

# 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*

# I. Introduction

## *Goals:*

- ❖ get “feel” and terminology
- ❖ defer depth and detail to *later* in course
- ❖ understand concepts using the Internet as example

# I. Introduction: roadmap

## I.1 what is the Internet?

### I.2 network edge

- end systems, access networks, links

### I.3 network core

- packet switching, circuit switching, network structure

### I.4 delay, loss, throughput in networks

### I.5 protocol layers

### I.6 networks under attack: security

### I.7 history

Hobbe's Internet Timeline - <http://www.zakon.org/robert/internet/timeline/>

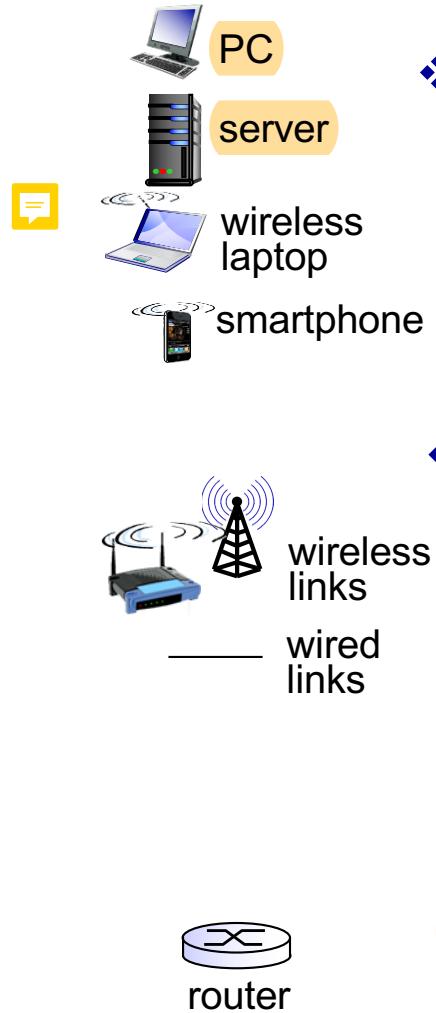


## Quiz: What is the Internet?

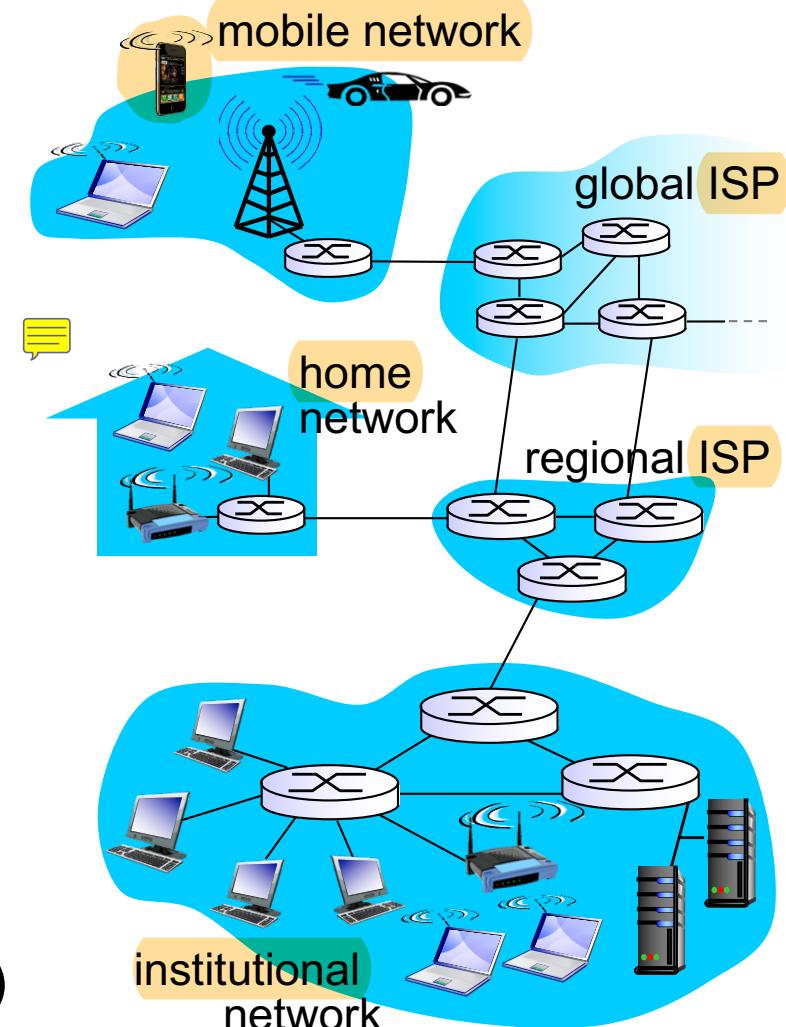
- A. One single homogenous network
- B. An interconnection of different computer networks 
- C. An infrastructure that provides services to networked applications 
- D. Something else (be prepared to discuss)

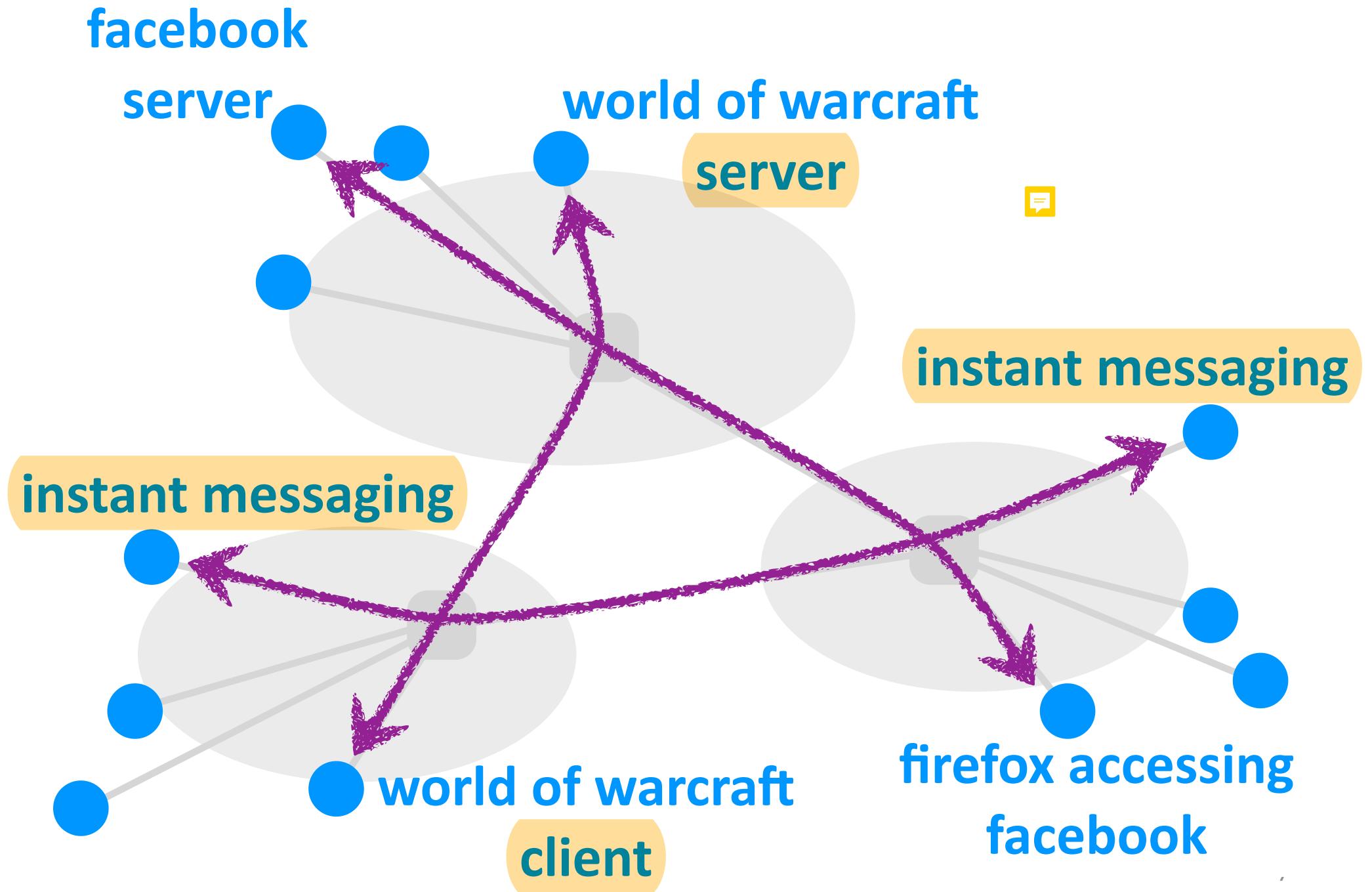
Open a browser and type: [www.zetings.com/salil](http://www.zetings.com/salil)

# What's the Internet: “nuts and bolts” view



- ❖ millions of connected computing devices:
  - *hosts* = **end systems**
  - running **network apps**
- ❖ communication links
  - fiber, copper, radio, satellite
  - transmission rate: **bandwidth**
- ❖ *Packet switches*: forward packets (chunks of data)
  - **routers** and **switches**





# “Fun” Internet appliances



Picture frame



Web-enabled toaster + weather forecaster



Tweet-a-watt:  
monitor energy use



Internet refrigerator



Networked TV Set top Boxes

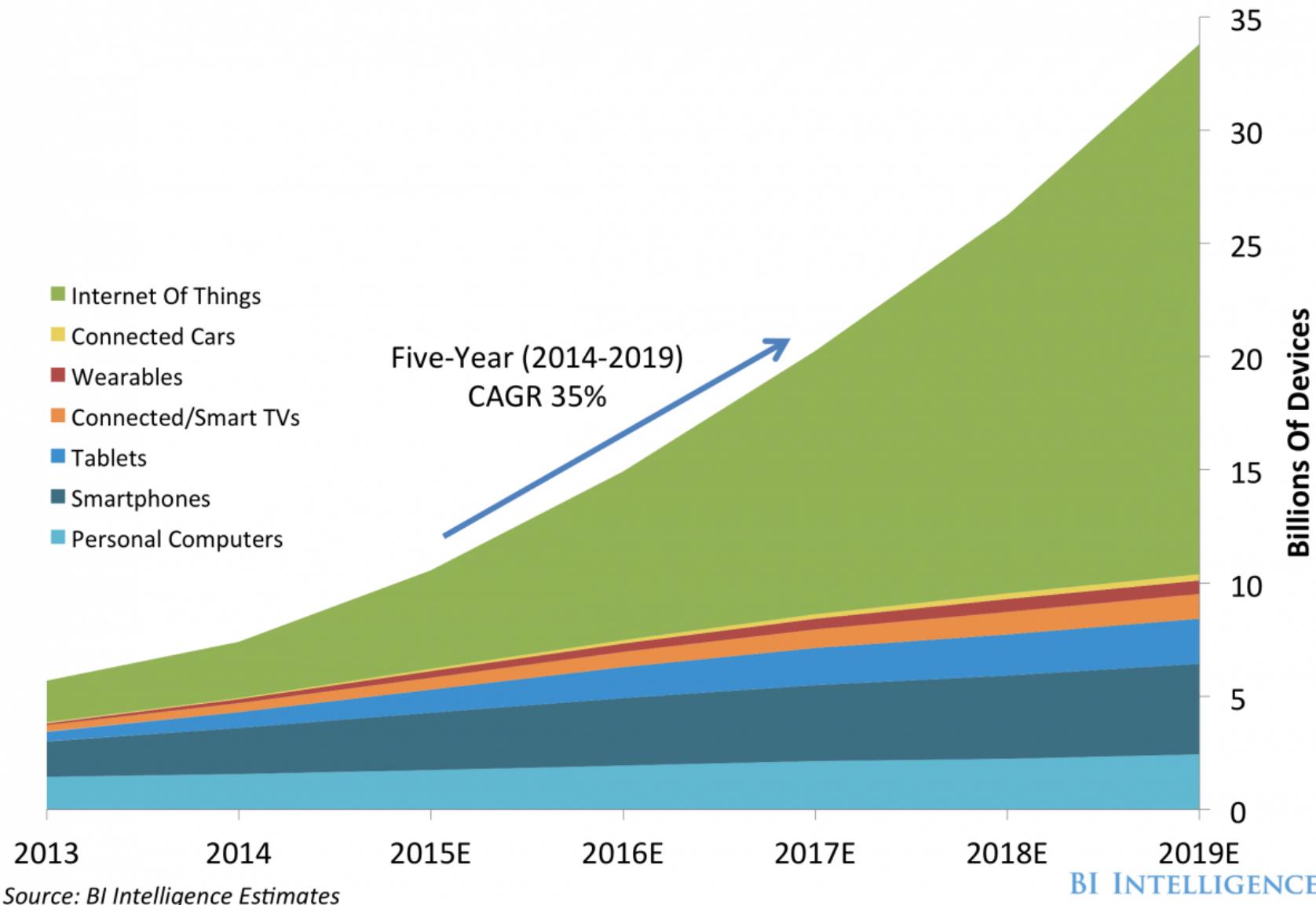


sensorized,  
bed  
mattress



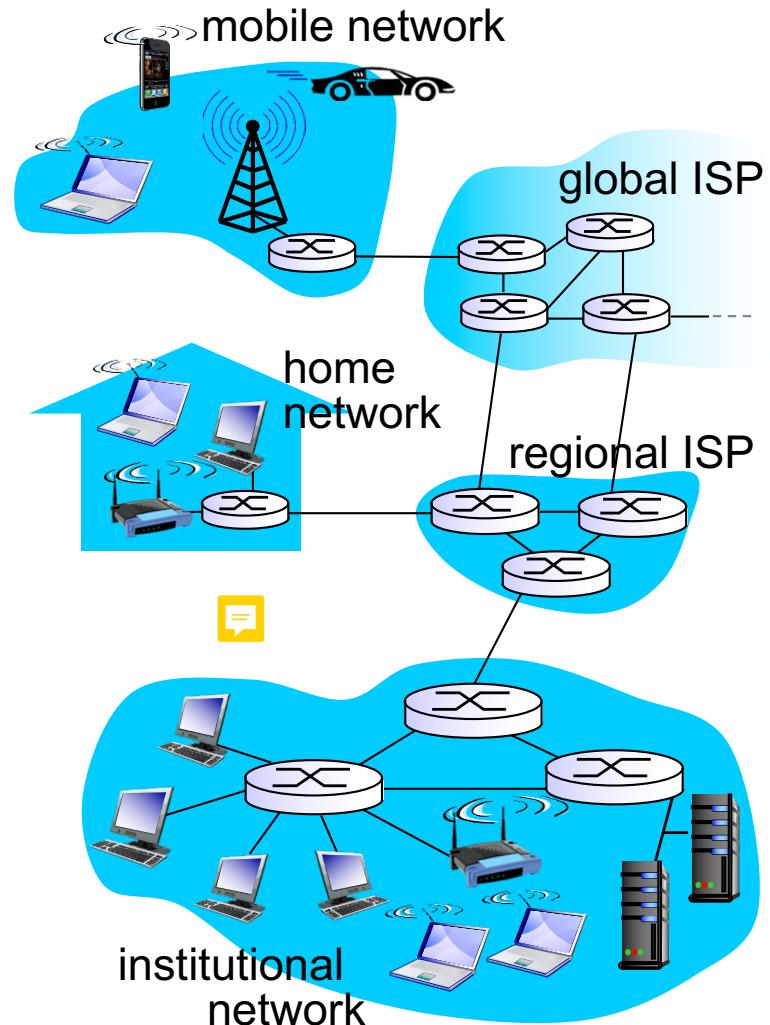
Smart Lightbulbs

# Number Of Devices In The Internet Of Everything



# What's the Internet: “nuts and bolts” view

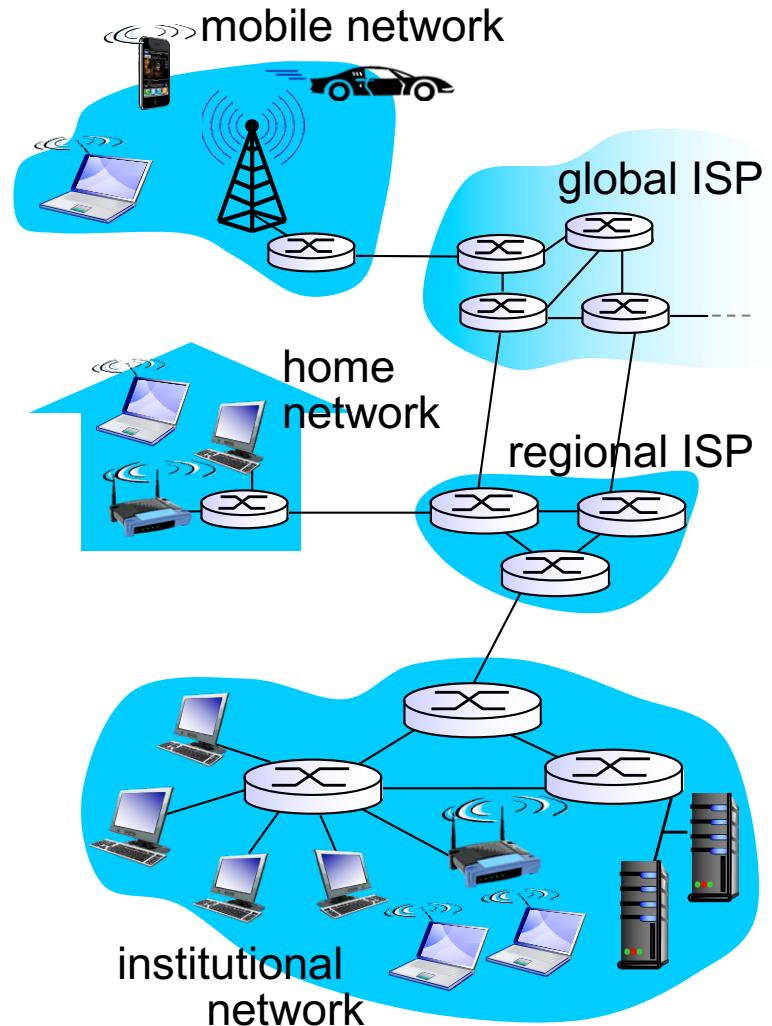
- ❖ *Internet: “network of networks”*
  - Interconnected ISPs
- ❖ *protocols control sending, receiving of msgs*
  - e.g., TCP, IP, HTTP, Skype, 802.11
- ❖ *Internet standards*
  - RFC: Request for comments
  - IETF: Internet Engineering Task Force

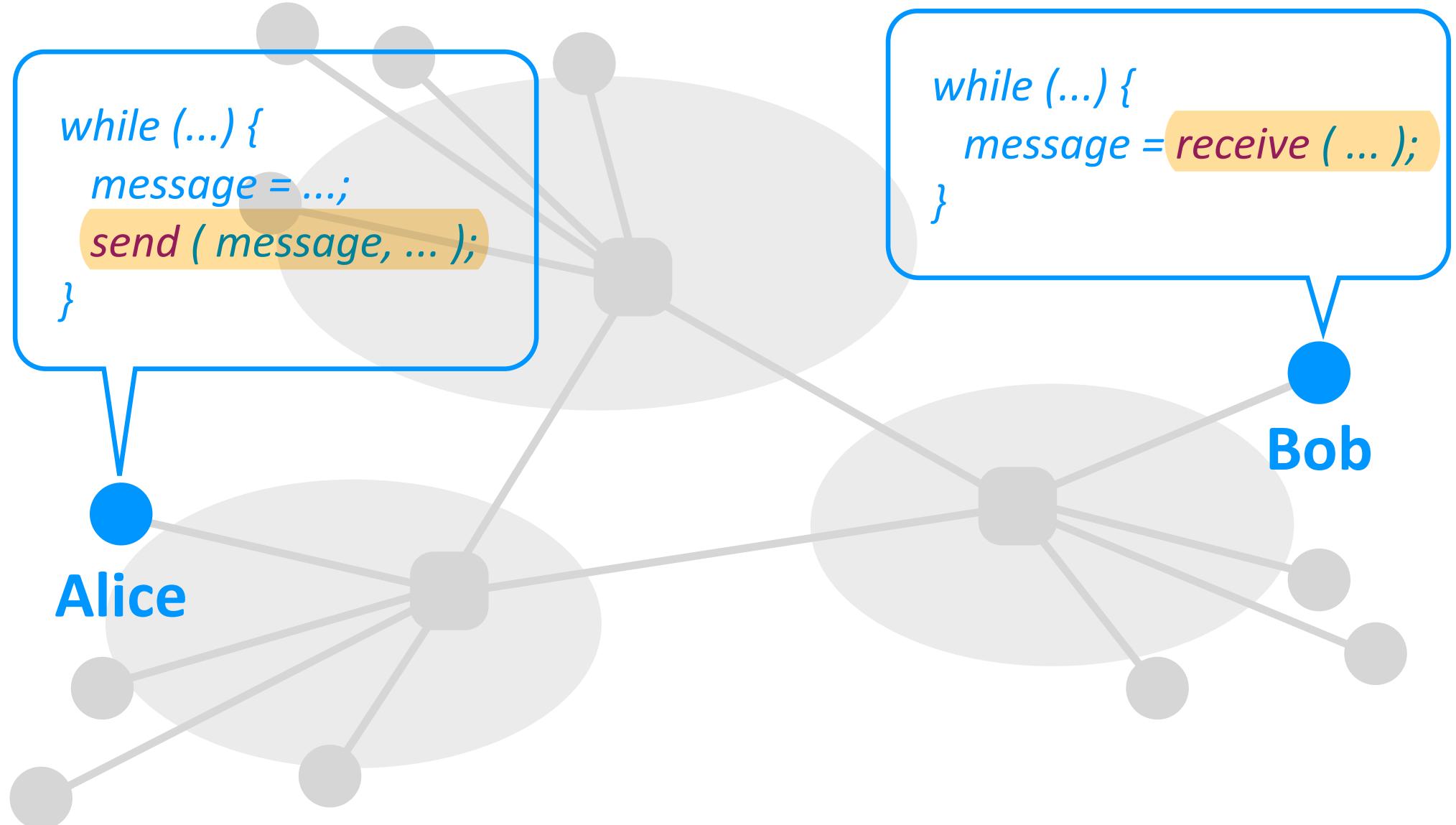


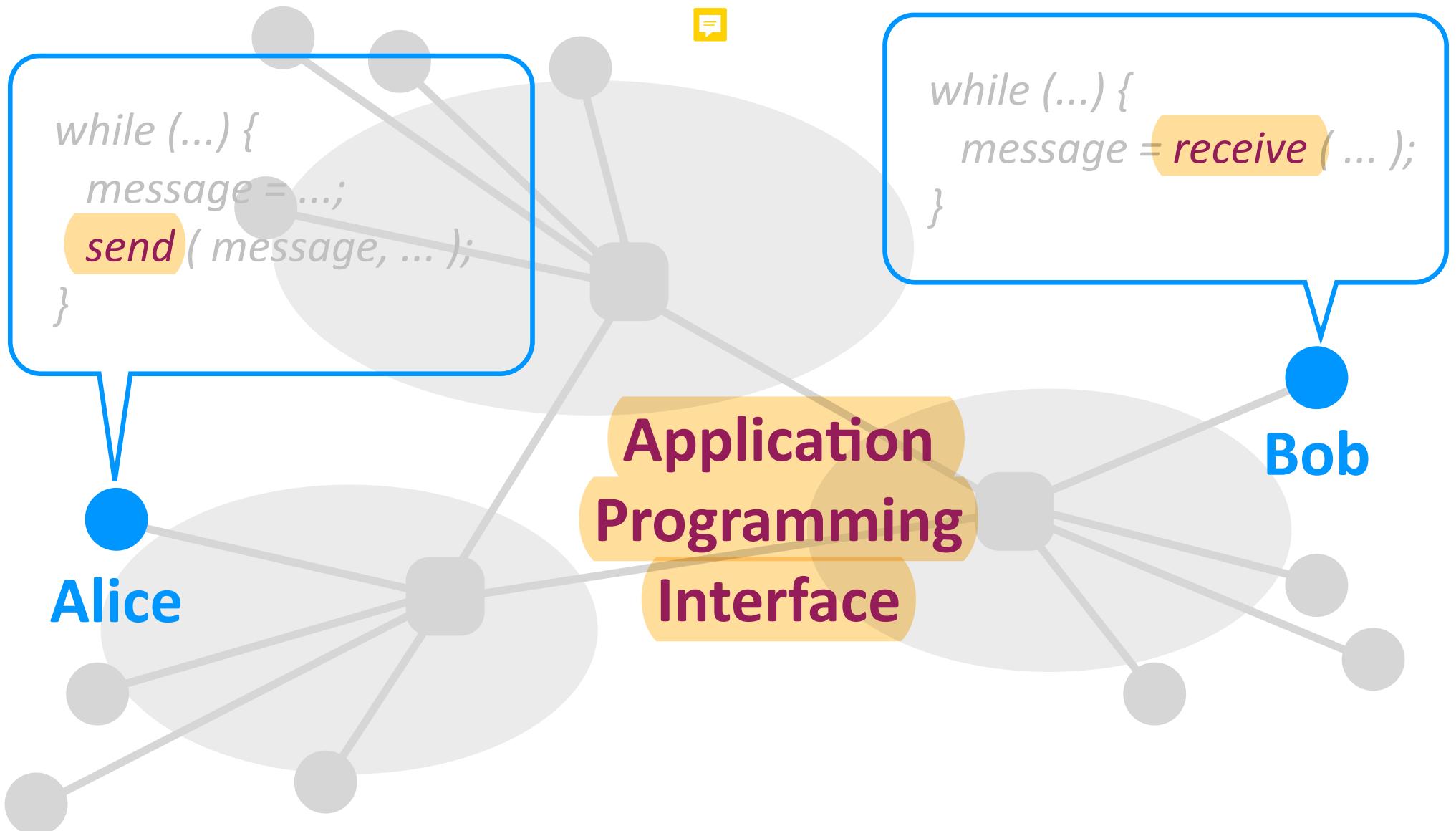
# What's the Internet: a service view



- ❖ *Infrastructure that provides services to applications:*
  - Web, VoIP, email, games, e-commerce, social nets, ...
- ❖ *provides programming interface to apps*
  - hooks that allow sending and receiving app programs to “connect” to Internet
  - provides service options, analogous to postal service







# What's a protocol?

## *human protocols:*

- ❖ “what’s the time?”
- ❖ “I have a question”
- ❖ introductions

... specific msgs sent

... specific actions taken  
when msgs received, or  
other events

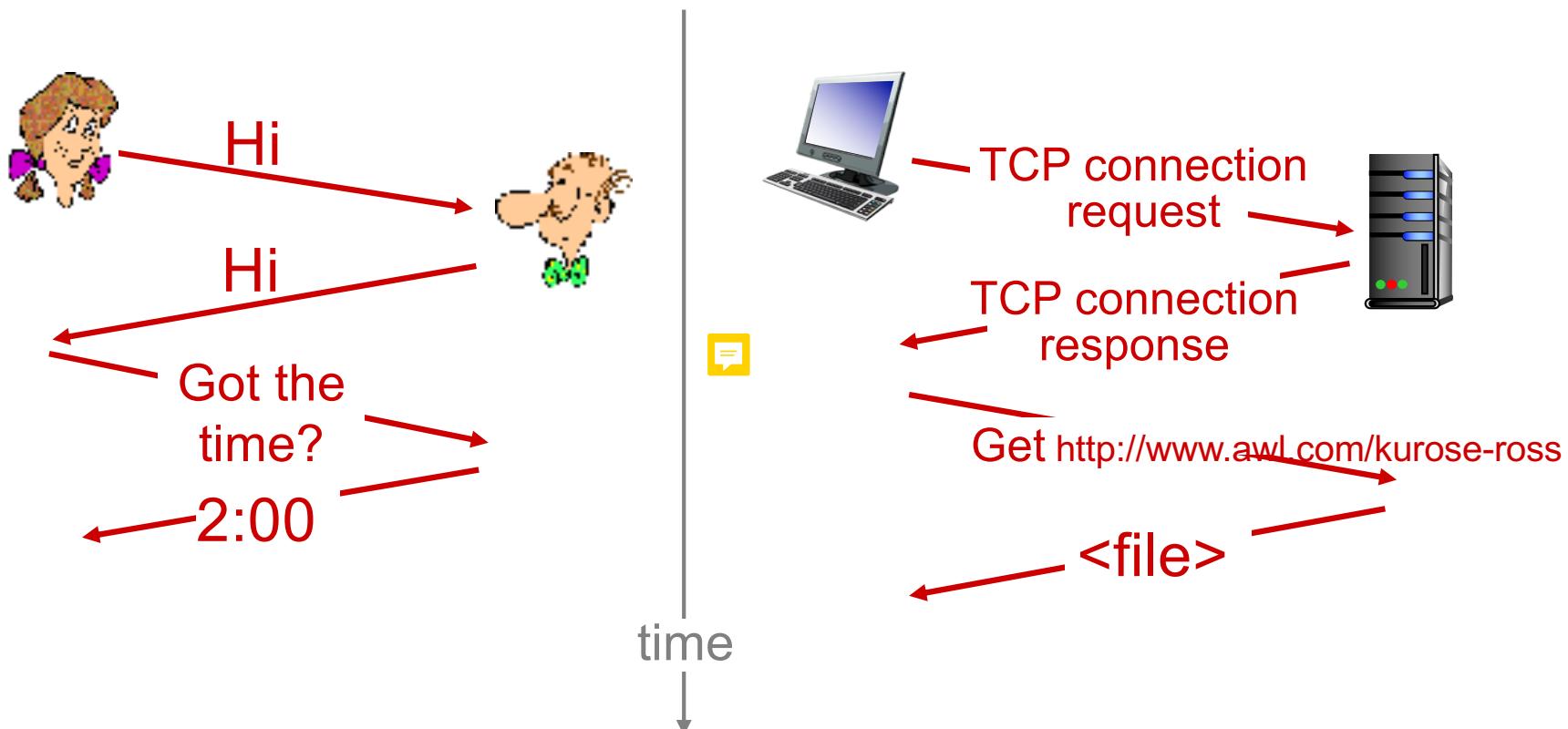
## *network protocols:*

- ❖ machines rather than humans
- ❖ all communication activity in Internet governed by protocols

*protocols define format, order  
of msgs sent and received  
among network entities,  
and actions taken on msg  
transmission, receipt*

# What's a protocol?

a human protocol and a computer network protocol:



Q: other human protocols?

