Bandwidth and Propagation Delay

Lecture 3, Spring 2026

Links

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

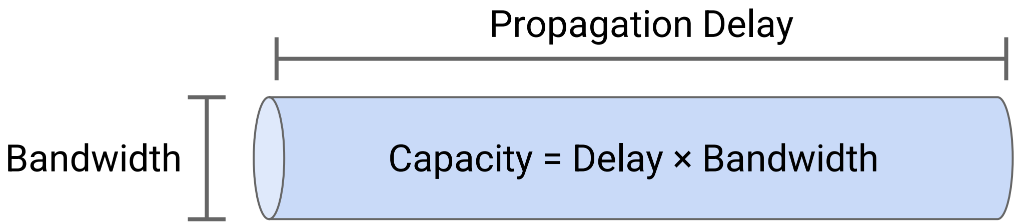
Brief Preview of the Semester

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.)*

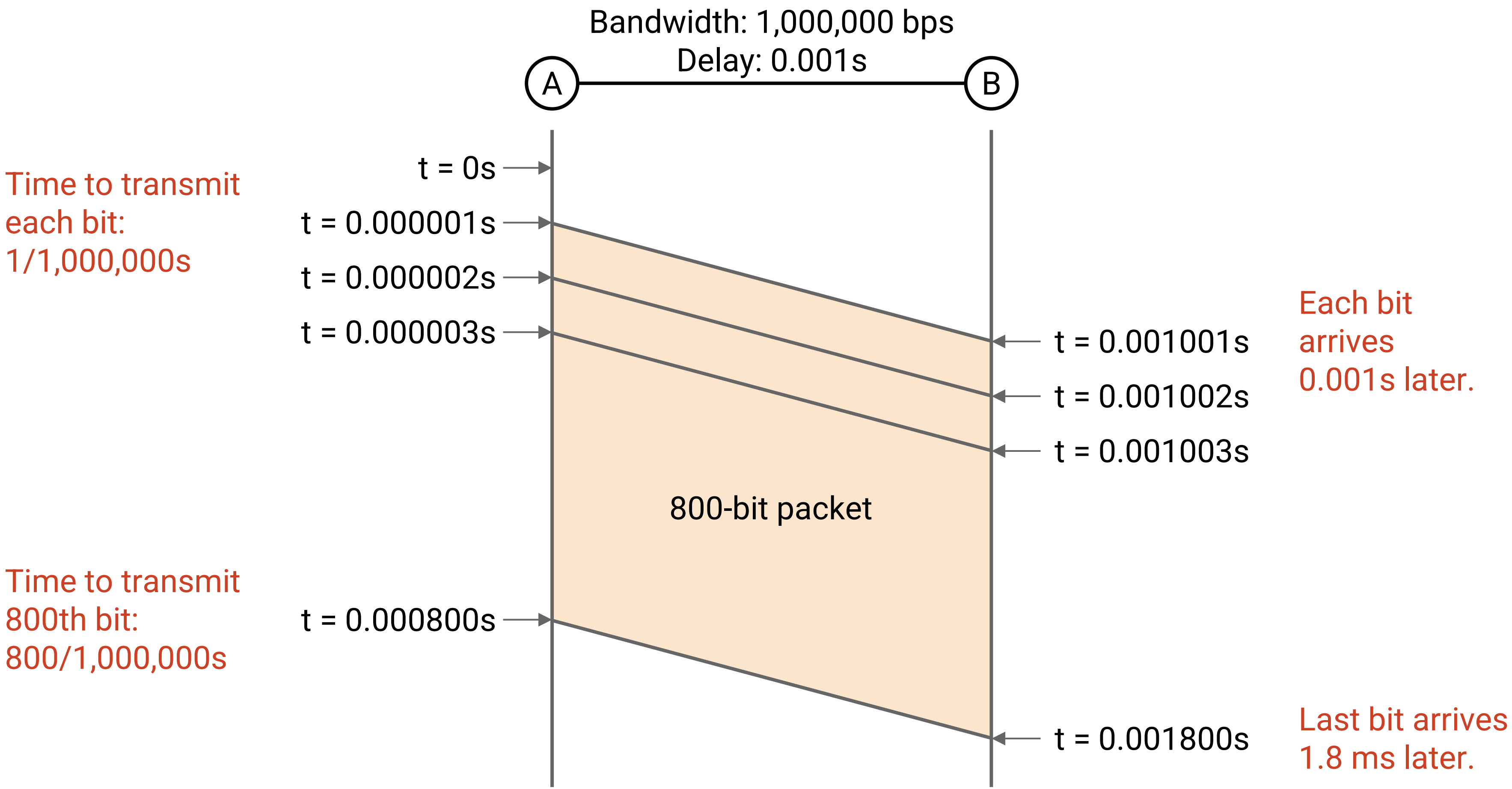
Note: We measure in **bits** per second, not **bytes**!

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.

