

CS 43: Computer Networks

09: Network Performance

September 28, 2026



Adapted from L. Vanbever and Jim Kurose

Reading Quiz

(graded for correctness)

Put devices away

Note: Reading quiz slides will have an orange border.

End of Reading Quiz!

Where we are

Application: the application (e.g., DNS, Email)

Transport: end-to-end connections, reliability

Network: routing

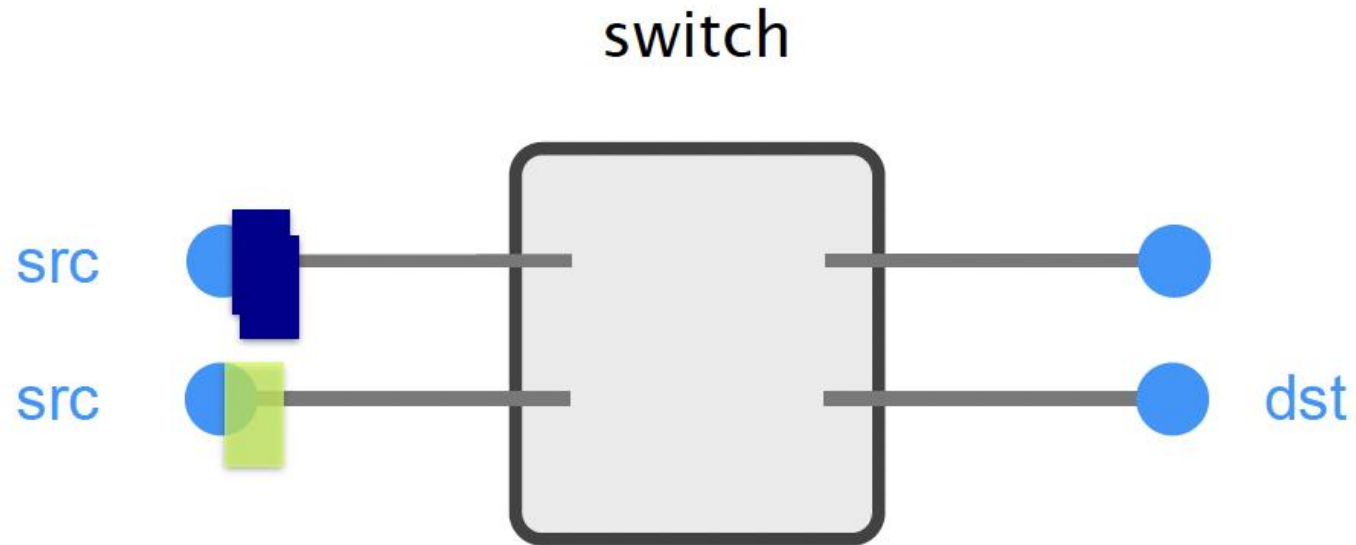
Link (data-link): framing, error detection

Physical: 1's and 0's/bits across a medium
(copper, the air, fiber)

Today: How do we characterize networks?

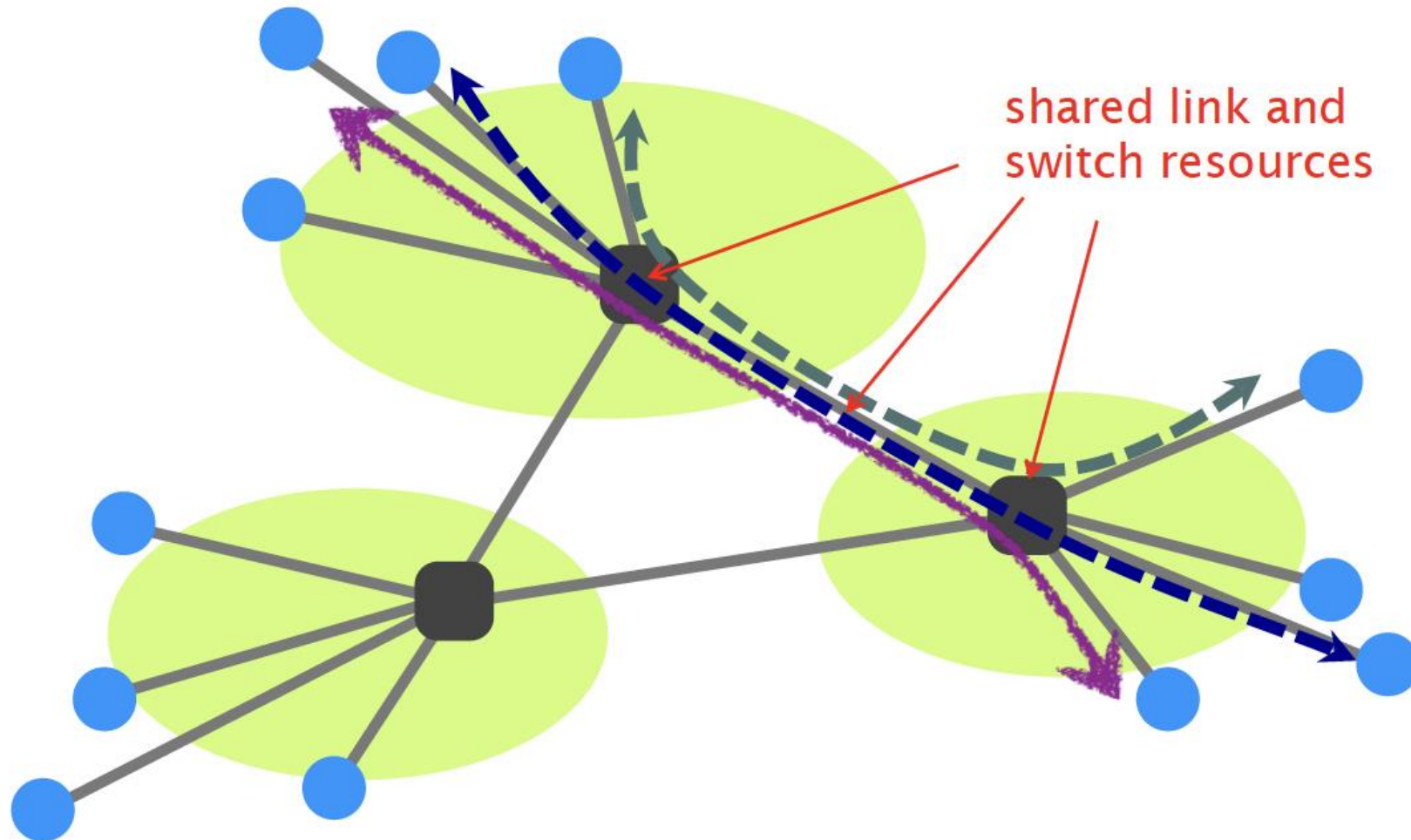
- What is a packet switched network?
- Delays
- Loss
- Throughput

In packet switching,
data transfer is done using independent packets

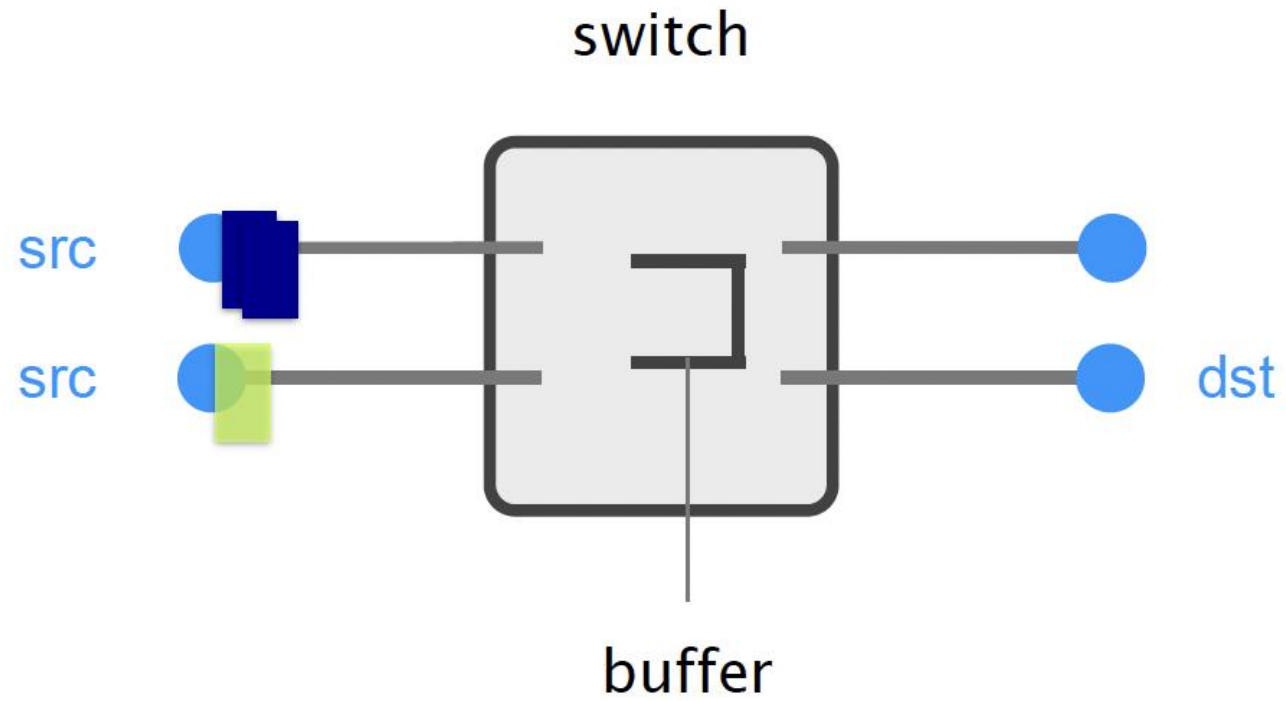


Each packet contains a destination (**dst**)

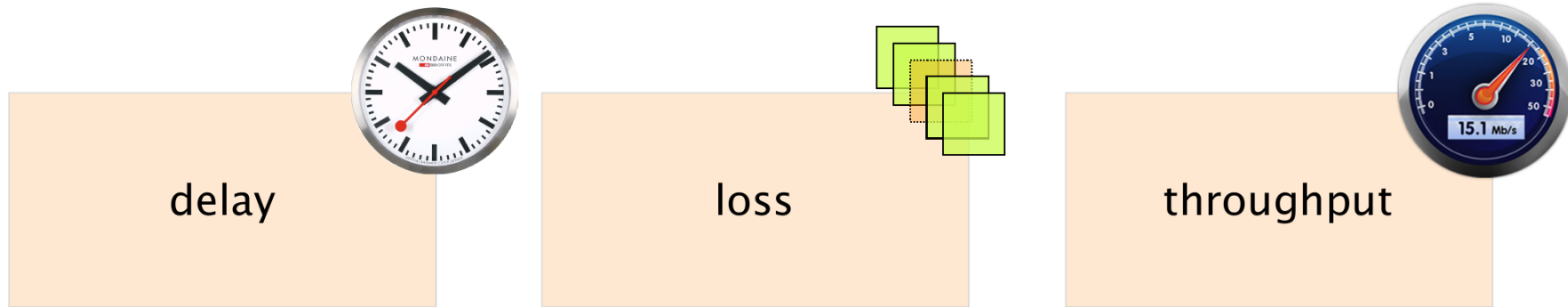
Links and switches are shared between flows



To absorb transient overload,
packet switching relies on buffers



A network *connection* is characterized by its delay, loss rate and throughput

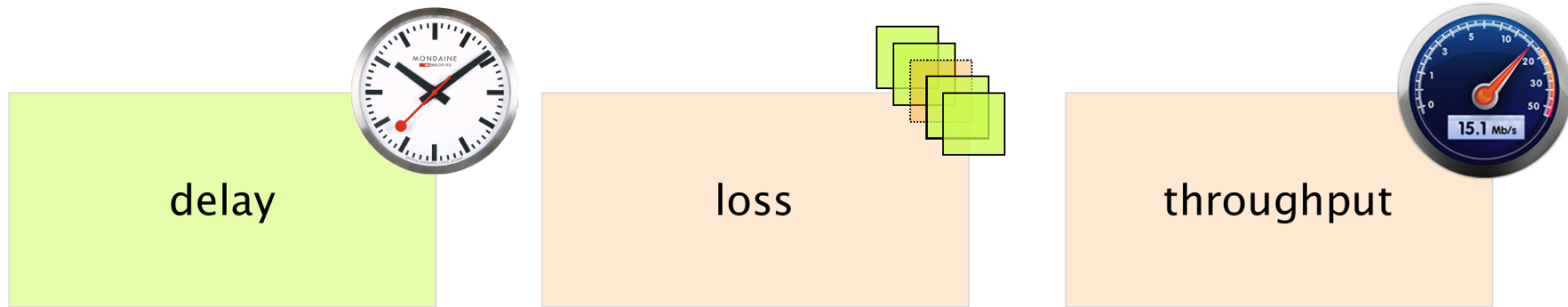


How long does it take for a packet to reach the destination

What fraction of packets sent to a destination are dropped?

