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1 True or False

1.1 On a fast cross-continental link (~100Gbps), **propagation delay** usually dominates **end-to-end packet delay** (Most messages are smaller than 100MB).

True. On a 100Gbps link, even a 100MB file download would only take 0.008 seconds to get on the wire, compared to 0.02 seconds propagation delay from New York to London (in the best case). Most communications (web page, emails) don't come close to this size.

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

False. Sending a 100GB file over a 100Gbps link will have at least 8 seconds transmission delay.

1.3 On-demand circuit-switching is adopted by the Internet.

False. Circuit-switching shares bandwidth through reservation. Packet-switching shares bandwidth on demand. Packet-switching is adopted by the Internet.

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

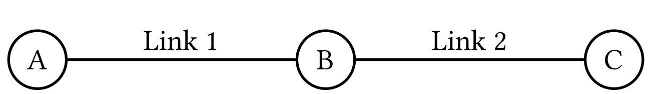
True. Statistical multiplexing leverages this to use available scarce resources more effectively.

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

False. Queuing delay happens when arrival rate is larger than transmission rate (ignoring processing delays). Bursty traffic does not necessarily imply arrival rate is larger than transmission rate. Queuing delay depends on traffic patterns, router internals, and link properties.

2 End-to-End Delay

In the diagram below, we have two different links, each with different physical properties (e.g. because they're made of different materials):



	Link 1	**Link 2**
Physical length of link	L_1 meters	L_2 meters
Speed of data propagation	S_1 meters/sec	S_2 meters/sec
Bandwidth of link	T_1 bits/sec	T_2 bits/sec

Assumptions:

- All nodes can send and receive bits at full rate.
- Processing delay is negligible. For example, a node has received a packet the instant it receives the last byte of the packet.
- A node can only start forwarding a packet after it has received all bytes of the packet.

2.1 Suppose $T_1 = 10000$, $L_1 = 100000$, and $S_1 = 2.5 \times 10^8$.

How long would it take to send a 500-byte packet from Node A to Node B?

The total time needed is the sum of the transmission delay to push the packet onto Link 1 and the propagation delay for the packet to travel from Node A to Node B.

$$t_{\text{total}} = t_{\text{transmission}} + t_{\text{propagation}}$$

$$t_{\text{total}} = \frac{\text{packet size}}{\text{transmission rate of Link 1}} + \frac{\text{distance between A and B}}{\text{propagation speed}}$$

$$t_{\text{total}} = \frac{500 \text{ bytes} \times 8 \frac{\text{bits}}{\text{byte}}}{10000 \frac{\text{bits}}{\text{second}}} + \frac{100000 \text{ meters}}{2.5 \times 10^8 \frac{\text{meters}}{\text{second}}}$$

$$t_{\text{total}} = 0.4s + 0.0004s = \boxed{0.4004\text{s}}$$

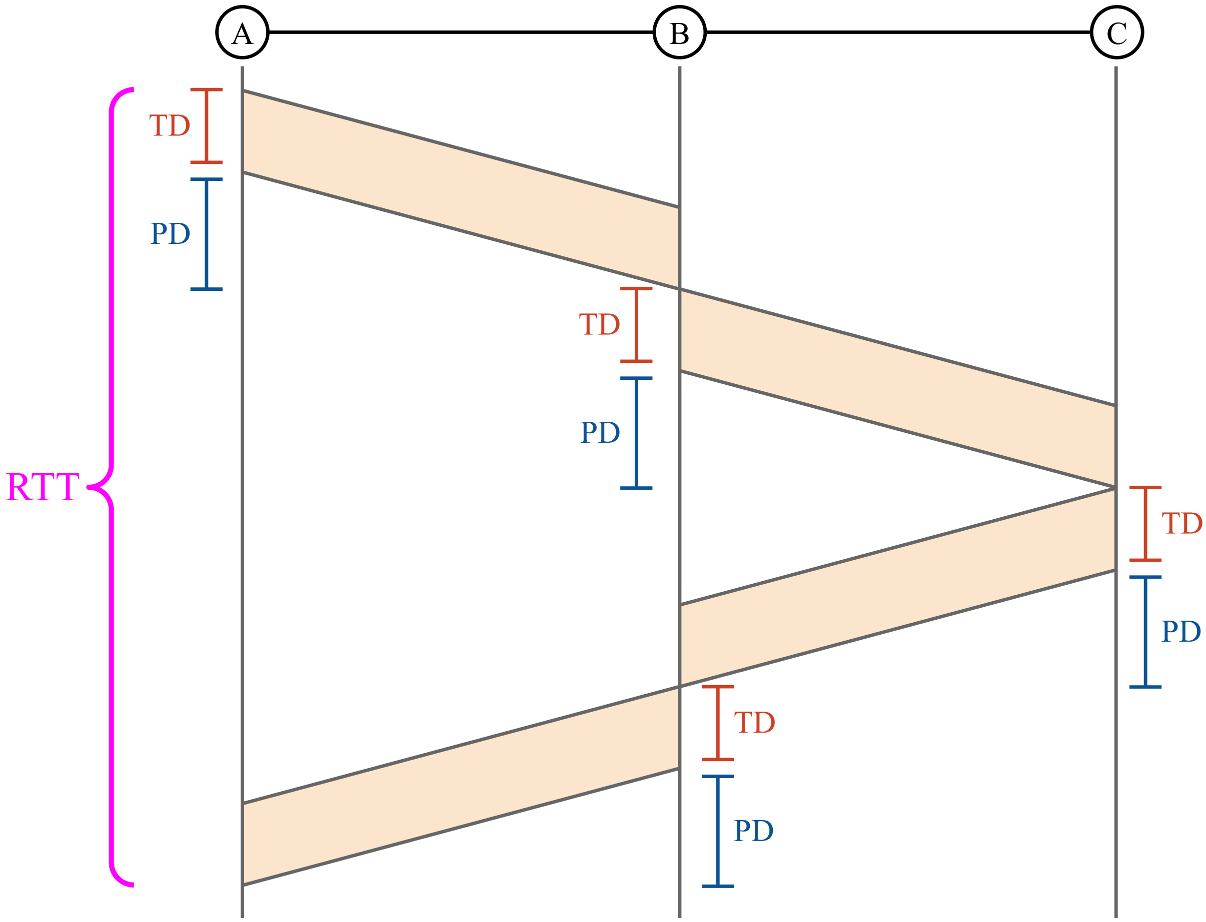
Notice that transmission delay dominates more than 99.9% in this case.

