Packets in Flight

CS 168 – Fall 2022 – Discussion 2

Delays

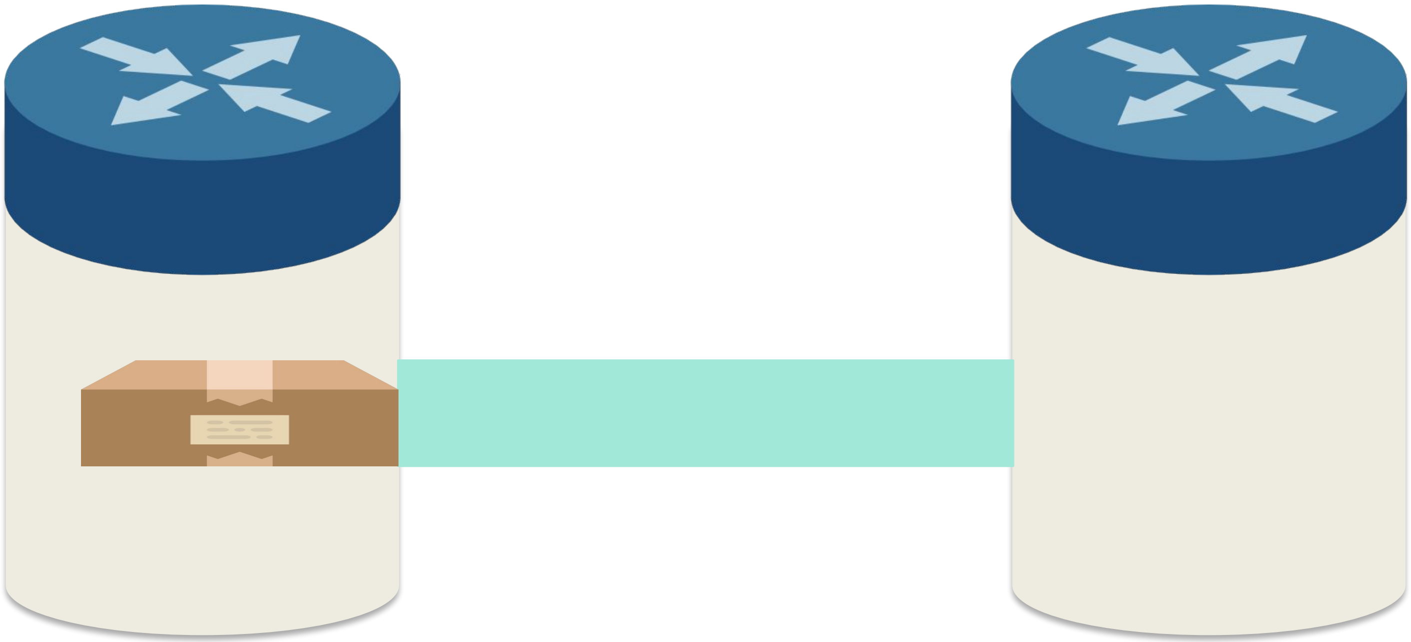
- How long does it take for your packet to travel through the network?
- It depends on…
  - **how much data** you're sending and the **link speed**
    → transmission delay
  - your **distance** from the destination
    → propagation delay
  - the **traffic** pattern
    → queuing delay
  - how fast **routers** process the packet header
    → processing delay

Delays

- How long does it take for your packet to travel through the network?
- It depends on…
  - how much data you're sending and the **link speed**
    → transmission delay
  - your **distance** from the destination
    → propagation delay
  - the **traffic pattern**
    → queuing delay
  - ~~how fast routers process the packet header~~
    ~~→ processing delay~~

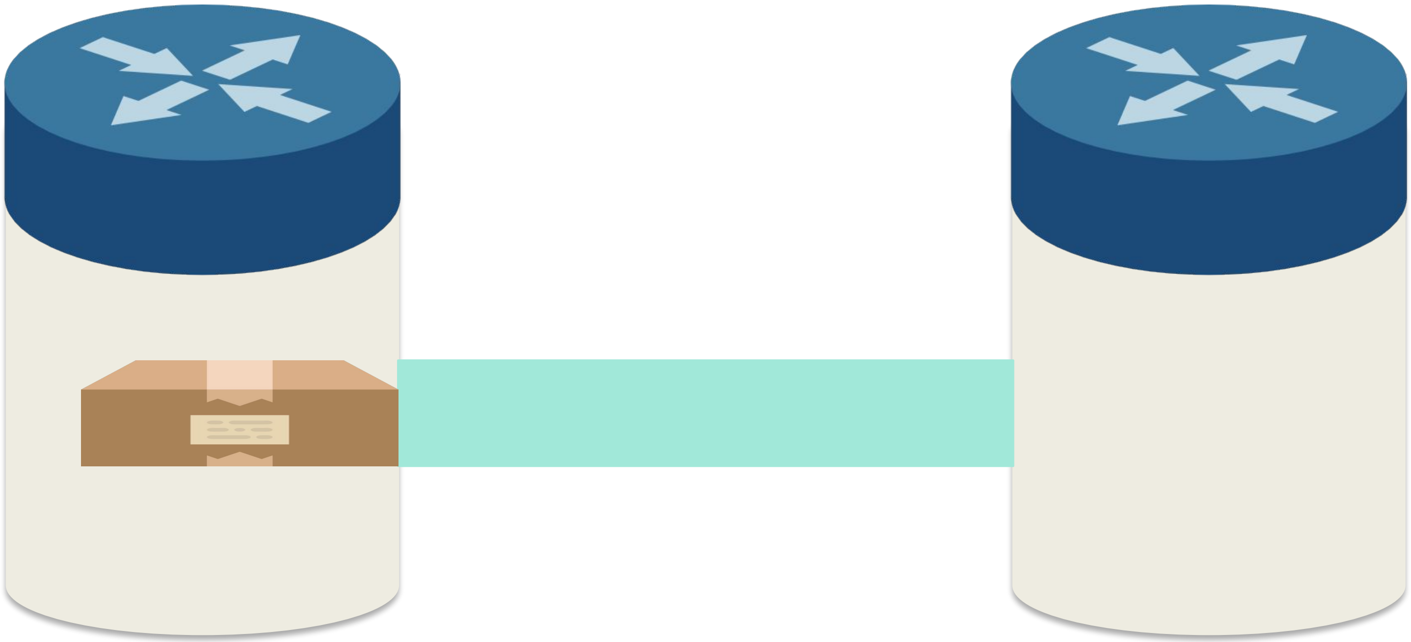
Transmission Delay

- How long it takes for the all bits in the packet to get on the wire
  - The time between when the first and last bits enter the link



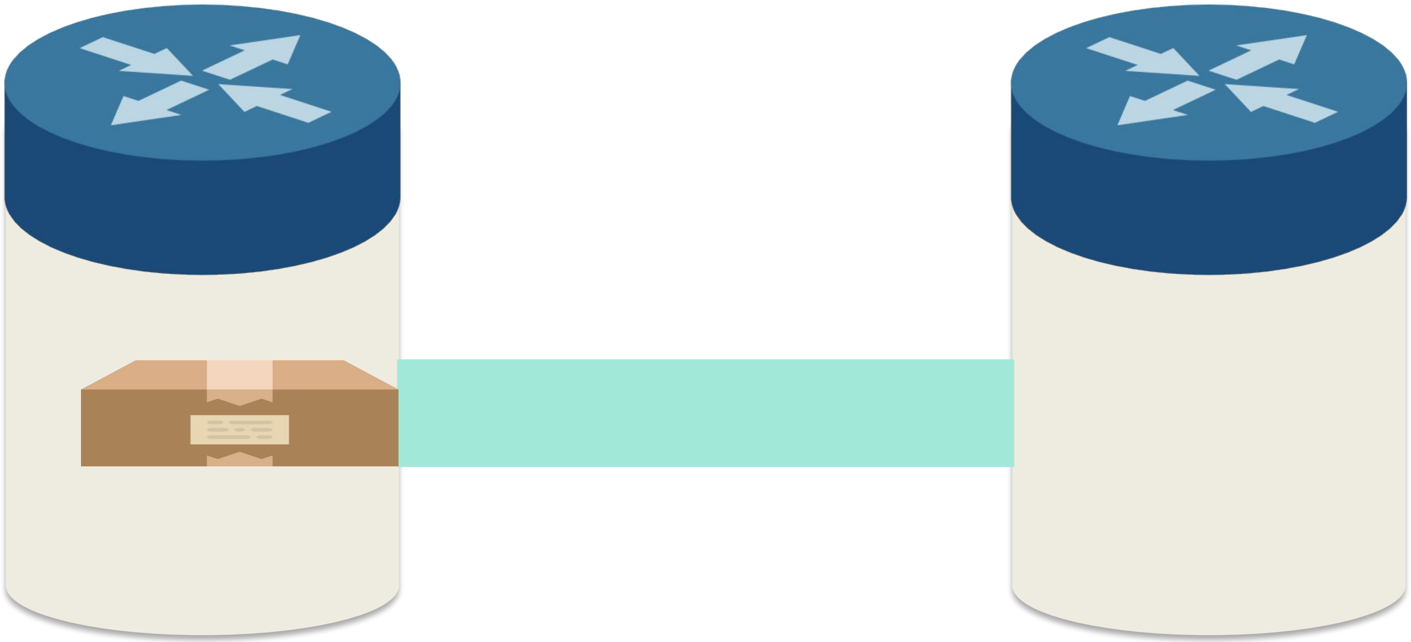
Transmission Delay

- How long it takes for the all bits in the packet to get on the wire
  - The time between when the first and last bits enter the link
- Limited by the bandwidth
  - Bandwidth: Number of bits you can send through a wire per unit of time



Transmission Delay

- How long it takes for the all bits in the packet to get on the wire
  - The time between when the first and last bits enter the link
- Limited by the bandwidth
  - Bandwidth: Number of bits you can send through a wire per unit of time
- Function of packet size