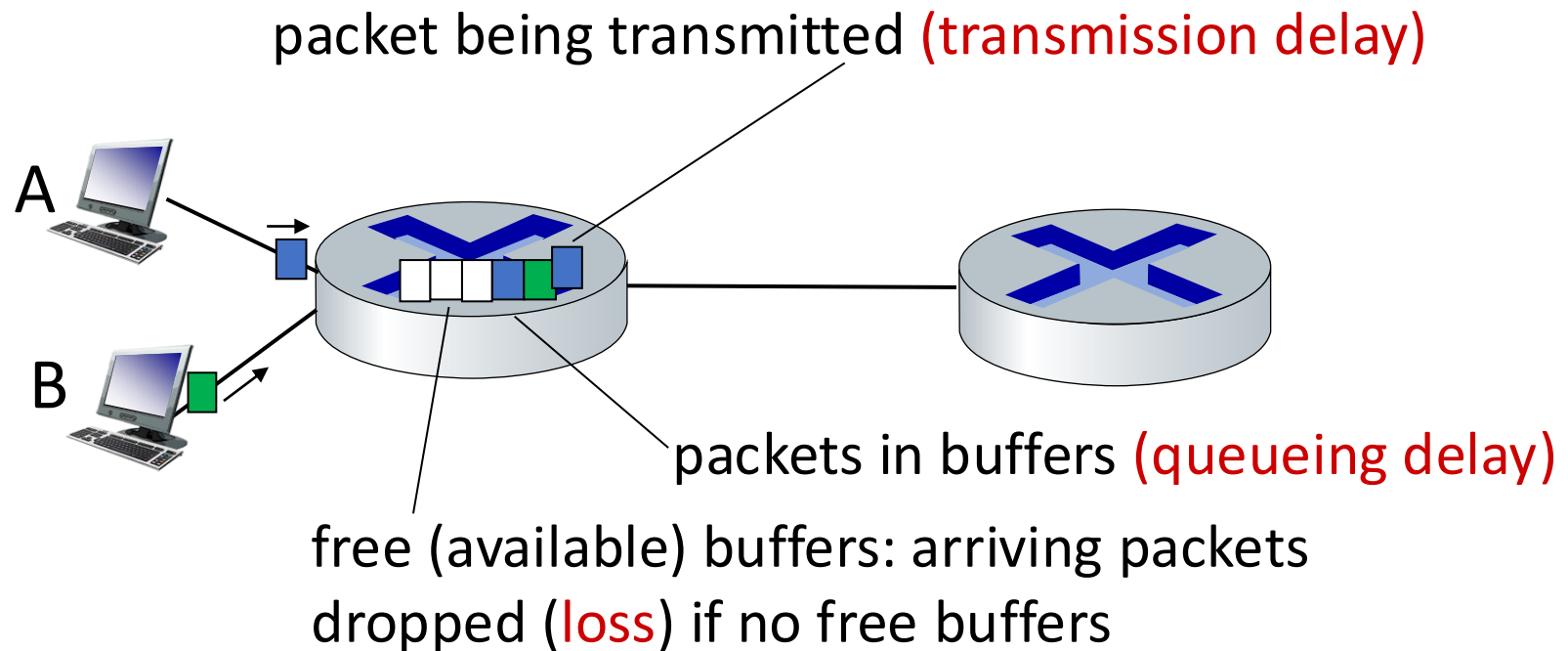
At what rate is the destination receiving data from the source?

A network *connection* is characterized by its delay, loss rate and throughput

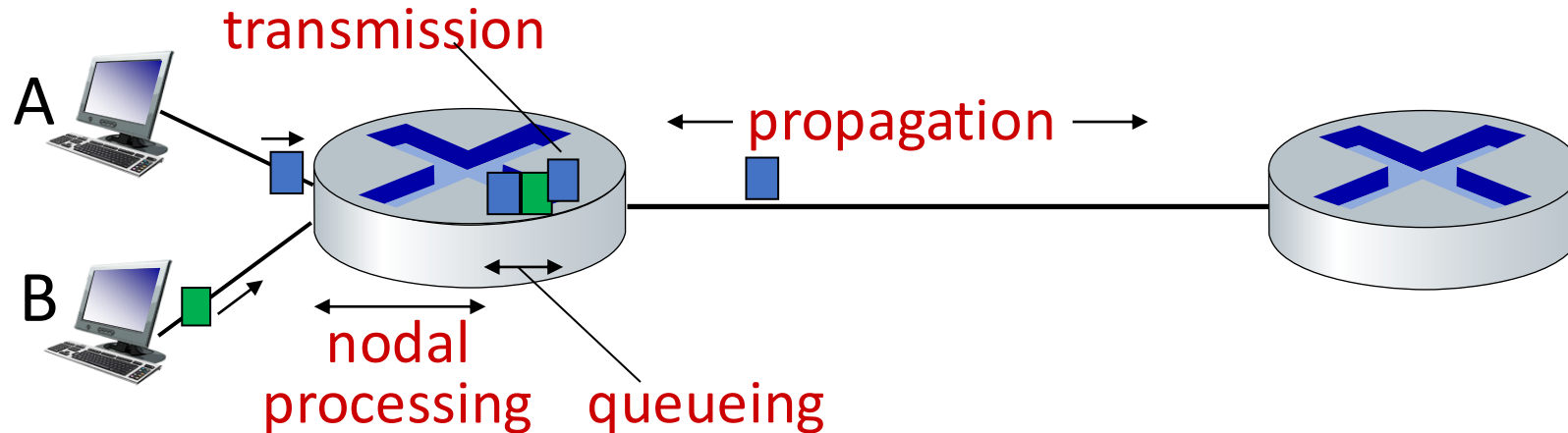


How do packet delay and loss occur?

- packets *queue* in router buffers, waiting for turn for transmission
 - queue length grows when arrival rate to link (temporarily) exceeds output link capacity
- packet *loss* occurs when memory to hold queued packets fills up



Packet delay: four sources



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

d_{proc} : nodal processing

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

d_{queue} : queueing delay

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

The transmission delay is the amount of time required to push all of the bits onto the link

$$\begin{array}{lcl} \text{Transmission delay} & = & \frac{\text{packet size}}{\text{link bandwidth}} \\ \text{[sec]} & & \begin{array}{l} \text{[#bits]} \\ \text{[#bits/sec]} \end{array} \end{array}$$

$$\begin{array}{lcl} \text{Example} & & \frac{1\,000\text{ bits}}{100\text{ Gbps}} \\ & & 10\text{ ns} \end{array}$$

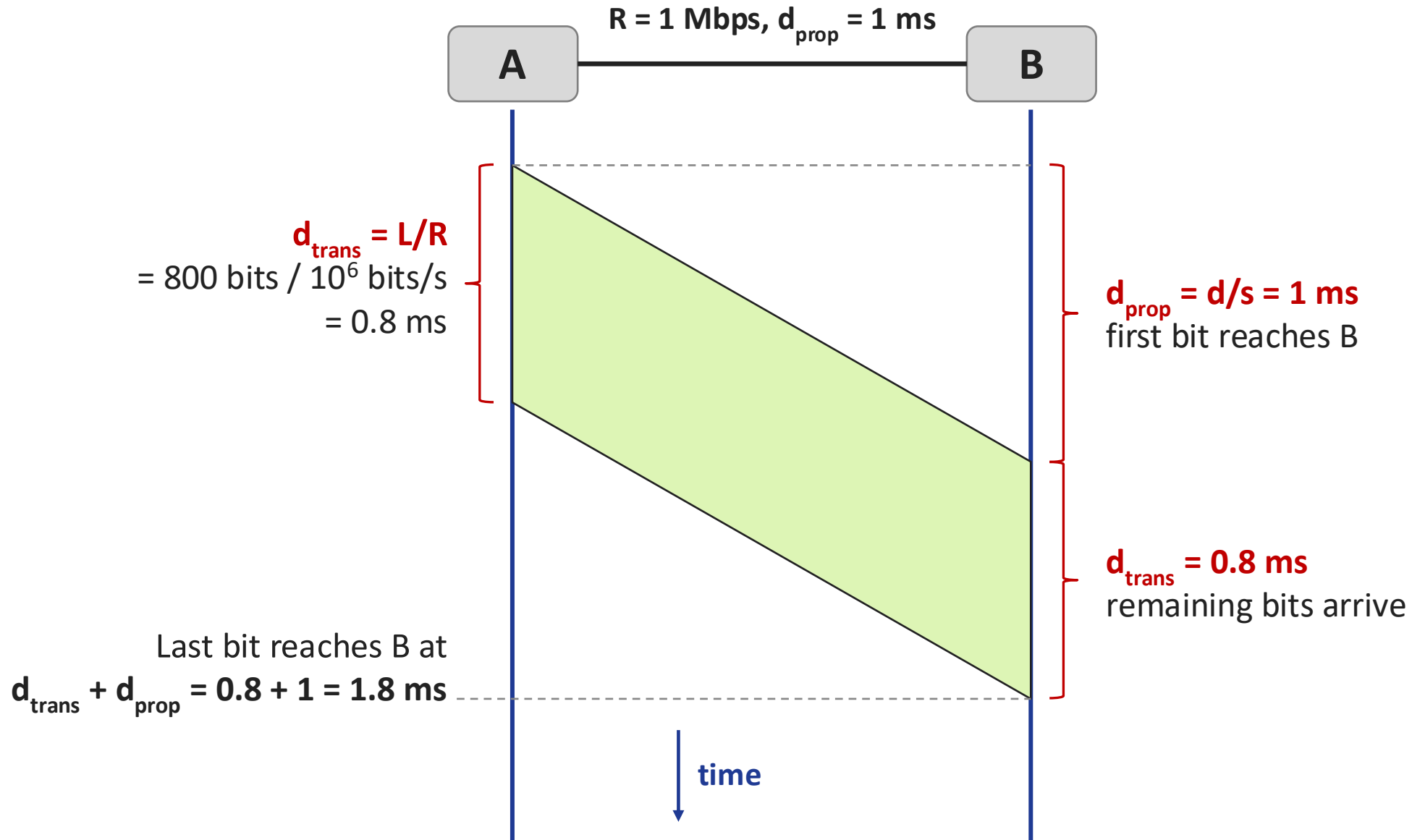
The propagation delay is the amount of time required for a bit to travel to the end of the link

$$\begin{array}{lcl} \text{Propagation delay} & = & \frac{\text{link length}}{\text{propagation speed}} \\ [\text{sec}] & & \begin{array}{l} [\text{m}] \\ [\text{m/sec}] \\ (\text{fraction of speed of light}) \end{array} \end{array}$$

$$\begin{array}{lcl} \text{Example} & & \\ & = & \frac{30\,000\text{ m}}{2 \times 10^8\text{ m/sec}} \\ & & \begin{array}{l} 150\text{ }\mu\text{sec} \\ (\text{speed of light in fiber}) \end{array} \end{array}$$

How long does it take for a packet to travel from A to B?
(not considering queuing for now)

How long does it take to send a 100-byte packet?



A packet crosses the link from router A to router B. The queue is empty and there is no other traffic.