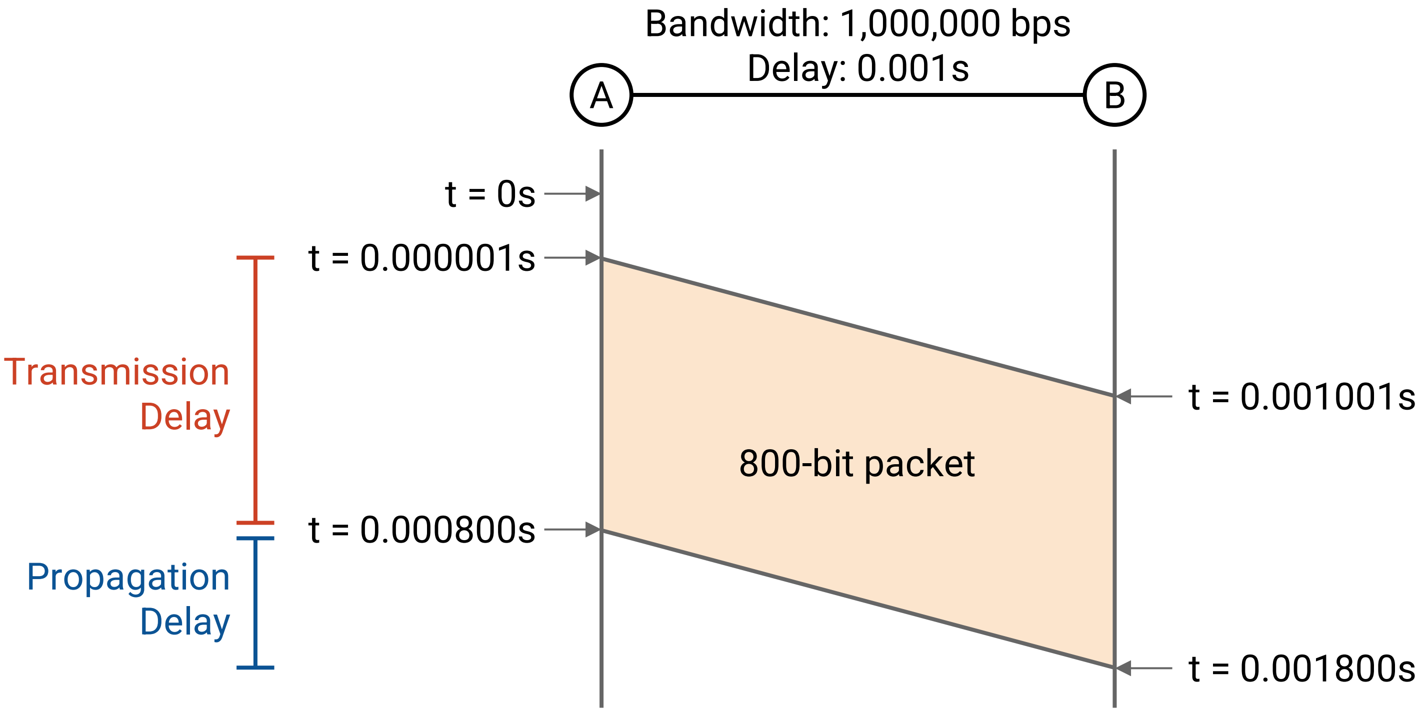
Measuring Packet Delay with Timing Diagrams



Measuring Packet Delay with Timing Diagrams

Packet Delay = Transmission Delay + Propagation Delay

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



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 ms with Link 1. ~1 ms with Link 2.
- 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.
- For large packet, transmission delay dominates.

Pipe Diagrams

Lecture 3, CS 168, Spring 2026

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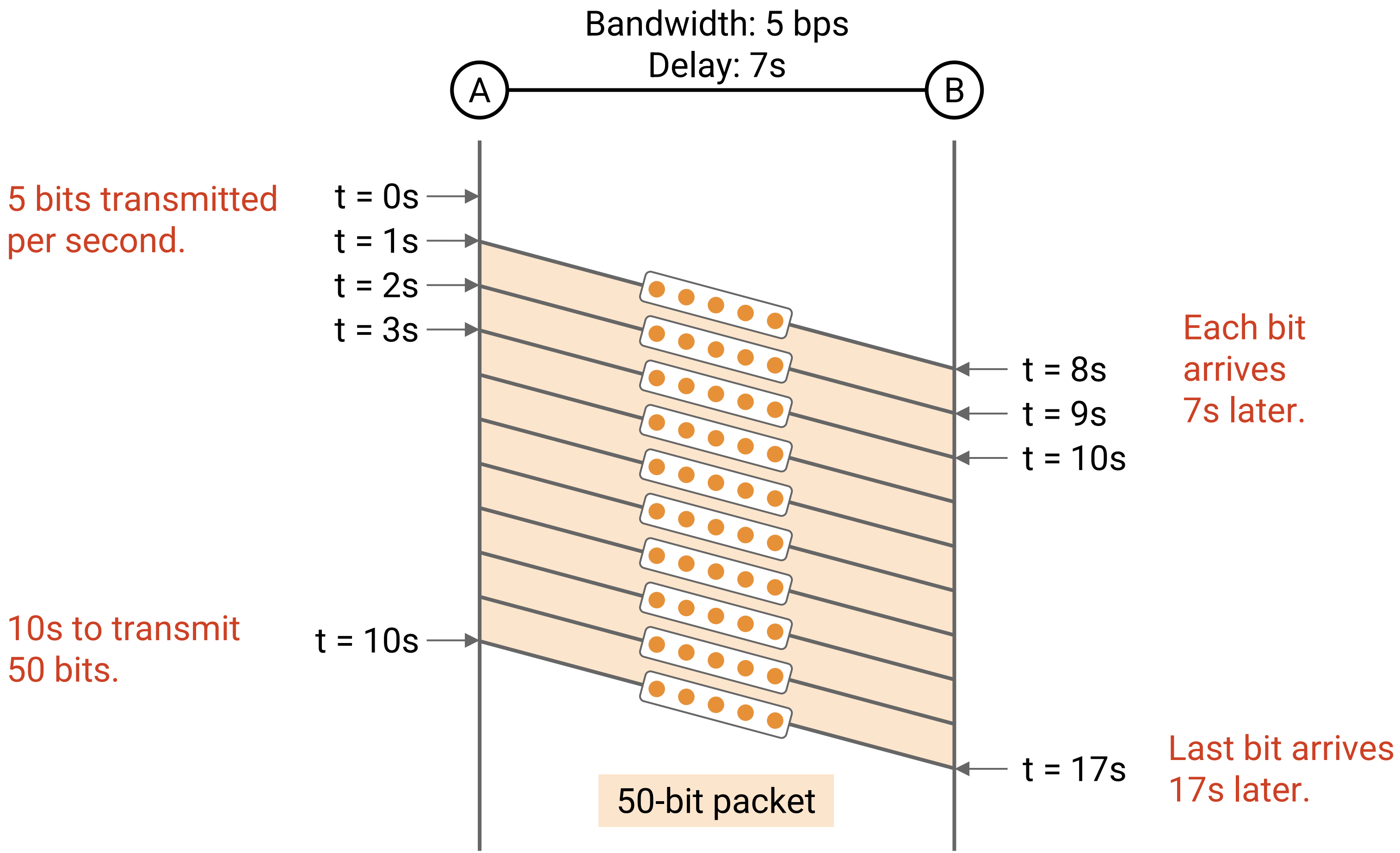
Brief Preview of the Semester

