Chapter 1: roadmap

1.1 What is the Internet?

1.2 Network edge

- end systems, access networks, links

1.3 Network core

- circuit switching, packet switching
- hierarchical Internet structure

1.4 Performance:

- delay, loss and throughput

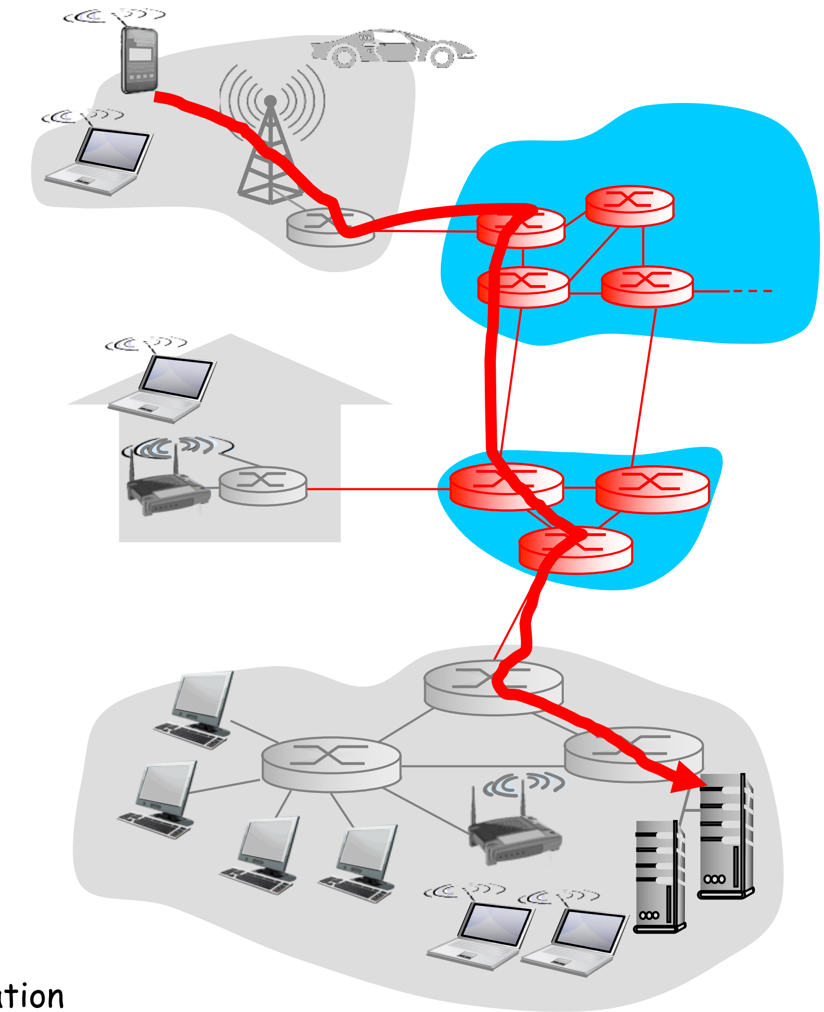
1.5 Protocol layers, service models

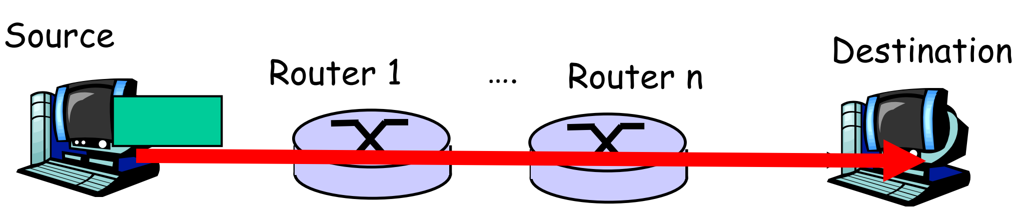
1.6 Networks under attack: security

1.7 History

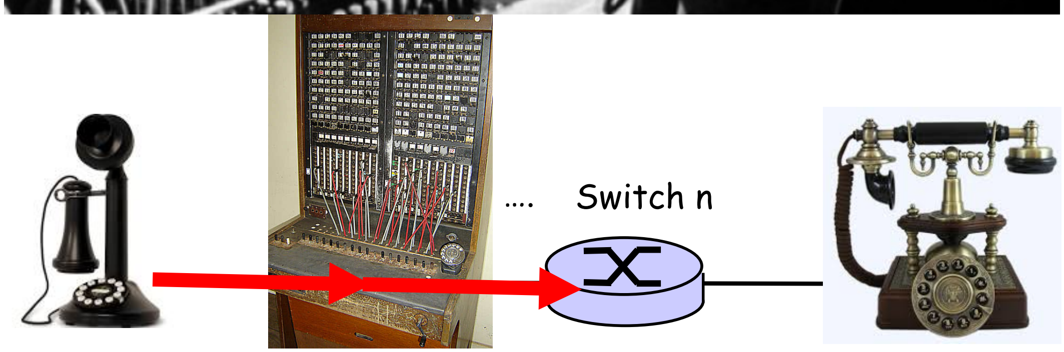
The network core

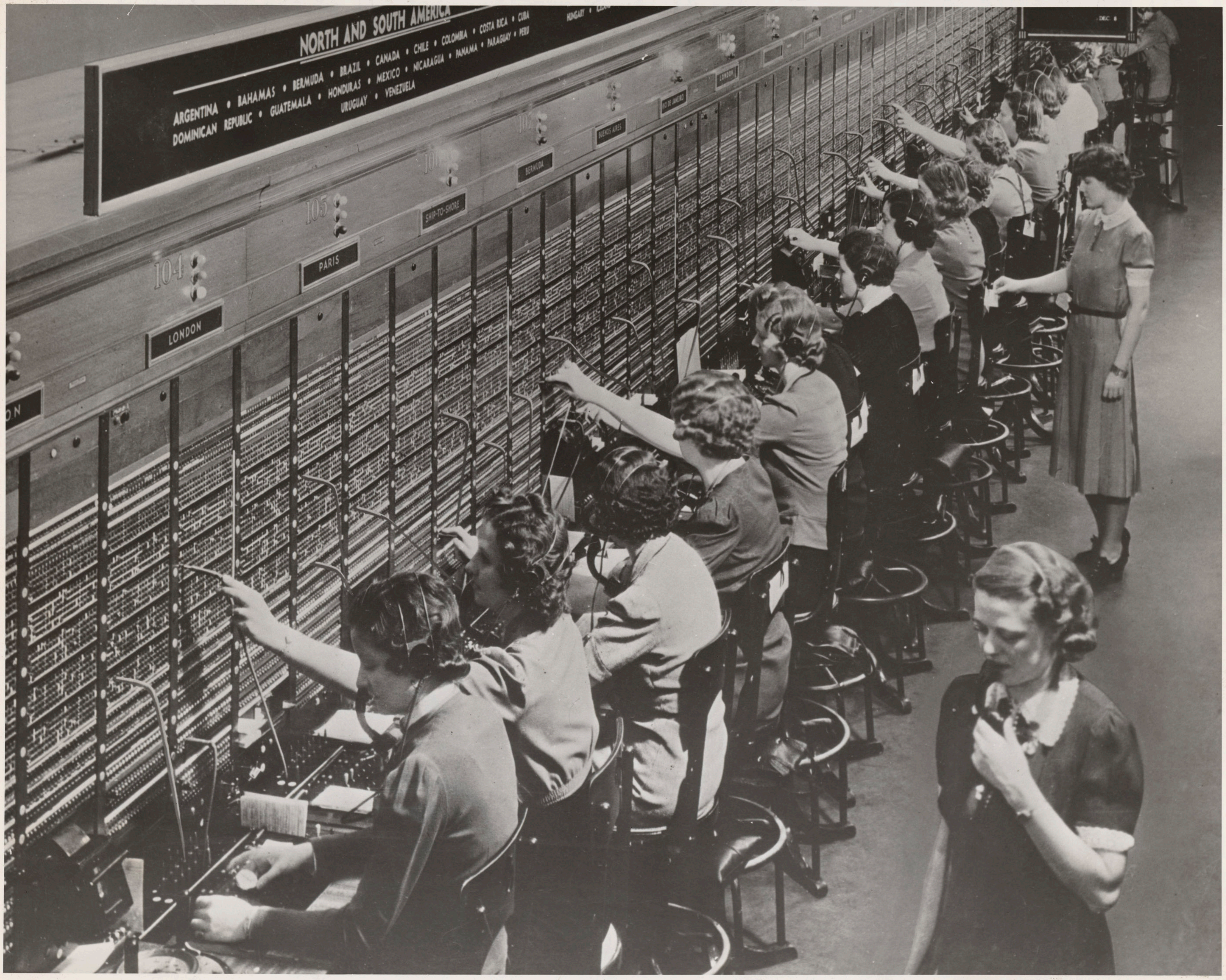
- mesh of interconnected routers





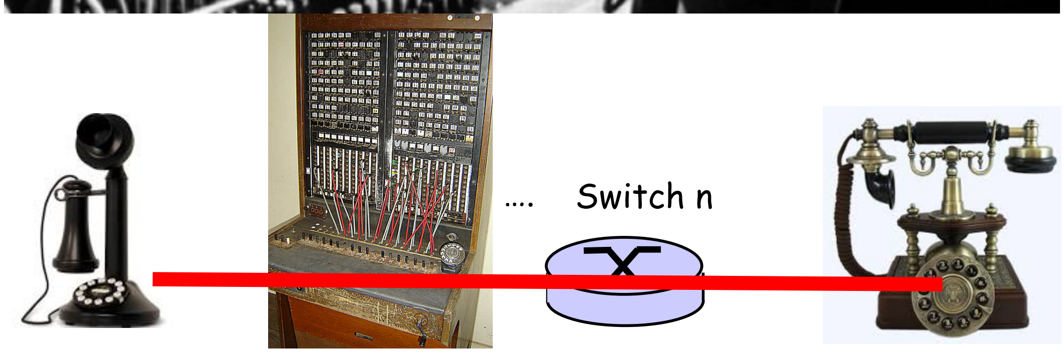
Telephone Switching




NORTH AND SOUTH AMERICA
ARGENTINA • BAHAMAS • BERMUDA • BRAZIL • CANADA • CHILE • COLOMBIA • COSTA RICA • CUBA
DOMINICAN REPUBLIC • GUATEMALA • HONDURAS • MEXICO • NICARAGUA • PANAMA • PARAGUAY • PERU
URUGUAY • VENEZUELA
HUNGARY
104
LONDON
105
PARIS
SHIP-TO-SHORE
BERMUDA
BUENOS AIRES

Telephone Switching

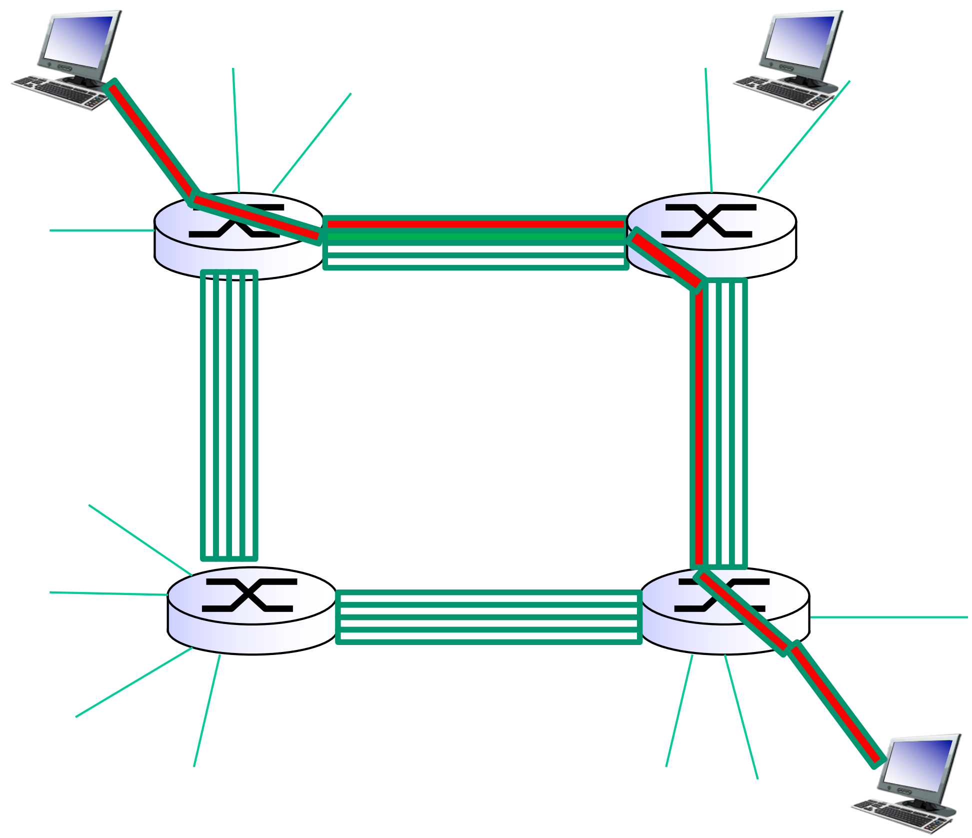
- Establishes an end-to-end circuit that is used for the duration of the call



Early core: 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
- circuit segment idle if not used by call *(no sharing)*
- Commonly used in traditional telephone networks

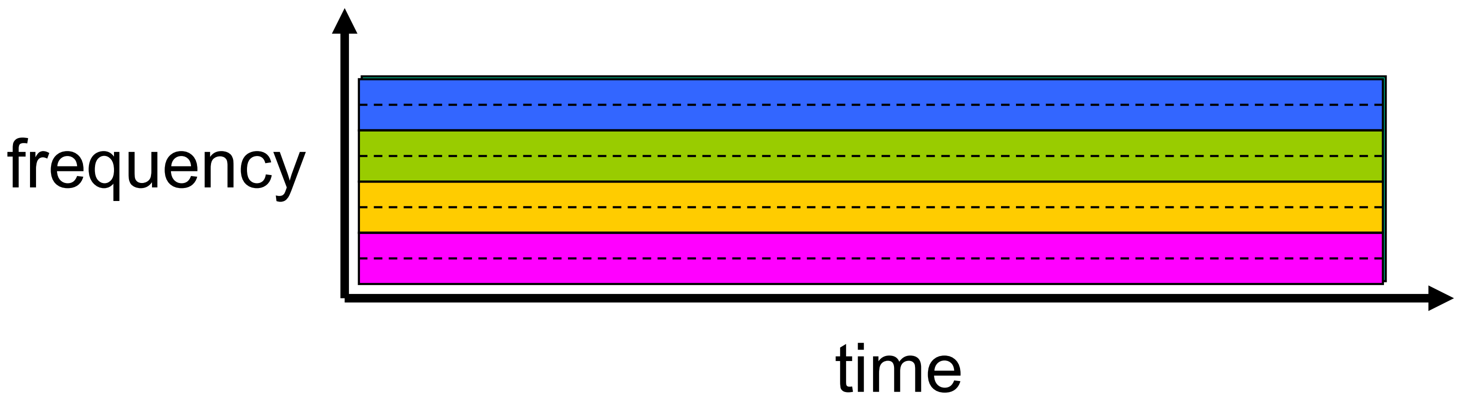


There are ways to reserving bandwidth on a link today

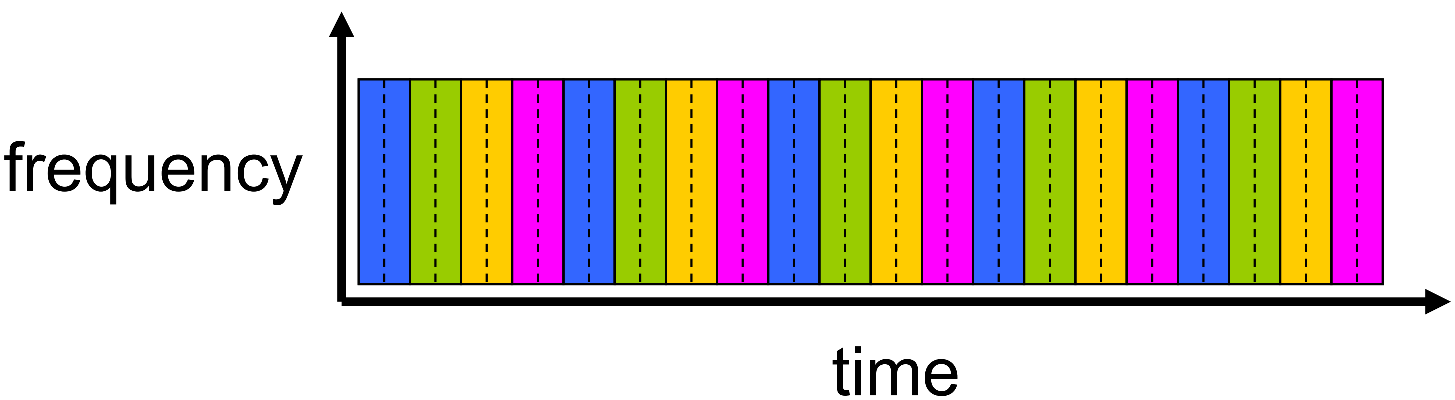
FDM

Example:

4 users



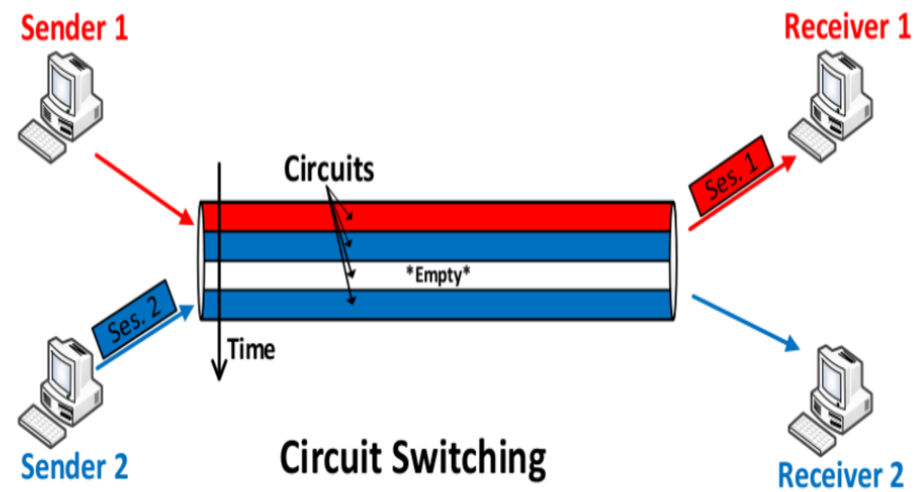
TDM



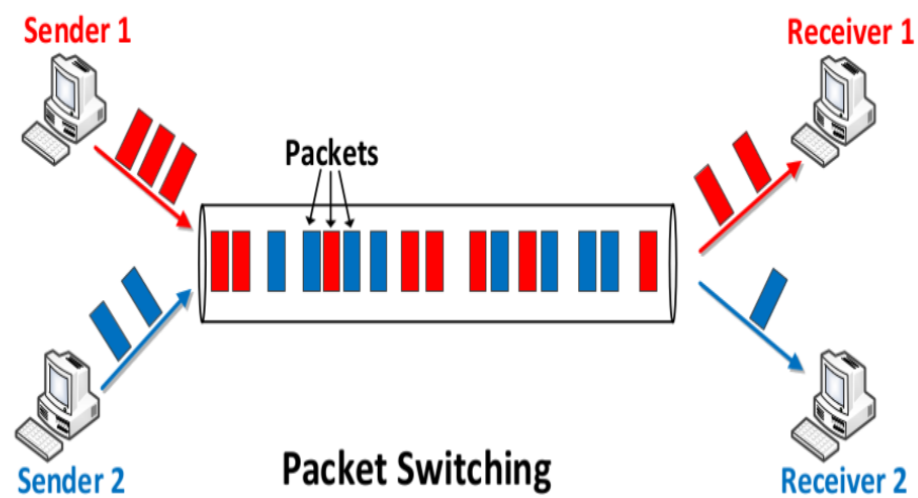
CDMA

From Circuit to Packet Switching

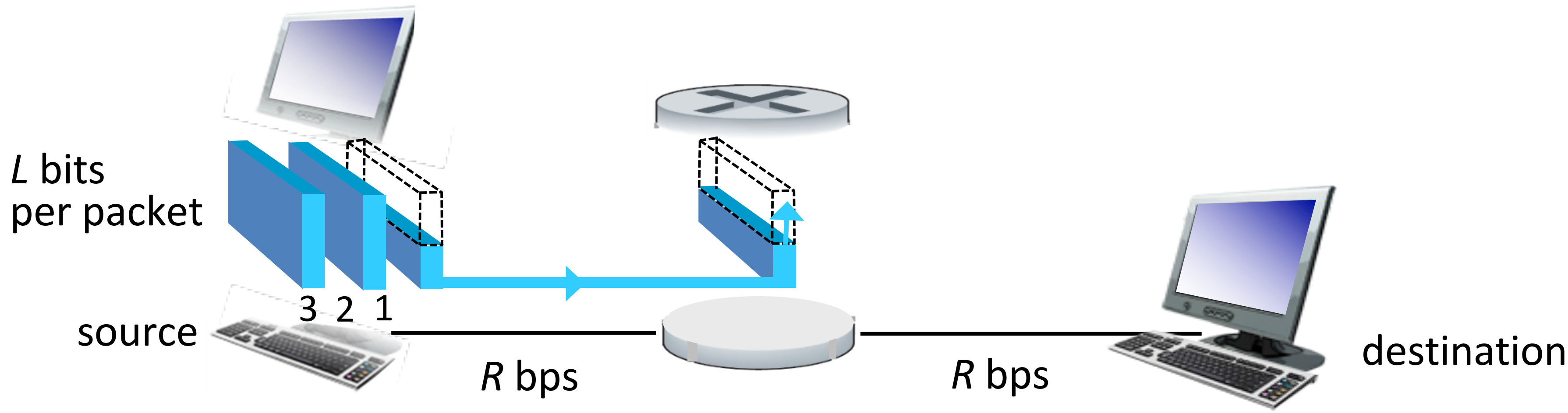
- FDMA, TDMA, CDMA
  - Circuit-switched: dedicate /assign network resources



- Paradigm shift
  - Packet-switched: Let everyone share the resources

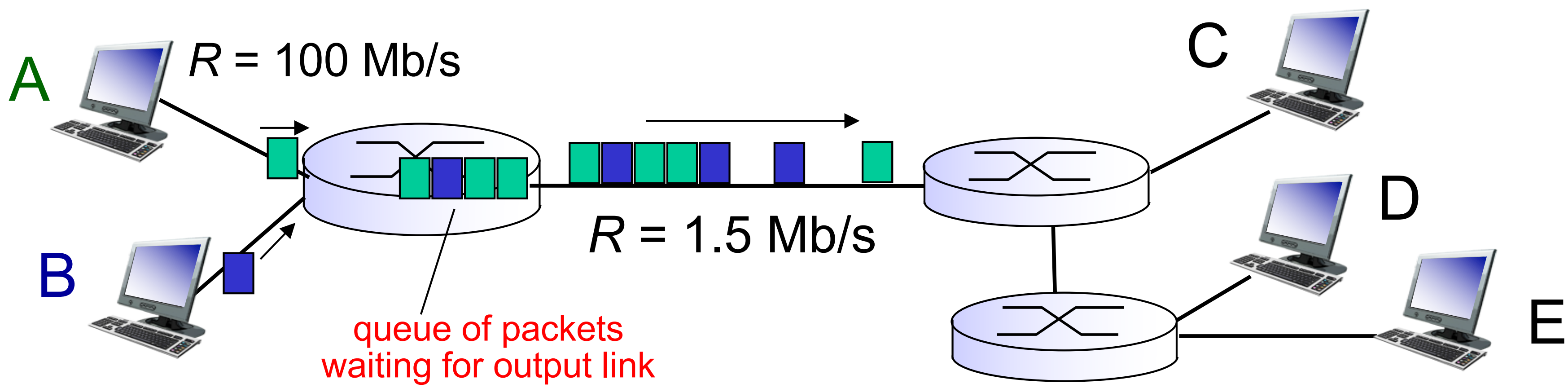


Packet-switching: single flow



- Message gets divided into multiple packets, L bits each.
- Each packet takes *L/R* seconds to transmit (push out) into link at *R* bps
  - L: bits per packet, R: transmission bandwidth
- Each packet takes d/s seconds to propagate across the link
  - d: length of physical link, s: propagation speed in medium (~3×10^8 m/sec)
- *store and forward:* entire packet must arrive at router before it can be transmitted on next link

Packet Switching: multiple flows



- Packets from flows A, B *share* network resources – no reservations
  - each packet is transmitted at full link bandwidth
    - bandwidth shared on demand, as needed: statistical multiplexing
  - all packets are stored (FIFO queue) at the buffer at the router
    - If arrival rate to link exceeds transmission rate of link, for a period of time:
      - packets will queue, wait to be transmitted on link→ queuing delay
      - packets can be dropped if queue (buffer) fills up→ packet loss

Resource Allocation

Human Analogies:

- reservation at a restaurant
- a reserved lane on the highway
- *Q:* other human analogies of reserved resources vs. on-demand allocation?

Networks:

- Resources (bandwidth, buffer) divided into pieces and allocated to calls or packets
- Reservations: circuit-switching
- No reservations: packet-switching

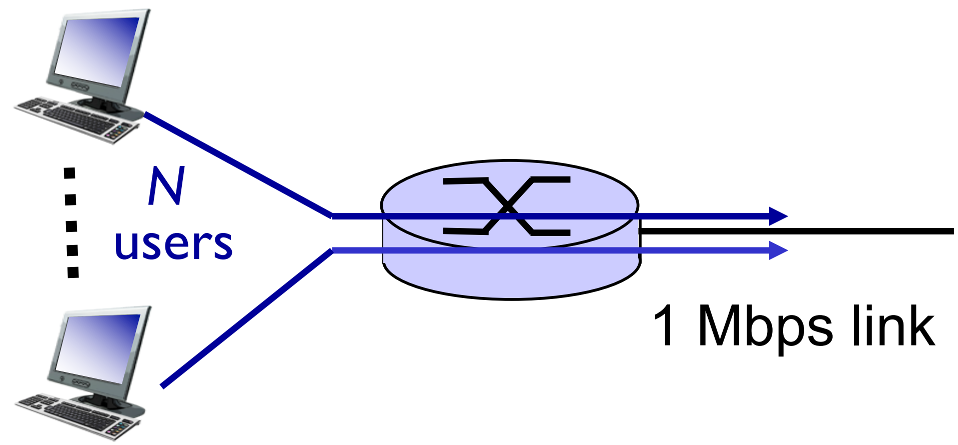
Packet vs. Circuit Switching

+ Statistical multiplexing: Packet switching allows more (bursty) users

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 <0.0004



Q1: how did we get value 0.0004?

Q2: what happens if > 35 users ?

More online interactive exercises for Chapter 1:
http://gaia.cs.umass.edu/kurose_ross/interactive/ps_versus_cs.php

Packet vs Circuit Switching

Packet Switching: + and -

+ great for bursty data
  - network's pov: resource sharing ("statistical multiplexing")
  - user's pov: simpler (no call setup), less delay to start service

- excessive congestion possible
  - packet delay and loss
  - protocols needed for reliable data transfer, congestion control
  - no bandwidth guarantees needed for audio/video apps

Property	Circuit Switching	Packet Switching
Guarantee of Quality	✓	X
Ease of Connectivity	X	✓
Scalability	X	✓

In the end (2000s+), packet switching won the day

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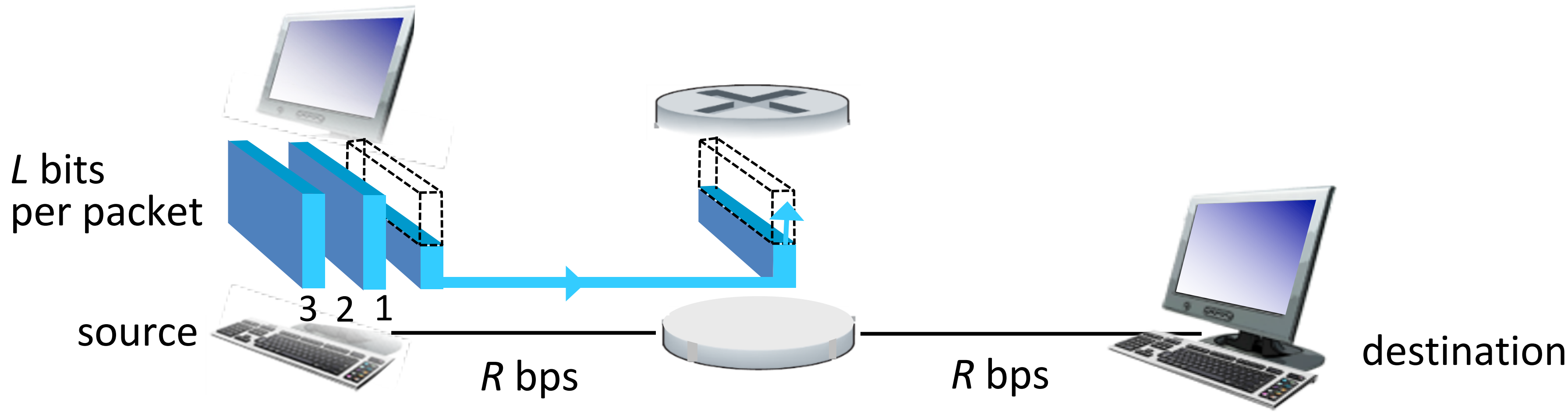
Packet-switching: at source