Current $d_{\text{trans}} = 120$ ms and $d_{\text{prop}} = 100$ ms

the link transmission rate R doubles. Nothing else changes.
What is $d_{\text{trans}} + d_{\text{prop}}$ now?

- A. 110 ms
- B. 170 ms
- C. 160 ms
- D. 220 ms
- E. 340 ms

A packet crosses the link from router A to router B. The queue is empty and there is no other traffic.

Current $d_{\text{trans}} = 120$ ms and $d_{\text{prop}} = 100$ ms

the link transmission rate R doubles. Nothing else changes.
What is $d_{\text{trans}} + d_{\text{prop}}$ now?

- A. 110 ms
- B. 170 ms
- C. 160 ms**
- D. 220 ms
- E. 340 ms

A packet crosses the link from router A to router B. The queue is empty and there is no other traffic.

Current $d_{\text{trans}} = 120$ ms and $d_{\text{prop}} = 100$ ms

the link length doubles. Nothing else changes.
What is $d_{\text{trans}} + d_{\text{prop}}$ now?

- A. 220 ms
- B. 440 ms
- C. 340 ms
- D. 320 ms
- E. 170 ms

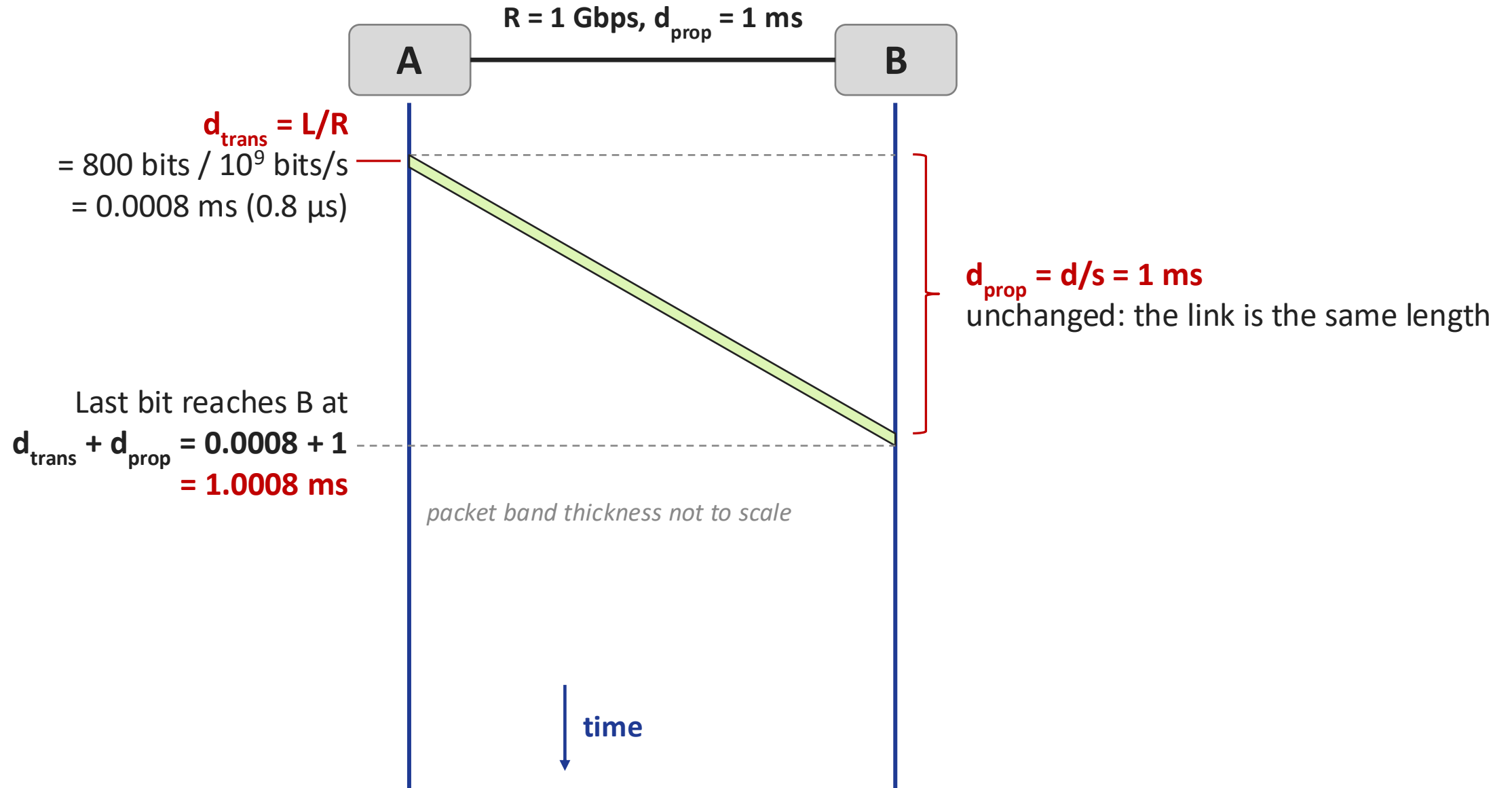
A packet crosses the link from router A to router B. The queue is empty and there is no other traffic.

Current $d_{\text{trans}} = 120$ ms and $d_{\text{prop}} = 100$ ms

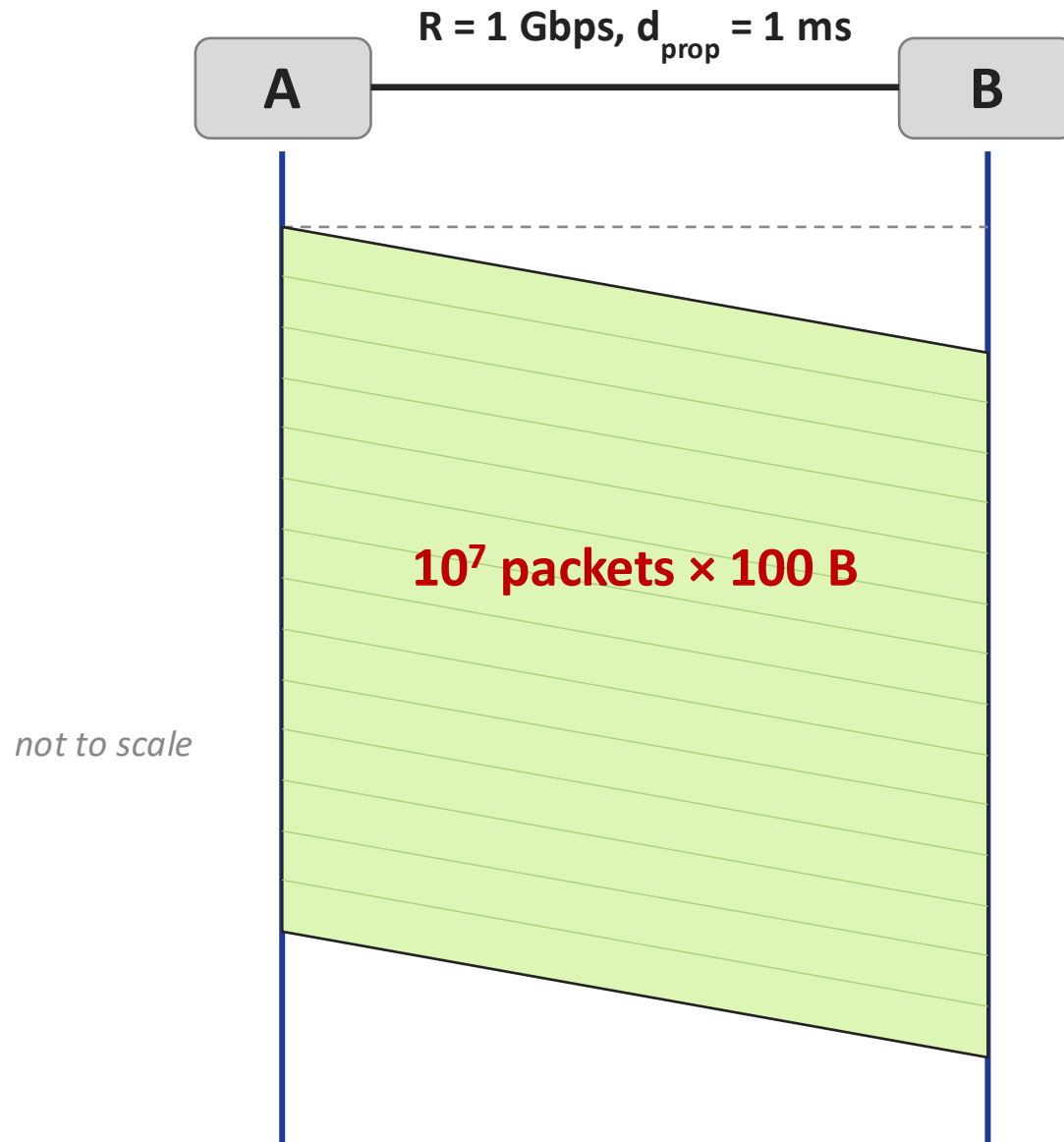
the link length doubles. Nothing else changes.
What is $d_{\text{trans}} + d_{\text{prop}}$ now?

- A. 220 ms
- B. 440 ms
- C. 340 ms
- D. 320 ms**
- E. 170 ms

With a 1 Gbps link, the total time drops to 1.0008 ms

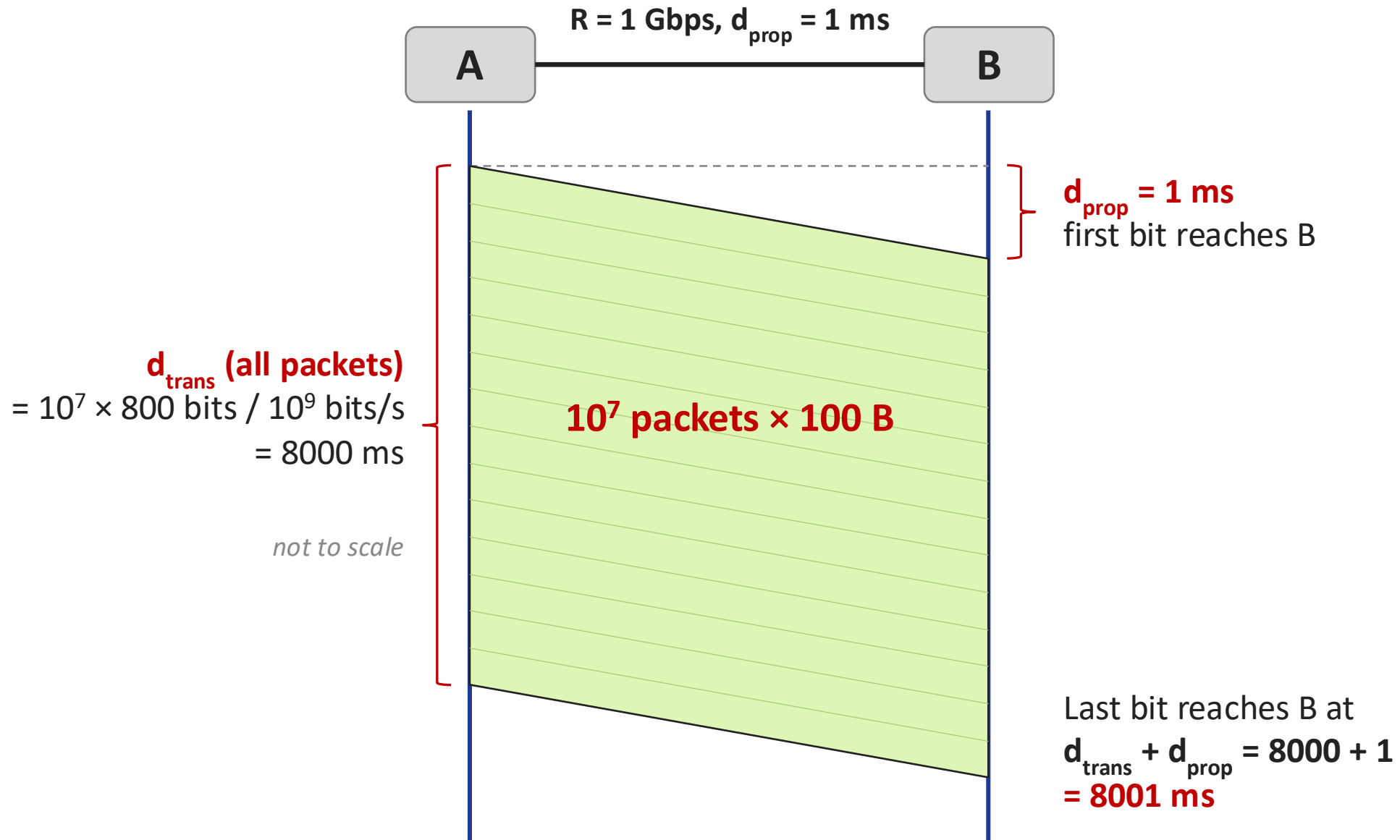


What if we send a 1 GB file split into 100-byte packets?