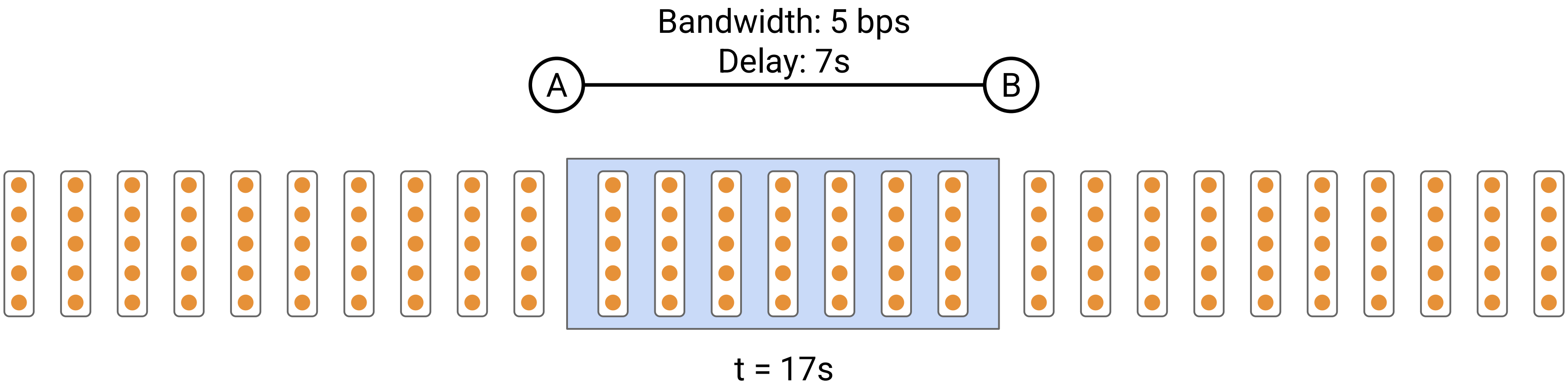
Timing Diagrams and Pipe Diagrams



Timing Diagrams and Pipe Diagrams

The pipe diagram is an alternate view of the link.

- Shows the bits on the link at a frozen moment in time.

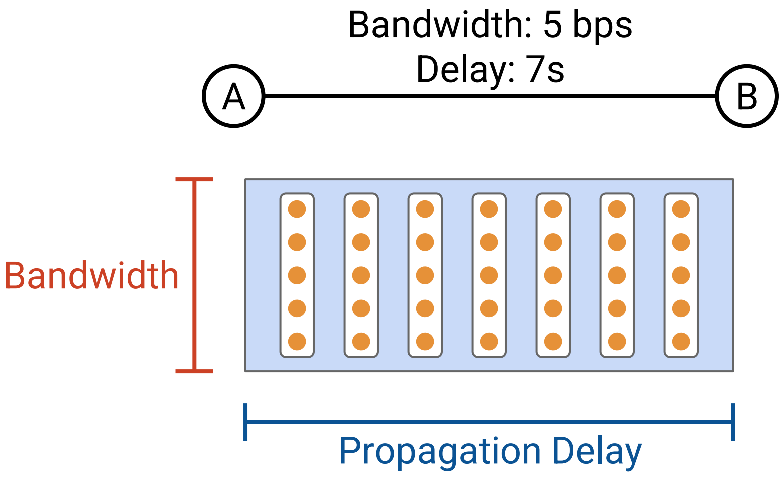


(This diagram needs to be viewed with animation to make sense.)