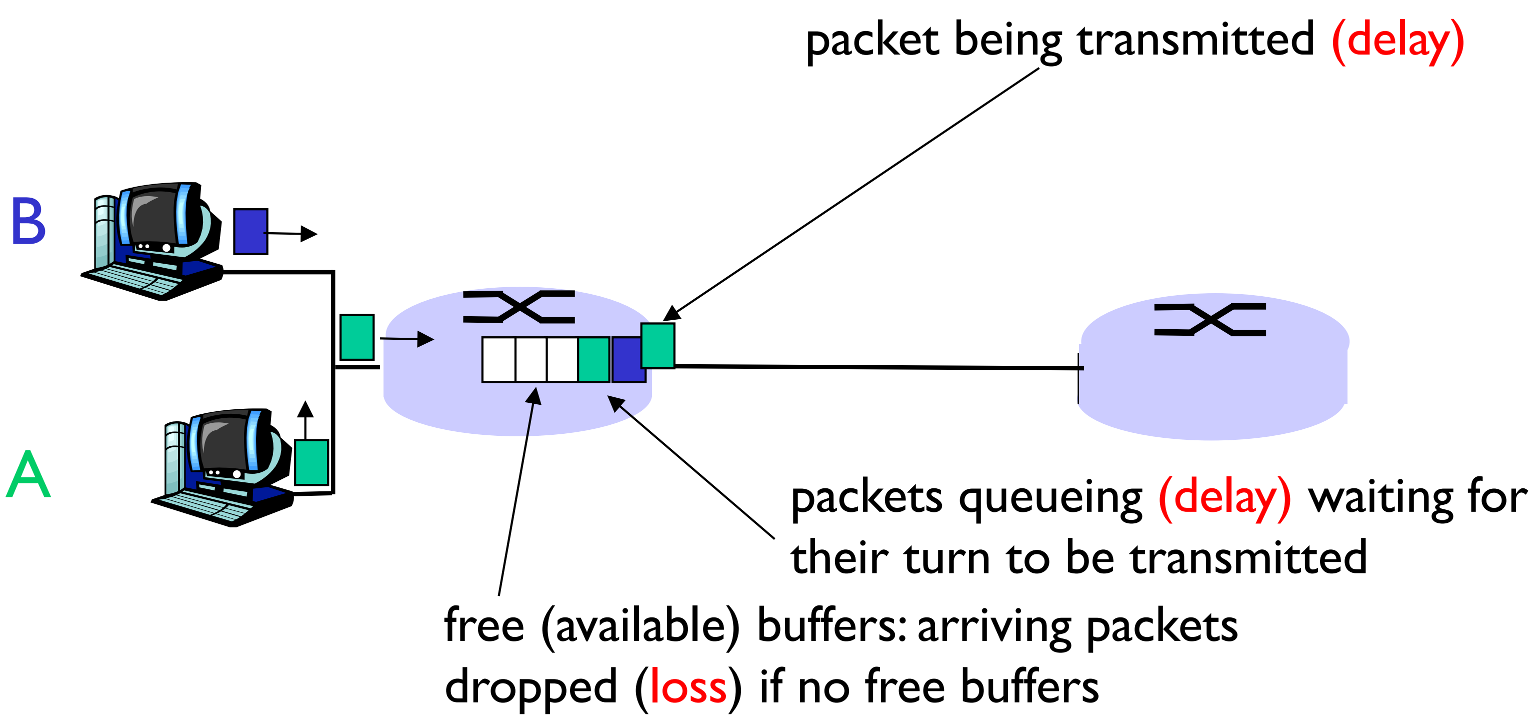


- takes L/R seconds to transmit (push out) L-bit packet into link at R bps
- *store and forward:* entire packet must arrive at router before it can be transmitted on next link

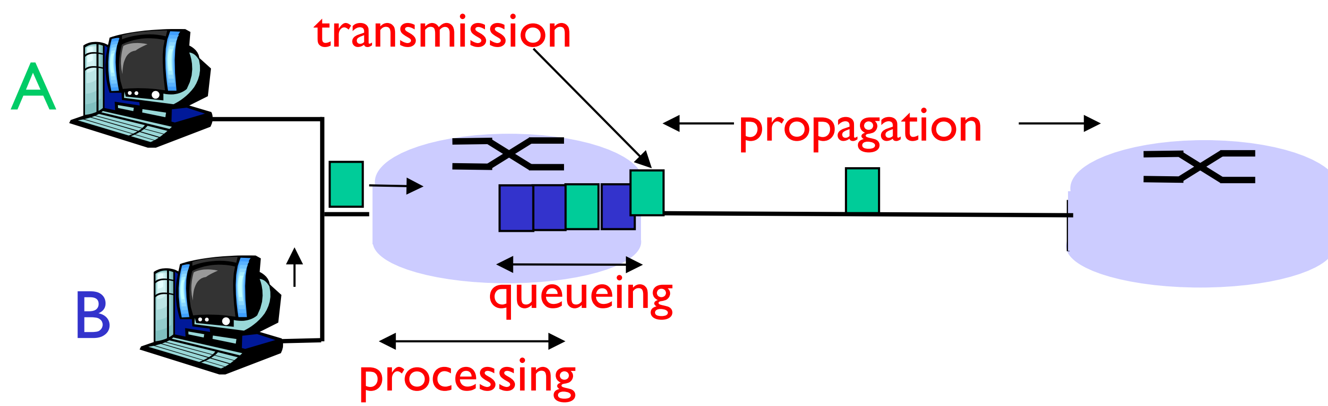
At intermediate nodes (routers)

Packets *queue* in router buffers

- if packet arrival rate to link exceeds output link capacity



Four sources of packet delay



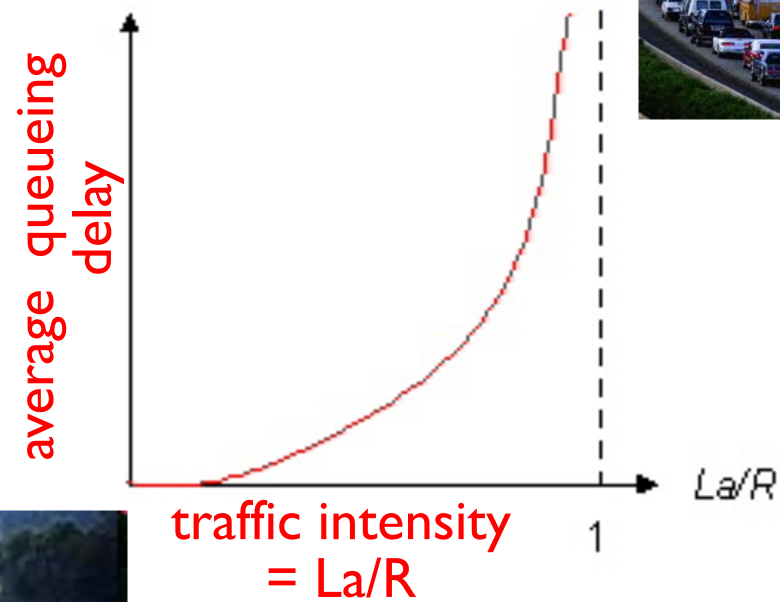
$$d = d_{proc} + d_{queue} + d_{trans} + d_{prop}$$

- d_{proc}: processing of the packet at the router
  - e.g. check but errors, determine output link, … Typically < 1ms.
- d_{queue}: queueing delay
  - time waiting at output buffer for transmission, depends on congestion level at router)
- d_{trans}: transmission delay =L/R
- d_{prop}: propagation delay = d/s

Queueing delay

- R: link bandwidth (bps)
- L: packet length (bits)
- a: average packet arrival rate (packets/sec)

La/R → 1

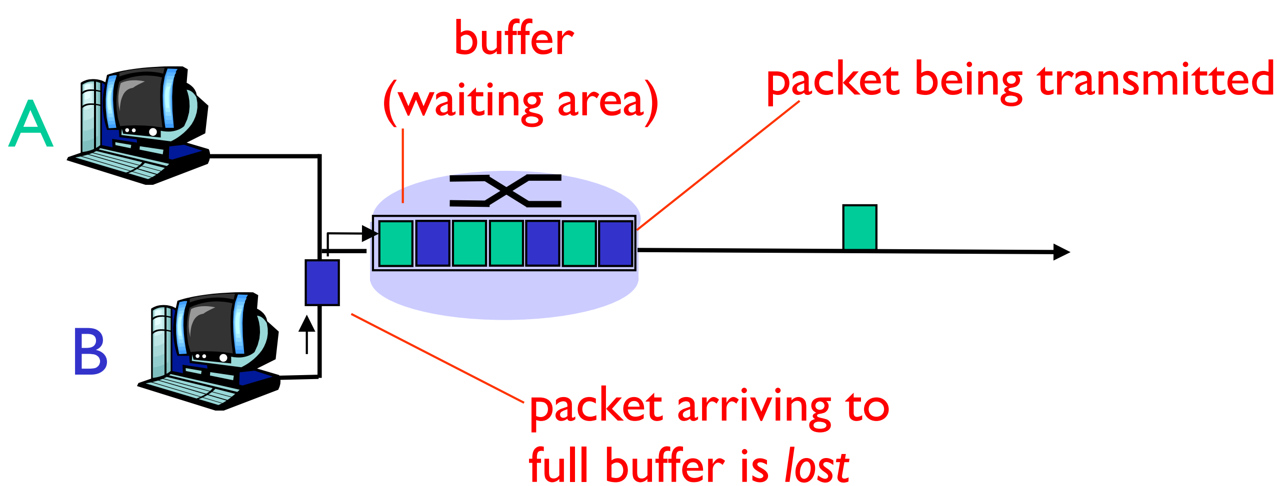


La/R ~ 0

- La/R ~ 0: avg. queueing delay small
- La/R → 1: avg. queueing delay large
- La/R > 1: more work arriving than can be serviced, average delay infinite!

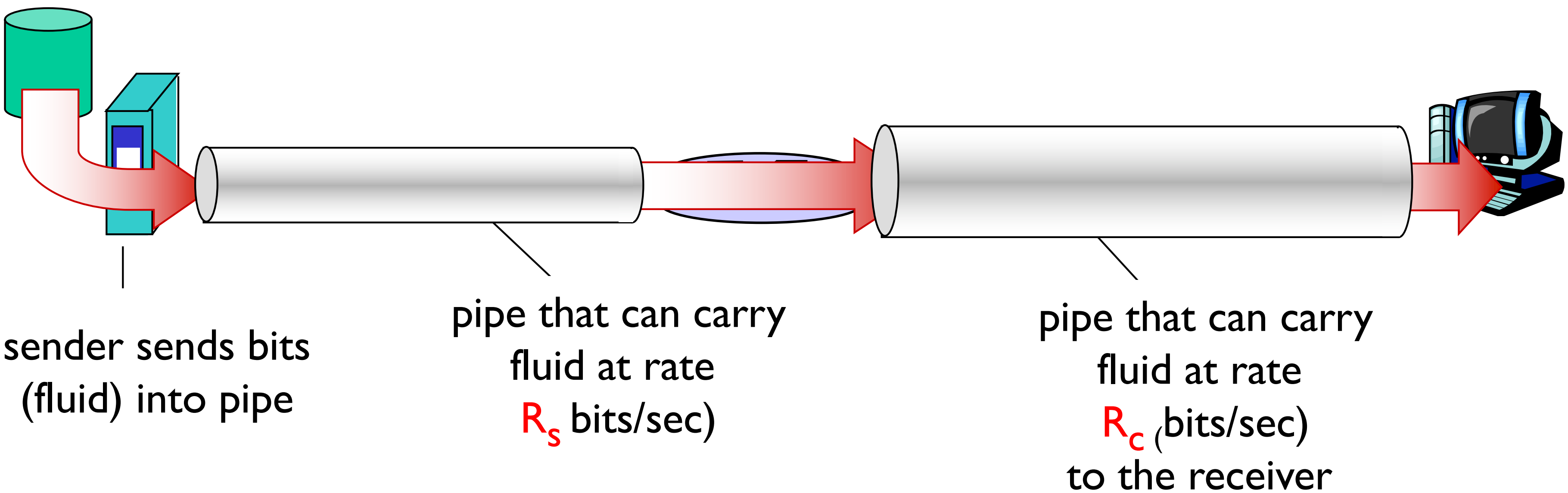
Packet loss

- Packets get dropped due to congestion at queues:
  - 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, by source end system, or not at all
- Packets can also be lost due to link failure, misconfiguration etc.



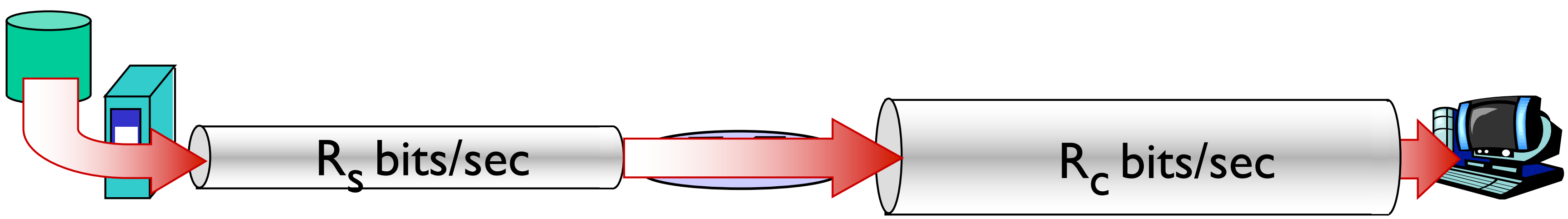
Throughput

- throughput: rate (bits/time unit) at which bits transferred between sender/receiver

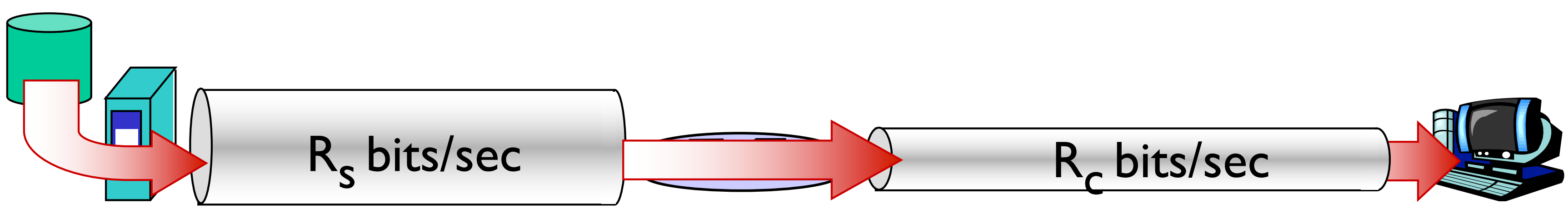


Throughput (cont'd)

