Bandwidth and Propagation Delay

Lecture 3, Spring 2026

Links

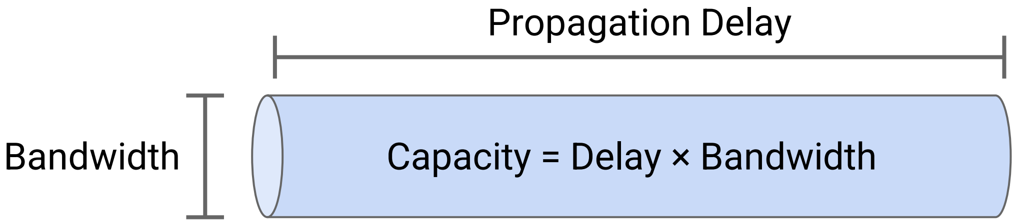
- **Bandwidth and Propagation Delay**
- Pipe Diagrams
- Overloaded Links

Properties of Links

A link connects two devices. 

Properties of a link:

- **Bandwidth**: Number of bits sent/received per unit time.
  - "Width" of the link.
  - Measured in bits per second (bps).
- **Propagation delay**: Time it takes a bit to travel along the link.
  - "Length" of the link.
  - Measured in seconds.
- **Bandwidth-delay product**: Bandwidth × delay.
  - "Capacity" of the link.



Measuring Packet Delay with Timing Diagrams

Suppose we have a link with:

- Bandwidth = 1 Mbps. *(1,000,000 bits per second.)*
- Propagation delay = 1 ms. *(0.001 seconds.)*

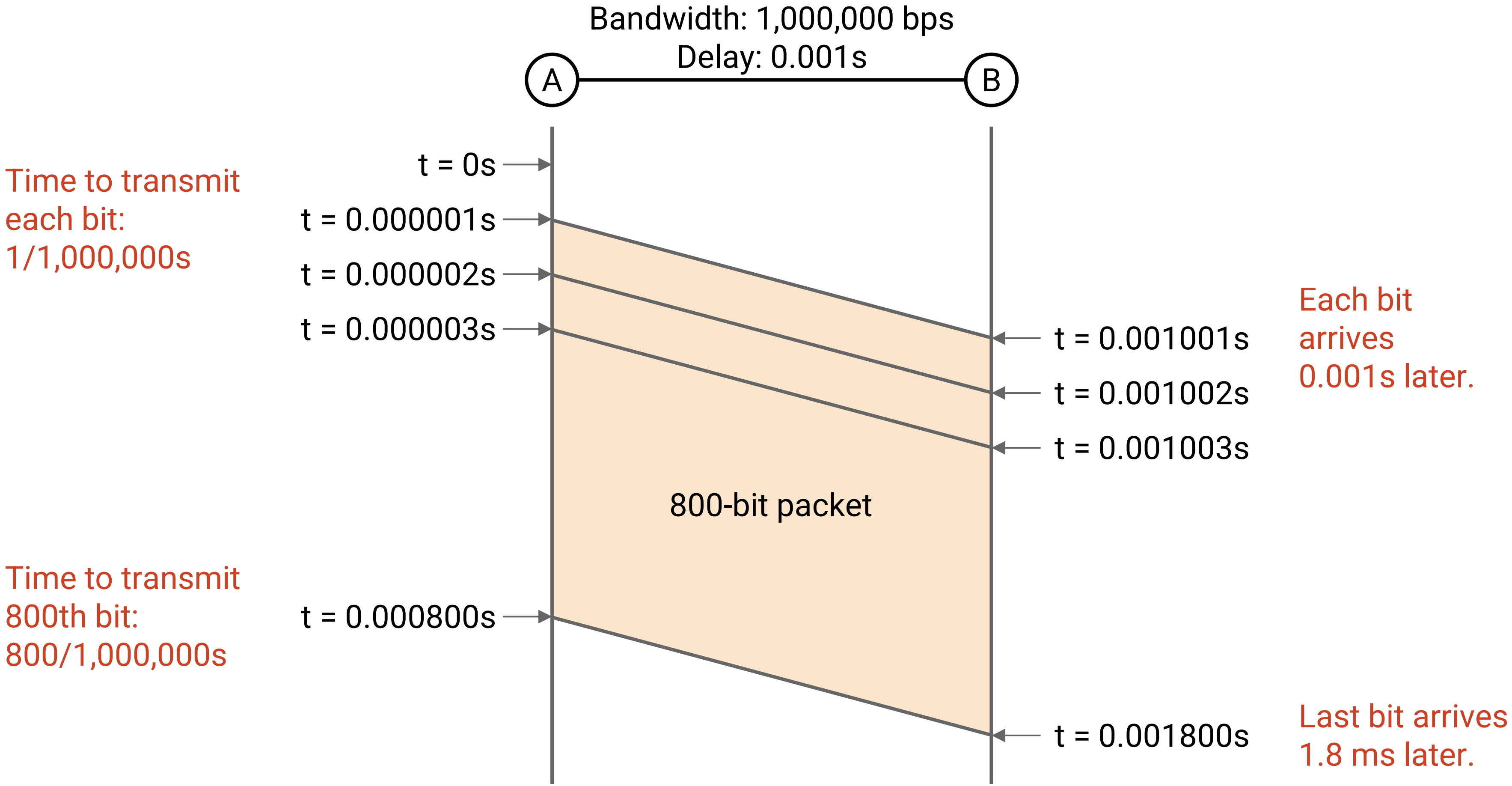
Note: We measure in **bits** per second, not **bytes**!

How long does it take to send a 100-byte *(800-bit)* packet?

- From the time the first bit is sent,
- To the time the last bit is received.

Let's draw a timing diagram to help.