# I. Introduction: roadmap

I.1 what *is* the Internet?

I.2 network edge

- end systems, access networks, links

I.3 network core

- packet switching, circuit switching, network structure

I.4 delay, loss, throughput in networks

I.5 protocol layers, service models

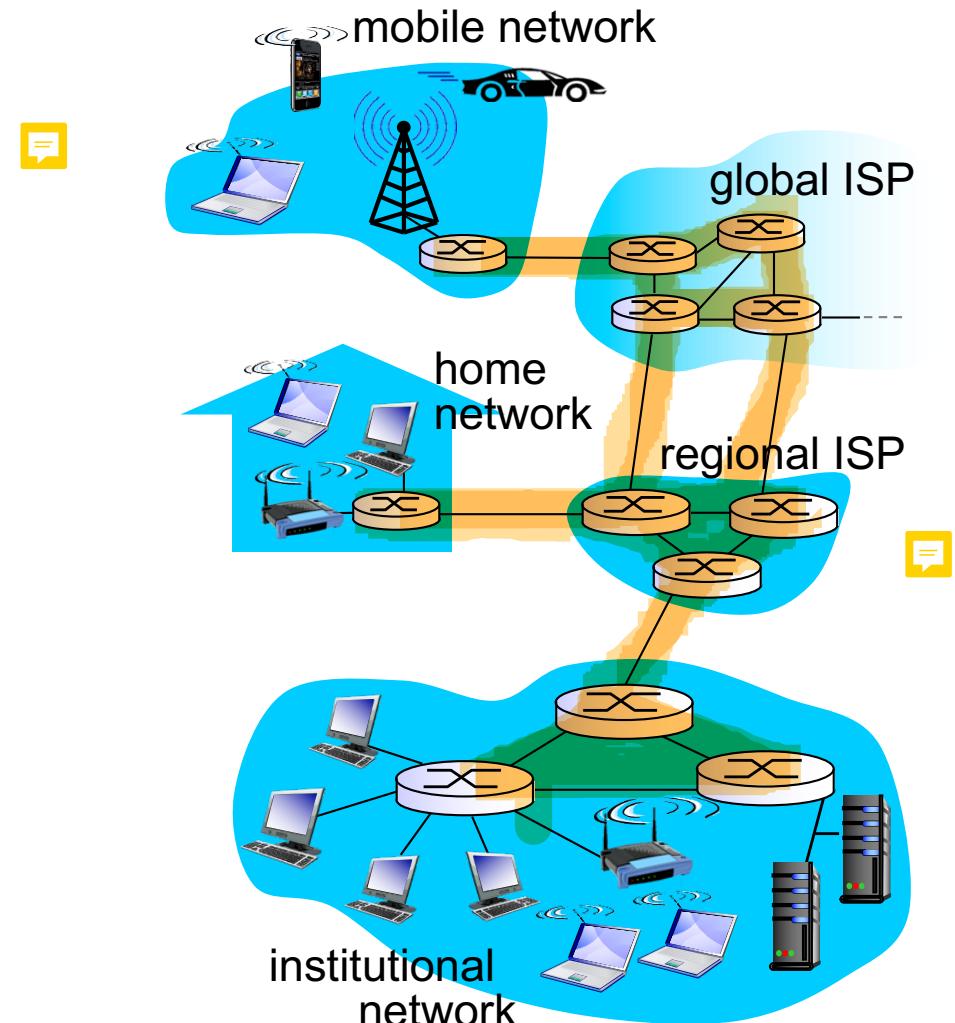
I.6 networks under attack: security

I.7 history

# A closer look at network 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

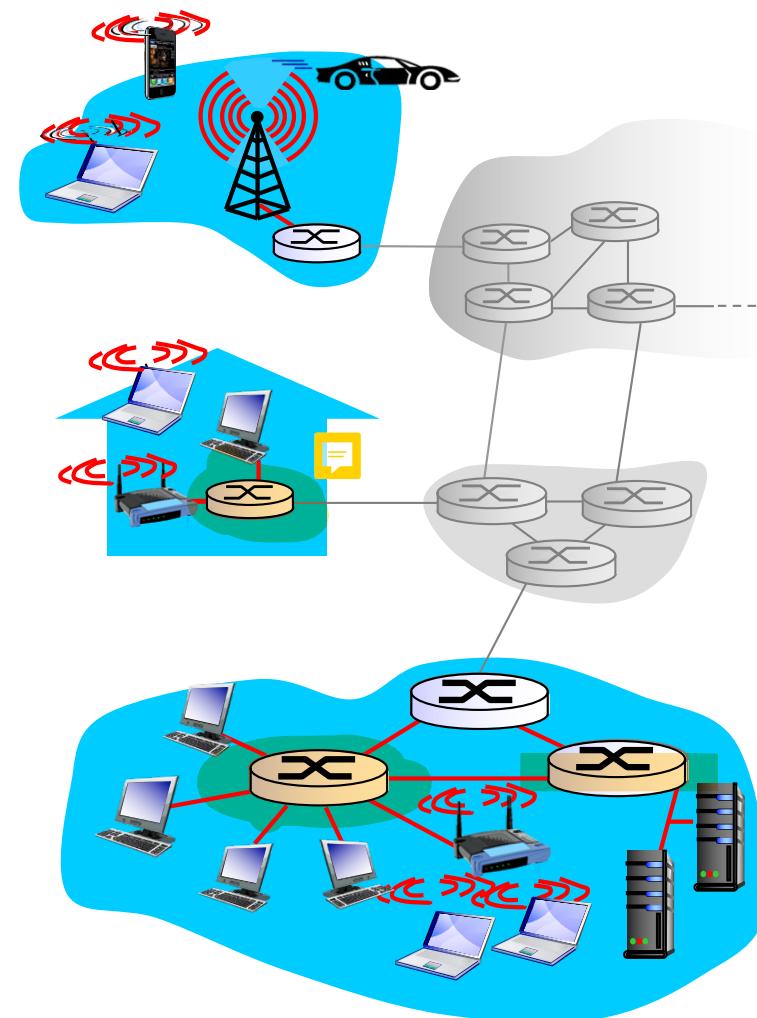
*Q: How to connect end systems to edge router?*

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

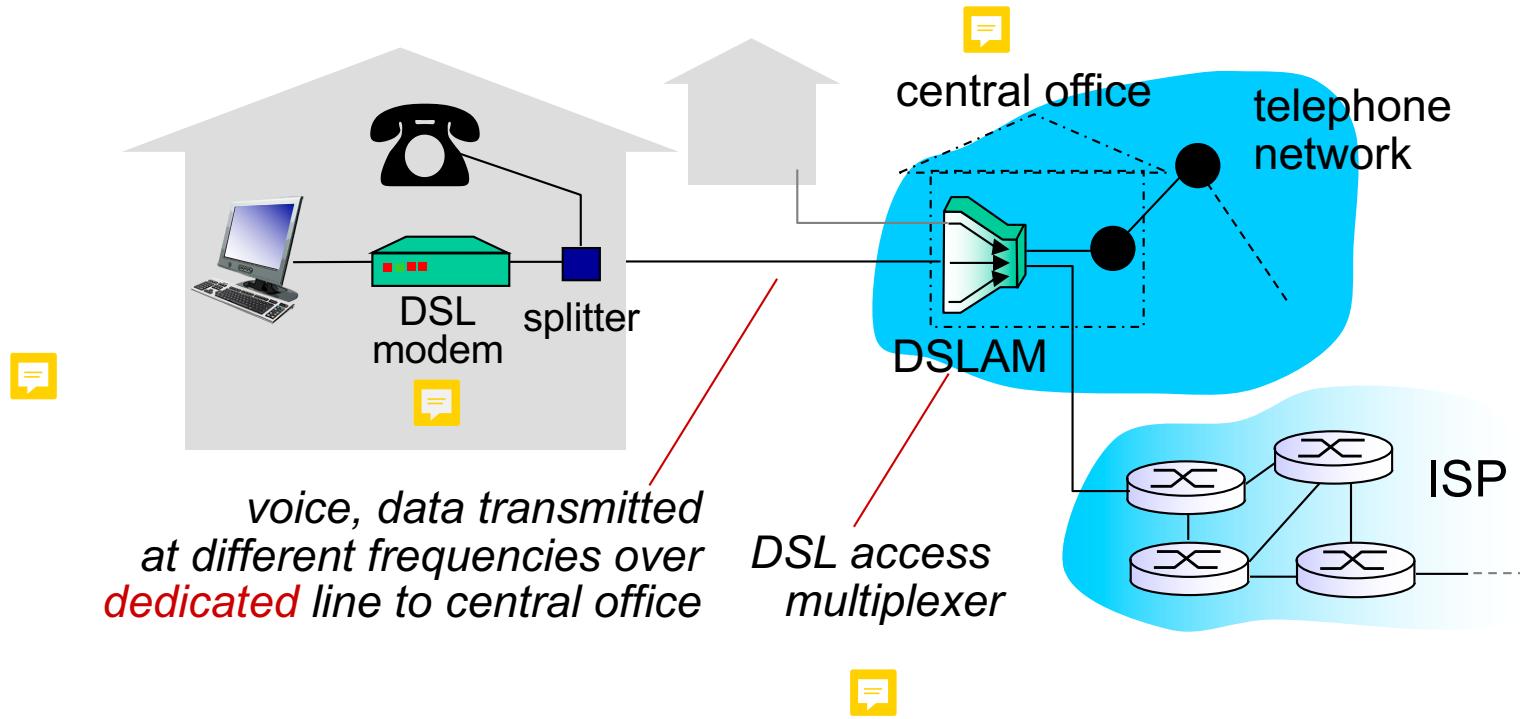


*keep in mind:*

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

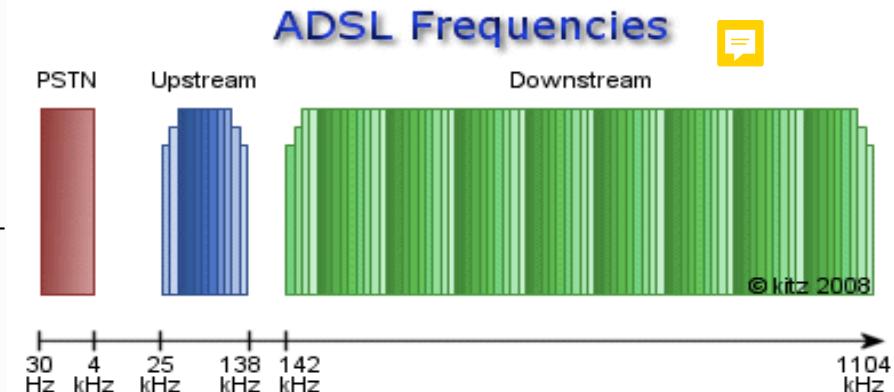
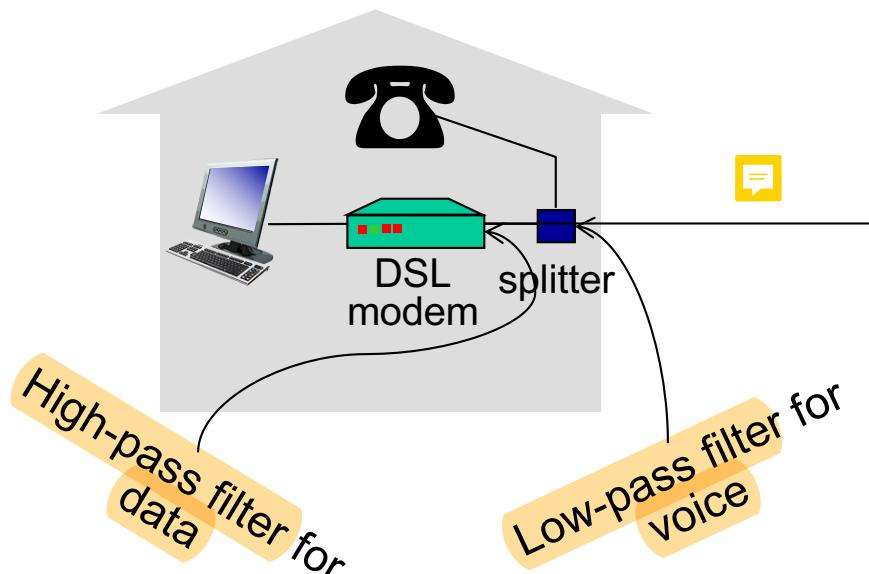


# Access net: digital subscriber line (DSL)



- ❖ 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)



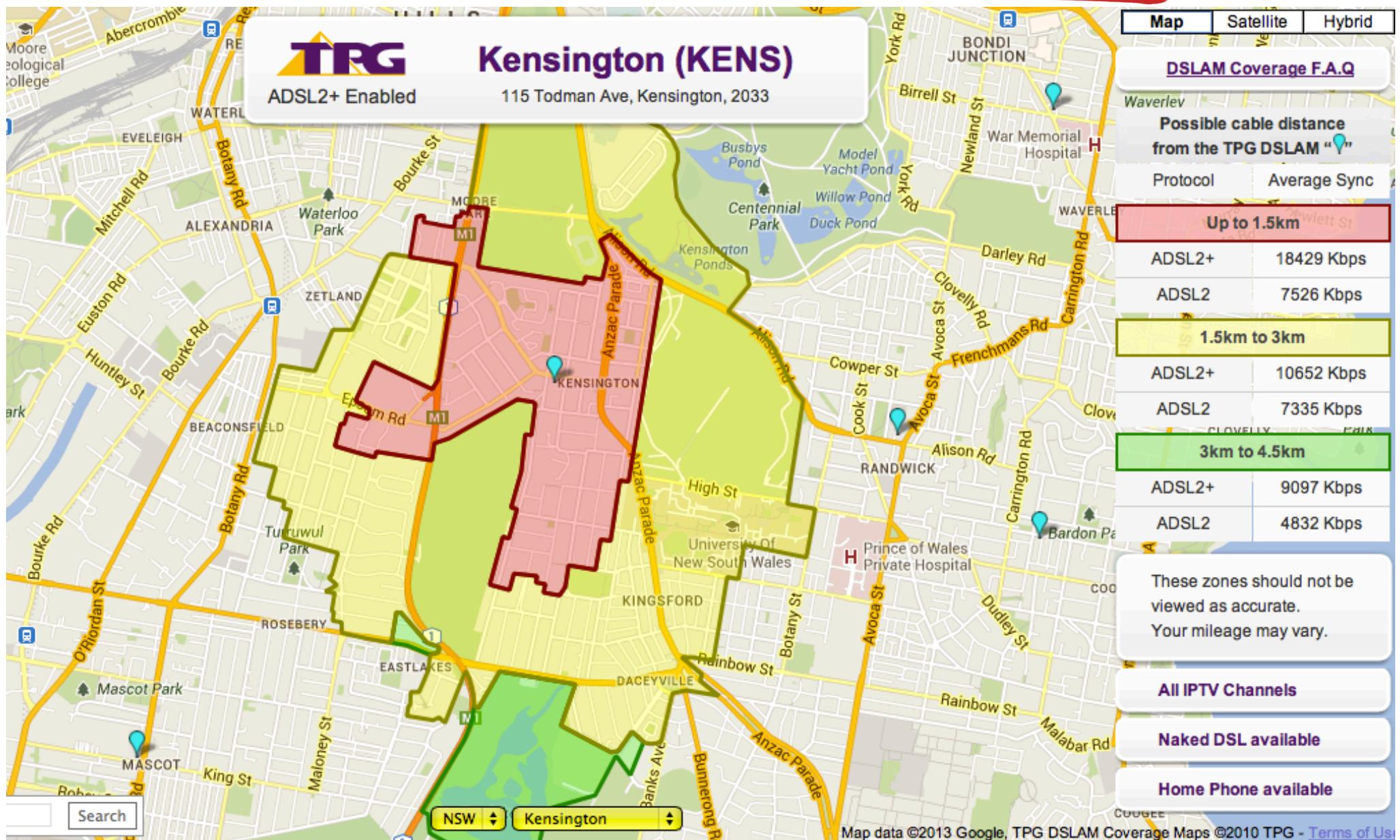
ADSL over POTS

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

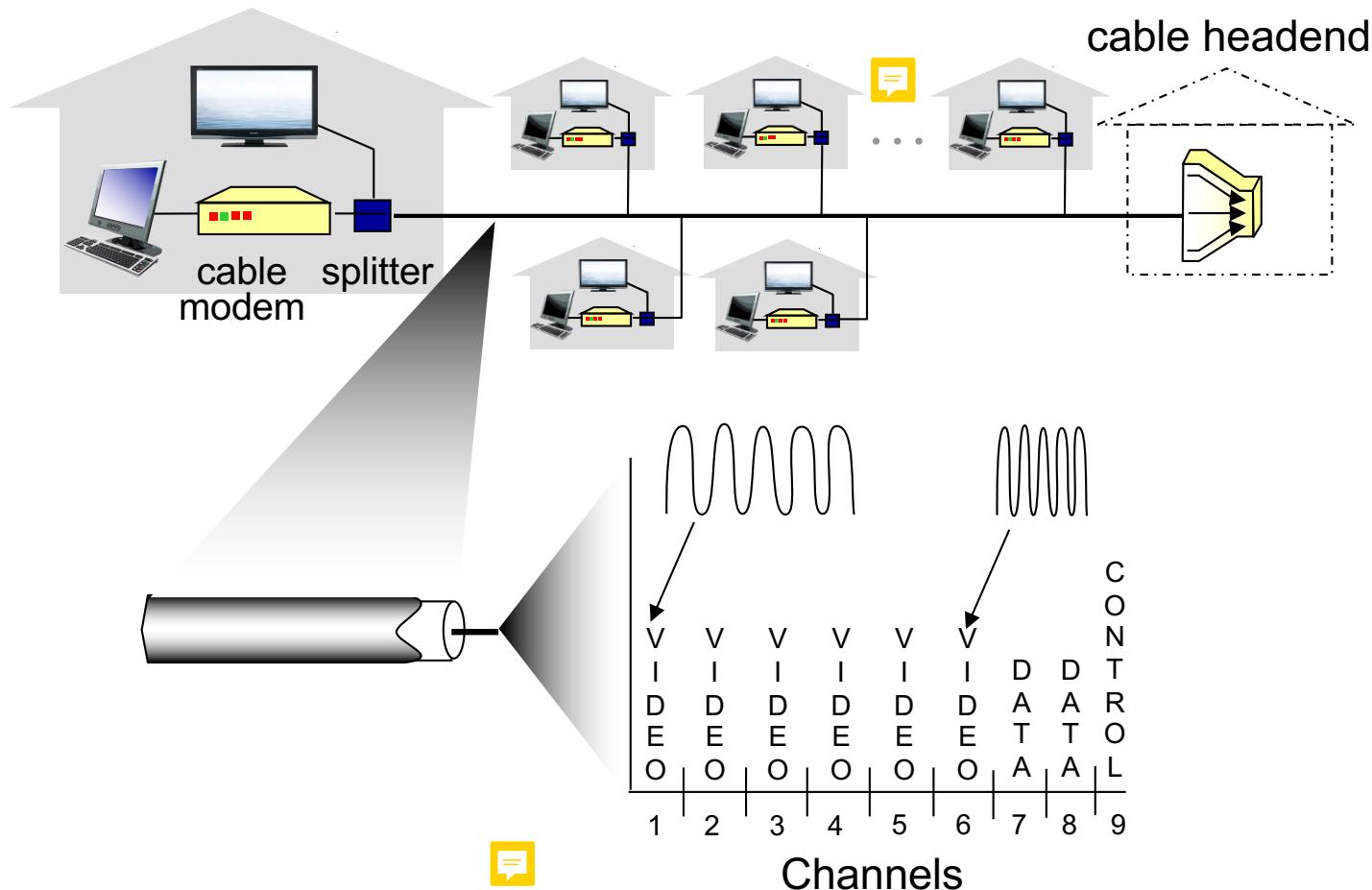
- Different data rates for upload and download (ADSL)
  - < 2.5 Mbps upstream transmission rate (typically < 1 Mbps)
  - < 24 Mbps downstream transmission rate (typically < 10 Mbps)



# Access net: digital subscriber line (DSL)

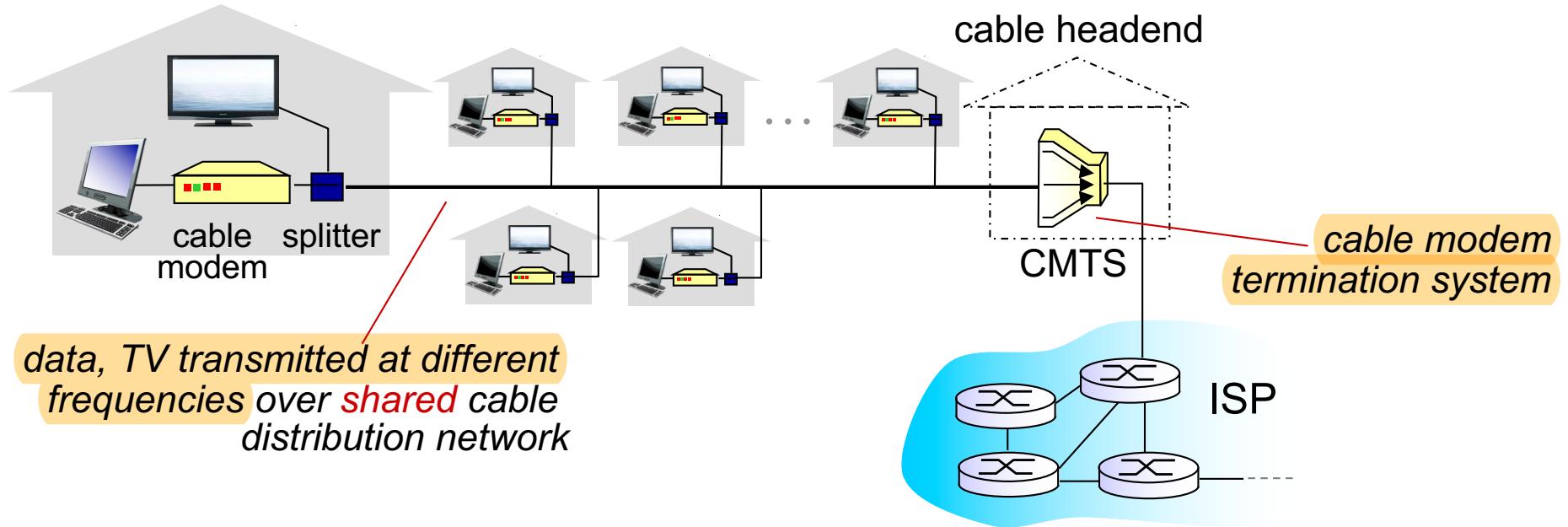


# Access net: cable network



**frequency division multiplexing:** different channels transmitted in different frequency bands

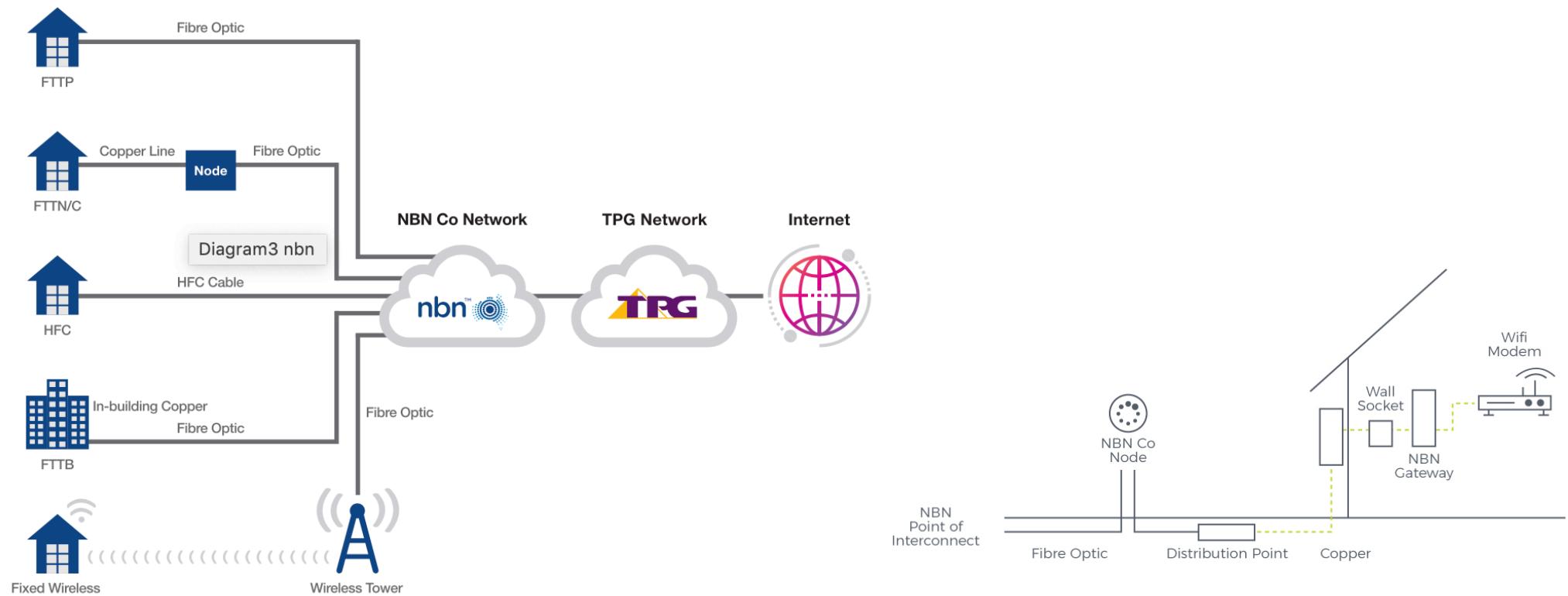
# Access net: cable network



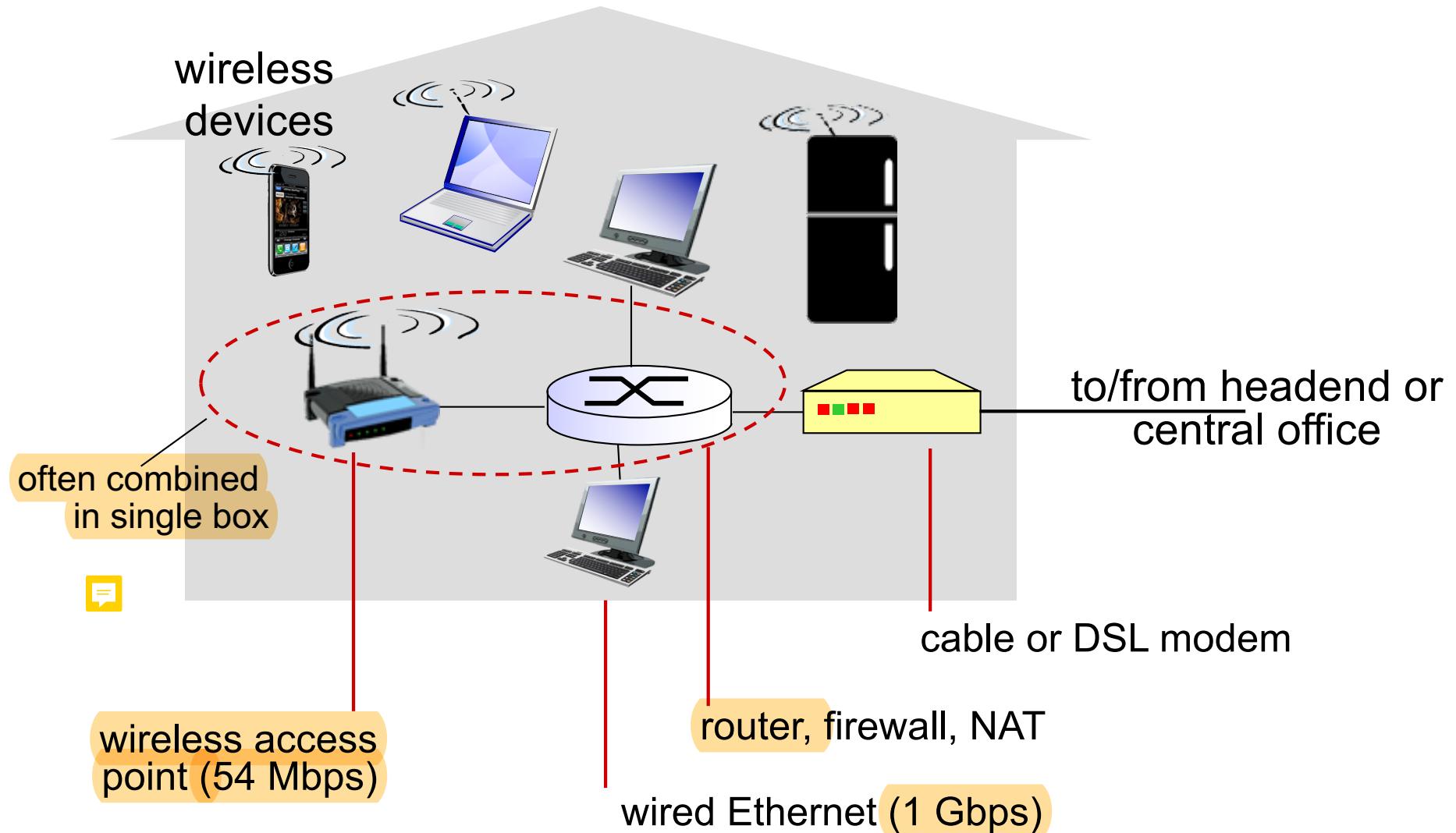
- ❖ HFC: hybrid fiber coax
  - asymmetric: up to 30Mbps downstream transmission rate, 2 Mbps upstream transmission rate
- ❖ network of cable, fiber attaches homes to ISP router
  - homes **share access network** to cable headend
  - unlike DSL, which has **dedicated access** to central office