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



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

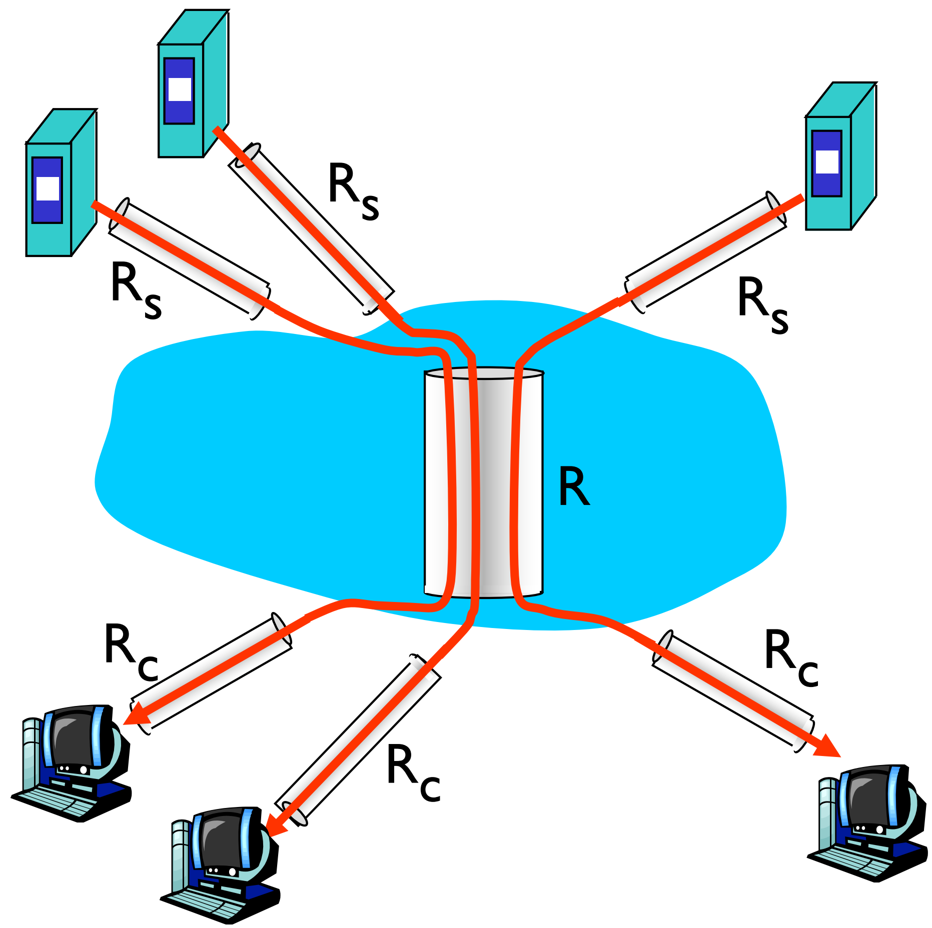


bottleneck link

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 the bottleneck



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

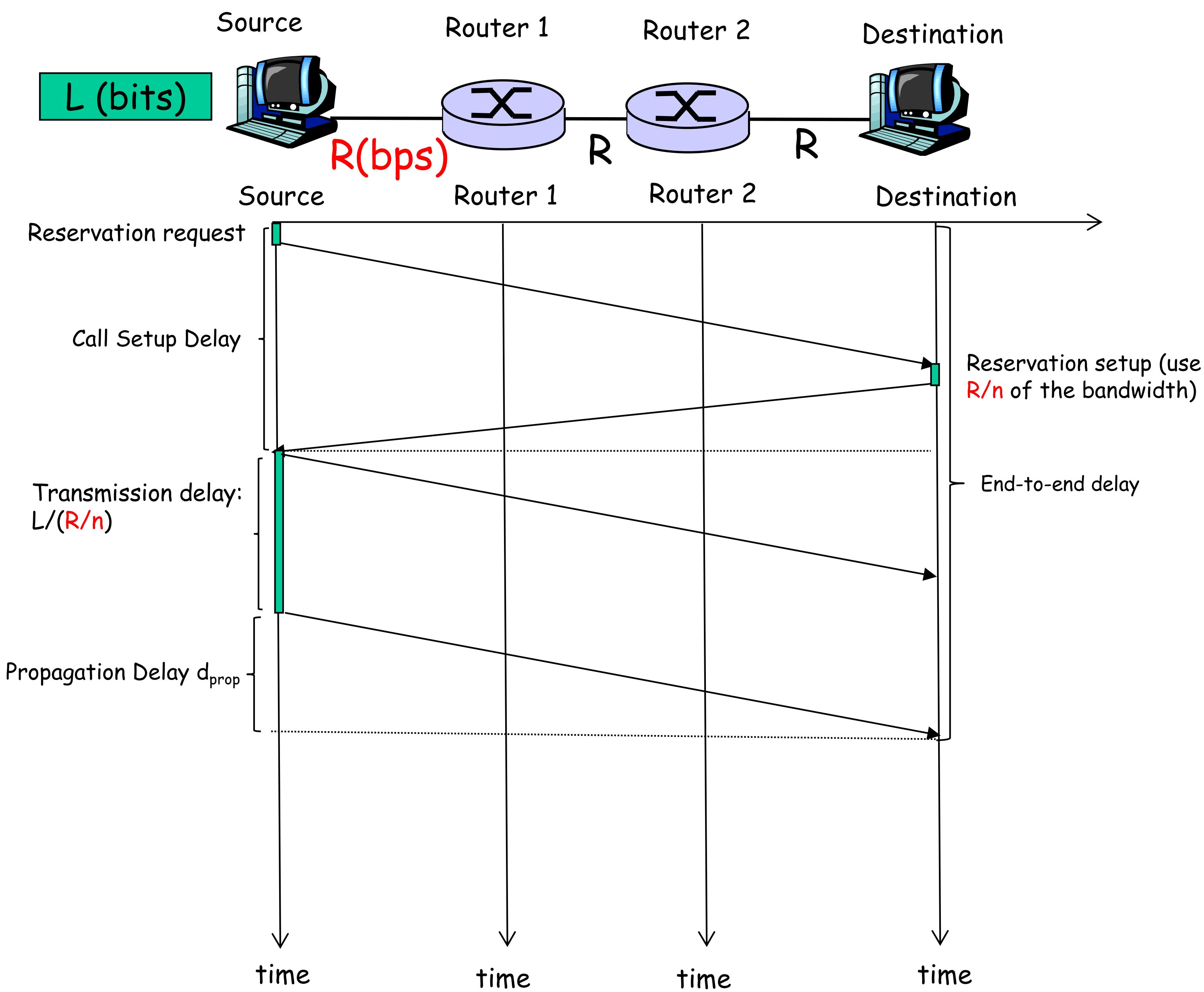
Practice to compute performance metrics

- End-to-end delay (transmission, propagation, delay, processing)
  - http://gaia.cs.umass.edu/kurose_ross/interactive/end-end-delay.php
- End-to-end throughput
  - http://gaia.cs.umass.edu/kurose_ross/interactive/end-end-throughput-simple-v2.php
- [Loss]
- Circuit vs Packet Switching
  - http://gaia.cs.umass.edu/kurose_ross/interactive/ps_versus_cs.php

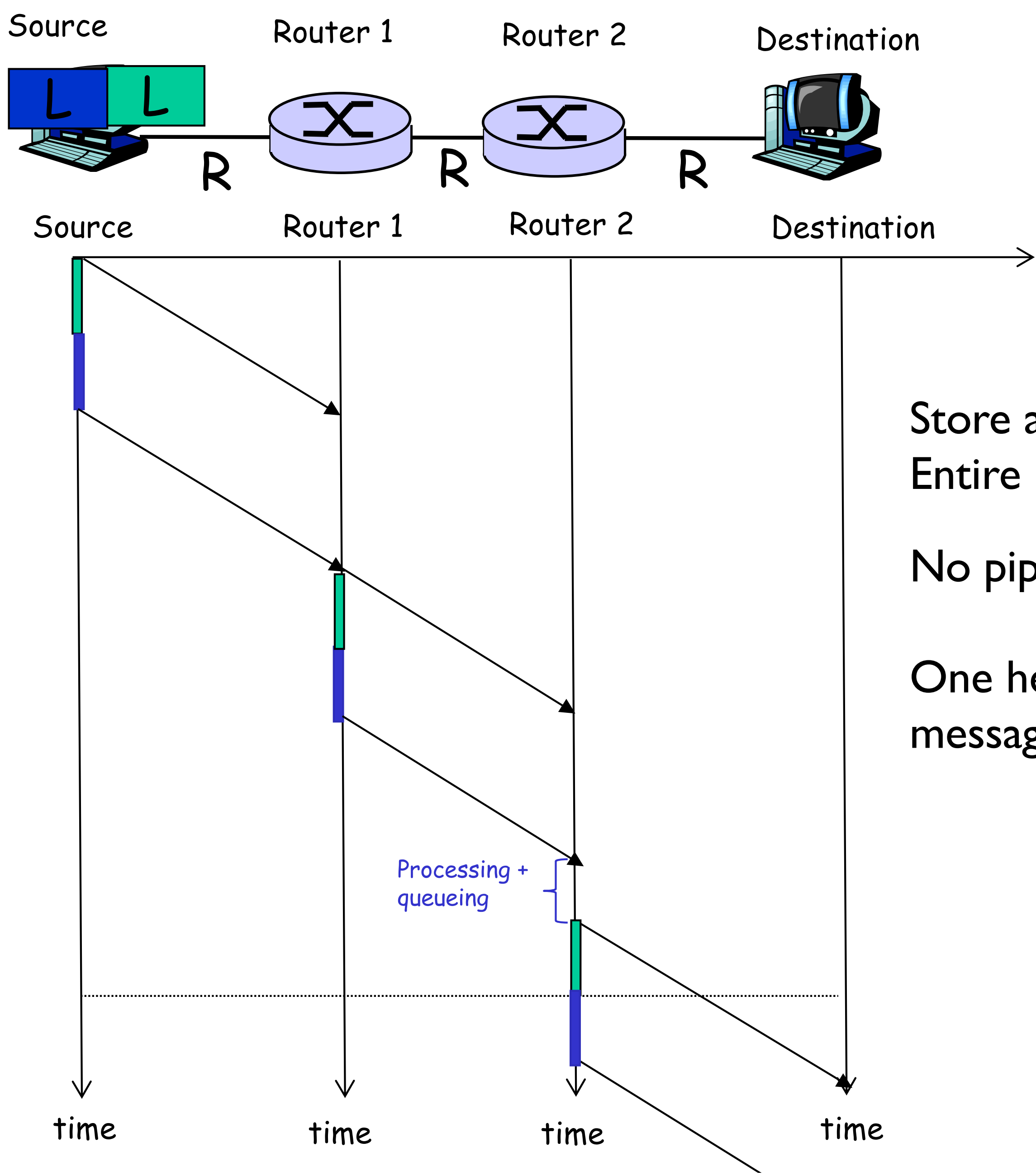
- All 4 Interactive exercises for Ch.1
  - http://gaia.cs.umass.edu/kurose_ross/interactive/
- All 3 interactive animations for Ch.1
  - Tranmission vs propagation, Queeing and Loss Applet, Message Segmentation
  - https://media.pearsoncmg.com/aw/ecs_kurose_compnetwork_7/cw/#interactiveanimations

- Use space-time diagrams!

