

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

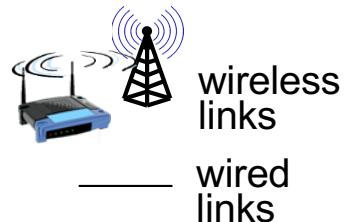
Hobbe's Internet Timeline - <http://www.zakon.org/robert/internet/timeline/>

Quiz: What is the Internet?

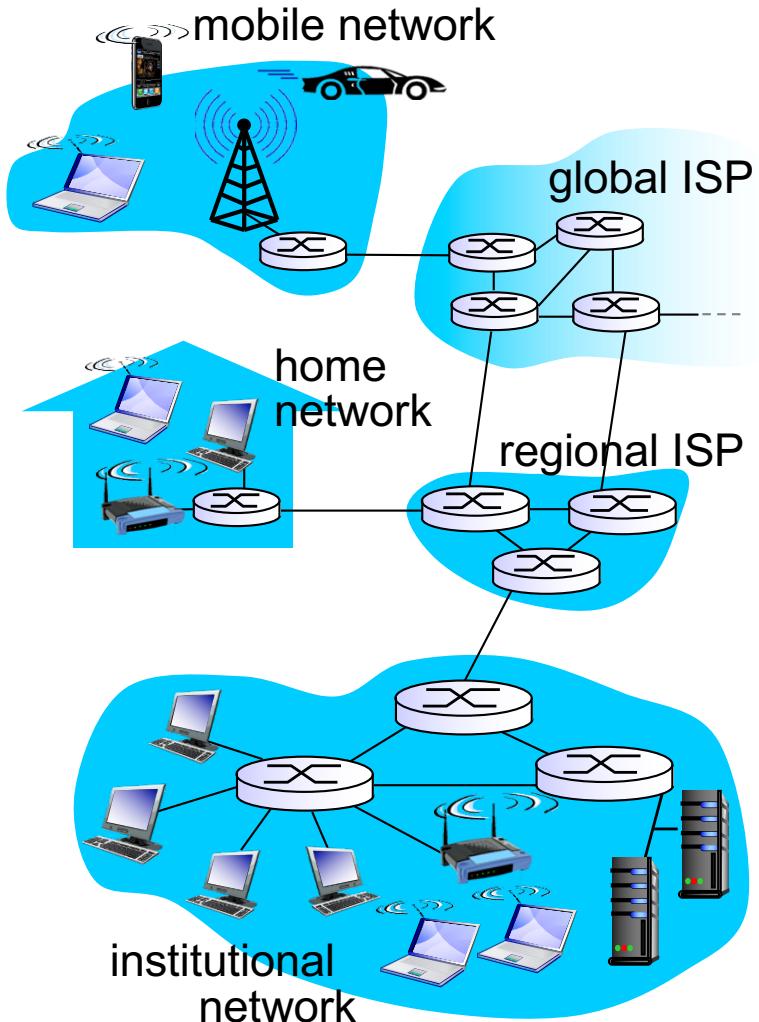


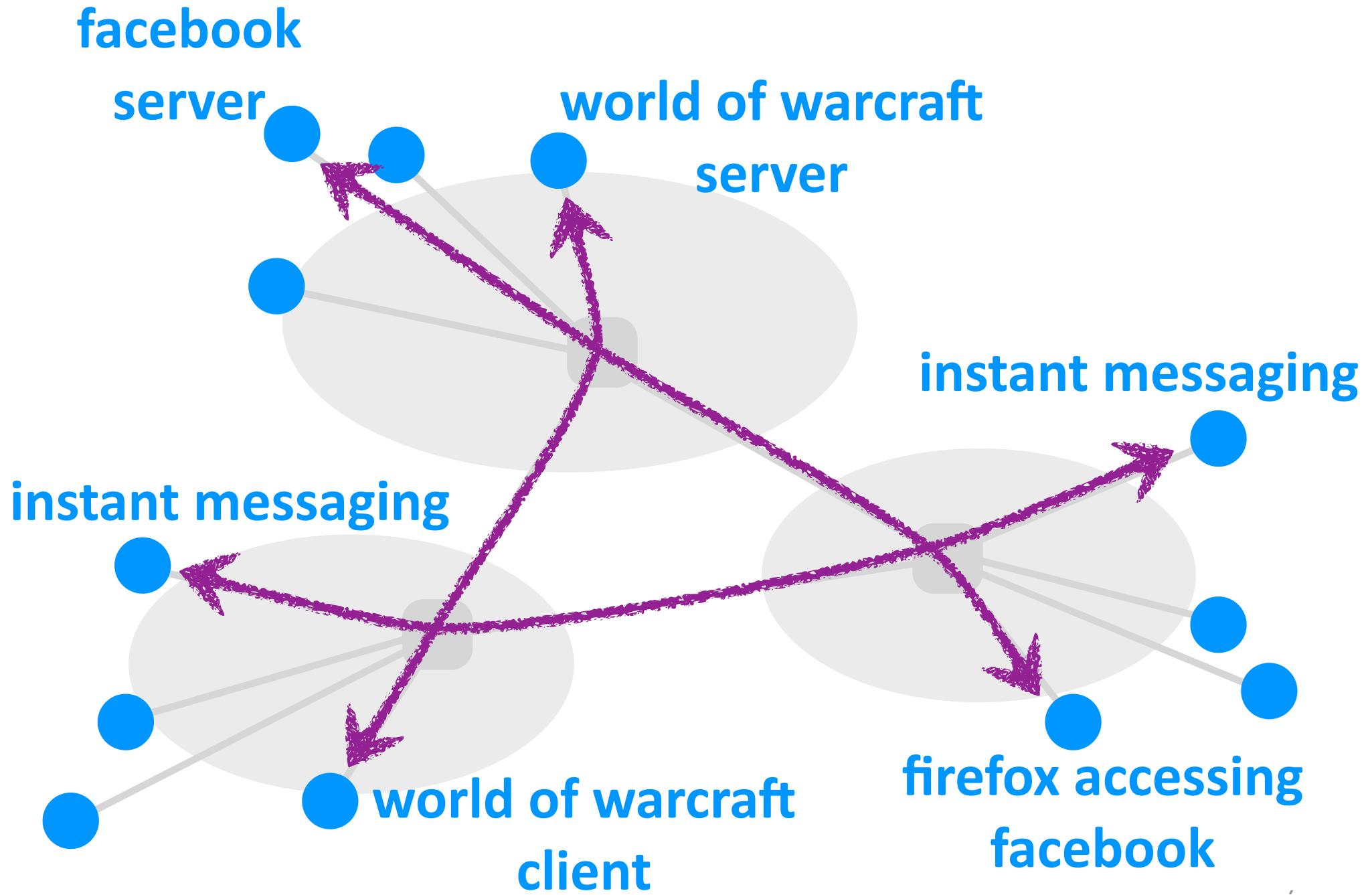
- A.** One single homogenous network
- B.** An interconnection of different computer networks
- C.** An infrastructure that provides services to networked applications
- D.** Something else (be prepared to discuss)

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*
带宽
- ❖ *Packet switches*: forward packets (chunks of data)
 - *routers* and *switches*





“Fun” Internet appliances



Internet refrigerator



Picture frame



sensorized,
bed
mattress



Networked TV Set top Boxes



Web-enabled toaster +
weather forecaster

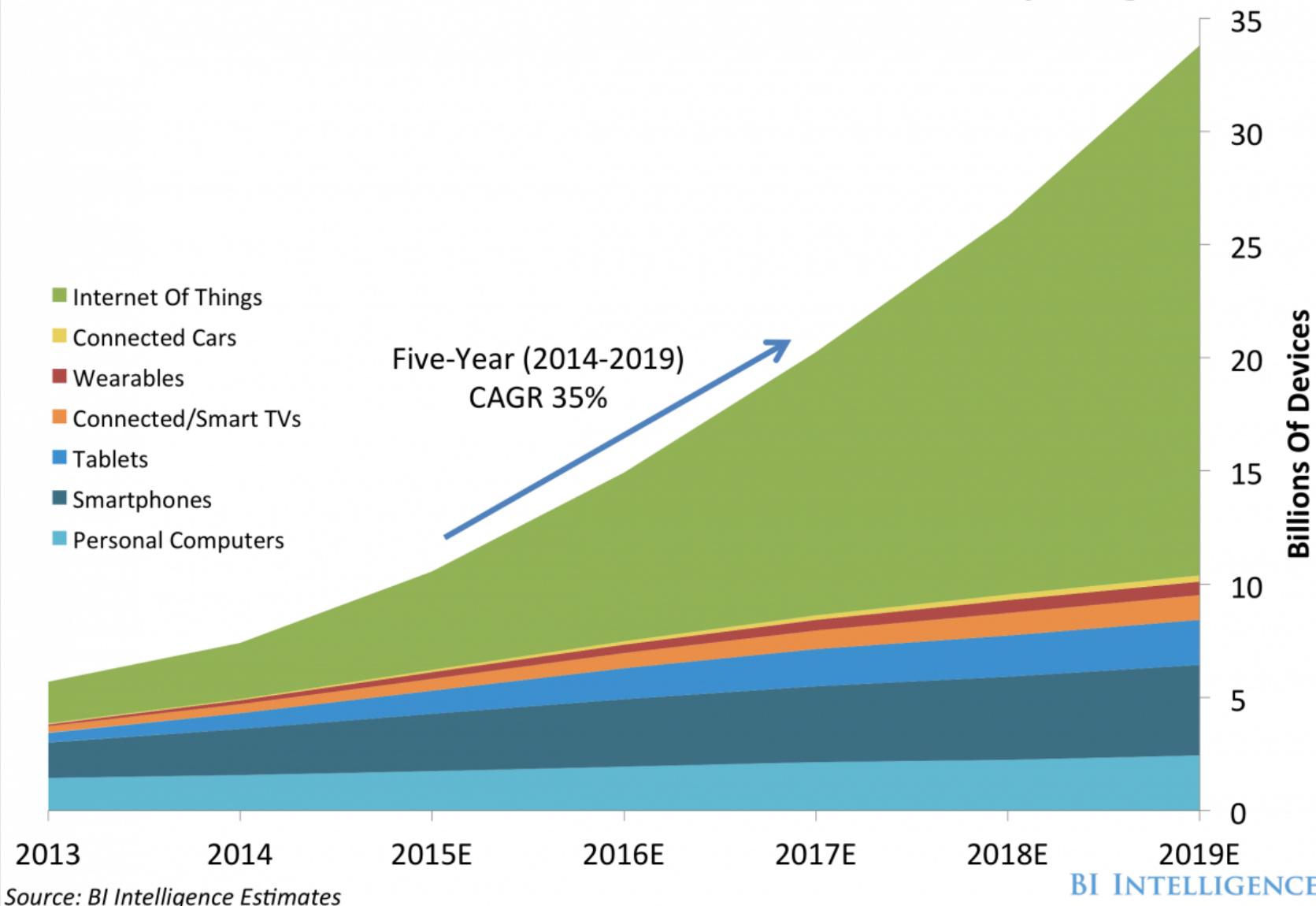


Tweet-a-watt:
monitor energy use



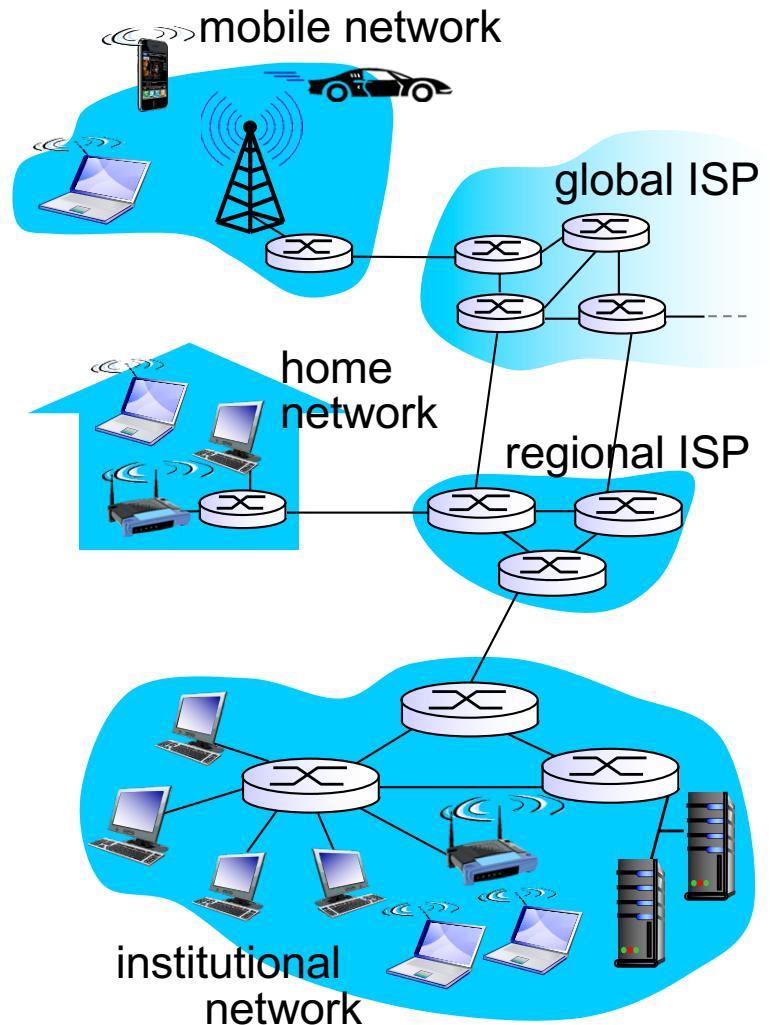
Smart Lightbulbs

Number Of Devices In The Internet Of Everything



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

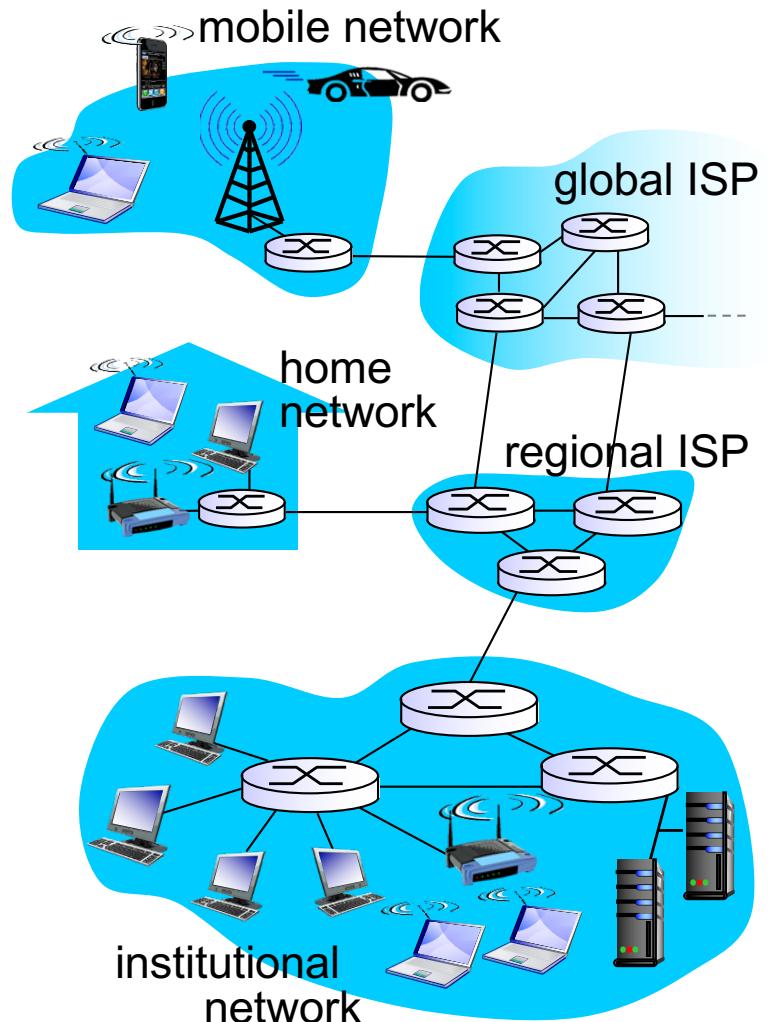
- ❖ *Internet: “network of networks”*
 - Interconnected ISPs
- ❖ *protocols* control sending, receiving of msgs
 - e.g., TCP, IP, HTTP, Skype, 802.11
- ❖ *Internet standards*
 - RFC: Request for comments
 - IETF: Internet Engineering Task Force

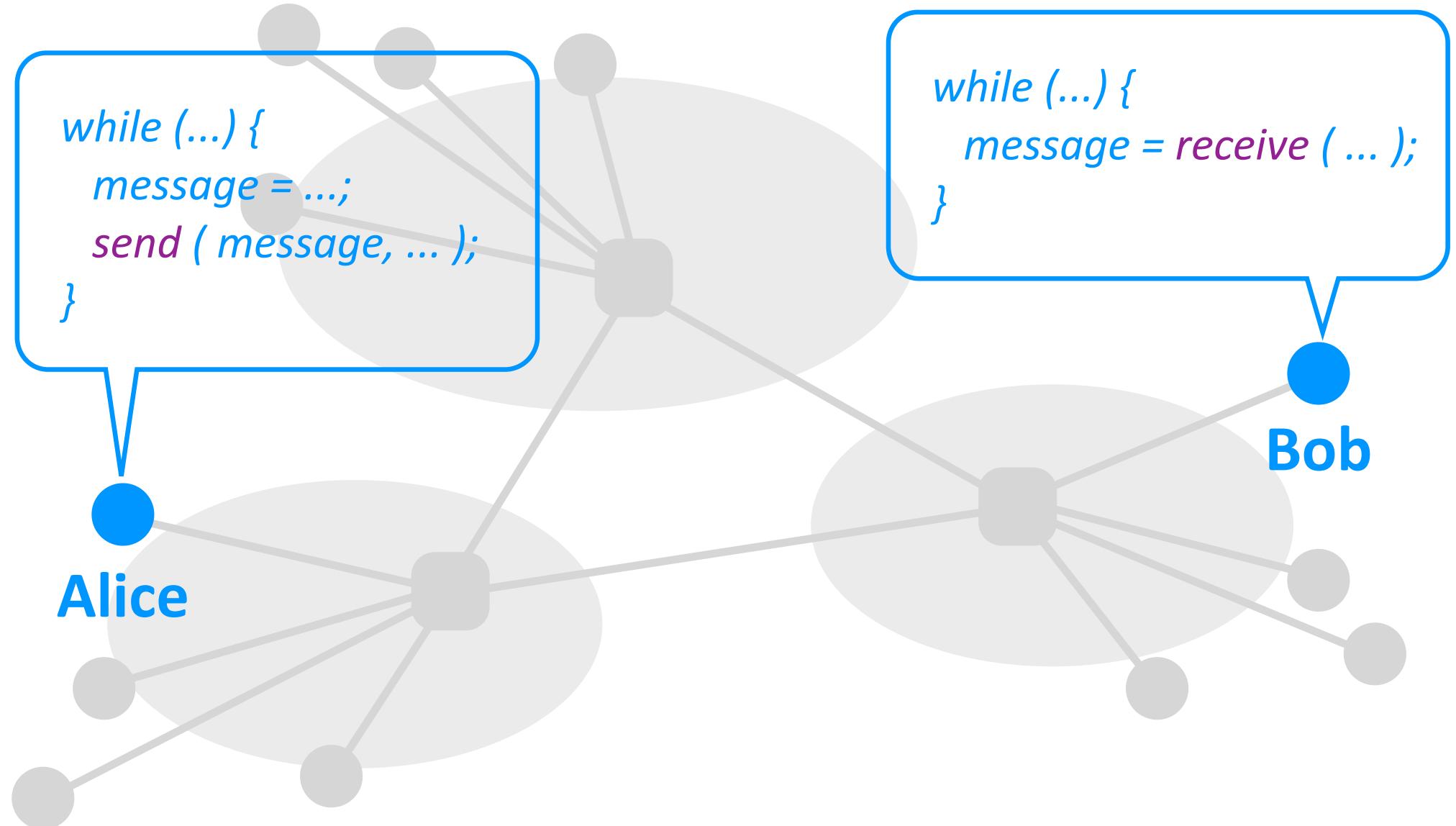


What's the Internet: a service view

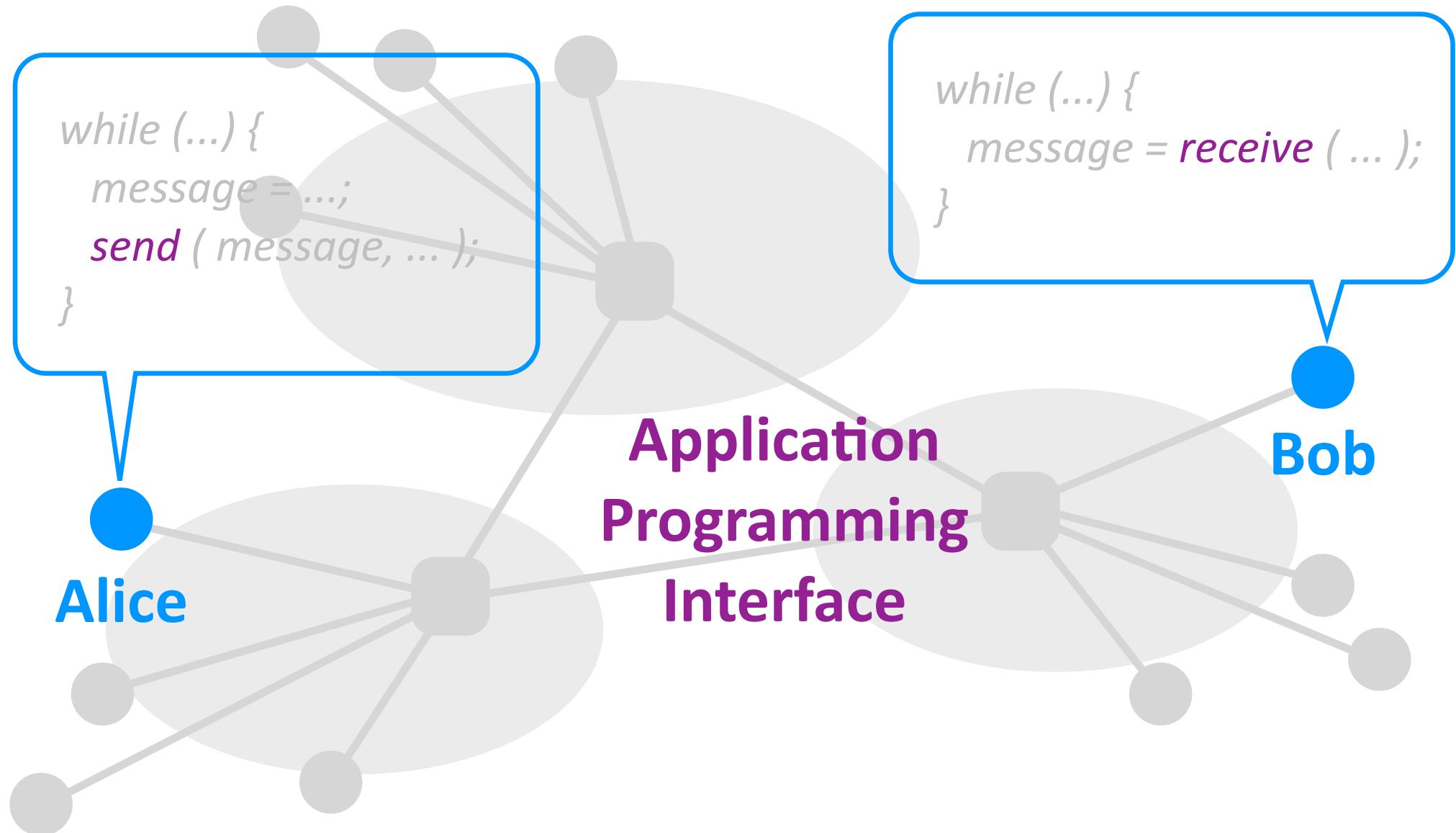
- ❖ *Infrastructure that provides services to applications:*
 - Web, VoIP, email, games, e-commerce, social nets, ...
- ❖ *provides programming interface to apps*
 - hooks that allow sending and receiving app programs to “connect” to Internet
 - provides service options, analogous to postal service

类比的





Application Programming Interface



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

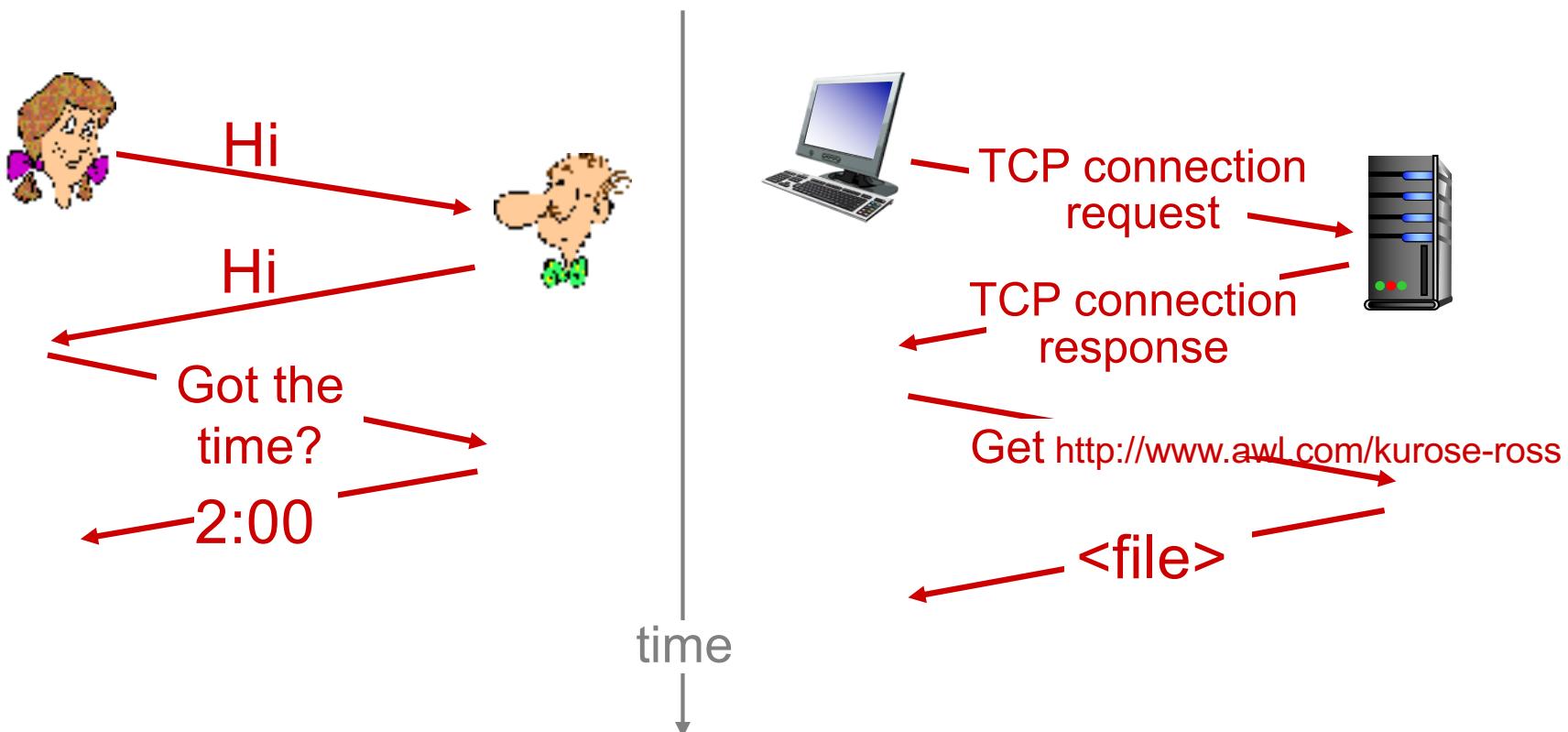
network protocols:

- ❖ 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

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I.2 network edge

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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:

网络边界

❖ *network edge:*

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

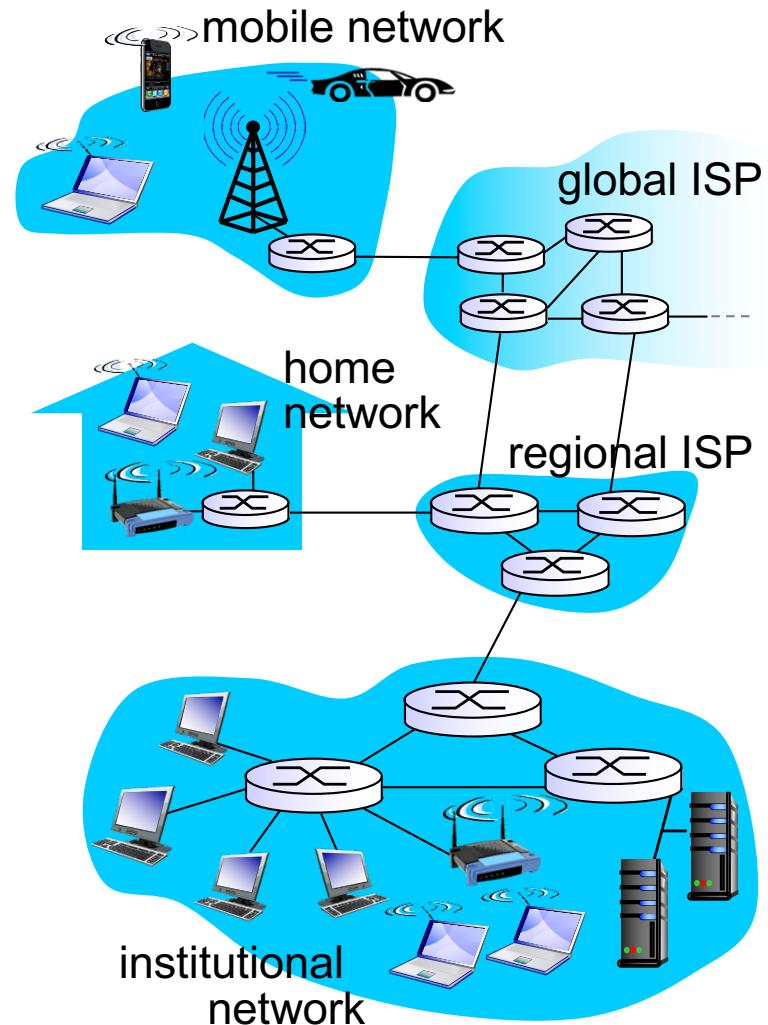
物理媒介

❖ *access networks, physical media:* wired, wireless communication links

网络核心

❖ *network core:*

- interconnected routers
- network of networks



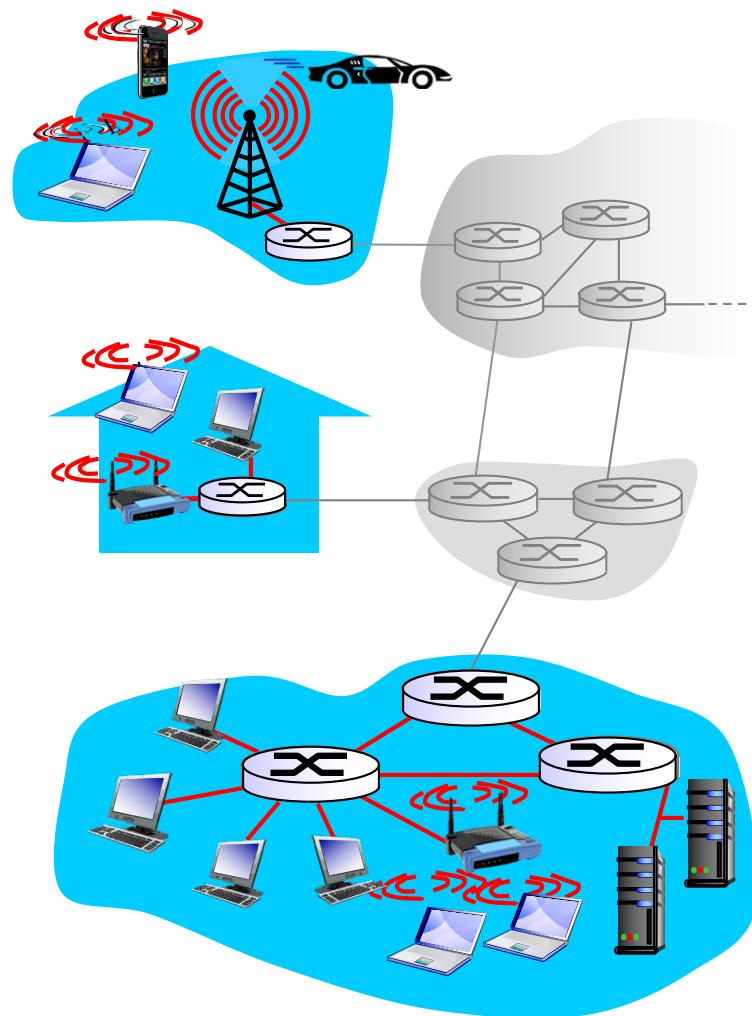
Access networks and physical media

Q: How to connect end systems to edge router?

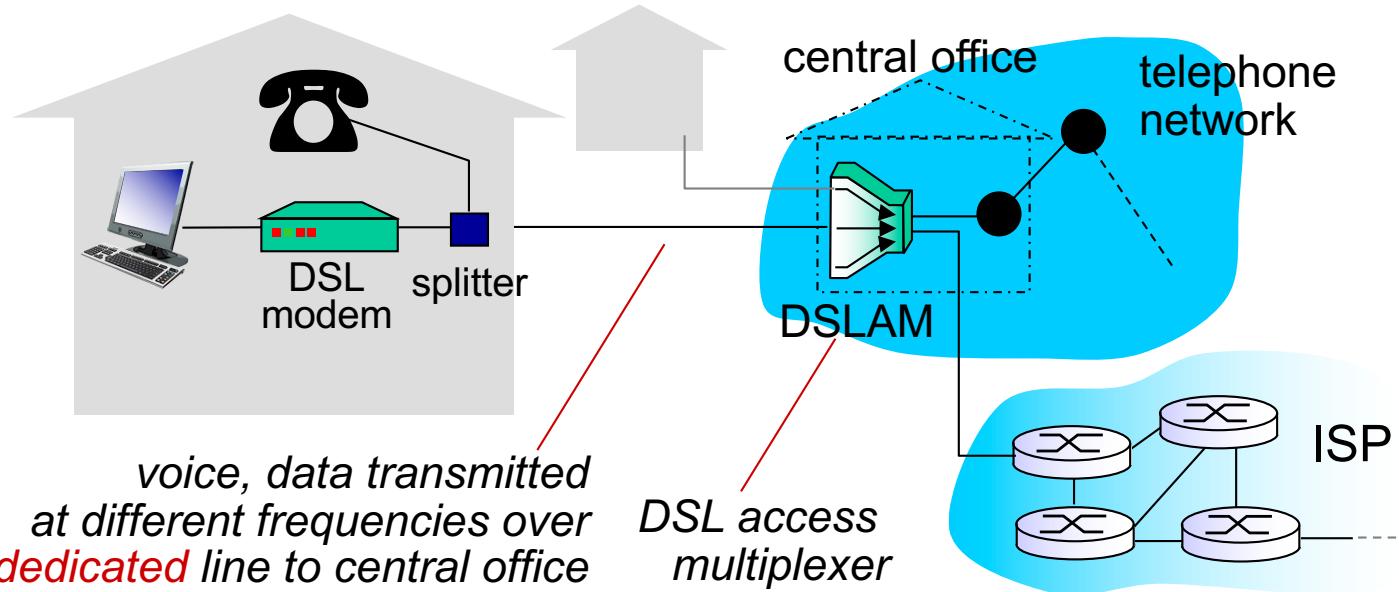
- ❖ residential access nets
- ❖ institutional access networks (school, company)
- ❖ mobile access networks

keep in mind:

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

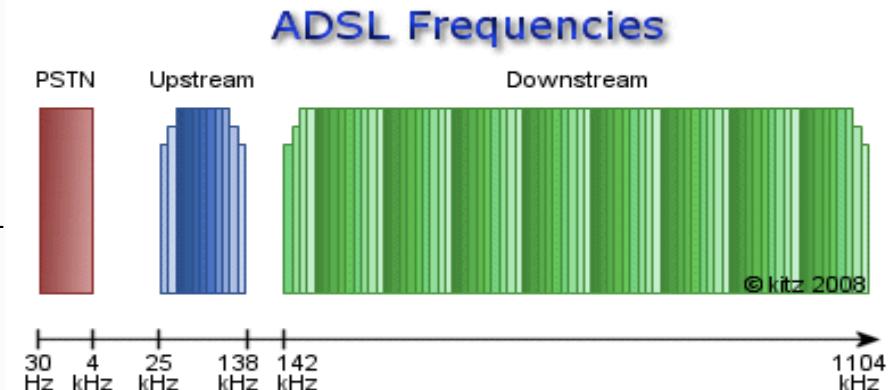
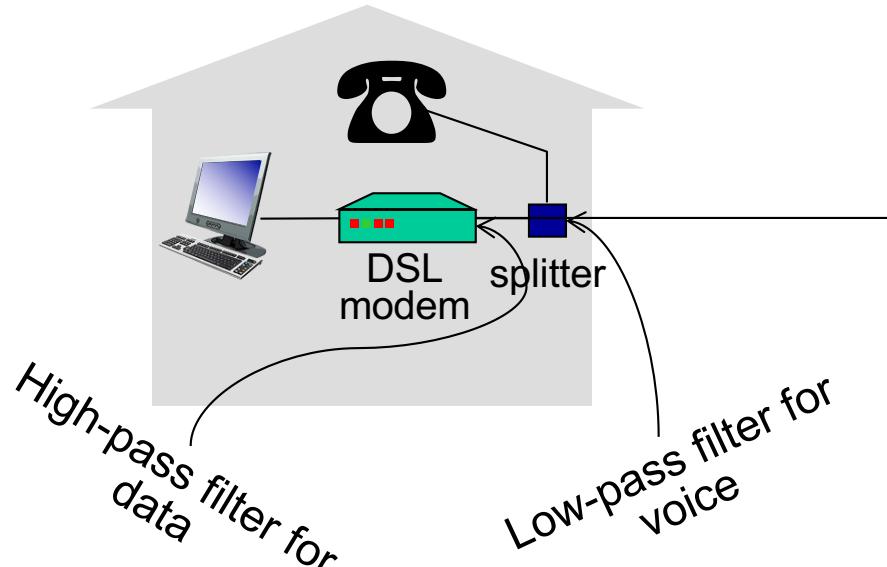


Access net: digital subscriber line (DSL)



- ❖ 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)

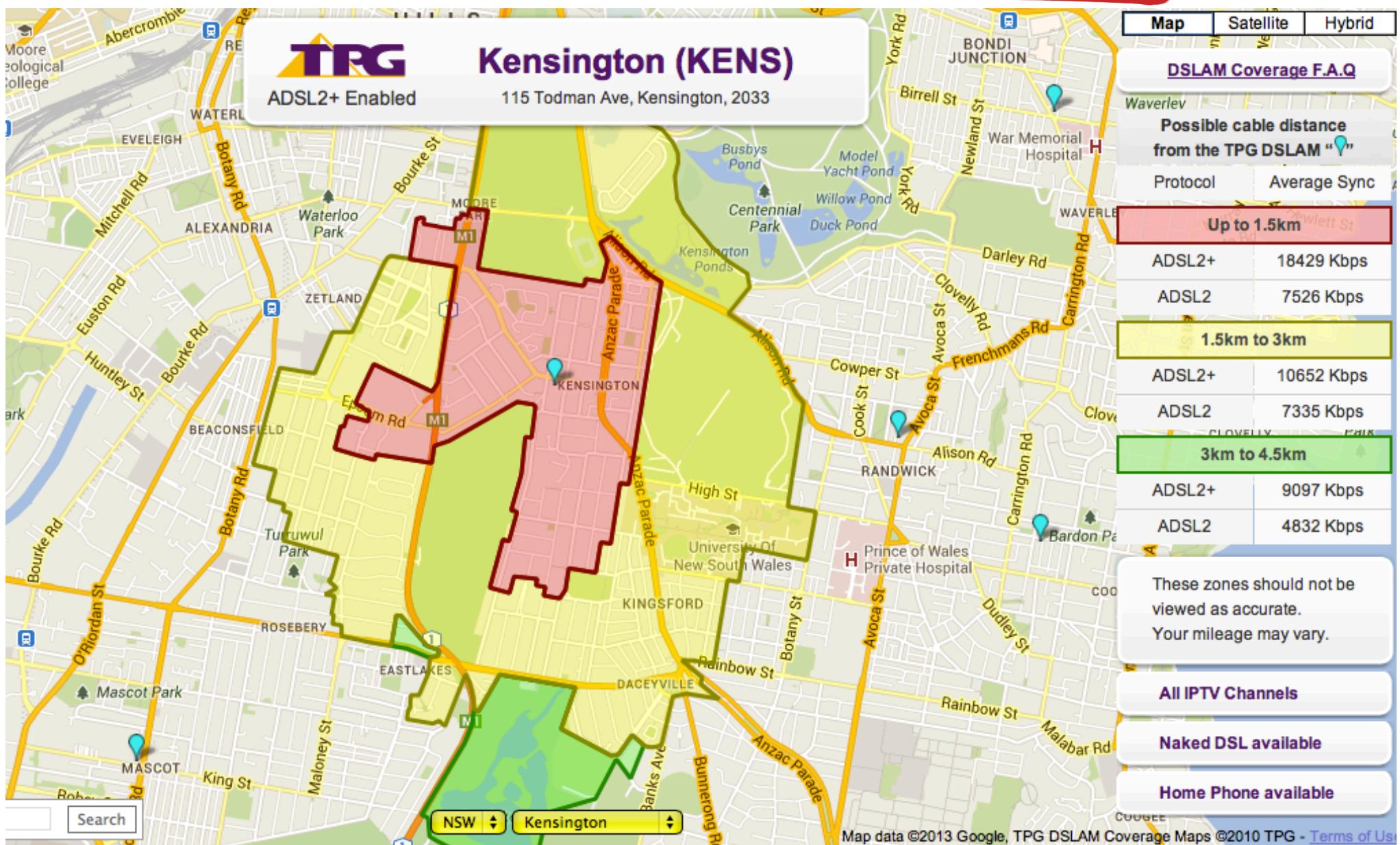


ADSL over POTS

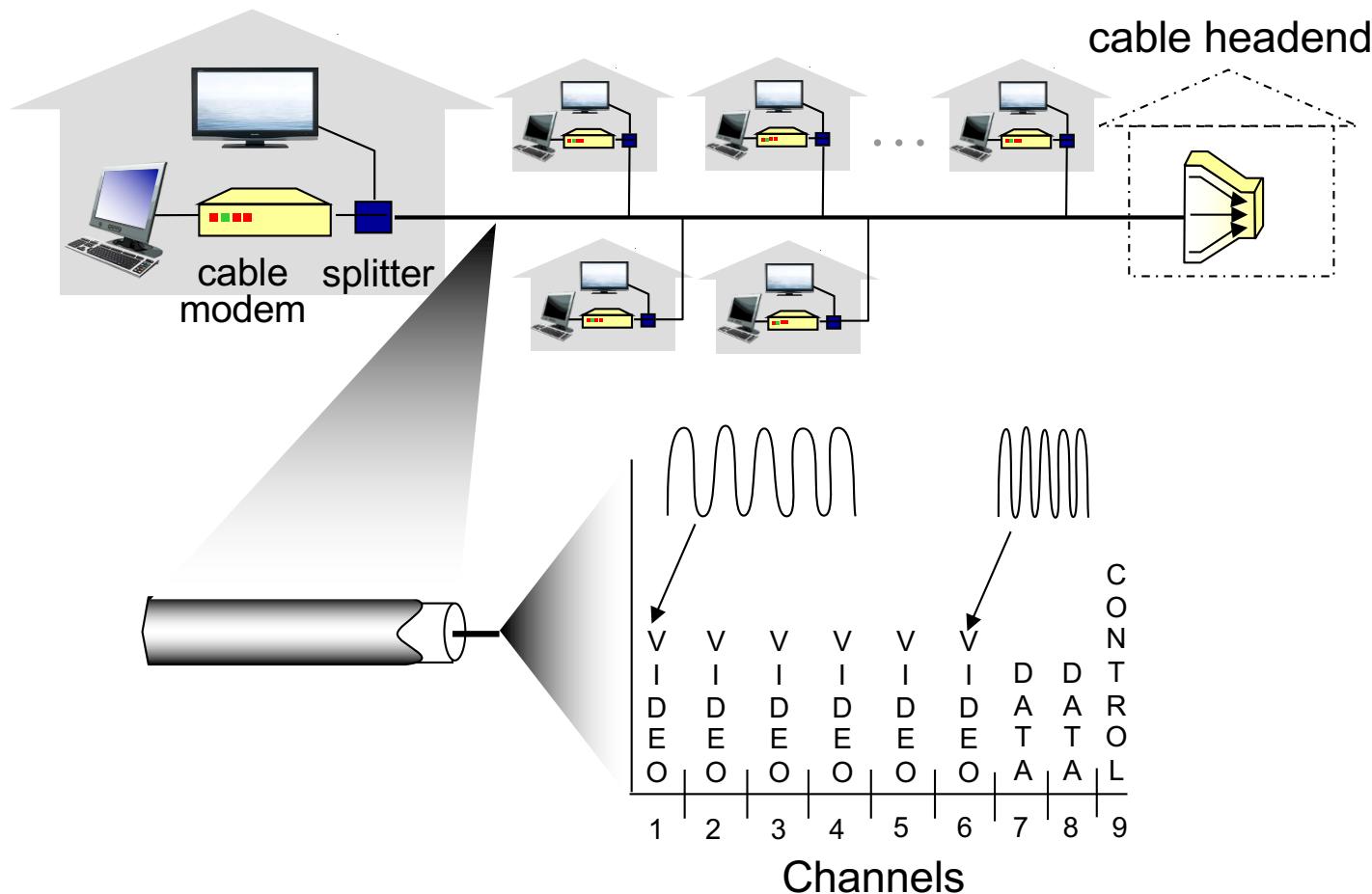
*voice, data transmitted
at different frequencies over
dedicated line to central office*

- 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)

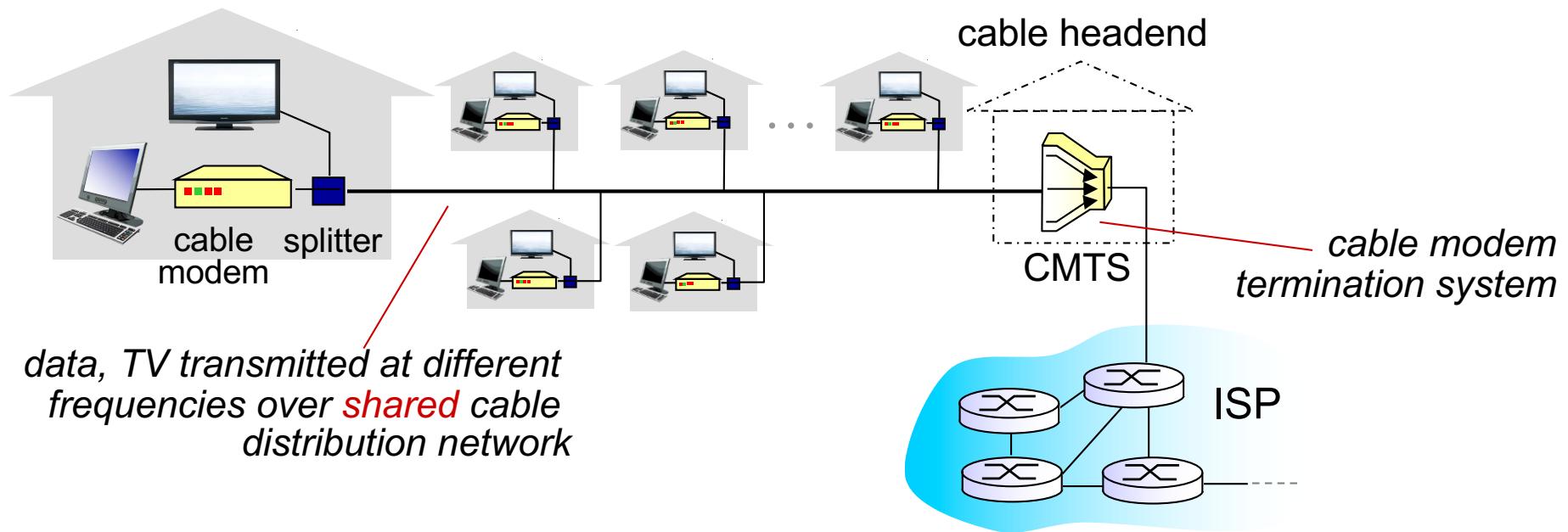


Access net: cable network



frequency division multiplexing: different channels transmitted in different frequency bands

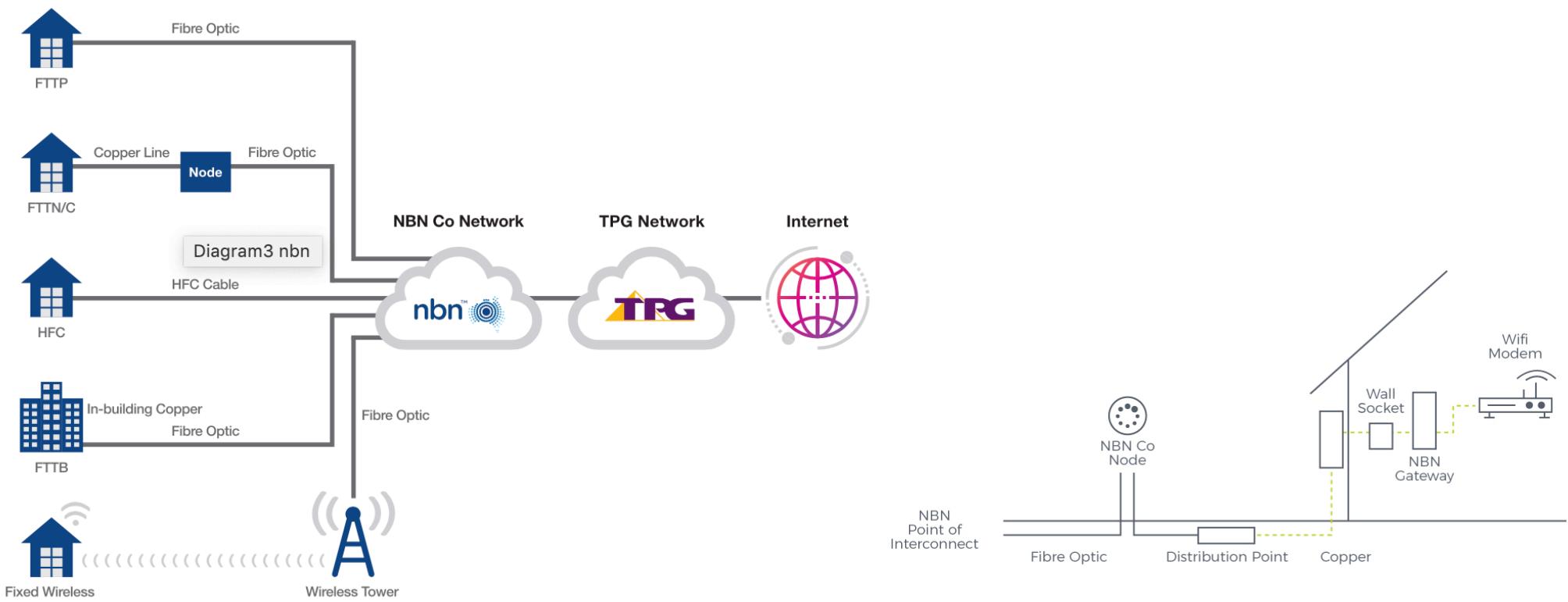
Access net: cable network



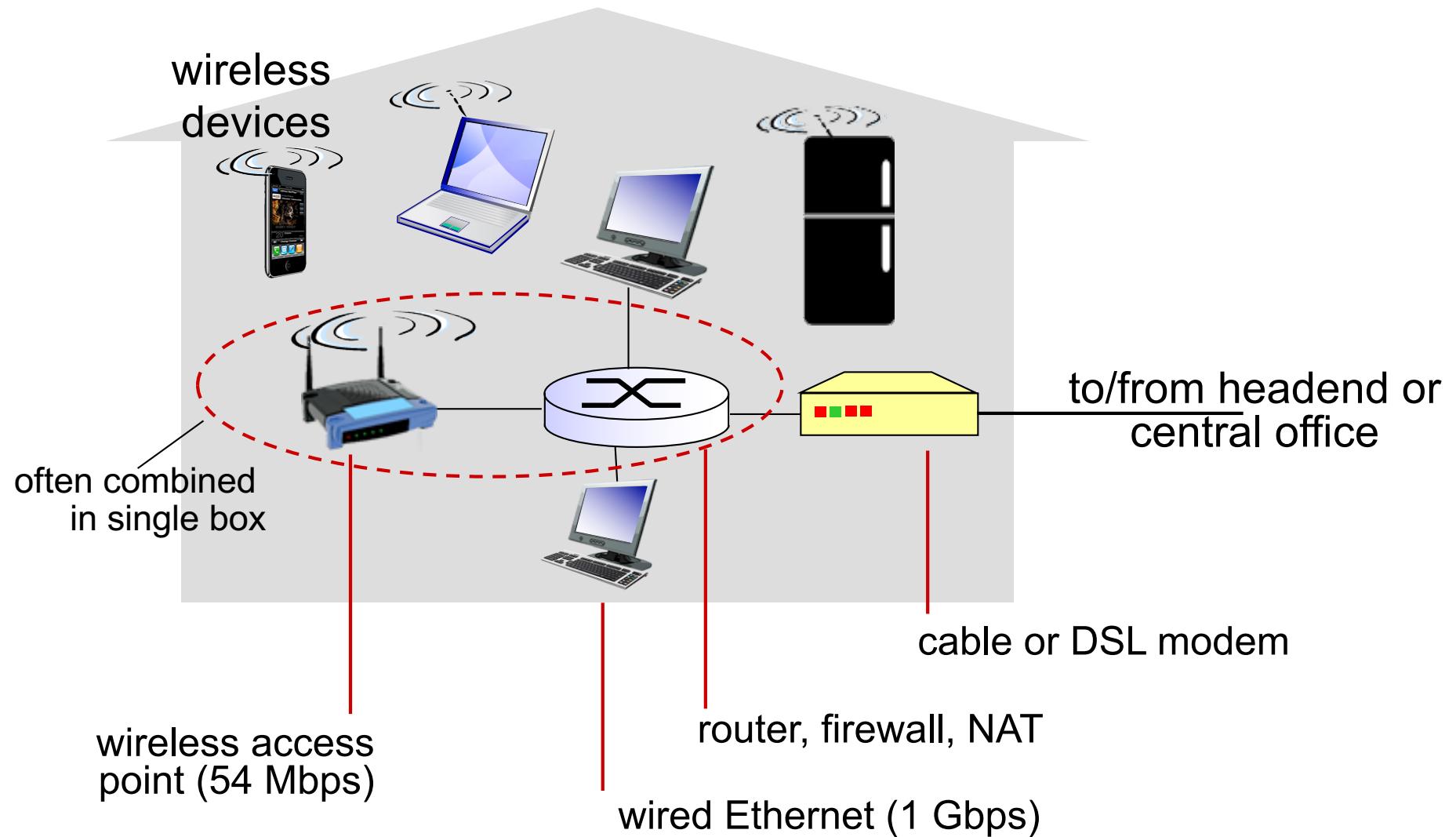
- ❖ **HFC: hybrid fiber coax**
 - asymmetric: up to 30Mbps downstream transmission rate, 2 Mbps upstream transmission rate
- ❖ **network** of cable, fiber attaches homes to ISP router
 - homes **share access network** to cable headend
 - unlike DSL, which has dedicated access to central office