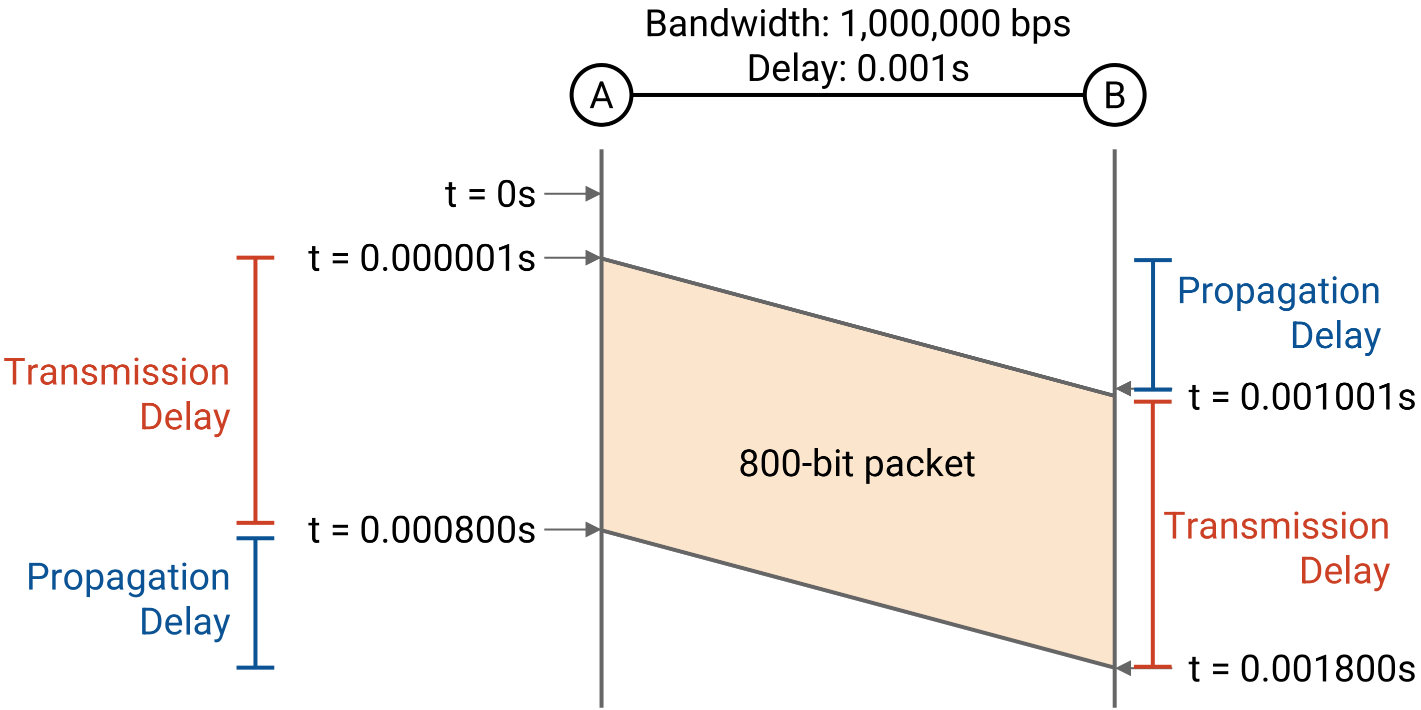
Measuring Packet Delay with Timing Diagrams



Measuring Packet Delay with Timing Diagrams

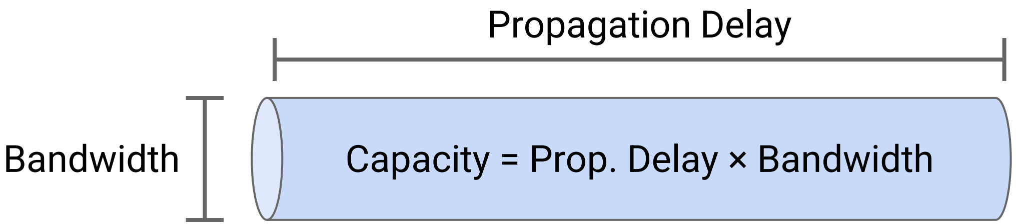
Packet Delay = Transmission Delay + Propagation Delay

= (Packet Size / Bandwidth) + Propagation Delay



Transmission Delay and Propagation Delay

- **Transmission Delay:** How long it takes to push all bits in the packet onto the link
    - From the time the first bit enters the link, to the time the last bit enters the link
- Depends on packet size and link bandwidth
- **Propagation Delay (latency):** How long it takes for one bit to travel across the link
    - Depends on the distance/length of the link, and propagation speed of the link (close to speed of light)
    - Does *NOT* depend on packet size



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

(bits/second)

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

Link Tradeoffs

Which link is better? It depends.

- Link 1: Bandwidth 10 Mbps Propagation Delay = 10 ms
- Link 2: Bandwidth 1 Mbps Propagation Delay = 1 ms

10-byte packet: Link 2 is better.

- 10.008ms with Link 1. 1.08ms with Link 2.
  - Link 1: t_{tx} = 10 byte / 10Mbps = 80 bits / 10Mbps = 0.008ms, t_{prop} = 10ms, Total delay = 10.008ms
  - Link 2: t_{tx} = 10 byte / 1Mbps = 80 bits / 1Mbps = 0.08ms, t_{prop} = 1ms, Total delay = 1.08ms
- For small packet, transmission delay is negligible. Propagation delay dominates.

10,000-byte packet: Link 1 is better.

- 18 ms with Link 1. 81 ms with Link 2.
  - Link 1: t_{tx} = 10000 byte / 10Mbps = 80000 bits / 10Mbps = 8ms, t_{prop} = 10ms, Total delay = 18ms
  - Link 2: t_{tx} = 10000 byte / 1Mbps = 80000 bits / 1Mbps = 80ms, t_{prop} = 1ms, Total delay = 81ms
- For large packet, transmission delay dominates.