2.2 The RTT (Round Trip Time) is the time it takes to send a packet (from source to destination) and receive a response (from destination to source). Count from the time the source transmits the first byte, to the time the source receives the last byte of the response.

Node A sends a x-byte packet to Node C. Then, Node C sends an x-byte response back to Node A. What is the RTT for this exchange?

Note: We assume processing delay is negligible, so Node C starts transmitting the response immediately after it receives the last byte of the packet.

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:

$$\boxed{\frac{8x}{T_1} + \frac{L_1}{S_1} + \frac{8x}{T_2} + \frac{L_2}{S_2} + \frac{8x}{T_2} + \frac{L_2}{S_2} + \frac{8x}{T_1} + \frac{L_1}{S_1}}$$

2.3 Node A sends two packets:

- Packet P_1 of size D_1 bytes.
- Packet P_2 of size D_2 bytes.

Node A starts sending packet P_1 at $t = 0$. Node A immediately starts sending packet P_2 after it finishes transmitting all the bits of P_1.

When will Node C receive the last bit of packet P_2?

There are two packets, so we might need to consider queuing delays.

There will be a queuing delay at Node B if packet P_2 arrives at Node B before packet P_1 is finished being pushed onto Link 2.

Let's start by computing the time at which P_1 finishes being pushed onto Link 2. P_1 takes $\frac{8D_1}{T_1}$ seconds to be pushed onto Link 1, $\frac{L_1}{S_1}$ seconds to propagate from Node A to Node B, and then $\frac{8D_1}{T_2}$ seconds to be pushed onto Link 2. Hence P_1 leaves Node B at time:

$$t_1 = \frac{8D_1}{T_1} + \frac{L_1}{S_1} + \frac{8D_1}{T_2}$$

Next, let's figure out the time when P_2 arrives at Node B. It first waits $\frac{8D_1}{T_1}$ seconds for P_1 to be completely pushed onto Link 1, then takes $\frac{8D_2}{T_1}$ seconds of transmission delay to be pushed onto Link 1 itself, before finally needing $\frac{L_1}{S_1}$ seconds of propagation delay to reach Node B. With this, we know that P_2 reaches Node B at time:

$$t_2 = \frac{8D_1}{T_1} + \frac{8D_2}{T_1} + \frac{L_1}{S_1}$$

There's queuing delay if $t_1 > t_2$, and the length of the delay can be expressed as:

$$t_1 - t_2 = \left(\frac{8D_1}{T_1} + \frac{L_1}{S_1} + \frac{8D_1}{T_2}\right) - \left(\frac{8D_1}{T_1} + \frac{8D_2}{T_1} + \frac{L_1}{S_1}\right) = \frac{8D_1}{T_2} - \frac{8D_2}{T_1}$$

