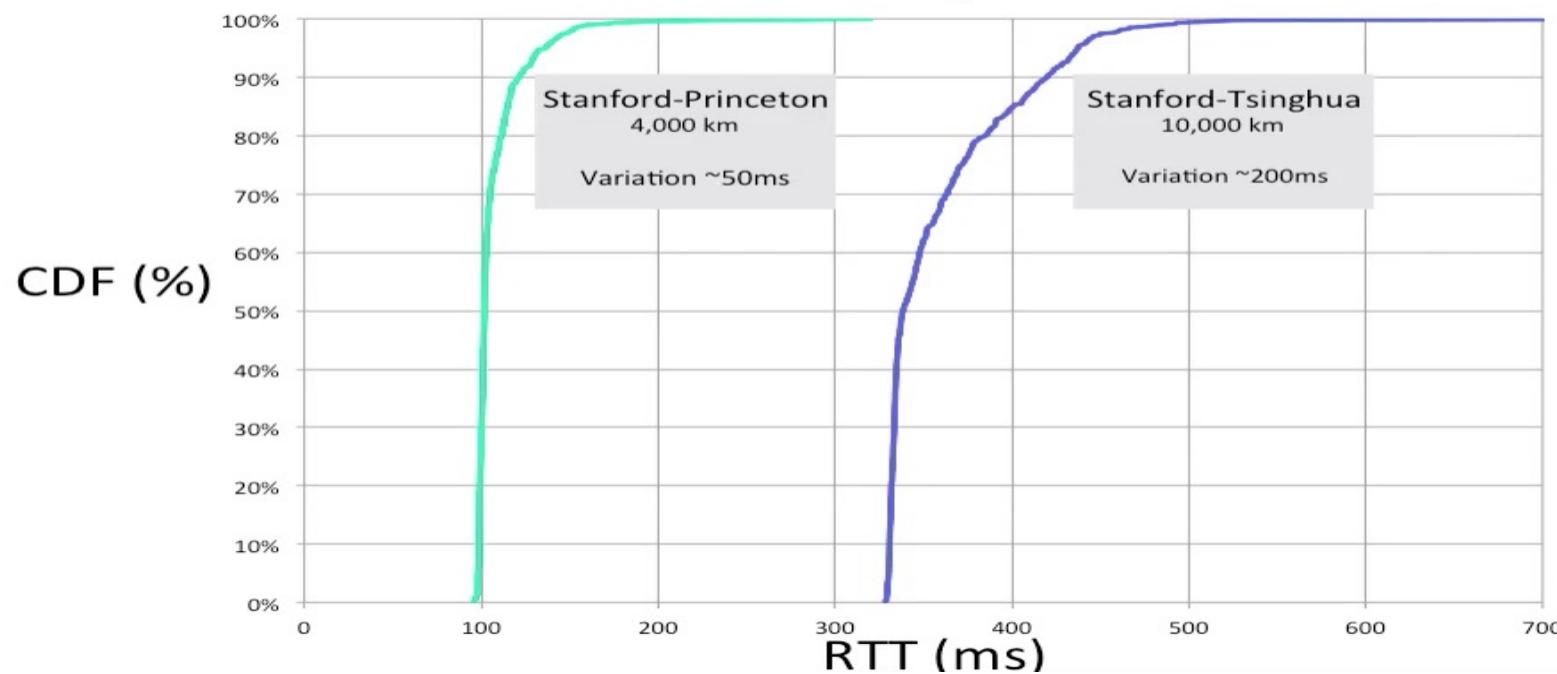


\* Do some traceroutes from exotic countries at [www.traceroute.org](http://www.traceroute.org)