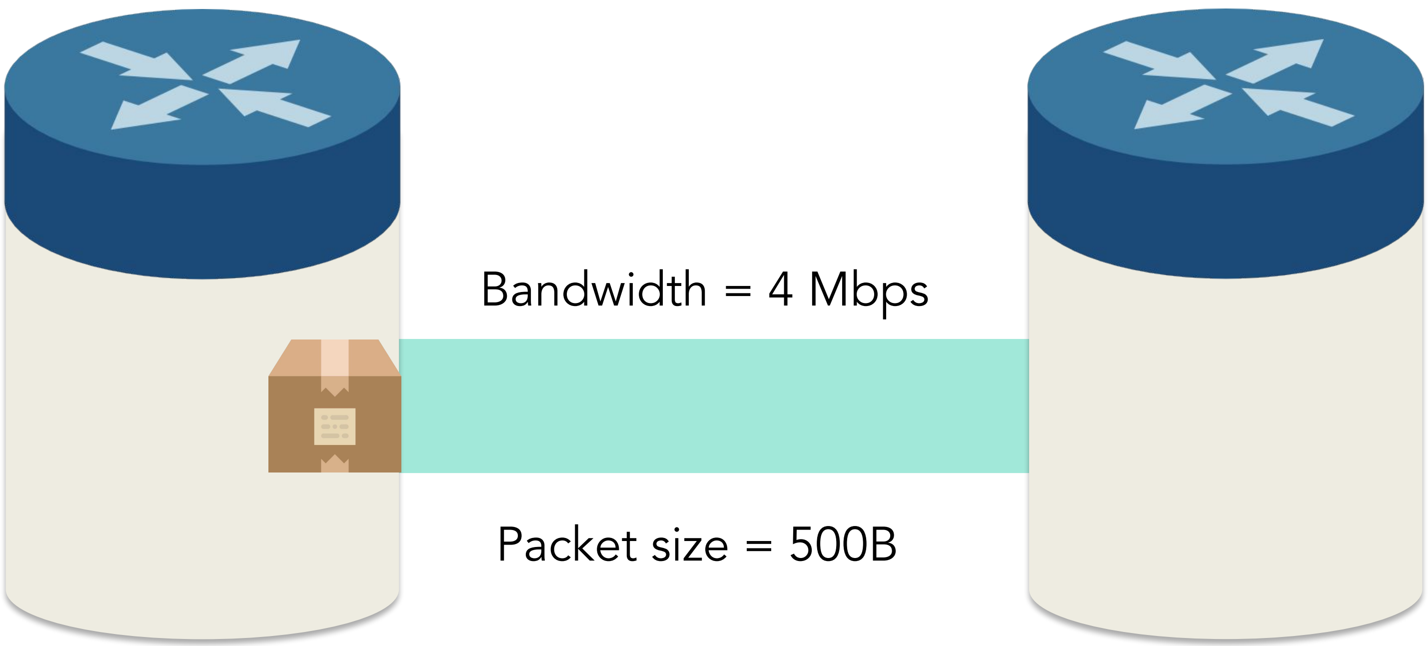
Transmission Delay

$$\text{Transmission Delay} = \frac{\text{packet size (bytes)}}{\text{bandwidth}}$$

Usually **bits**/second

Transmission Delay: Example

$$\text{Transmission Delay} = \frac{\text{packet size (bytes)}}{\text{bandwidth}}$$

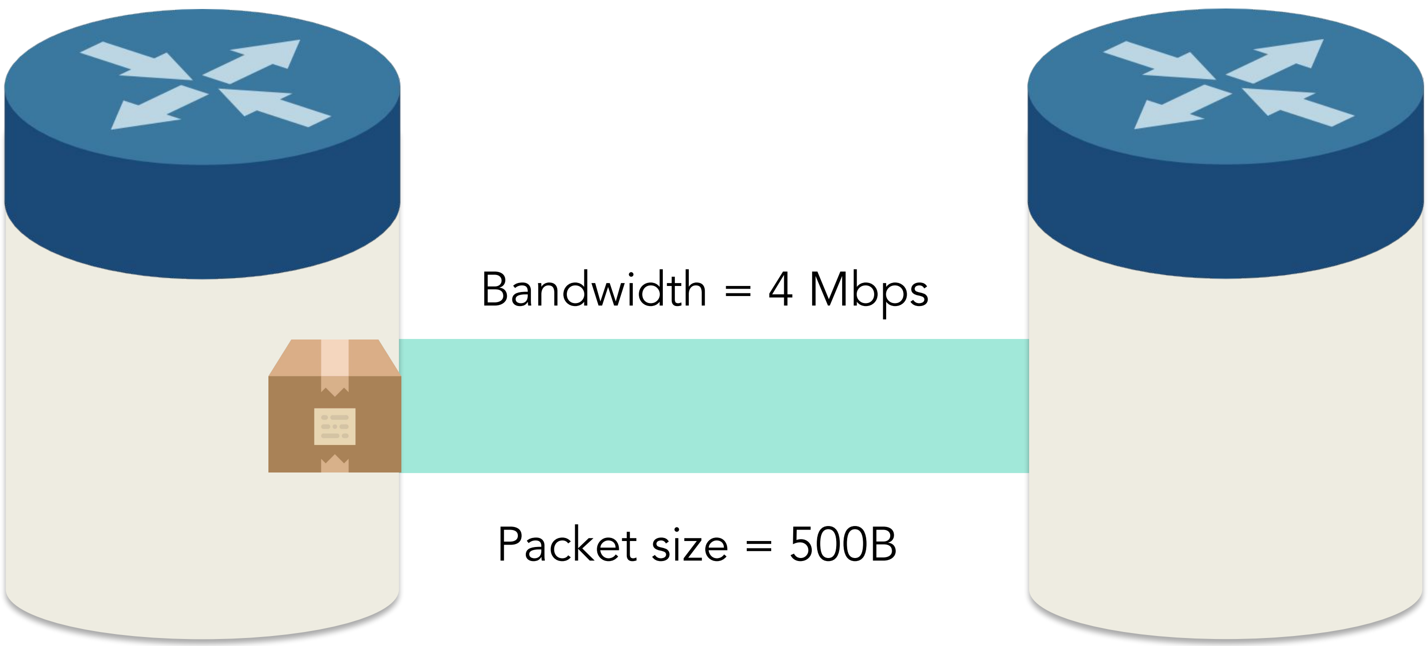


Transmission Delay: Example

Why did we have to do this?

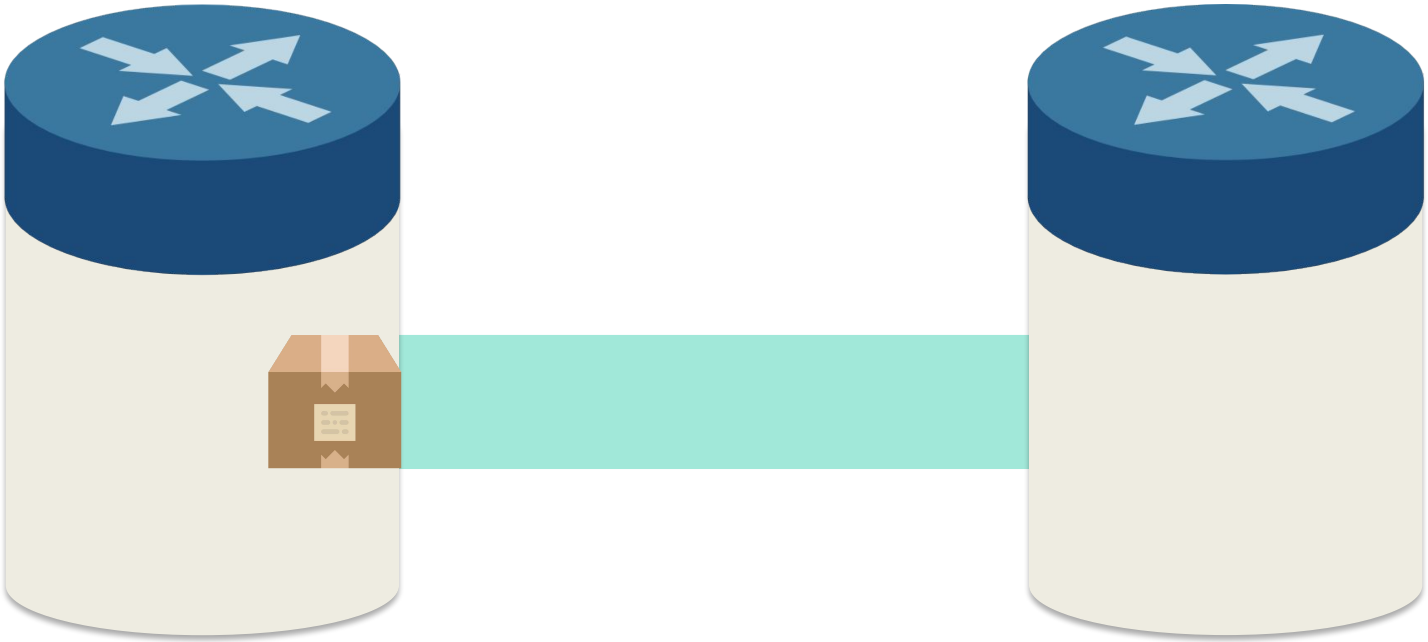
$$\text{Bandwidth} = \frac{4{\cdot}10^6 \text{ bits}}{1 \text{ second}} \cdot \frac{1 \text{ byte}}{8 \text{ bits}} = \frac{1}{2} \cdot 10^6 \frac{\text{Bytes}}{\text{second}}$$

$$\text{Transmission Delay} = \frac{\text{packet size (bytes)}}{\text{bandwidth}} = \frac{500 \text{ Bytes}}{\frac{1}{2}{\cdot}10^6 \frac{\text{Bytes}}{\text{second}}} = 1 \text{ ms}$$



Propagation Delay (latency)

- End-to-end transmission time of one bit
- Depends on the length of the link
- Limited by the speed of light (propagation speed of link)
- <u>Does NOT depend on the size of the packet</u>