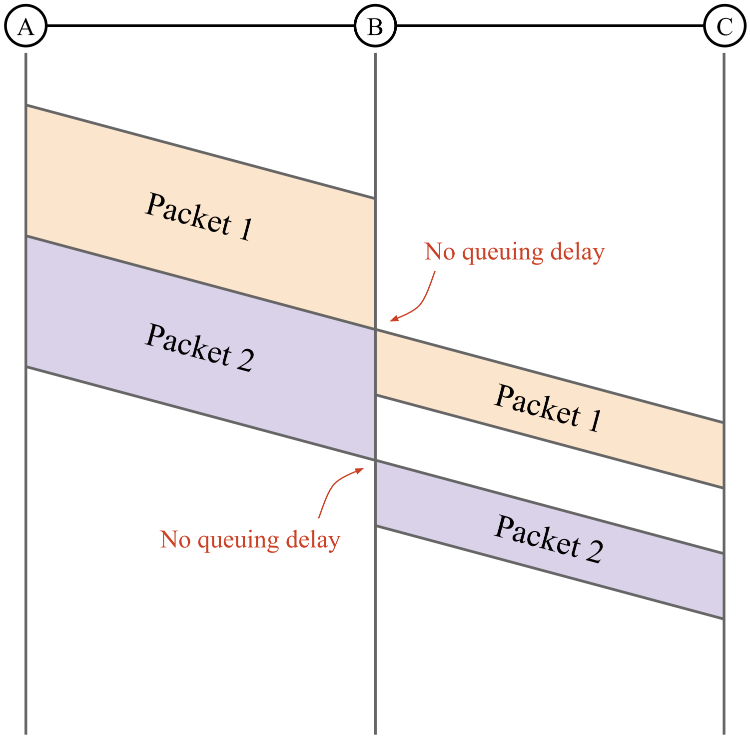
With this analysis in hand, we can express the time at which Node C receives the last bit of P_2 as follows:

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

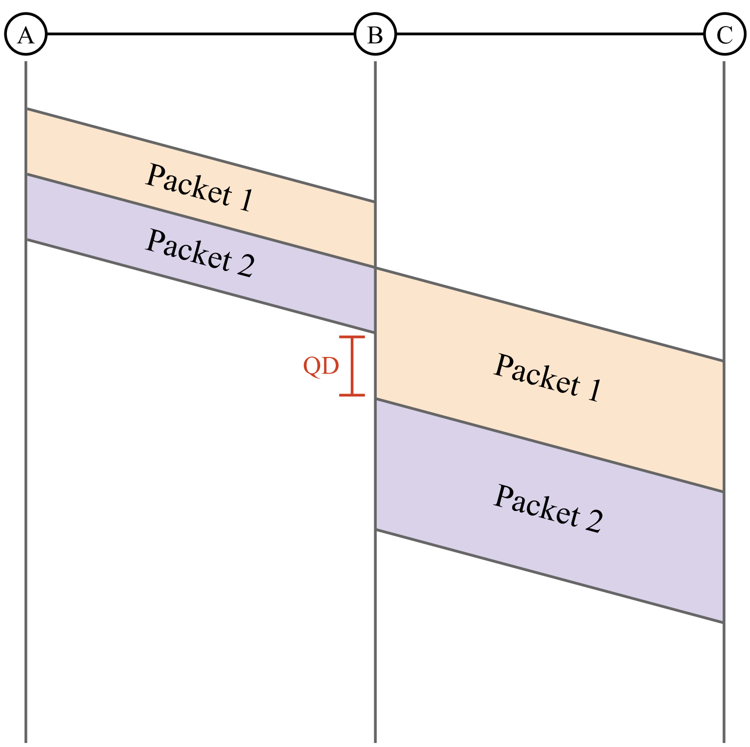
From left to right, the terms in this sum are:

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 queuing 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 queuing 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.

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



And with queuing delay:



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

From the analysis we conducted in the previous part, we know there will be queuing delays if $t_1 > t_2$, or $\frac{8D_1}{T_2} > \frac{8D_2}{T_1}$. Hence, there are no queuing delays if: $\frac{8D_1}{T_2} \le \frac{8D_2}{T_1}$ After simplifying, we see the relation that must be satisfied is:

$$\boxed{\frac{D_1}{T_2} \le \frac{D_2}{T_1}}$$

3 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

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

The peak rate is the highest the flow gets throughout the whole period. The peak rate of F_1 is 34, the peak rate of F_2 is 40, and the peak rate of F_3 is 45.

The sum of their peaks is 34 + 40 + 45 = 119.

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

Summing the flows together, we get the following values for an aggregate flow:

Time (s)	1	2	3	4	5	6	7	8	9	10
Aggregate Flow	52	44	23	25	16	50	43	42	40	43

The peak of the aggregate flow happens at 1s, where it is 52.

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

The sum of the peaks is 119, whereas the peak of the aggregate is 52, so the sum of the peaks is much higher. This is the insight from Statistical Multiplexing! The peak of the aggregate can only be at most the sum of the peaks, but that only happens in the case that all of the peaks happen at the same time. This is very unlikely, so usually, the peak of the aggregate is much lower than the sum of the peaks.