- A. 1.0008 ms
- B. 1001 ms
- C. 8000 ms
- D. 8001 ms
- E. About 10,000 s ($10^7 \times 1.008\text{ms}$)

What if we send a 1 GB file split into 100-byte packets?



Different transmission characteristics imply
different tradeoffs in terms of which delay dominates

$10^7 \times 100\text{B}$	pkt	1 Gbps link	transmission delay dominates
---------------------------	-----	-------------	------------------------------

$1 \times 100\text{B}$	pkt	1 Gbps link	propagation delay dominates
------------------------	-----	-------------	-----------------------------

$1 \times 100\text{B}$	pkt	1 Mbps link	both matter
------------------------	-----	-------------	-------------

In the Internet, we **can't know** in advance which one matters!

The queuing delay is the amount of time a packet waits in a buffer to be transmitted on a link

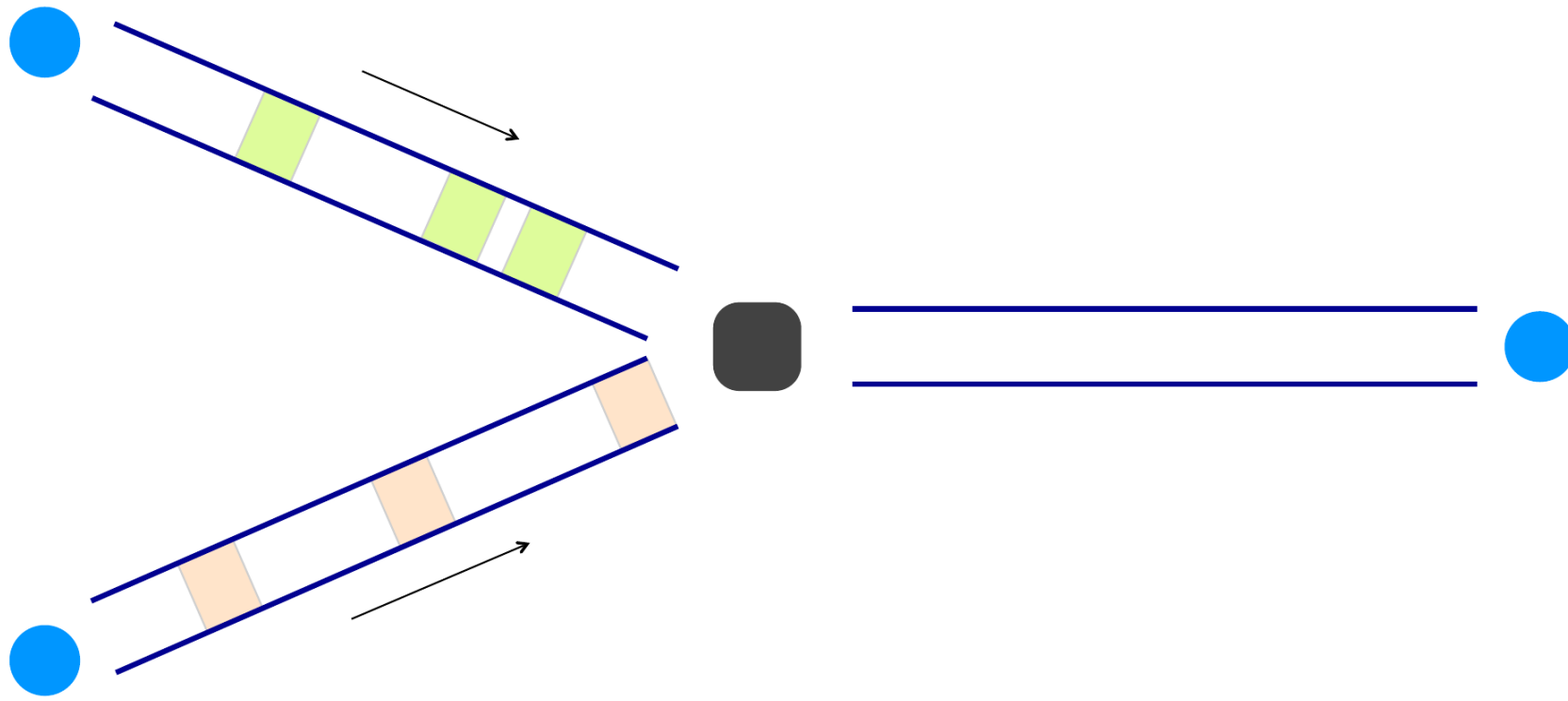
Queuing delay is the hardest to evaluate
as it varies from packet to packet

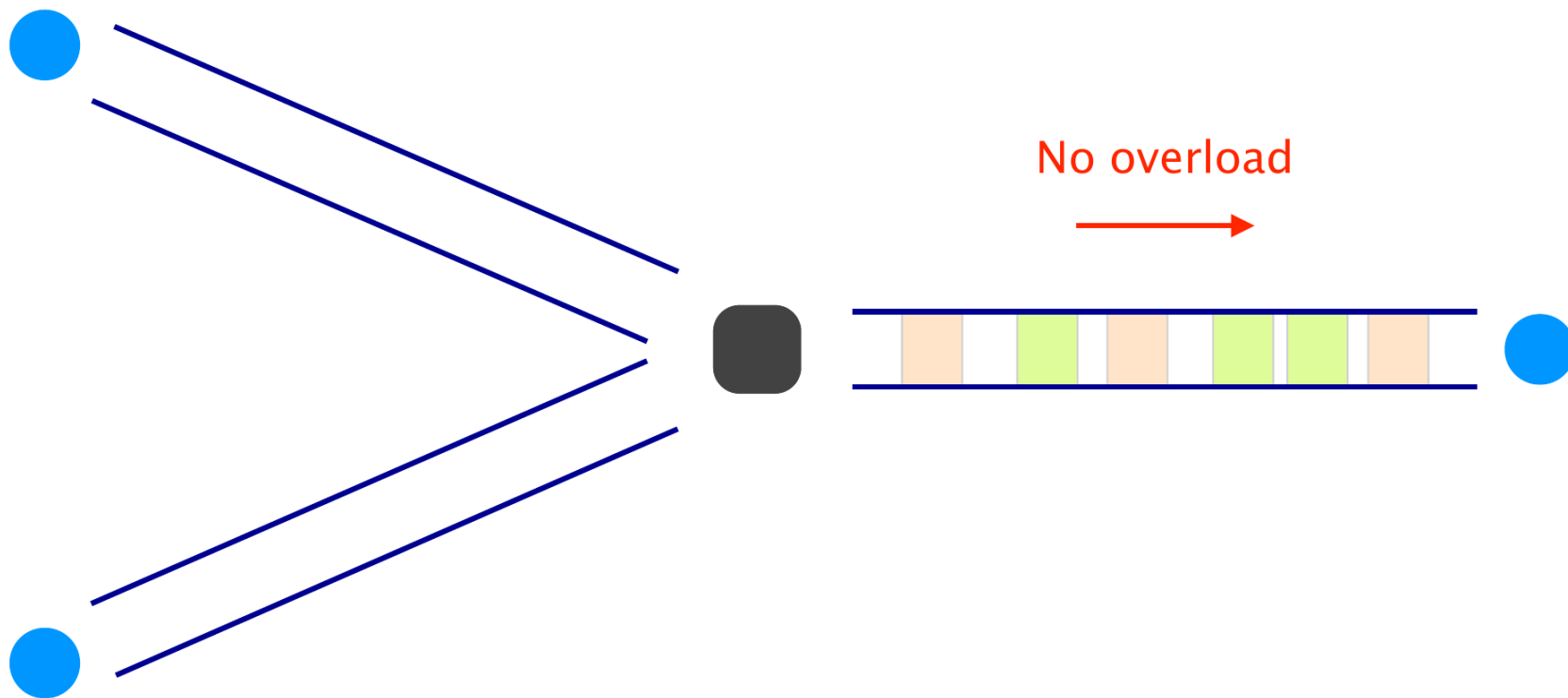
It is characterized with statistical measures
e.g., average delay & variance, probability of exceeding x

Checkout this animation illustration:

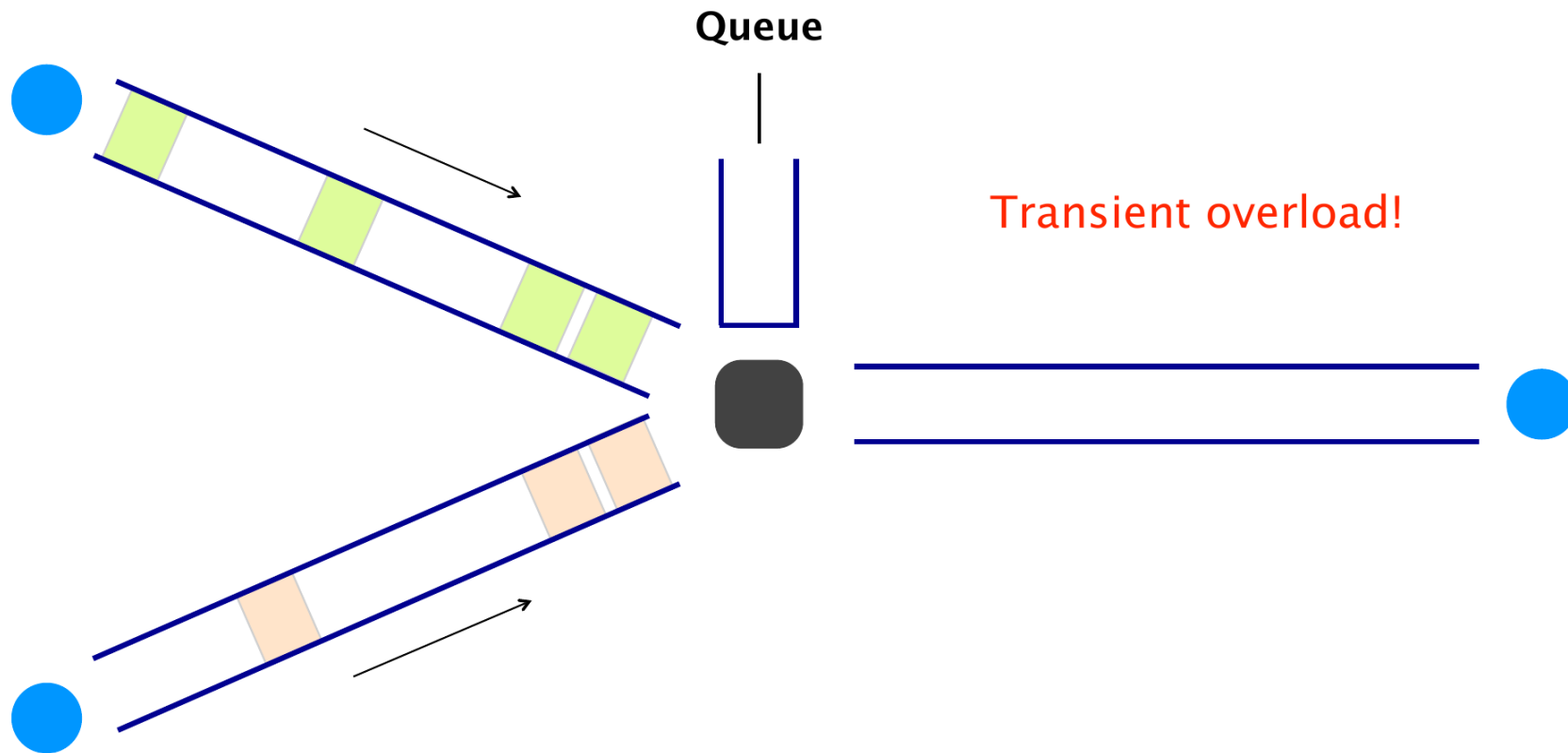
[Queuing loss animation](#)