Pipe Diagrams

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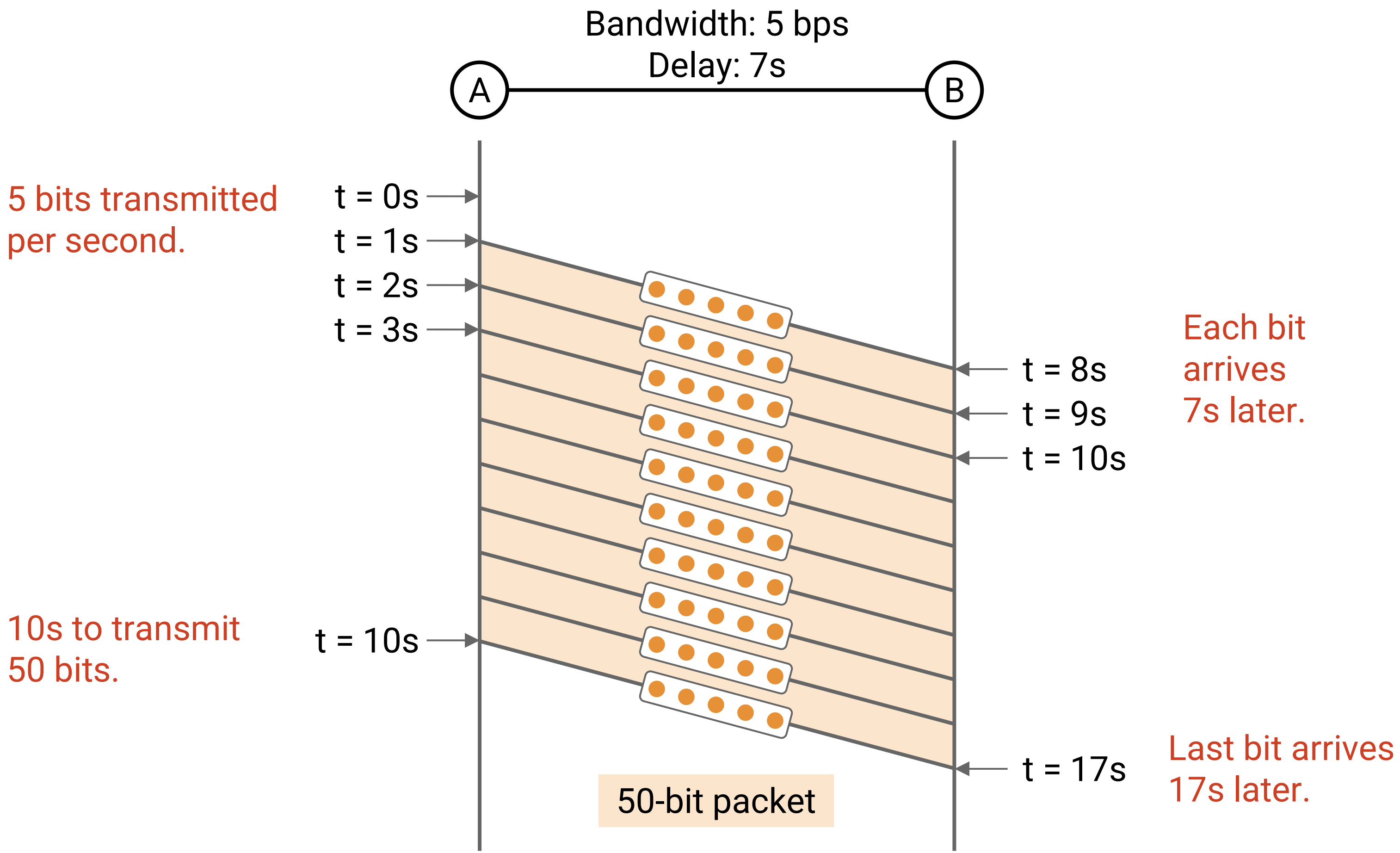
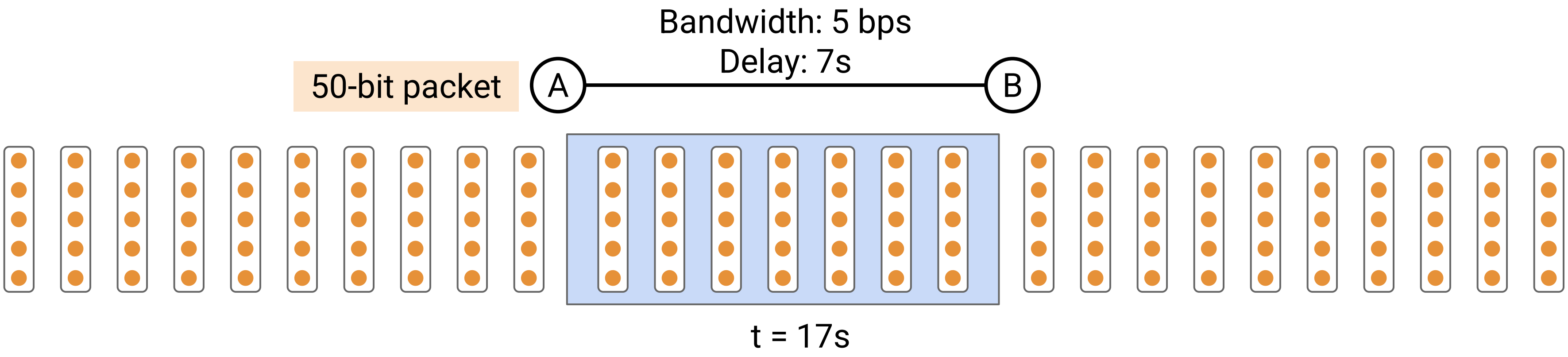
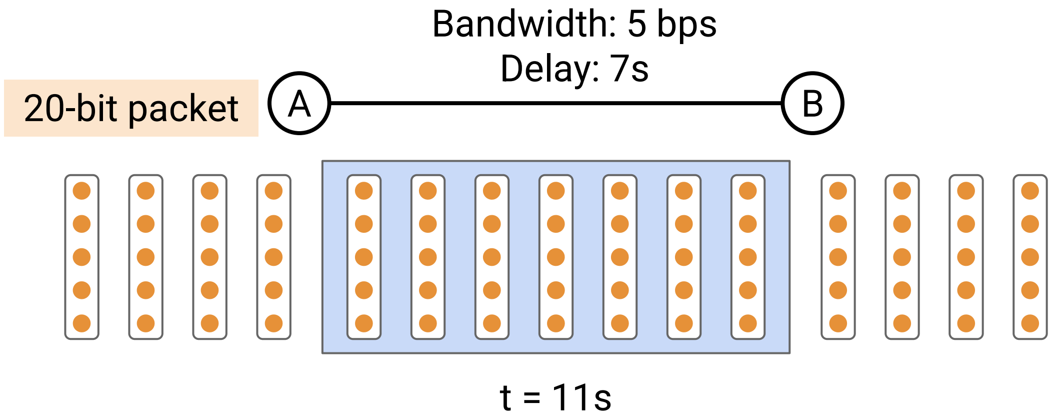
- **Pipe Diagrams**
- Overloaded Links

Timing Diagrams and Pipe Diagrams



The pipe diagram shows the bits on the link at any given moment in time.

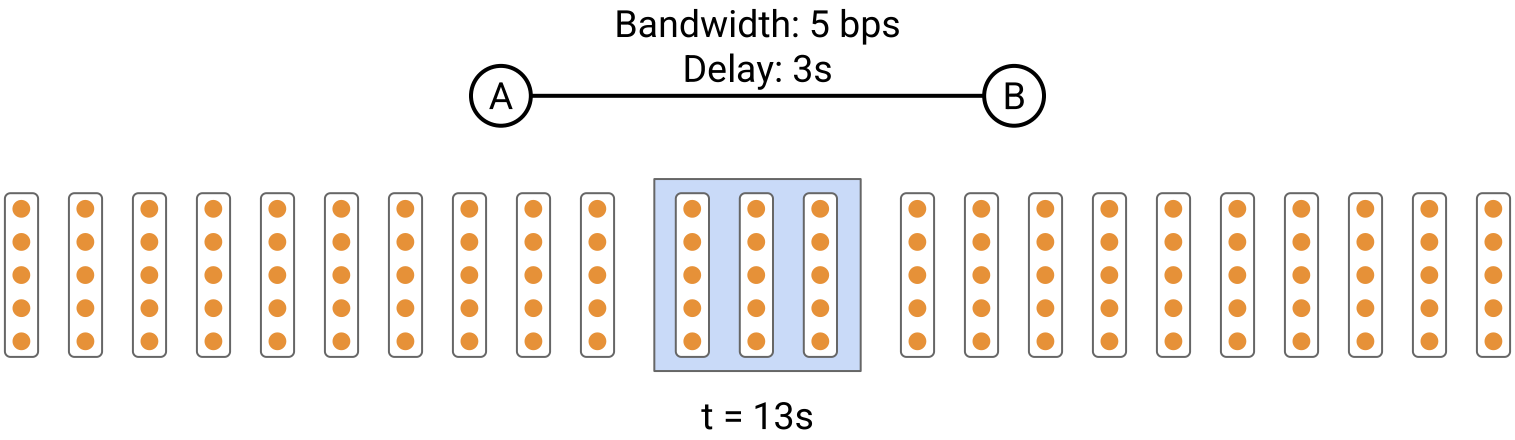




(These diagrams needsto be viewed with animation to make sense.)

Pipe Diagrams

Shorter propagation delay: Pipe length is shorter.