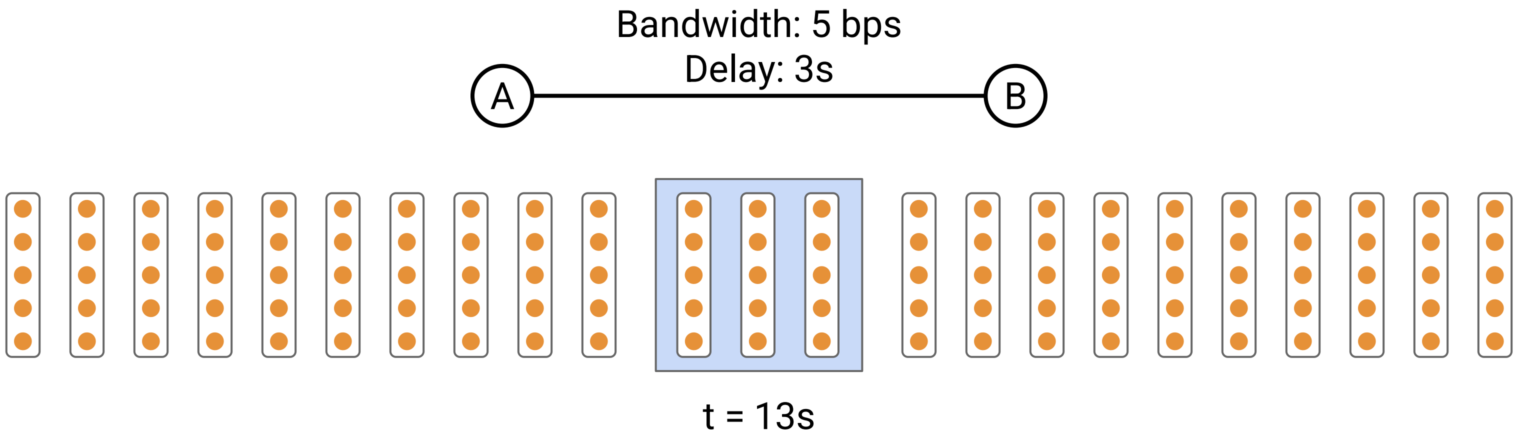
Pipe Diagrams

Pipe diagram shows the bits on the link at a frozen 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 fit in the pipe at a given instant.



Shorter propagation delay: Pipe length is shorter.



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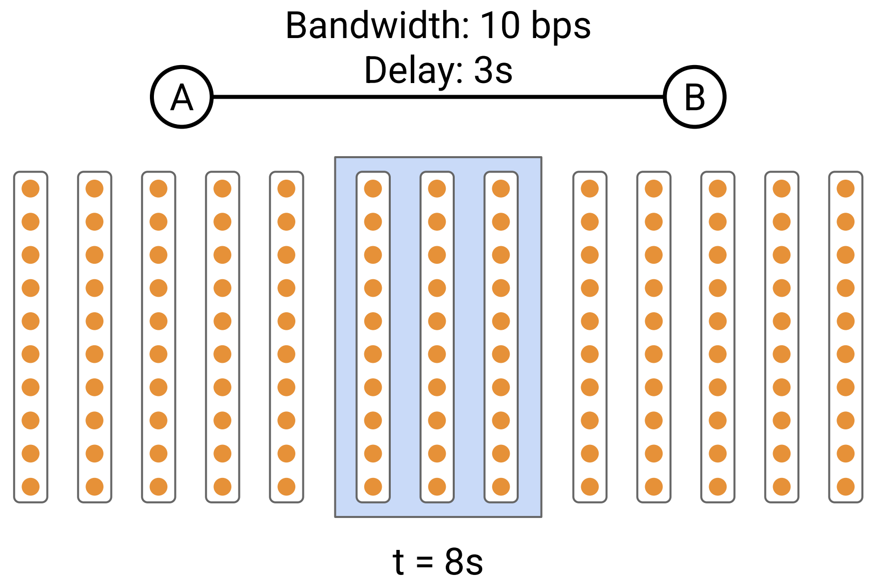
Pipe Diagrams

Higher bandwidth: Pipe height is taller.



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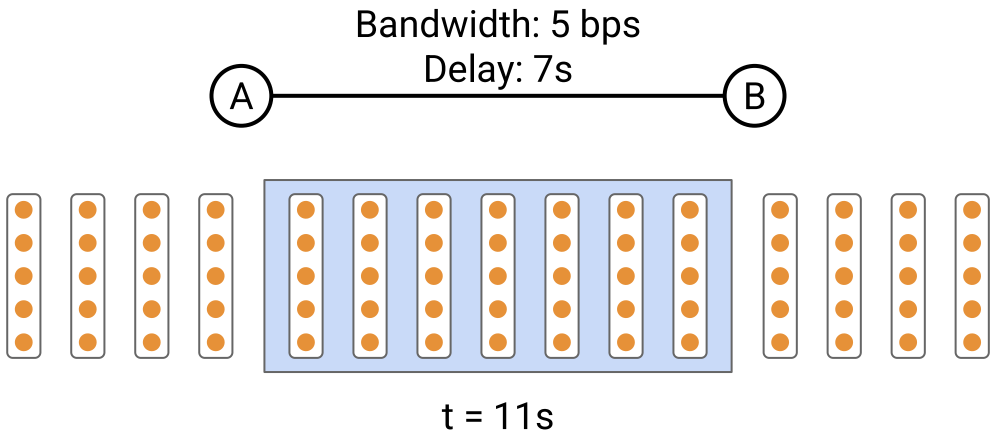
Pipe Diagrams – Transmission Delay

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

- How long it takes to put all the bits in the pipe.
- More bandwidth = taller pipe = more bits in pipe per unit time
  = narrower packet in pipe.