# Fiber to the home/premise/curb

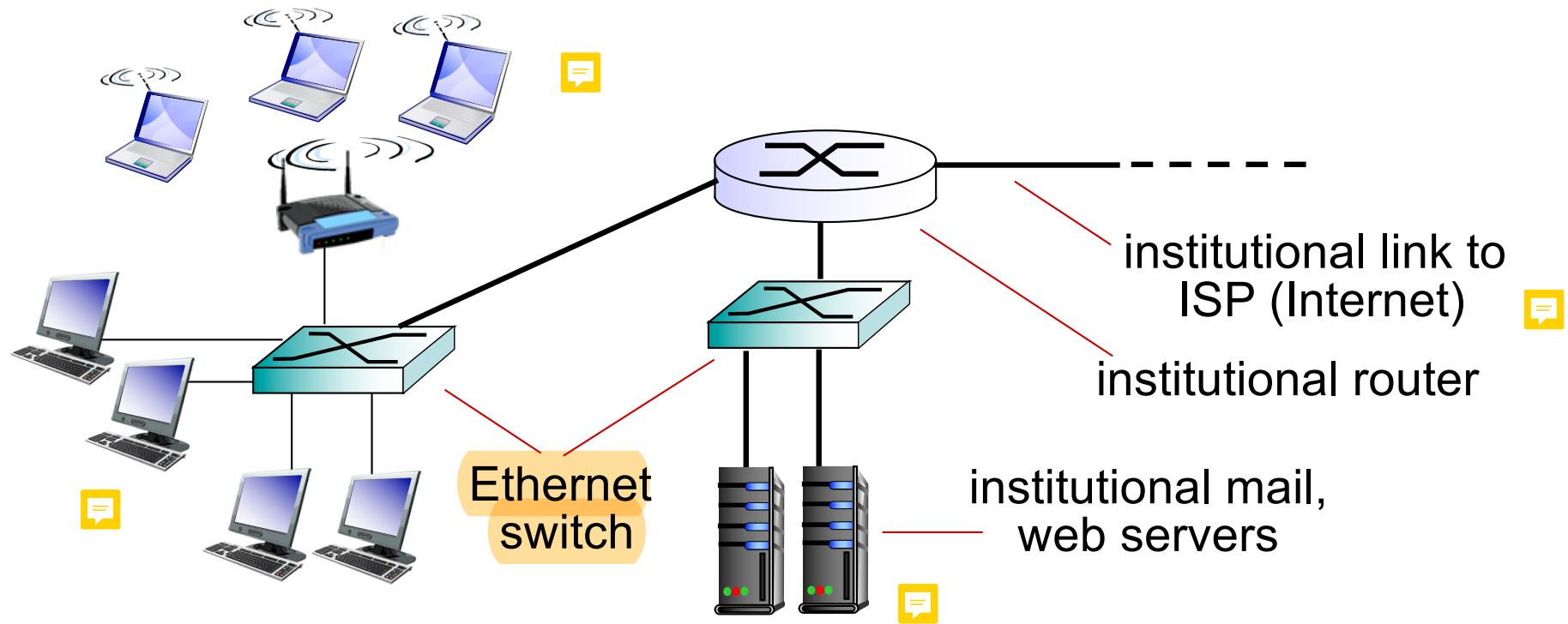
- ❖ Fully optical fiber path all the way to the home
  - e.g., NBN, Google, Verizon FIOS
  - ~30 Mbps to 1 Gbps



# Access net: home network



# Enterprise access networks (Ethernet)



- ❖ typically used in companies, universities, etc
- ❖ 10 Mbps, 100Mbps, 1Gbps, 10Gbps transmission rates
- ❖ today, end systems typically connect into **Ethernet switch**

# Wireless access networks

- ❖ shared wireless access network connects end system to router
  - via base station aka “access point”

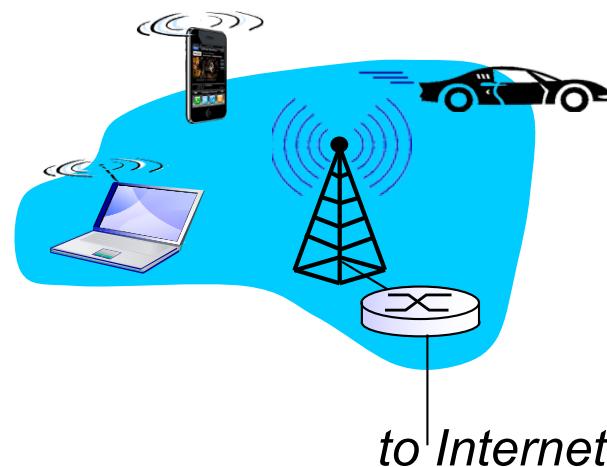
## wireless LANs:

- within building (100 ft)
- 802.11b/g/n (WiFi): 11, 54, 300 Mbps transmission rate
- 802.11ac: 1 Gbps(2.4GHz) + 4.34Gbps (5GHz)
- 802.11ax: WiFi 6



## wide-area wireless access

- provided by telco (cellular) operator, 10's km
- between 10 and 100 Mbps
- 4G, 5G

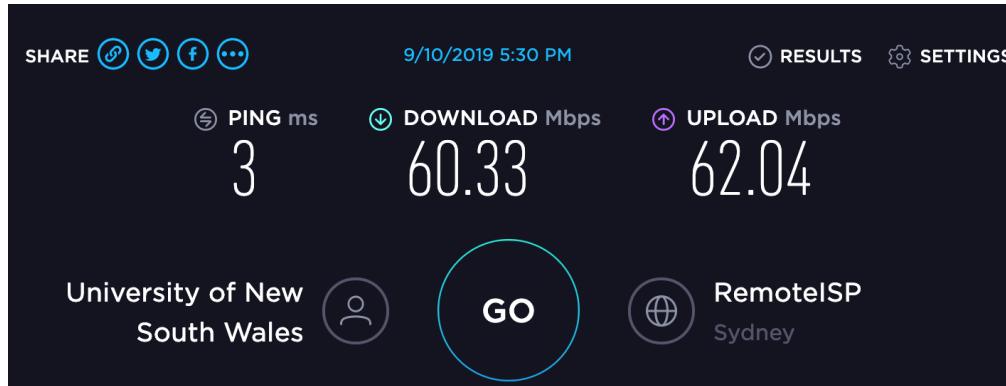


# Sample results

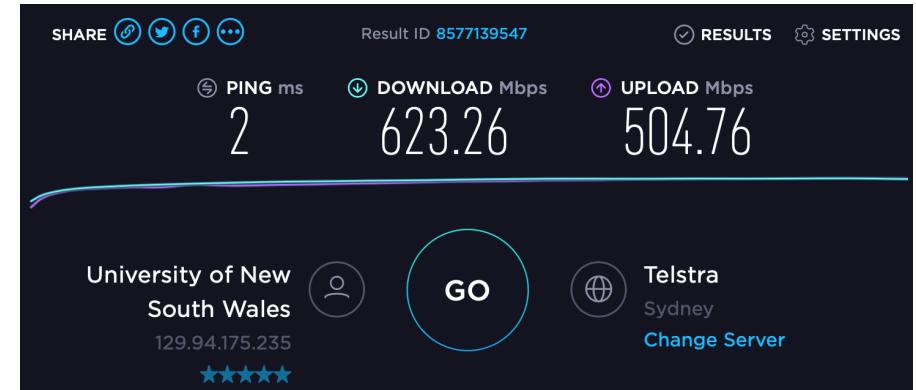
Can you explain the differences?



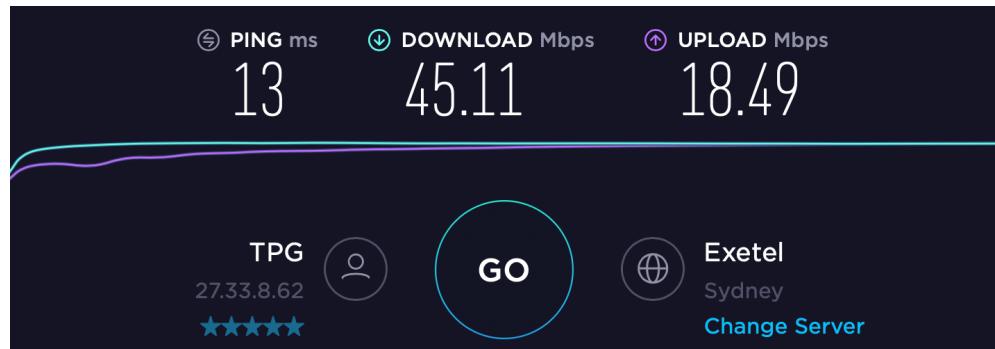
## Uniwide



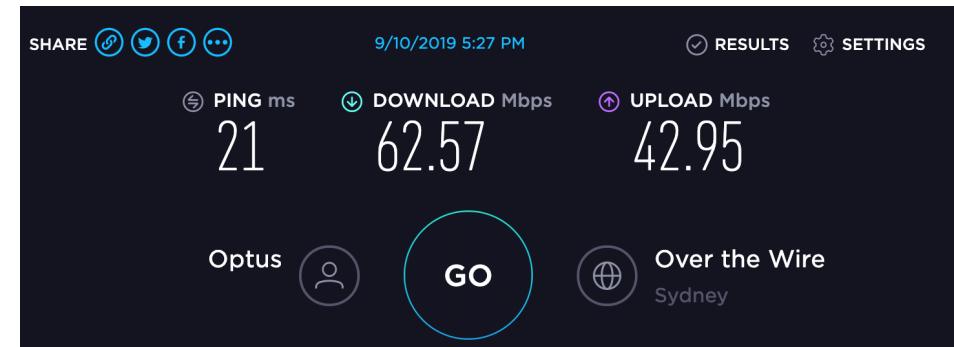
## Wired Network @ CSE



## FTTC + Cable + WiFi @ my home



## 4G Network



# Physical media

Self Study

- ❖ **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

# Physical media: twisted pair, coax, fiber

## *twisted pair (TP)*

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



## *coaxial cable:*

- ❖ two concentric copper conductors
- ❖ broadband:
  - multiple channels on cable
  - HFC



Self Study

## *fiber optic cable:*

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



# Physical media: radio

Self Study

- ❖ signal carried in electromagnetic spectrum, i.e., no physical “wire”
- ❖ propagation environment effects:
  - reflection
  - obstruction by objects
  - interference

## *radio link types:*

- ❖ **terrestrial microwave**
  - e.g. up to 45 Mbps channels
- ❖ **LAN** (e.g., WiFi)
  - 11Mbps, 54 Mbps, 450 Mbps, Gbps
- ❖ **wide-area** (e.g., cellular)
  - 4G cellular: ~ 10 Mbps
- ❖ **satellite**
  - Kbps to 45Mbps channel (or multiple smaller channels)
  - 270 msec end-end delay
  - geosynchronous versus low earth-orbiting (LEO)

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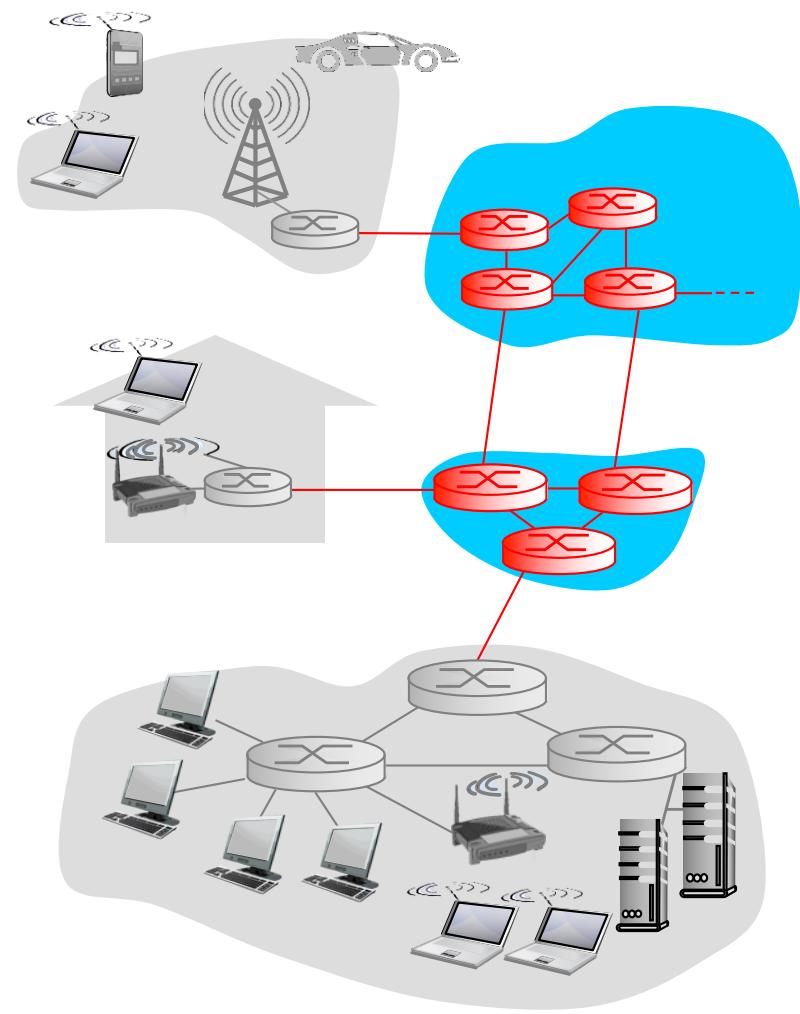
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# The network core

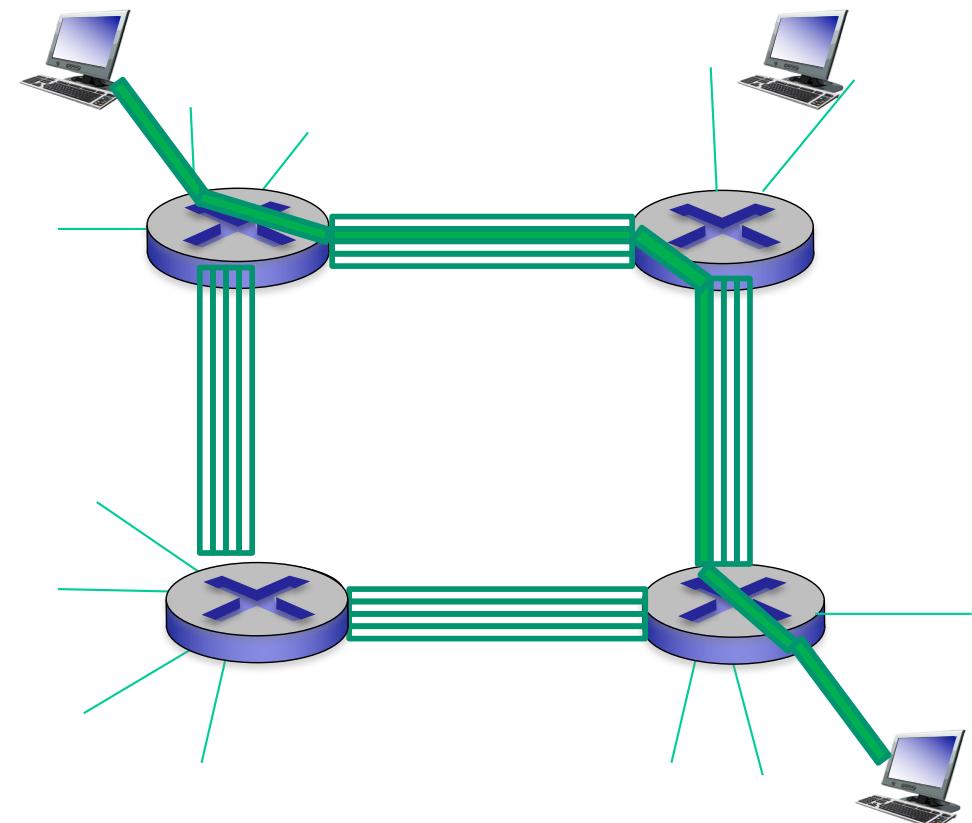
- ❖ mesh of interconnected routers/switches
- ❖ Two forms of switched networks:
  - Circuit switching: used in the legacy telephone networks
  - Packet switching: used in the Internet



# Circuit Switching

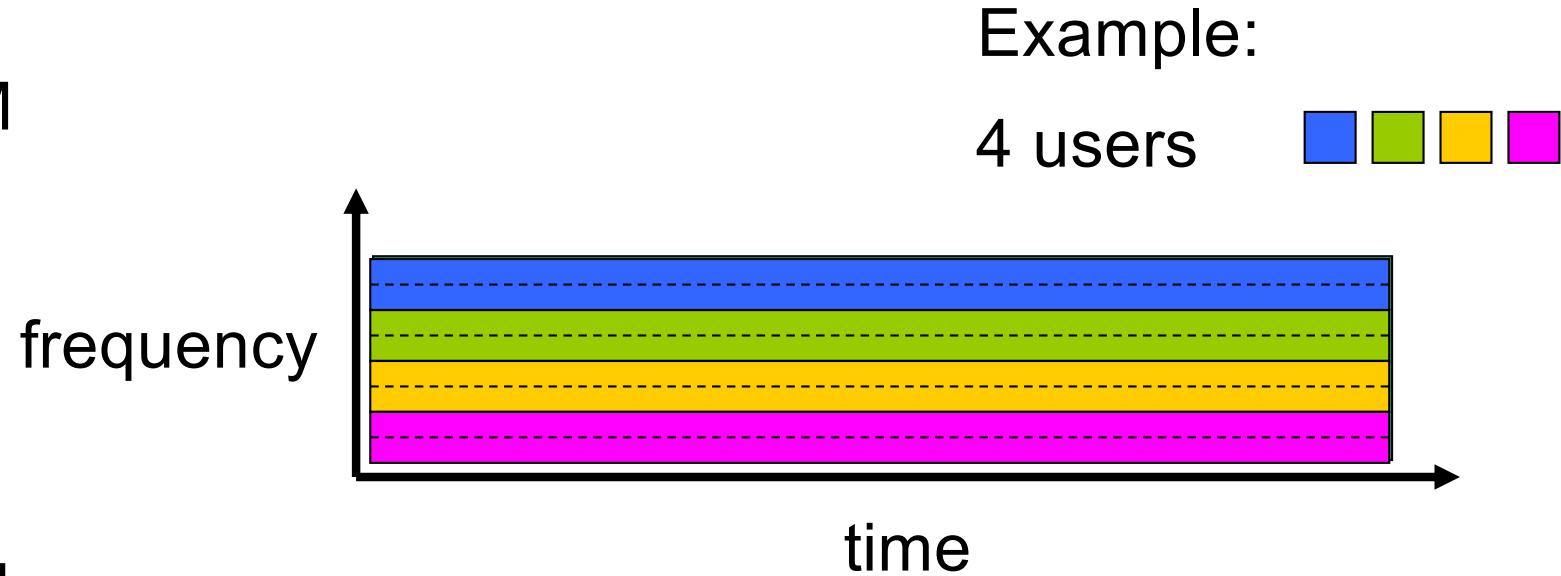
end-end resources allocated to, reserved for “call” between source & dest:

- 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

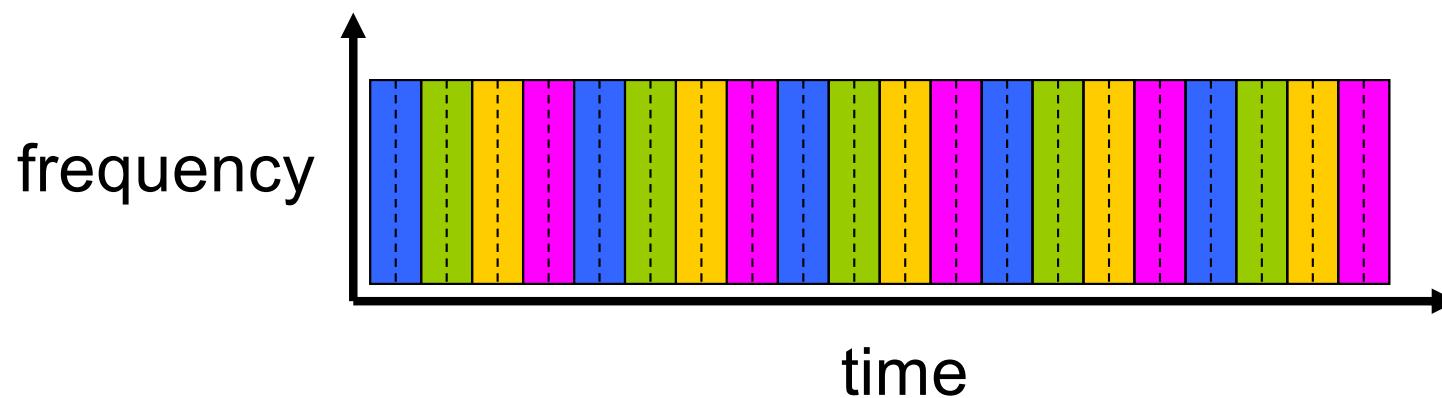


# Circuit switching: FDM versus TDM

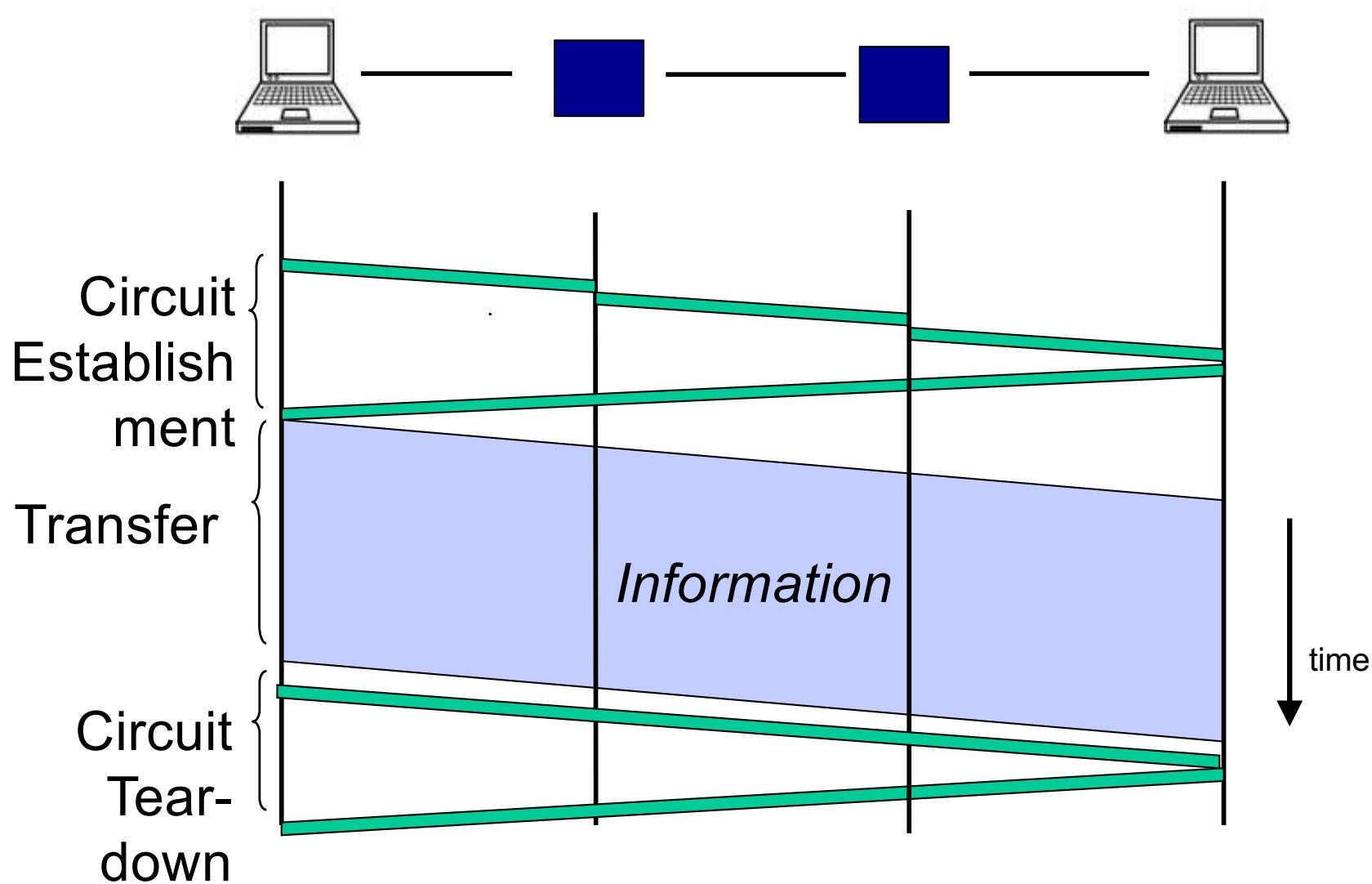
FDM



TDM



# Timing in Circuit Switching



## **Quiz: What are the pros and cons of circuit switching? Let's discuss ..**



❖ Pros:

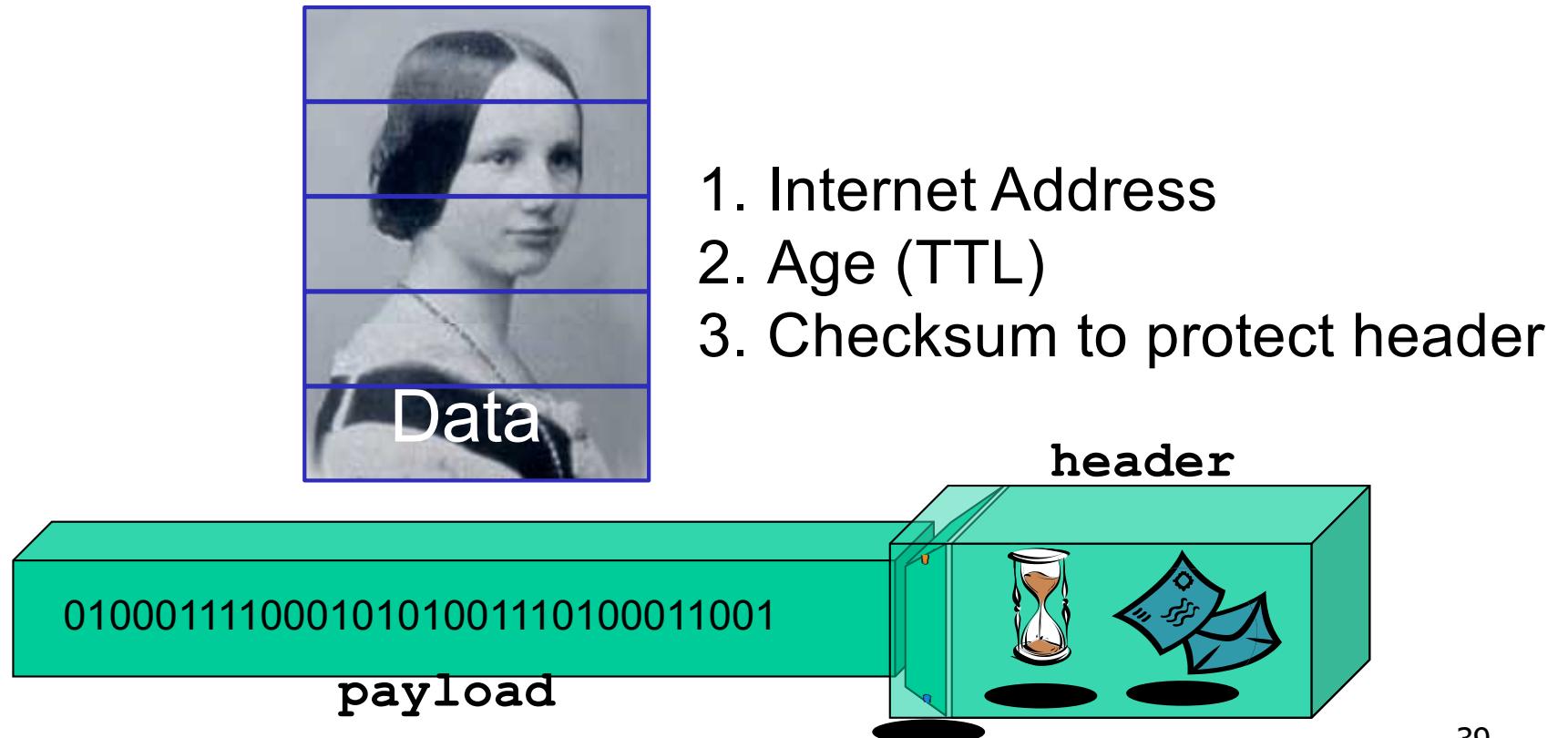
❖ Cons:

# 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 adopt 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”



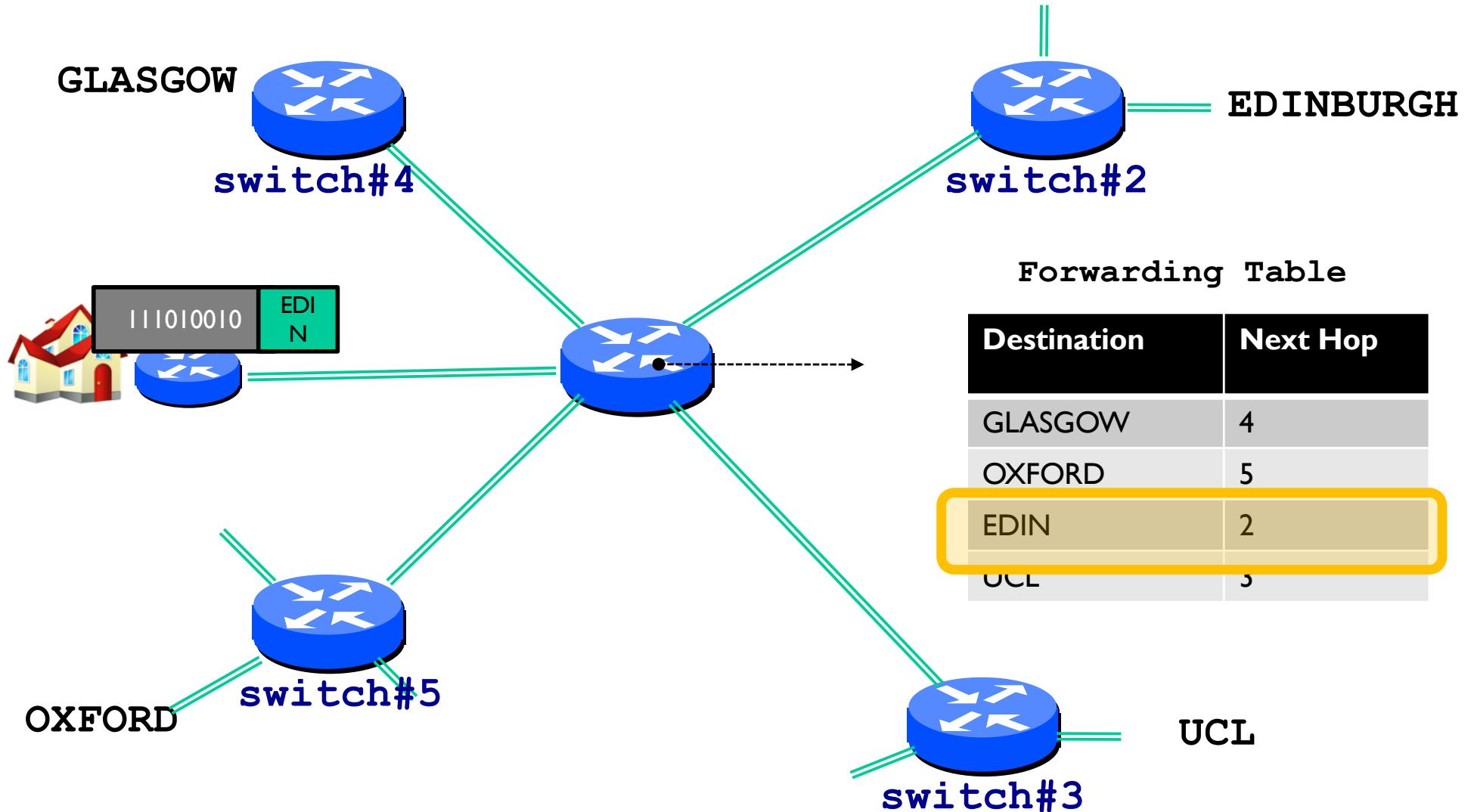
# Packet Switching

- ❖ 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)

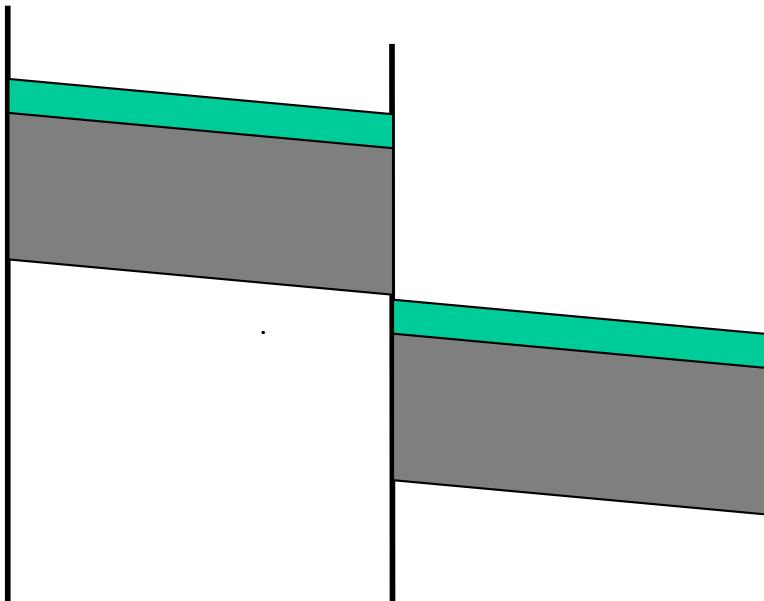
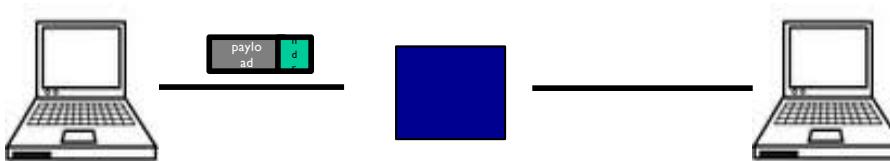
# Packet Switching

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

# Switches forward packets



# Timing in Packet Switching

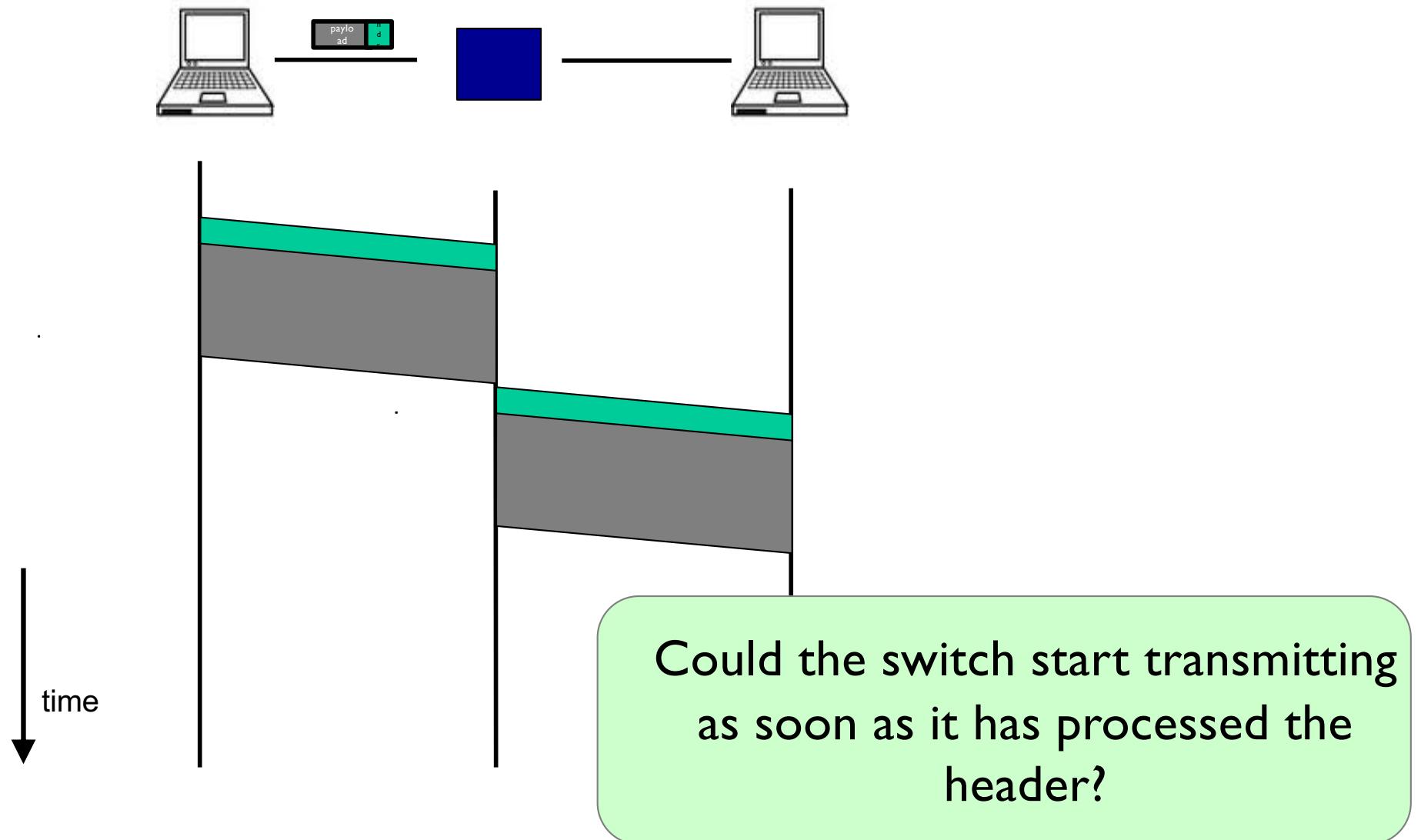


time

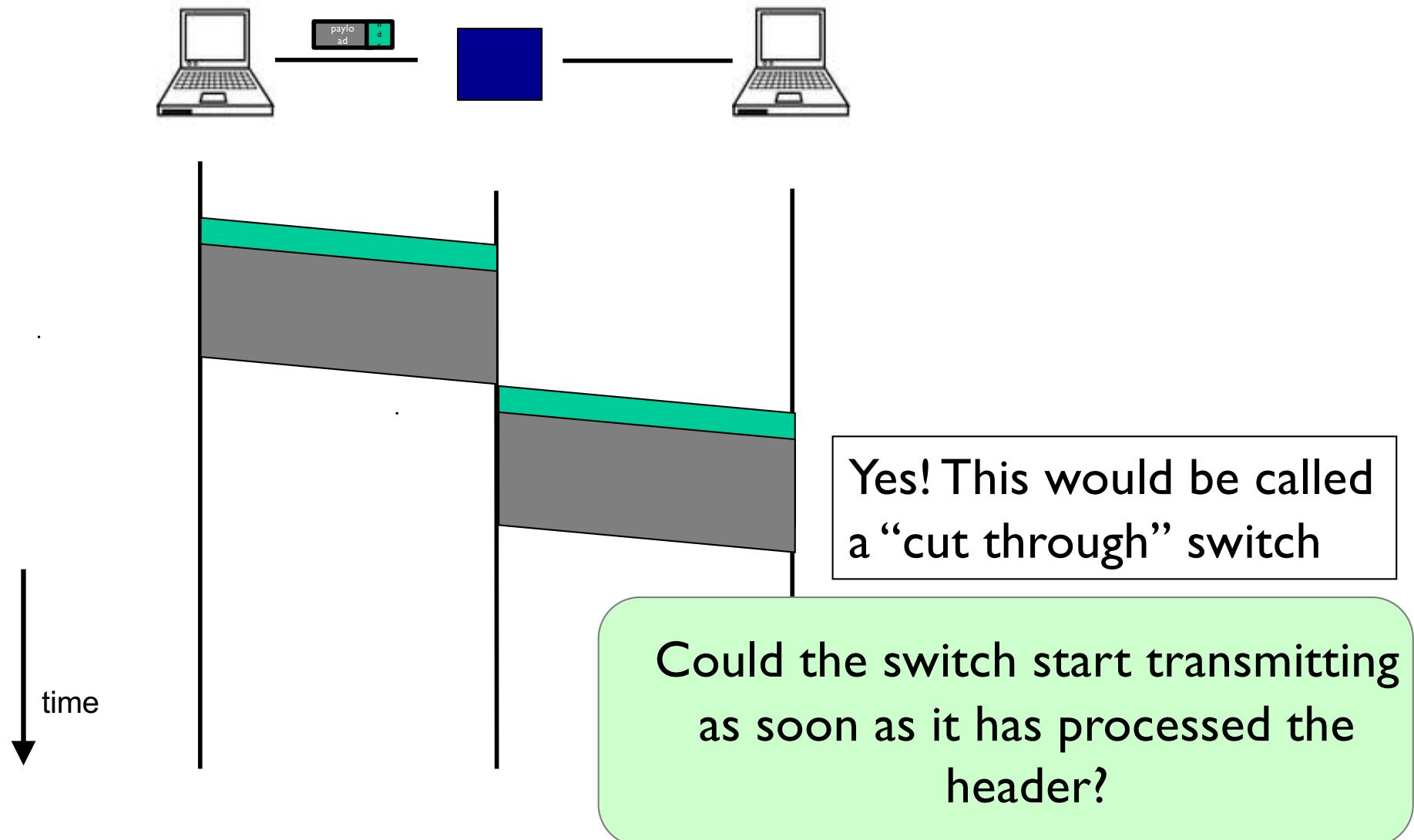
What about the time to process the packet at the switch?

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

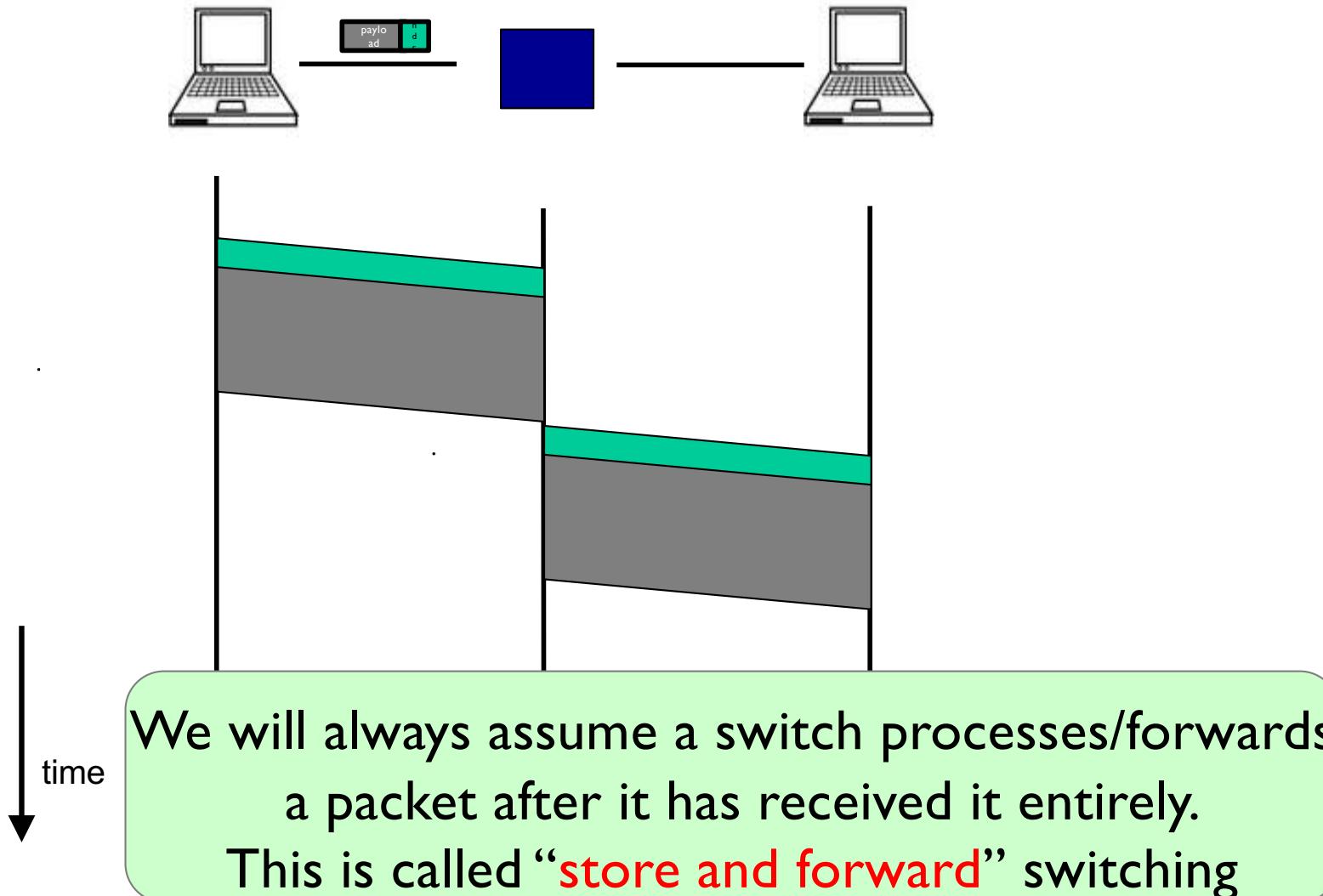
# Timing in Packet Switching



# Timing in Packet Switching



# Timing in Packet Switching



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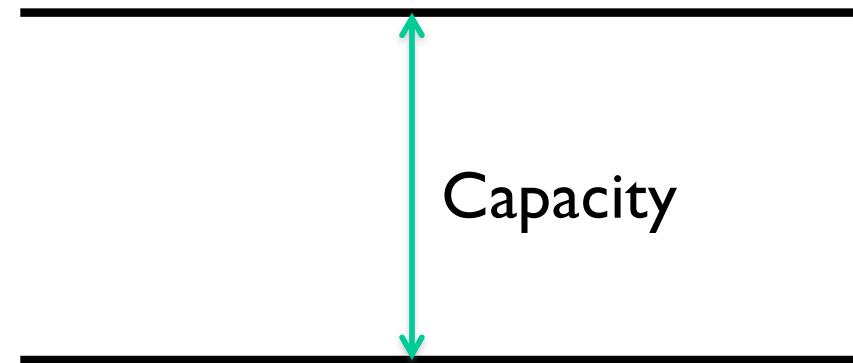
# Packet Switching

- ❖ 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”

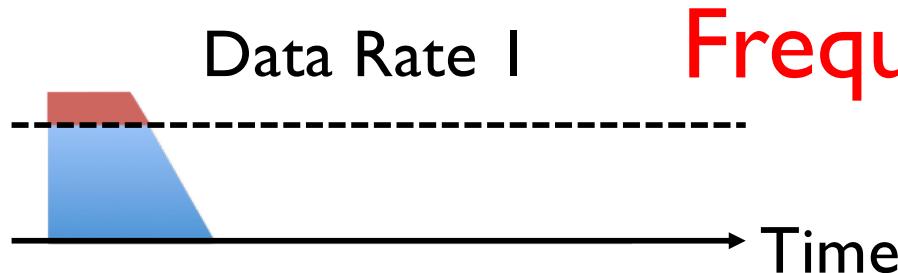
# Packet Switching

- ❖ 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 in advance. Instead packet switching leverages **statistical multiplexing**

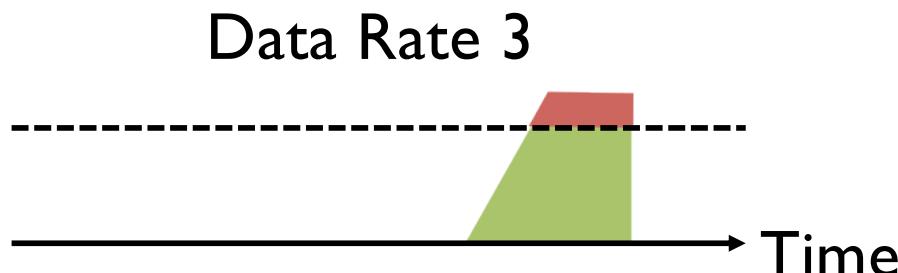
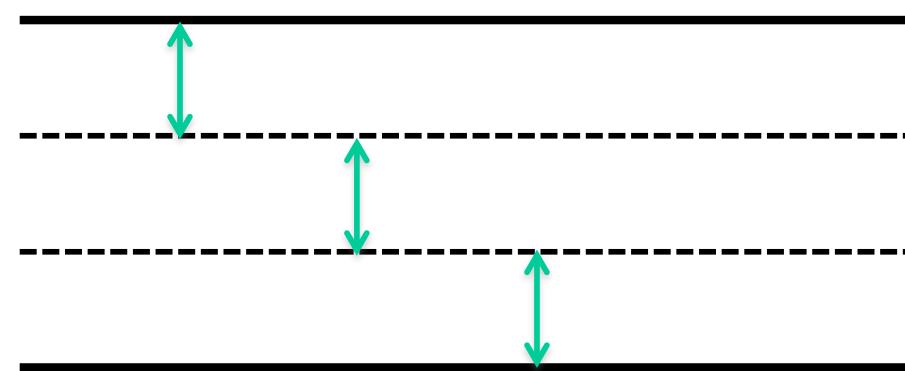
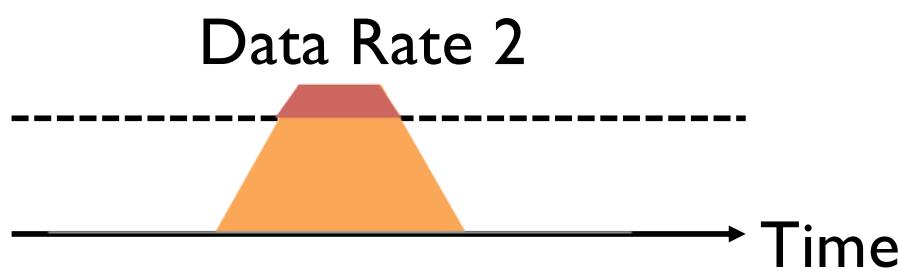
# Three Flows with Bursty Traffic



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



Frequent Overloading



# When Flows Share Total Capacity

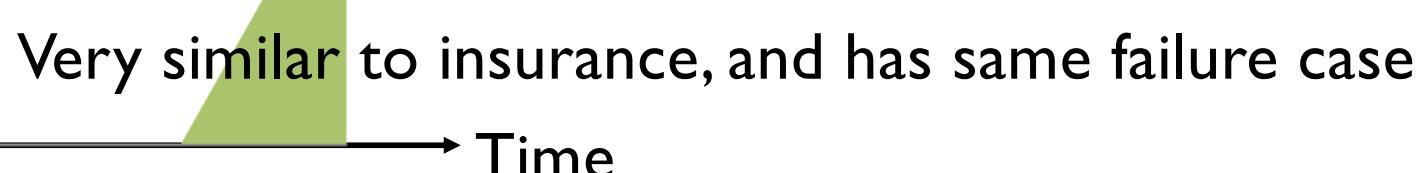
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No Overloading

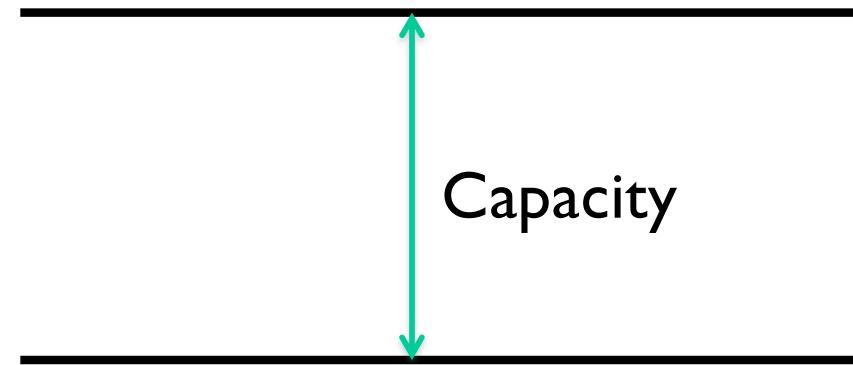
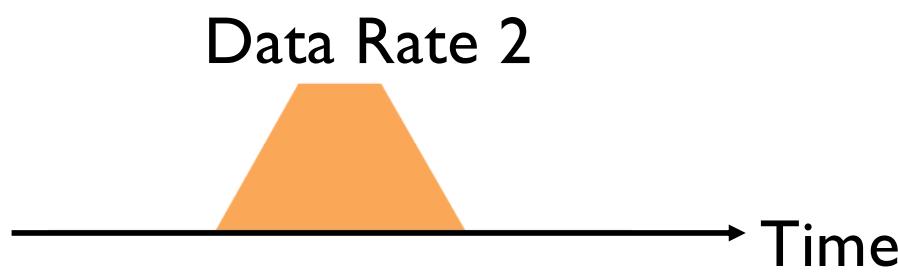


Statistical multiplexing relies on the assumption  
that not all flows burst at the same time.