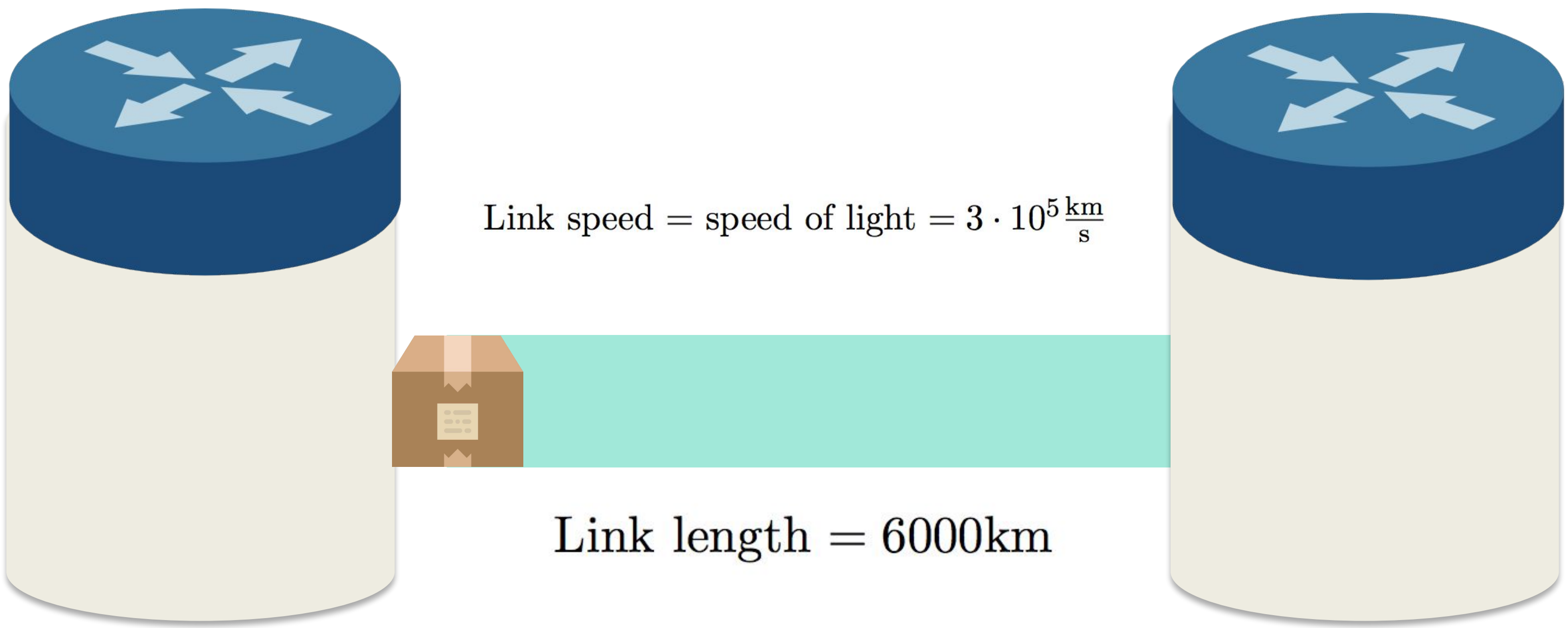


Propagation Delay: Formula

$$\text{Propagation Delay} = \frac{\text{length of link (meters)}}{\text{speed of light (meters/second)}}$$

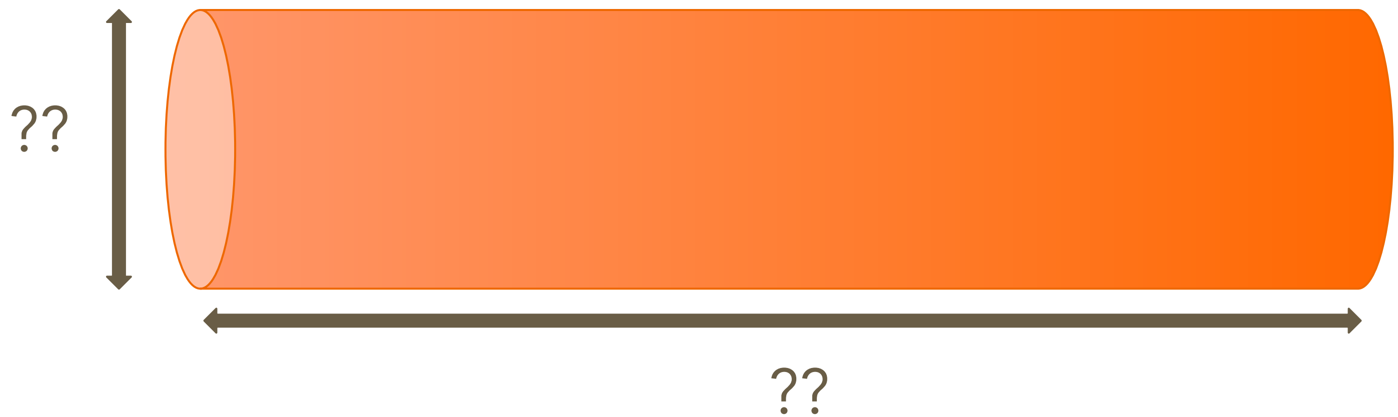
Propagation Delay: Example

$$\text{Propagation Delay} = \frac{6000\text{km}}{3 \cdot 10^5 \frac{\text{km}}{\text{s}}} = 20\text{ms}$$



Bandwidth Delay Product (BDP)

- Now that we know the propagation delay, we can tell how many bits are “in flight” (on the link) at any time



BDP = ?? * ??

Bandwidth Delay Product (BDP)

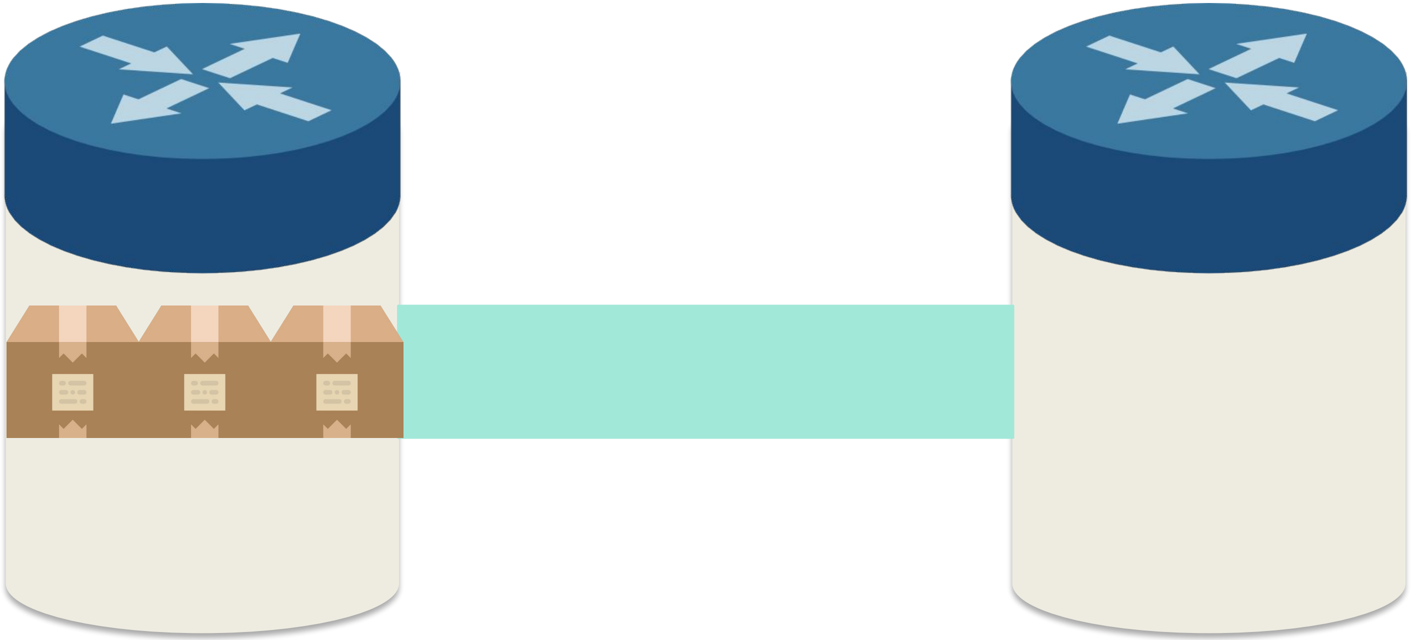
- Now that we know the propagation delay, we can tell how many bits are "in flight" (on the link) at any time

$$\text{Bandwidth Delay Product (BDP)} = \text{Bandwidth} \cdot \text{Propagation Delay}$$

Packets might have to wait before they can be transmitted…

Queuing Delay

- How long the packet waits to get transmitted on the wire
- <u>Happens only when arrival rate is greater than transmission rate</u>



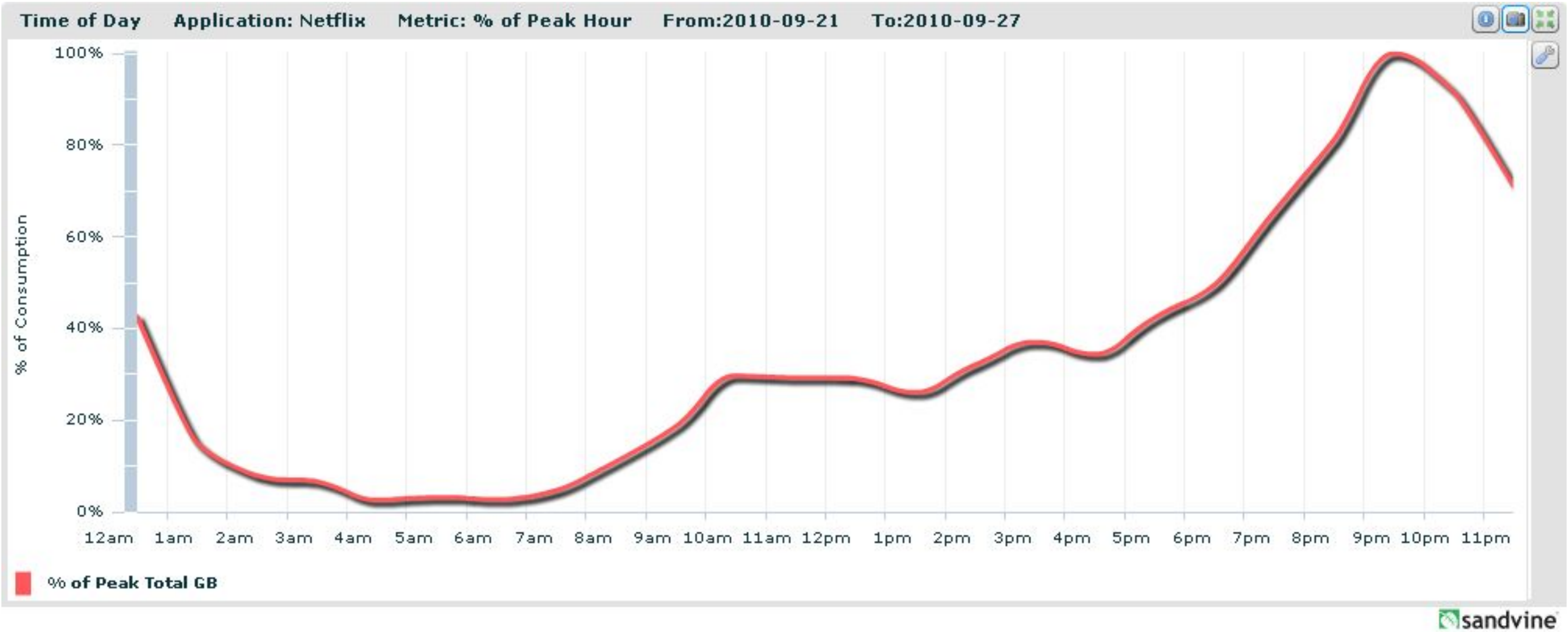
An easy fix for queuing delay?