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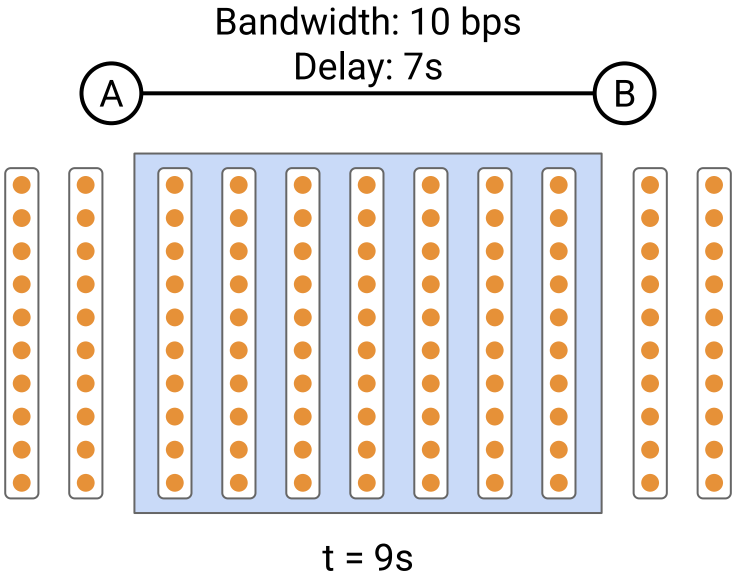

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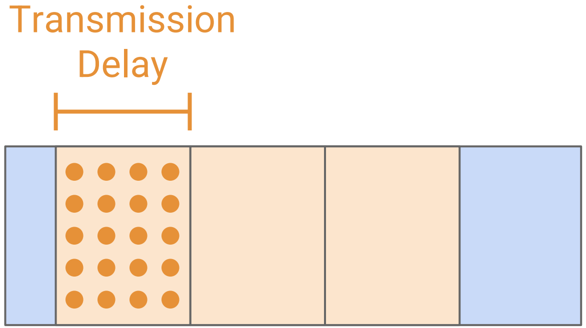
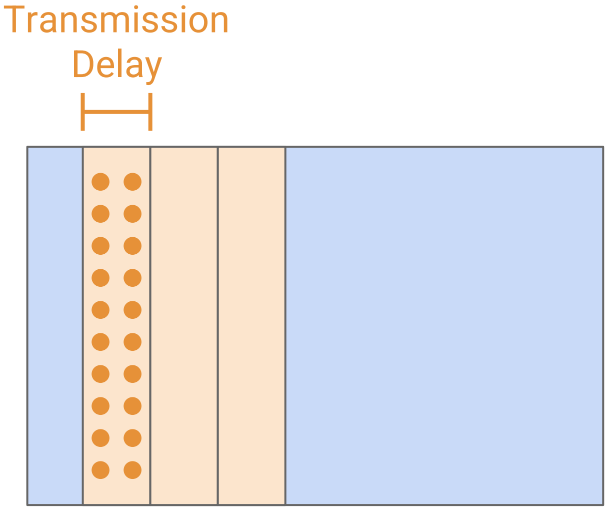




Overloaded Links

Lecture 3, CS 168, Spring 2026

Links

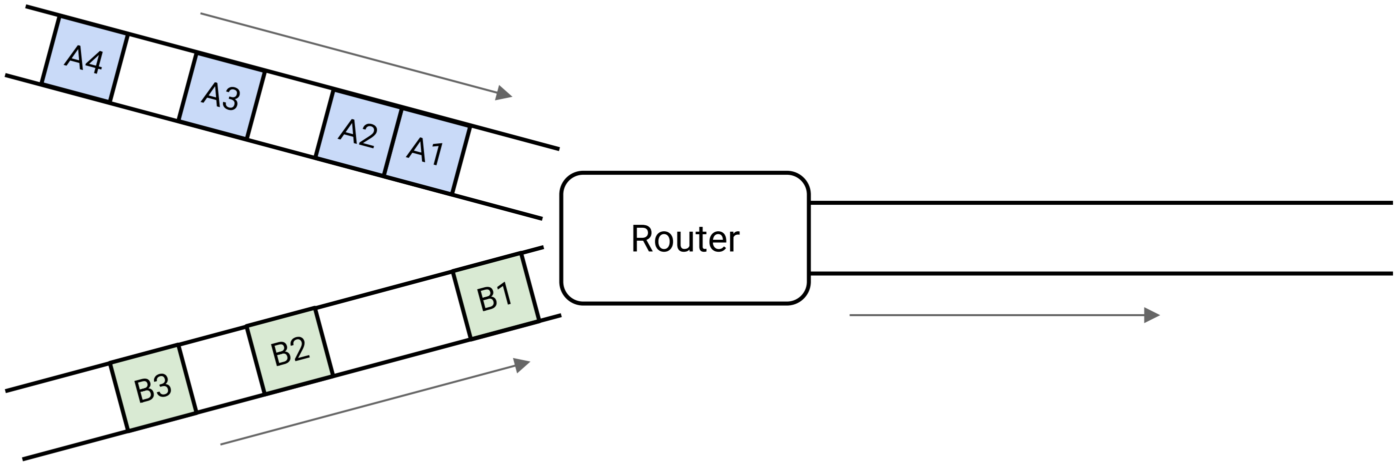
- Bandwidth and Propagation Delay
- Pipe Diagrams
- **Overloaded Links**