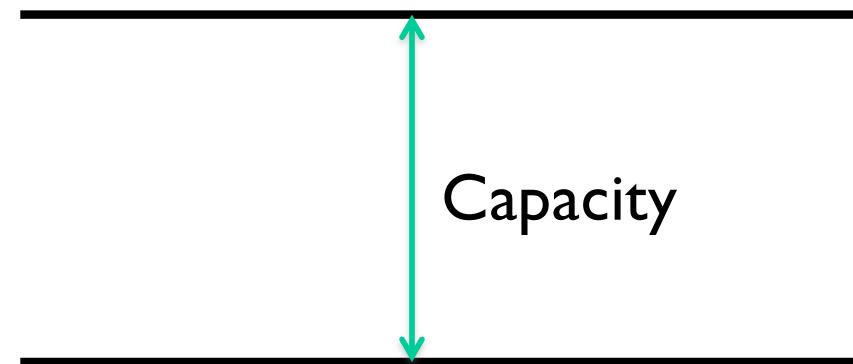
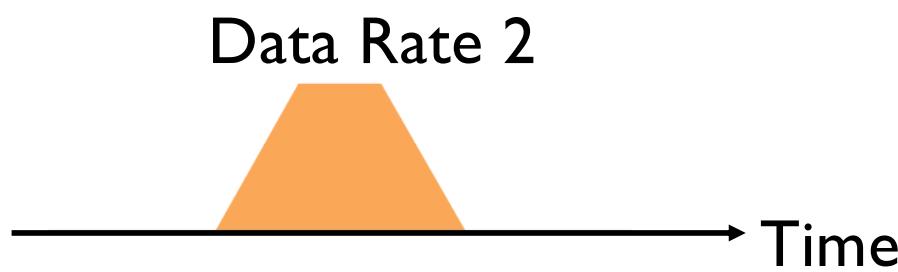
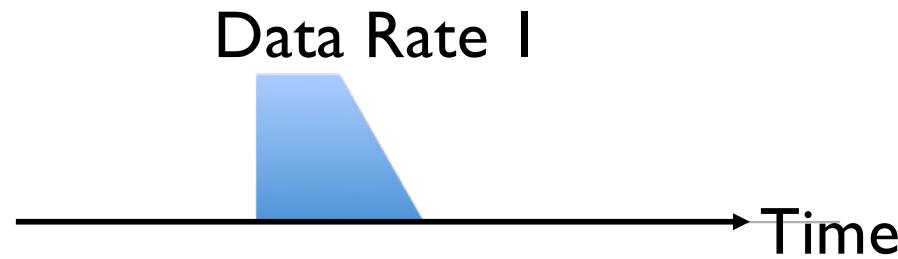
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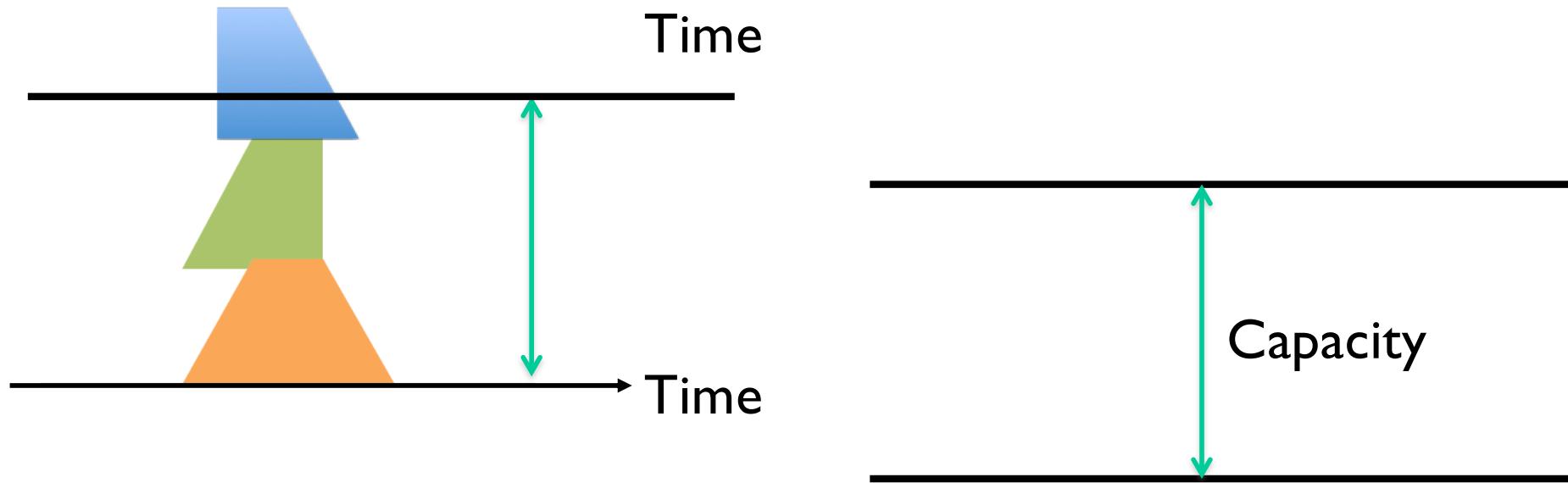
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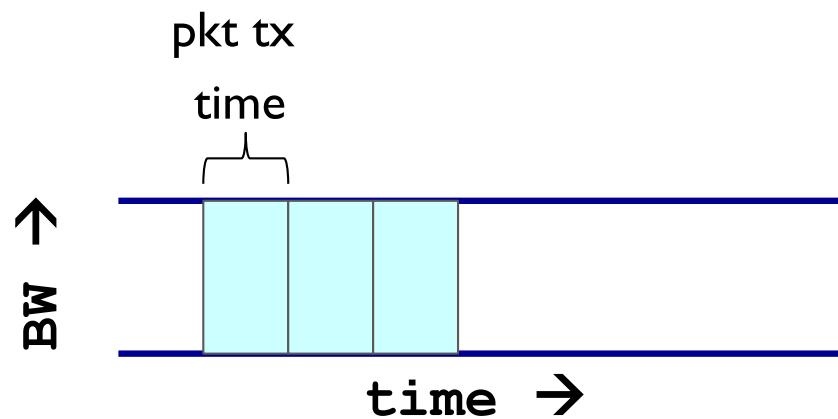
# Three Flows with Bursty Traffic

Data Rate 1+2+3 >> Capacity



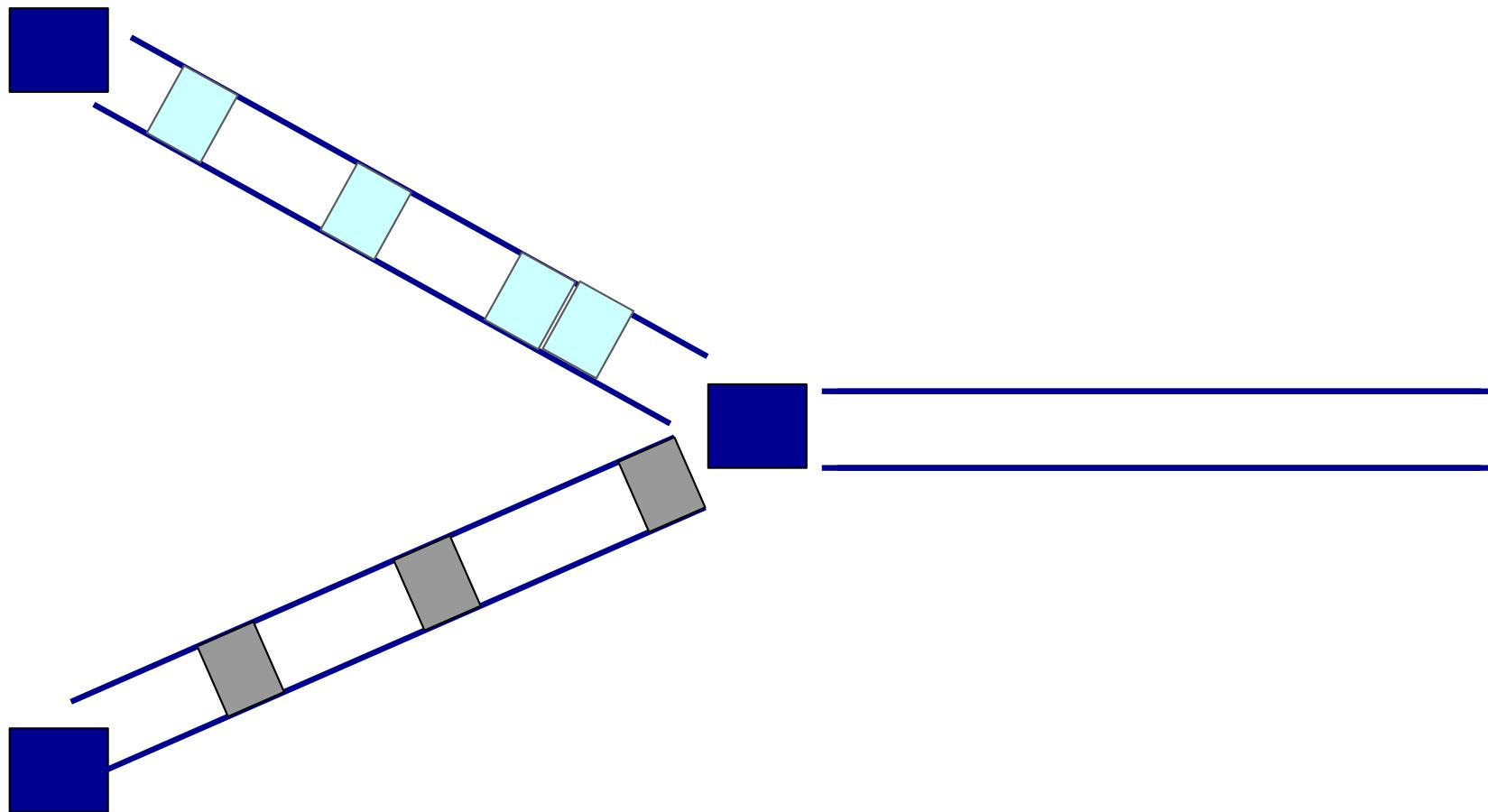
What do we do under overload?

# Statistical multiplexing: pipe view

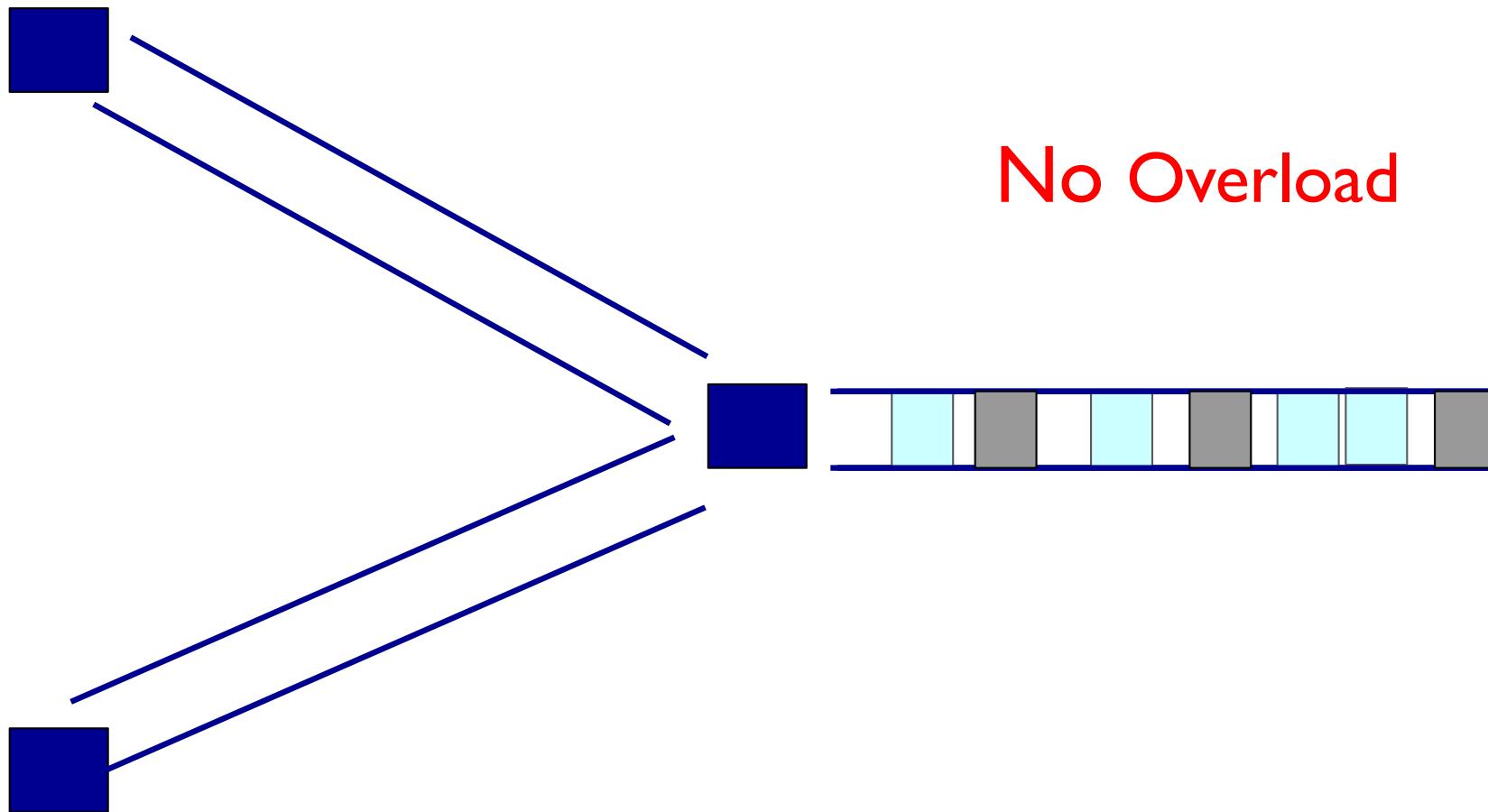


# Statistical multiplexing: pipe view

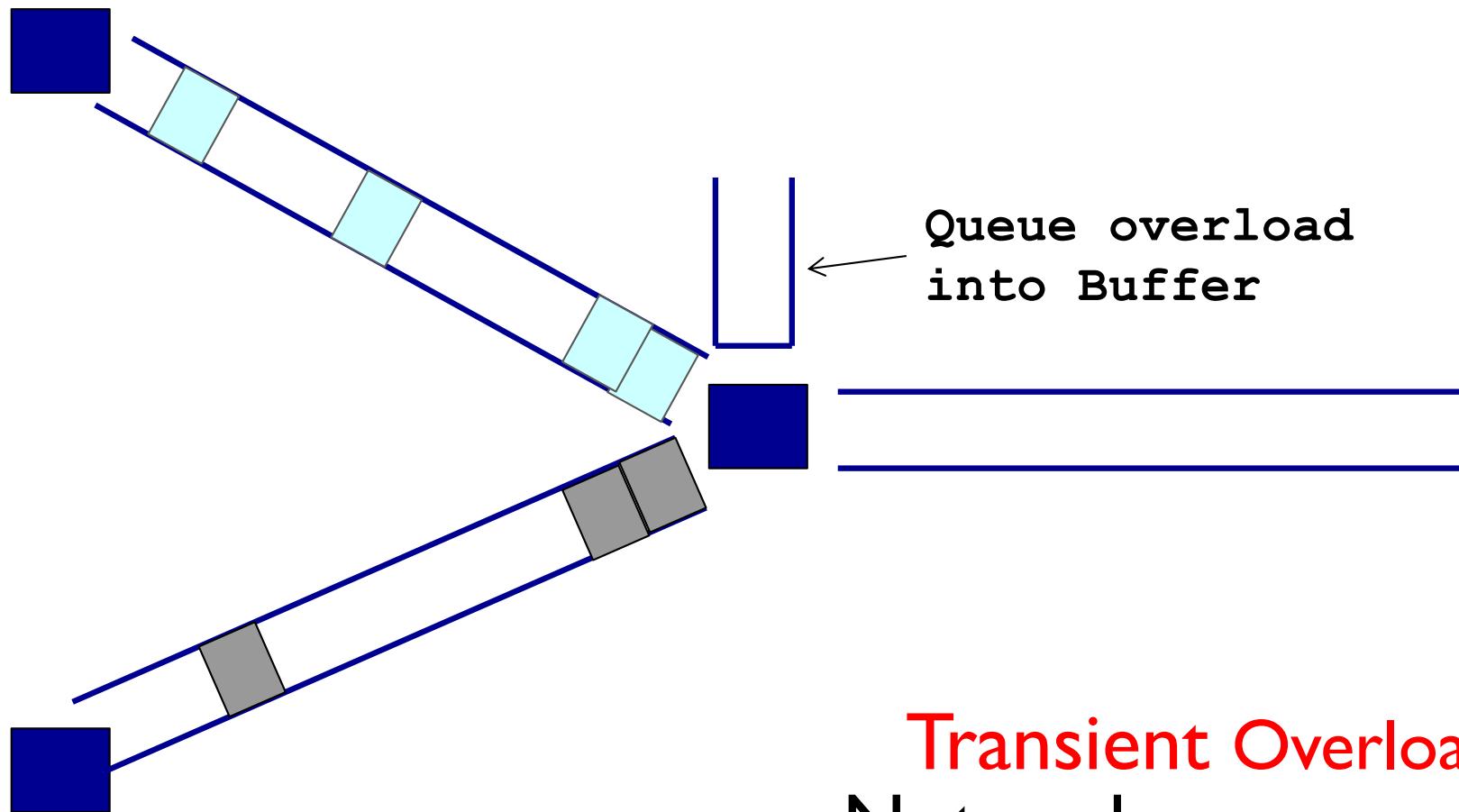
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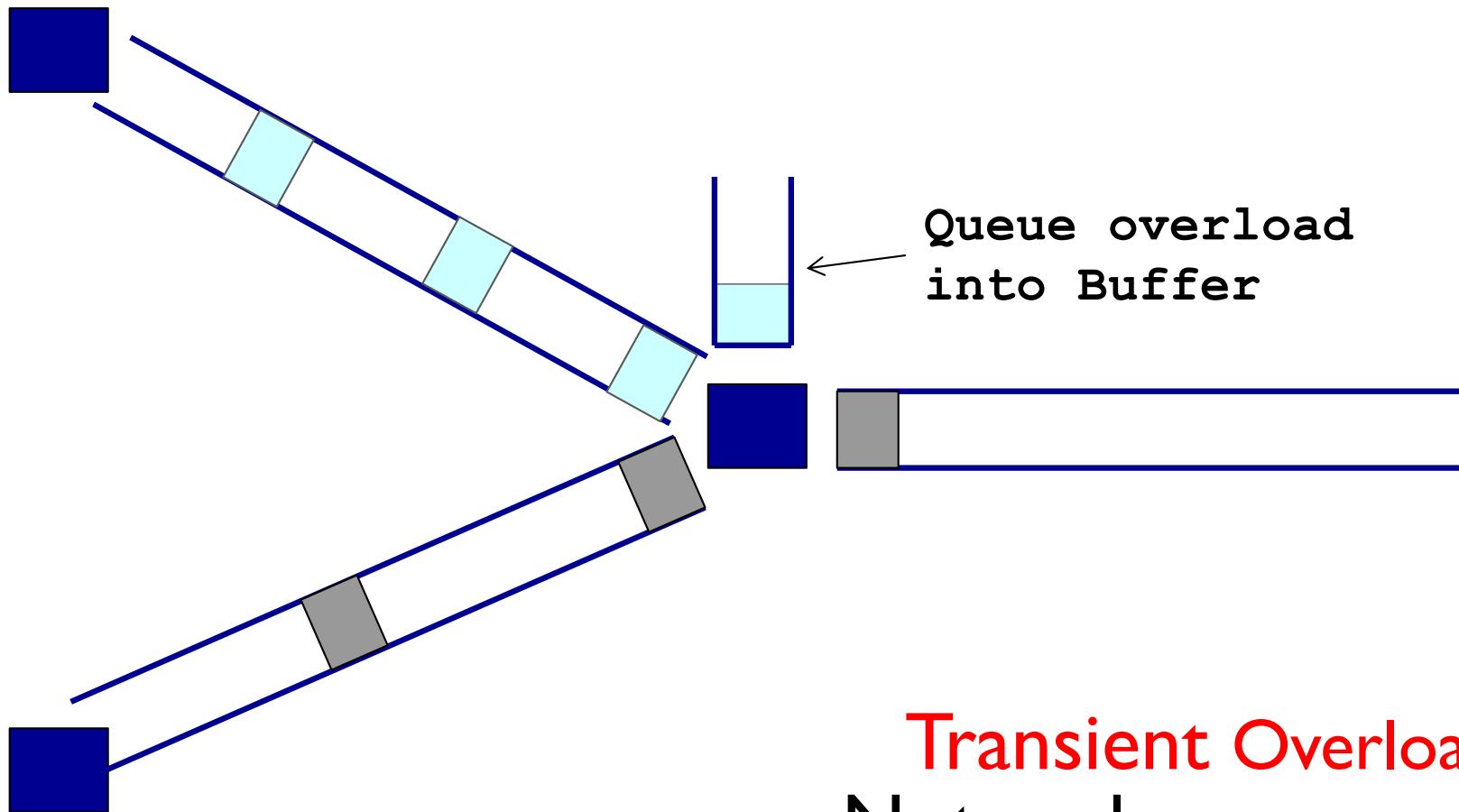
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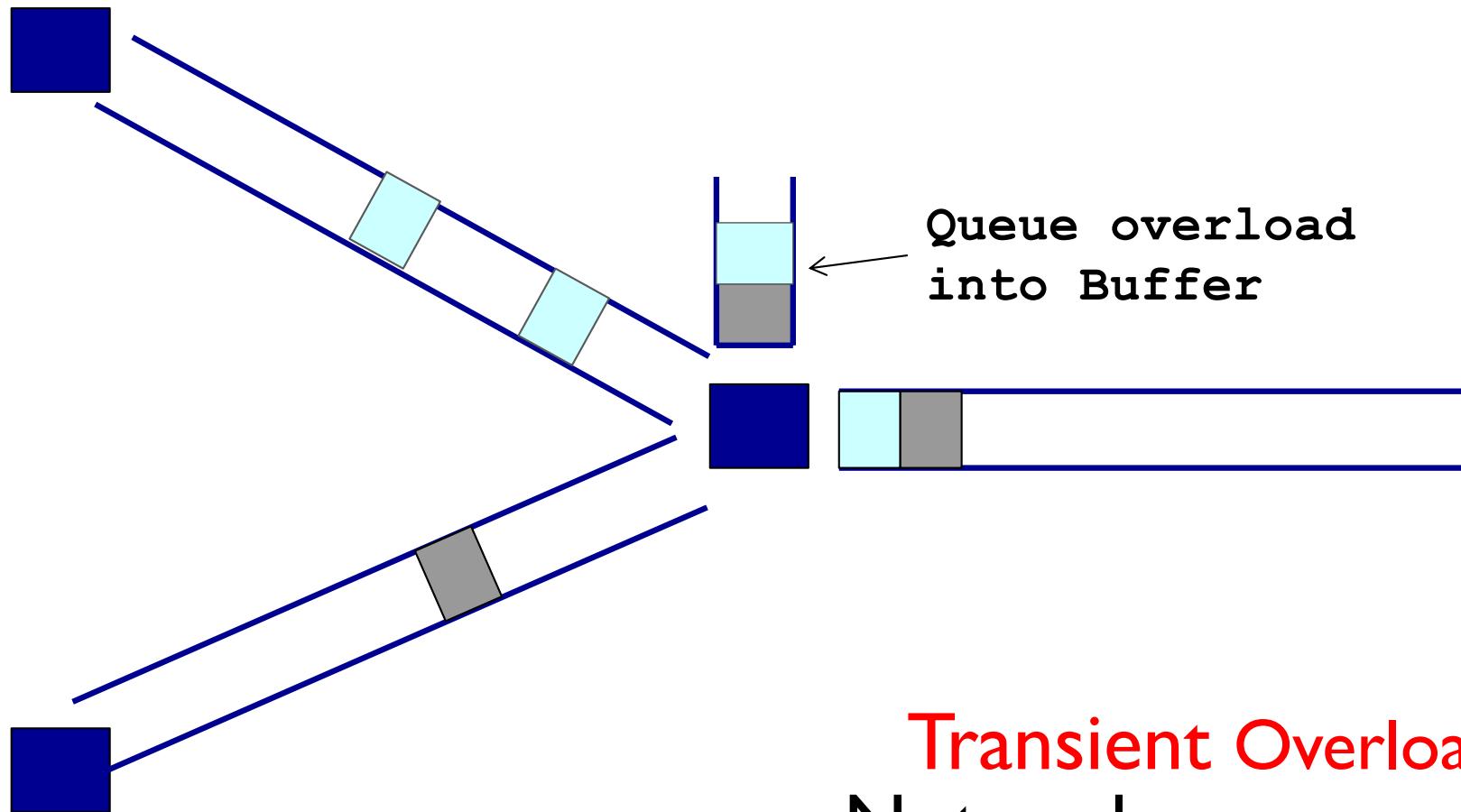
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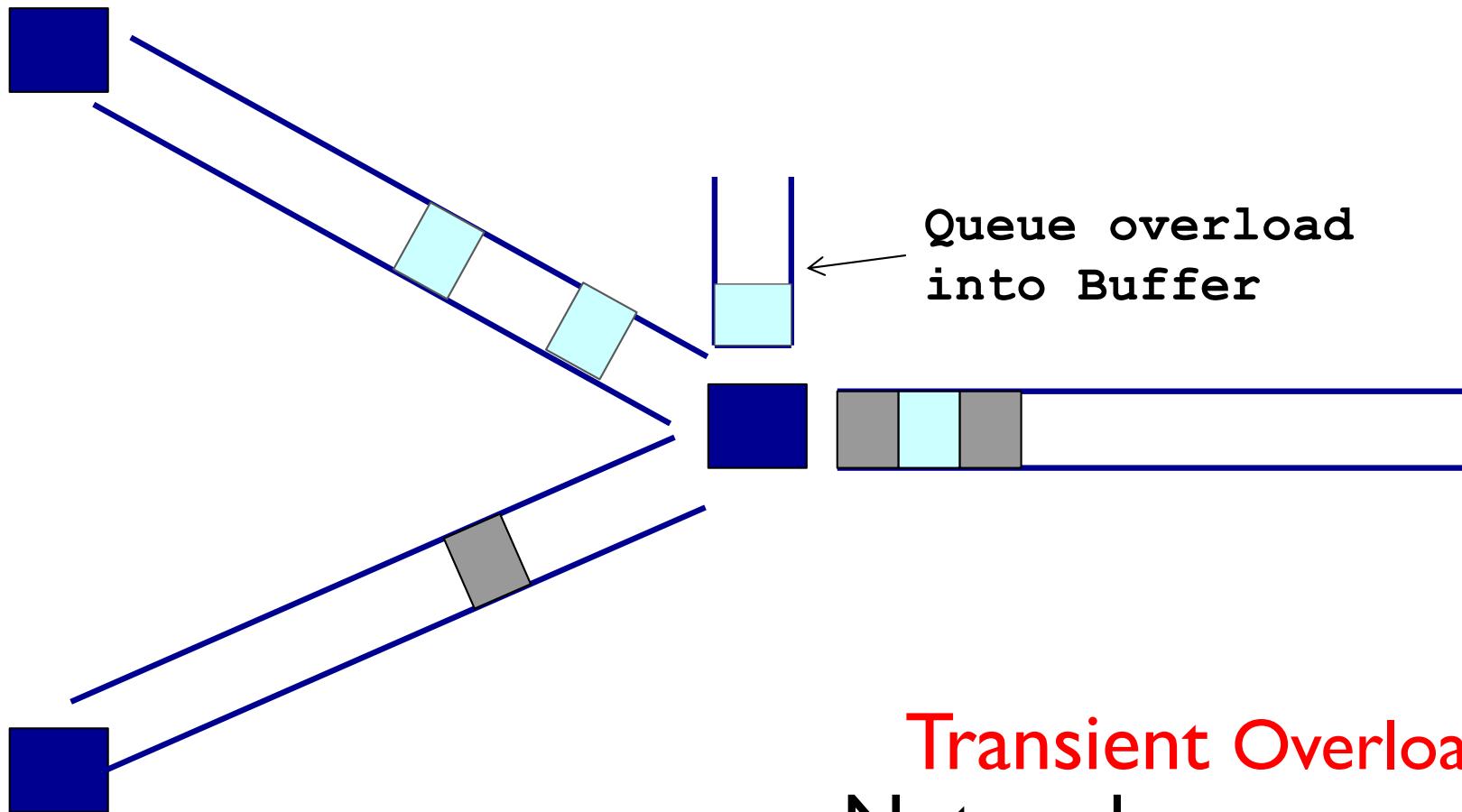
# Statistical multiplexing: pipe view