Fiber to the home/premise/curb

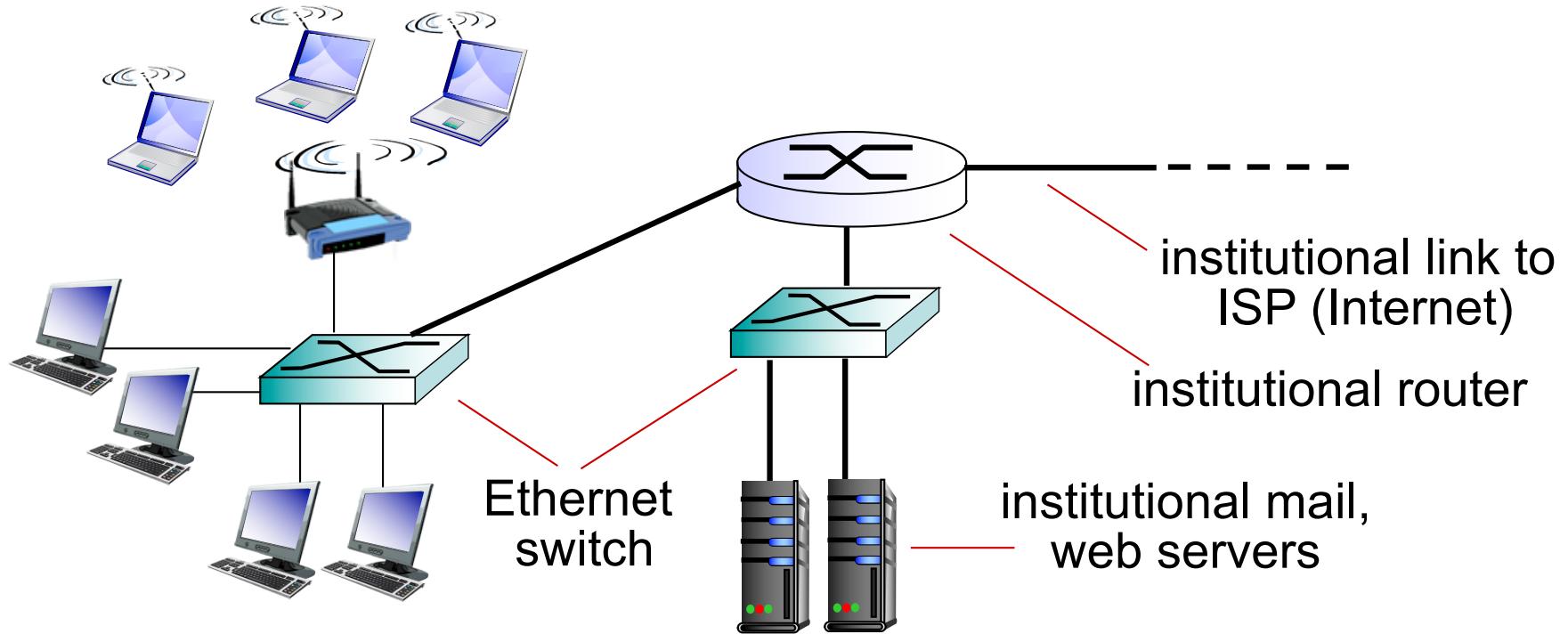
- ❖ Fully optical fiber path all the way to the home
 - e.g., NBN, Google, Verizon FIOS
 - ~30 Mbps to 1 Gbps



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”

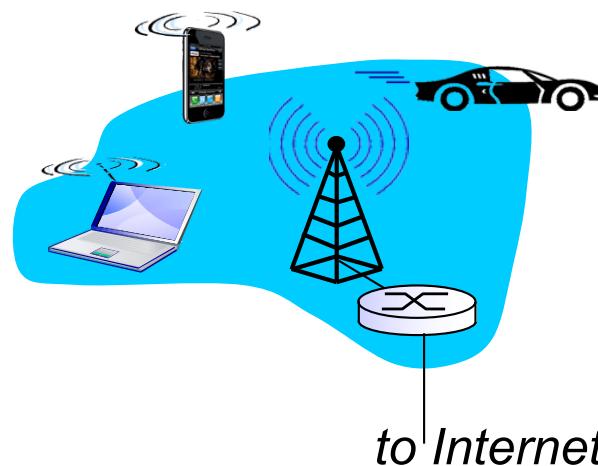
wireless LANs:

- 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



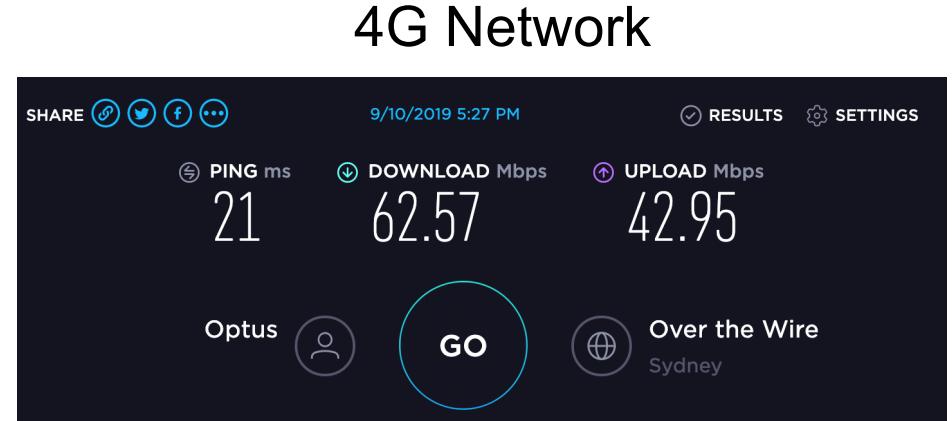
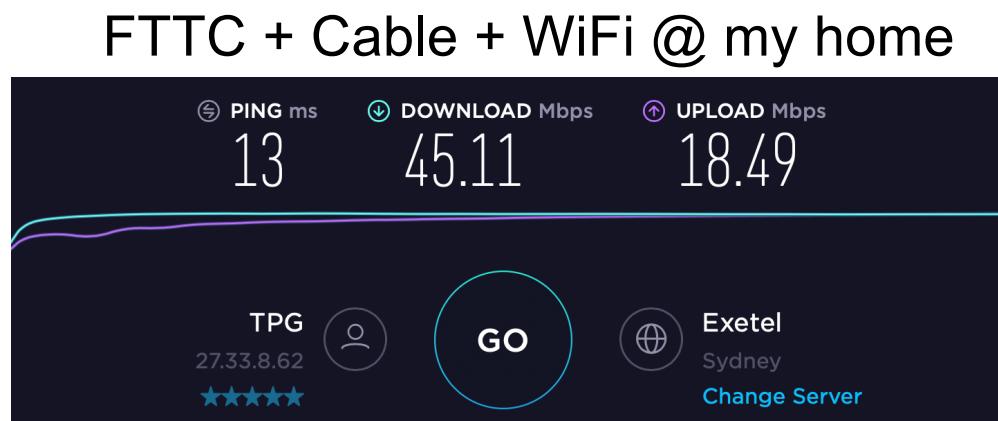
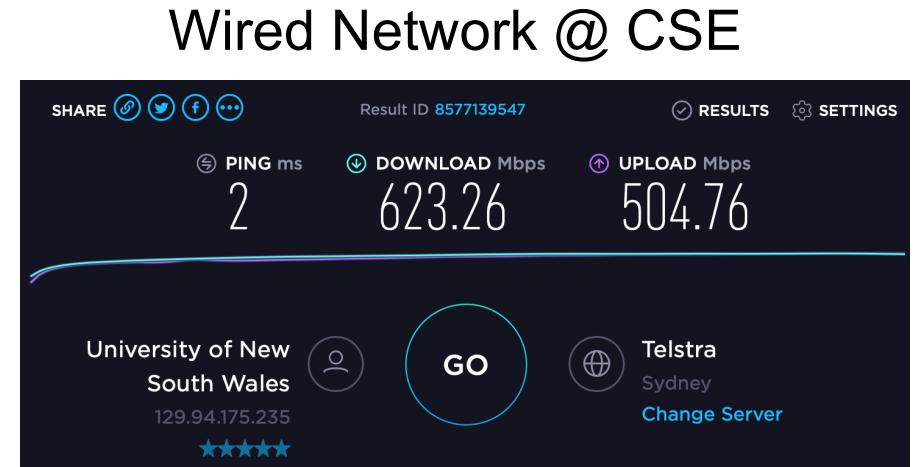
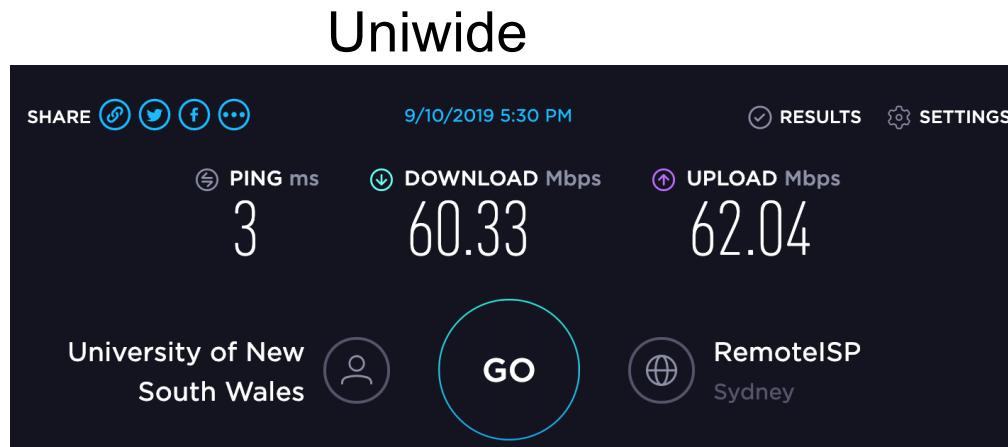
wide-area wireless access

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



Sample results

Can you explain the differences?



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 铜线, 光纤, 同轴电缆
- ❖ **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 Gpbs 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 Gpbs transmission rate)
- ❖ low error rate:
 - repeaters spaced far apart
 - immune to electromagnetic noise



Physical media: radio

Self Study

- ❖ signal carried in **光谱, 频谱** 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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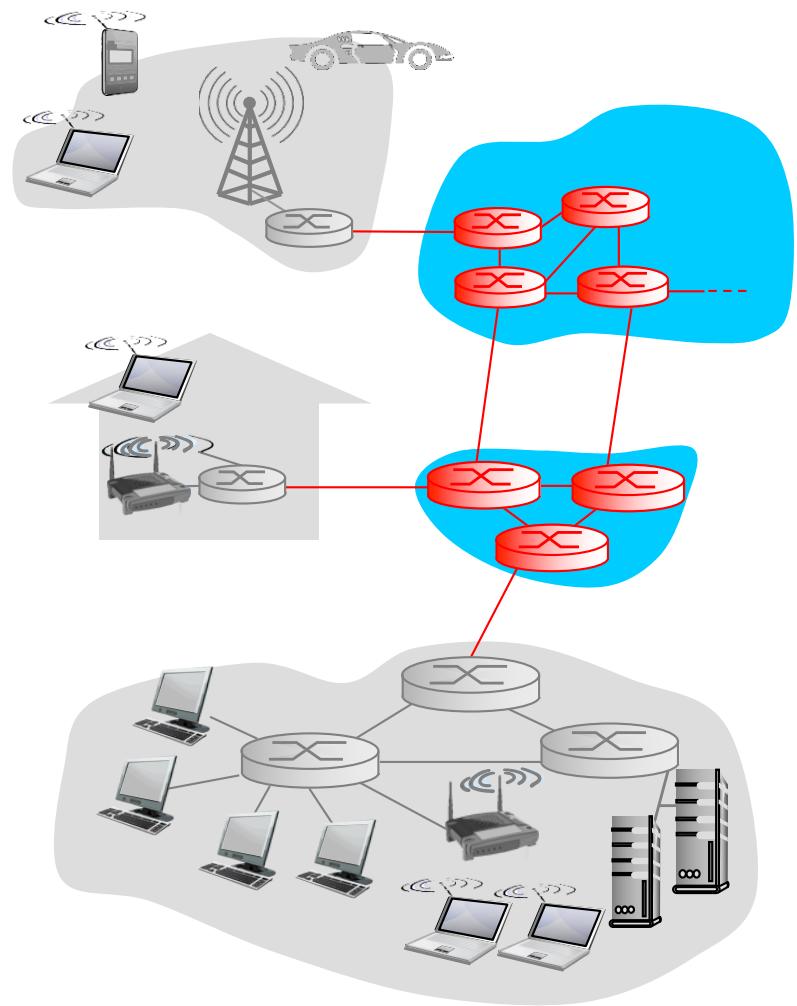
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The network core

网格

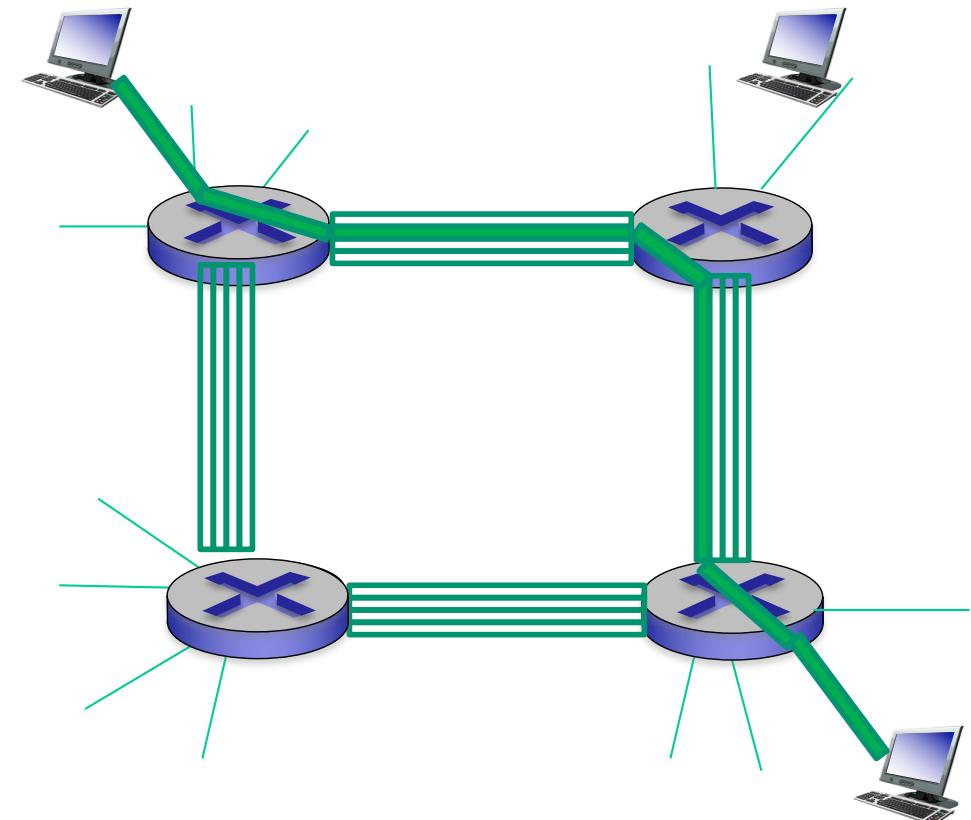
- ❖ mesh of interconnected routers/switches
- ❖ Two forms of switched networks:
 - Circuit switching: used in the legacy telephone networks
 - Packet switching: used in the Internet



Circuit Switching

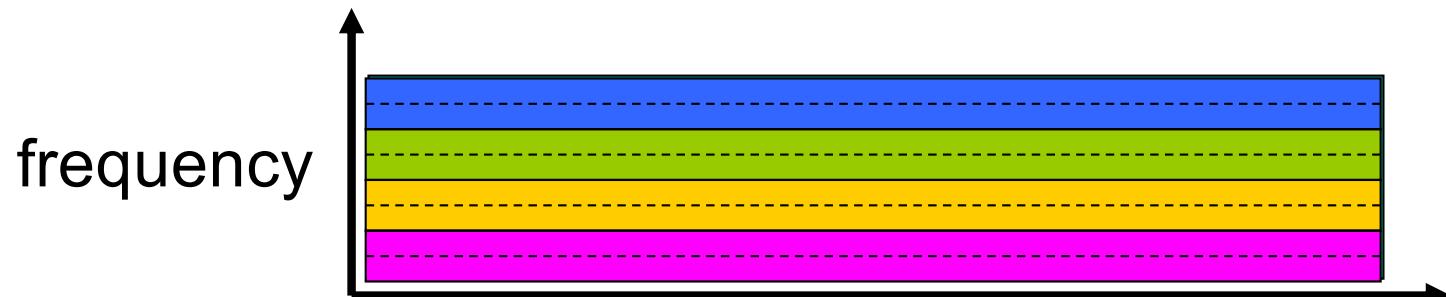
end-end resources allocated to, reserved for “call” between source & dest:

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



Circuit switching: FDM versus TDM

FDM

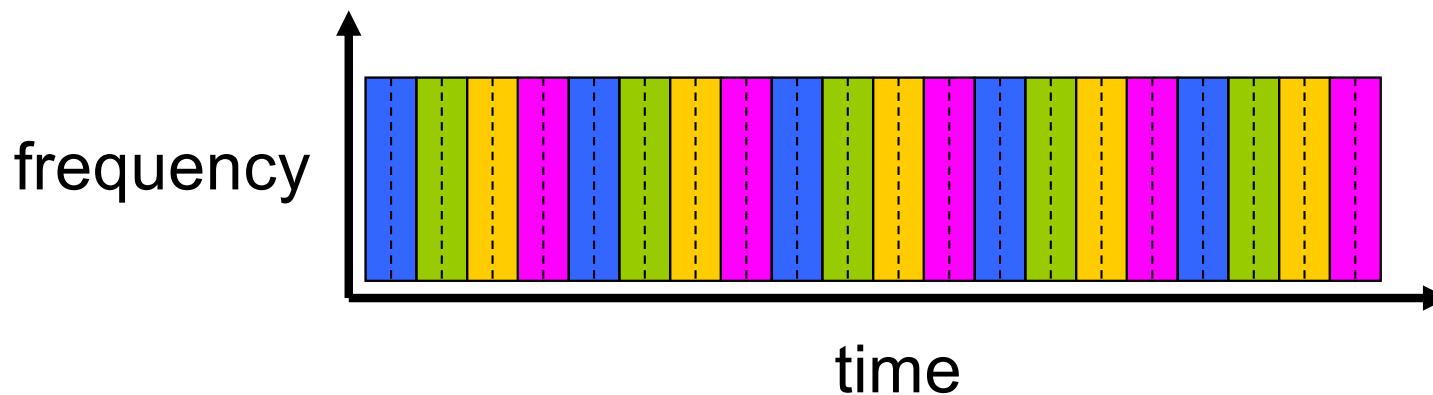


Example:

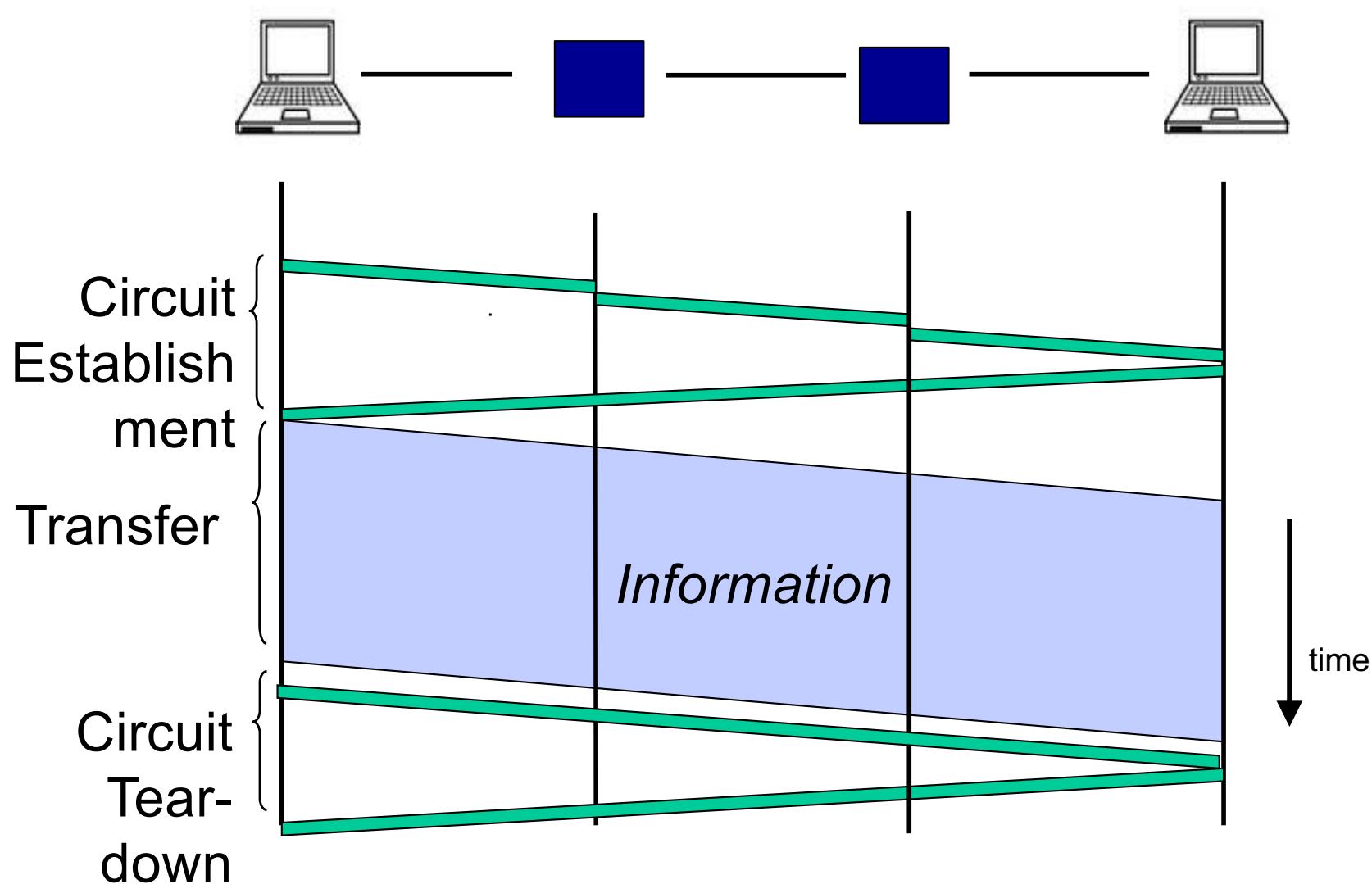
4 users



TDM



Timing in Circuit Switching



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



❖ Pros:

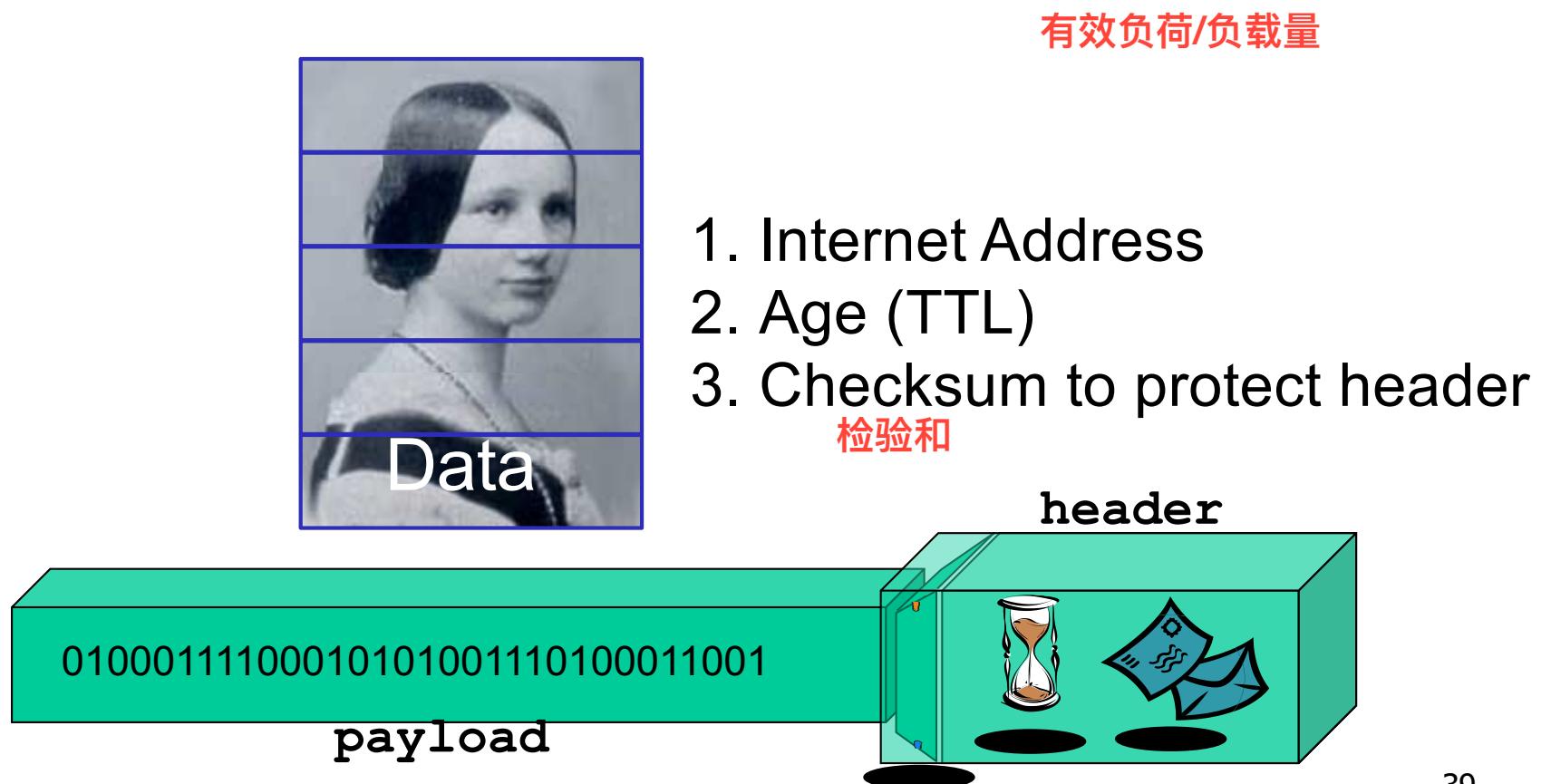
❖ Cons:

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 **动态网络**
- **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
可度量的

Packet Switching

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



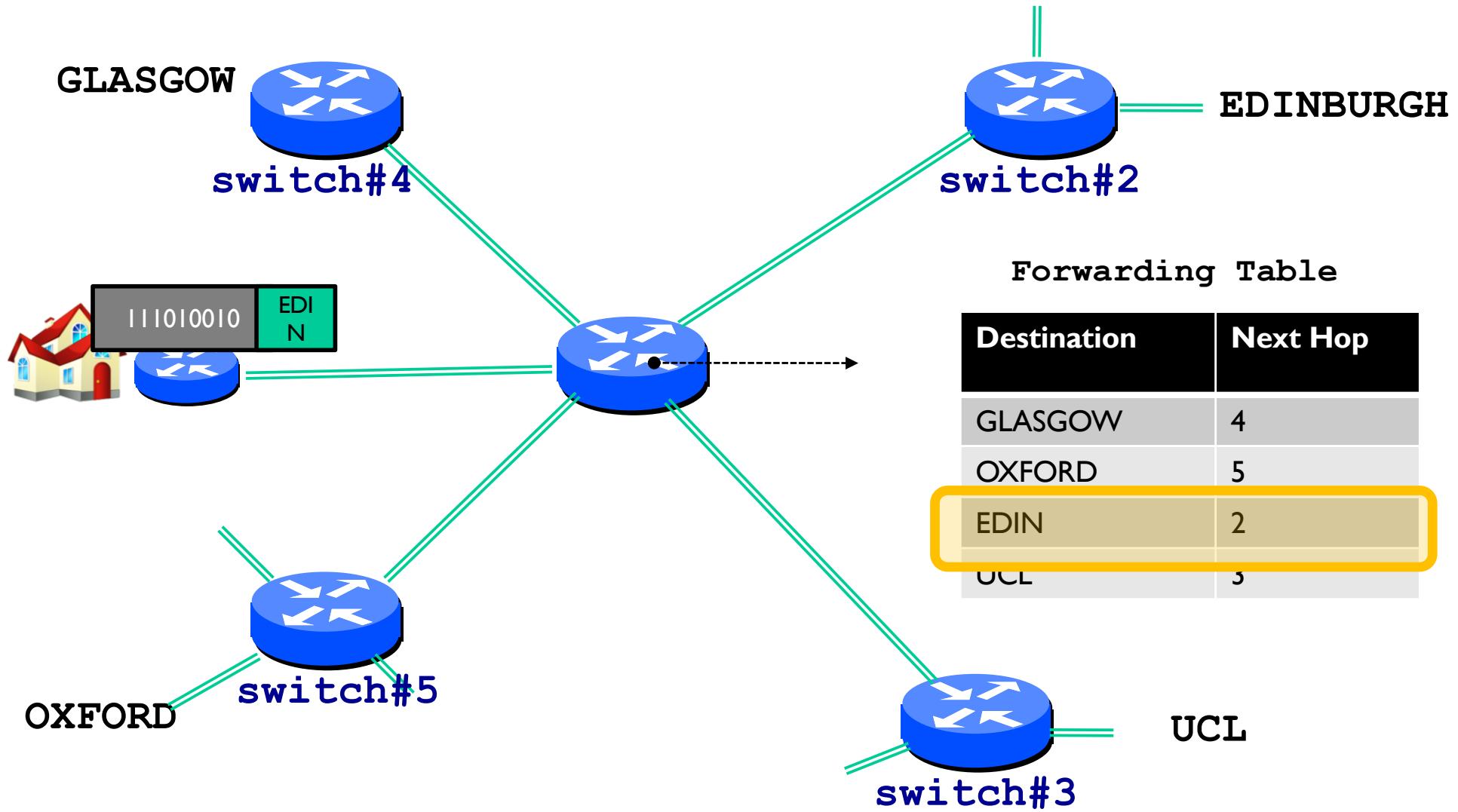
Packet Switching

- ❖ 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)