Brief Preview of the Semester

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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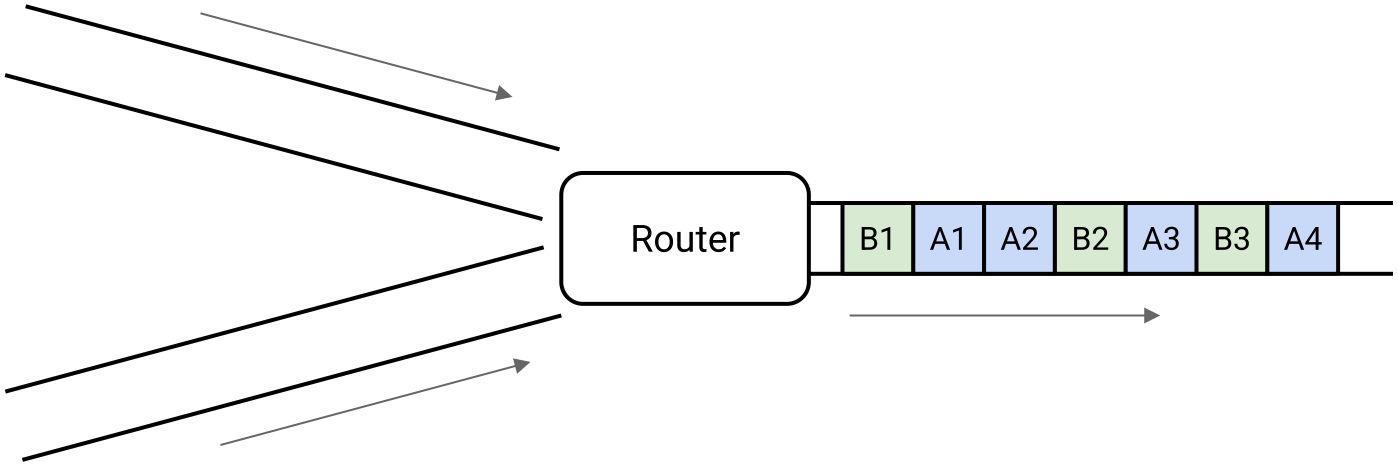
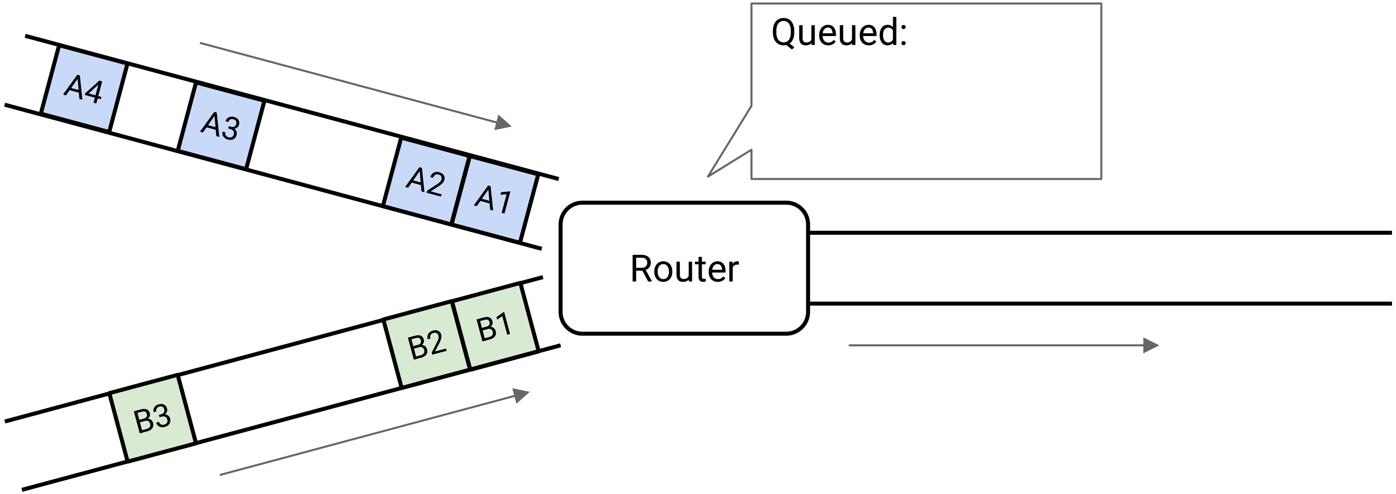