Naïve solution: *max(arrival rate, transmission rate)*

Is this sufficient?

Burstiness!

- Transmission rate = constant over time
- Arrival rate = not constant over time



Netflix Traffic, circa 2010

Burstiness and Queues

- How does burstiness affect queuing delays?

- What happens when the queue is full?

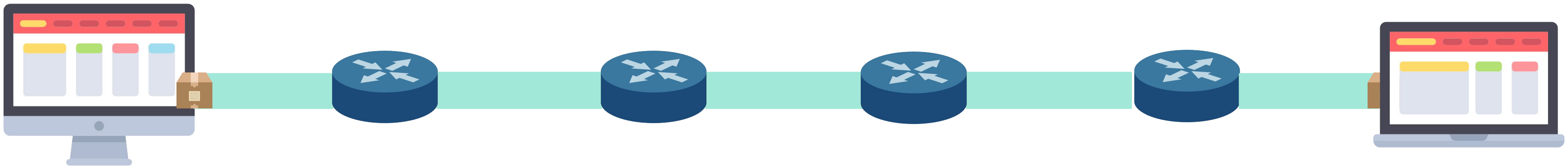
Burstiness and Queues

- How does burstiness affect queuing delays?
  - Bursty flows tend to increase queuing delay

- What happens when the queue is full?
  - Packets are dropped

End-to-End Delay

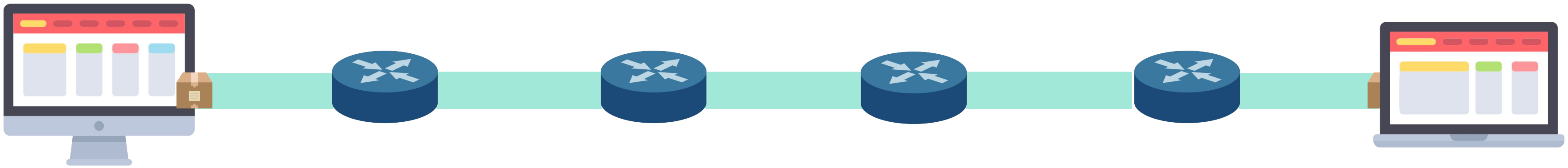
Sum of all nodal delays on the path



End-to-End Delay = Propagation Delay + Transmission Delay + Queuing Delay

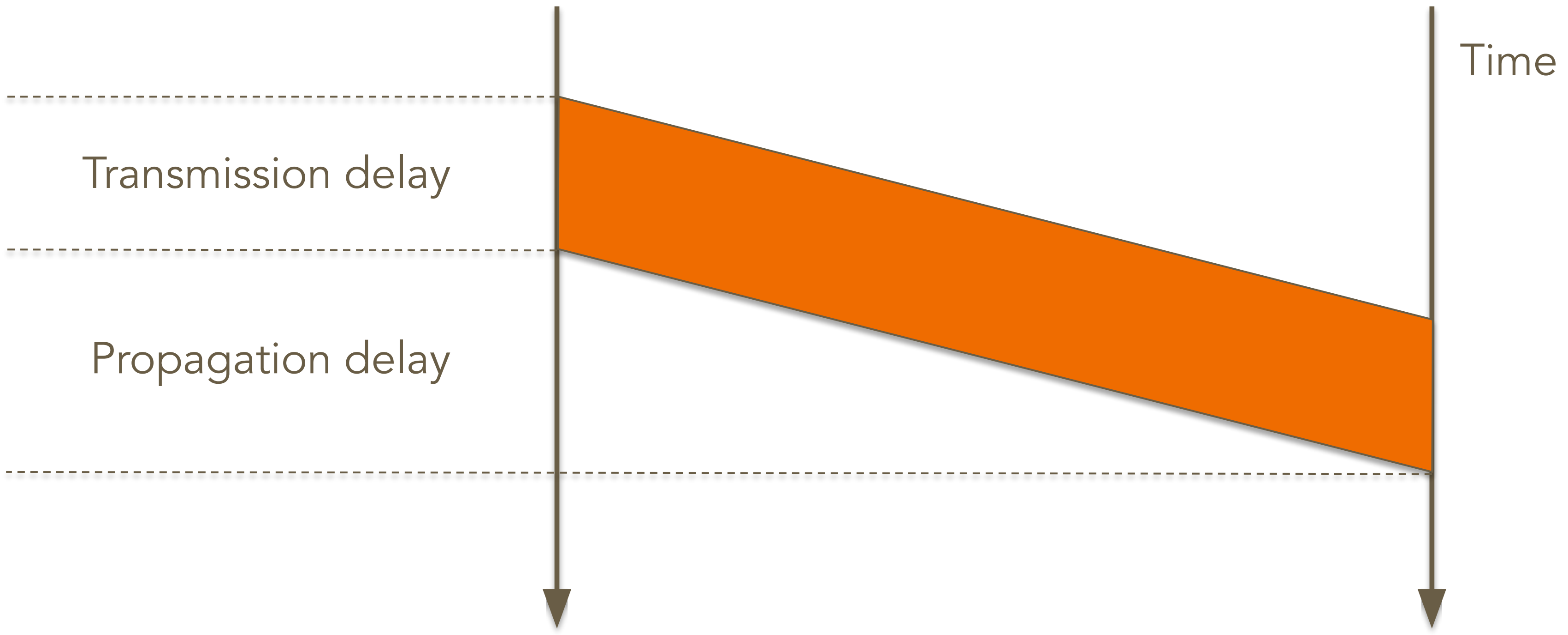
Round Trip Time (RTT)

The time it for the packet to reach its destination and receive a response

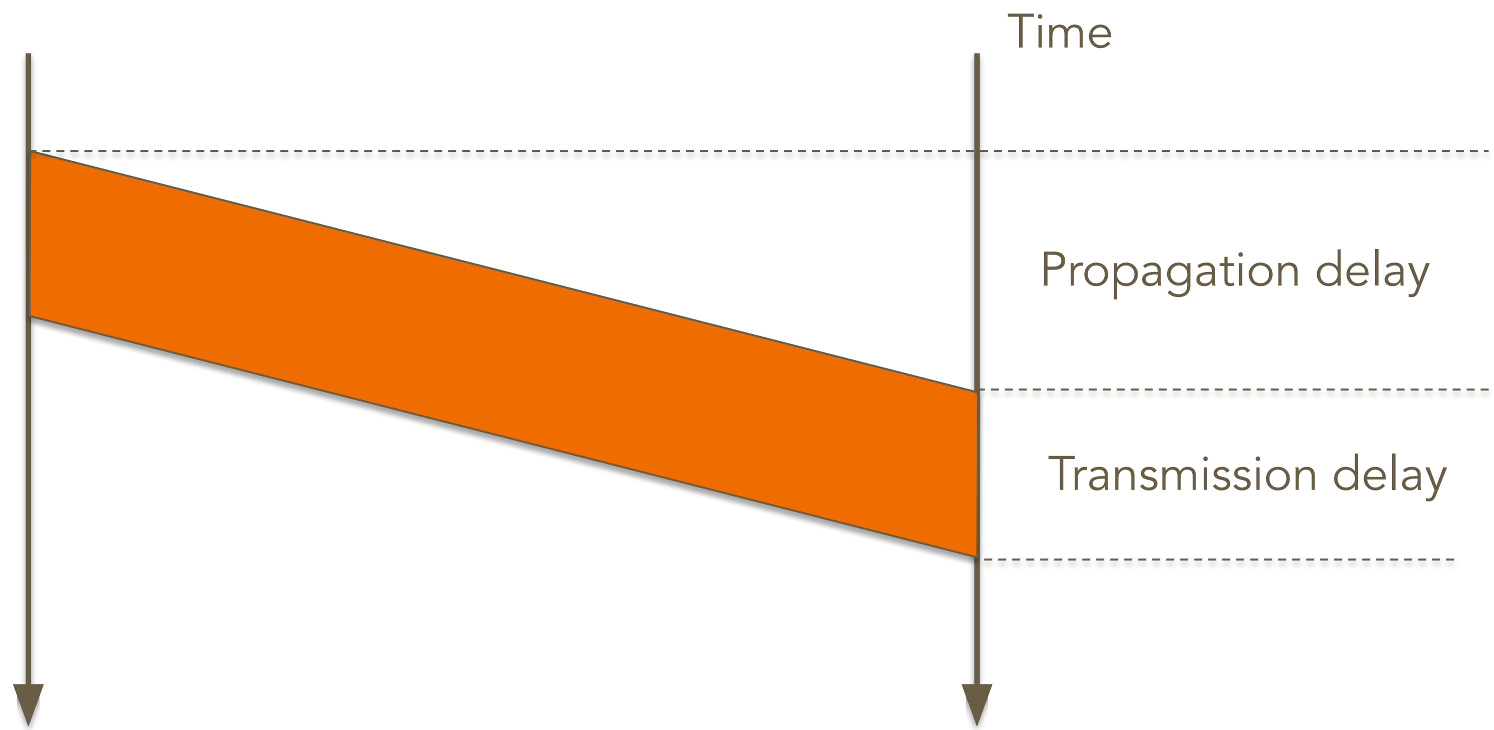


RTT = 2 * (End-to-End Delay)