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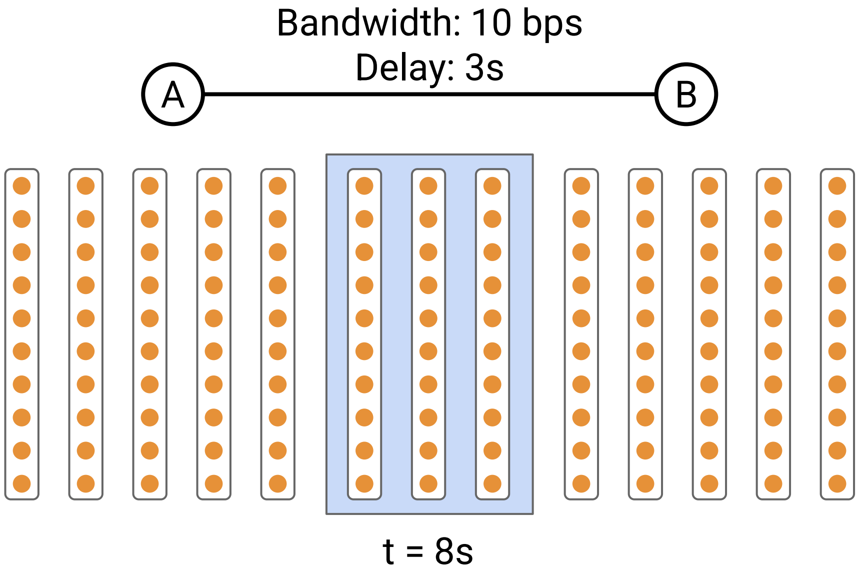
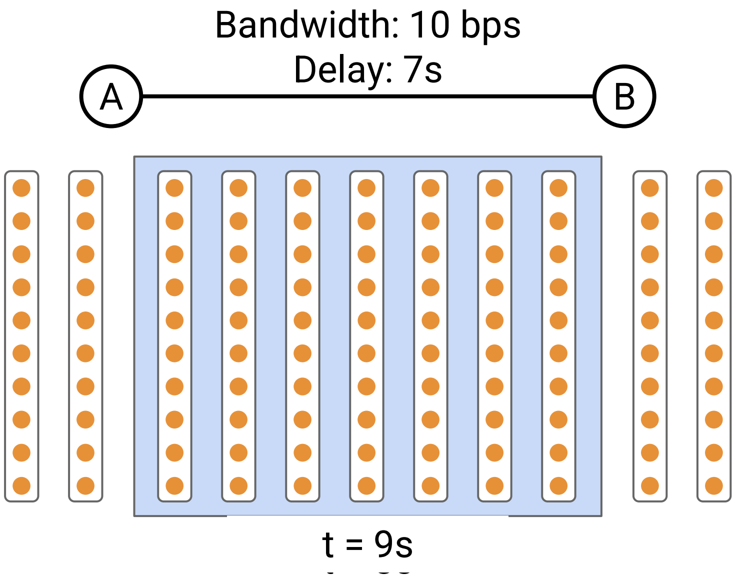
Higher bandwidth: Pipe height is taller.





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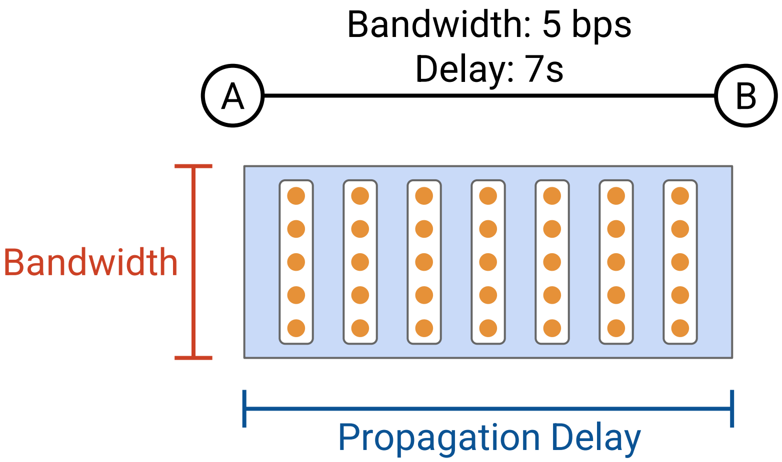
Pipe Diagrams

IMPORTANT

The pipe diagram shows the bits on the link at any given moment in time.

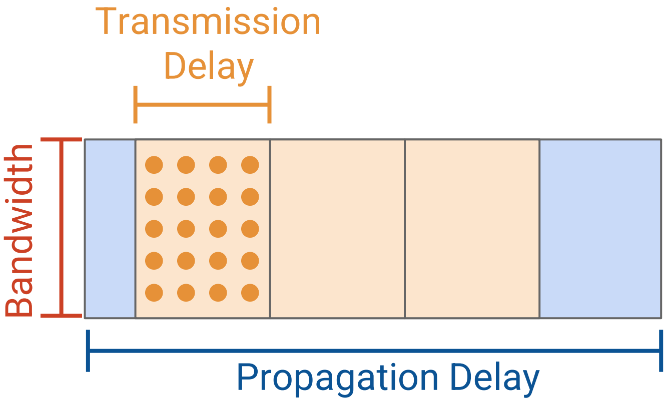
- **Height = bandwidth.** How many bits we can put in the pipe per unit time.
- **Width = propagation delay.** How long it takes for bits to travel through the pipe.
- **Area = bandwidth-delay product**. How many bits can fit in the pipe (bits in flight on the link) at a given instant.
- Examples:
  - **Long & thin pipe**: satellite links → delay dominates, capacity small
  - **Short & fat pipe**: LAN Ethernet → delay negligible, capacity huge
  - **Long & fat pipe**: transoceanic fiber backbones → delay long, but capacity enormous
  - **Short & thin pipe**: local low-rate links (serial bus, IoT, legacy modem) → delay tiny, but bandwidth the bottleneck

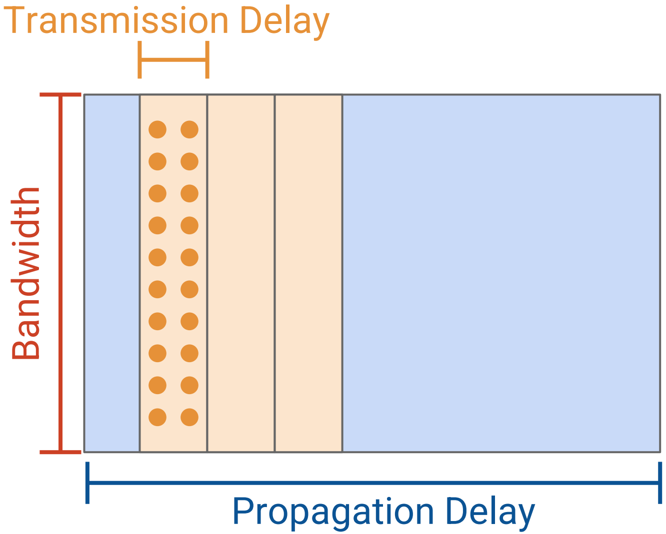


Pipe Diagrams – Packet Transmission Delay

The **width of the packet** in the pipe represents the transmission delay.