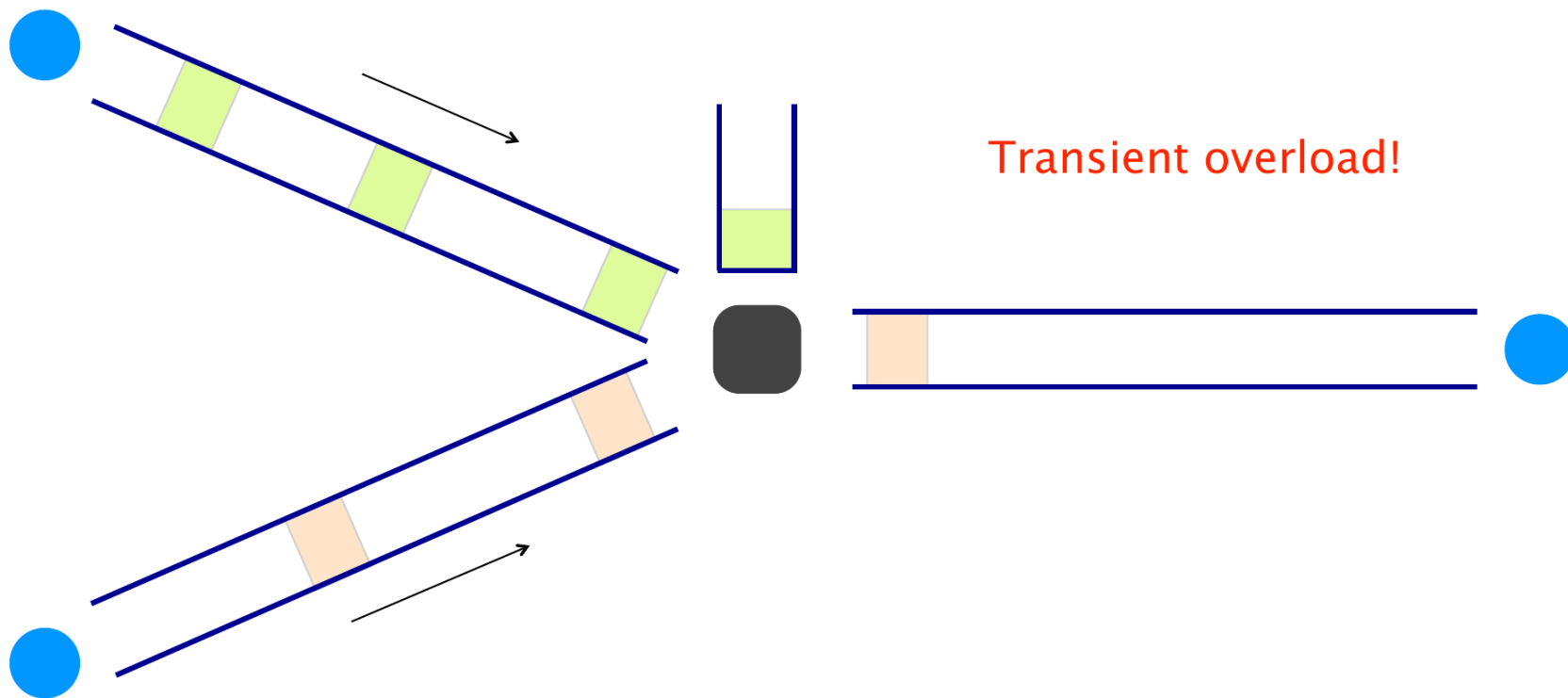
Queuing delay depends on the traffic pattern