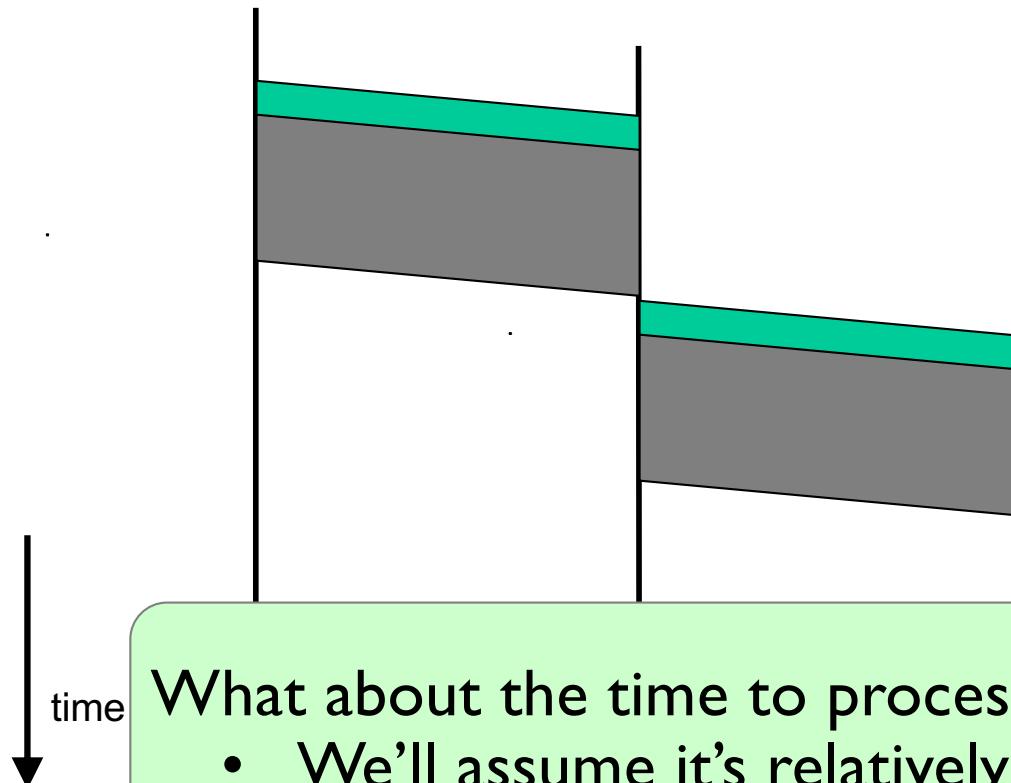
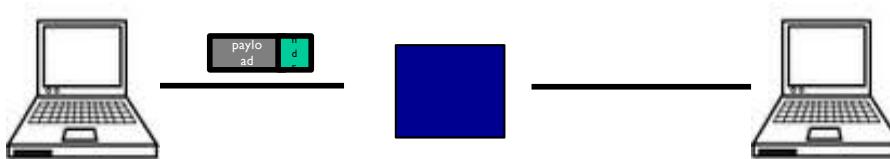
Packet Switching

- ❖ 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

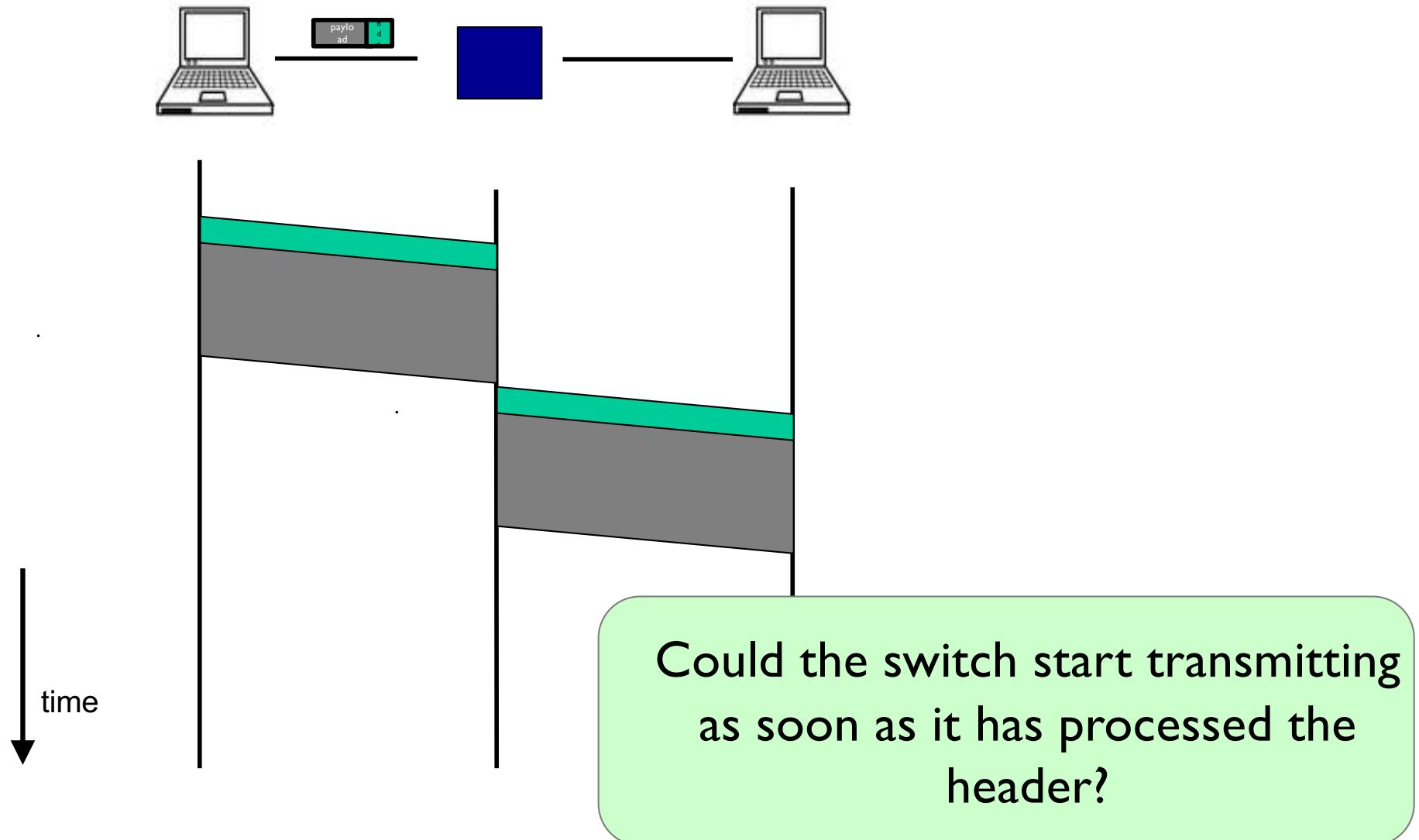


Timing in Packet Switching

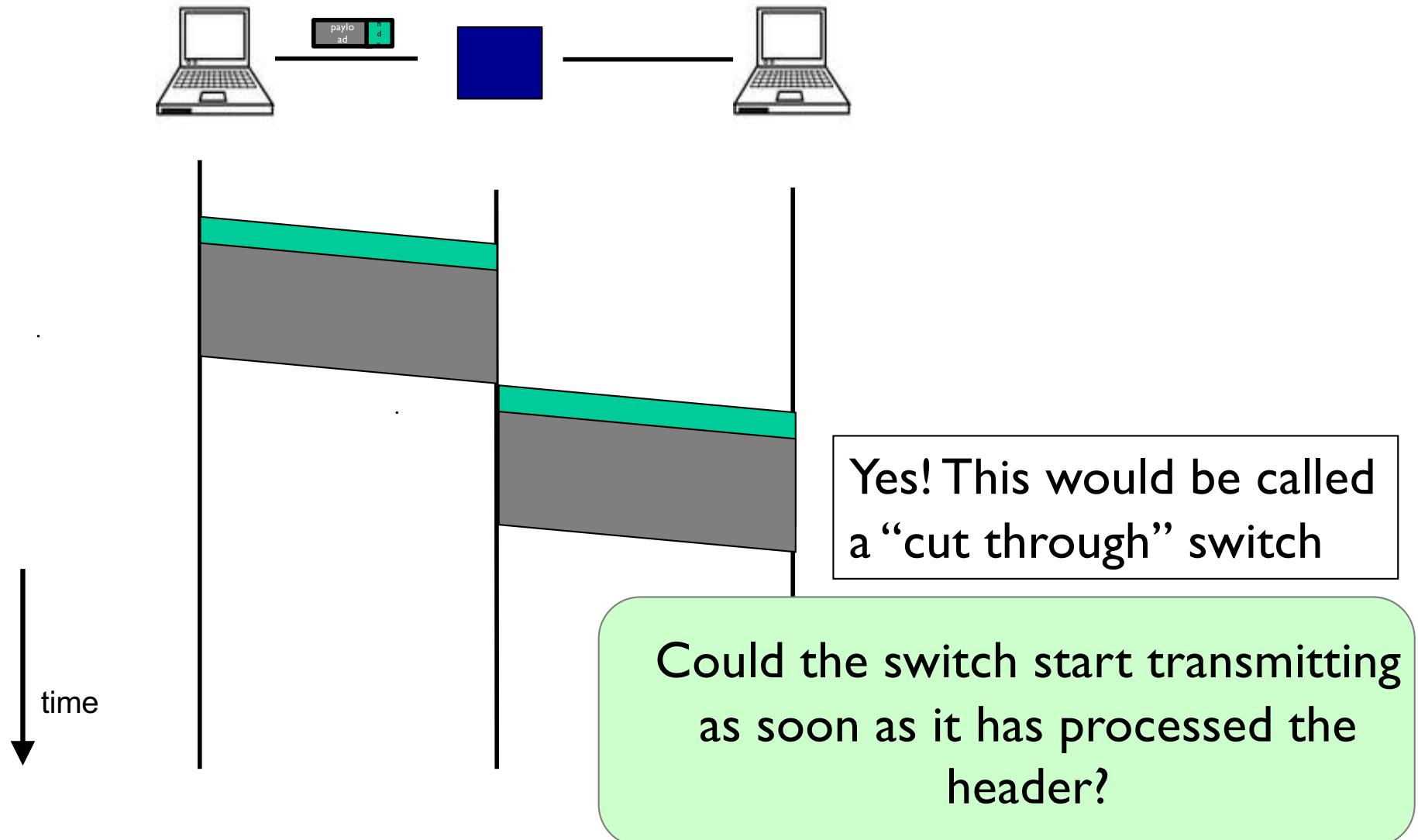


What about the time to process the packet at the switch?
• We'll assume it's relatively negligible (mostly true)

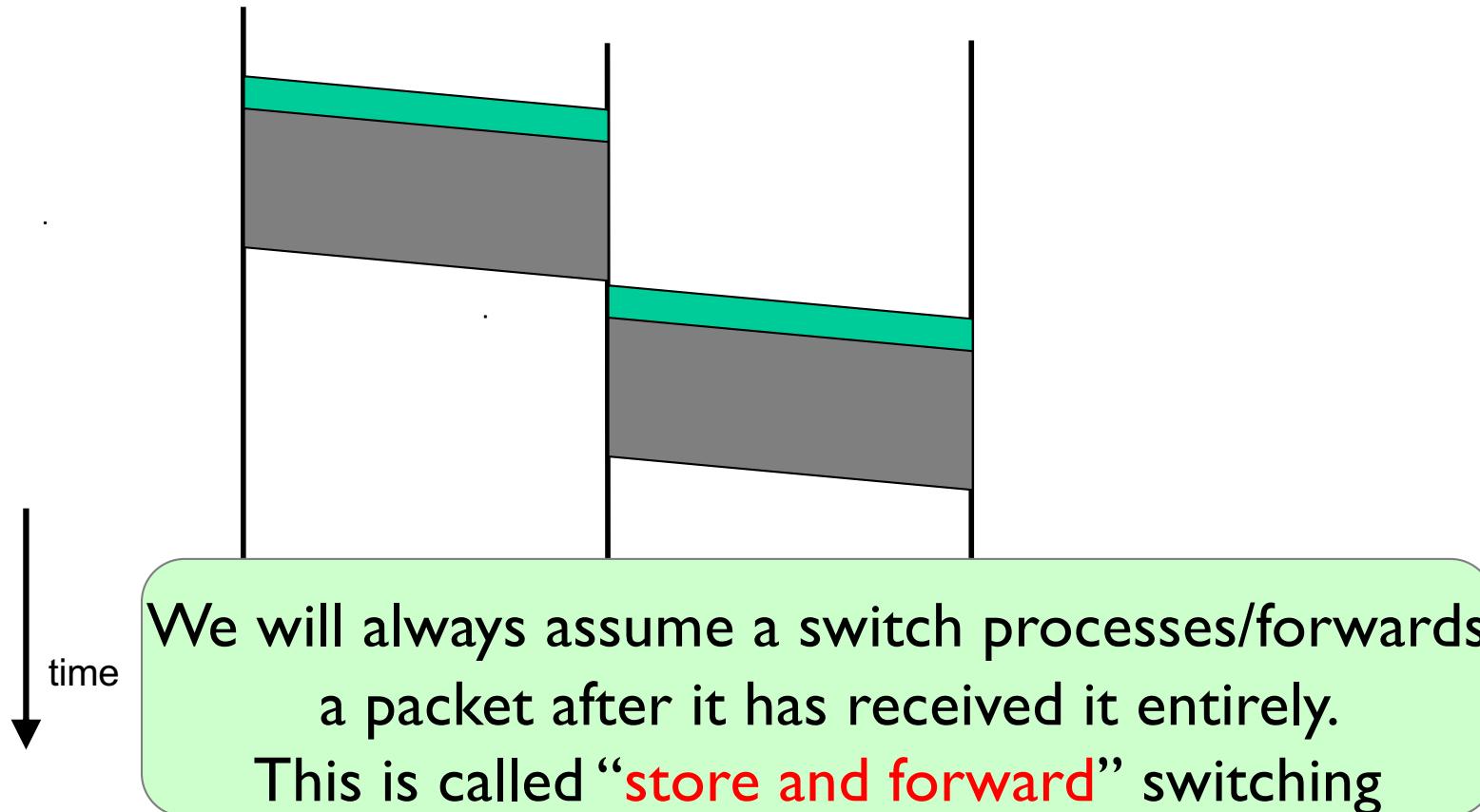
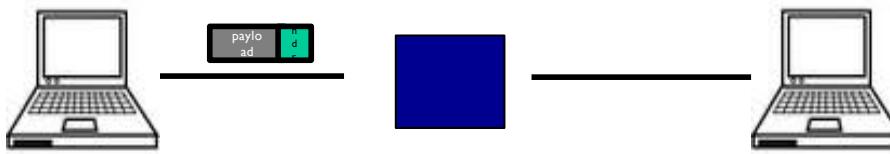
Timing in Packet Switching



Timing in Packet Switching



Timing in Packet Switching



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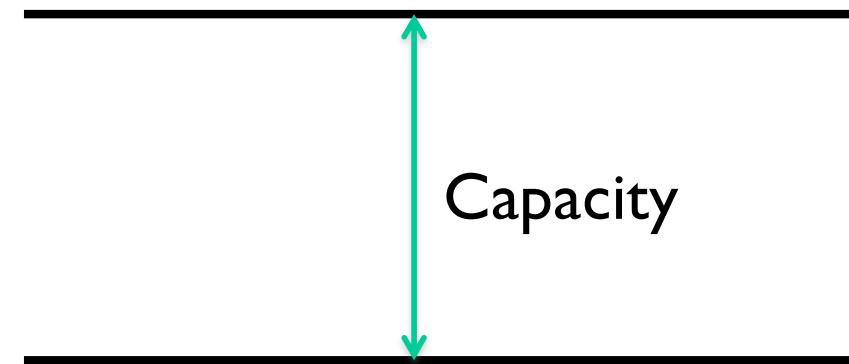
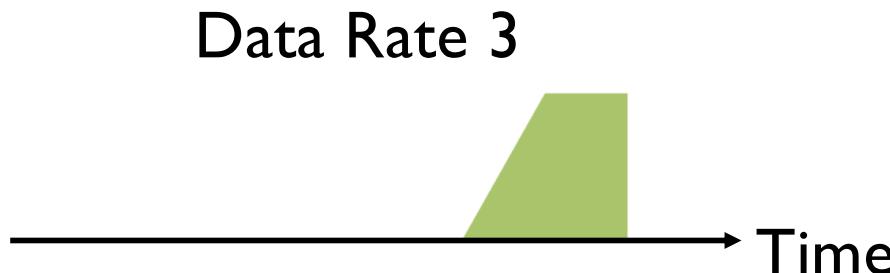
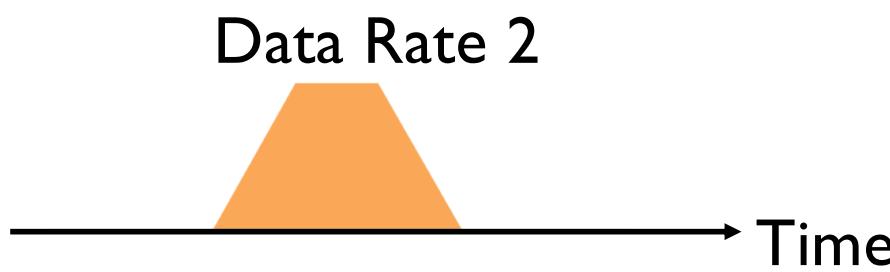
Packet Switching

- ❖ 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**
统计复用

Three Flows with Bursty Traffic



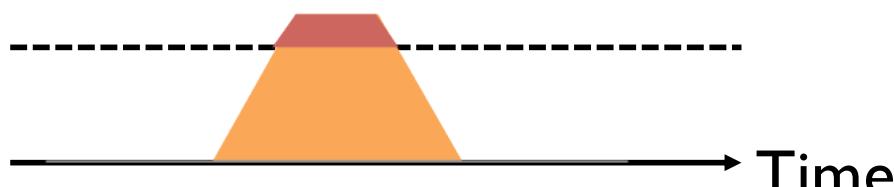
When Each Flow Gets 1/3rd of Capacity

Data Rate 1

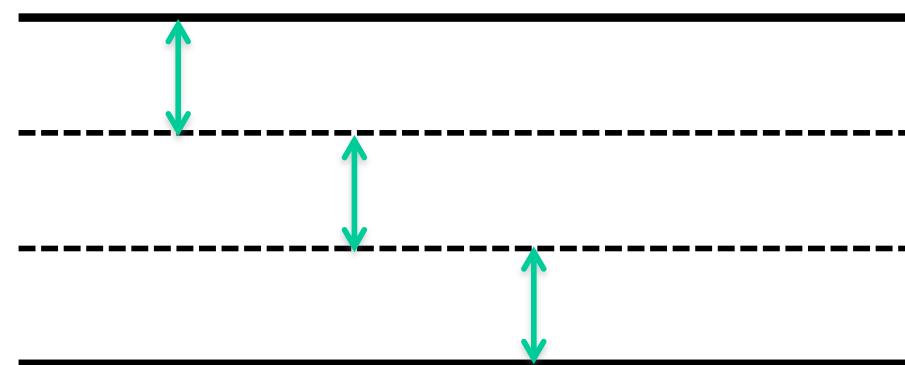
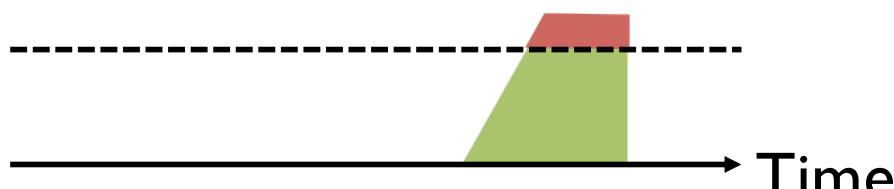
Frequent Overloading



Data Rate 2



Data Rate 3



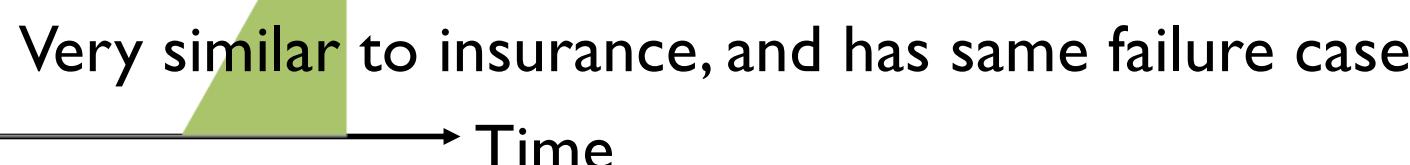
When Flows Share Total Capacity



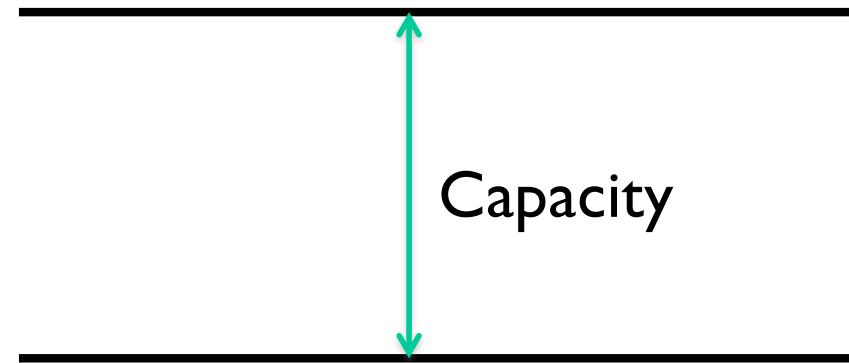
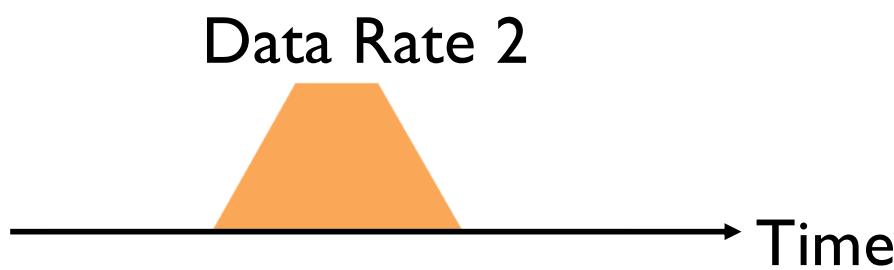
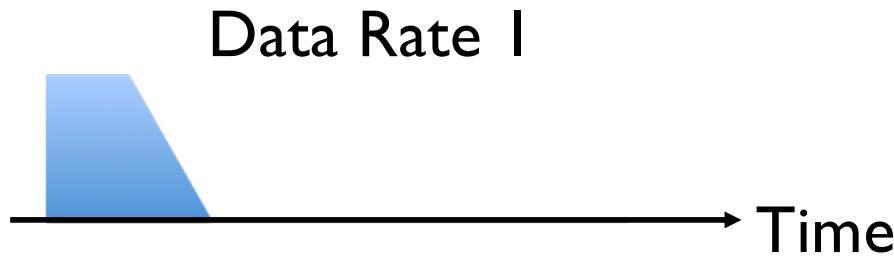
No Overloading



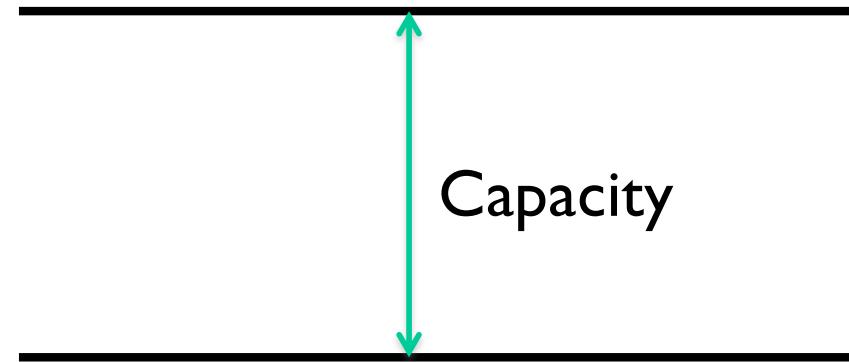
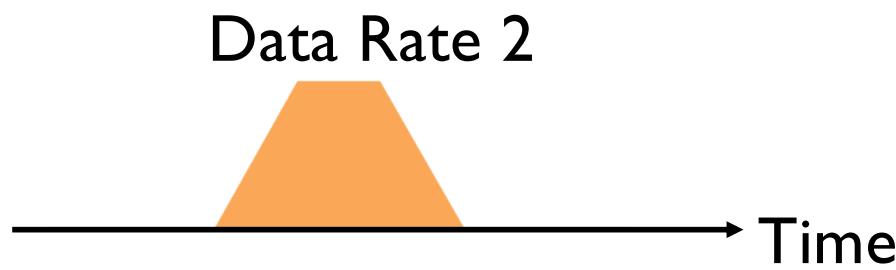
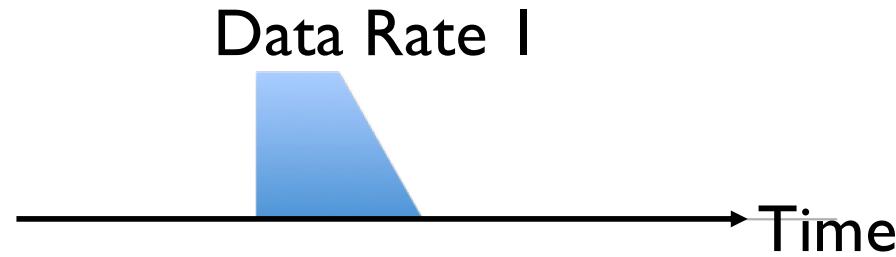
Statistical multiplexing relies on the assumption
that not all flows burst at the same time.