Transient Overload

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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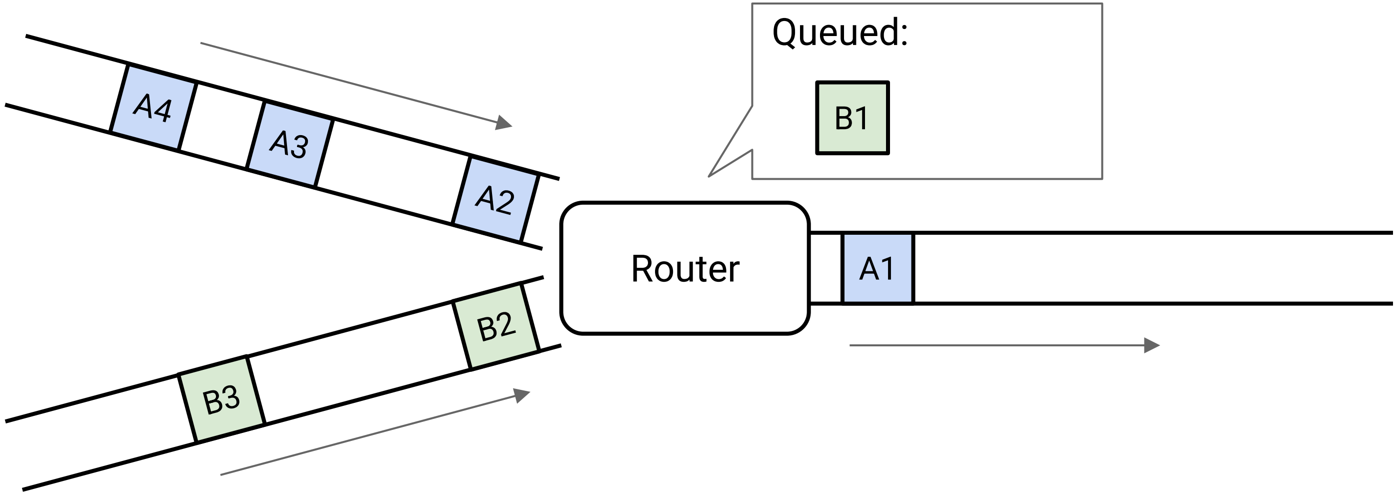

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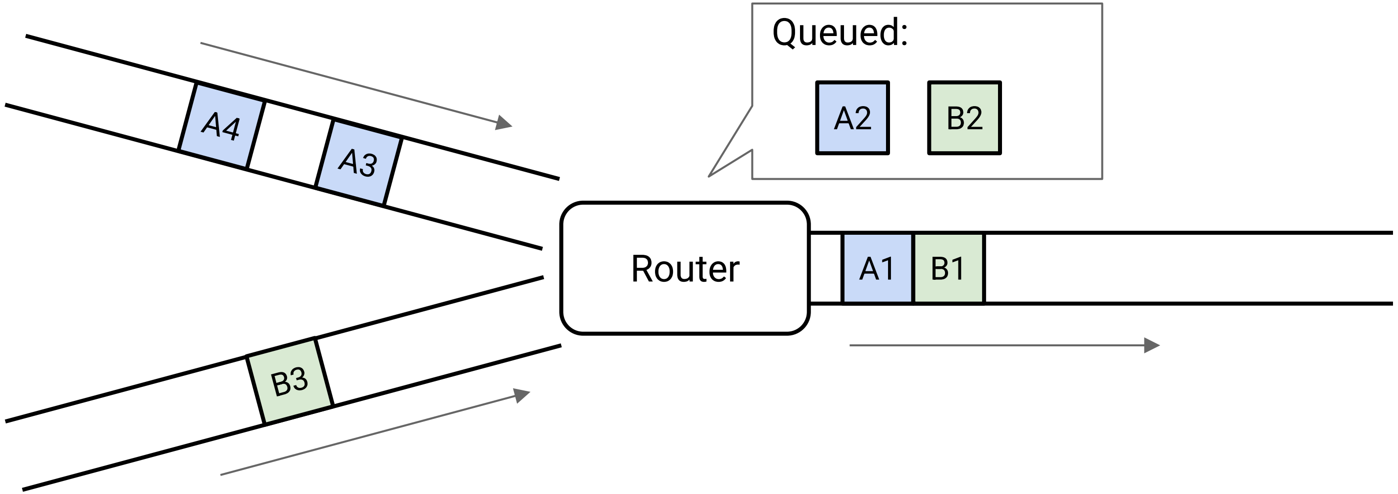

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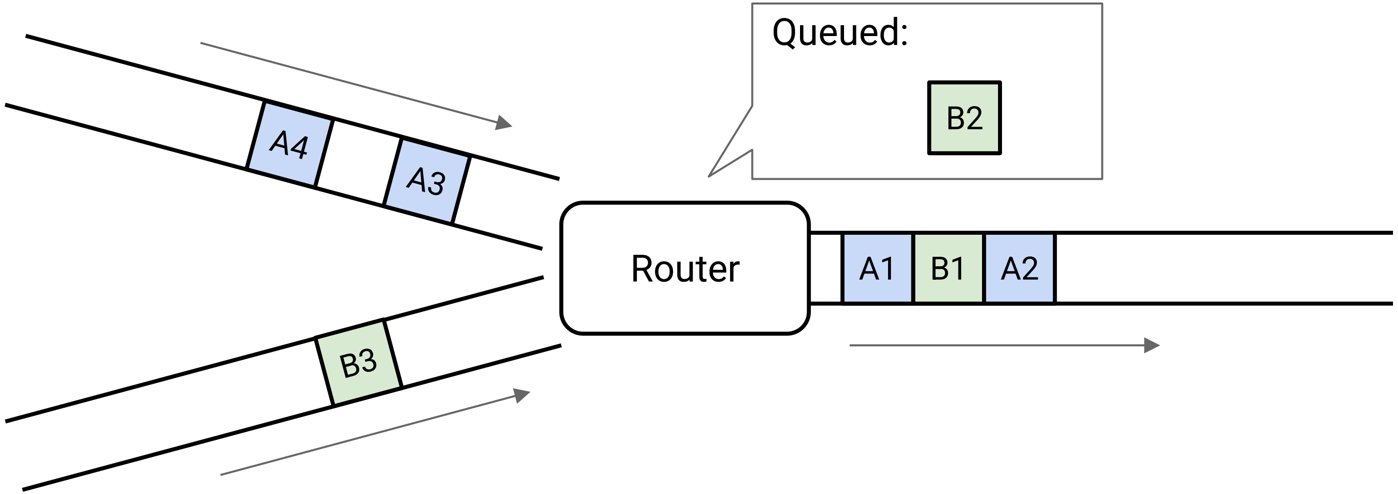