- How long it takes to push all the bits onto the link.
- **Link capacity = Propagation Delay × Bandwidth**
- **Packet size = Transmission Delay × Bandwidth**
    - For **a packet of given size**: higher bandwidth → shorter transmission delay (higher bandwidth = fatter pipe = more bits in pipe per unit time = narrower packet in pipe).





Overloaded Links

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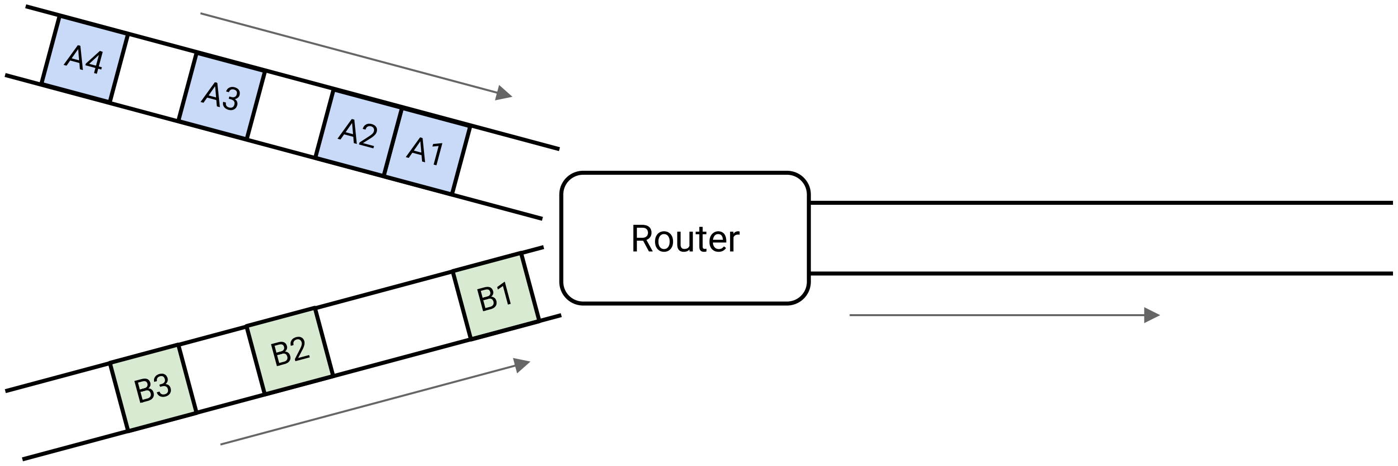
Links

- Bandwidth and Propagation Delay
- Pipe Diagrams
- **Overloaded Links**

Packet Switching at Routers

Recall: Routers receive packets, and forward them toward their destinations.

- For simplicity, consider 2 links with incoming traffic.
- For simplicity, consider sending all outgoing traffic out of 1 link.



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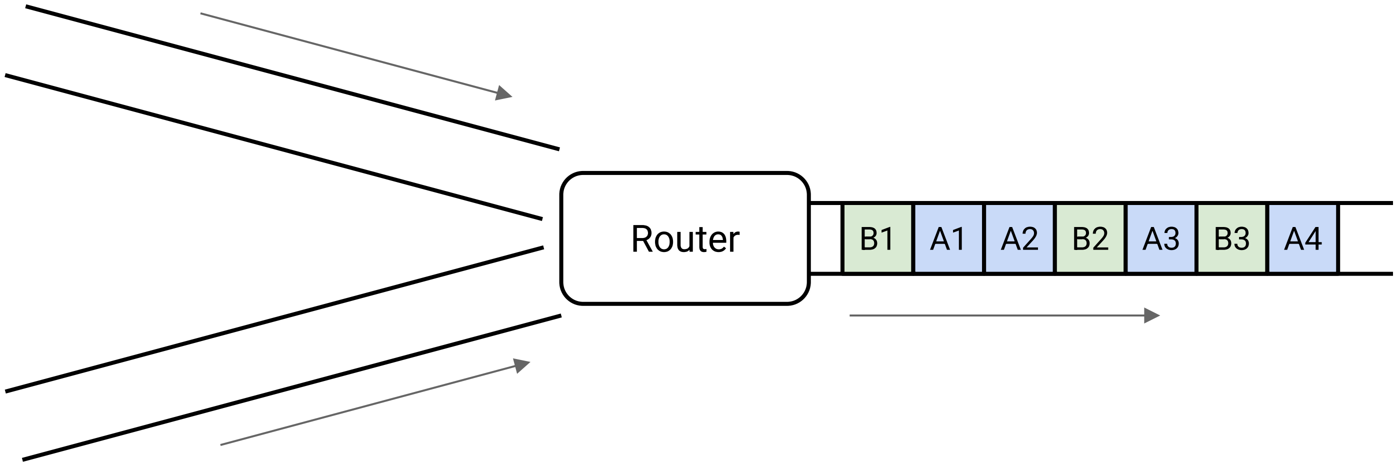
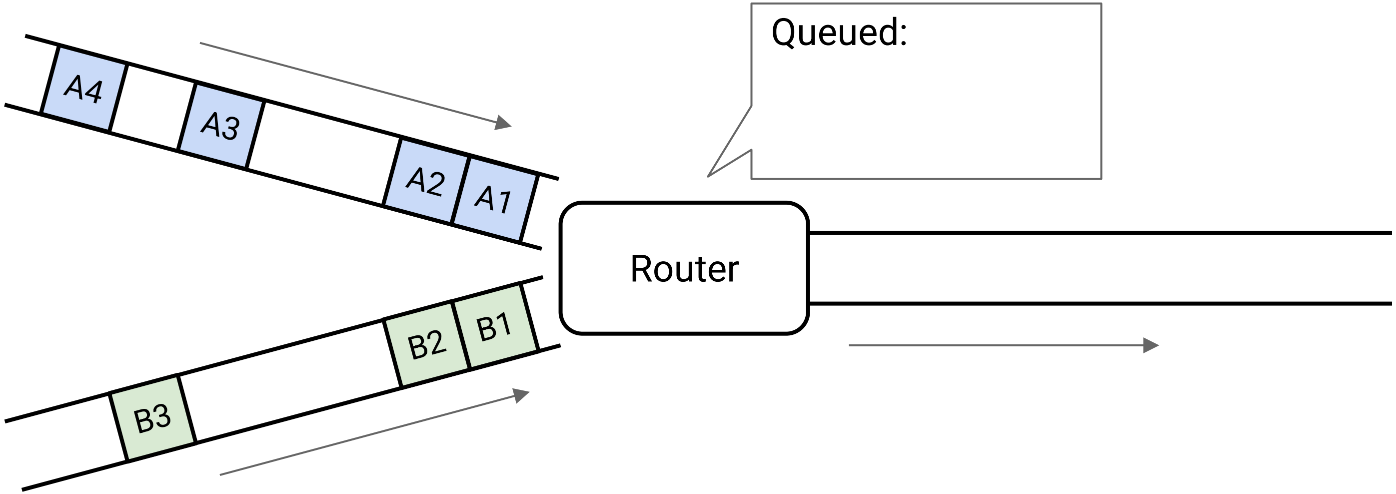


Transient Overload

What happens if two packets arrive at the router simultaneously?