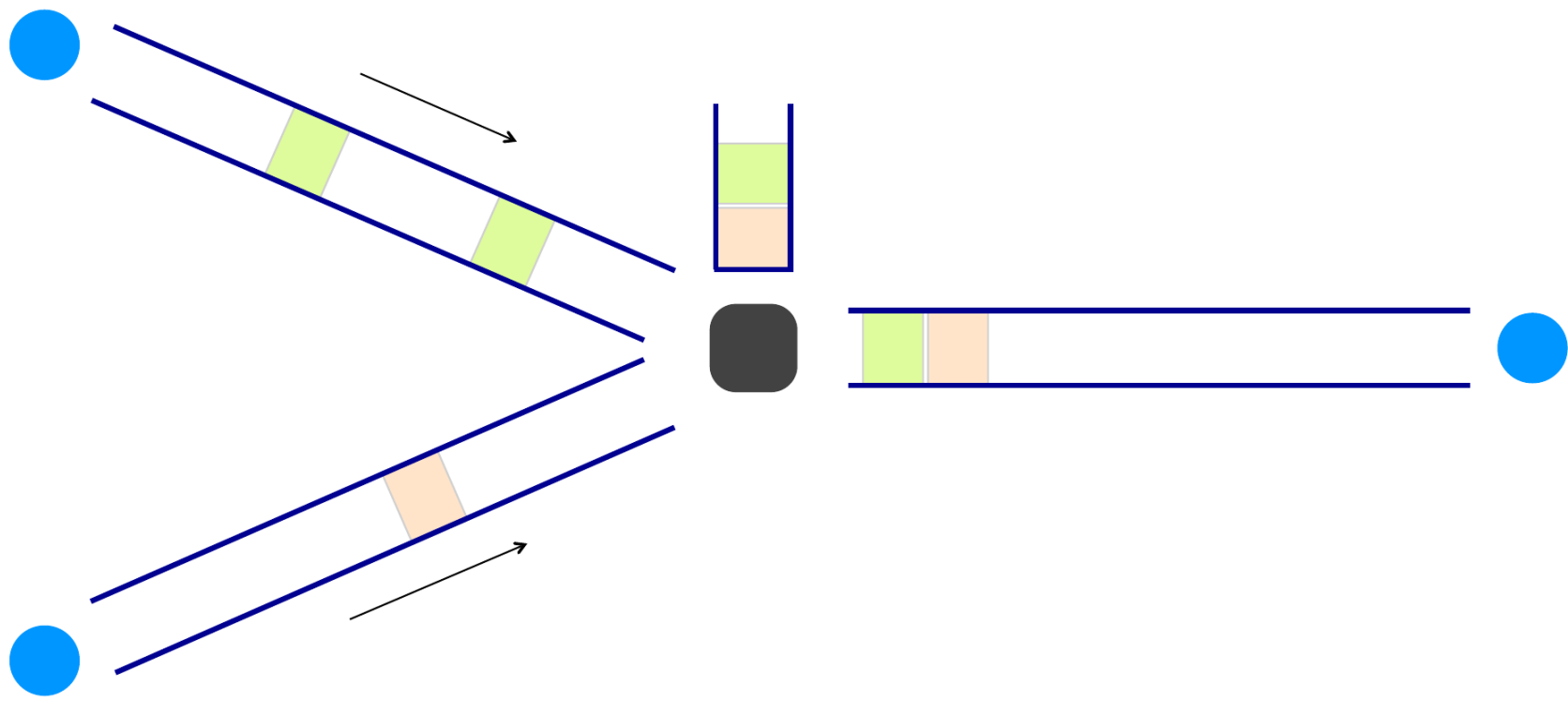


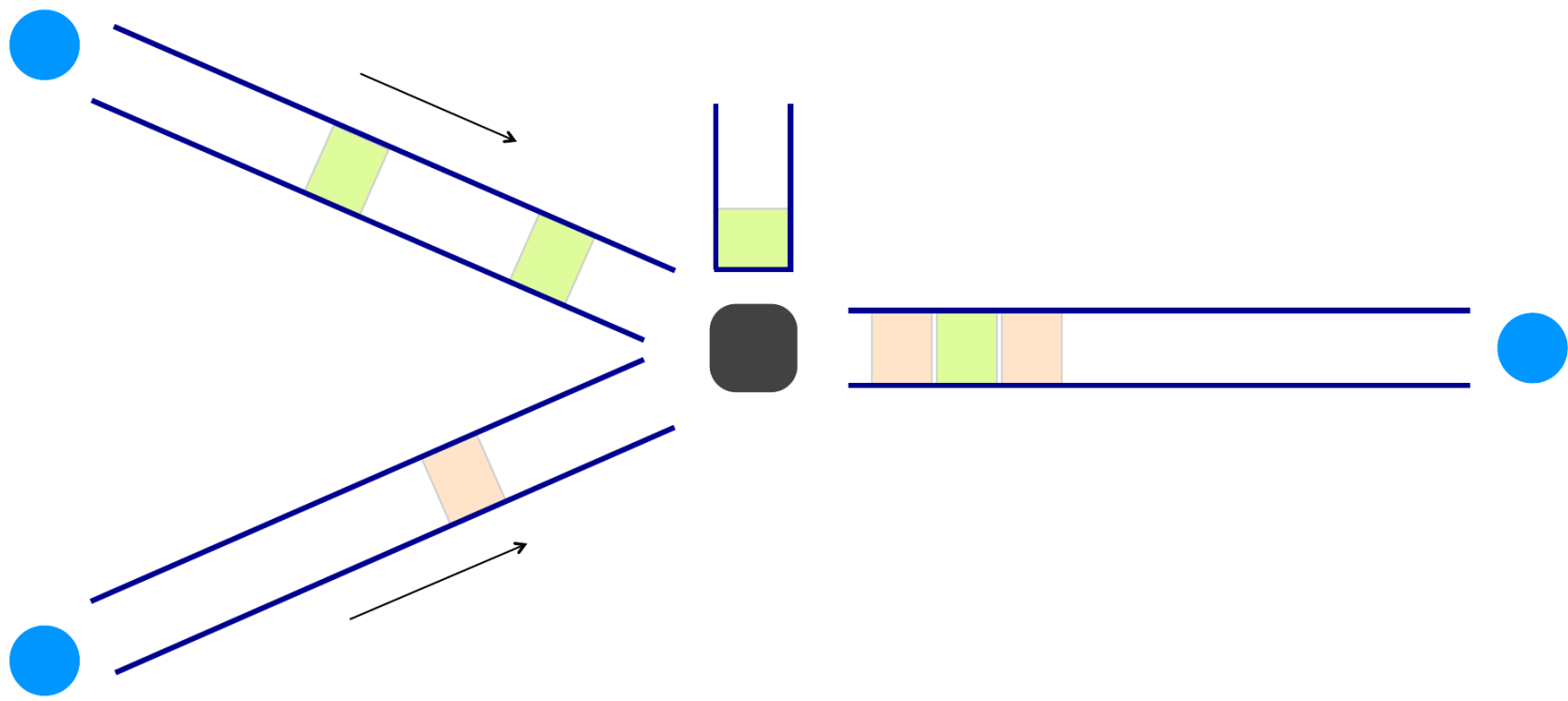


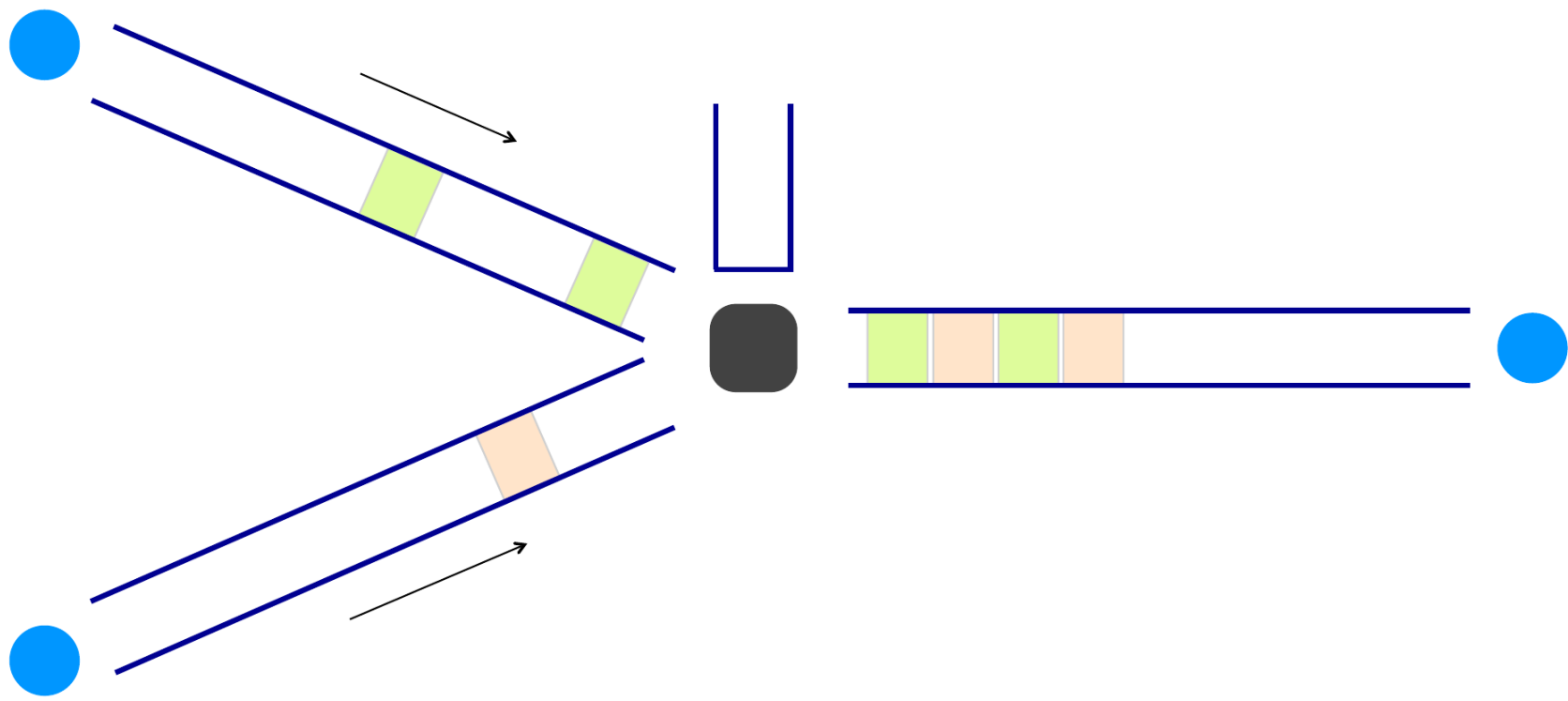
Queuing delay depends on the traffic pattern



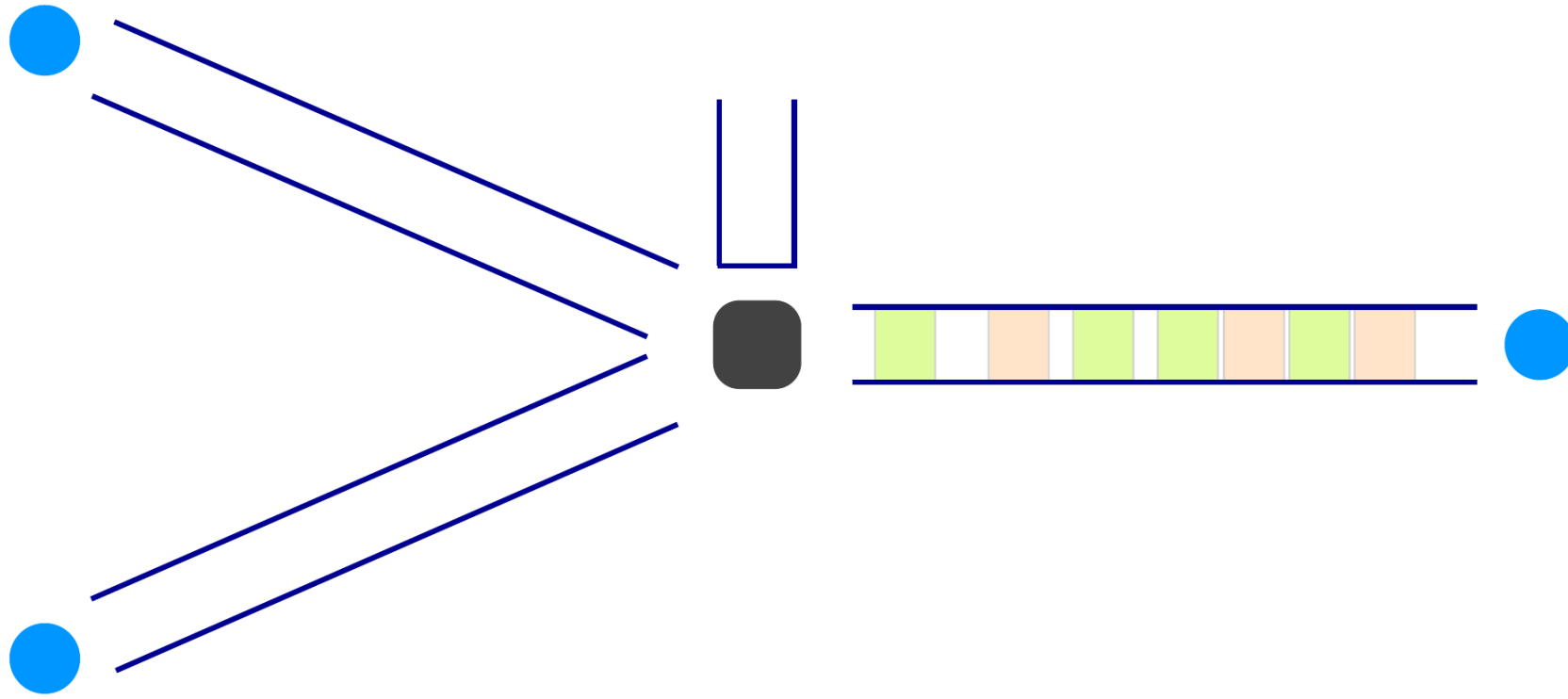








Queues absorb transient bursts,
but introduce queueing delays



The time a packet has to sit in a buffer before being processed depends on the traffic pattern

Queueing delay depends on:

- arrival rate at the queue
- transmission rate of the outgoing link
- traffic burstiness

average packet arrival rate	a	[packet/sec]
-----------------------------	-----	--------------

transmission rate of outgoing link	R	[bit/sec]
------------------------------------	-----	-----------

fixed packets length	L	[bit]
----------------------	-----	-------

average bits arrival rate	La	[bit/sec]
---------------------------	------	-----------

traffic intensity	La/R	
-------------------	--------	--

Two links both have rate R and carry L -bit packets. On average, both receive one packet every $2L/R$ seconds.

Link X: one packet arrives every $2L/R$ seconds, evenly spaced. Link Y: 10 packets arrive at once every $20L/R$ seconds.

Which statement about average queueing delay is correct?

- A. Both are the same because average arrival rate is the same
- B. Both are zero, because each link keeps up on average
- C. X is larger because packets arrive more often
- D. Y is larger; X is zero
- E. Both are larger than zero, and Y is larger

Two links both have rate R and carry L -bit packets. On average, both receive one packet every $2L/R$ seconds.

Link X: one packet arrives every $2L/R$ seconds, evenly spaced. Link Y: 10 packets arrive at once every $20L/R$ seconds.

Which statement about average queueing delay is correct?

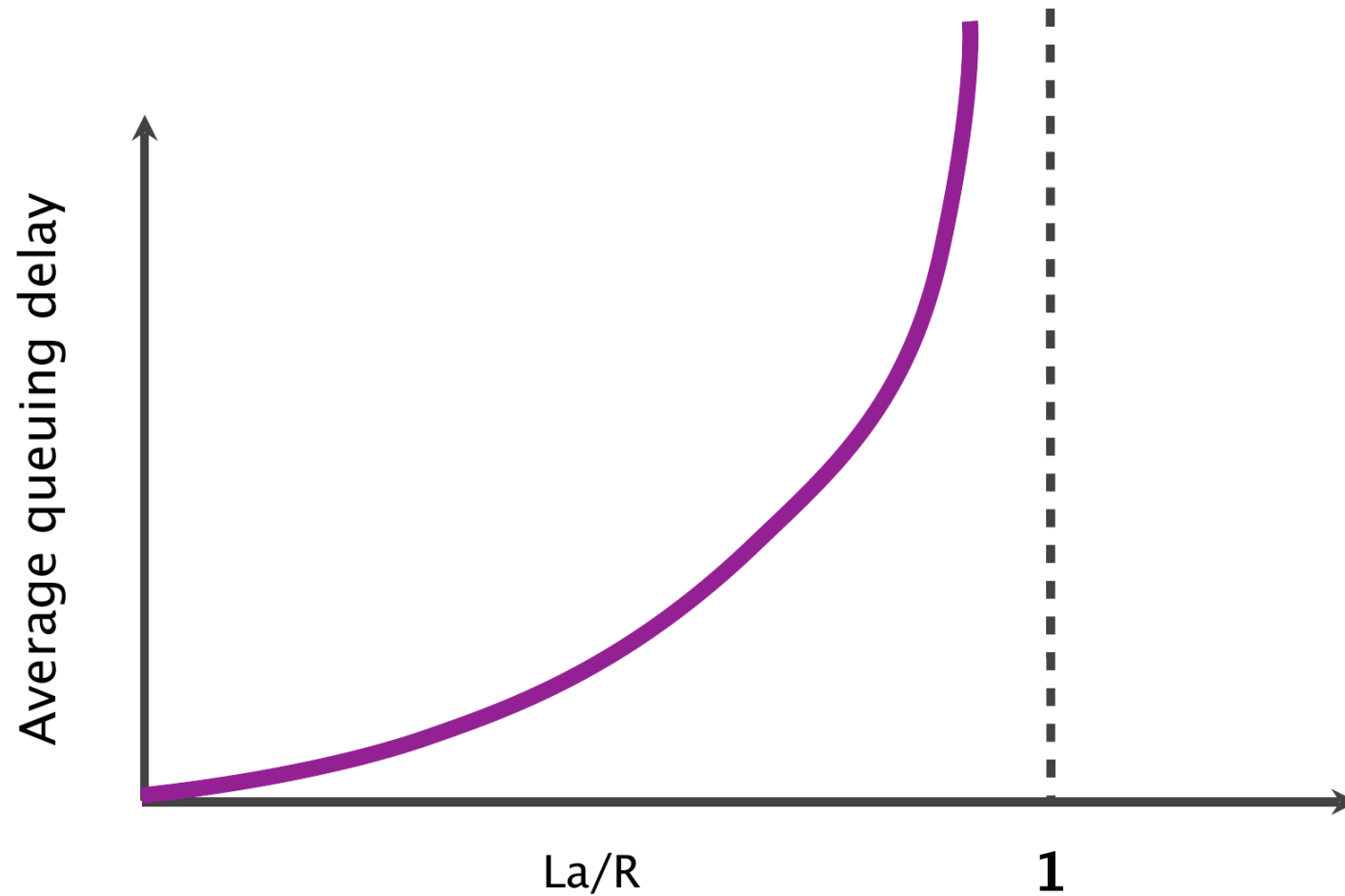
- A. Both are the same because average arrival rate is the same
- B. Both are zero, because each link keeps up on average
- C. X is larger because packets arrive more often
- D. Y is larger; X is zero**
- E. Both are larger than zero, and Y is larger

When the **traffic intensity is >1** , the queue will increase without bound, and so does the queuing delay