Three Flows with Bursty Traffic

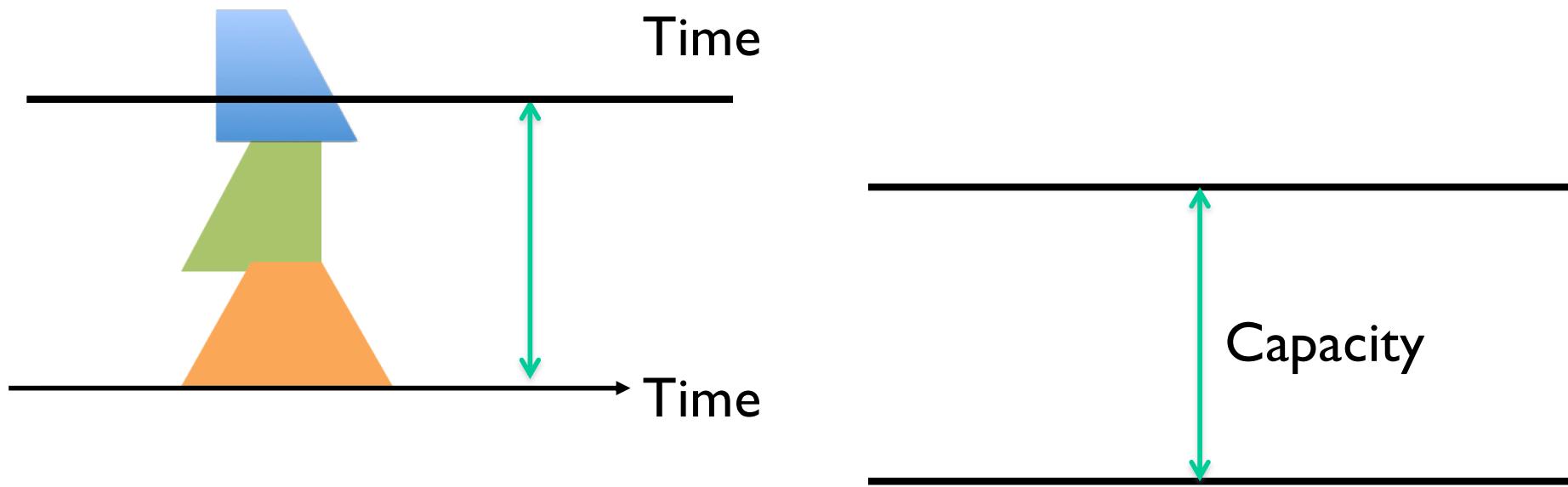


Three Flows with Bursty Traffic



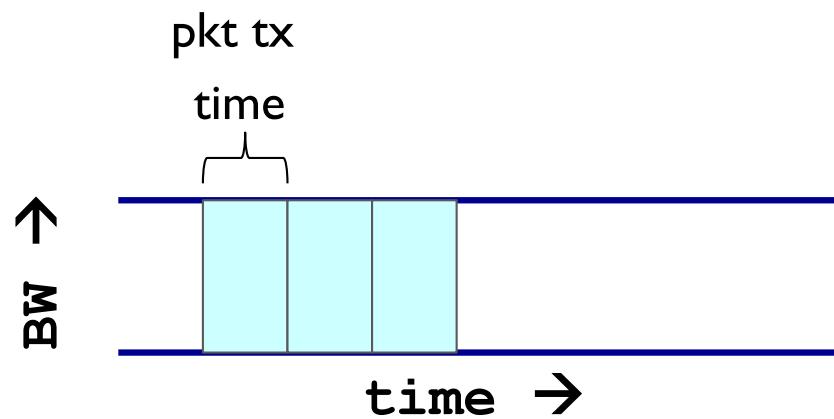
Three Flows with Bursty Traffic

Data Rate 1+2+3 >> Capacity

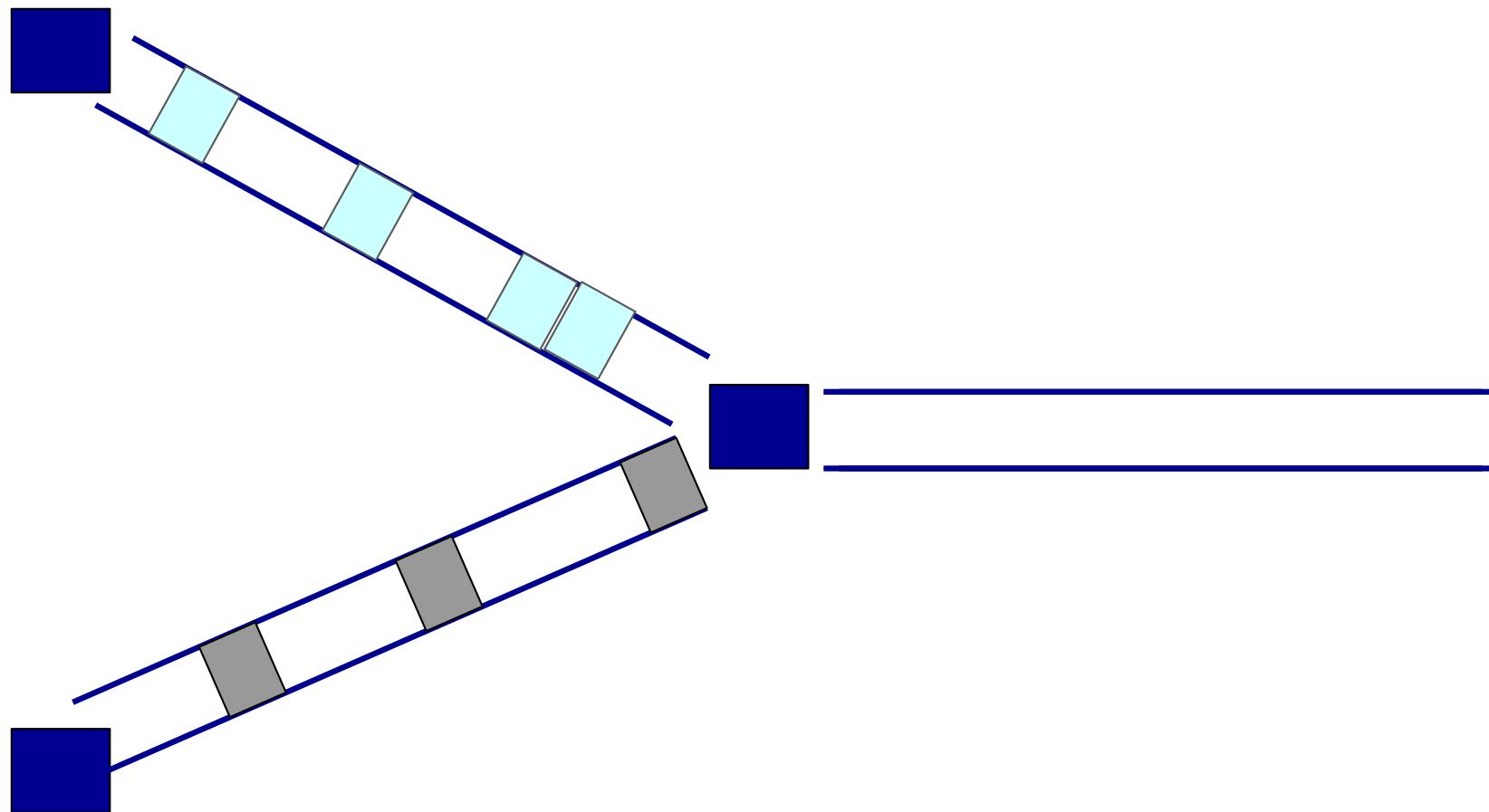


What do we do under overload?

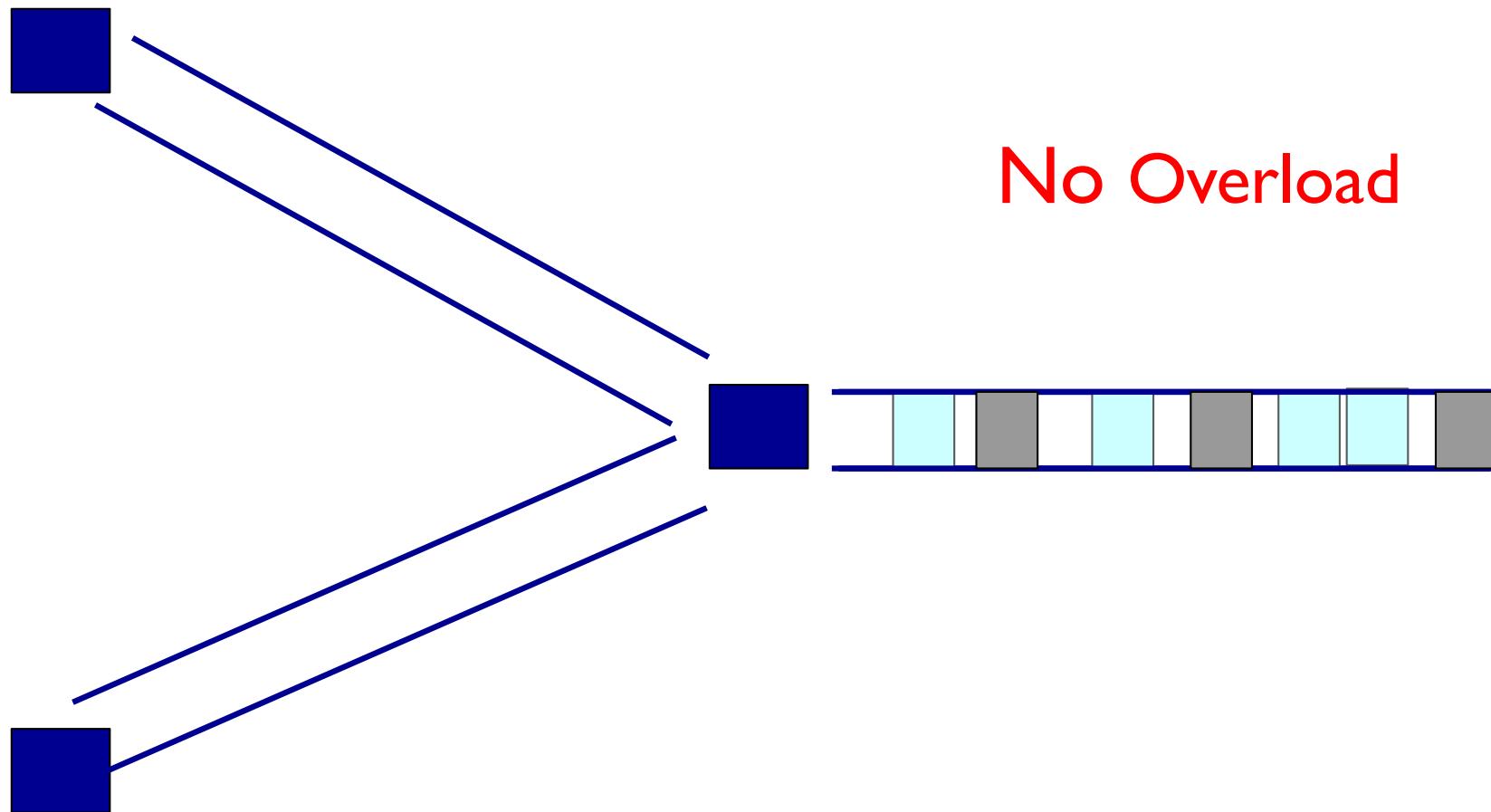
Statistical multiplexing: pipe view



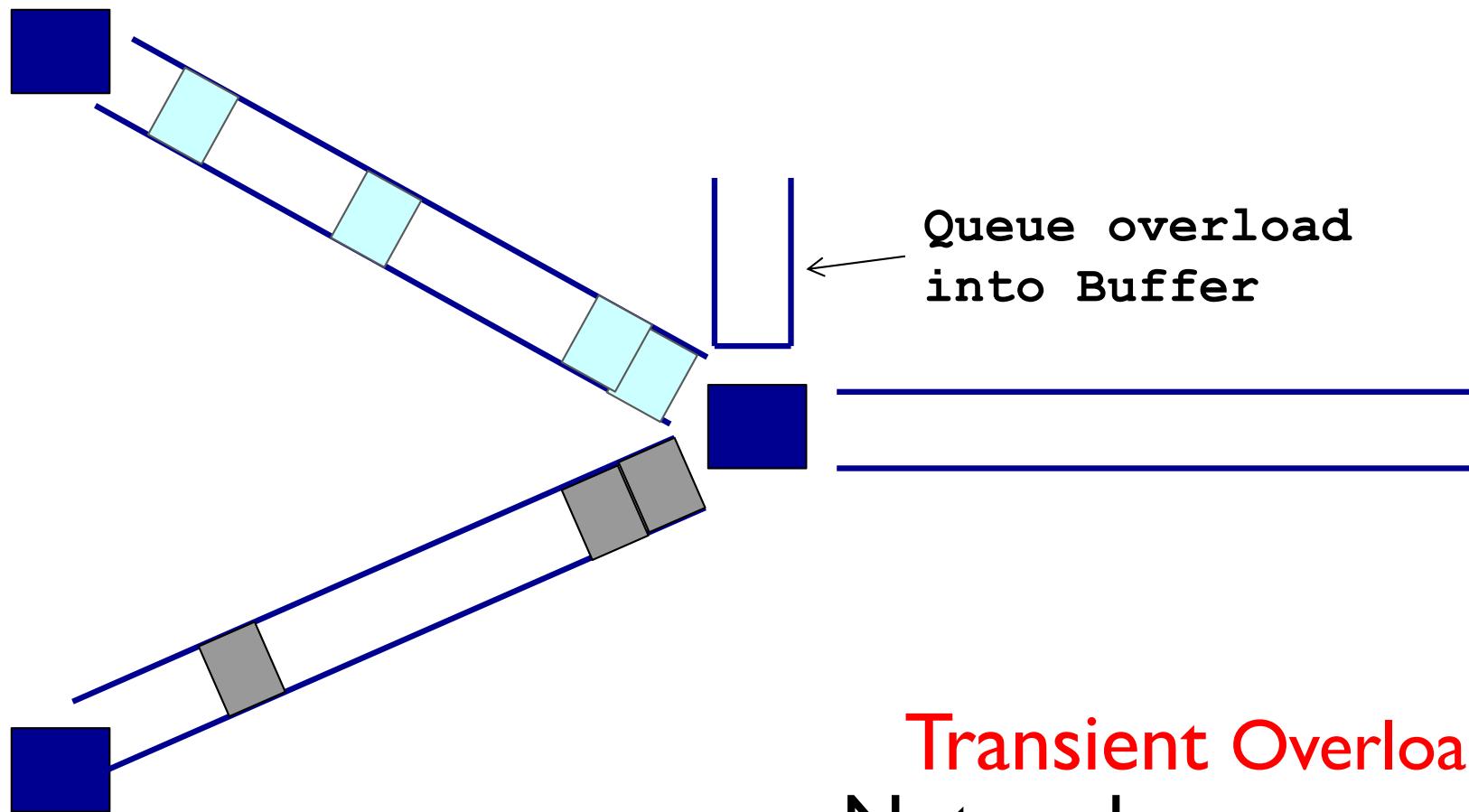
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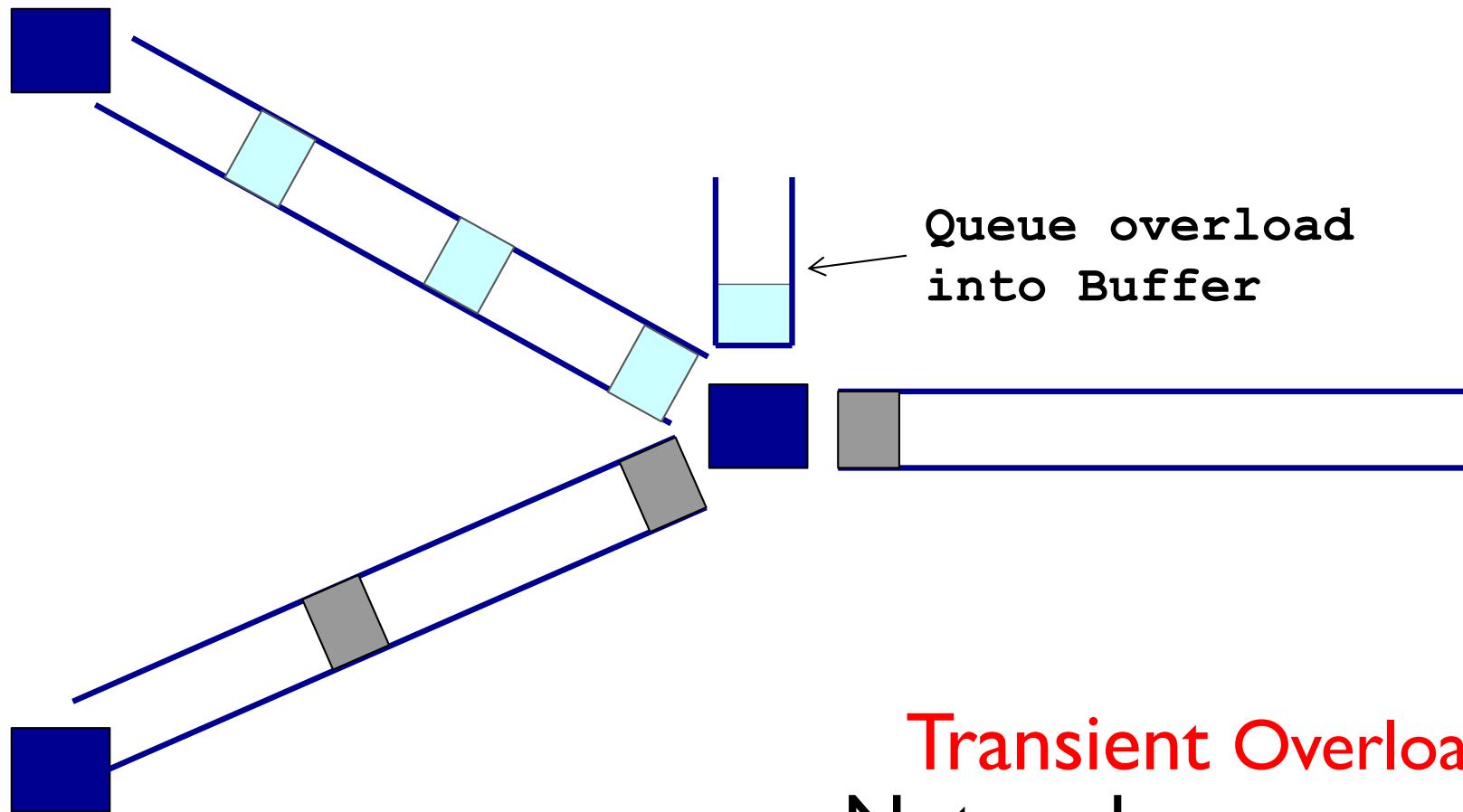
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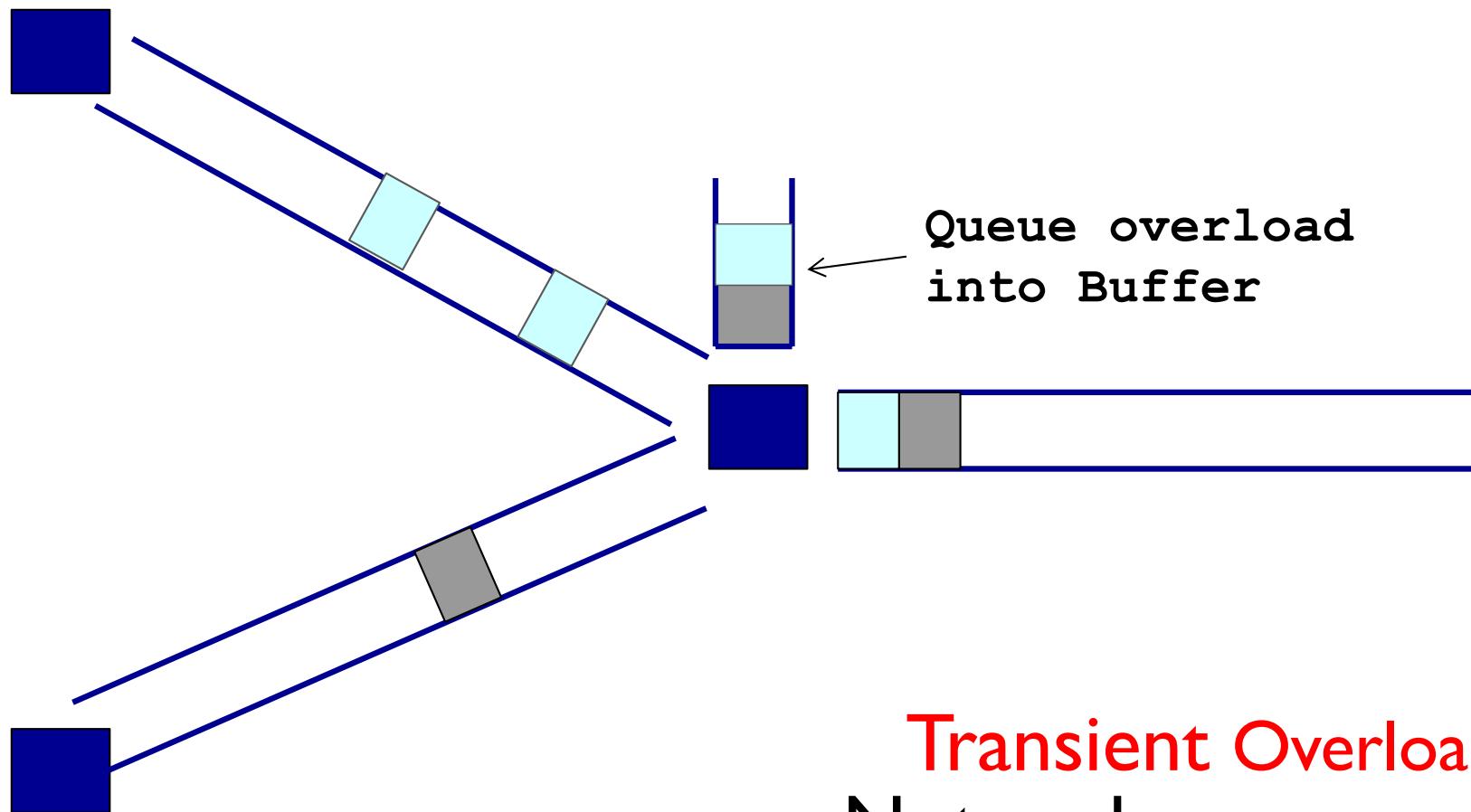
Statistical multiplexing: pipe view