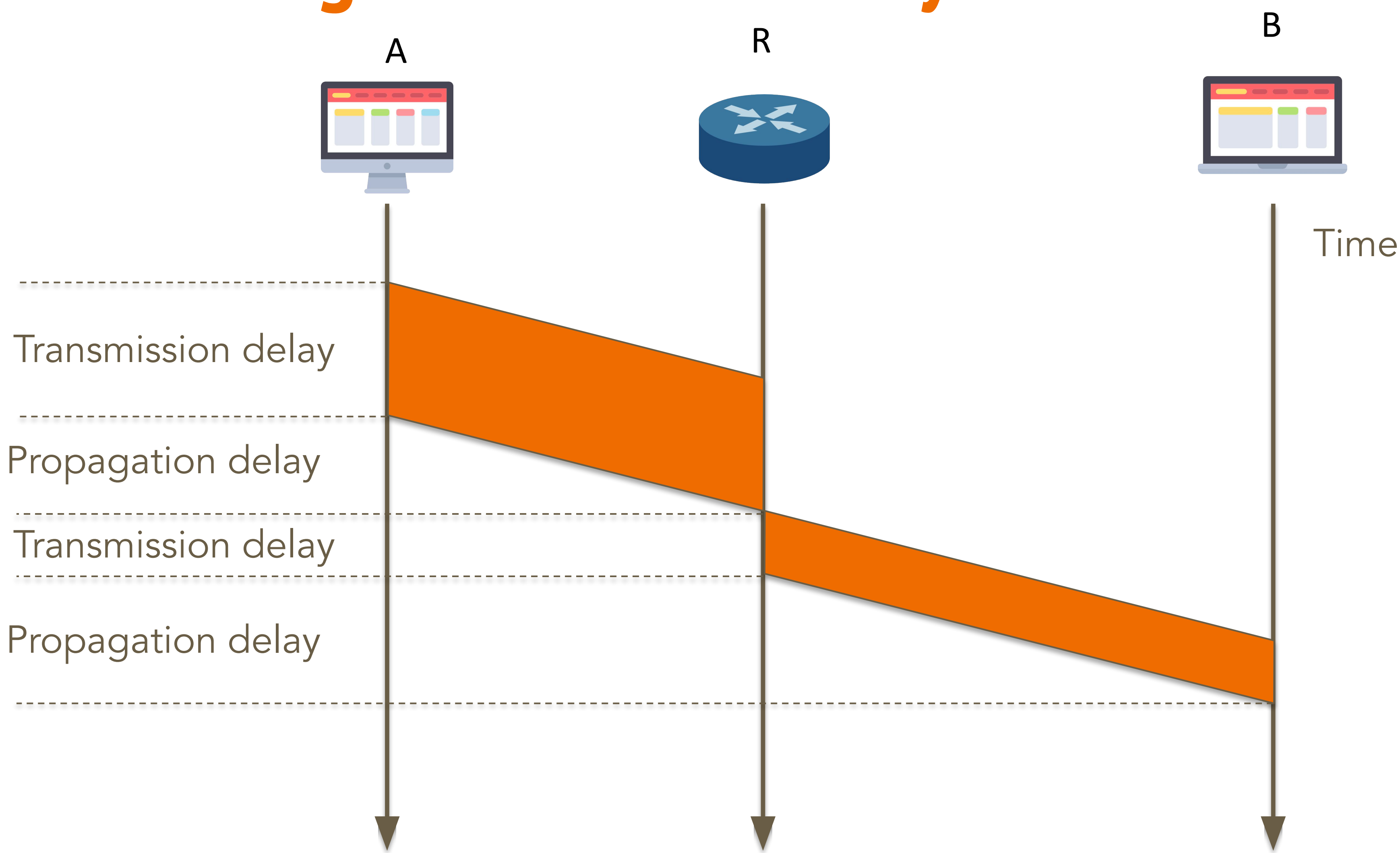
Visualizing packet delay...



Visualizing packet delay...

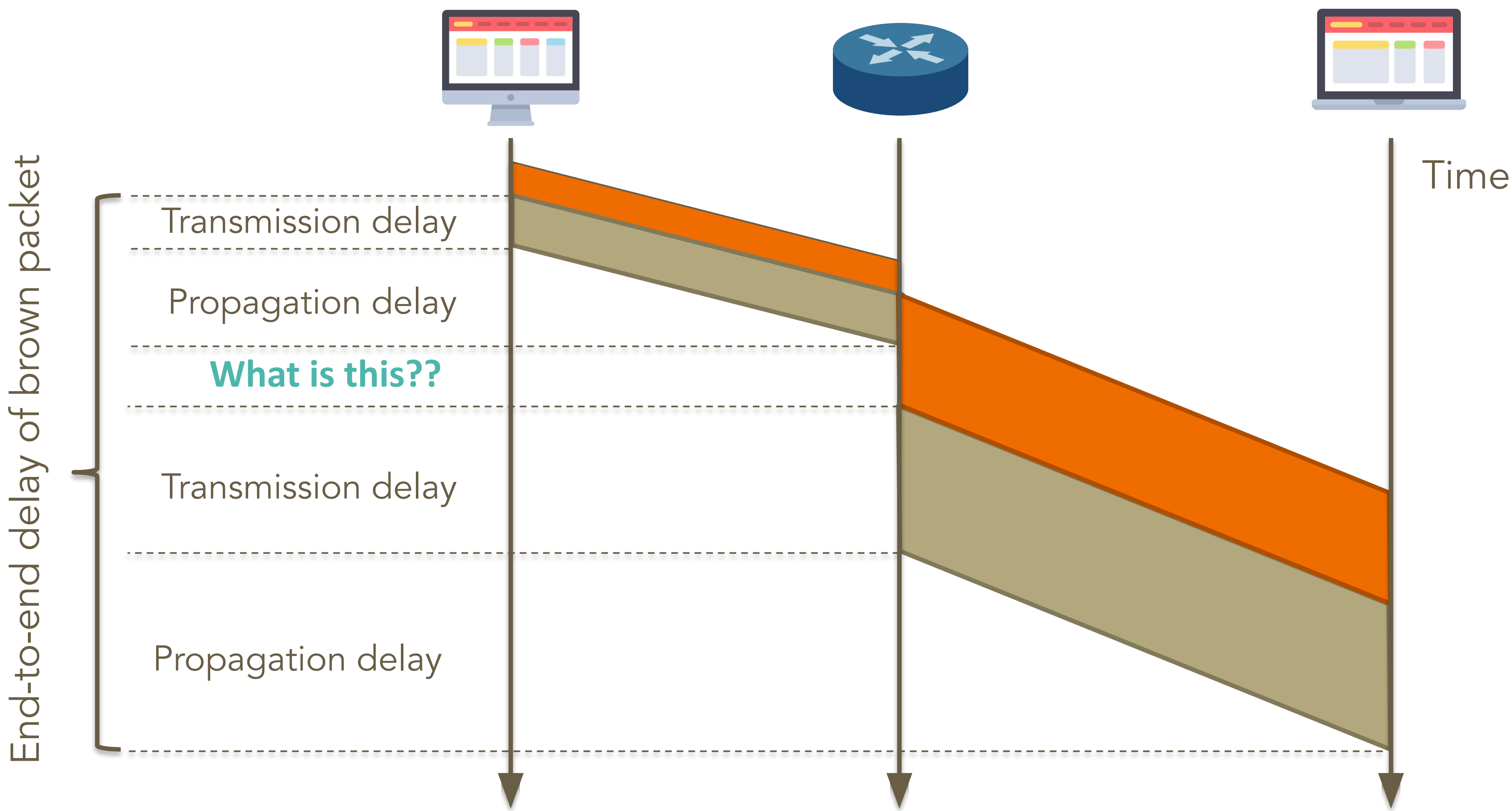


Visualizing end-to-end delay...



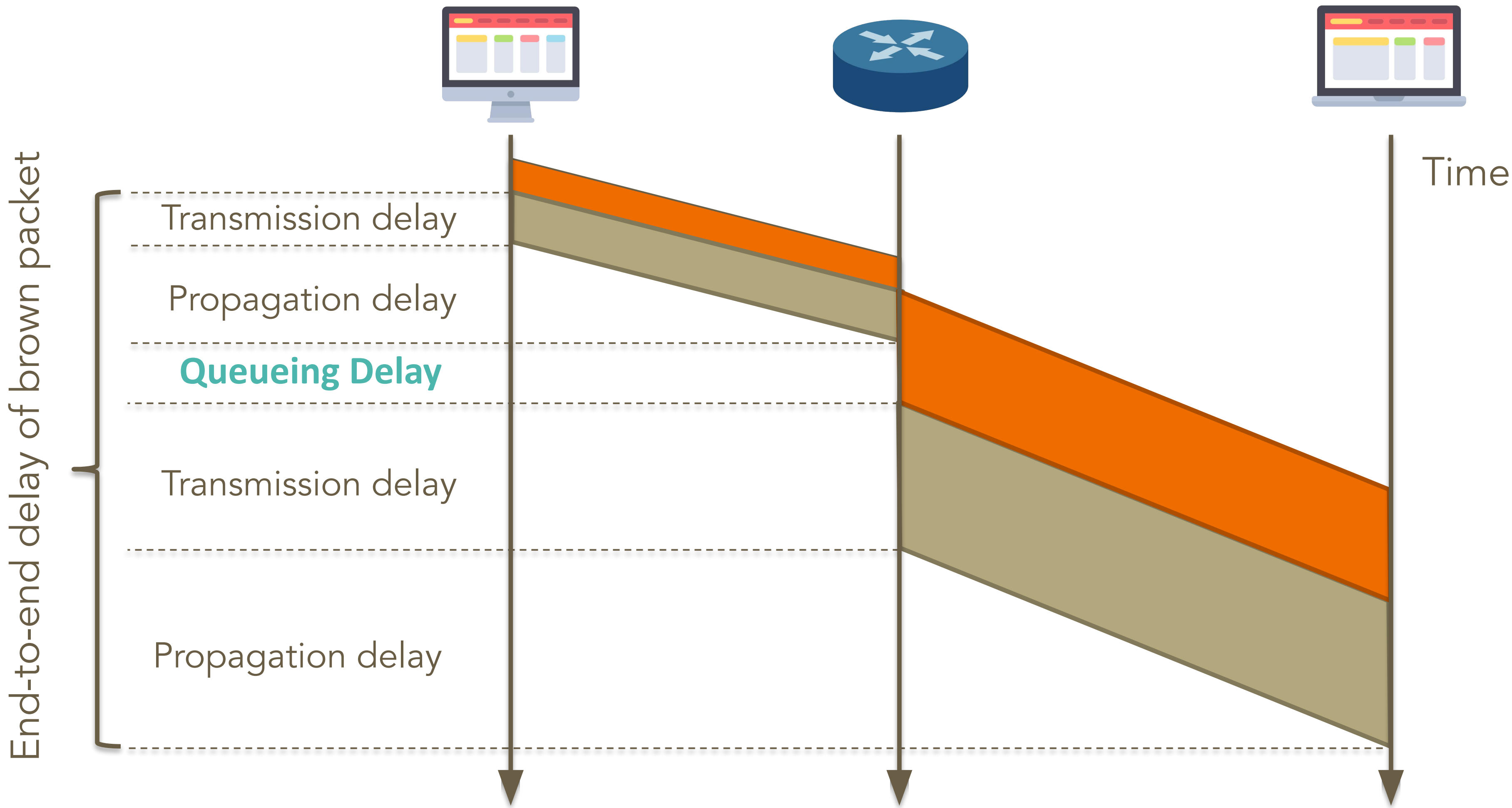
Visualizing end-to-end delay...