- Can't process both at the same time! Router must queue one for later.
- When there are no incoming packets, router can *drain* the queue.
- This is called **transient overload**, and it's fairly common.



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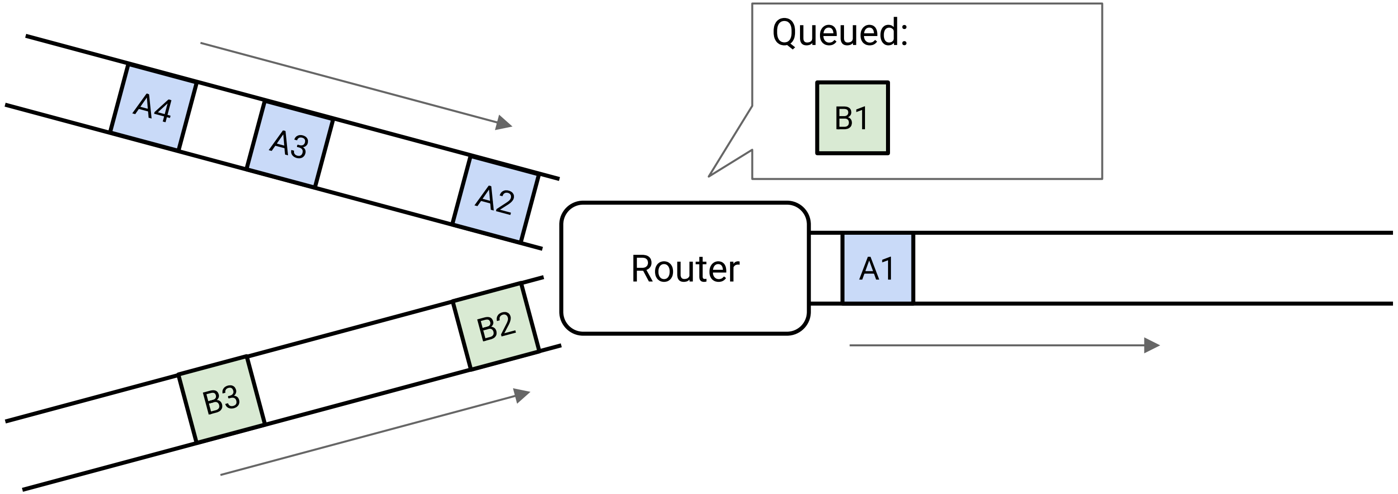

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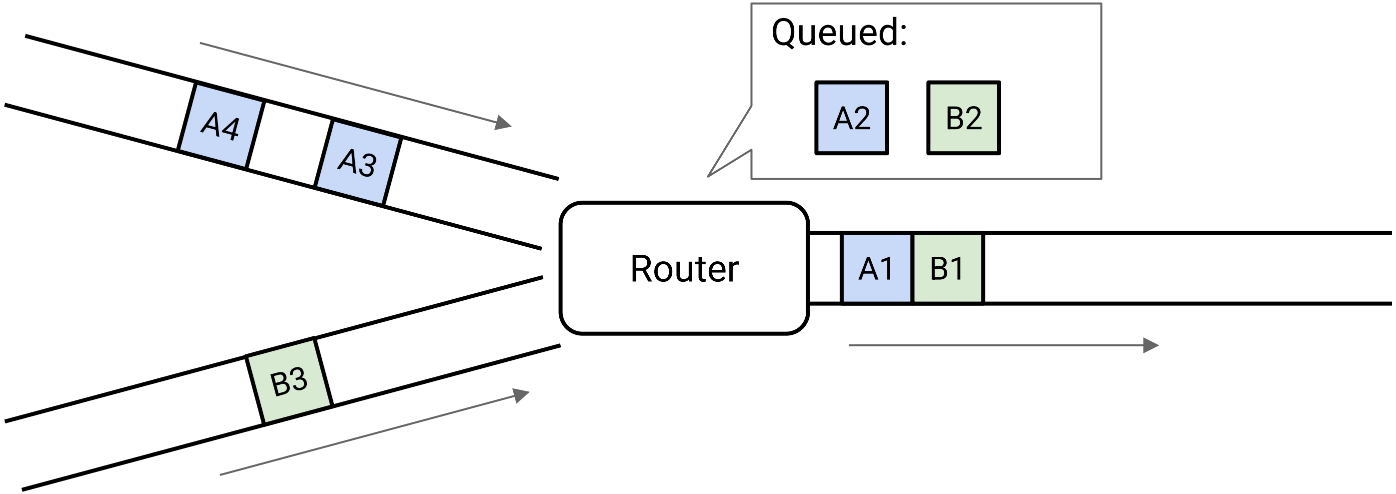

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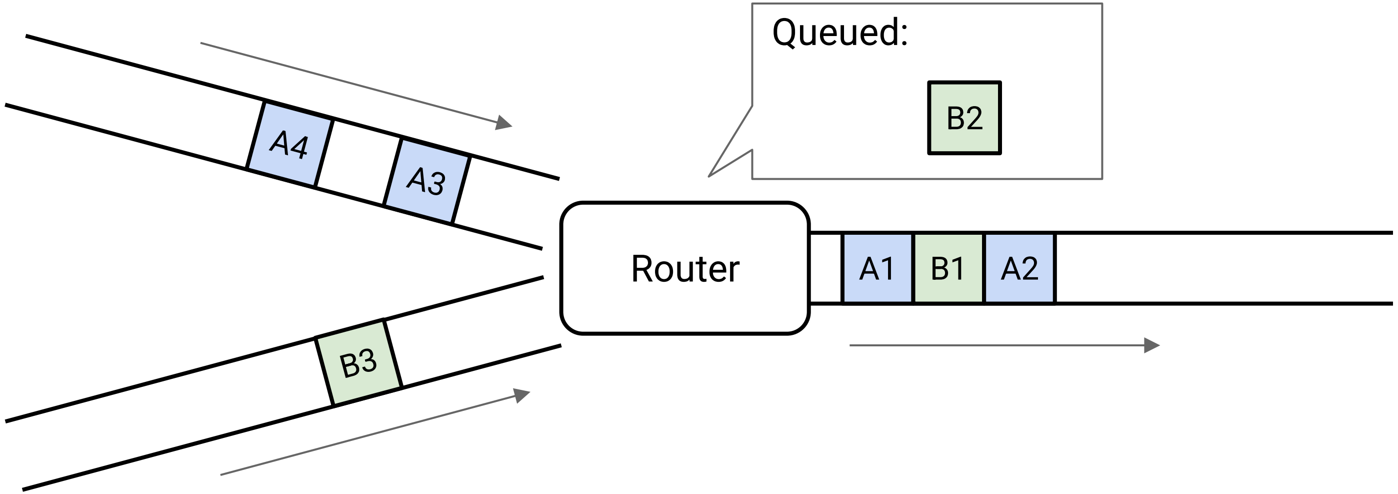