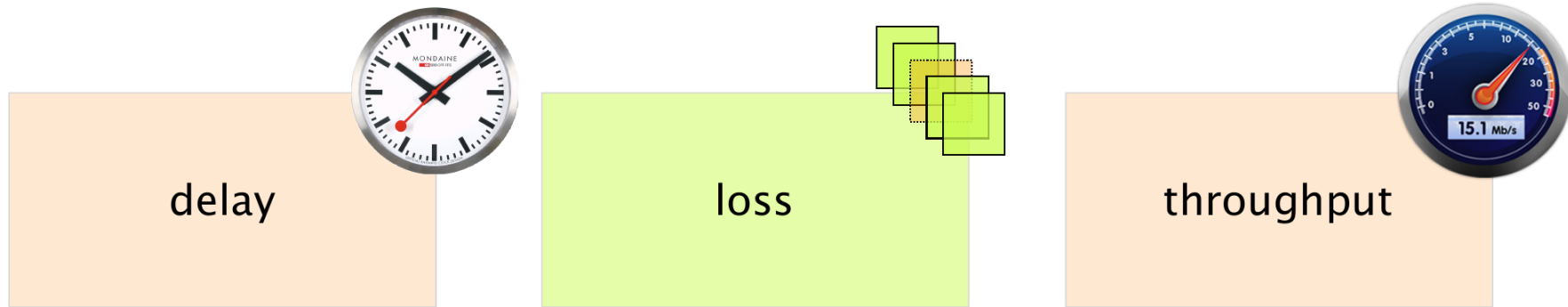
Golden rule

Design your queuing system,
so that it operates far from that point

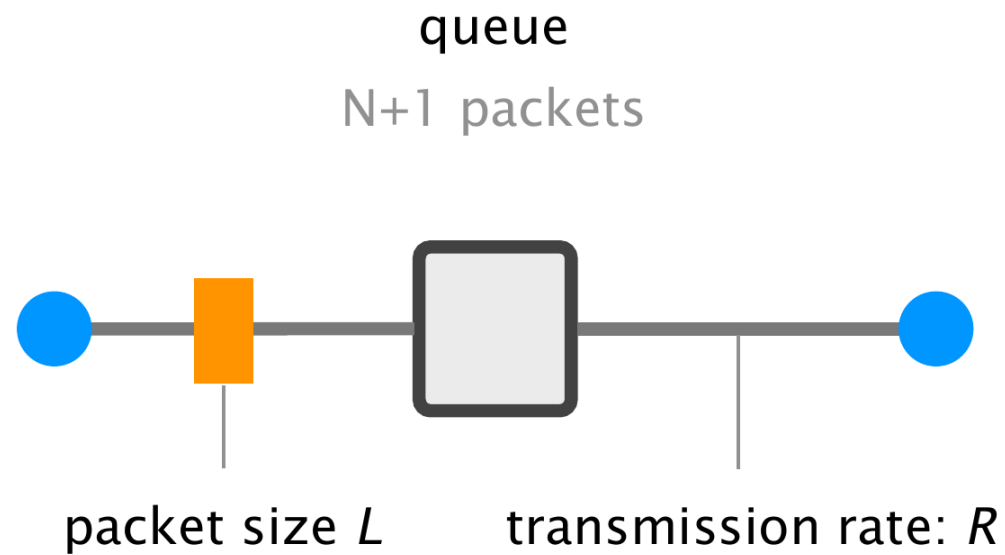
When the **traffic intensity is ≤ 1** ,
queueing delay depends on the burst size



A network *connection* is characterized by its delay, loss rate and throughput

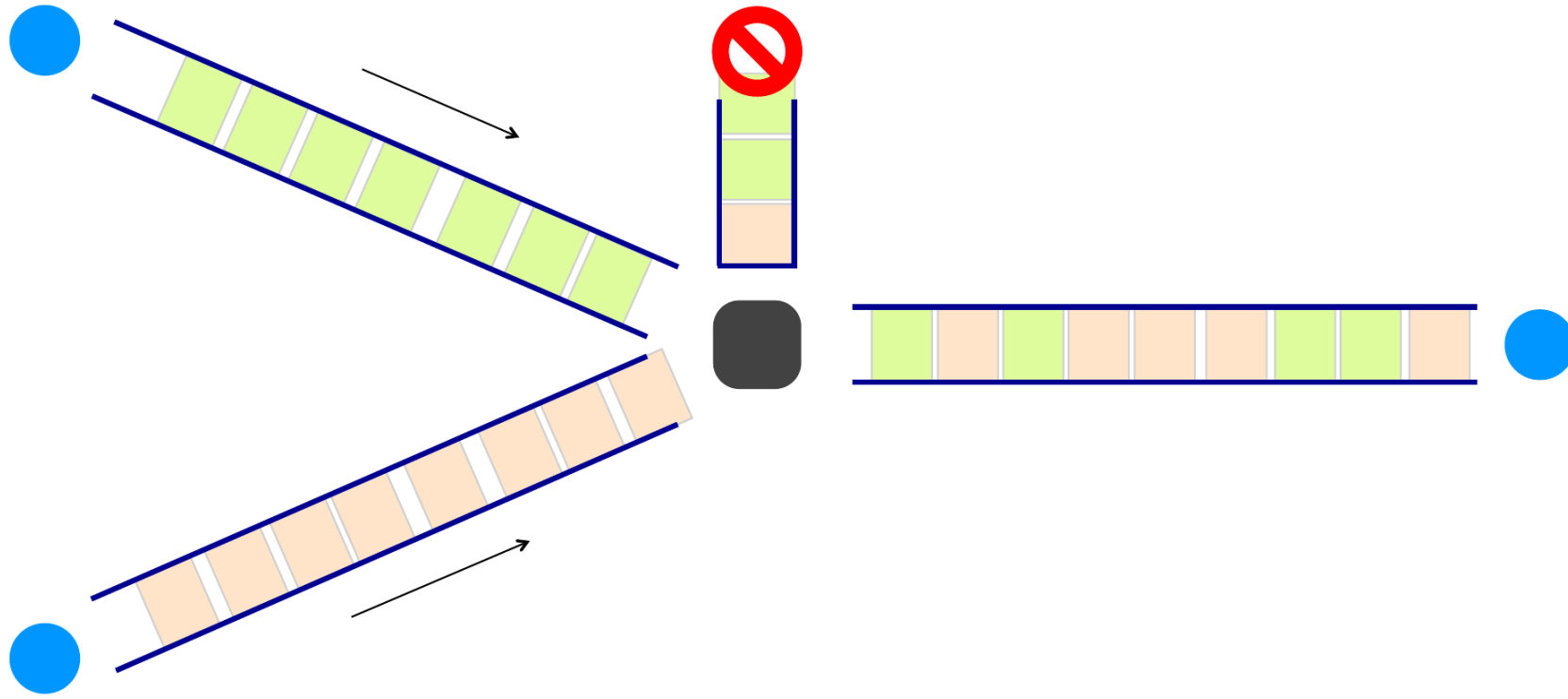


In practice, queues are not infinite.
There is an upper bound on queuing delay.

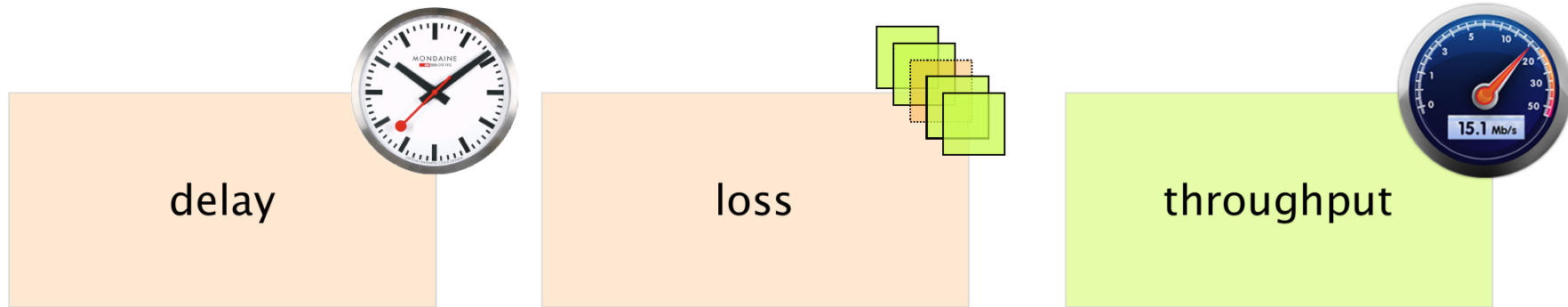


queuing delay upper bound: $N \cdot L / R$

If the queue is persistently overloaded,
it will eventually drop packets (loss)



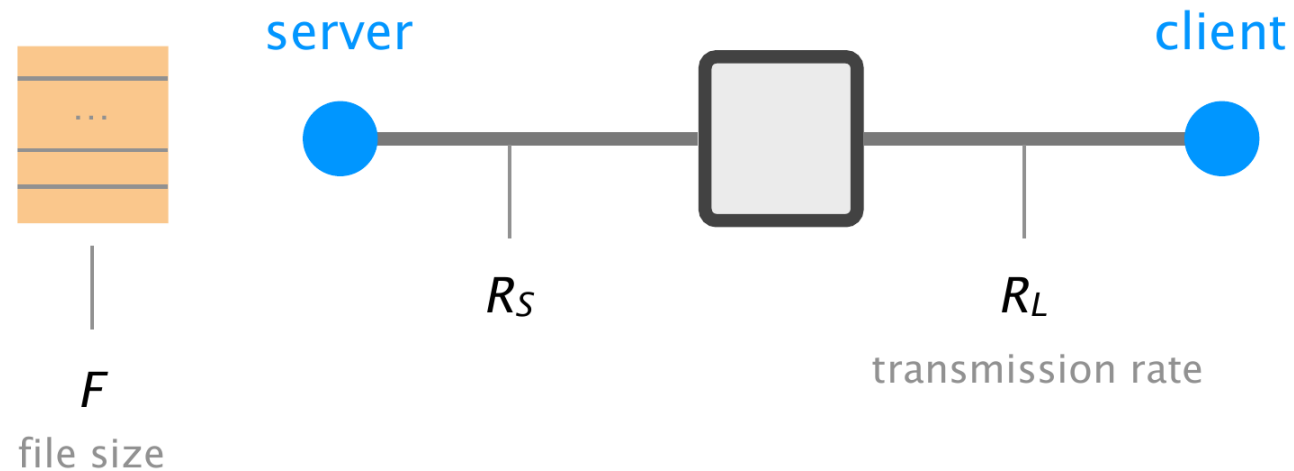
A network *connection* is characterized by its delay, loss rate and throughput



The throughput is the instantaneous rate at which a host receives data

$$\begin{array}{lcl} \text{Average throughput} & = & \frac{\text{data size}}{\text{transfer time}} \\ \text{[#bits/sec]} & & \begin{array}{l} \text{[#bits]} \\ \text{[sec]} \end{array} \end{array}$$