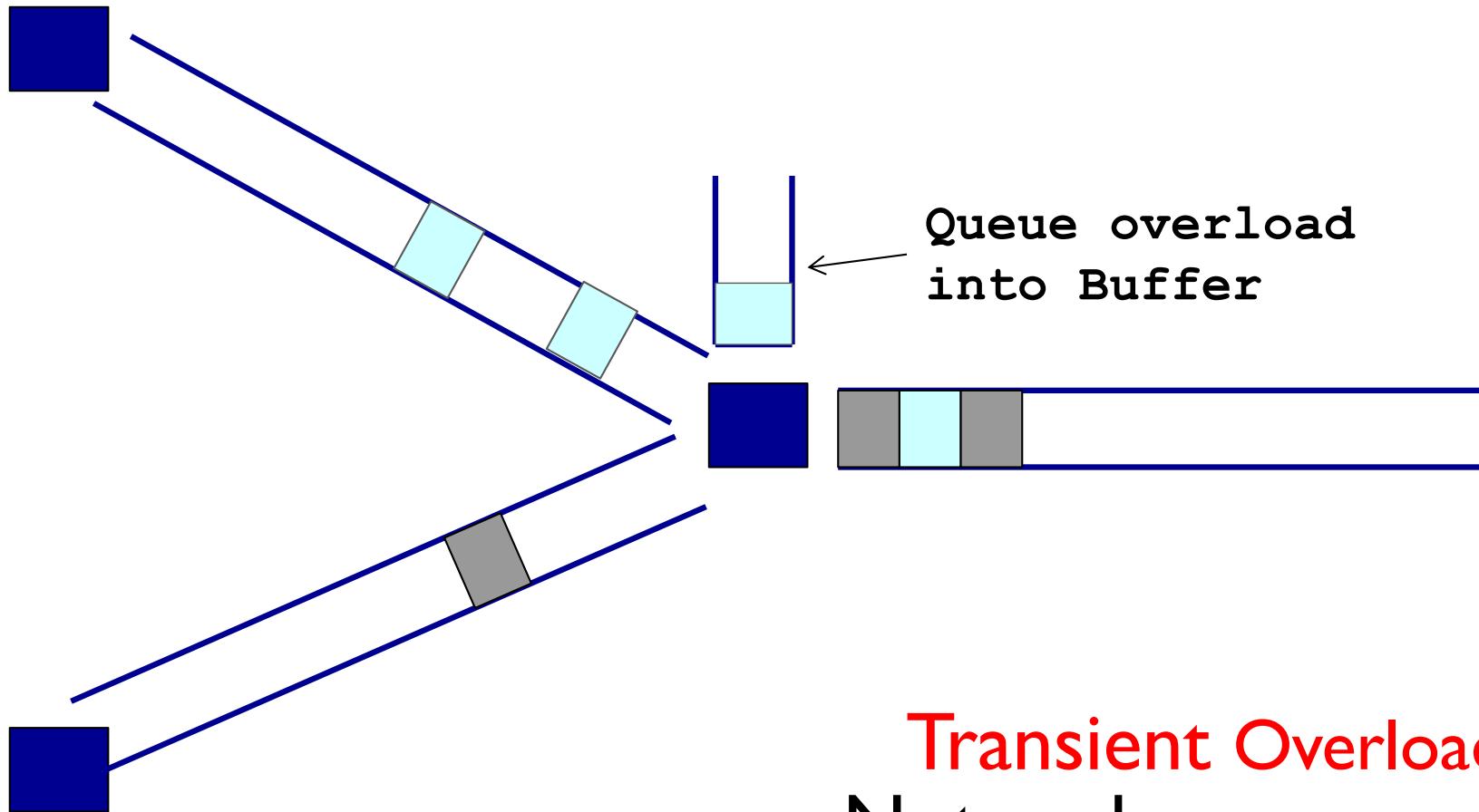
Statistical multiplexing: pipe view



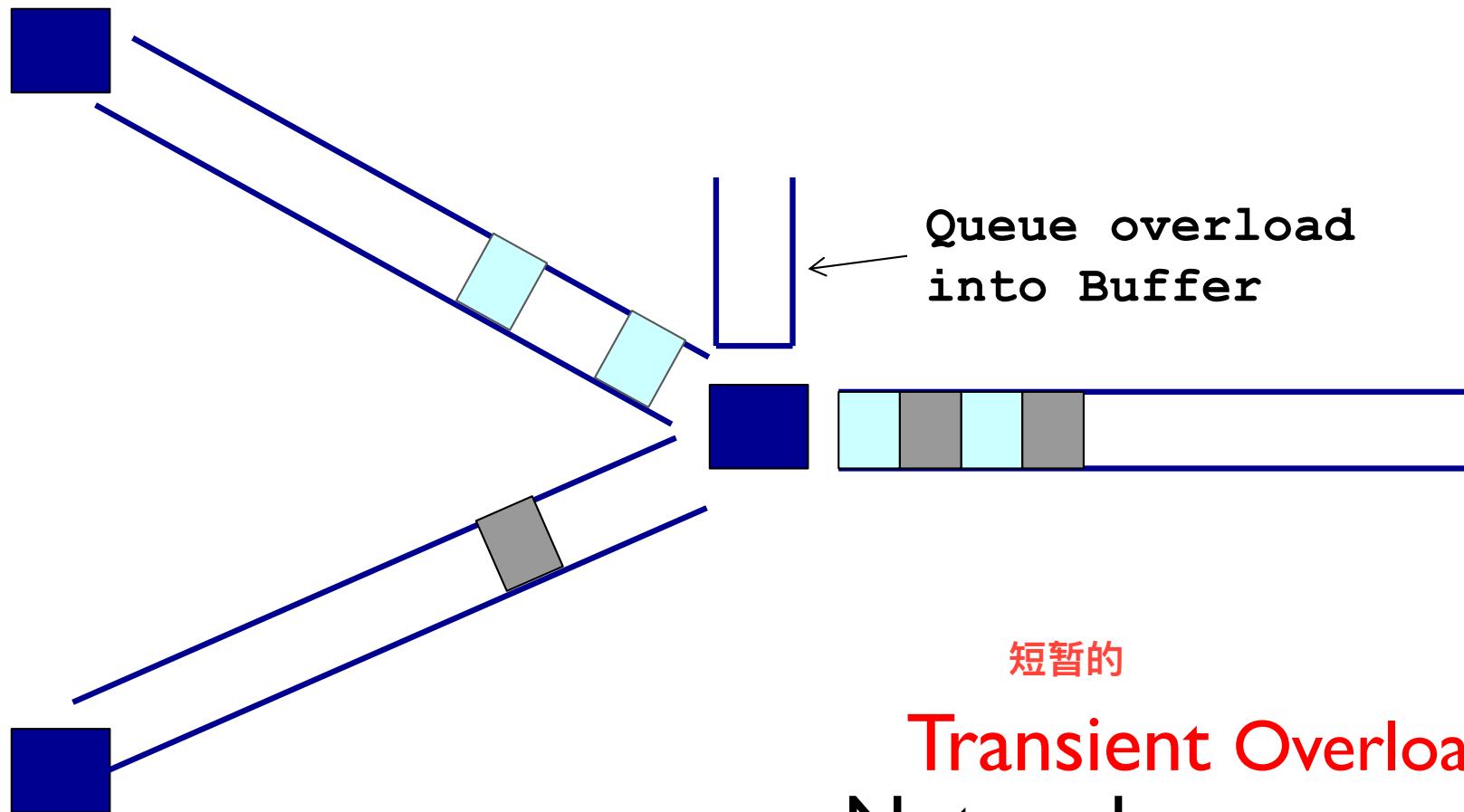
Statistical multiplexing: pipe view



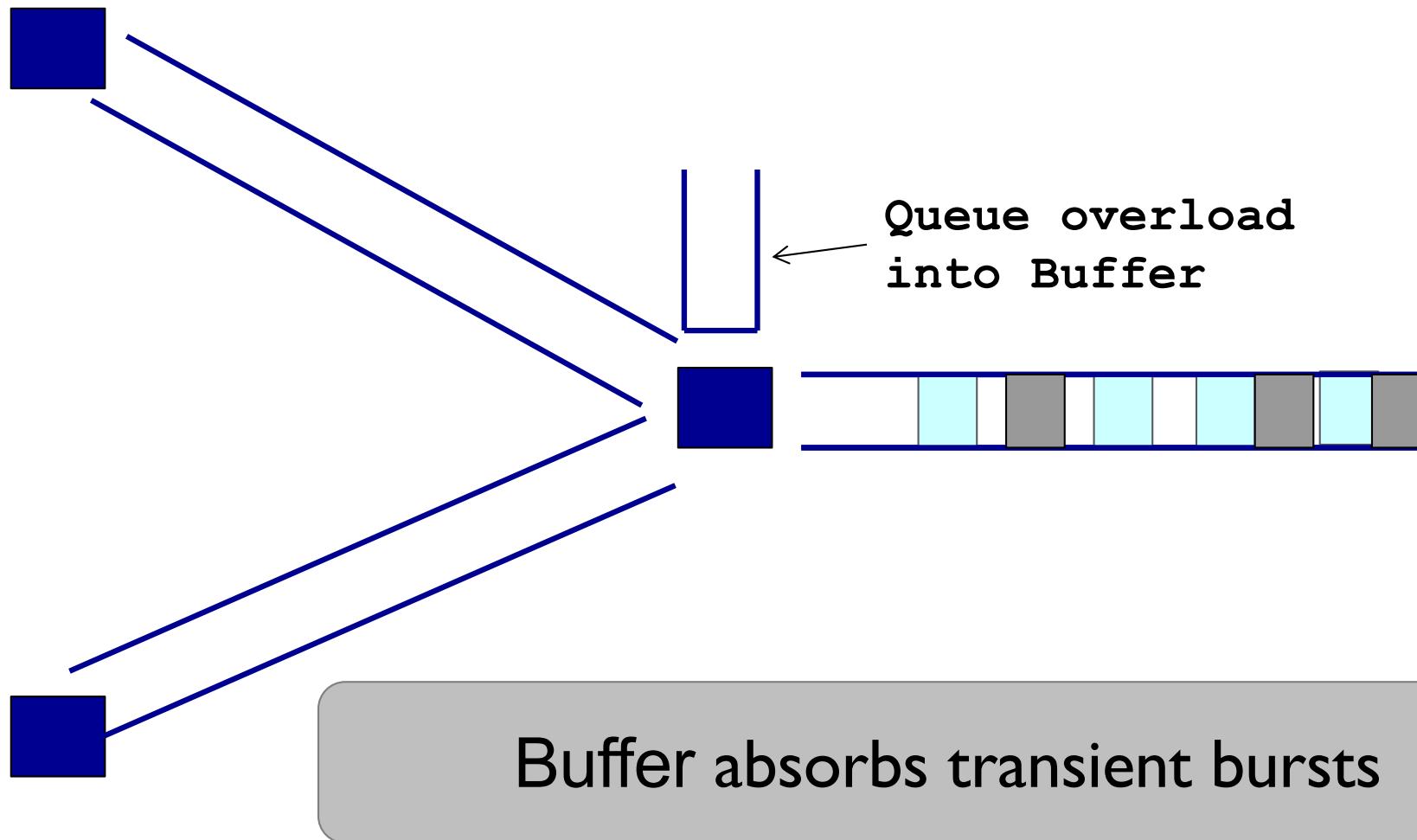
Statistical multiplexing: pipe view



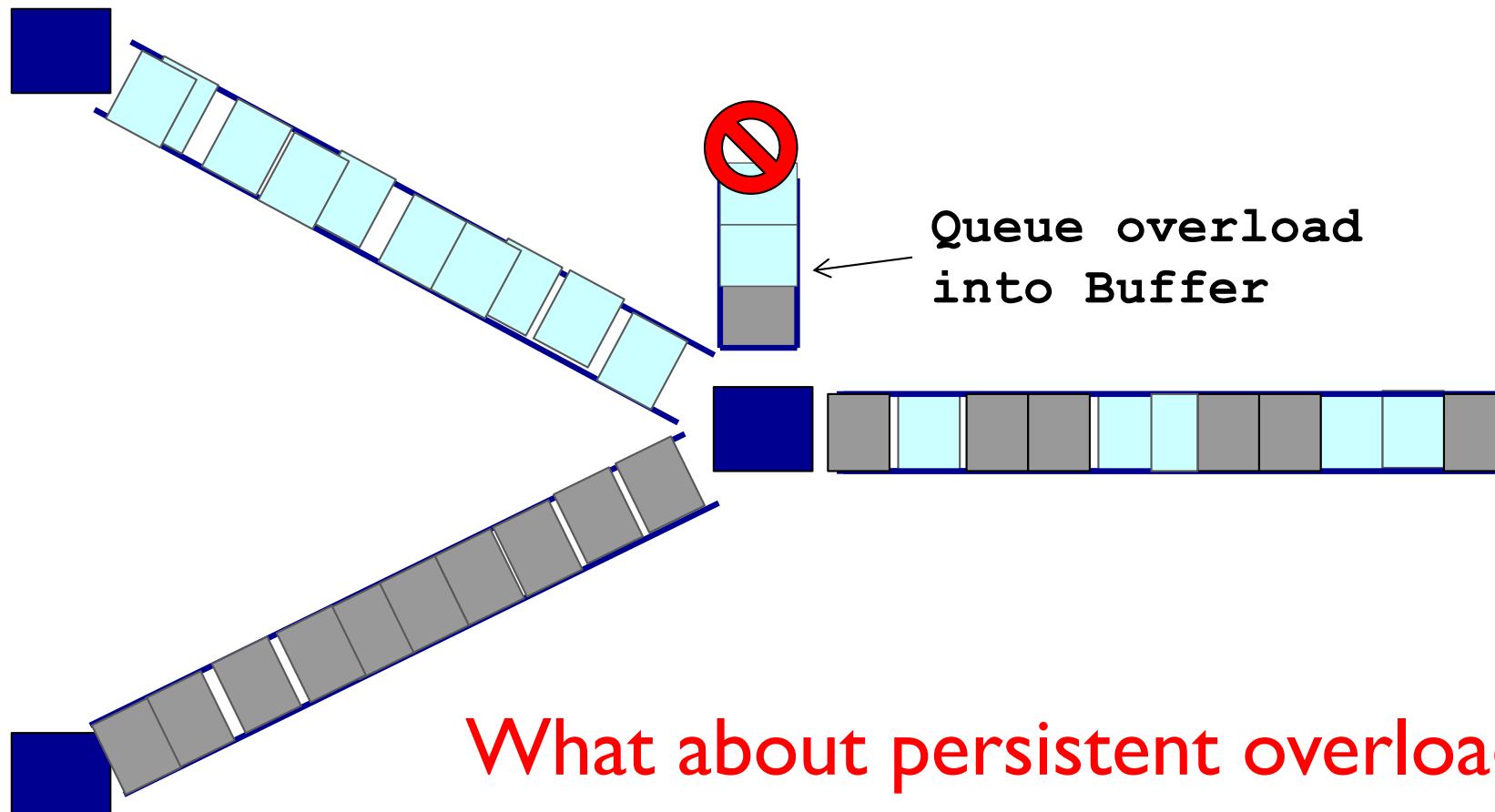
Statistical multiplexing: pipe view



Statistical multiplexing: pipe view



Statistical multiplexing: pipe view





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

- ❖ Pros:

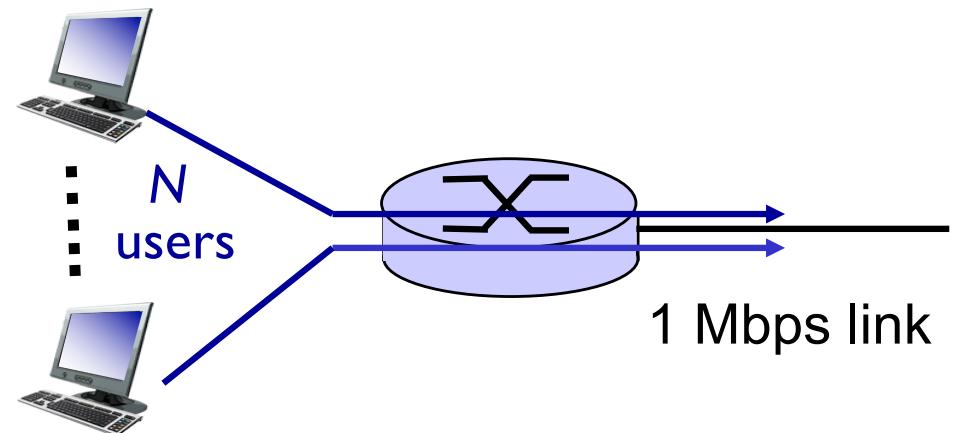
- ❖ Cons:

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

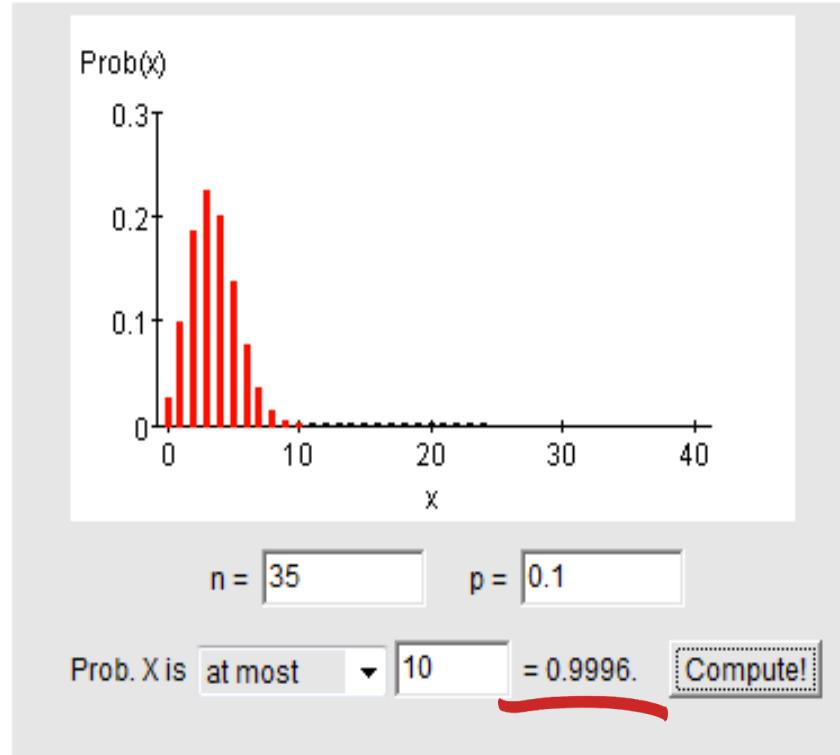
$$\binom{n}{k} = \frac{n!}{k!(n - k)!}$$

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

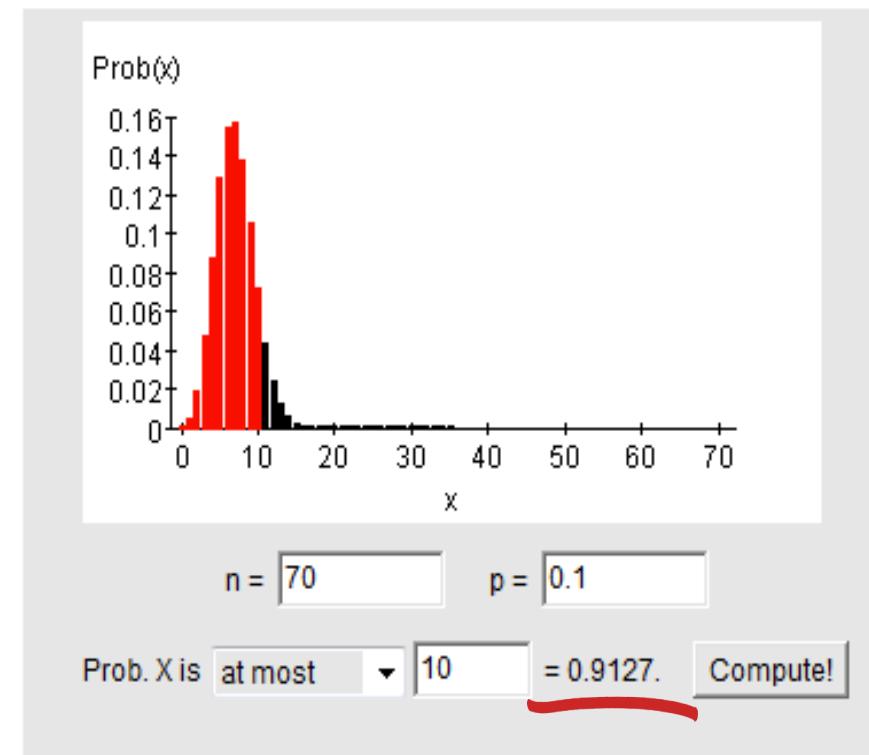
$$F(k; n, p) = \Pr(X \leq k) = \sum_{i=0}^{\lfloor k \rfloor} \binom{n}{i} p^i (1 - p)^{n-i}$$

Statistical Multiplexing Gain (SMG)

Binomial Calculator



Binomial Calculator



$$\text{SMG: } 35/10=3.5$$

$$\text{SMG: } 70/10=7$$

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



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

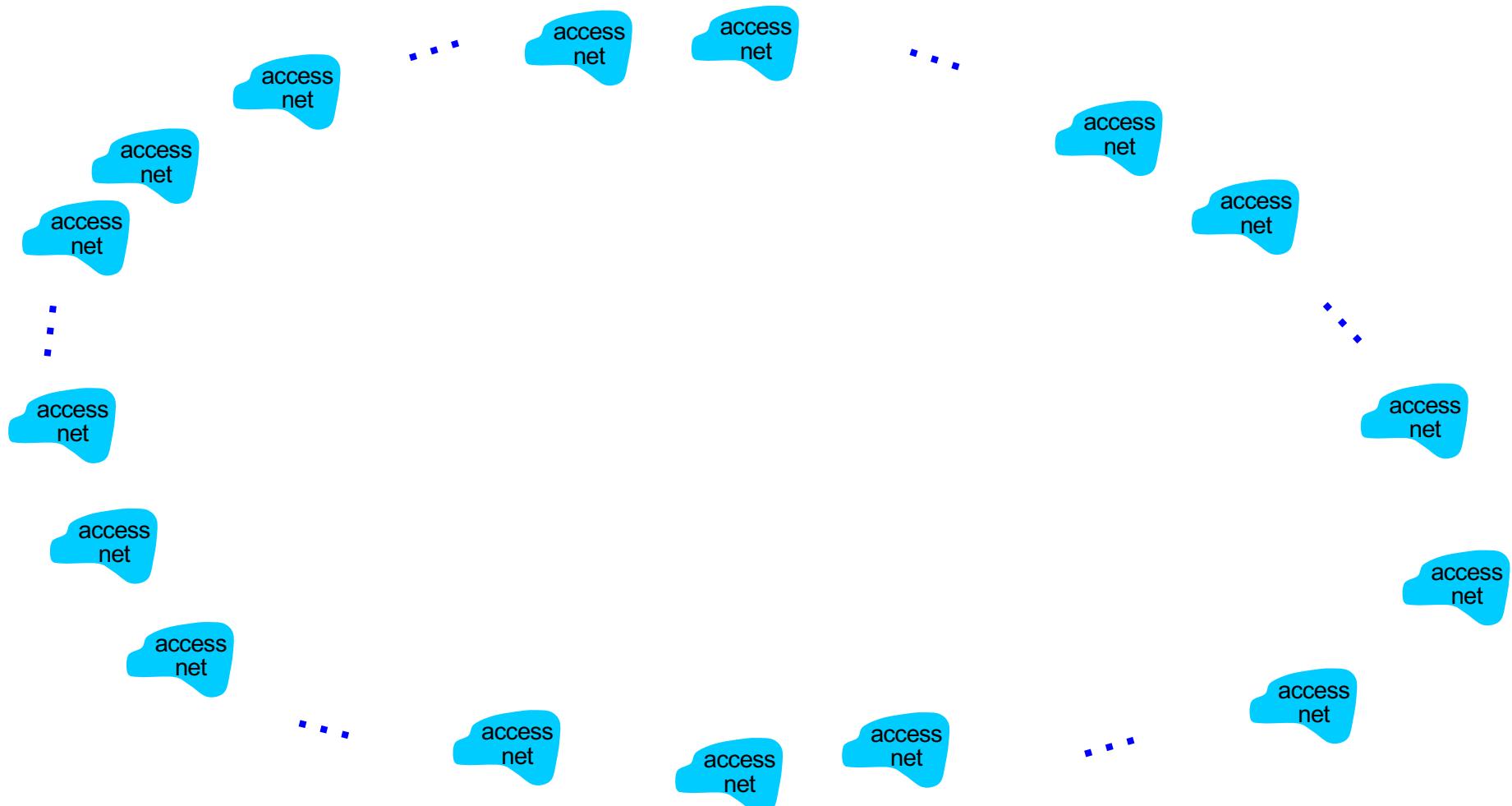
- A. is the same
- B. is independent
- C. is always different from

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

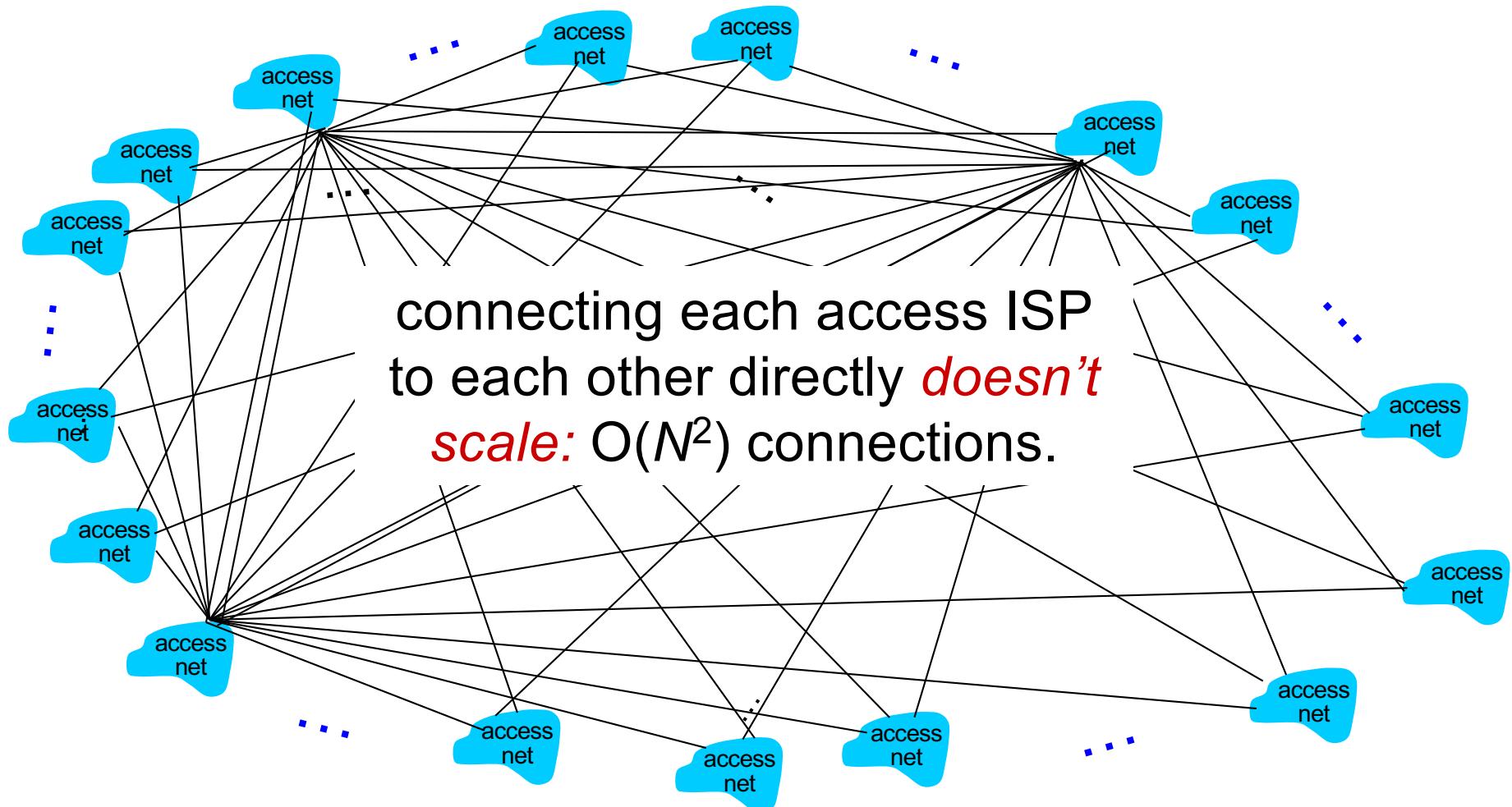
Internet structure: network of networks

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



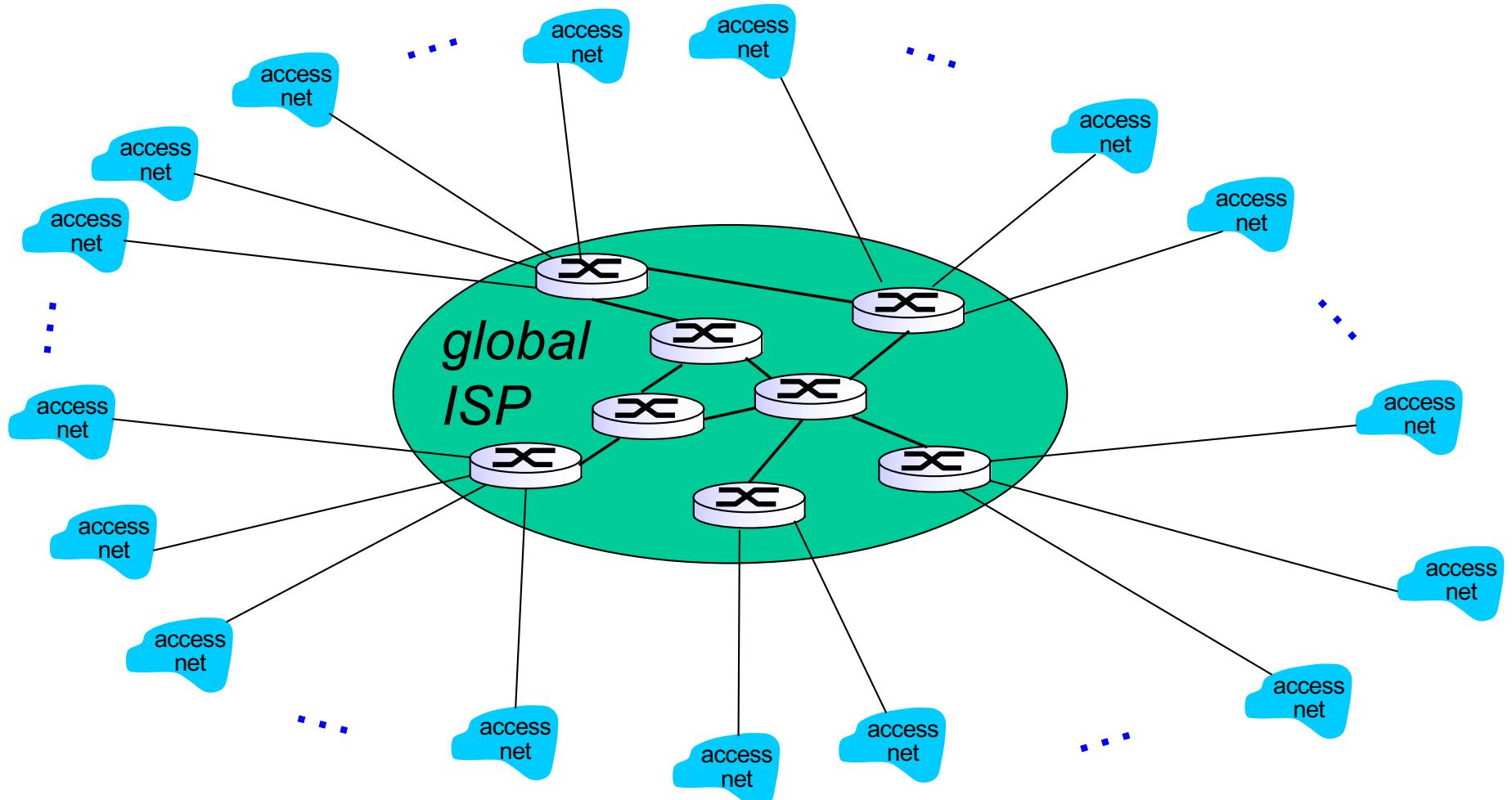
Internet structure: network of networks

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



Internet structure: network of networks

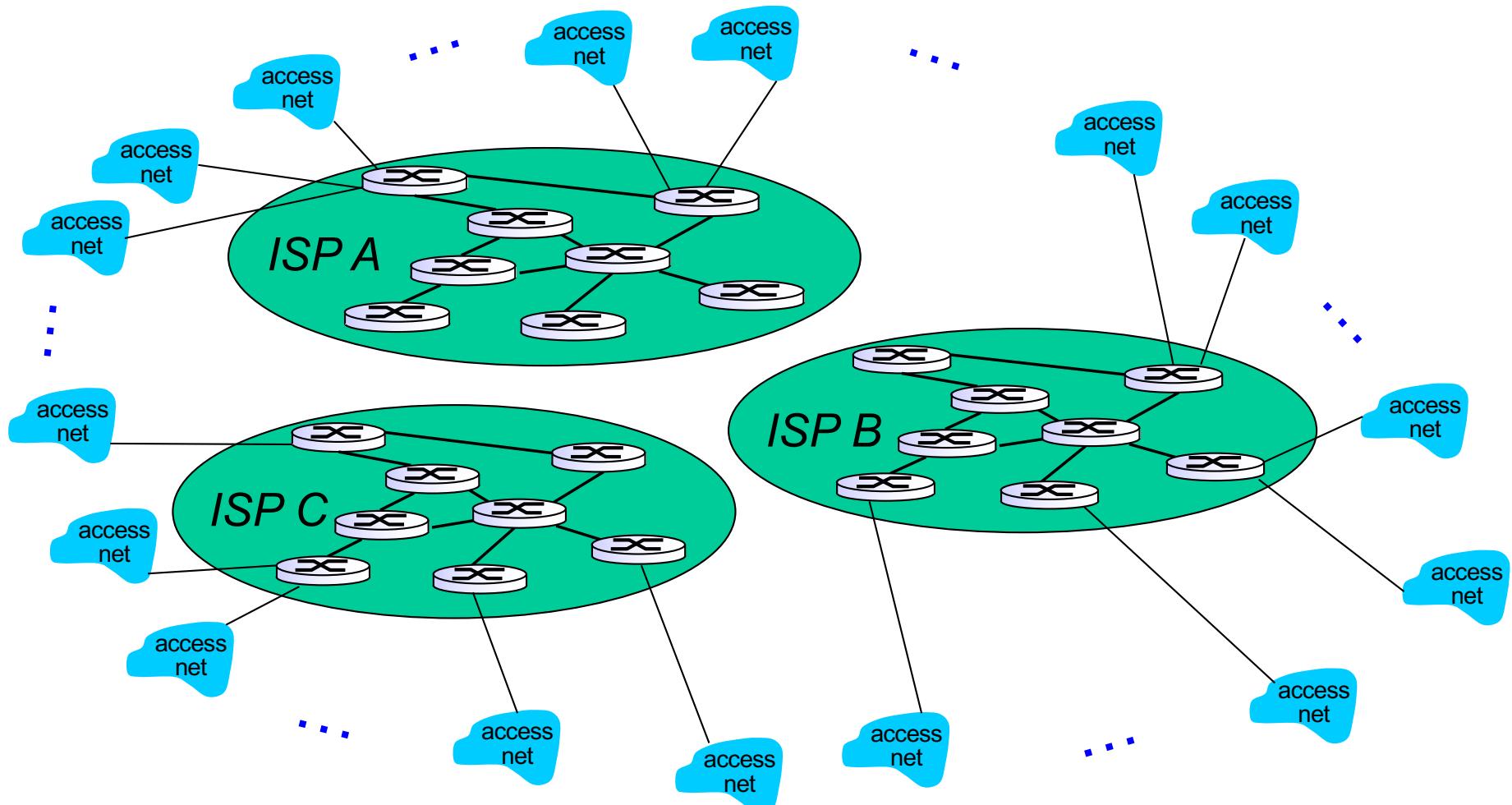
Option: connect each access ISP to a global transit ISP? *Customer and provider ISPs have economic agreement.*



Internet structure: network of networks

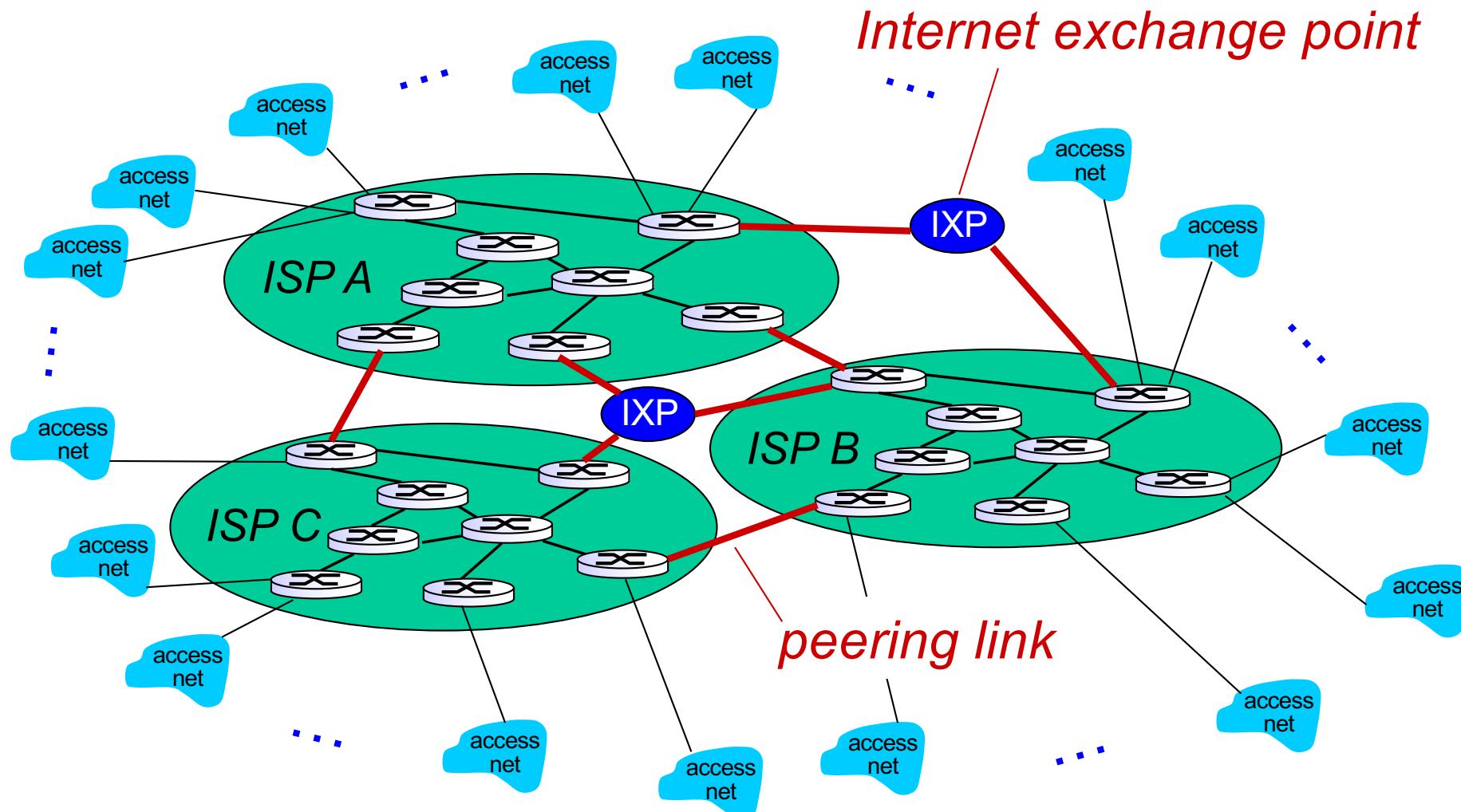
But if one global ISP is viable business, there will be competitors

....