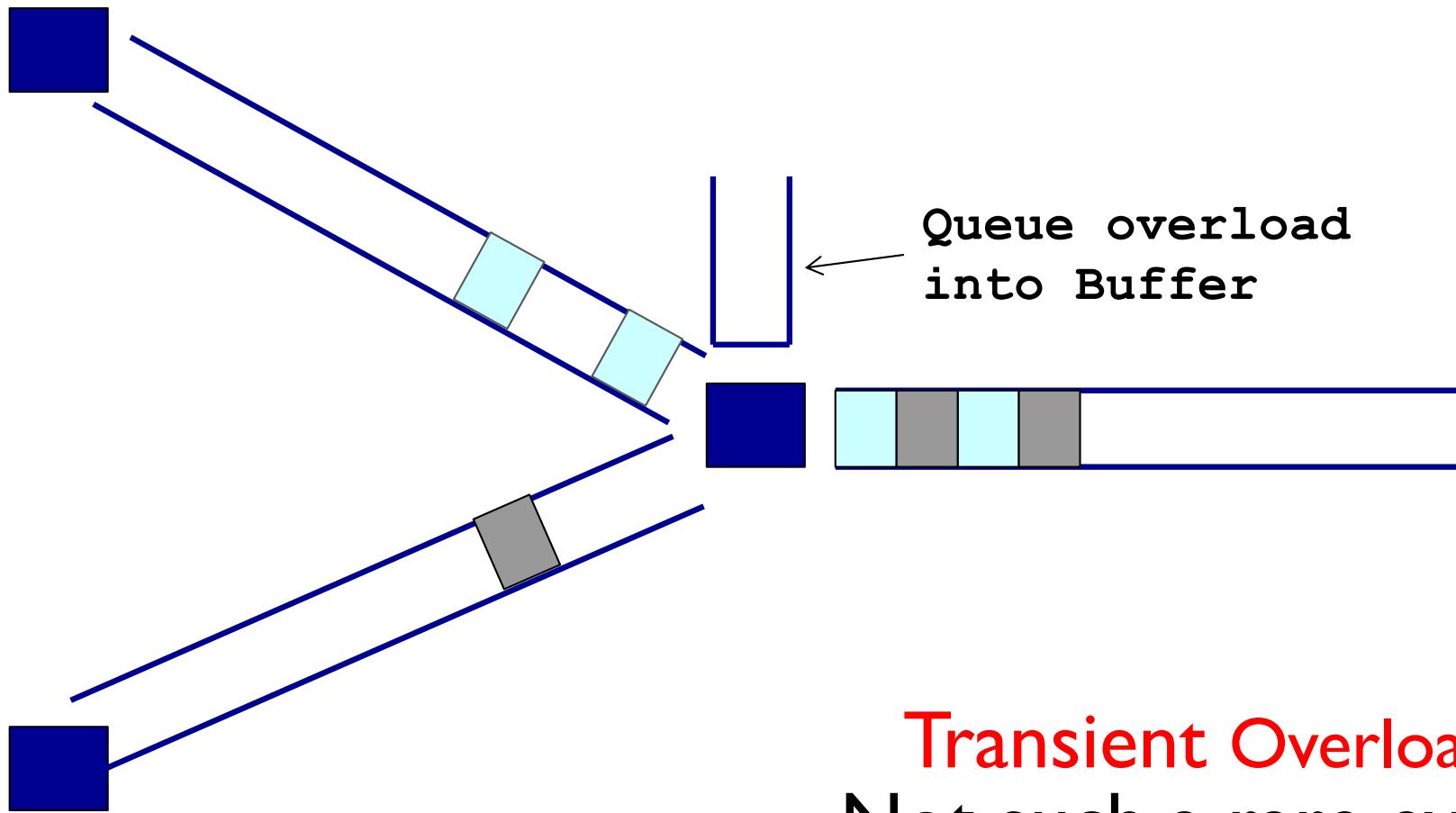
# Statistical multiplexing: pipe view



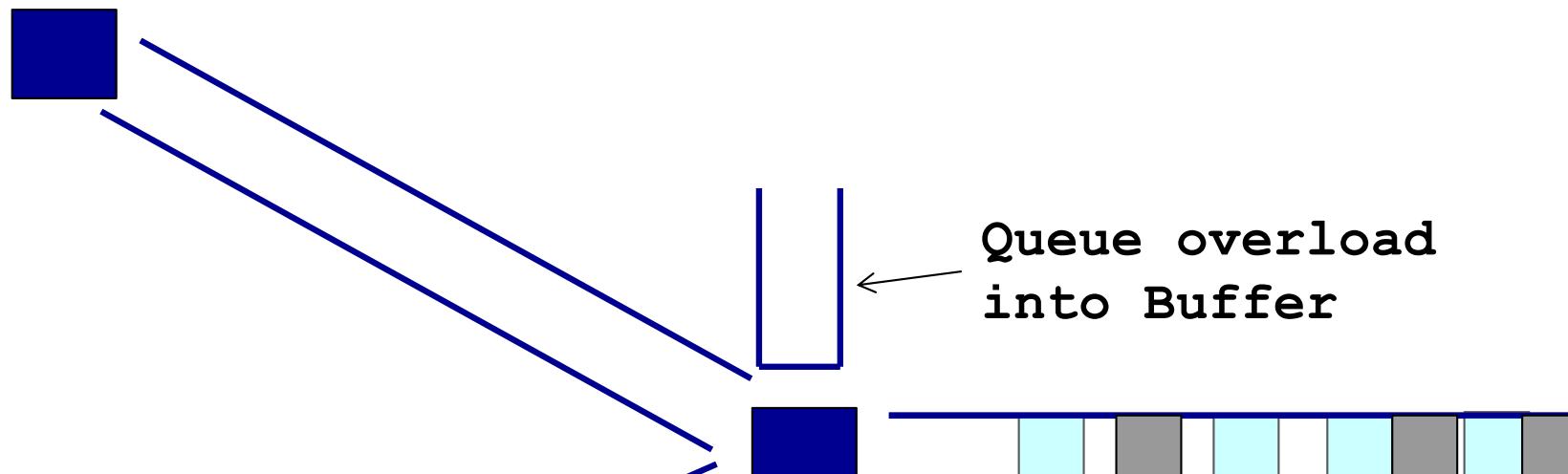
# Statistical multiplexing: pipe view



# Statistical multiplexing: pipe view

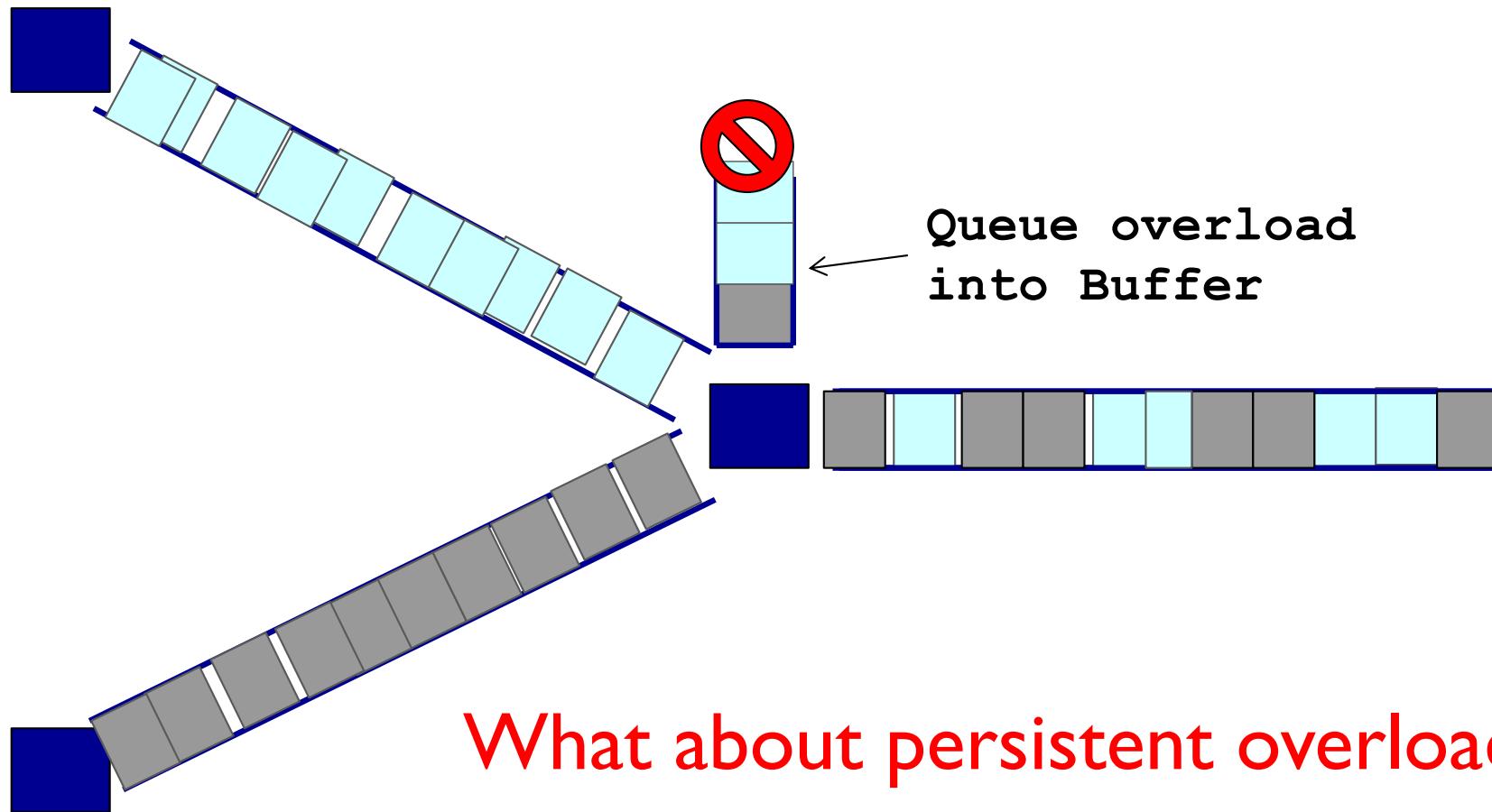


# Statistical multiplexing: pipe view



Buffer absorbs transient bursts

# Statistical multiplexing: pipe view





## **Quiz: What are the pros and cons of packet switching? Let's discuss ..**

- ❖ Pros:

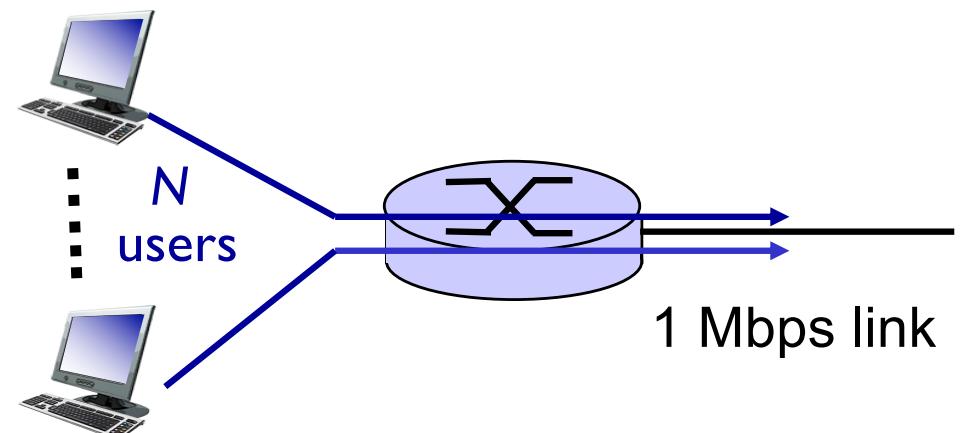
- ❖ Cons:

# 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**

# Probability Basics

In general, if the random variable  $X$  follows the binomial distribution with parameters  $n \in \mathbb{N}$  and  $p \in [0,1]$ , we write  $X \sim B(n, p)$ . The probability of getting exactly  $k$  successes in  $n$  trials is given by the **probability mass function**:

$$f(k, n, p) = \Pr(k; n, p) = \Pr(X = k) = \binom{n}{k} p^k (1 - p)^{n-k}$$

for  $k = 0, 1, 2, \dots, n$ , where

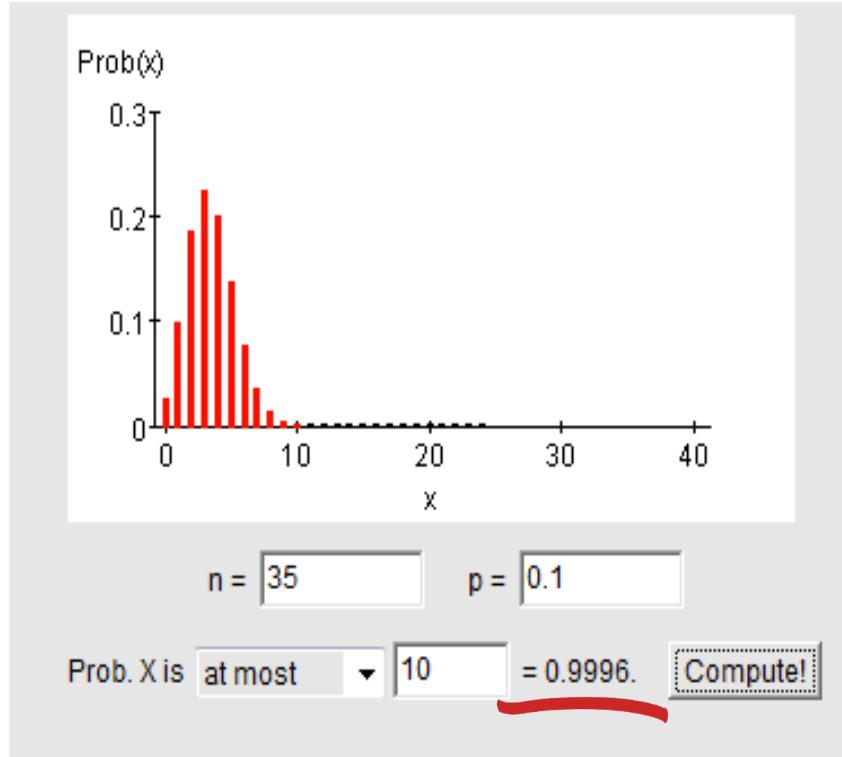
$$\binom{n}{k} = \frac{n!}{k!(n - k)!}$$

The **cumulative distribution function** can be expressed as:

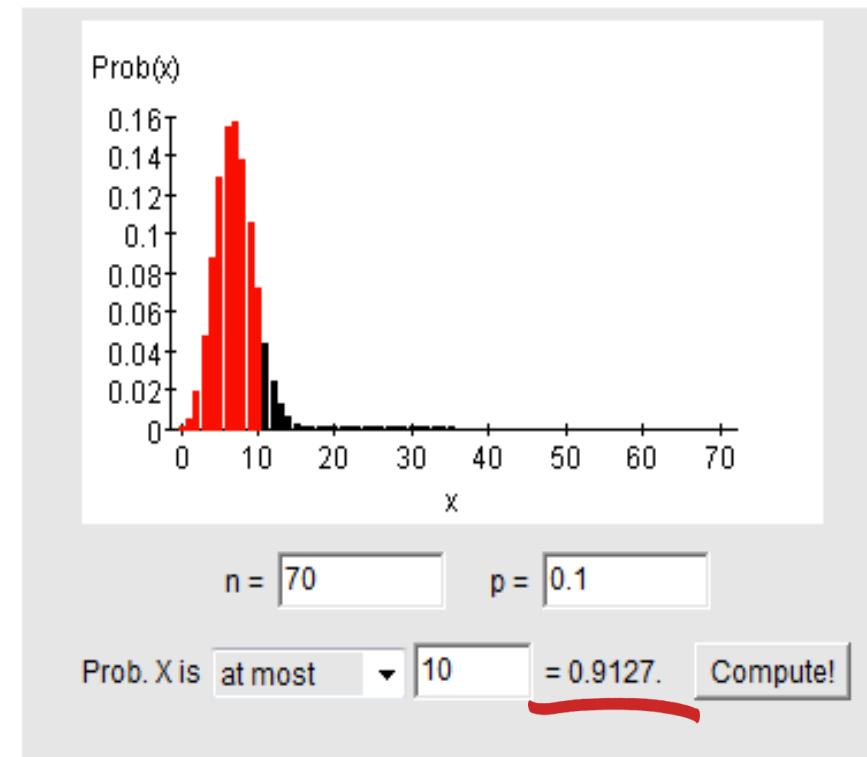
$$F(k; n, p) = \Pr(X \leq k) = \sum_{i=0}^{\lfloor k \rfloor} \binom{n}{i} p^i (1 - p)^{n-i}$$

# Statistical Multiplexing Gain (SMG)

Binomial Calculator



Binomial Calculator



$$SMG: 35/10=3.5$$

$$SMG: 70/10=7$$

# Packet switching versus circuit switching

is packet switching a “slam dunk winner?”

- ❖ great for bursty data
  - resource sharing
  - simpler, no call setup
- ❖ excessive congestion possible: packet delay and loss
  - protocols needed for reliable data transfer, congestion control
- ❖ Q: How to provide circuit-like behavior?
  - bandwidth guarantees needed for audio/video apps
  - still an unsolved problem

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



## Quiz: Switching

In \_\_\_\_\_ resources are allocated on demand

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

Open a browser and type: [www.zeetings.com/salil](http://www.zeetings.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

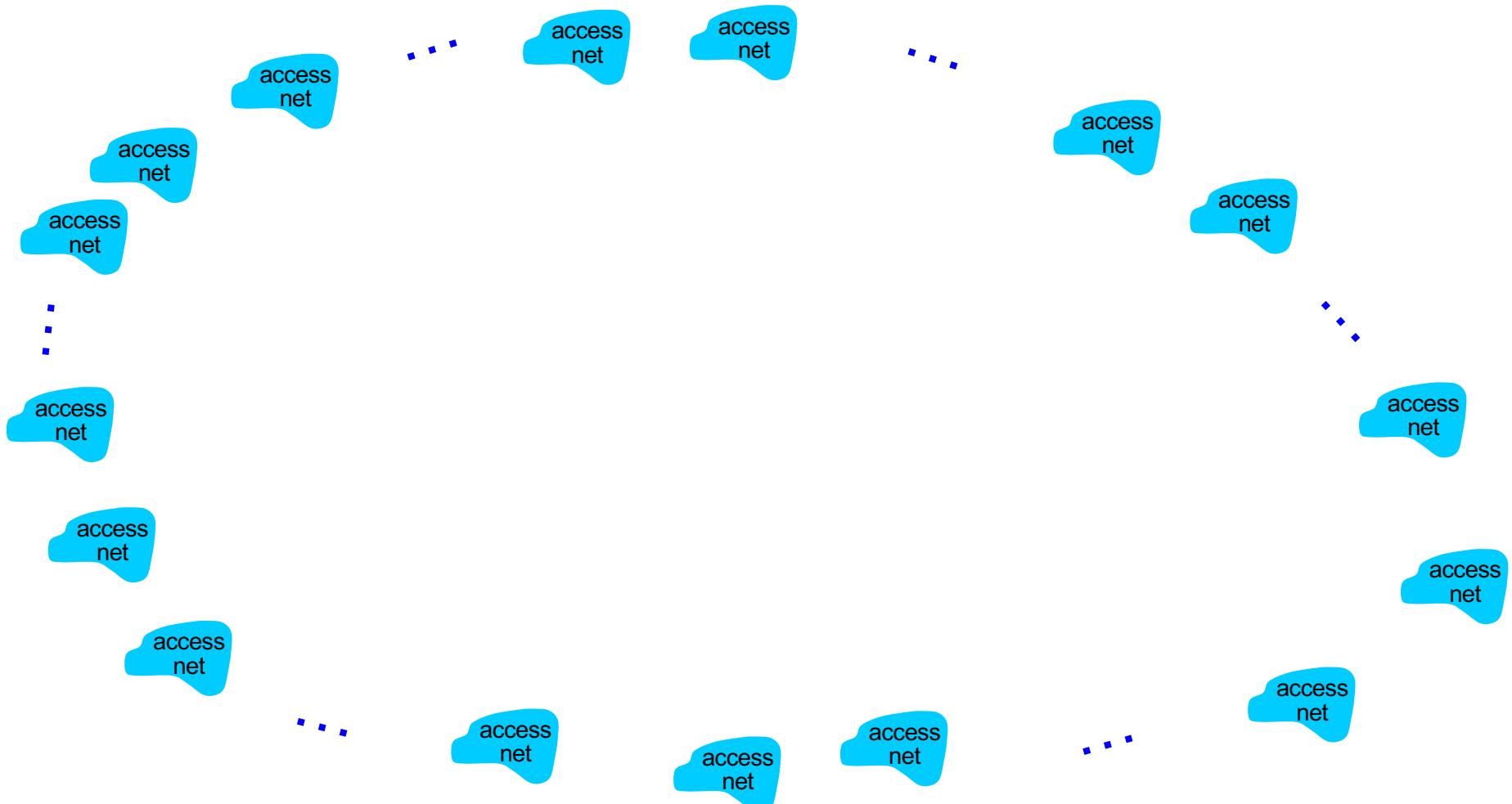
- A. is the same
- B. is independent
- C. is always different from

# Internet structure: network of networks

- ❖ End systems connect to Internet via **access ISPs** (Internet Service Providers)
  - Residential, company and university ISPs
- ❖ Access ISPs in turn must be interconnected.
  - ❖ So that any two hosts can send packets to each other
- ❖ Resulting network of networks is **very complex**
  - ❖ Evolution was driven by **economics** and **national policies**
- ❖ Let's take a stepwise approach to describe current Internet structure

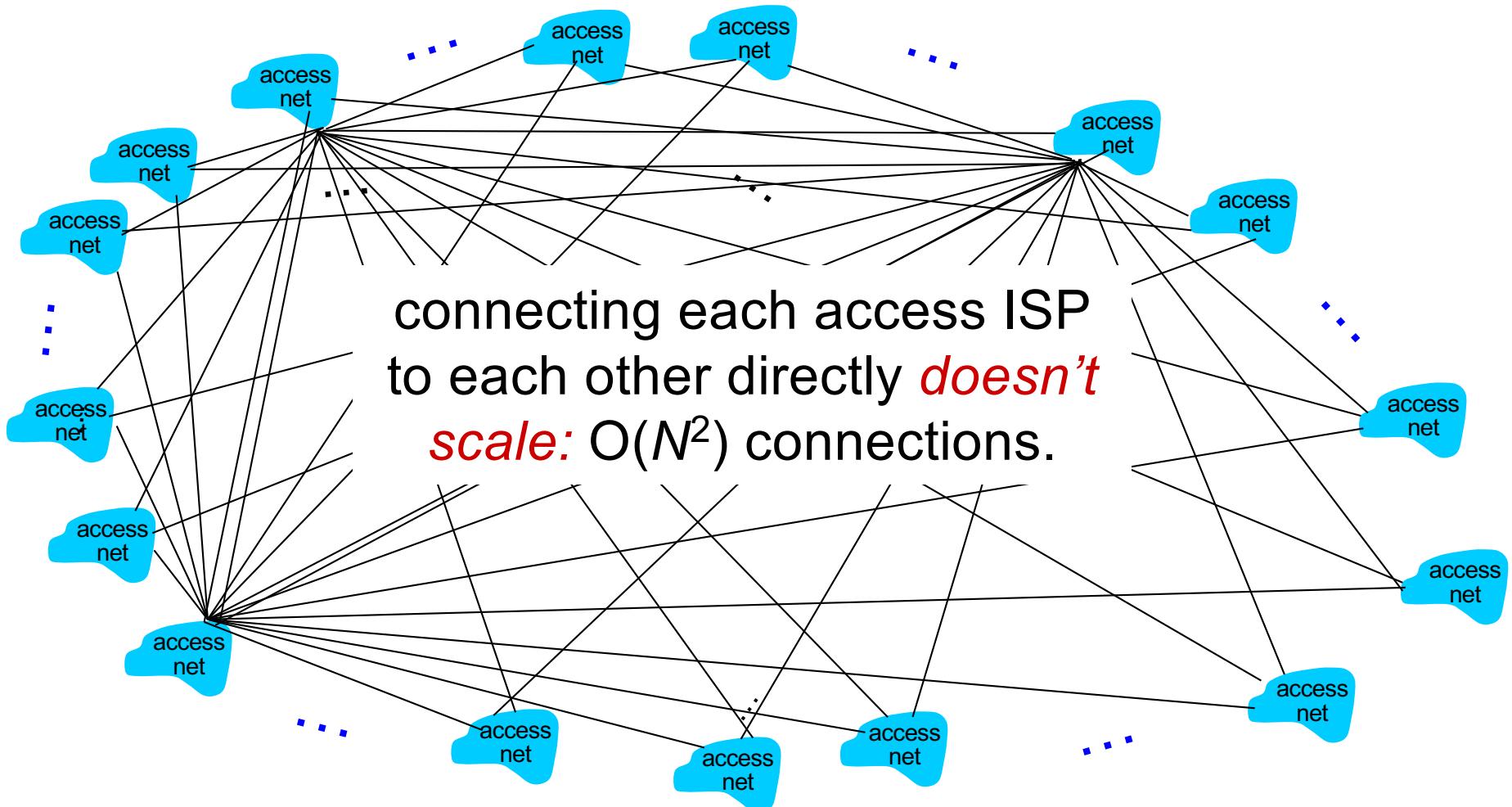
# Internet structure: network of networks

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



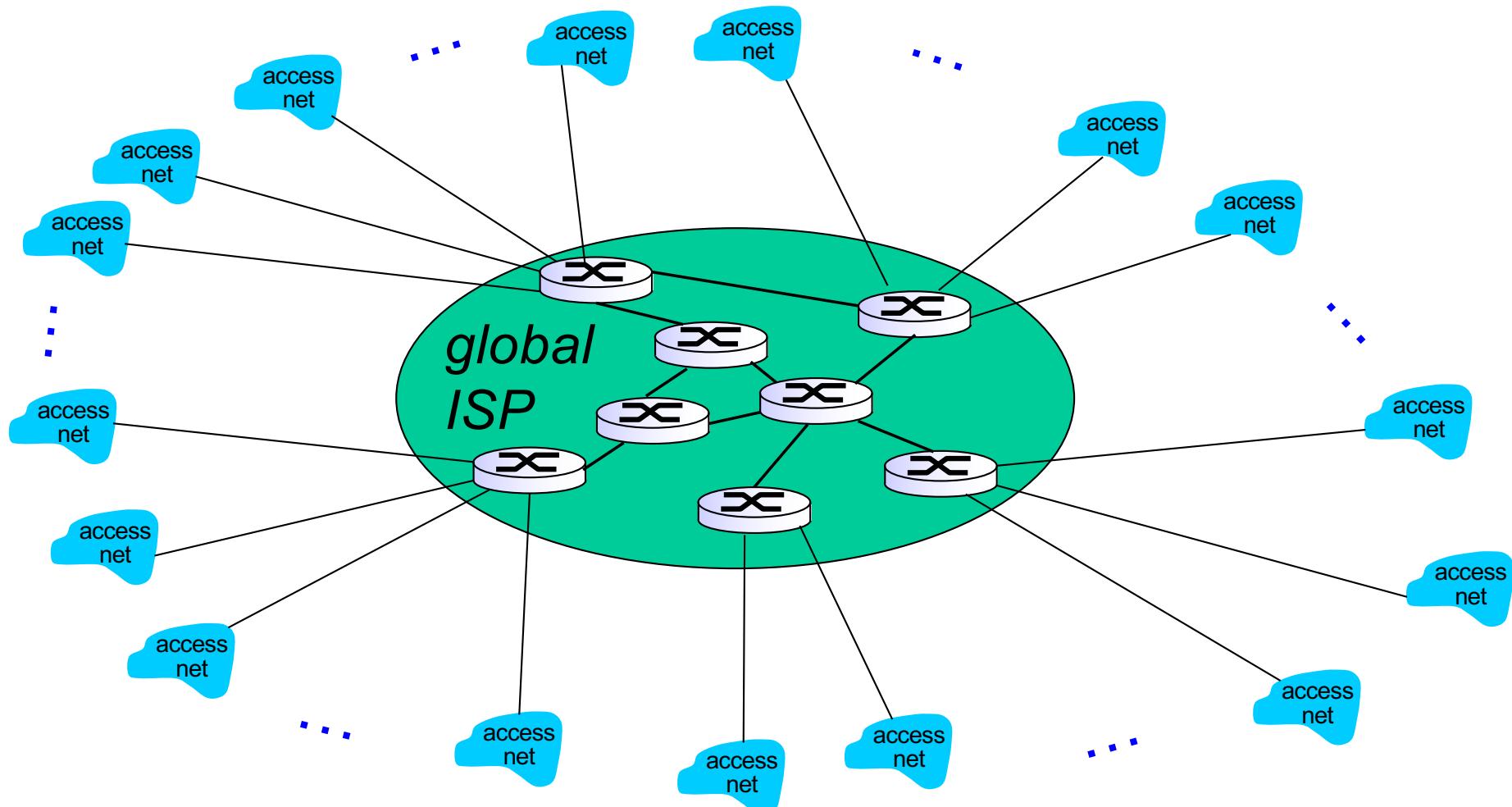
# Internet structure: network of networks

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



# Internet structure: network of networks

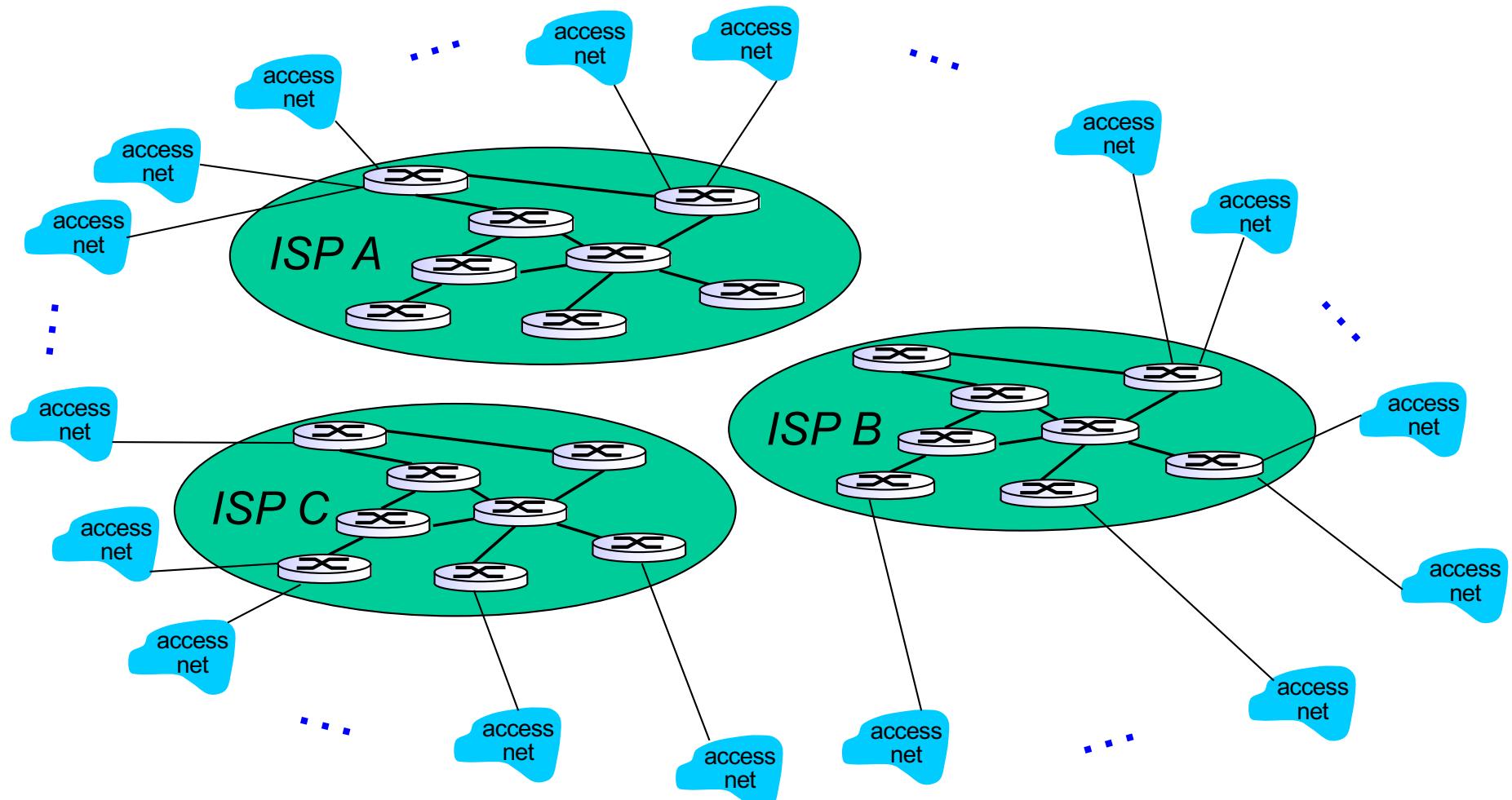
*Option: connect each access ISP to a global transit ISP? Customer and provider ISPs have economic agreement.*



# Internet structure: network of networks

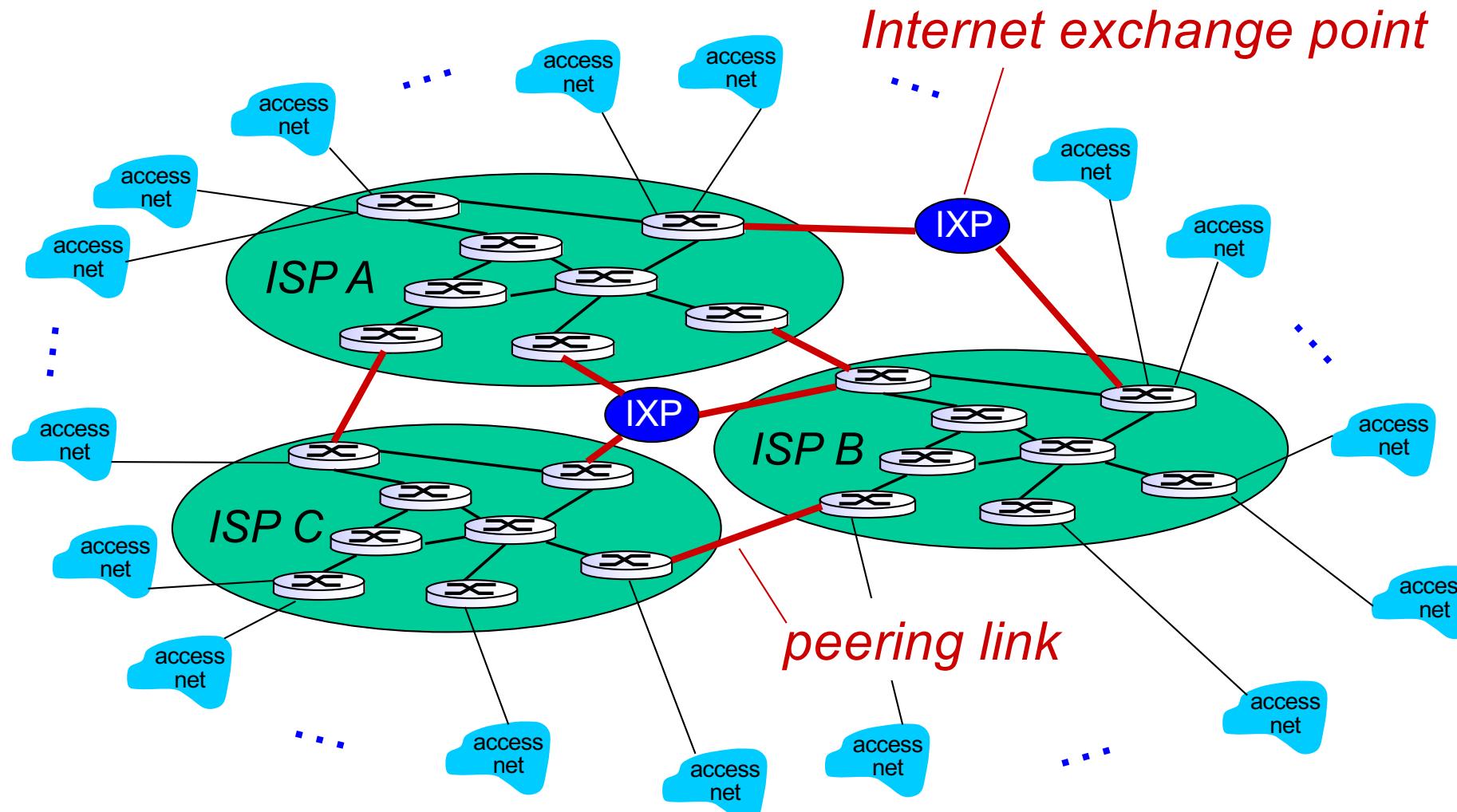
But if one global ISP is viable business, there will be competitors

....