Circuit-switching



Message Switching: no pipelining

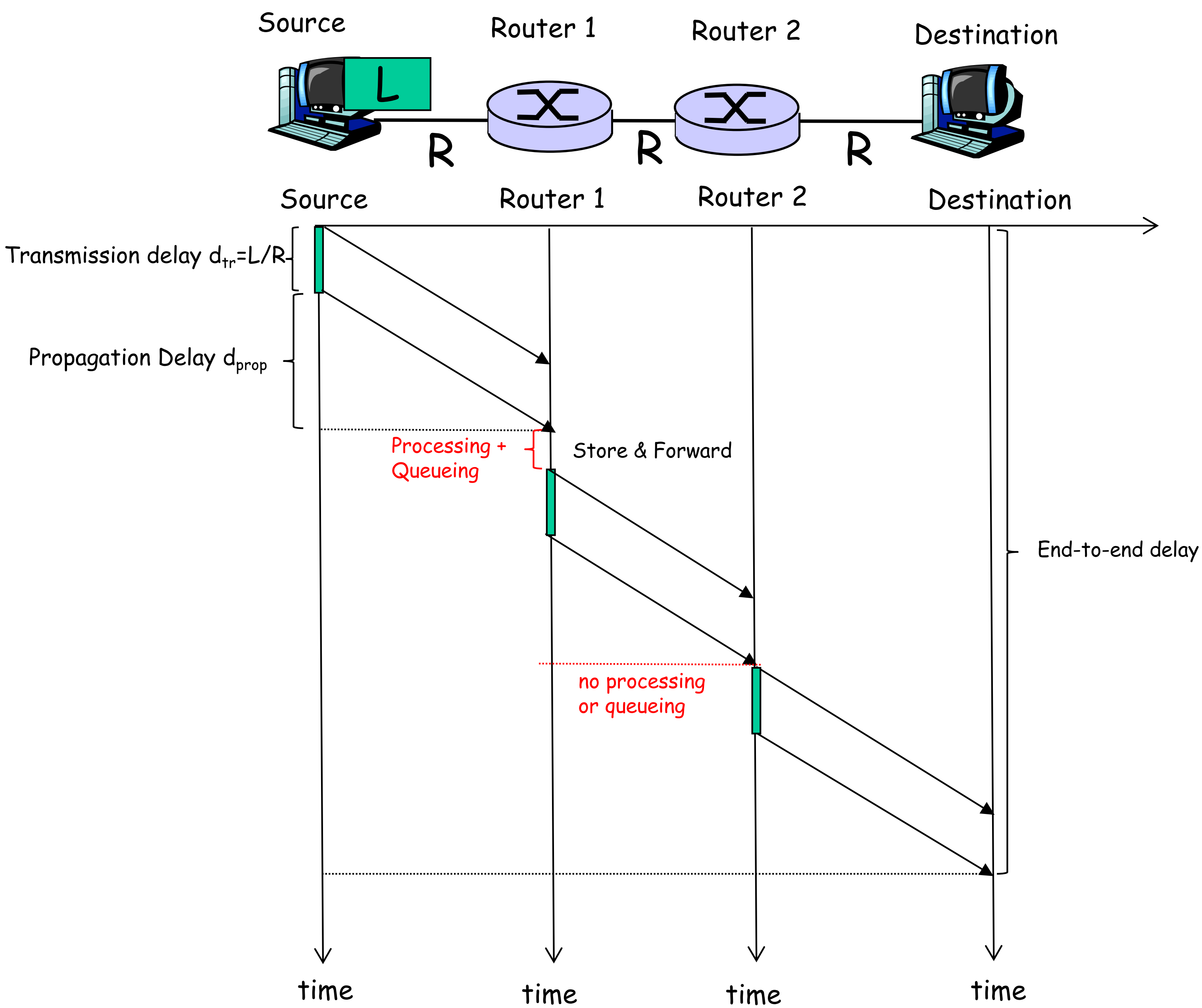


Store and Forward Entire Message

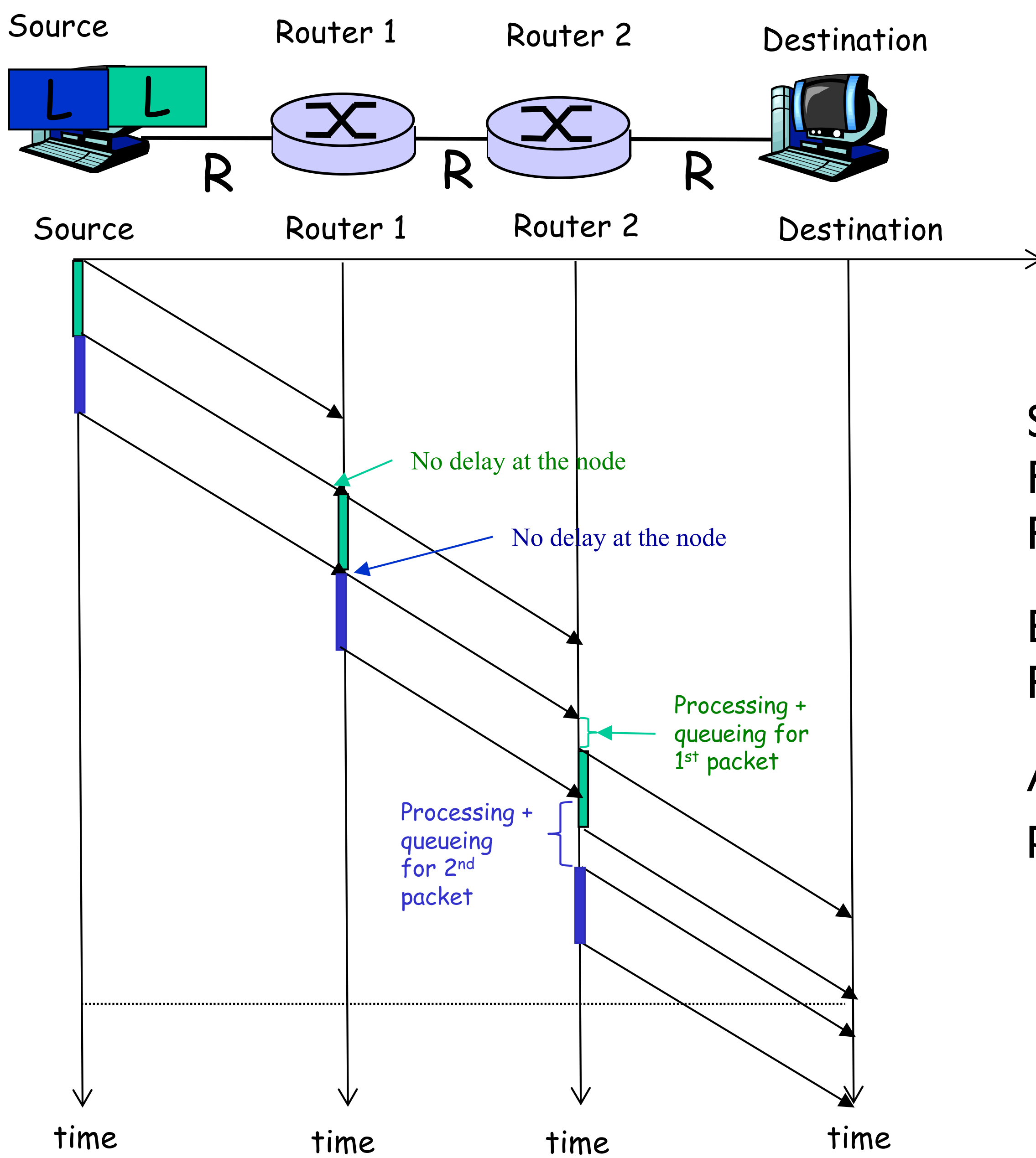
No pipelining

One header per message

Packet Switching: one packet



Packet Switching: multiple packets



Store and Forward each Packet

Benefit of Pipelining

Add a header per packet

Numerical example

- Question: How long does it take to send a file of F=640Kbits from Source to Destination over a packet switched network?
  - there are 3 links on the path
  - every link have speed: R=1.5 Mbps and propagation delay d_{prop}=10ms
  - processing and queuing delays are negligible
  - the file is broken into packets of P=1000 bits each (ignore added headers)

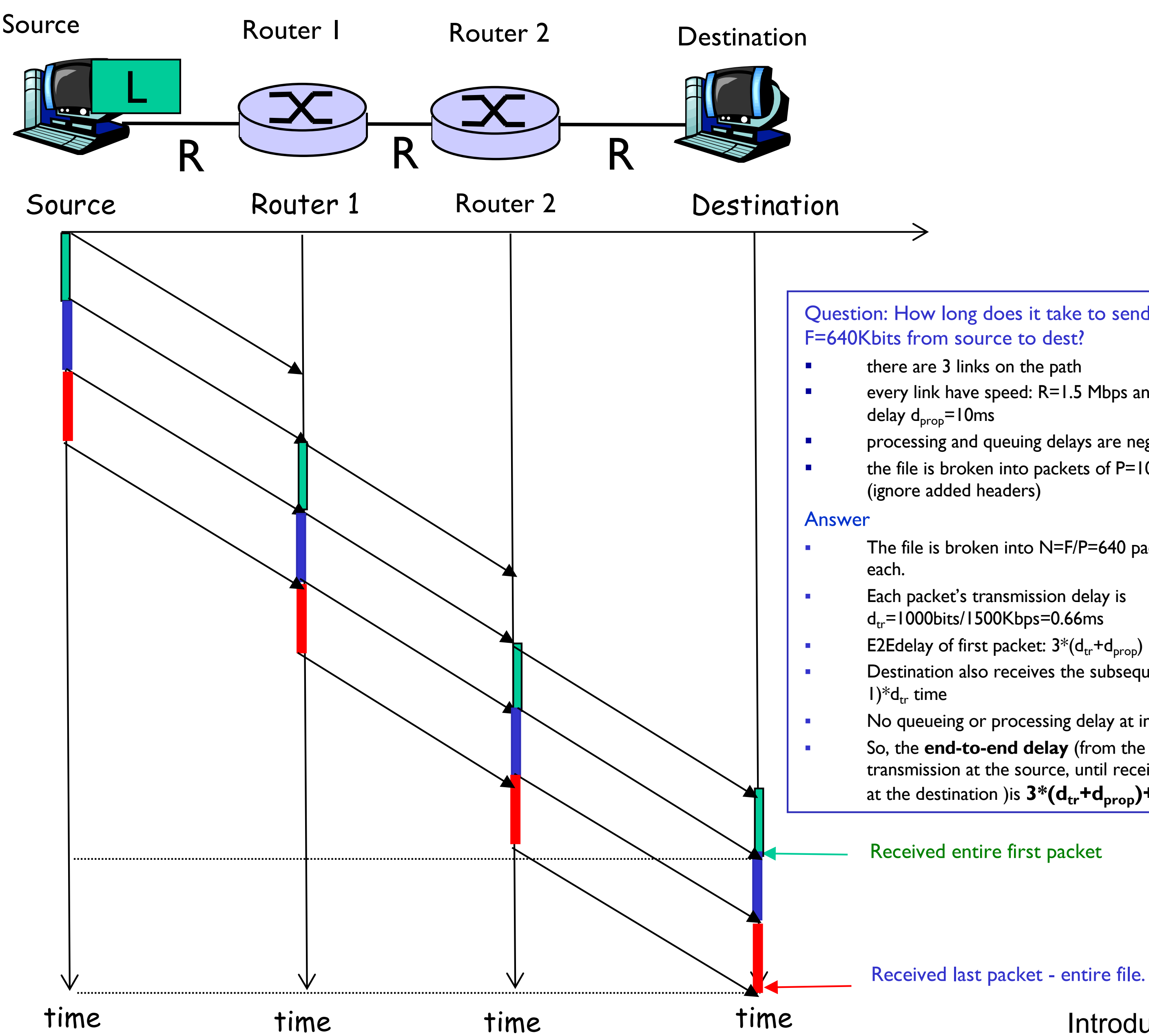
Interactive Exercise:
http://gaia.cs.umass.edu/kurose_ross/interactive/end-end-delay.php

Packet-switching

E2E delay

on every hop:

$$\boxed{d = d_{proc} + d_{queue} + d_{trans} + d_{prop}}$$



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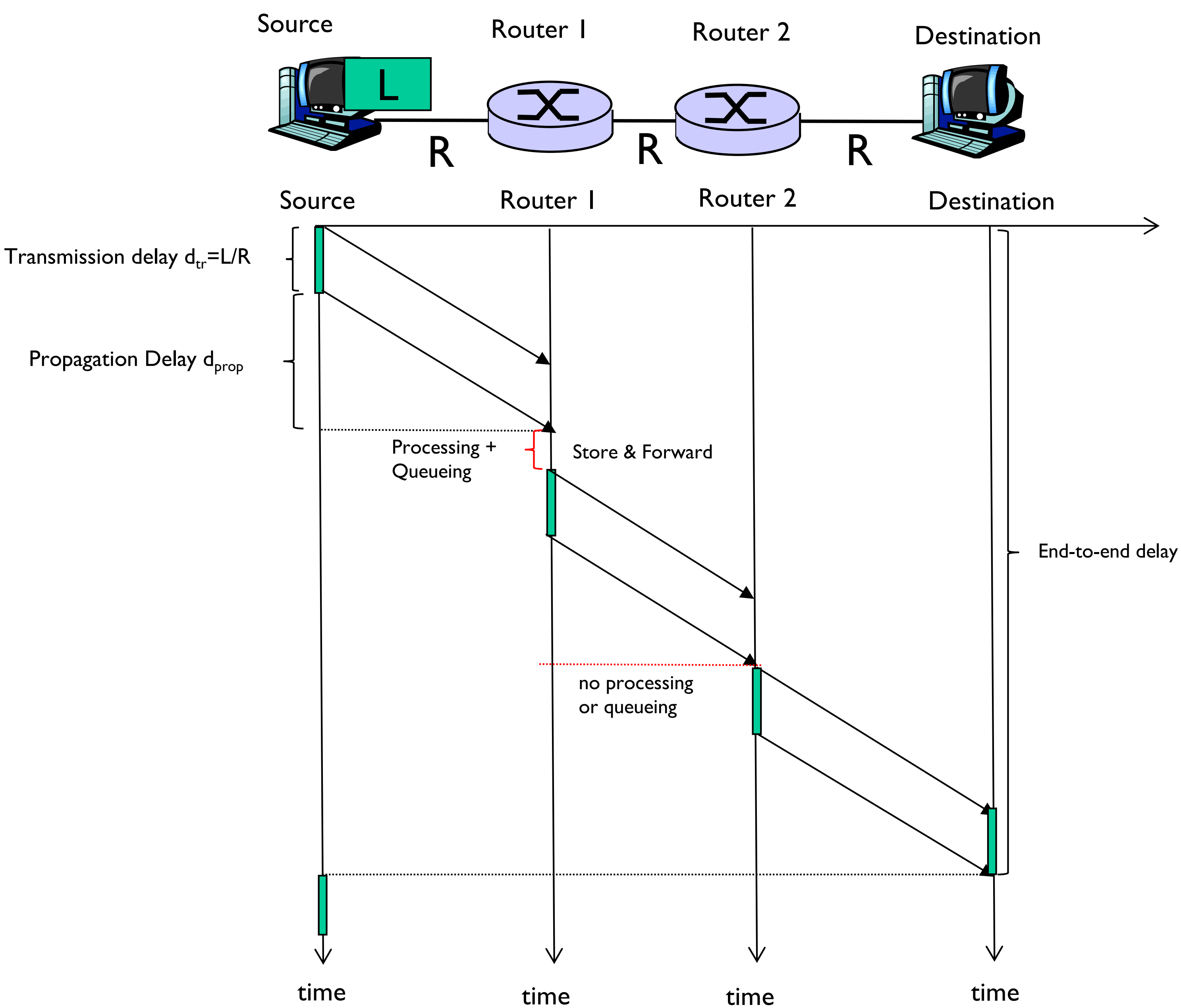
Answer

- The file is broken into N=F/P=640 packets of 1000 bits each.
- Each packet's transmission delay is d_{tr}=1000bits/1500Kbps=0.66ms
- E2Edelay of first packet: $3*(d_{tr}+d_{prop})$
- Destination also receives the subsequent packets in $(N-1)*d_{tr}$ time
- No queueing or processing delay at intermediate notes
- So, the **end-to-end delay** (from the beginning of transmission at the source, until receiving the entire file at the destination)is $\mathbf{3*(d_{tr}+d_{prop})+(N-1)*d_{tr}}$

Packet Switching

E2E throughput=L(bits)/e2e delay(sec)



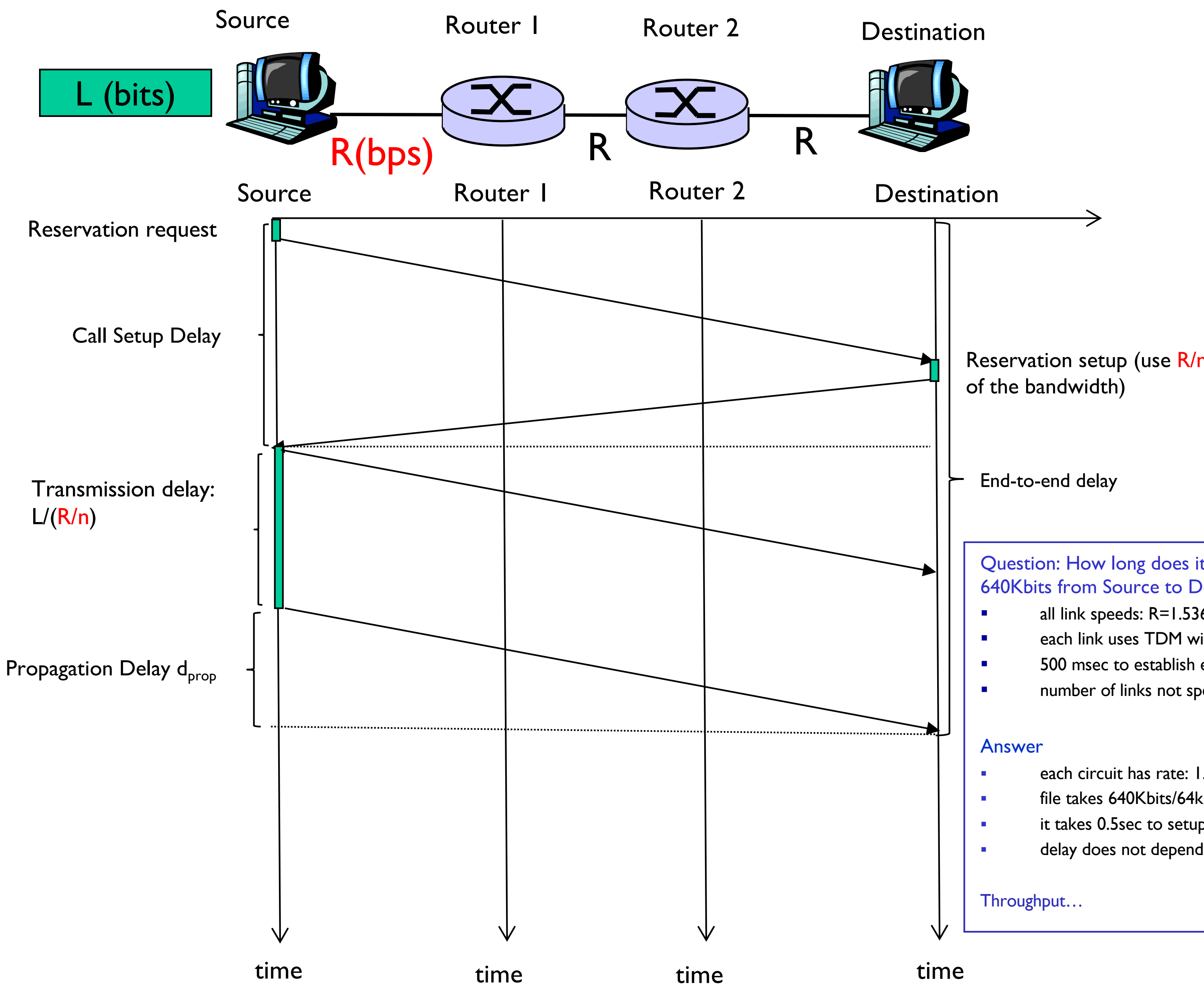
Notes on Throughput

- Alternative definition at source/receiver/router
- Goodput: only useful message counts, no headers or control messages
- End-to-end (e2e) throughput vs local thoughput
- Average vs instantaneous throughout
- Relatedt o but not the same with delay
- Interactive exercises

Numerical example

- Question: How long does it take to send a file of 640Kbits from Source to Destination over a circuit-switched network?
  - all link speeds: R=1.536 Mbps
  - each link uses TDM with n=24 slots/sec
  - 500 msec to establish end-to-end circuit