- Two packets, back-to-back



Visualizing end-to-end delay...

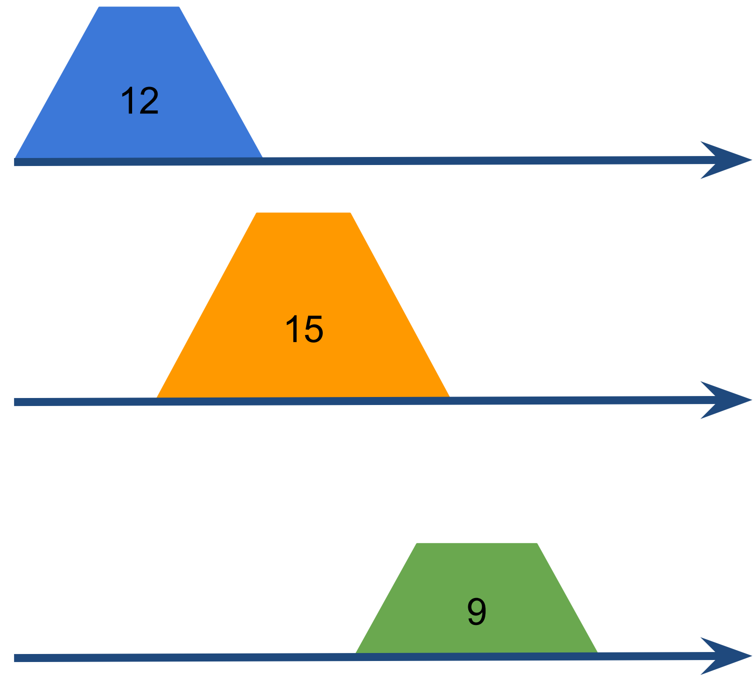
- Two packets, back-to-back

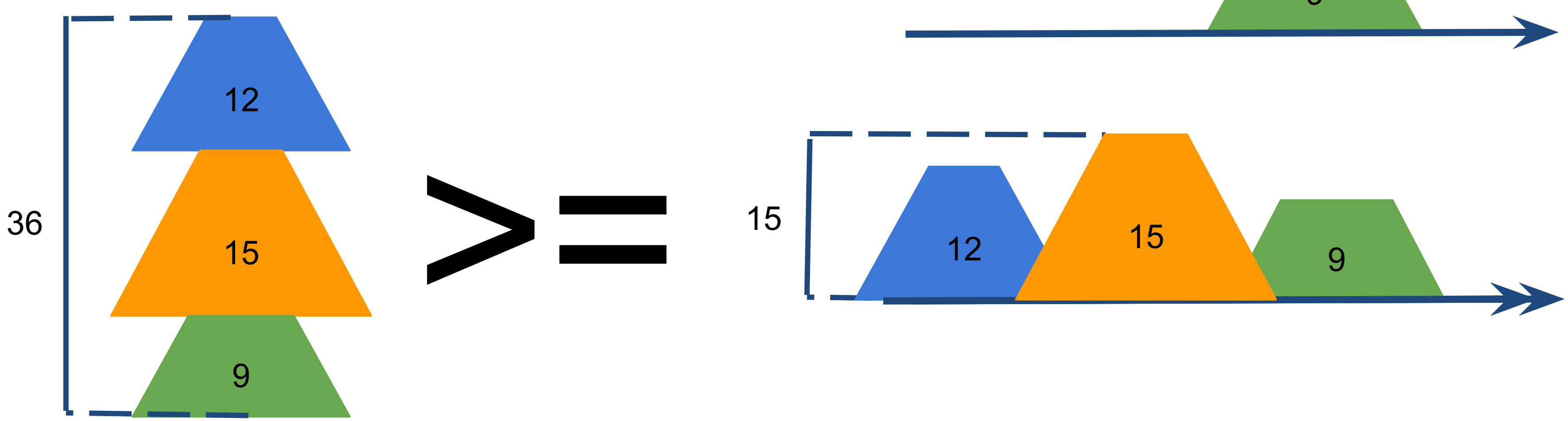


Questions on Queuing?

Statistical Multiplexing

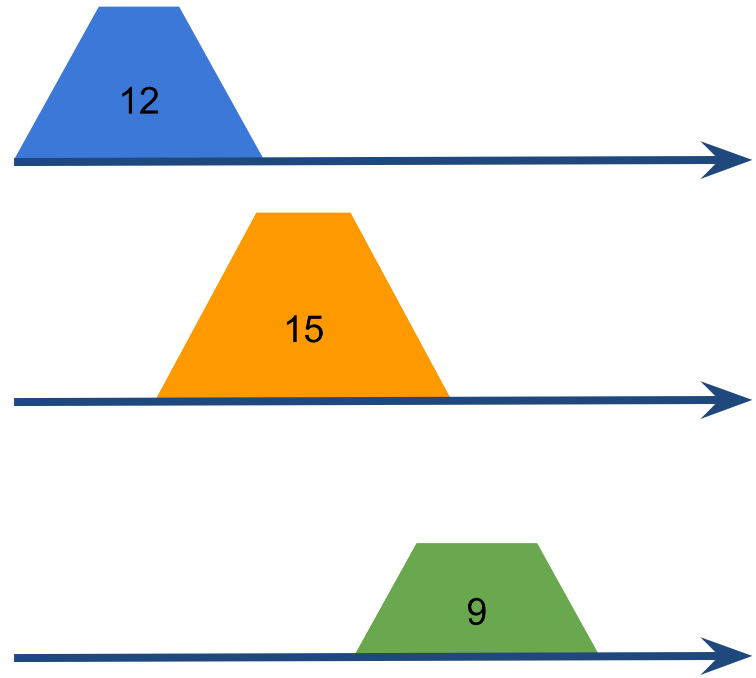
- Sum of the peaks is always greater than the peak of the sums (peak of the aggregate). Usually much greater.

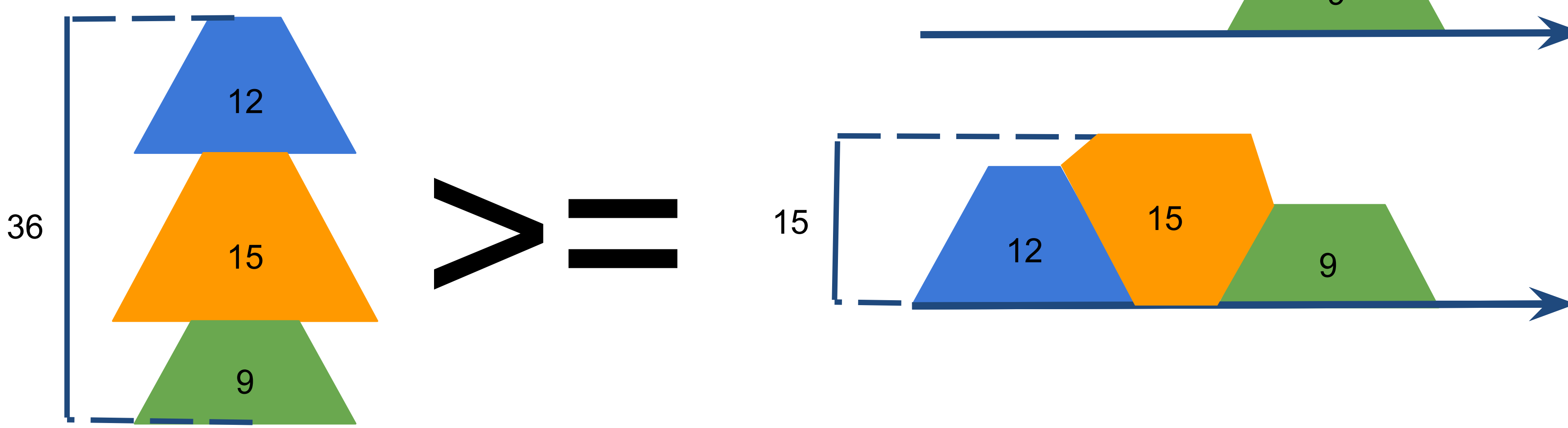




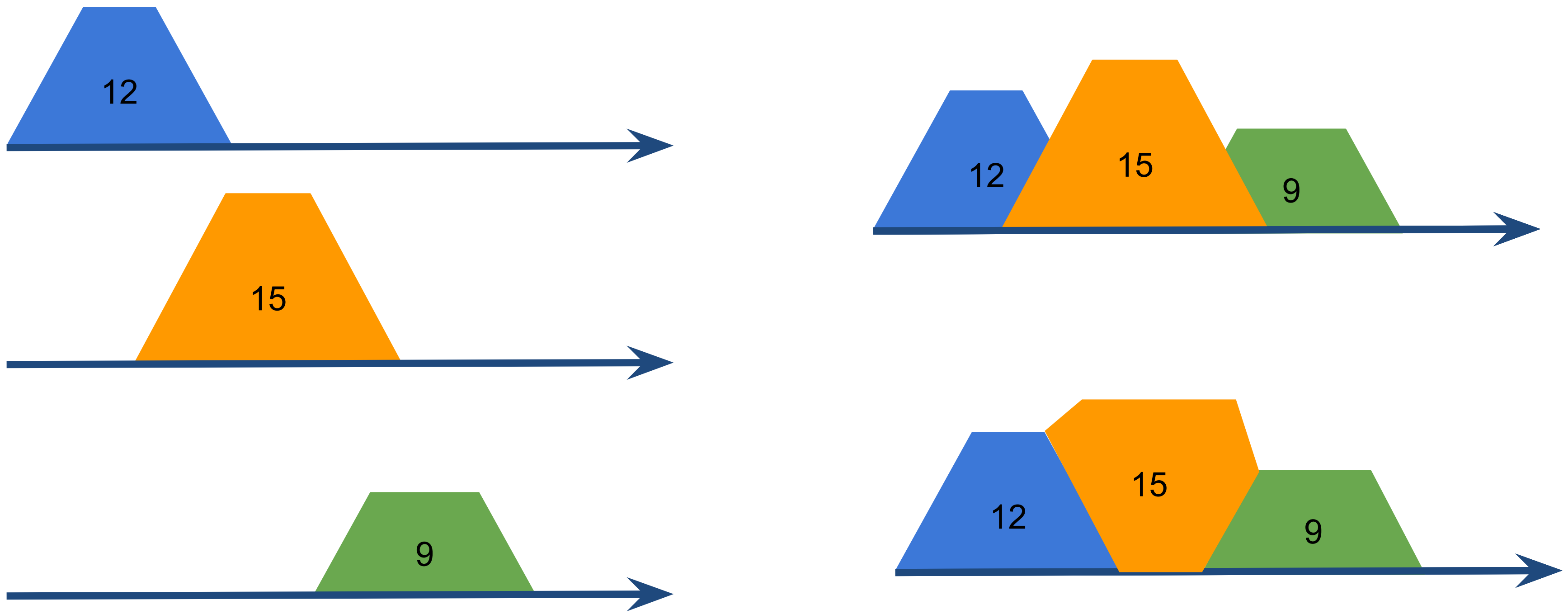
Statistical Multiplexing

- Sum of the peaks is always greater than the peak of the sums (peak of the aggregate). Usually much greater.