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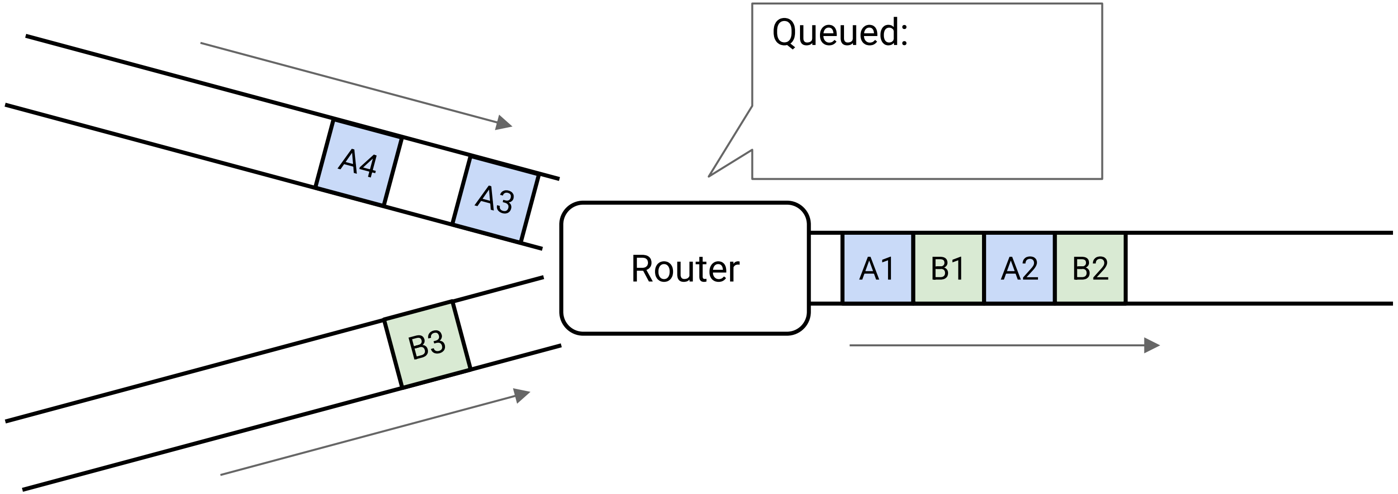

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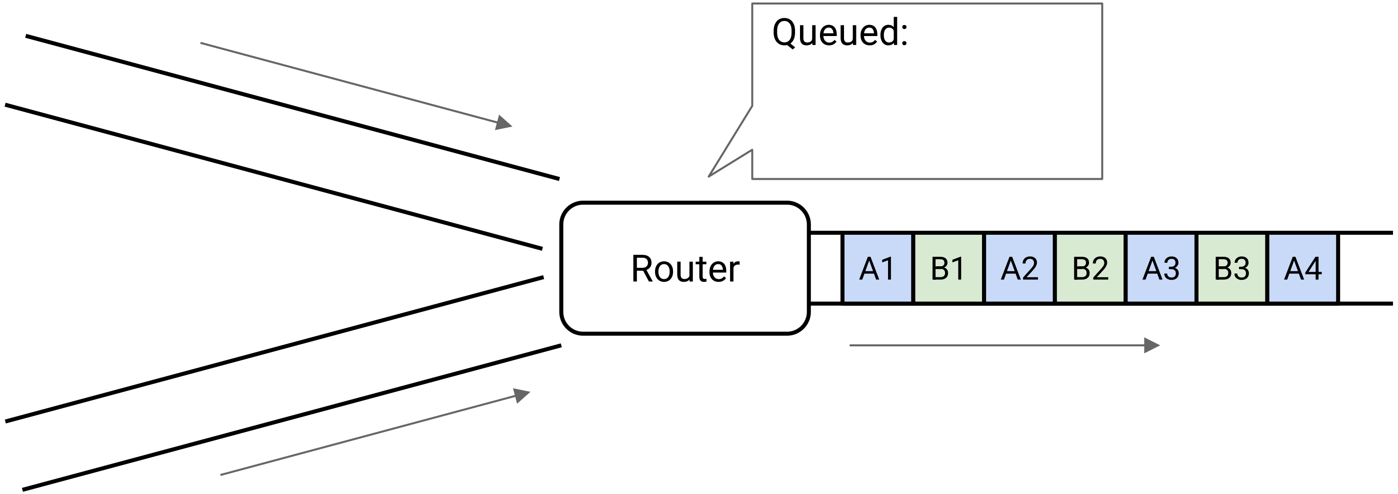
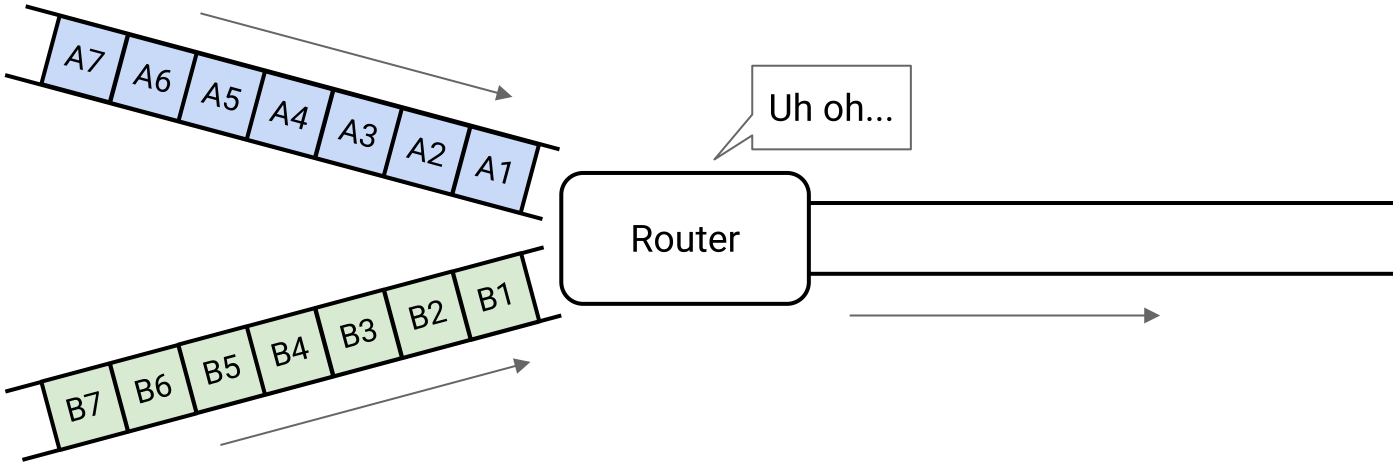


Persistent overload: Not enough capacity to handle the incoming packets!

- Queue won't help us. If the queue fills up, the router must drop packets.

How do we solve persistent overload?

- Operators can detect the overload and (manually) upgrade the link.
- Routers can tell the senders to slow down (throttling).