Circuit Switching: delay



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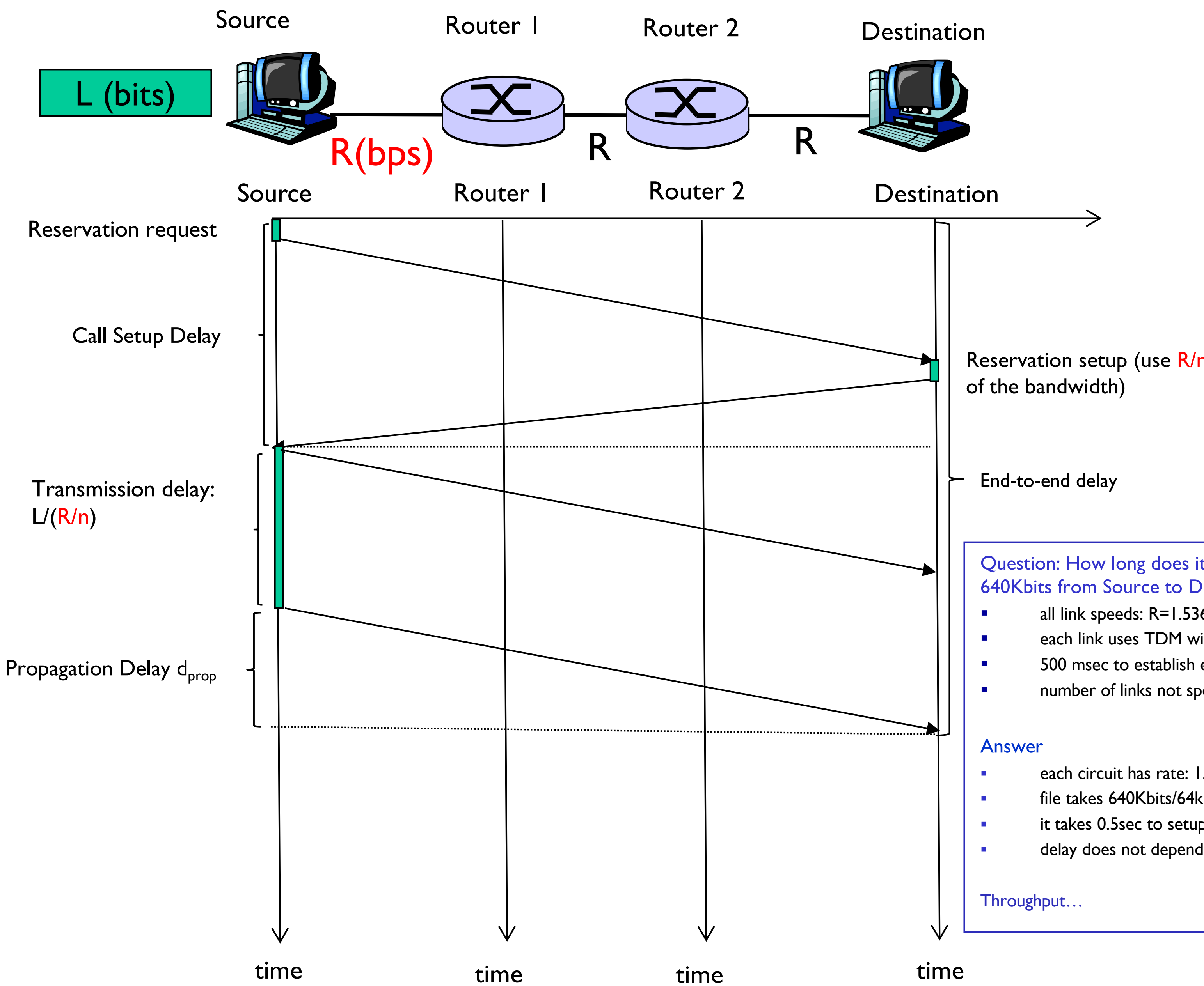
- number of links not specified

Answer

- each circuit has rate: 1.536Mbps/24=64kbps
- file takes 640Kbits/64kbps =10sec to transmit
- it takes 0.5sec to setup the circuit
- delay does not depend on the number of hops.

Throughput…

Circuit Switching: delay



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- ❖ circuit switching vs packet switching ✔
- ❖ network structure

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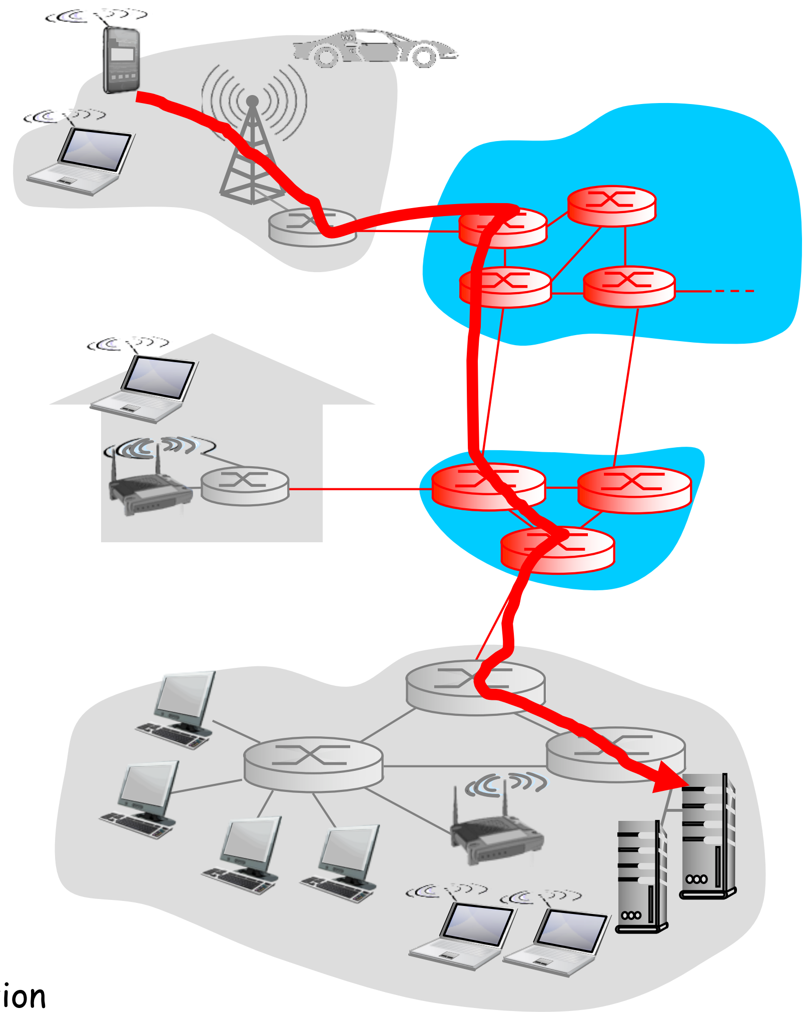
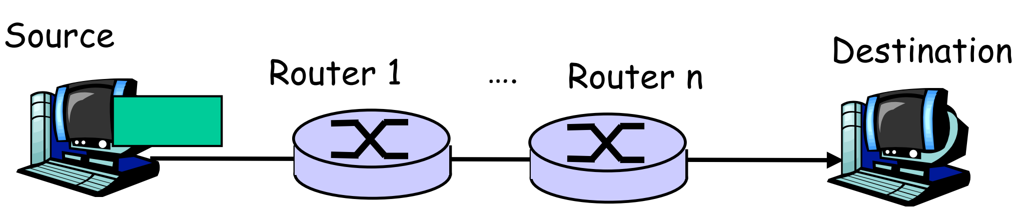
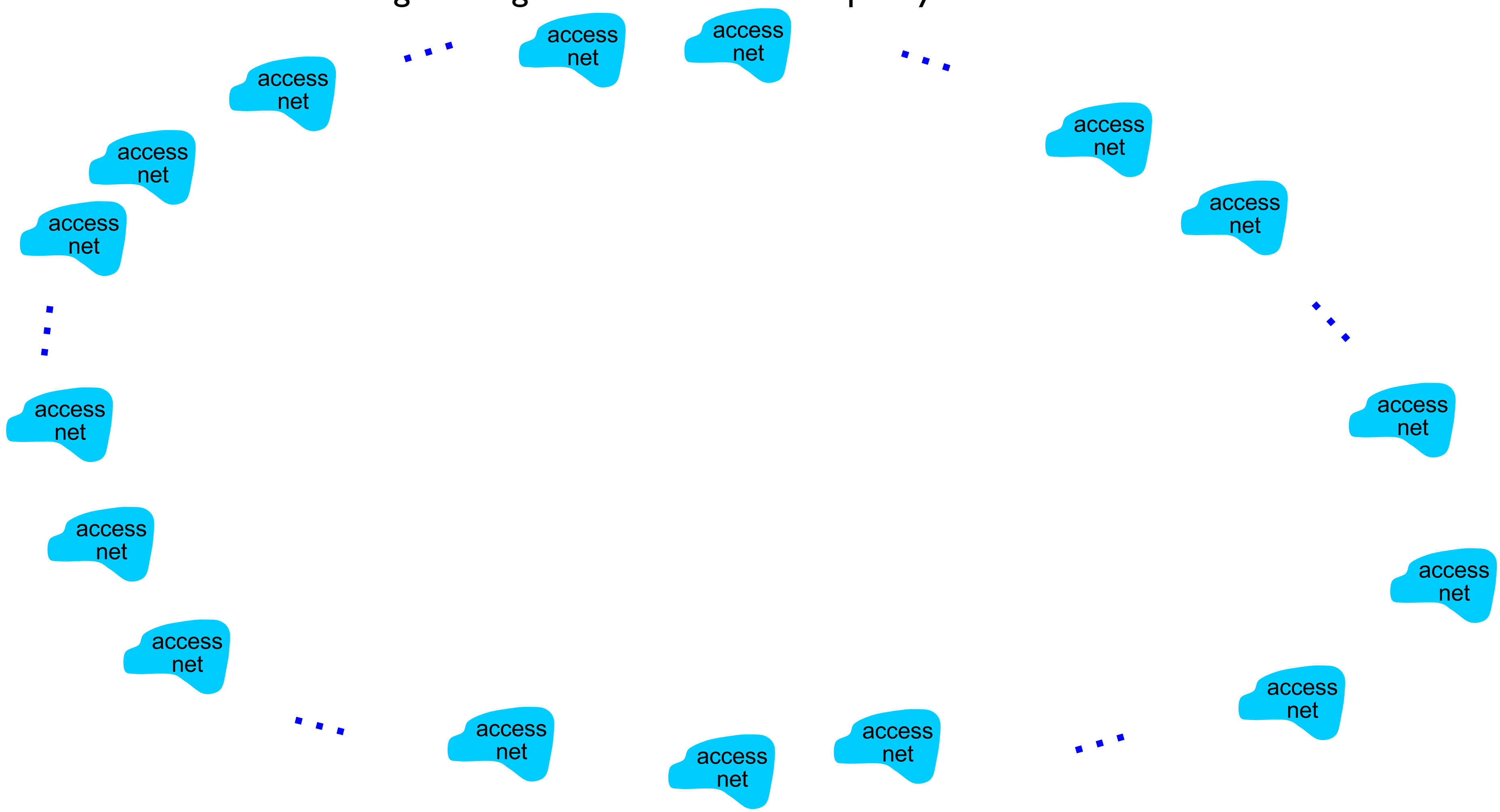
Internet's core





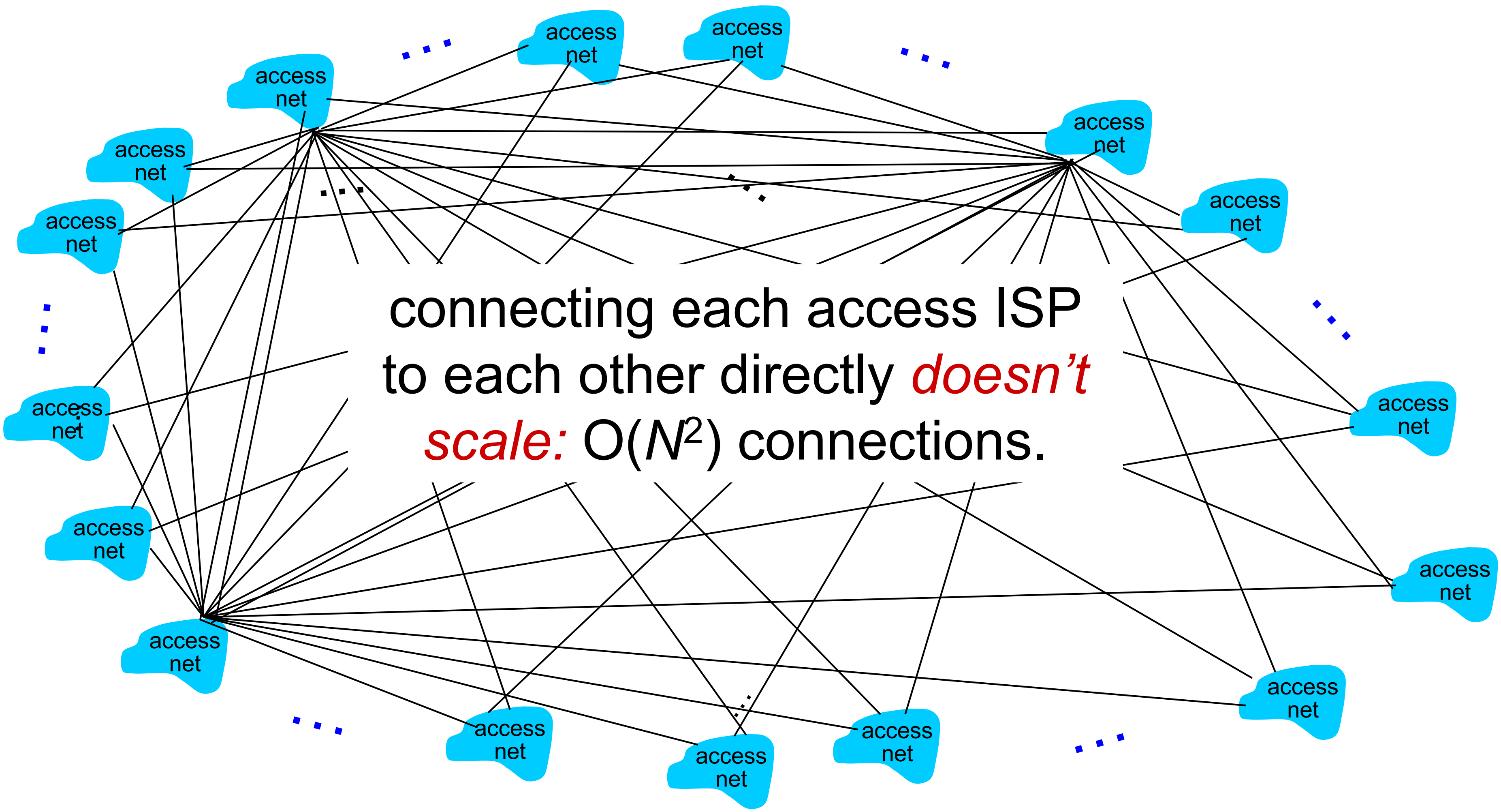
Internet structure: network of networks

- End systems connect to Internet via access ISPs:
  - residential, company and university ISPs
- *Question:* given *millions* of access ISPs, how to connect them together?
  - Considerations: engineering but also economics+policy