# “Real” delay variations

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

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





## Quiz: Propagation Delay

Propagation delay depends on the size of the packet

- A. True
- B. False

**Answer: B**

Open a browser and type: **pollev.com/salil**





## 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

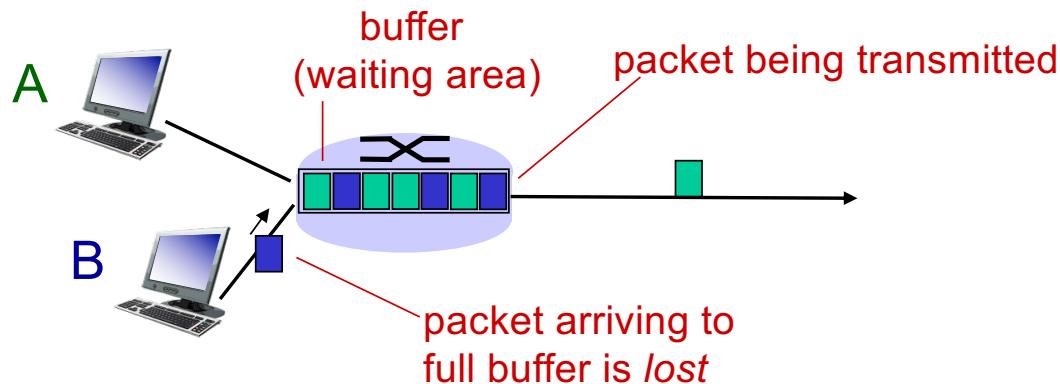
**Answer: C**



Open a browser and type: **pollev.com/salil**

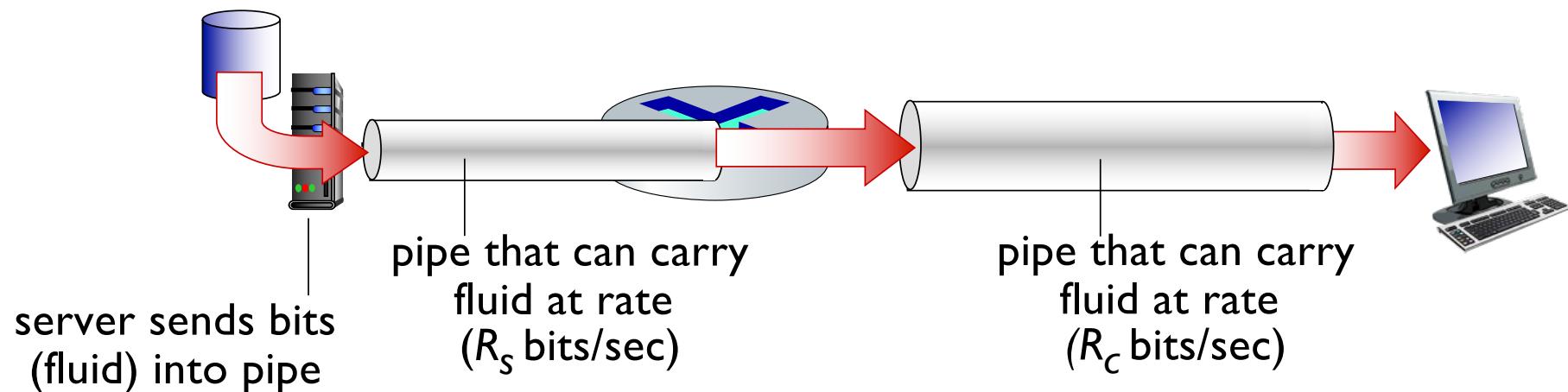
# Packet loss

- ❖ 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



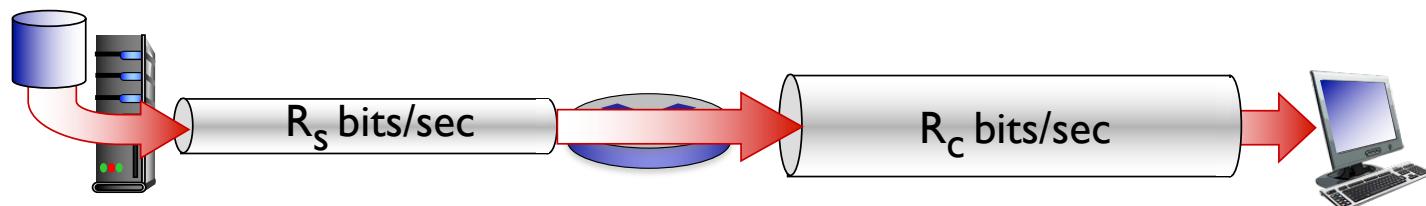
# Throughput

- **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

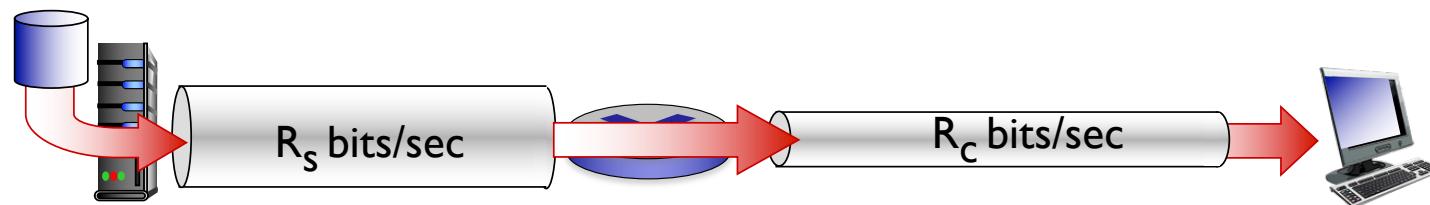


# Throughput

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



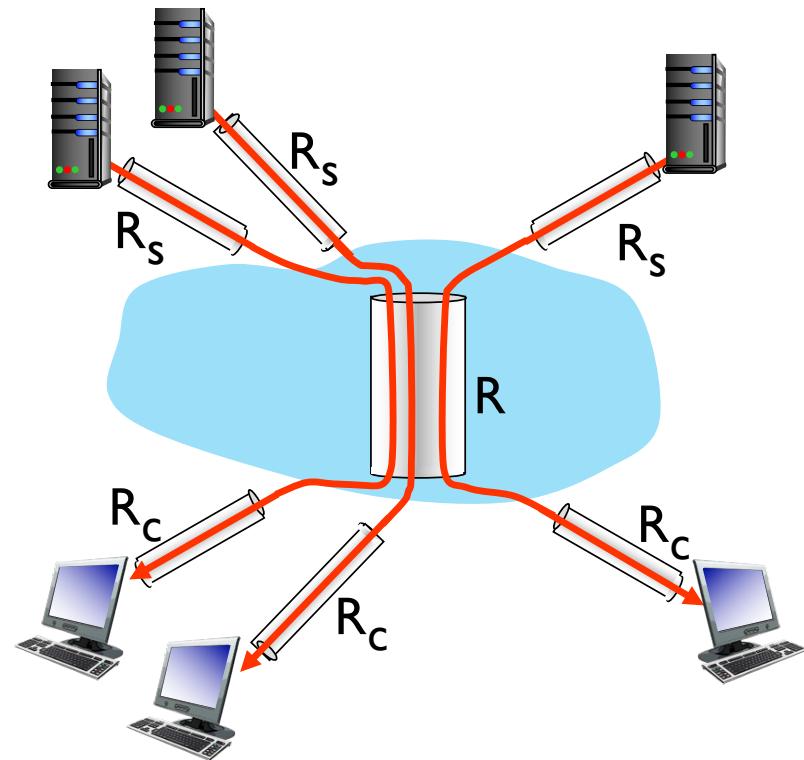
$R_s > R_c$  What is average end-end throughput?



*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