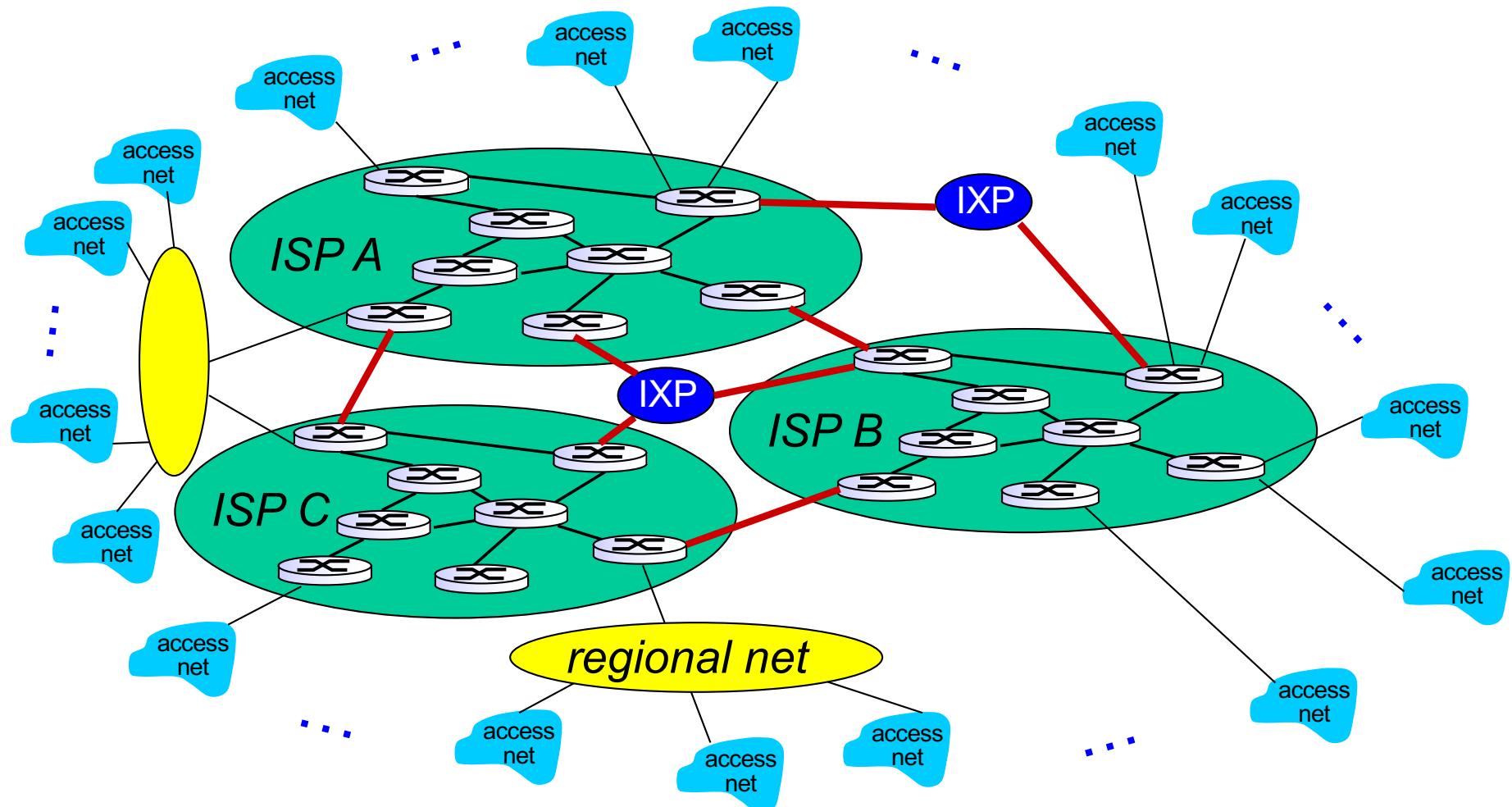
Internet structure: network of networks

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



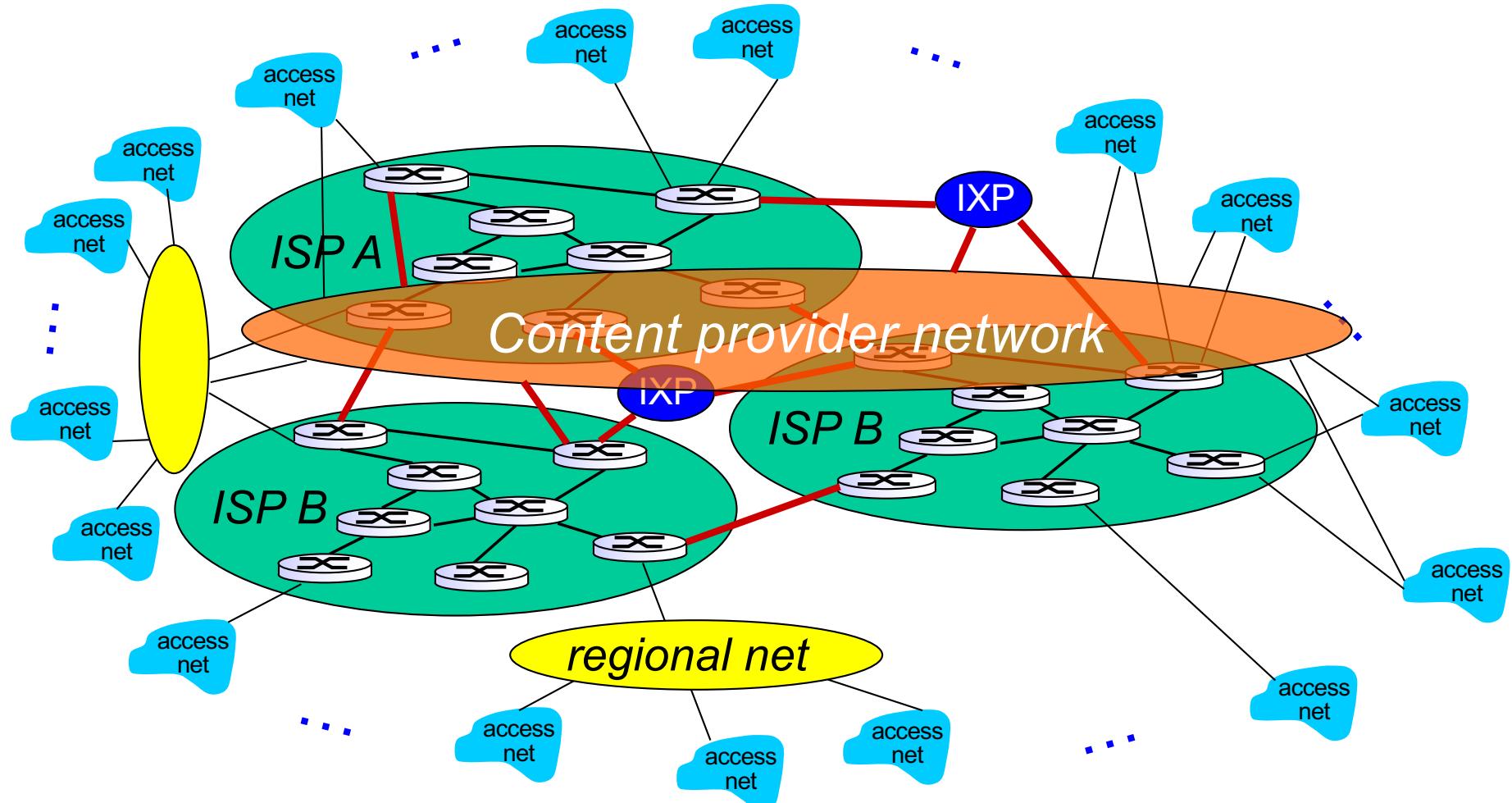
Internet structure: network of networks

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

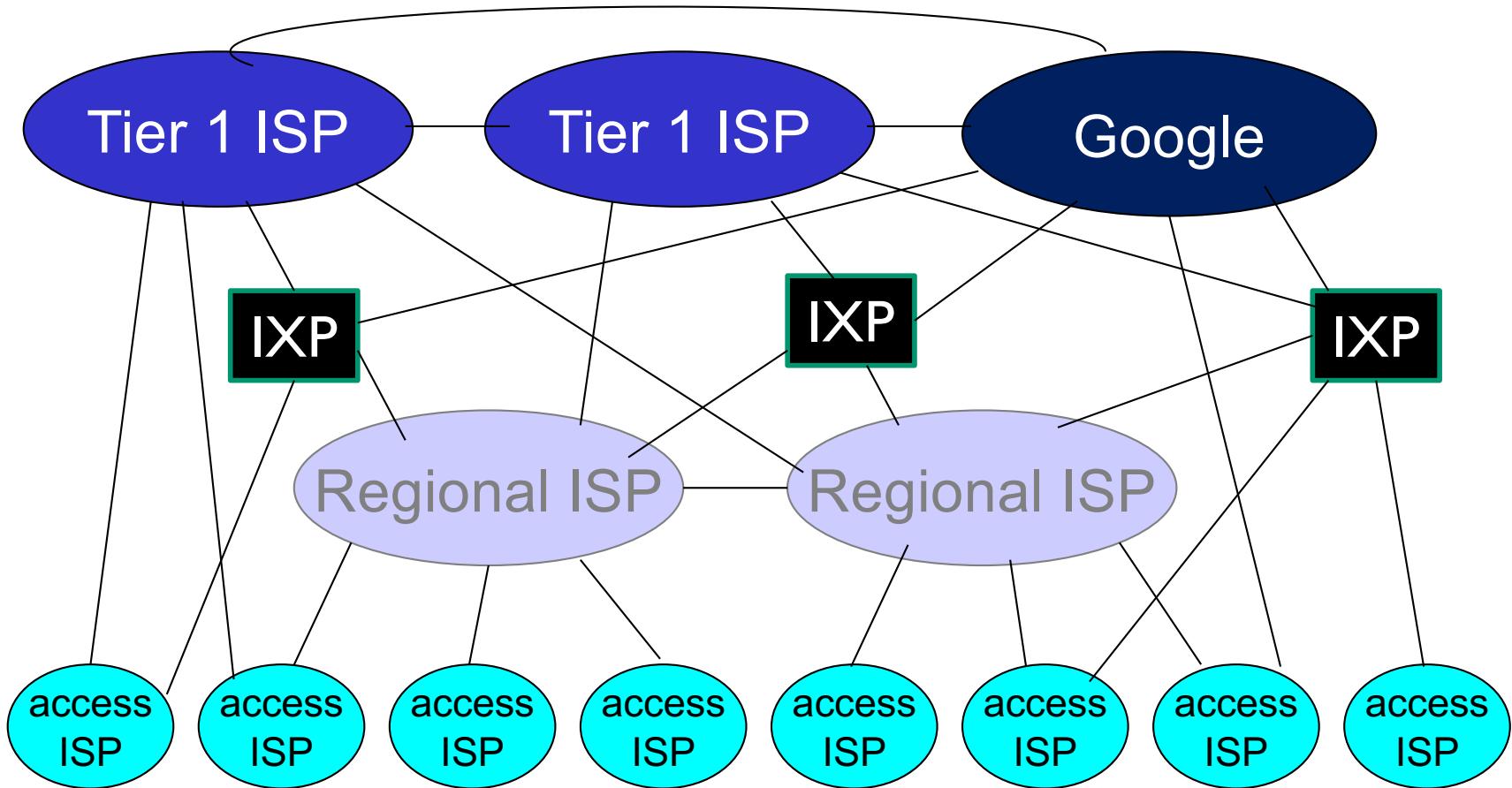


Internet structure: network of networks

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



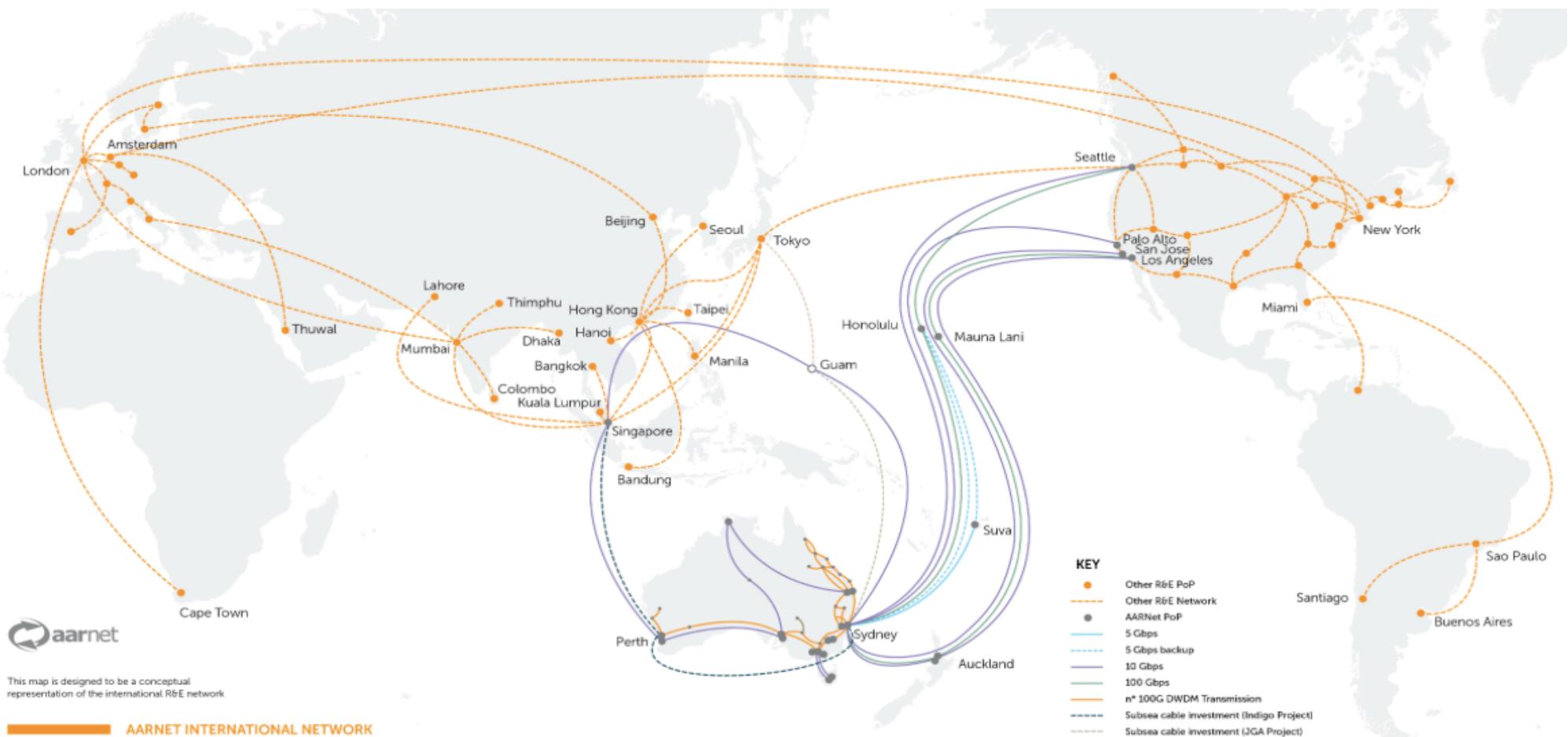
Internet structure: network of networks



- ❖ 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

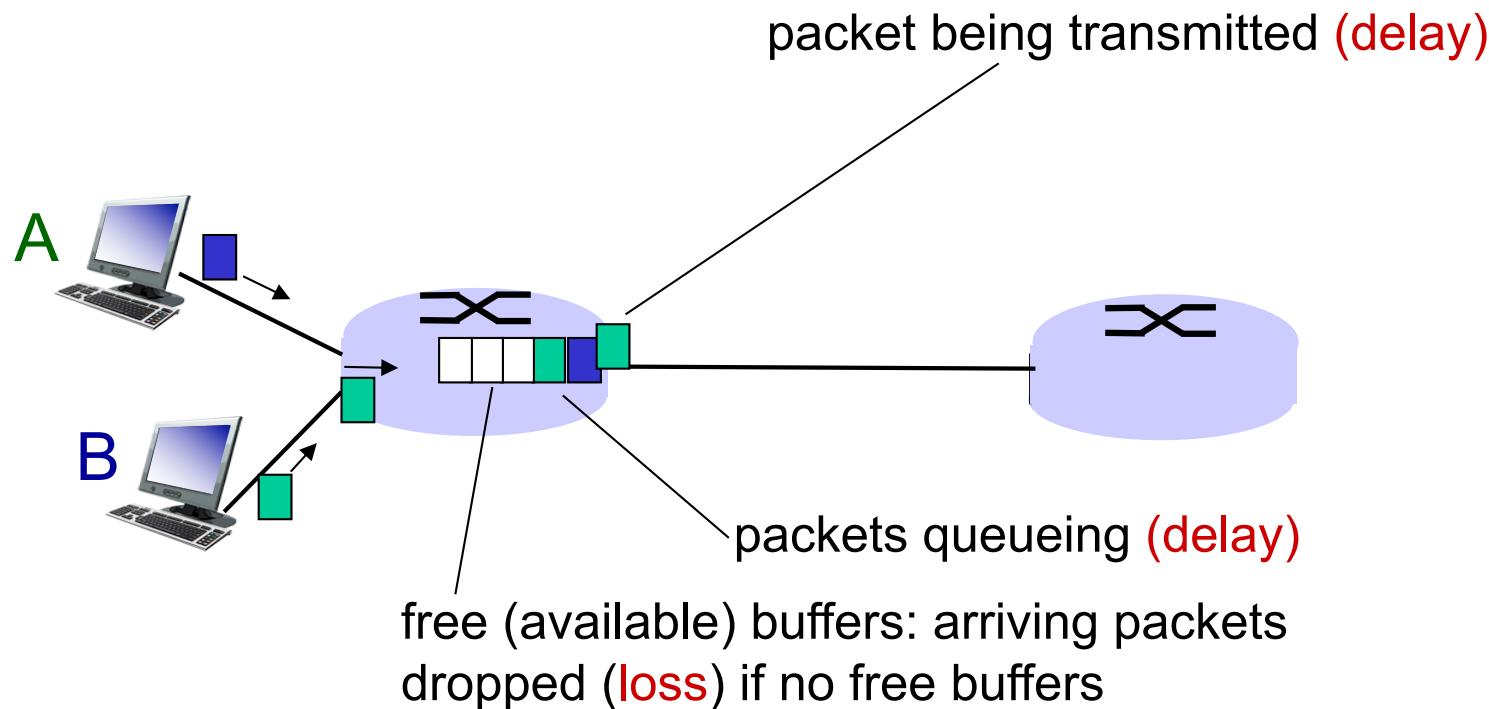
I.6 networks under attack: security

I.7 history

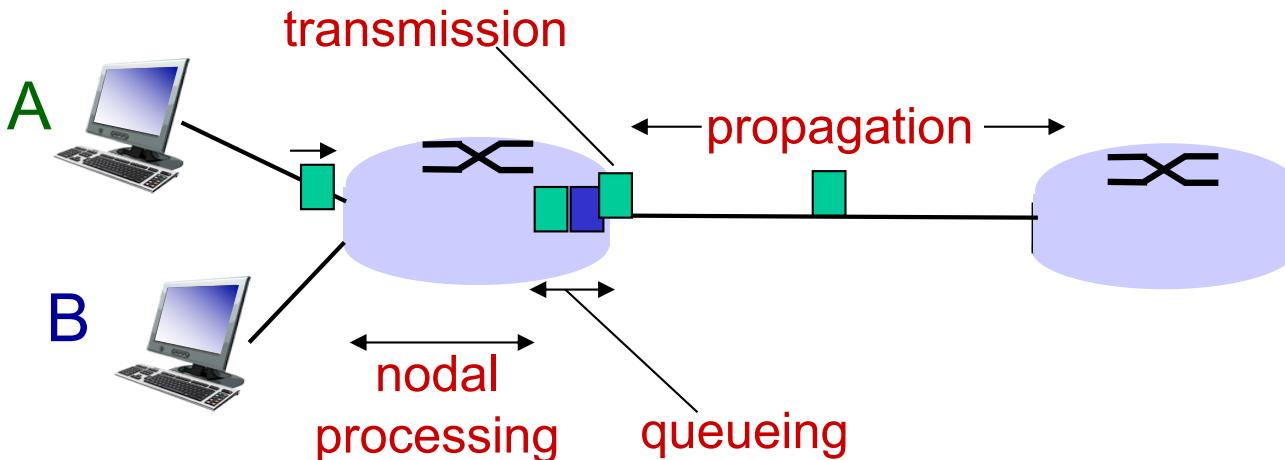
How do loss and delay occur?

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



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

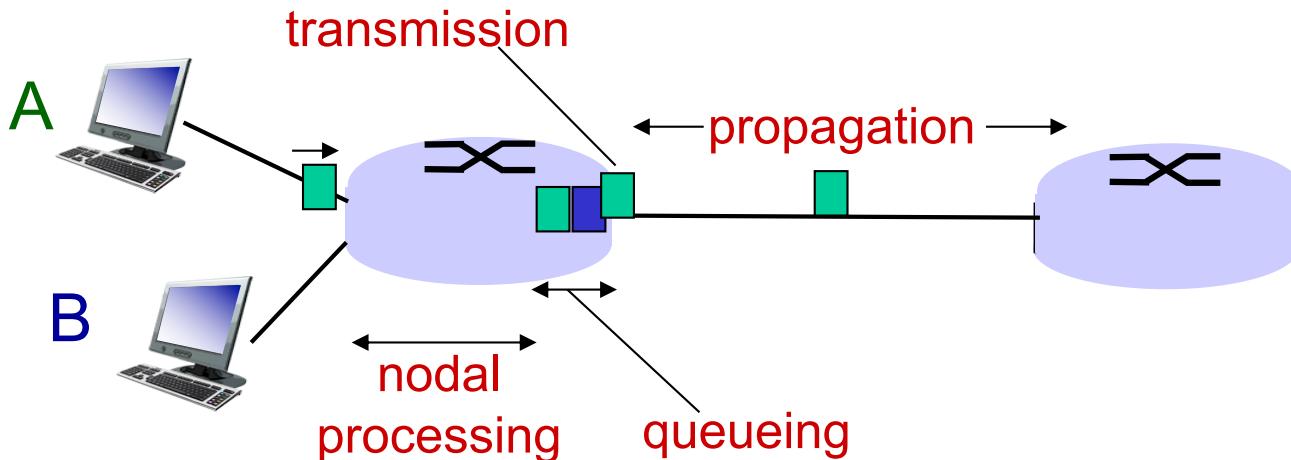
d_{proc} : nodal processing

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

d_{queue} : queueing delay

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

Four sources of packet delay



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

d_{trans} : transmission delay:

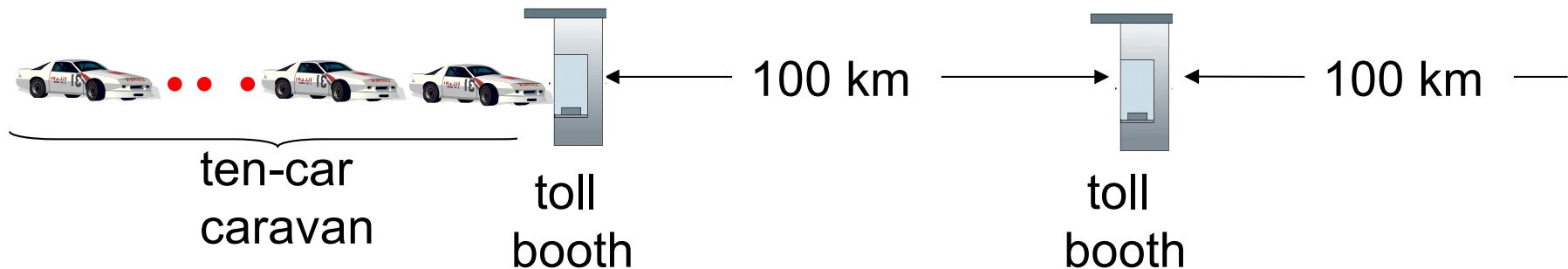
- L : packet length (bits)
- R : link bandwidth (bps)
- $d_{\text{trans}} = L/R$

d_{trans} and d_{prop}
very different

d_{prop} : propagation delay:

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

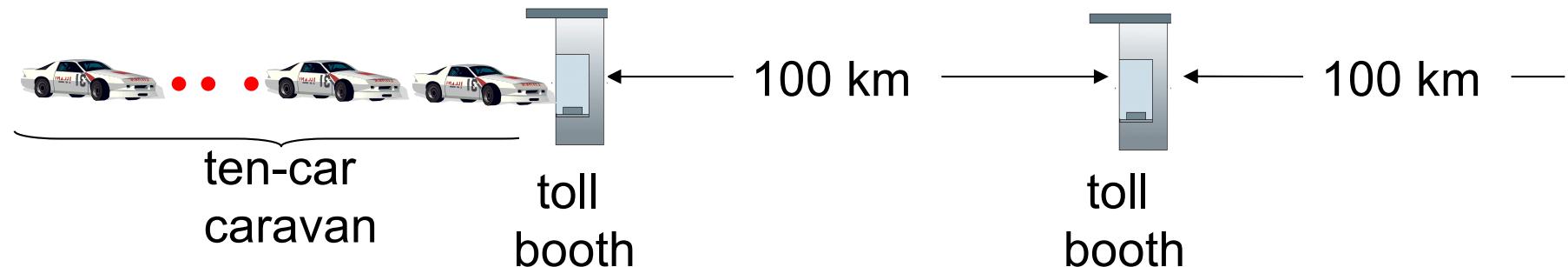
Caravan analogy



- 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?