Statistical Multiplexing



Discussion Questions

1 True or False

(1) On a fast cross-continental link ($\approx$ 100Gbps), *propagation delay* usually dominates *end-to-end packet delay*. (Most messages are smaller than 1GB.)

(2) On the same cross-continental link ($\approx$ 100Gbps), when transferring a 100GB file, *propagation delay* still dominates end-to-end file delivery.

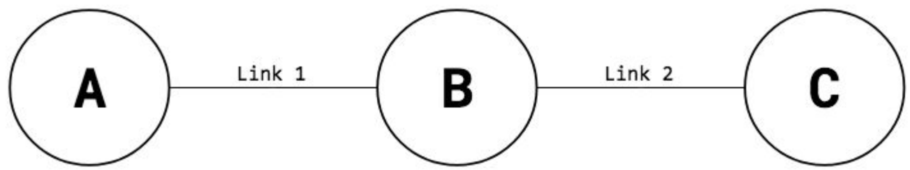
(3) On-demand circuit-switching is adopted by the Internet.

(4) The aggregate (i.e., sum) of peaks is usually much larger than peak of aggregates in terms of bandwidth usage.

(5) Bursty traffic (i.e., when packet arrivals are not evenly spaced in time) always leads to queuing delays.

2 End-to-End Delay

Consider the diagram below. Link 1 has length L_1 m (where m stands for meters) and allows packets to be propagated at speed $S_1 \frac{\text{m}}{\text{sec}}$, while Link 2 has length L_2 m but it only allows packets to be propagated at speed $S_2 \frac{\text{m}}{\text{sec}}$ (because two links are made of different materials). Link 1 has transmission rate $T_1 \frac{\text{bits}}{\text{sec}}$ and Link 2 has transmission rate $T_2 \frac{\text{bits}}{\text{sec}}$.

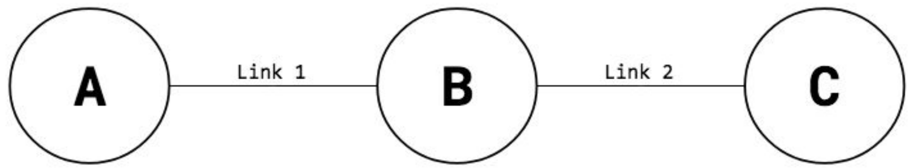


Assuming nodes can send and receive bits at full rate and ignoring processing delay, consider the following scenarios:

(1) How long would it take to send a packet of 500 Bytes from Node A to Node B given $T_1 = 10000$, $L_1 = 100000$, and $S_1 = 2.5 \cdot 10^8$?

2 End-to-End Delay

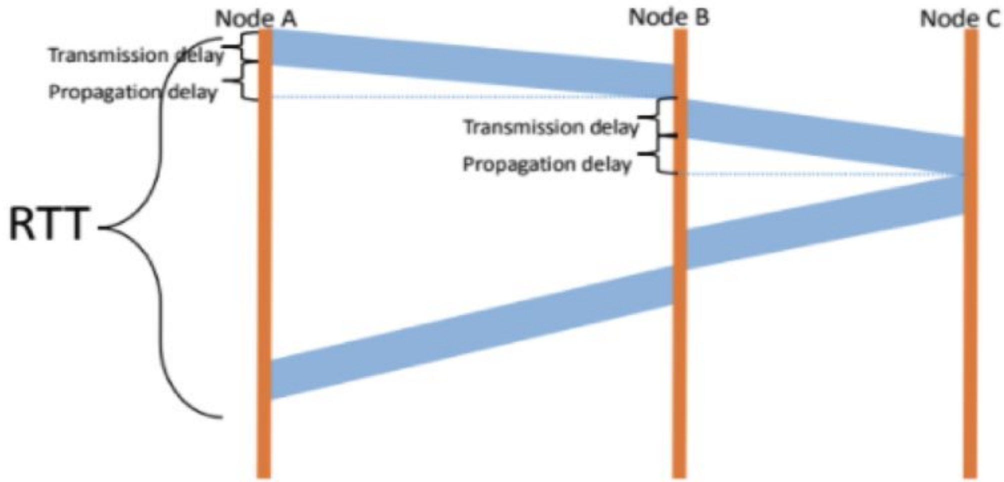
Consider the diagram below. Link 1 has length L_1 m (where m stands for meters) and allows packets to be propagated at speed $S_1 \frac{\text{m}}{\text{sec}}$, while Link 2 has length L_2 m but it only allows packets to be propagated at speed $S_2 \frac{\text{m}}{\text{sec}}$ (because two links are made of different materials). Link 1 has transmission rate $T_1 \frac{\text{bits}}{\text{sec}}$ and Link 2 has transmission rate $T_2 \frac{\text{bits}}{\text{sec}}$.



Assuming nodes can send and receive bits at full rate and ignoring processing delay, consider the following scenarios:

(2) Compute RTT (round trip time) for a packet of B Bytes sent from Node A to Node C (packet gets transmitted back from Node C immediately after Node C receives it).

Solution: There is only one packet so no need to worry about queuing delays. Consider the diagram below:



Note the sequence of delays the packet experiences during its route from A to C:

1. Transmission delay to push the packet onto Link 1.
2. Propagation delay as the packet travels from Node A to Node B.
3. Transmission delay to push the packet onto Link 2.
4. Propagation delay as the packet travels from Node B to Node C.
5. Transmission delay to push the packet onto Link 2.
6. Propagation delay as the packet travels from Node C to Node B.
7. Transmission delay to push the packet onto Link 1.
8. Propagation delay as the packet travels from Node B to Node A.

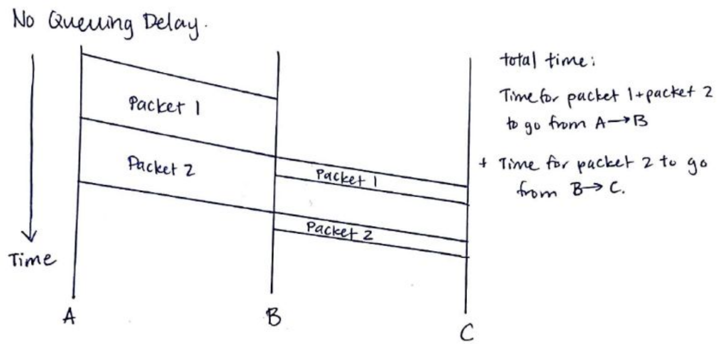
Summing these delays yields the total RTT:

$$\boxed{\text{RTT} = \frac{8B}{T_1} + \frac{L_1}{S_1} + \frac{8B}{T_2} + \frac{L_2}{S_2} + \frac{8B}{T_2} + \frac{L_2}{S_2} + \frac{8B}{T_1} + \frac{L_1}{S_1}}$$

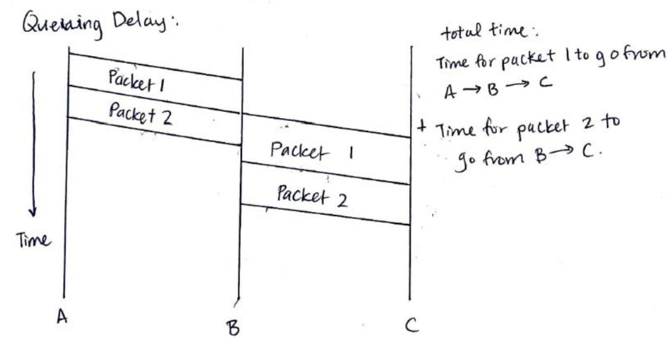
(3) At time 0, Node A sends packet P_1 with D_1 Bytes and then it sends another packet P_2 with D_2 Bytes immediately after it pushes all bits of P_1 onto Link 1. When will Node C receive the last bit of P_2?

(3) At time 0, Node A sends packet P_1 with D_1 Bytes and then it sends another packet P_2 with D_2 Bytes immediately after it pushes all bits of P_1 onto Link 1. When will Node C receive the last bit of P_2?

Below is the time-graph of a packet in flight without queuing delay:



And with queuing delay:



$$t_{\text{total}} = \frac{8D_1}{T_1} + \frac{8D_2}{T_1} + \frac{L_1}{S_1} + \max\left(\frac{8D_1}{T_2} - \frac{8D_2}{T_1}, 0\right) + \frac{8D_2}{T_2} + \frac{L_2}{S_2}$$

From left to right, the terms in this sum are:

1. The transmission delay to push P_1 onto Link 1.
2. The transmission delay to push P_2 onto Link 1.
3. The propagation delay as P_2 travels from Node A to Node B.
4. The queueing delay at Node B. Note that the use of the max operator allows us to express the two cases when there is and when there isn't queueing delay compactly.
5. The transmission delay to push P_2 onto Link 2.
6. The propagation delay as P_2 travels from Node B to Node C.

(4) Find the variable relations that need to be satisfied in order to have no queuing delays for part (c).