Life of a packet:

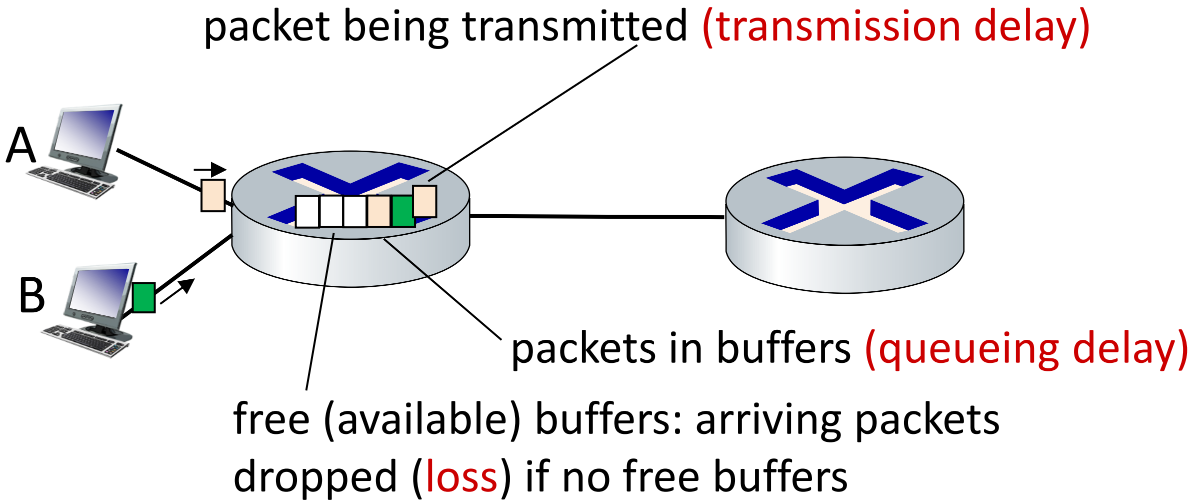
- Sender puts payload in a packet, adding headers.
- Packet travels along a link.
- Packet arrives at a router. Router forwards packet to the next hop.
    - Store-and-forward: A router can start forwarding a packet only after it has received all bytes of the packet.
    - Packet might be queued or dropped.
- Repeat the last step until:
    - Packet reaches destination.
    - Packet is dropped.

Packet Queuing

- How long does it take for your packet to travel through the network?
  - Packet delay = Transmission Delay + Propagation Delay + Queuing Delay
  - (There is also CPU processing delays, but they are typically very small and can be ignored. We focus on network delays only.)
- 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**

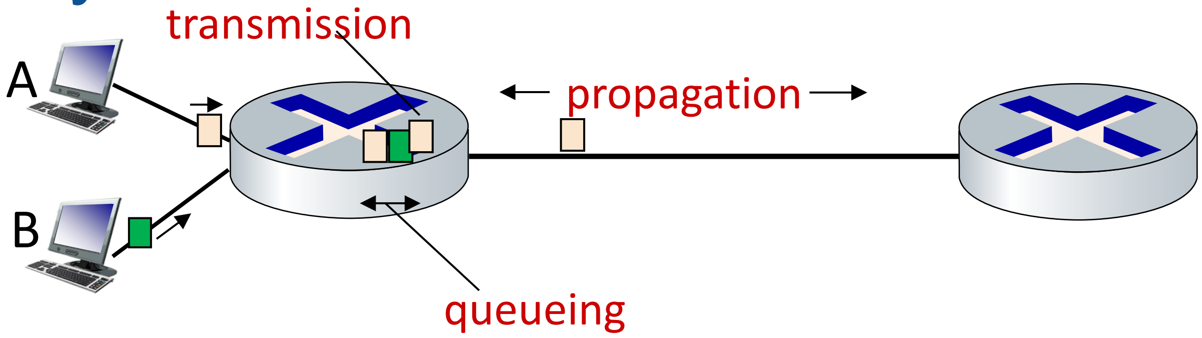
Packets queue in router buffers, waiting for turn for transmission

- queue length grows when arrival rate to link (temporarily) exceeds output link capacity
- packet *loss* occurs when memory to hold queued packets fills up



IMPORTANT

Packet delay: four sources



$$t_{total} = t_q + t_{tx} + t_{prop}$$

t_q: queueing delay
- time waiting at the output link for transmission
- depends on congestion level of router

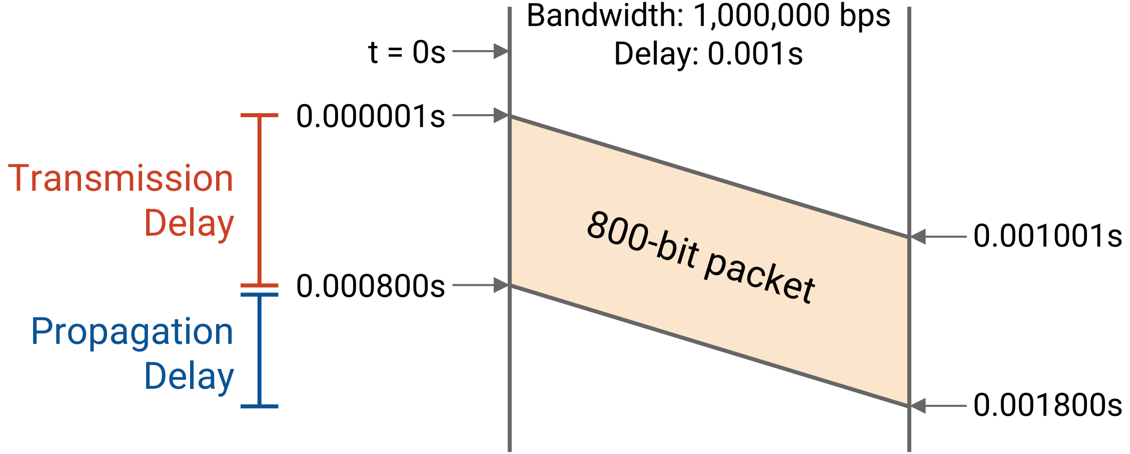
t_{tx}: transmission delay:
- L: packet length (bits)
- B: link bandwidth (bps)
- $t_{tx} = L/B$

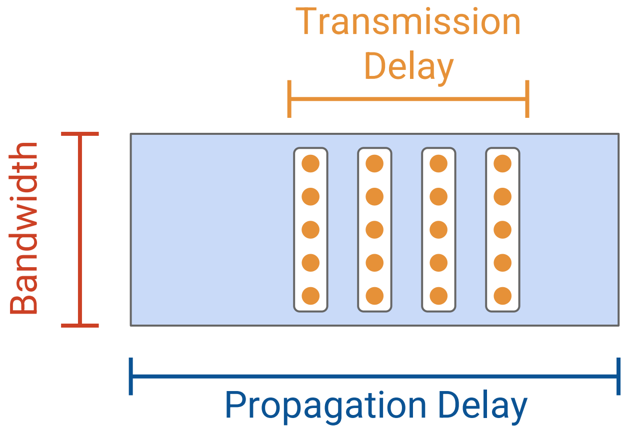
t_{prop}: propagation delay:
- d: distance of physical link
- s: propagation speed
- $t_{prop} = d/s$

- Packet Delay = (Packet Size / Bandwidth) + Propagation Delay + Queuing Delay

  (Packet Size / Bandwidth) = Transmission Delay

- Routers experience transient overload if packets arrive simultaneously.
  Solution: Packets get queued for later.
- Routers experience persistent overload if there's insufficient capacity.
  Queue gets full, and packets get dropped.





Capacity = Delay × Bandwidth