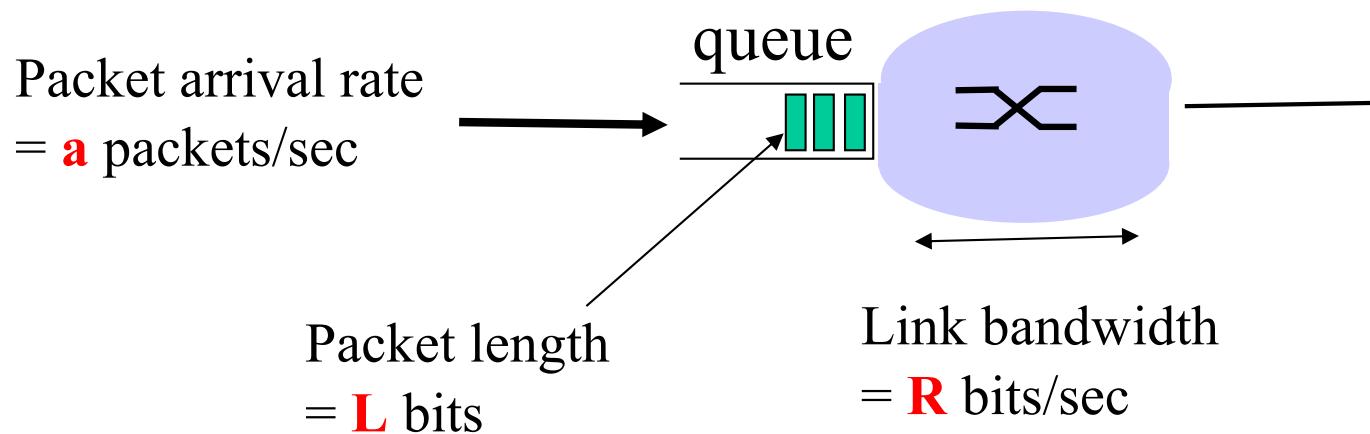
- time to “push” entire caravan through toll booth onto highway = $12*10 = 120$ sec
- time for last car to propagate from 1st to 2nd toll both:
 $100\text{km}/(100\text{km/hr}) = 1\text{ hr}$
- A: 62 minutes

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.

Queueing delay (more insight)

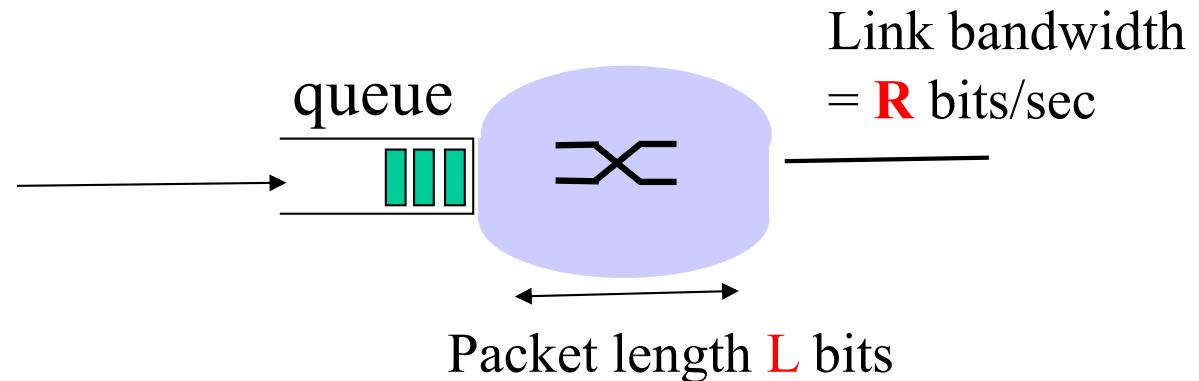


- ❖ Every second: aL bits arrive to queue
- ❖ Every second: R bits leave the router
- ❖ Question: what happens if $aL > R$?
- ❖ Answer: queue will fill up, and packets will get dropped!!

aL/R is called traffic intensity

Queueing delay: illustration

1 packet arrives
every L/R seconds



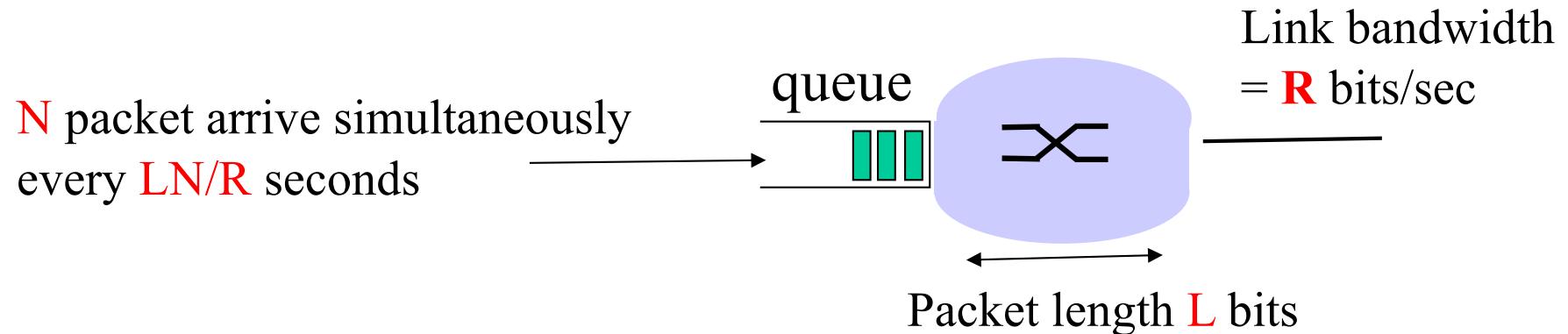
Arrival rate: $a = 1/(L/R) = R/L$ (packet/second)



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

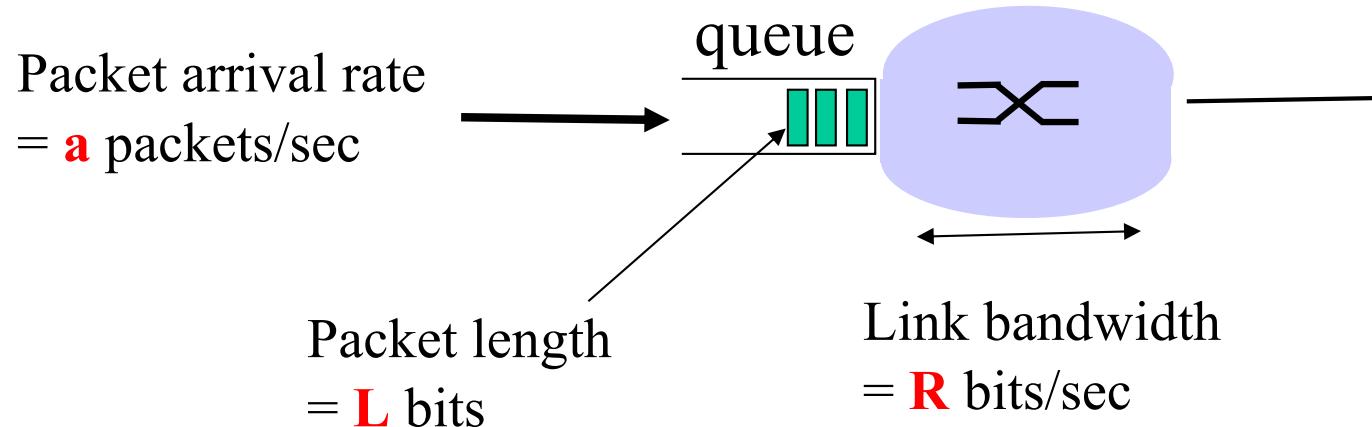


Average queueing delay (queue is empty at time 0) ?

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

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

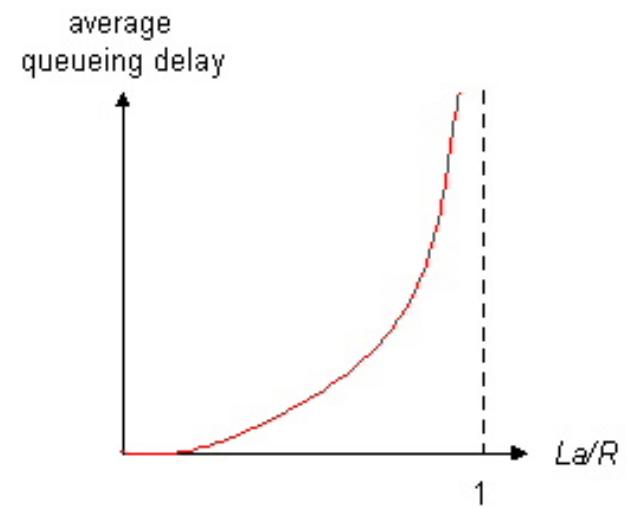
Queueing delay: behaviour



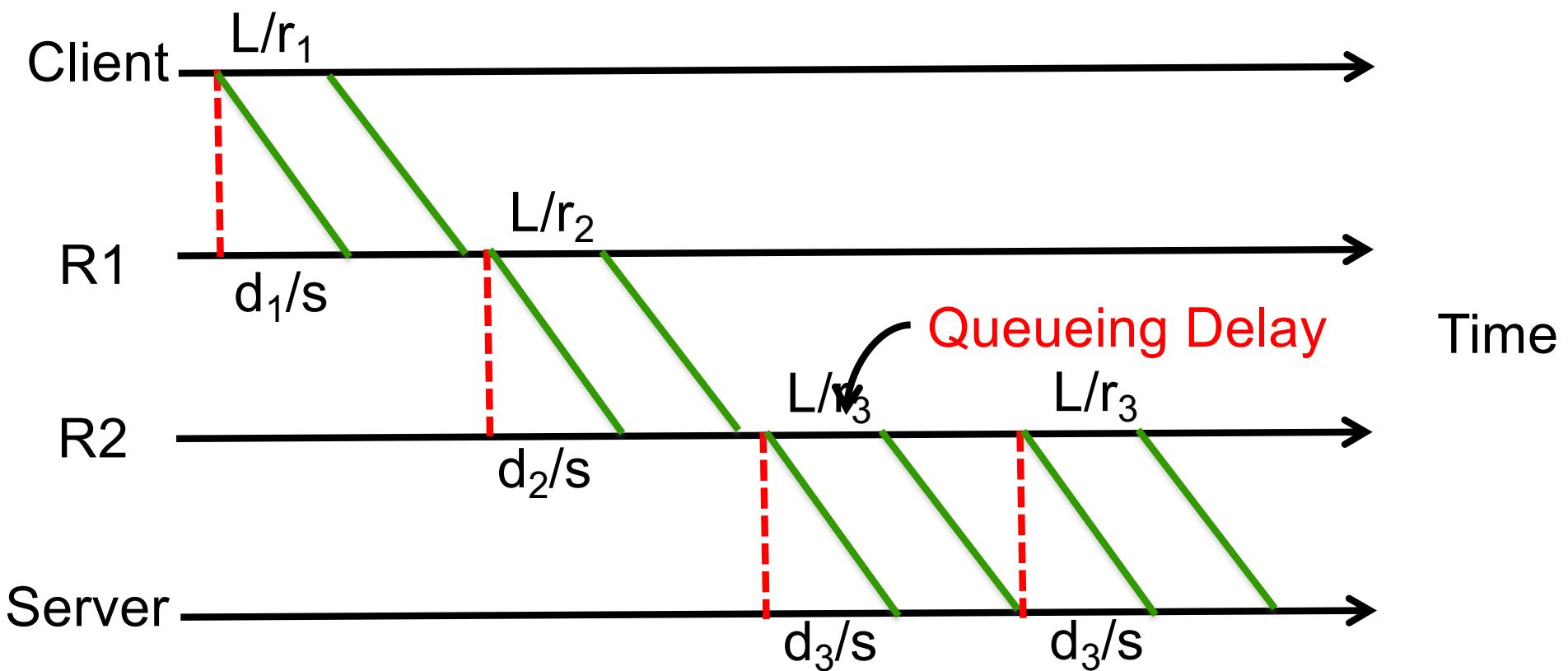
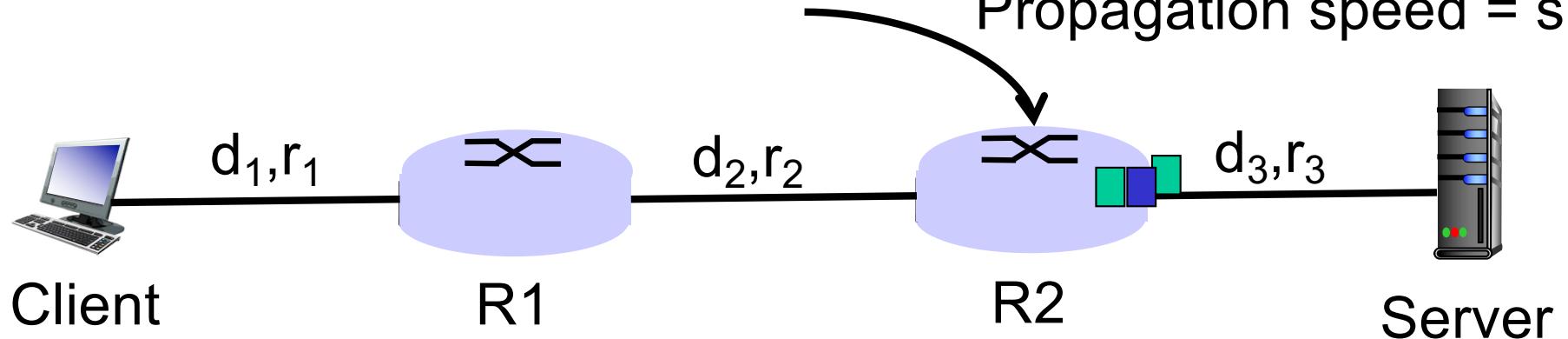
Interactive Java Applet:

<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!)

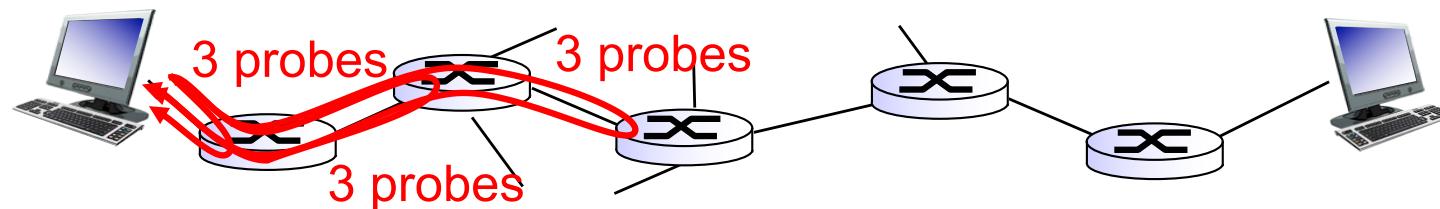


End to End Delay



“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

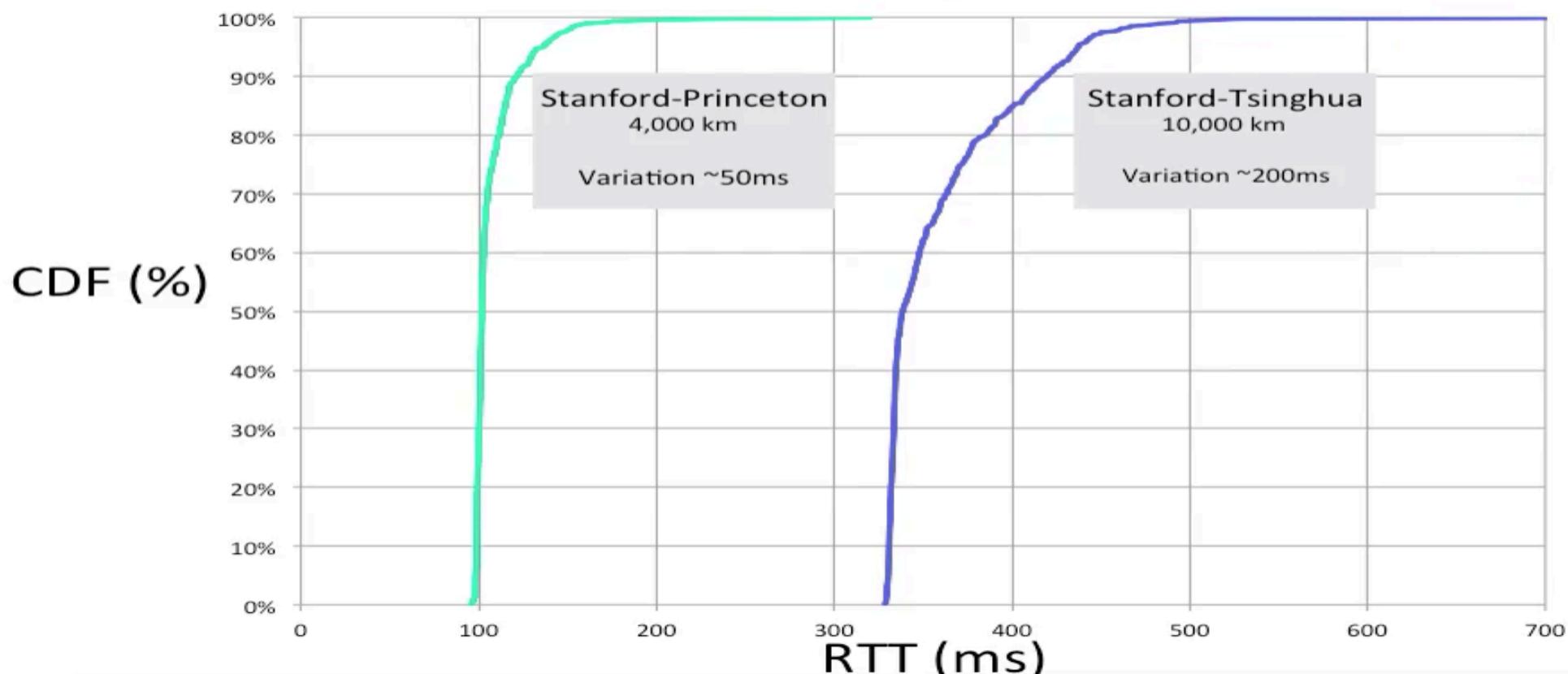
trans-oceanic link

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

“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_{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/sali



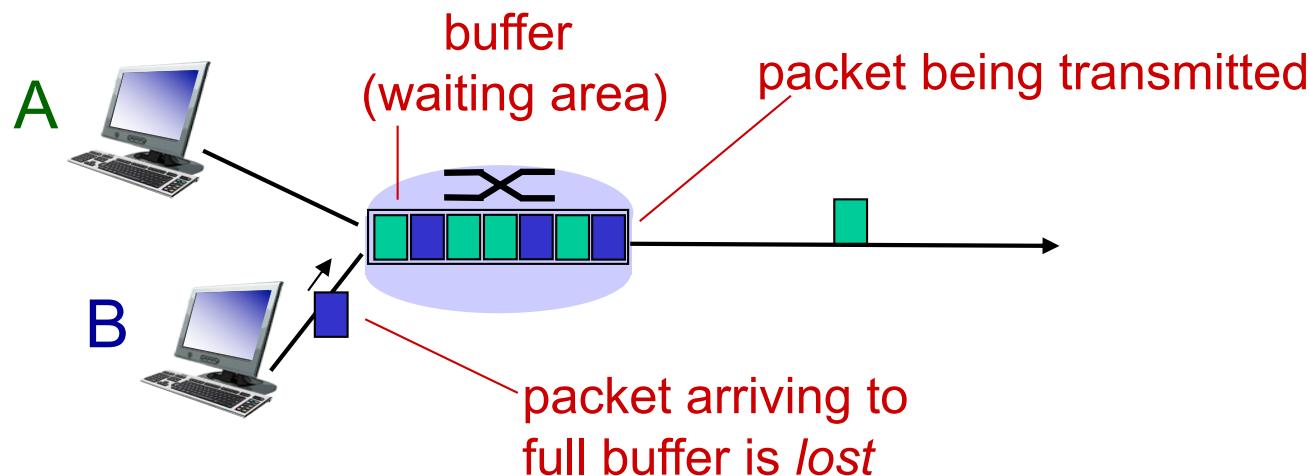
Quiz: Oh these delays

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

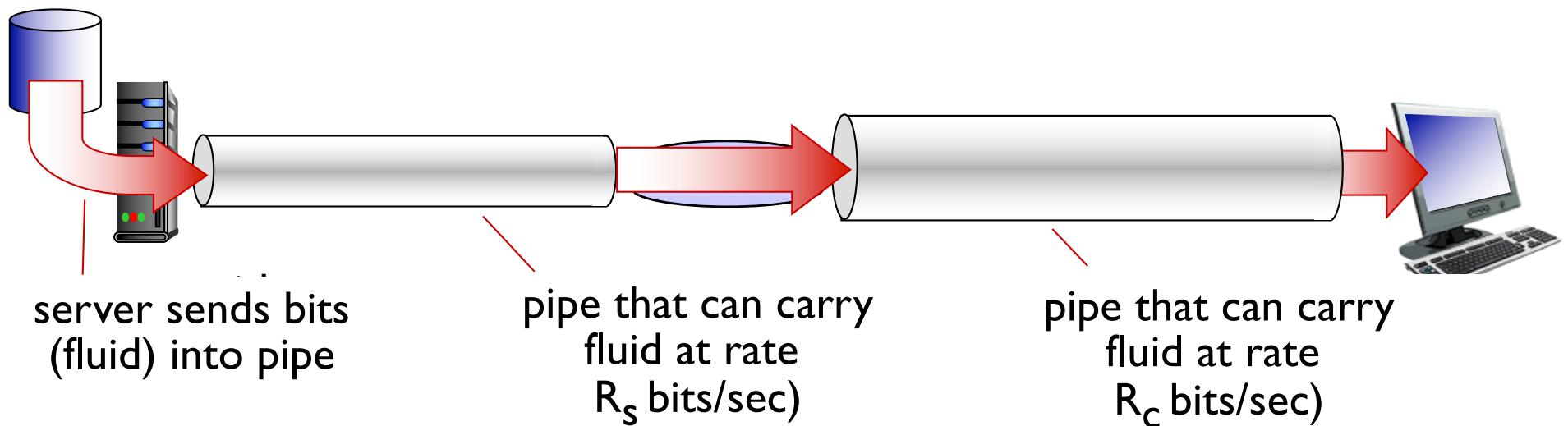
Packet loss

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



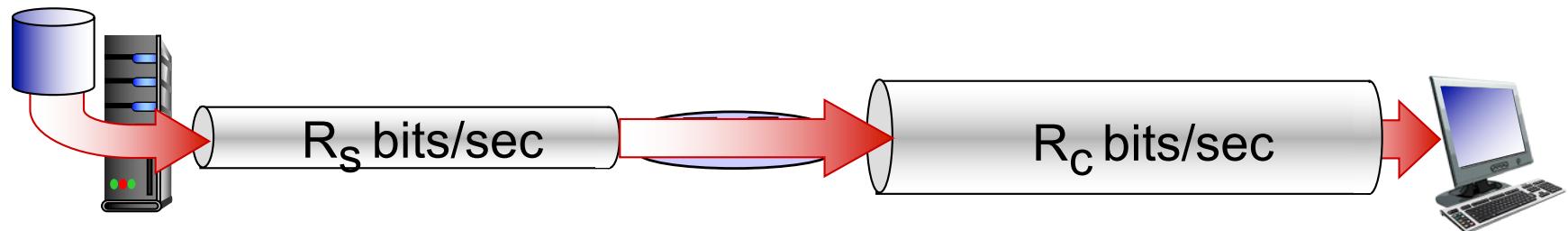
Throughput

- ❖ **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

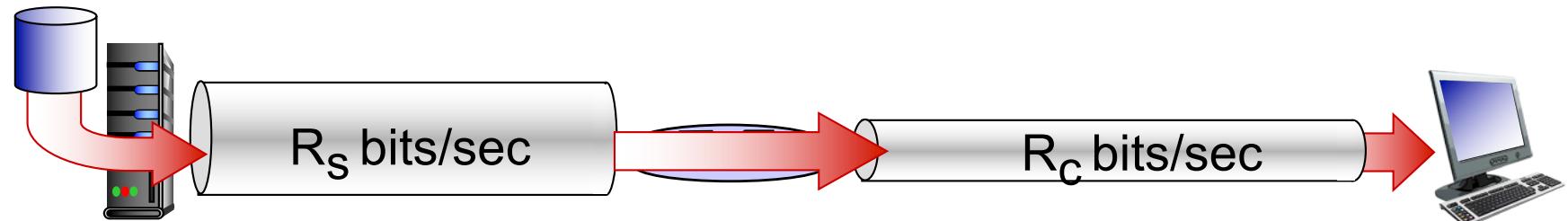


Throughput (more)

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



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

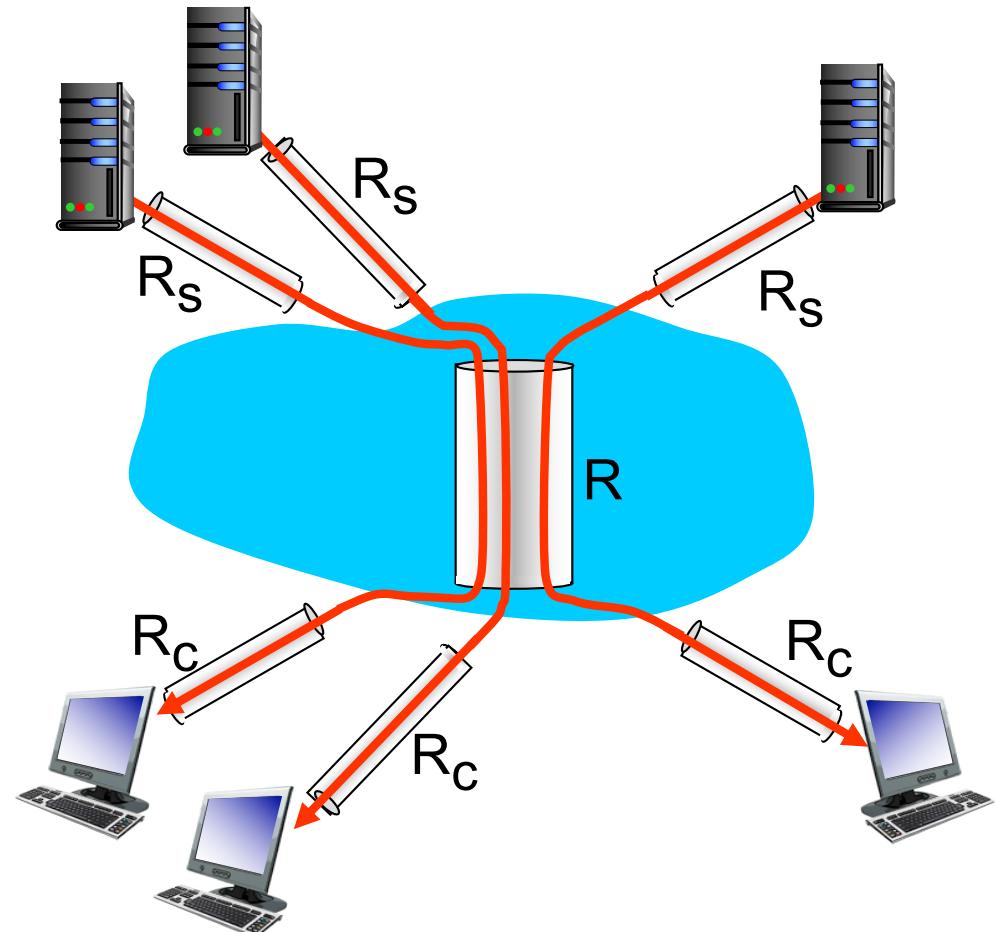


bottleneck link

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

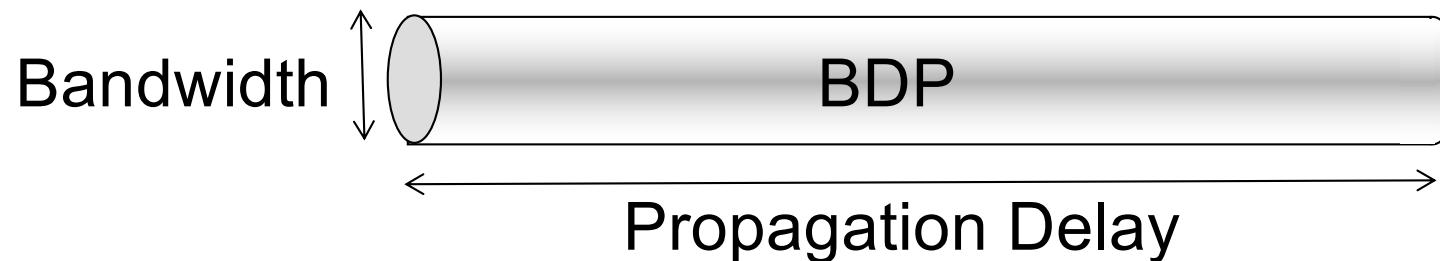
Throughput: Internet scenario

- ❖ 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

Key Properties of Links



- Bandwidth: “width” of the link
 - Number of bits sent per unit of time (bps)
- Propagation delay: “length” of the link
 - Propagation time to travel along the link (seconds)
- Bandwidth-Delay Product: “Volume” of the link
 - Amount of data in flight ($\text{bps} \times \text{s} = \text{bits}$)

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