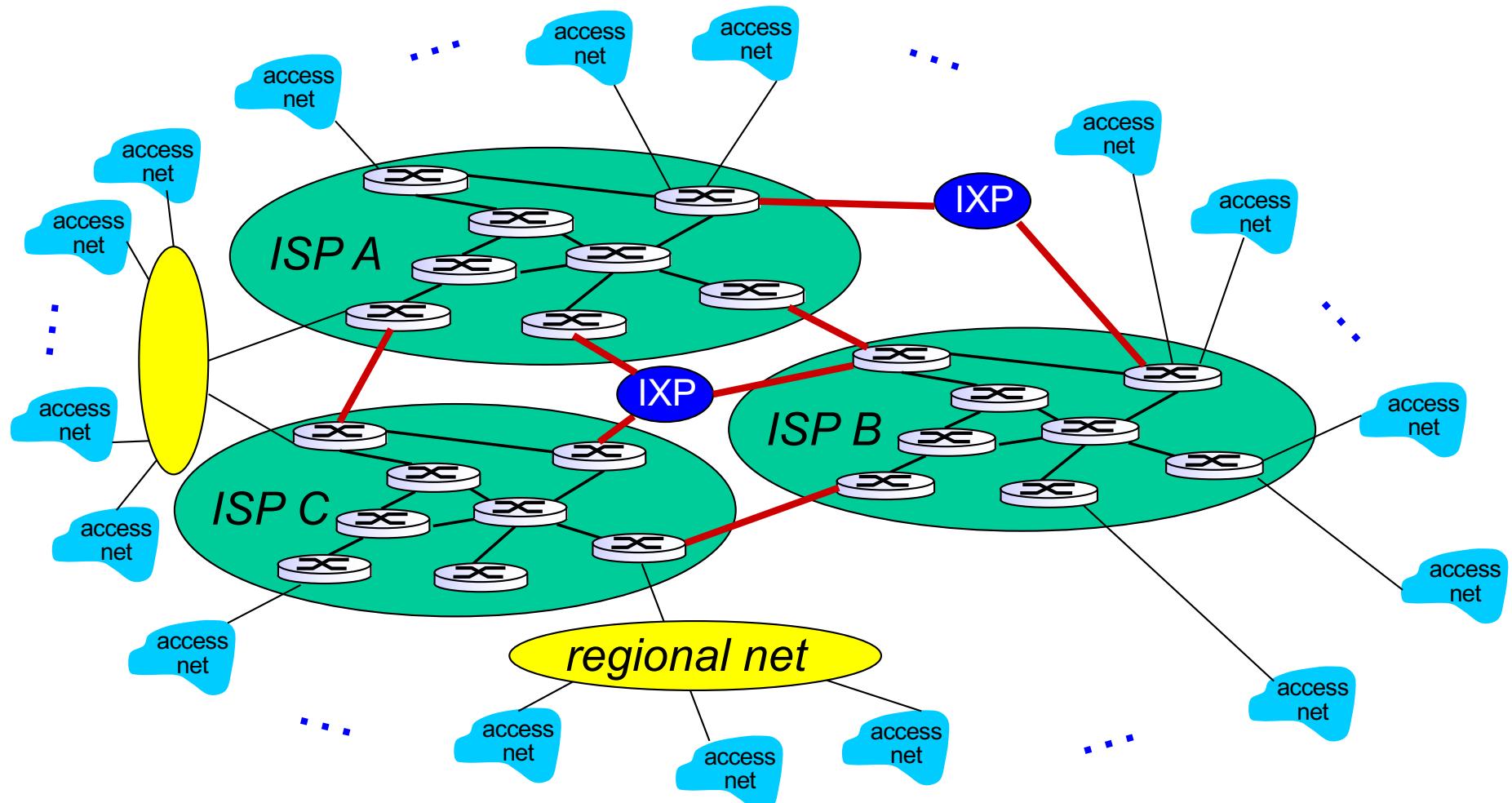
# Internet structure: network of networks

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



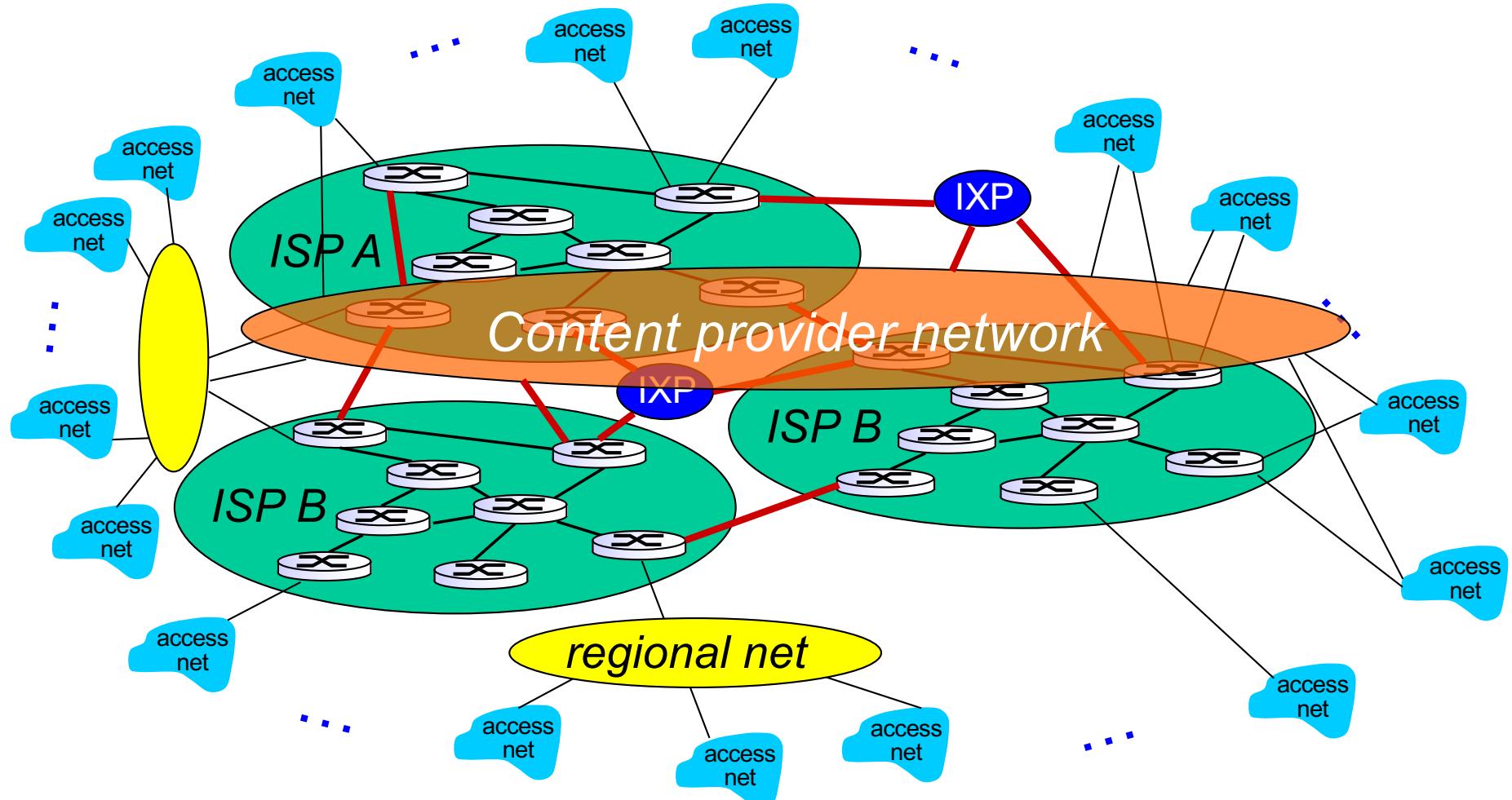
# Internet structure: network of networks

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

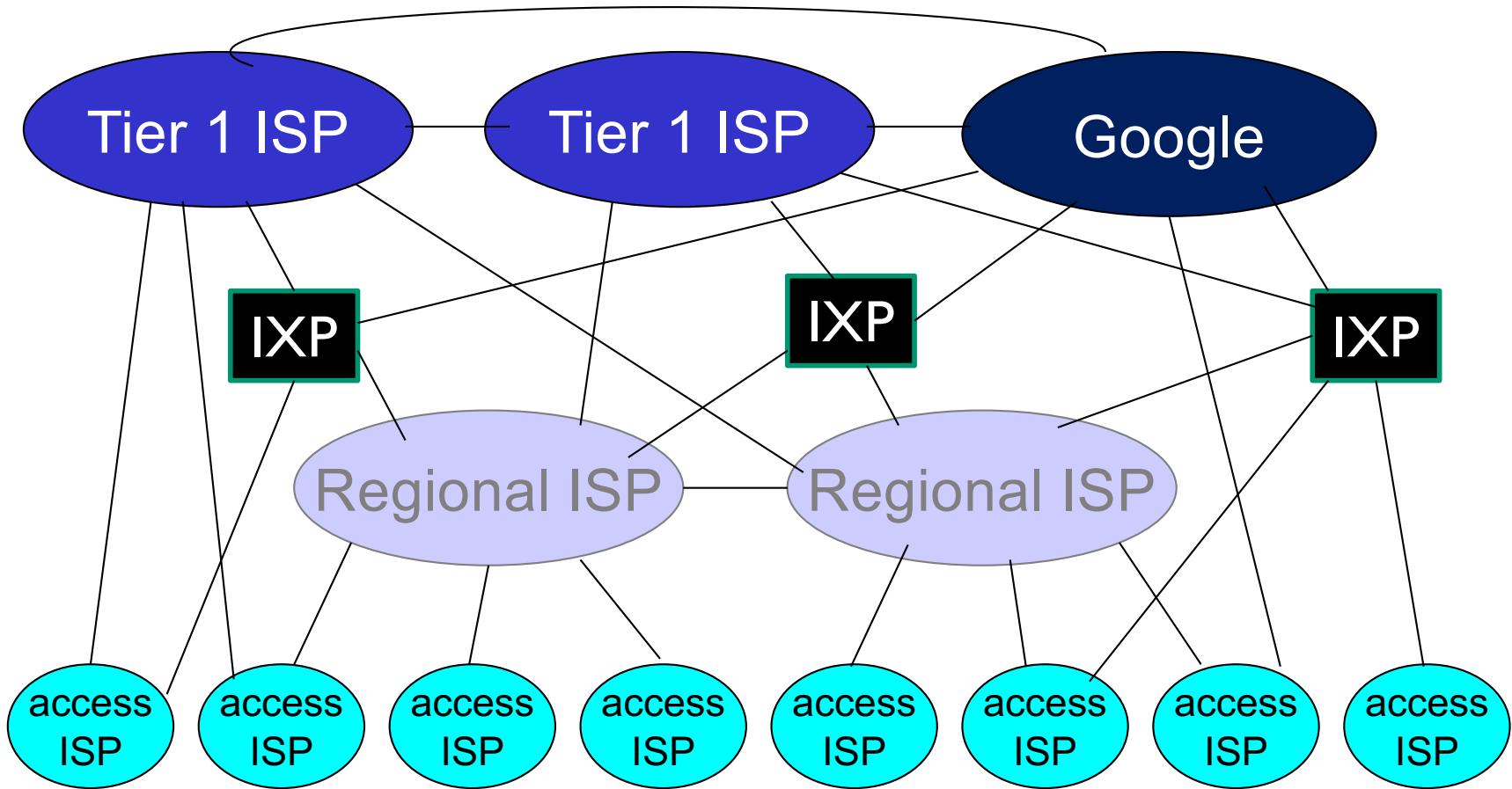


# Internet structure: network of networks

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



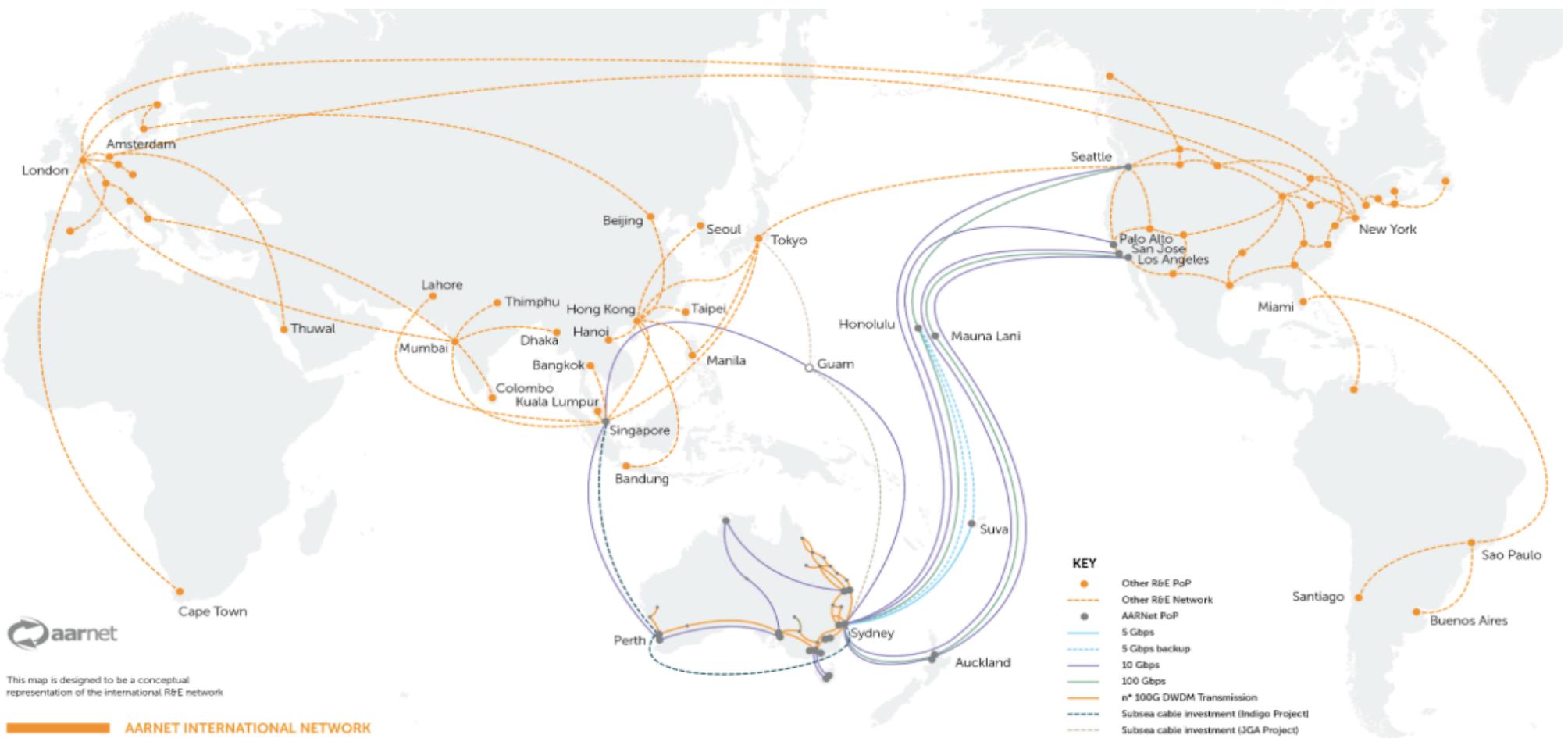
# Internet structure: network of networks



- ❖ at center: small # of well-connected large networks
  - “tier-1” commercial ISPs (e.g., Level 3, Sprint, AT&T, NTT, Orange, Deutsche Telekom), national & international coverage
  - content provider network (e.g., Google): private network that connects its data centers to Internet, often bypassing tier-1, regional ISPs

# AARNET: Australia's Academic and Research Network

- ❖ <https://www.aarnet.edu.au/>
- ❖ <https://www.submarinecablemap.com>



# I. Introduction: roadmap

I.1 what *is* the Internet?

I.2 network edge

- end systems, access networks, links

I.3 network core

- packet switching, circuit switching, network structure

I.4 delay, loss, throughput in networks

I.5 protocol layers, service models

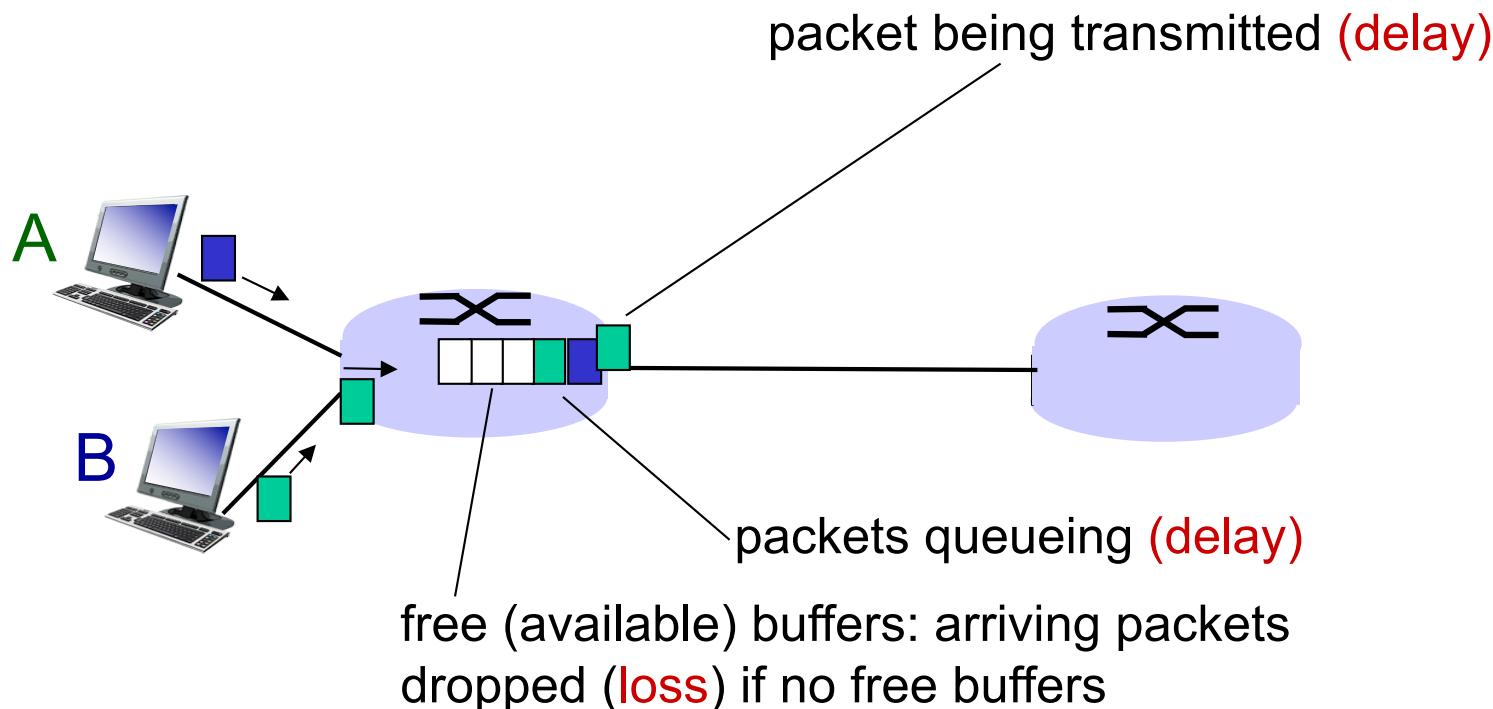
I.6 networks under attack: security

I.7 history

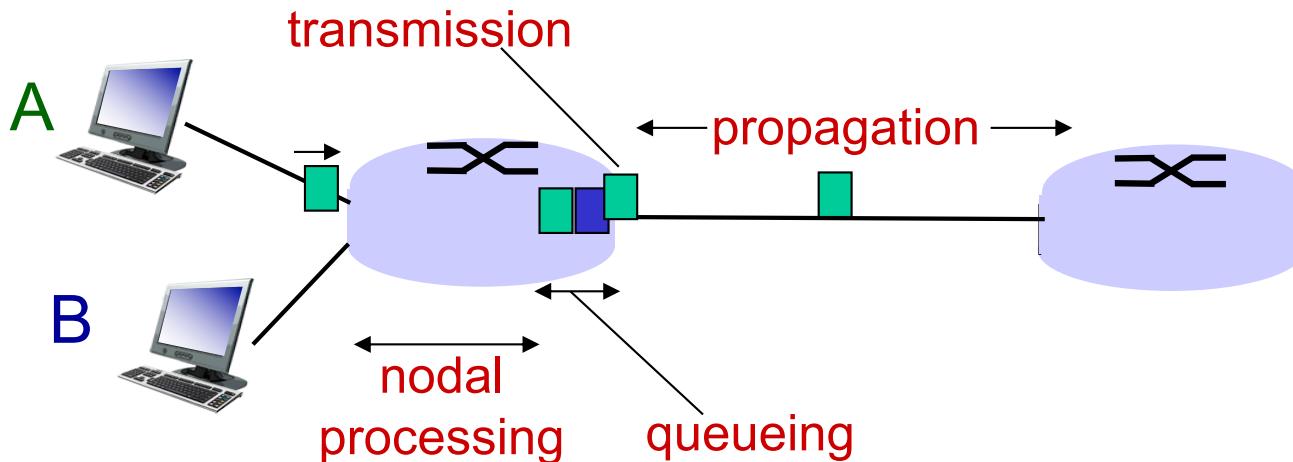
# How do loss and delay occur?

Packets queue in router buffers

- Packet arrival rate to link (temporarily) exceeds output link capacity
- Packets queue, wait for turn



# Four sources of packet delay



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

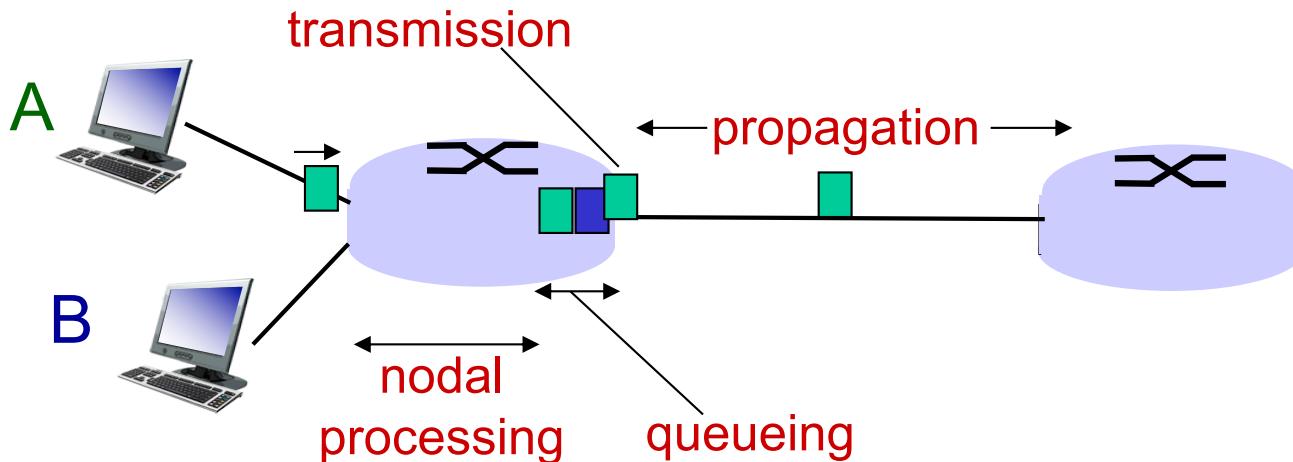
$d_{\text{proc}}$ : nodal processing

- 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

# Four sources of packet delay



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

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

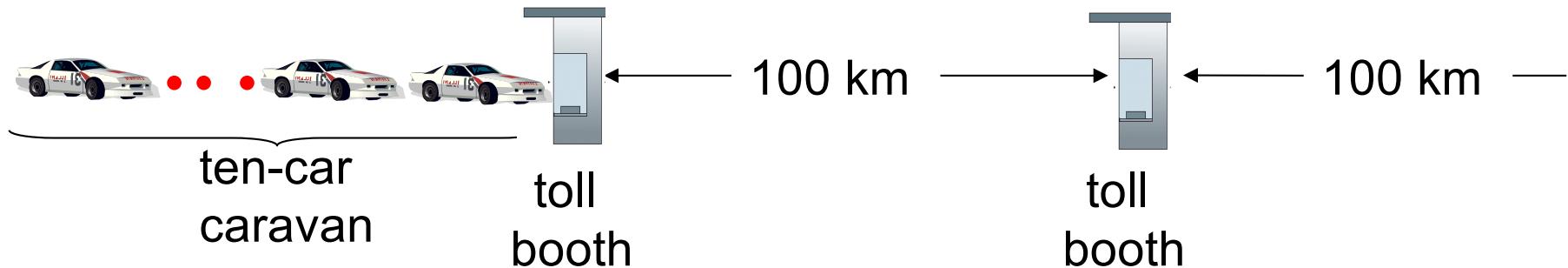
- $L$ : packet length (bits)
- $R$ : link bandwidth ( $\text{bps}$ )
- $d_{\text{trans}} = L/R$

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

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

- $d$ : length of physical link
- $s$ : propagation speed in medium ( $\sim 2 \times 10^8 \text{ m/sec}$ )
- $d_{\text{prop}} = d/s$

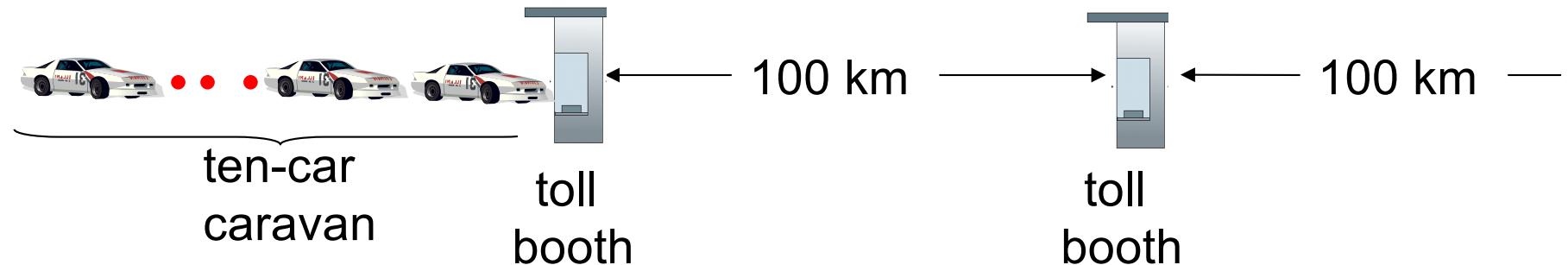
# Caravan analogy



- Car ~bit; Caravan ~ packet
- Cars “propagate” at 100 km/hr
- Toll booth takes 12 sec to service car (bit transmission time)
- Q: How long until caravan is lined up before 2nd toll booth?