To compute throughput, one has to consider the bottleneck link

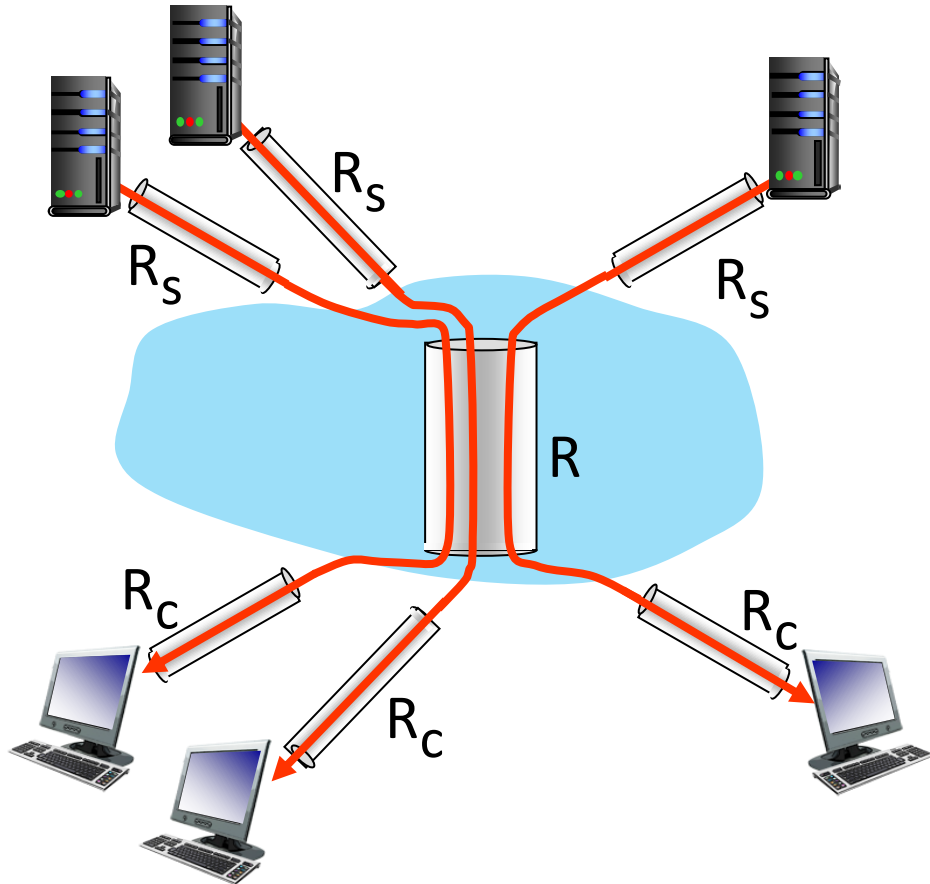


Average throughput

$$\min(R_S, R_L)$$

= transmission rate
of the bottleneck link

Throughput: network scenario



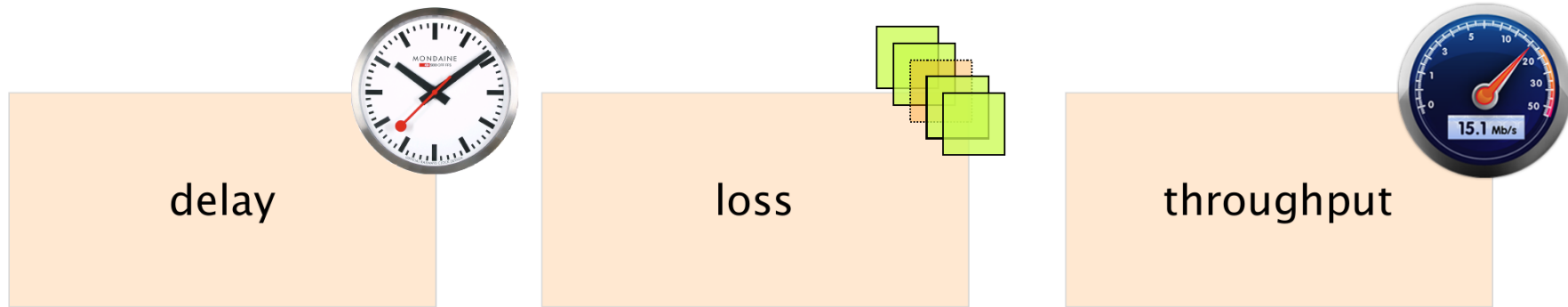
10 connections (fairly) share
backbone bottleneck link R bits/sec

Each server access link is $R_s = 2$ Mbps, each client access link is $R_c = 1$ Mbps, and all 10 share one core link that divides its rate equally. With a 5 Mbps shared link, each download gets 500 kbps.

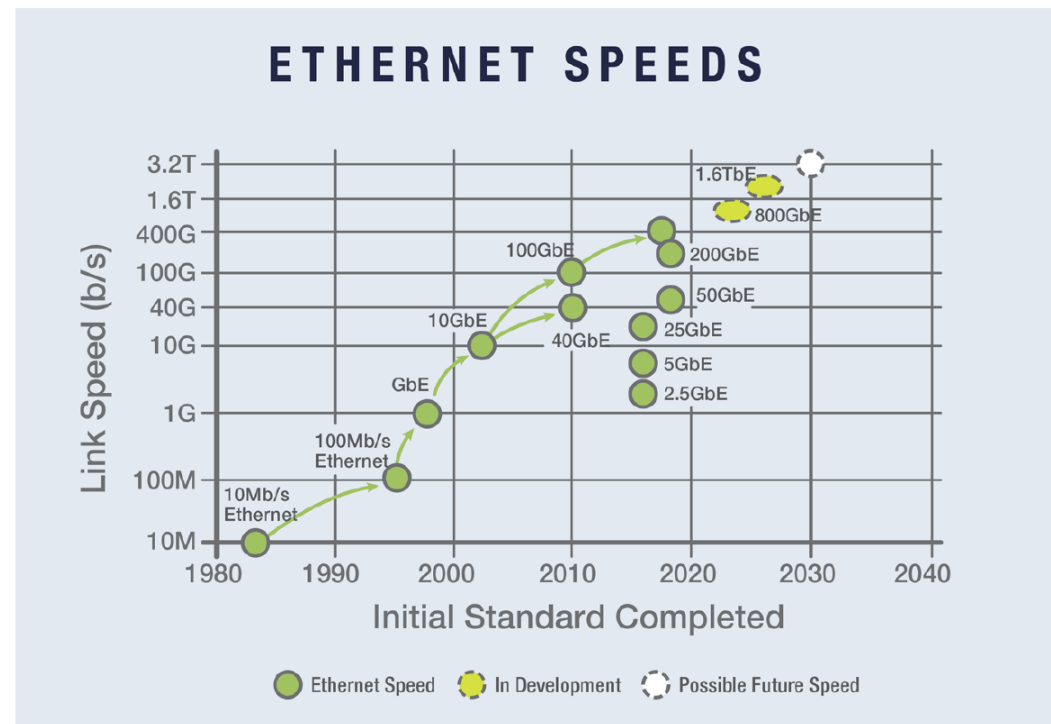
The shared link is upgraded to 50 Mbps. What is each download's throughput now?

- A. 500 Kbps
- B. 1 Mbps
- C. 2 Mbps
- D. 5 Mbps
- E. 50 Mbps

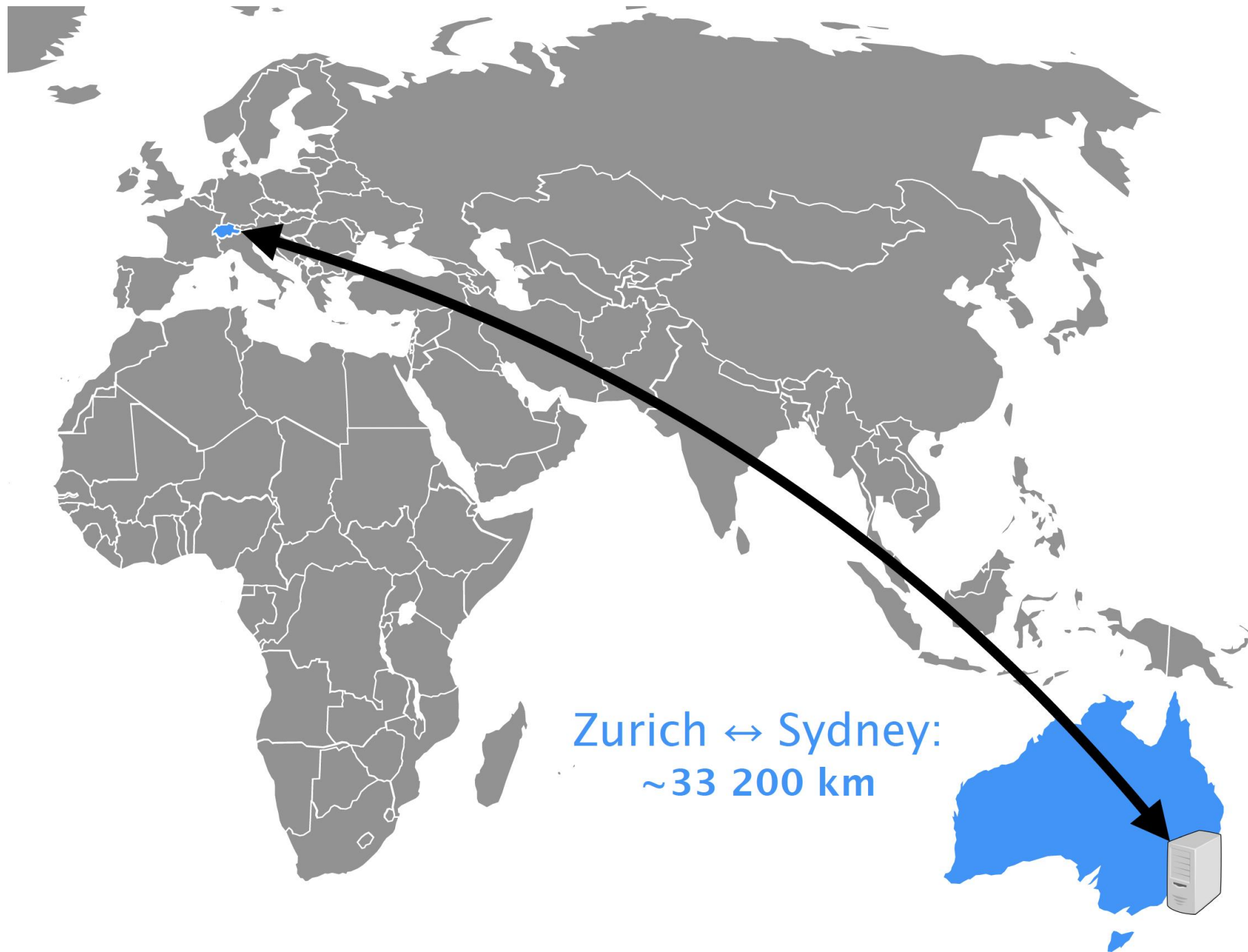
A network *connection* is characterized by its delay, loss rate and throughput



As technology improves, throughput increase & delays are getting lower except for propagation
(speed of light)



source: Ethernet Alliance

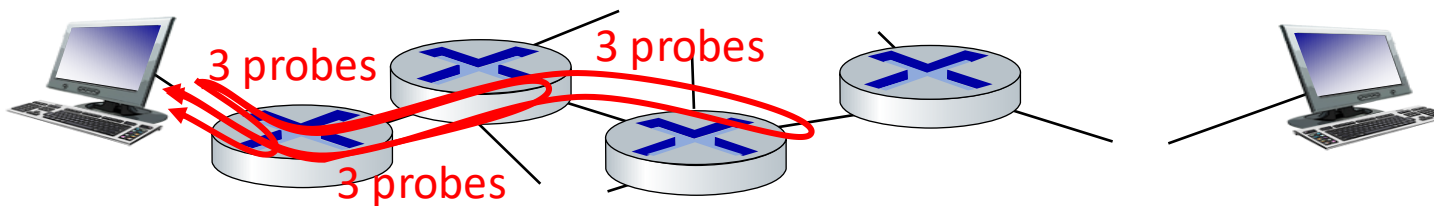


$$\begin{array}{rcl}
 & & \text{speed of light in} \\
 & & \text{optical fiber} \\
 & & | \\
 \frac{299,792,458 \text{ m/s}}{\text{refractive index} \quad \text{—} \quad 1.468 \quad \text{optical fiber}} & = & 204,218,296 \text{ m/s}
 \end{array}$$

$$\begin{array}{rcl}
 \frac{33,200,000 \text{ m}}{204,218,296 \text{ m/s}} & = & 163 \text{ ms} \\
 & & | \\
 & & \text{theoretical} \\
 & & \text{round-trip time}
 \end{array}$$

“Real” Internet delays and routes

- what do “real” Internet delay & loss look like?
- **traceroute** program: provides delay measurement from source to router along end-end Internet path towards destination. For all i :
 - sends three packets that will reach router i on path towards destination (with time-to-live field value of i)
 - router i will return packets to sender
 - sender measures time interval between transmission and reply



Real Internet delays and routes

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

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

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

trans-oceanic link

looks like delays
decrease! Why?

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

hop	hostname (ip)	1st	2nd	3rd
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

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

Because of propagation delays,
Content Delivery Networks move content closer to you