4 Statistical Multi-What?

Consider three flows (F_1, F_2, F_3) sending packets over a single link. The sending pattern of each flow is described by how many packets it sends within each one-second interval; the table below shows these numbers for the first ten intervals. A perfectly smooth (i.e., non-bursty) flow would send the same number of packets in each interval, but our three flows are very bursty, with highly varying numbers of packets in each interval:

Time (s)	1	2	3	4	5	6	7	8	9	10
F_1	1	8	3	15	2	1	1	34	3	4
F_2	6	2	5	5	7	40	21	3	34	5
F_3	45	34	15	5	7	9	21	5	3	34

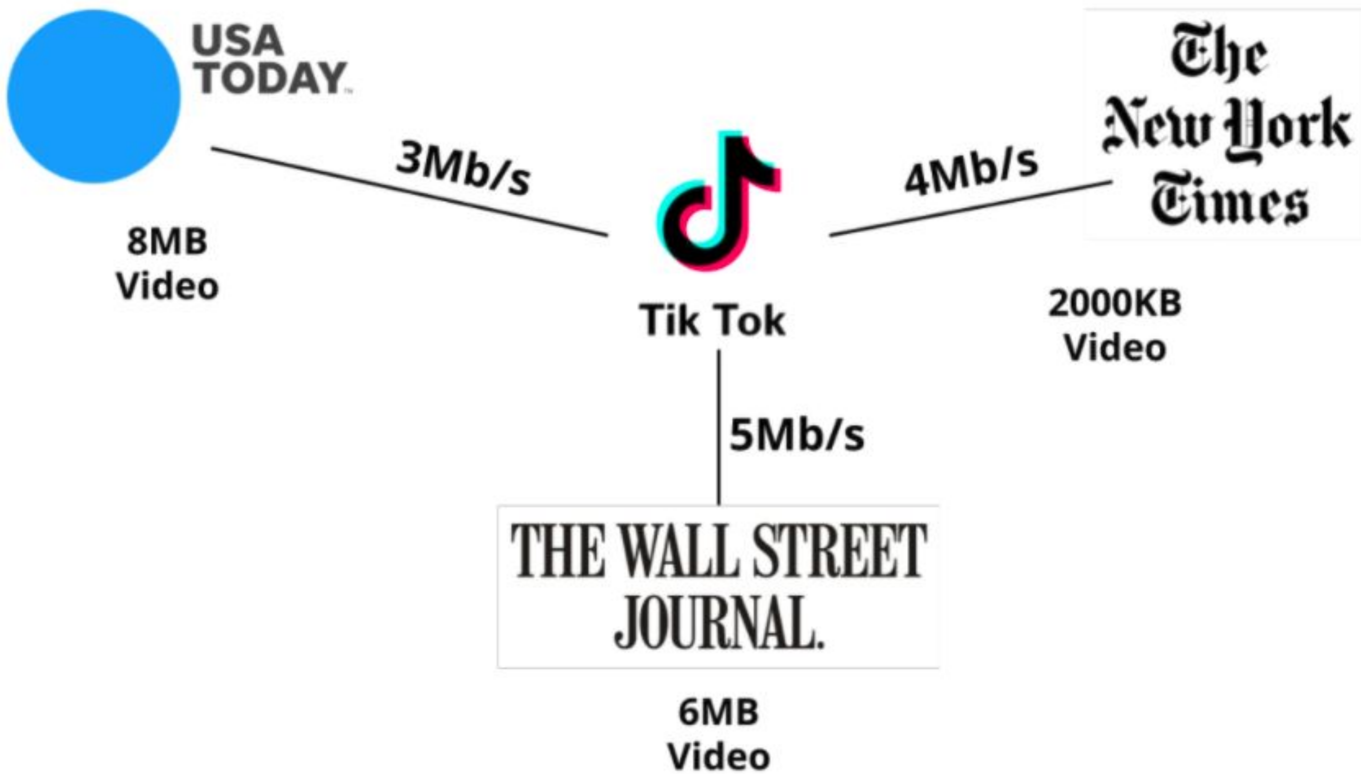
1. What is the peak rate of F_1? F_2? F_3? What is the sum of the peak rates?

2. Now consider all packets to be in the same aggregate flow. What is the peak rate of this aggregate flow?

3. Which is higher - the sum of the peaks, or the peak of the aggregate?

3 First one to TikTok wins!

As you may know, the Washington Post has a pretty spicy TikTok account. Execs at the New York Times, the Wall Street Journal, and USA Today have also noticed the Post's success and want to promote their brand on the platform. Each organization has filmed a take on the 9 to 5 challenge video to use as their first upload to TikTok. They are all waiting for the perfect moment to post.



Upon seeing the perfect opportunity, all three organizations begin uploading their video at almost the same time (within 3-seconds of each other). If we assume that propagation time is negligible, which news organization will be the first to publish their video (and ultimately become #1 trending on TikTok)?

Solution: Let's first compute the transmission time for the videos uploaded:

The NYTime's video is 2000KB and takes

$$\frac{2000\text{KB}}{1000\frac{\text{KB}}{MB}} \cdot 8\frac{\text{bits}}{\text{byte}} \div 4\frac{Mb}{s} = \boxed{4.0 \text{ seconds}}$$

to upload the entire video.

The USA Today's video would need around

$$8\text{MB} \cdot 8\frac{\text{bits}}{\text{byte}} \div 3\frac{Mb}{s} = \boxed{21.3 \text{ seconds}}$$

to be put onto the link.

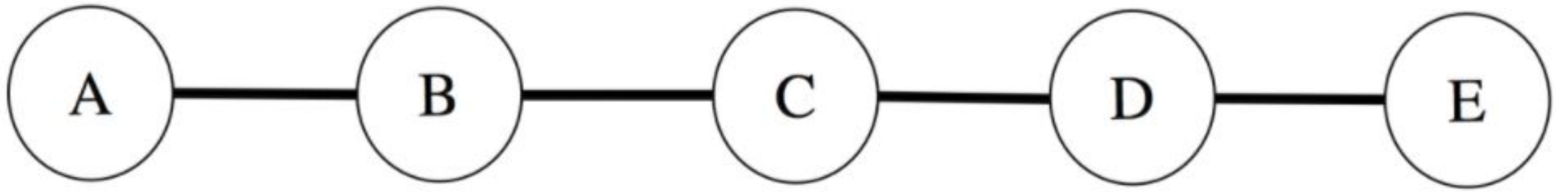
The WSJ's video would need around

$$6\text{MB} \cdot 8\frac{\text{bits}}{\text{byte}} \div 4\frac{Mb}{s} = \boxed{9.6 \text{ seconds}}$$

to be put onto the link.

The NYTimes video is the first uploaded because it's time to upload is 5.6 seconds faster than the next fastest upload from the WSJ (which is greater than the 3-second range of uploading).

5 Plenty of Packets



Let's suppose we have three packets (P_1, P_2, P_3) of size x, y, z bytes respectively. We want to send packet P_1 from A to C and packets P_2 and P_3 from C to E.

Use the following values for all calculations:

x	2000 bytes
y	500 bytes
z	1000 bytes
L_{AB}	100 km
L_{BC}	50 km
L_{CD}	75 km
L_{DE}	100 km
S_{AB}	$1.5 * 10^8 \frac{m}{s}$
S_{BC}	$2 * 10^8 \frac{m}{s}$
S_{CD}	$2 * 10^8 \frac{m}{s}$
S_{DE}	$1.75 * 10^8$
T_{AB}	$5000 \frac{b}{s}$
T_{BC}	$8000 \frac{b}{s}$
T_{CD}	$10000 \frac{b}{s}$
T_{DE}	$7000 \frac{b}{s}$

(1) Will P_1 reach its destination first or will P_2 and P_3 arrive before?

So, the time for P_1 to reach its destination is

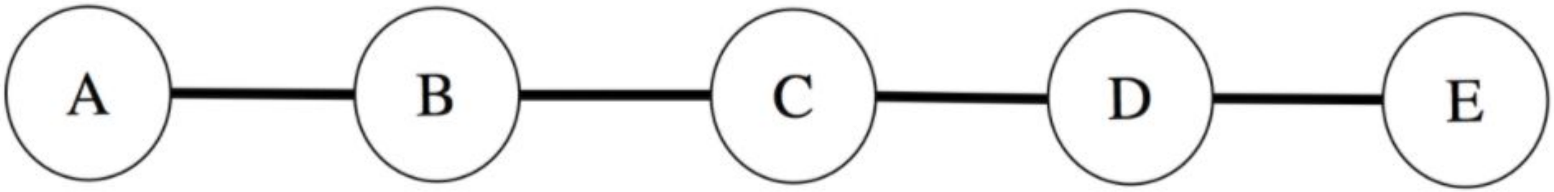
$$\frac{8x}{T_{AB}} + \frac{L_{AB}}{S_{AB}} + \frac{8x}{T_{BC}} + \frac{L_{BC}}{S_{BC}} = 5.20s.$$

. So, the total amount of time it takes to transmit both packets will be:

$$\frac{8y}{T_{CD}} + \frac{8z}{T_{CD}} + \frac{L_{CD}}{S_{CD}} + \frac{8z}{T_{DE}} + \frac{L_{DE}}{S_{DE}} = 2.34s.$$

We see that P_2 and P_3 will arrive at their destination before P_1.

5 Plenty of Packets



Let's suppose we have three packets (P_1, P_2, P_3) of size x, y, z bytes respectively. We want to send packet P_1 from A to C and packets P_2 and P_3 from C to E.

Use the following values for all calculations:

x	2000 bytes
y	500 bytes
z	1000 bytes
L_{AB}	100 km
L_{BC}	50 km
L_{CD}	75 km
L_{DE}	100 km
S_{AB}	$1.5 * 10^8 \frac{m}{s}$
S_{BC}	$2 * 10^8 \frac{m}{s}$
S_{CD}	$2 * 10^8 \frac{m}{s}$
S_{DE}	$1.75 * 10^8$
T_{AB}	$5000 \frac{b}{s}$
T_{BC}	$8000 \frac{b}{s}$
T_{CD}	$10000 \frac{b}{s}$
T_{DE}	$7000 \frac{b}{s}$

(2) How small would P_1 have to be for it to take longer to send the other two packets?

Solution: To solve this, we will set the time it takes for P_1 to reach its destination to be less than the time we calculated for the other two packets in the first part.

$$\frac{8x}{T_{AB}} + \frac{L_{AB}}{S_{AB}} + \frac{8x}{T_{BC}} + \frac{L_{BC}}{S_{BC}} < 2.34$$
$$x < 901.11$$

So, P_1 can be at most 901 bytes for it to arrive at its destination faster than the other two packets.