Internet structure: network of networks

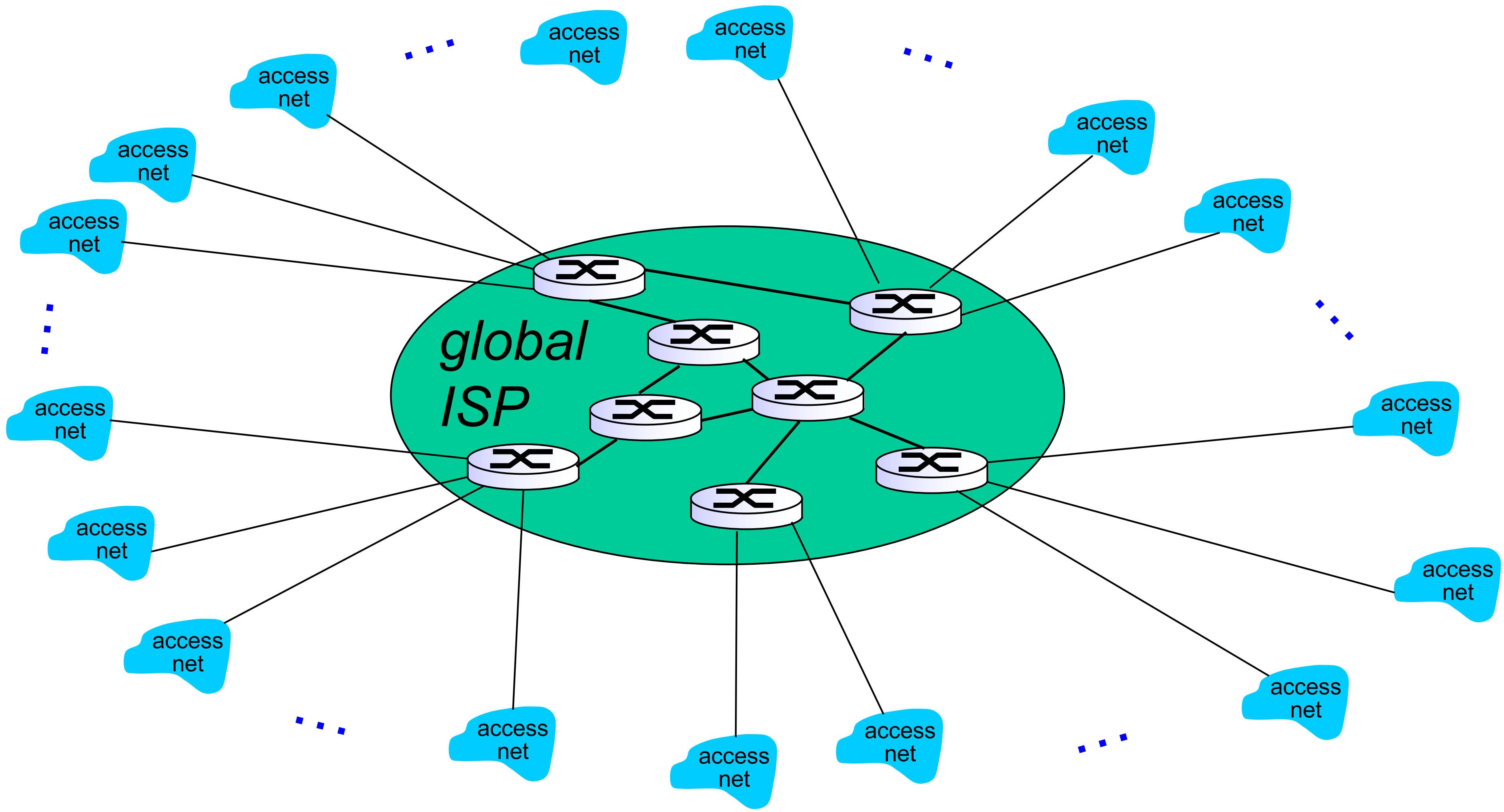
Option: connect each access ISP to every other access ISP?



connecting each access ISP to each other directly *doesn't scale:* O(N^2) connections.