- time to “push” entire caravan through toll booth onto highway =  $12*10 = 120$  sec
- time for last car to propagate from 1st to 2nd toll both:  
 $100\text{km}/(100\text{km/hr}) = 1\text{ hr}$
- A: 62 minutes

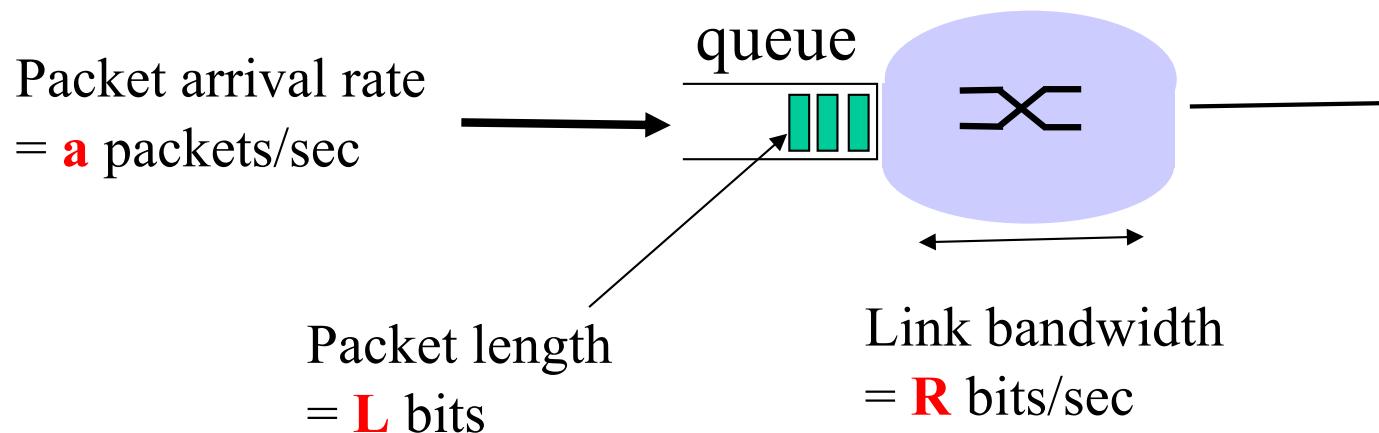
# Caravan analogy (more)



- 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, 1st car arrives at second booth; three cars still at 1st booth.

Animation: <http://www.ccs-labs.org/teaching/rn/animations/propagation/>

# Queueing delay (more insight)

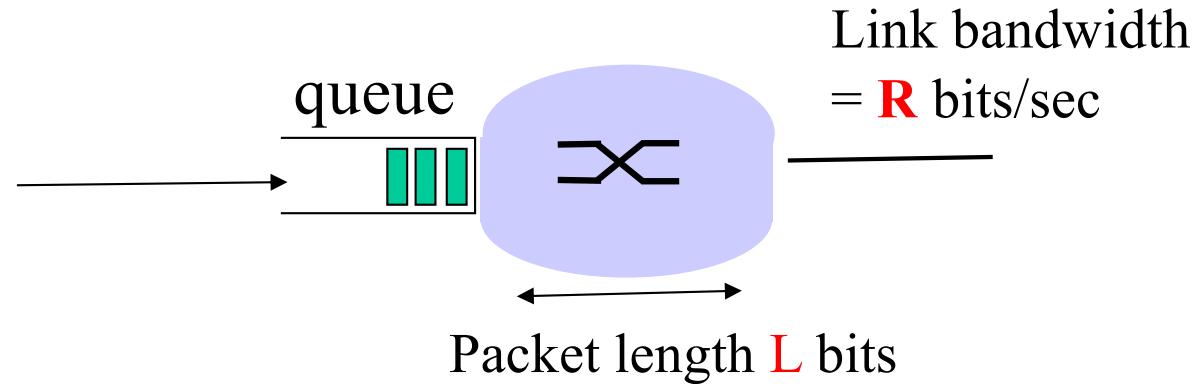


- ❖ Every second:  $aL$  bits arrive to queue
- ❖ Every second:  $R$  bits leave the router
- ❖ Question: what happens if  $aL > R$  ?
- ❖ Answer: queue will fill up, and packets will get dropped!!

$aL/R$  is called traffic intensity

# Queueing delay: illustration

1 packet arrives  
every  $L/R$  seconds



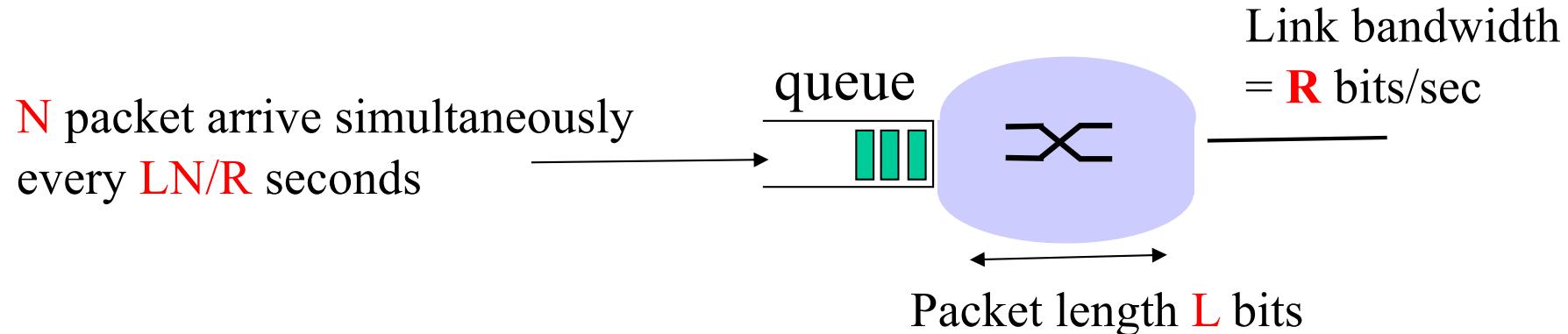
**Arrival rate:**  $a = 1/(L/R) = R/L$  (packet/second)



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

**Average queueing delay** = 0  
(queue is initially empty)

# Queueing delay: illustration



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

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

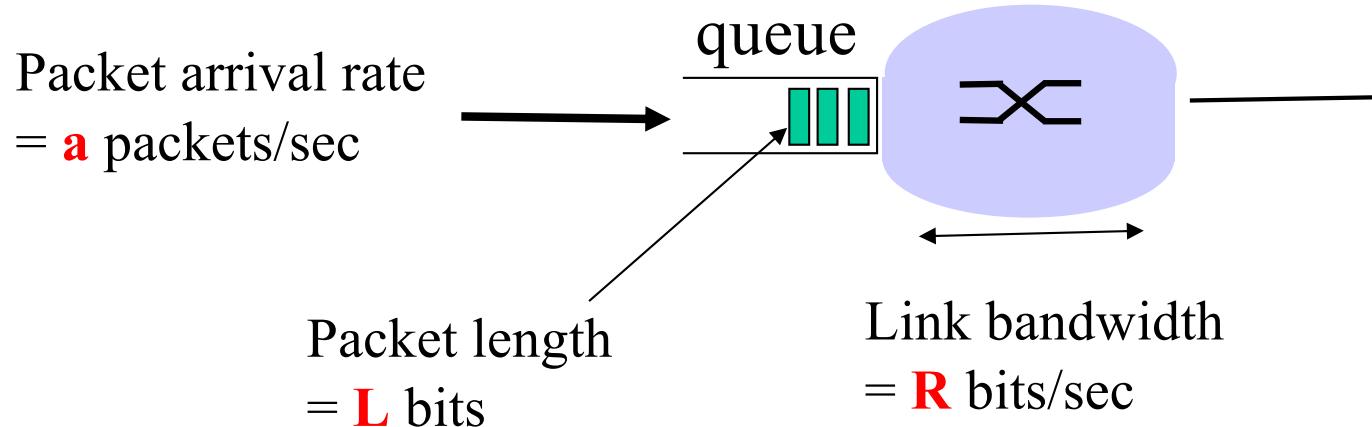


Average queueing delay (queue is empty at time 0) ?

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

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

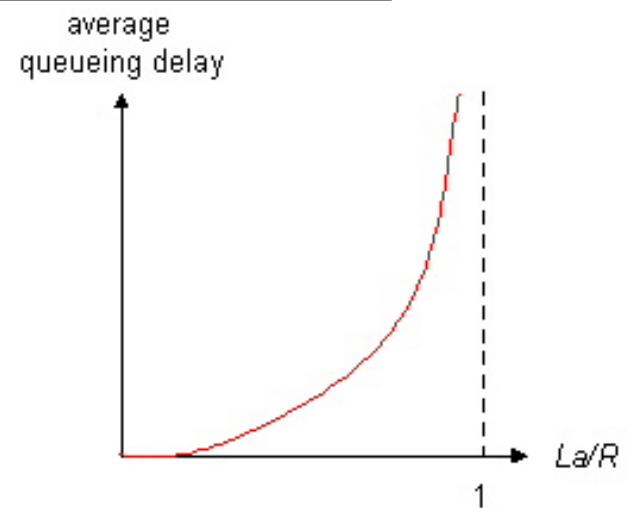
# Queueing delay: behaviour



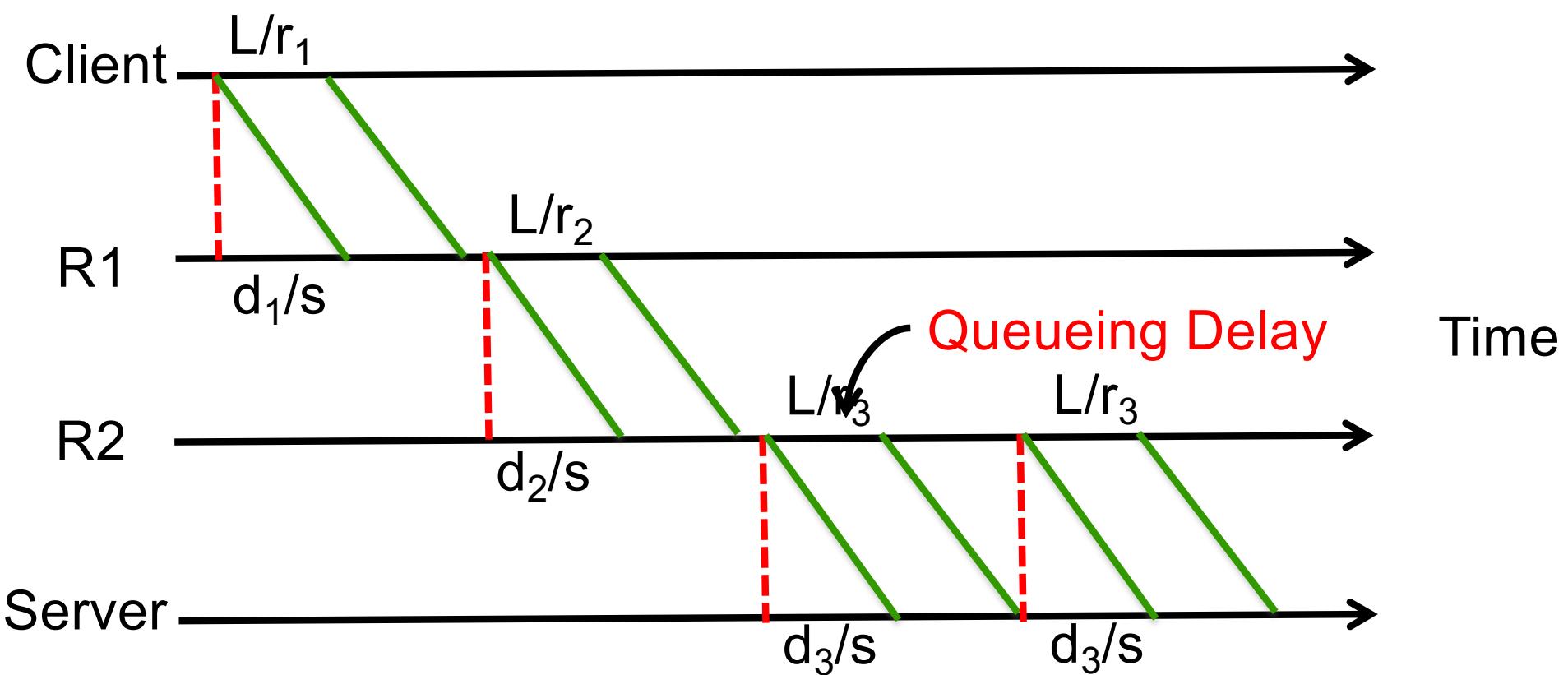
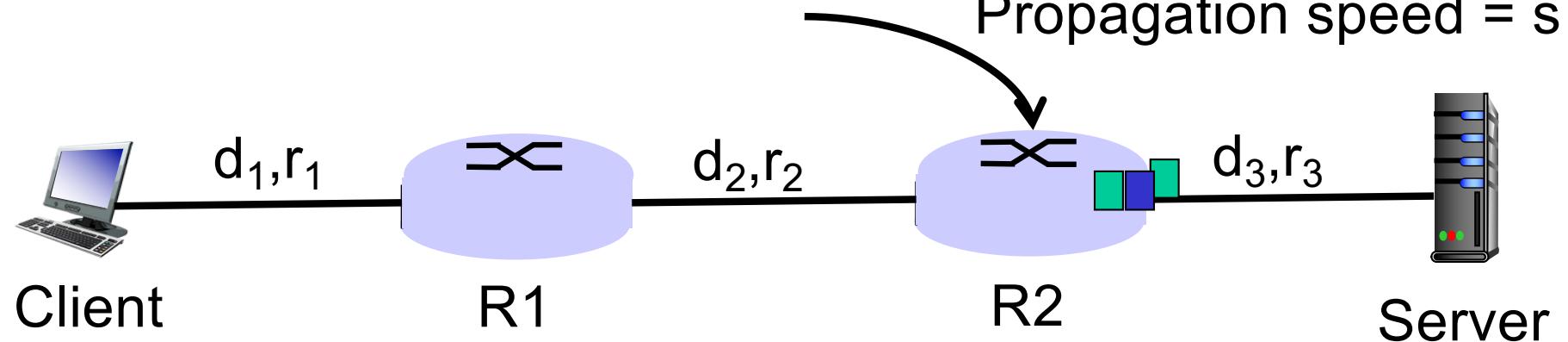
Interactive Java Applet:

<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!)

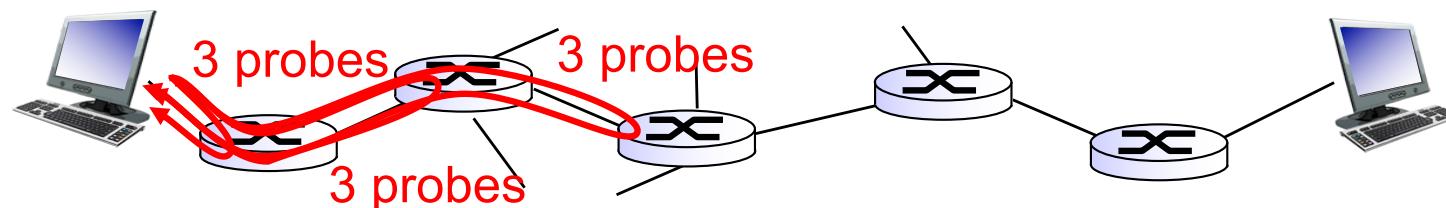


# End to End Delay



# “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
  - router  $i$  will return packets to sender
  - sender times interval between transmission and reply.



# “Real” Internet delays, 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	***	*	means no response (probe lost, router not replying)	
19	fantasia.eurecom.fr (193.55.113.142)	132 ms	128 ms	136 ms

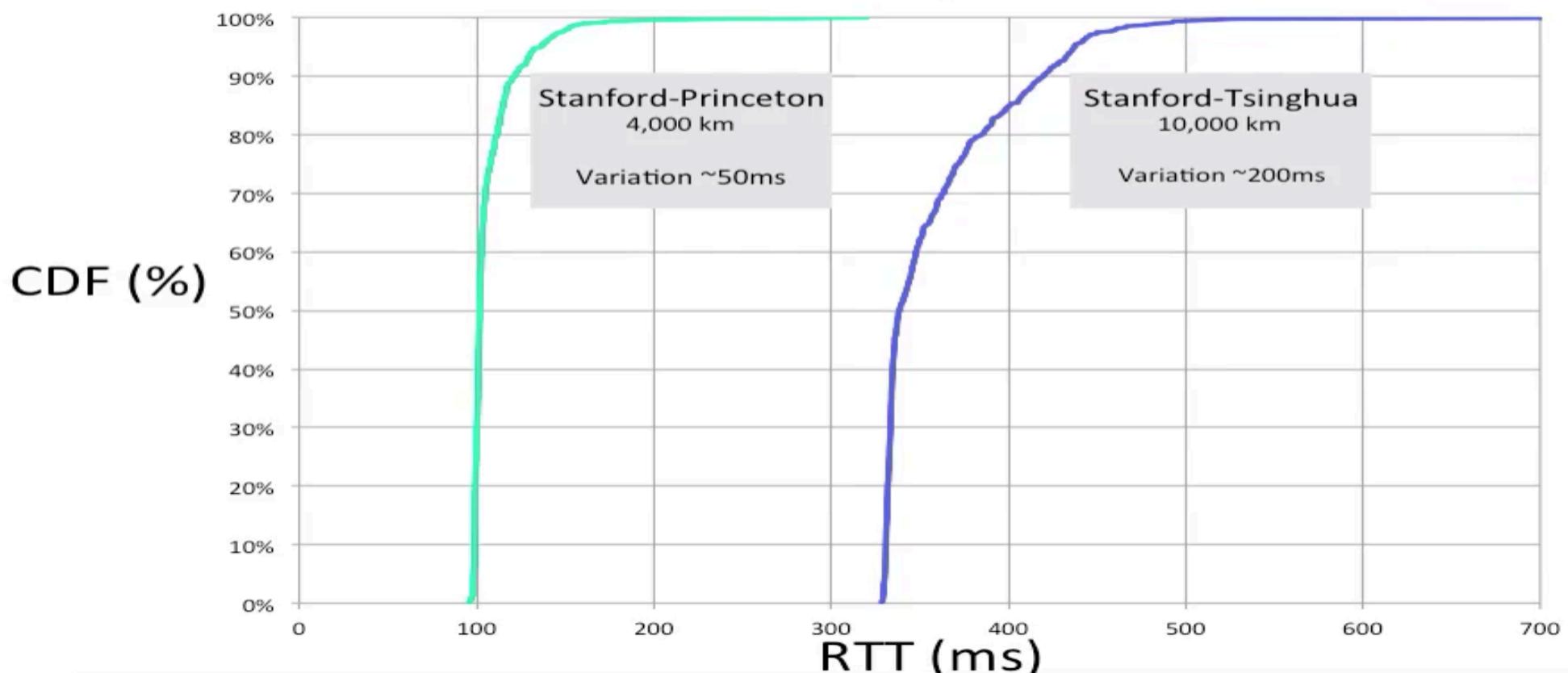
trans-oceanic link

\* Do some traceroutes from 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

Open a browser and type: [www.zeetings.com/salil](http://www.zeetings.com/salil)



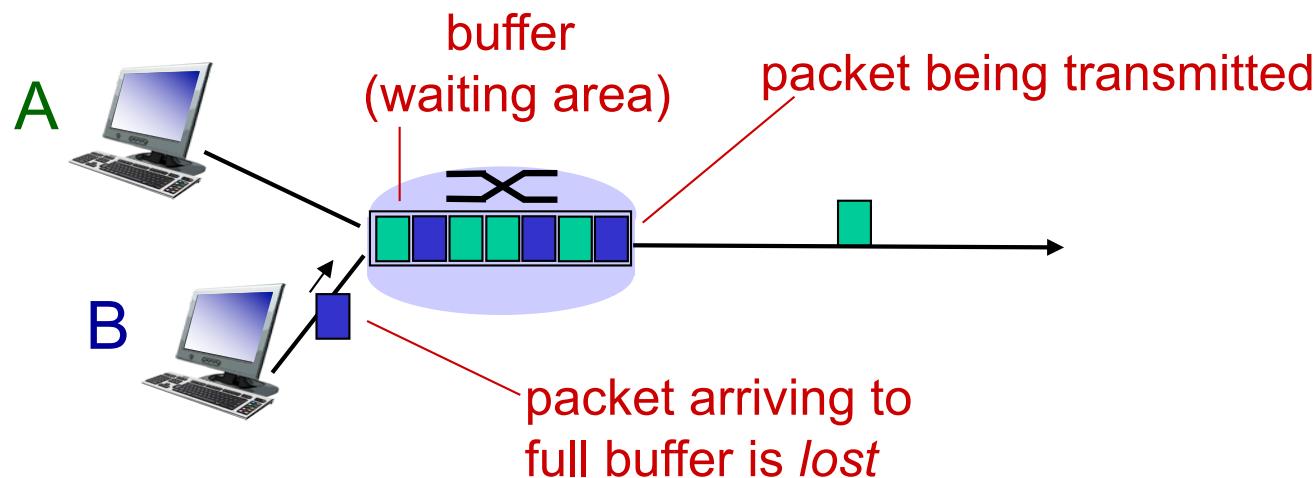
## Quiz: Oh these delays

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

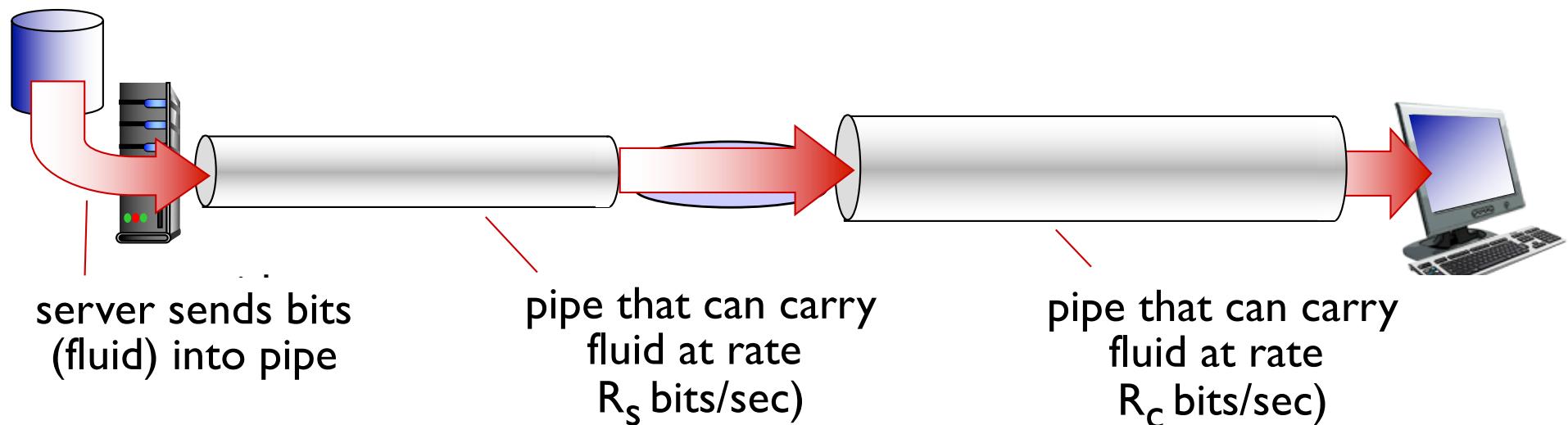
# Packet loss

- ❖ queue (aka buffer) preceding link in buffer has finite capacity
- ❖ packet arriving to full queue dropped (aka lost)
- ❖ lost packet may be retransmitted



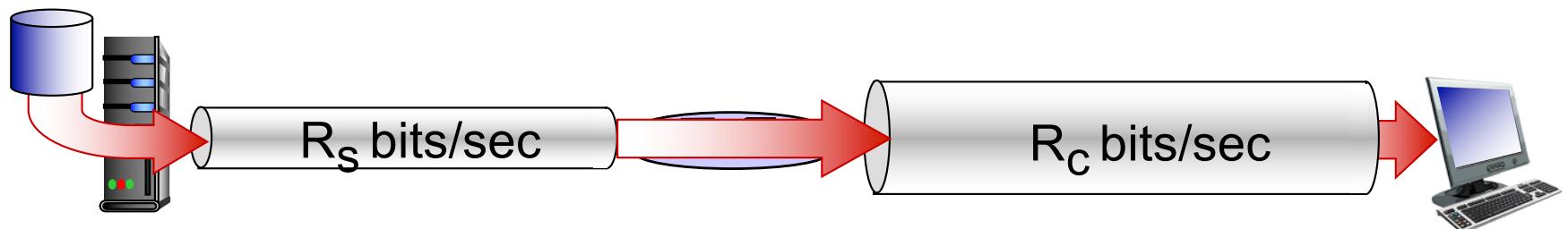
# Throughput

- ❖ *throughput*: rate (bits/time unit) at which bits transferred between sender/receiver
  - *instantaneous*: rate at given point in time
  - *average*: rate over longer period of time

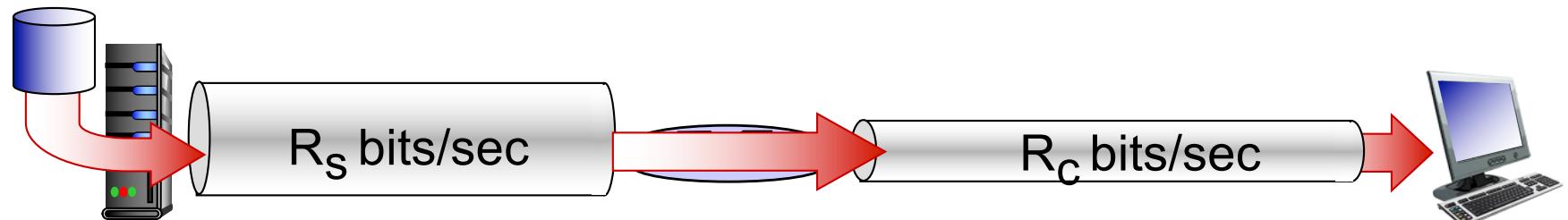


# Throughput (more)

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



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

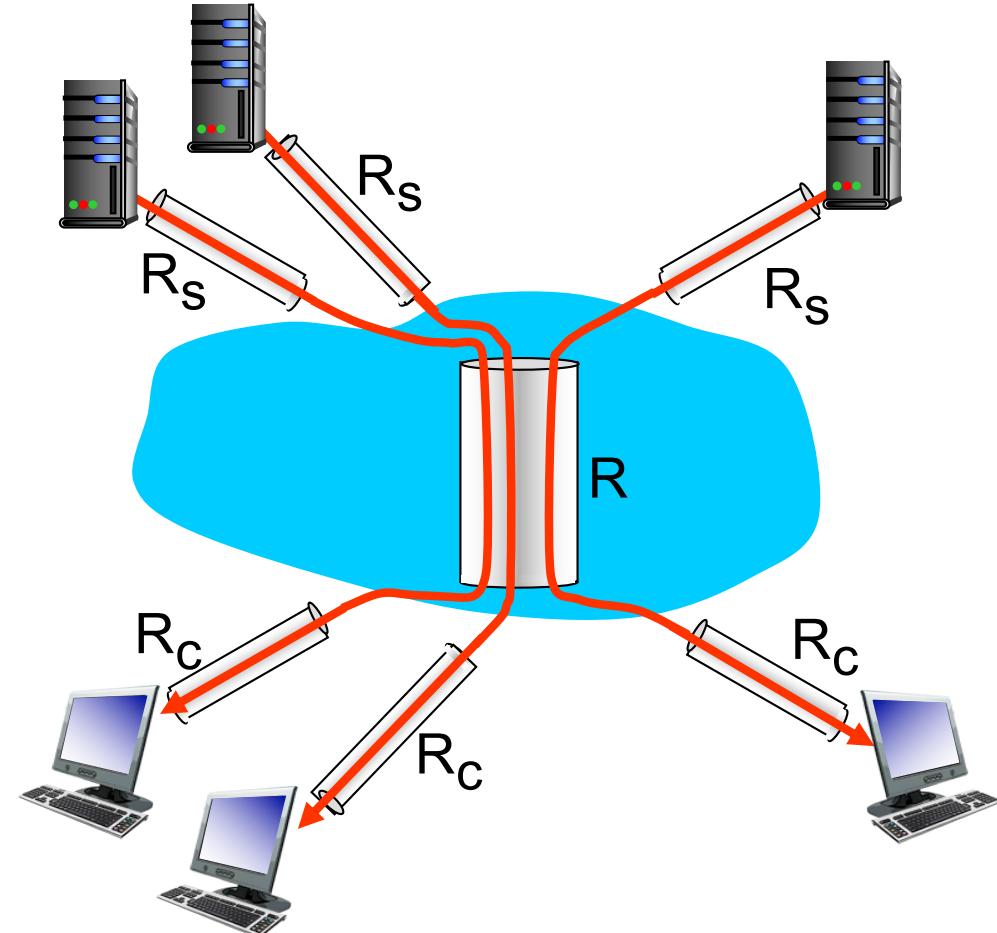


*bottleneck link*

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

# Throughput: Internet scenario

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



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

# 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