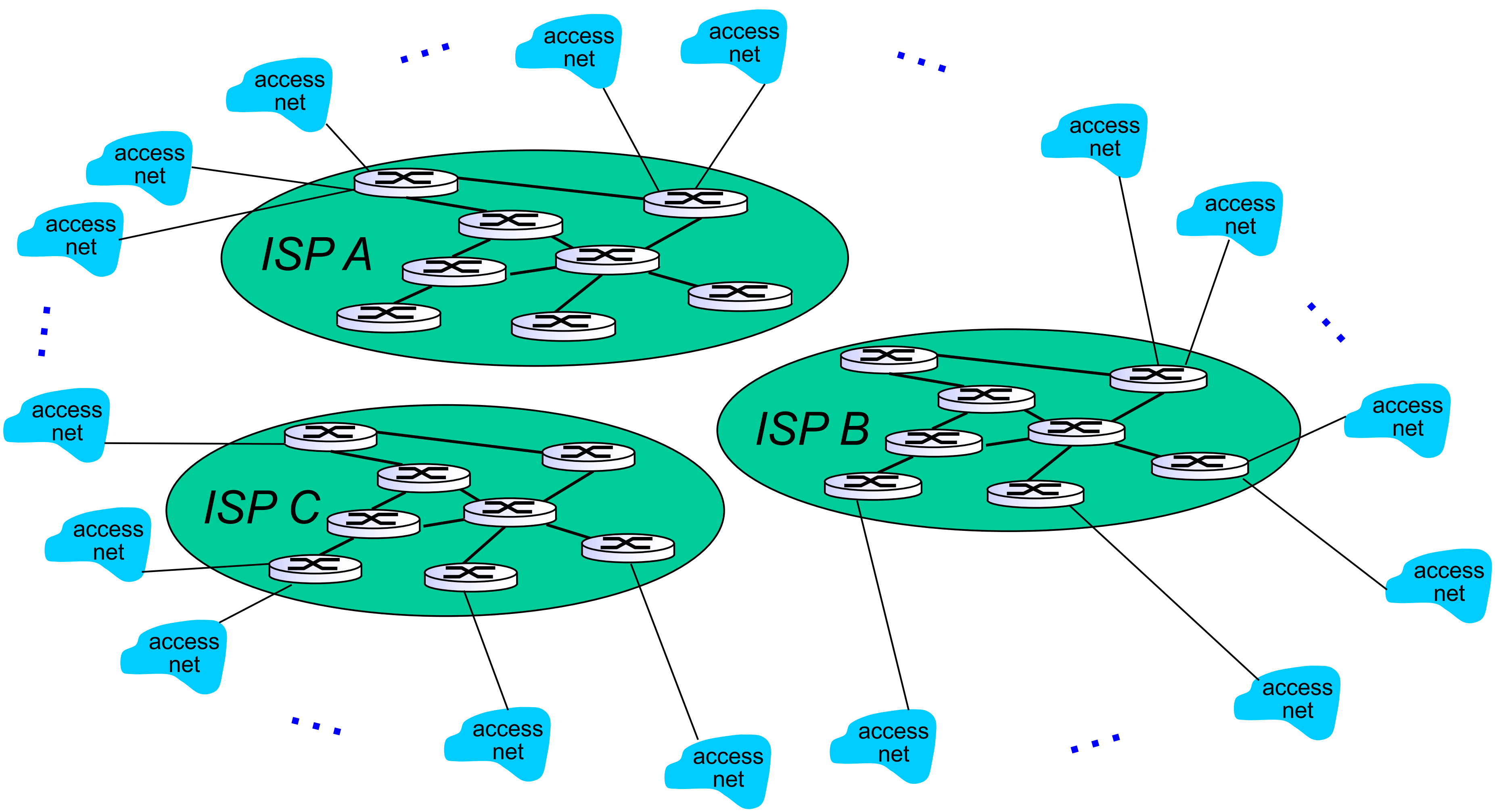
Internet structure: network of networks

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



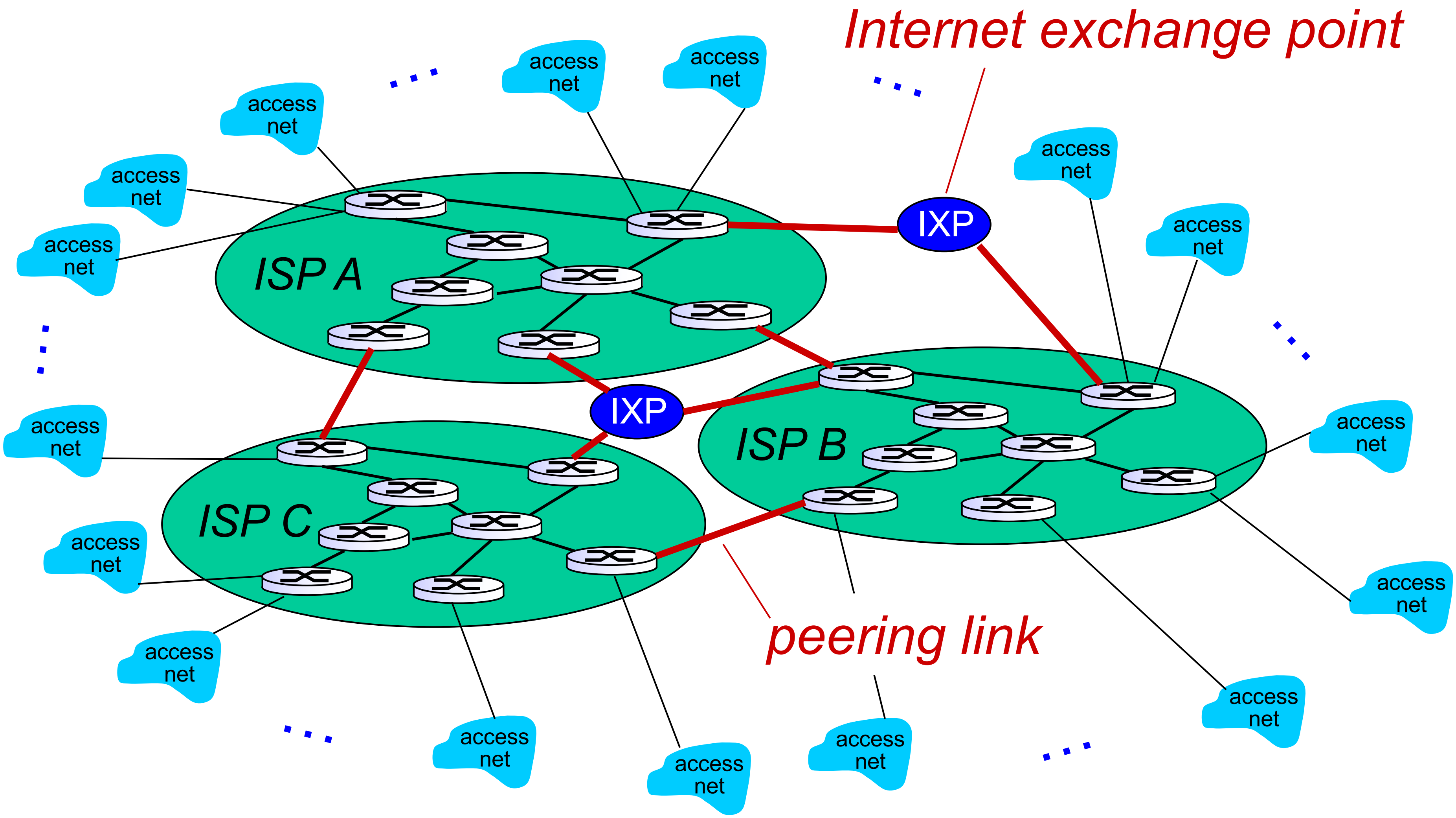
Internet structure: network of networks

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



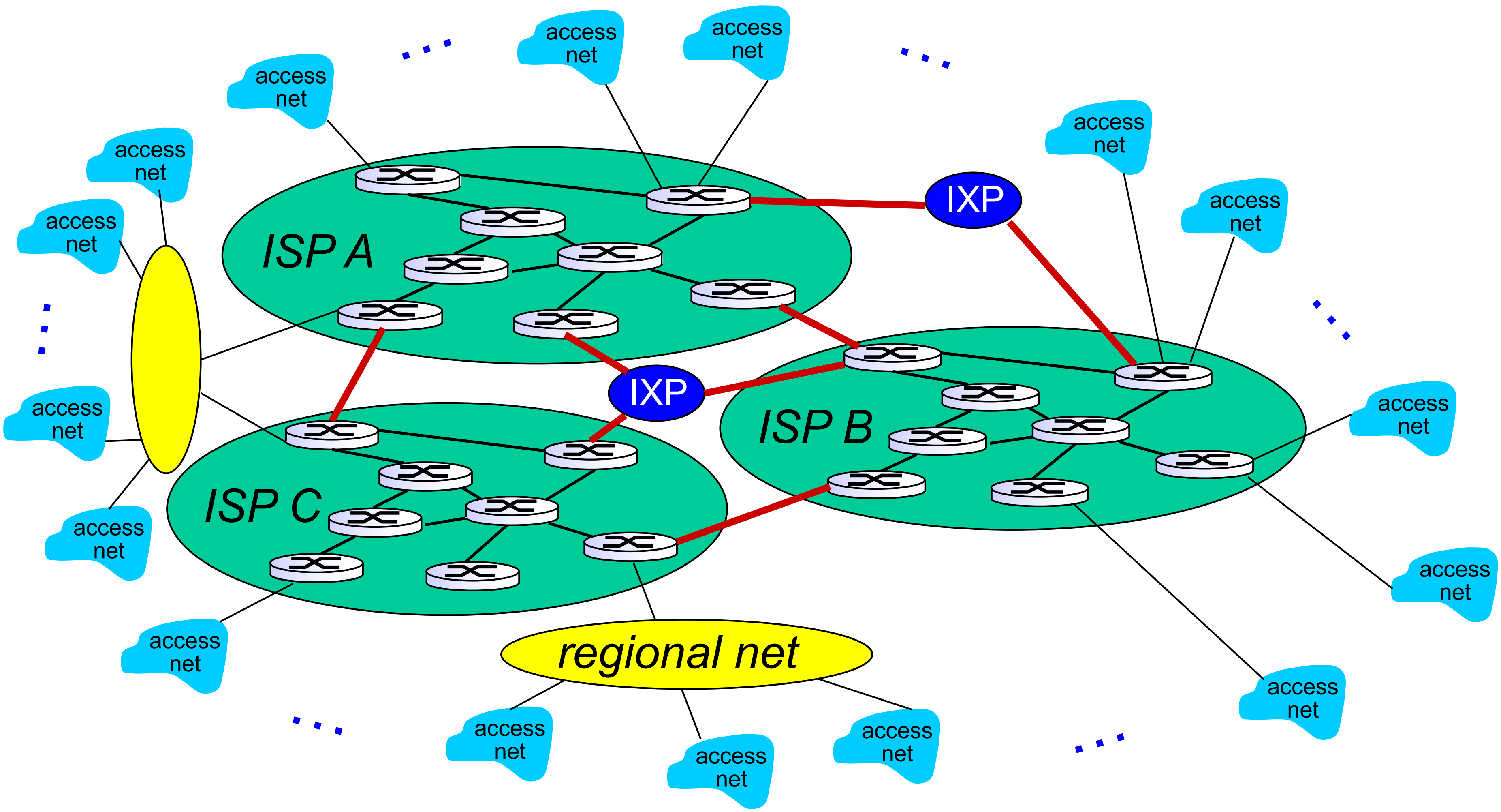
Internet structure: network of networks

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



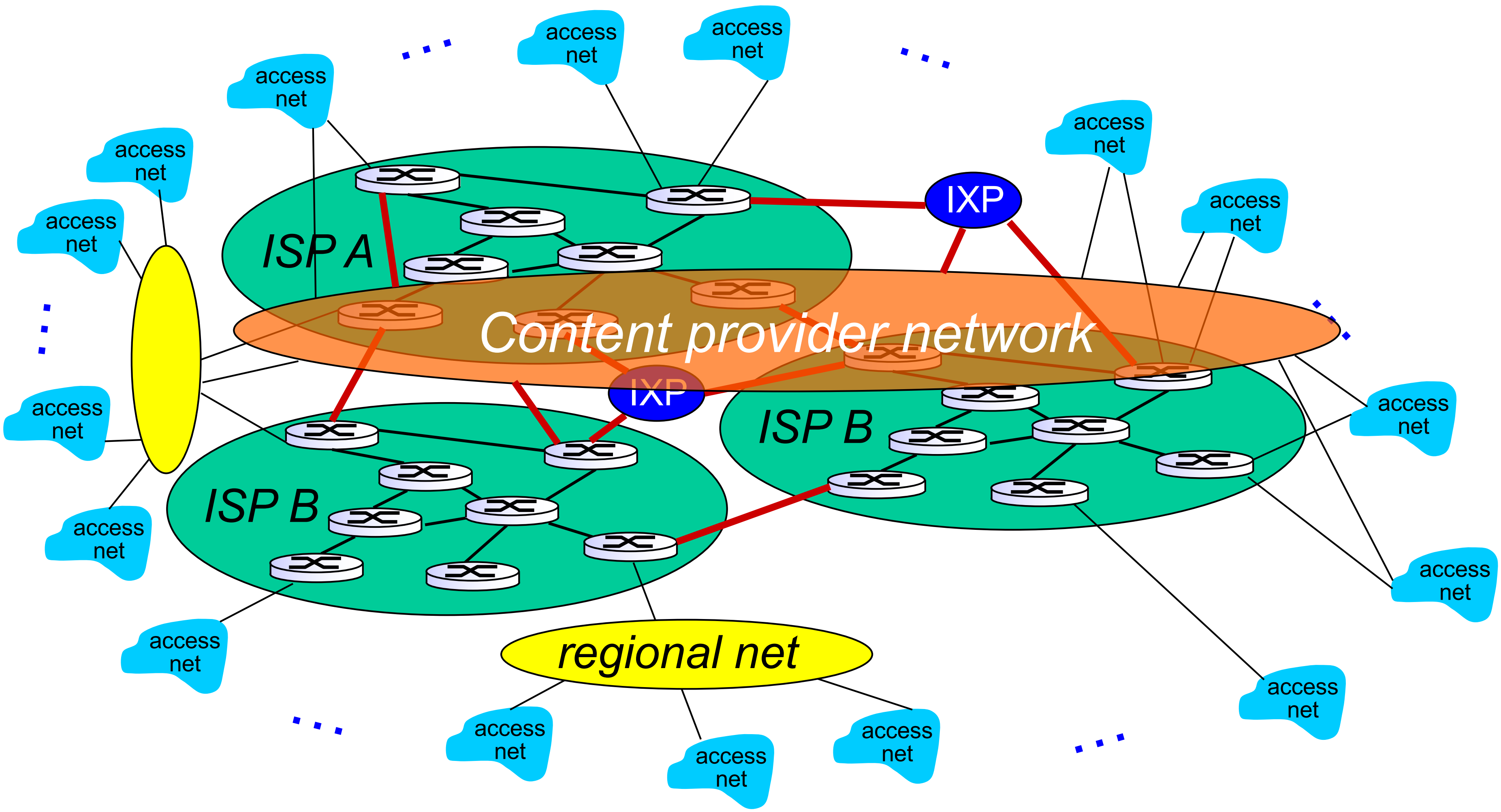
Internet structure: network of networks

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

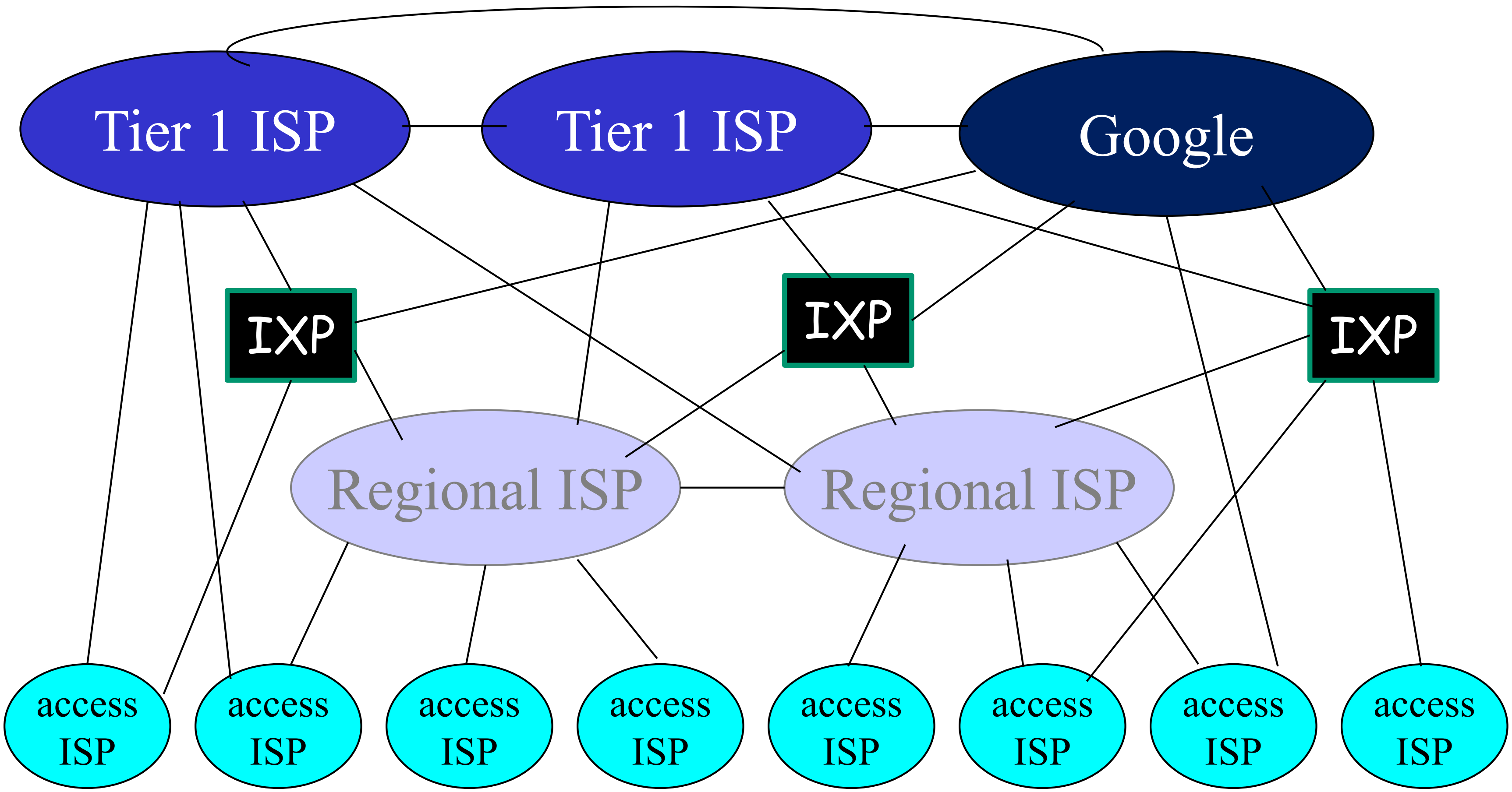


Internet structure: network of networks

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

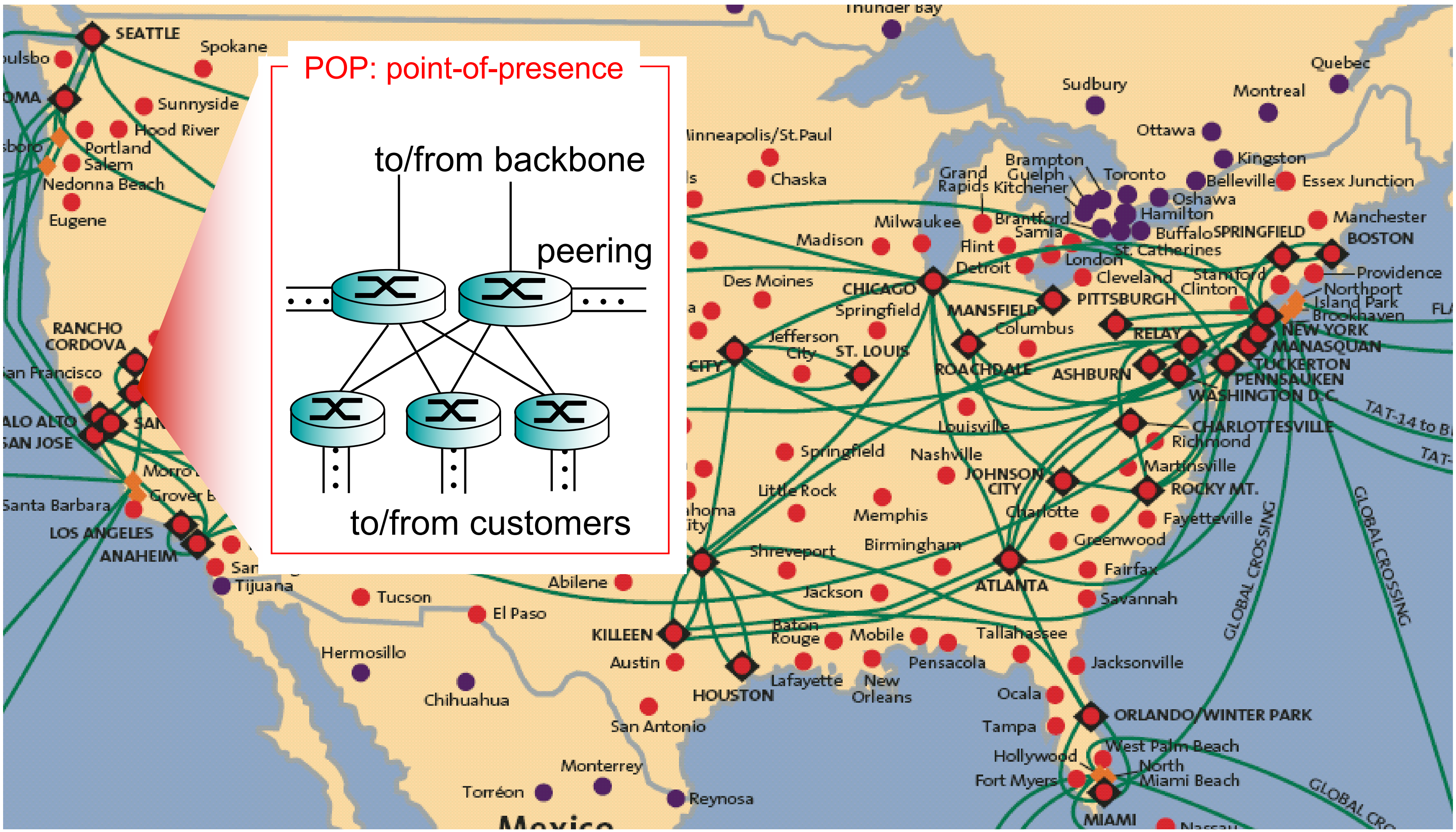


Internet structure: network of networks



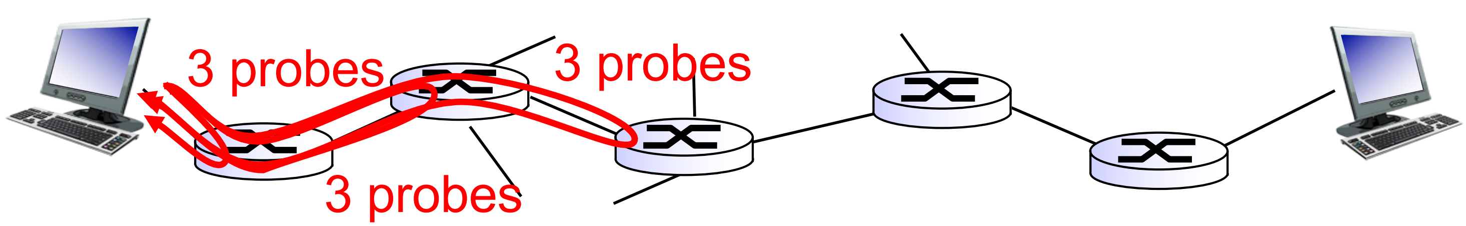
- at center: small # of well-connected large networks
  - "tier-1" commercial ISPs (e.g., Level 3, Sprint, AT&T, NTT), national & international coverage
  - content provider network (e.g, Google): private network that connects it data centers to Internet, often bypassing tier-1, regional ISPs

Tier-1 ISP: e.g., Sprint



"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 and routes

traceroute: from gaia.cs.umass.edu to www.eurecom.fr

Three delay measurements from gaia.cs.umass.edu to cs-gw.cs.umass.edu

```
1  cs-gw (128.119.240.254)  1 ms  1 ms  2 ms
2  border1-rt-fa5-1-0.gw.umass.edu (128.119.3.145)  1 ms  1 ms  2 ms
3  cht-vbns.gw.umass.edu (128.119.3.130)  6 ms 5 ms 5 ms
4  jn1-at1-0-0-19.wor.vbns.net (204.147.132.129)  16 ms 11 ms 13 ms
5  jn1-so7-0-0-0.wae.vbns.net (204.147.136.136)  21 ms 18 ms 18 ms
6  abilene-vbns.abilene.ucaid.edu (198.32.11.9)  22 ms  18 ms  22 ms
7  nycm-wash.abilene.ucaid.edu (198.32.8.46)  22 ms  22 ms  22 ms
8  62.40.103.253 (62.40.103.253)  104 ms 109 ms 106 ms
9  de2-1.de1.de.geant.net (62.40.96.129)  109 ms 102 ms 104 ms
10  de.fr1.fr.geant.net (62.40.96.50)  113 ms 121 ms 114 ms
11  renater-gw.fr1.fr.geant.net (62.40.103.54)  112 ms  114 ms  112 ms
12  nio-n2.cssi.renater.fr (193.51.206.13)  111 ms  114 ms  116 ms
13  nice.cssi.renater.fr (195.220.98.102)  123 ms  125 ms  124 ms
14  r3t2-nice.cssi.renater.fr (195.220.98.110)  126 ms  126 ms  124 ms
15  eurecom-valbonne.r3t2.ft.net (193.48.50.54)  135 ms  128 ms  133 ms
16  194.214.211.25 (194.214.211.25)  126 ms  128 ms  126 ms
17  * * *
18  * * *
19  fantasia.eurecom.fr (193.55.113.142)  132 ms  128 ms  136 ms
```

trans-oceanic link

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

Try traceroute yourself

Athinas-MacBook-Pro:~ athina$ traceroute gaia.cs.umass.edu

Athinas-MacBook-Pro:~ athina$ traceroute www.uci.edu

Athinas-MacBook-Pro:~ athina$ traceroute www.google.com

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