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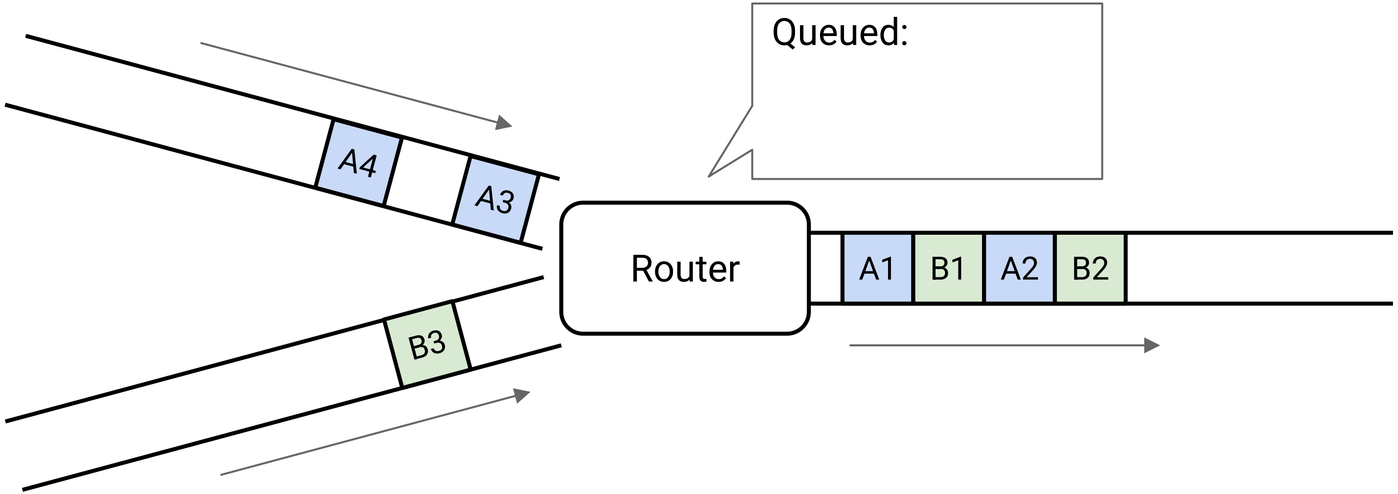

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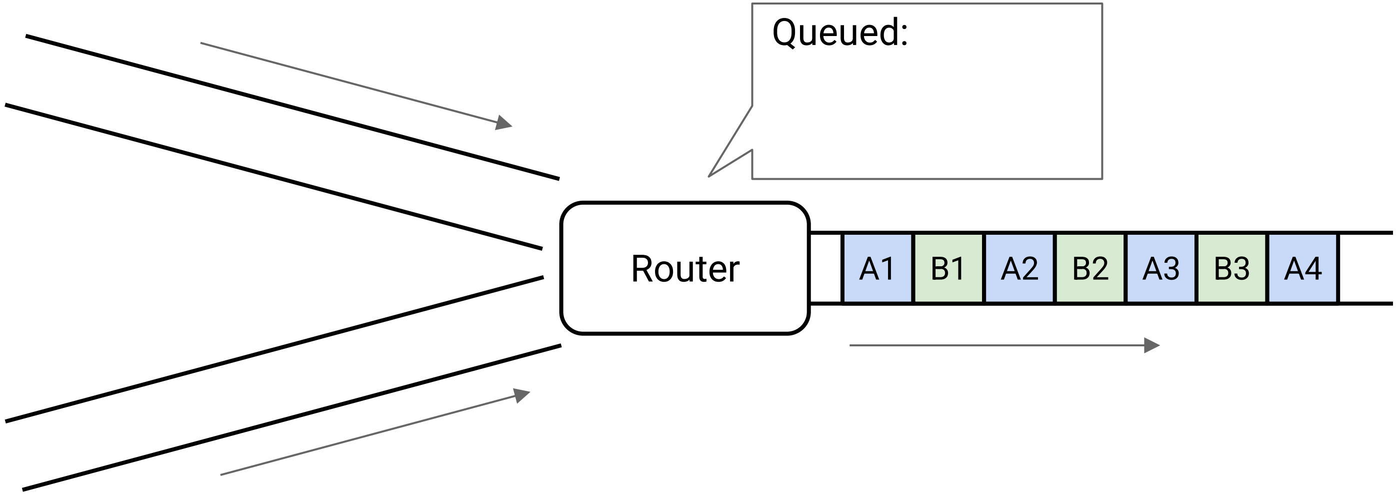


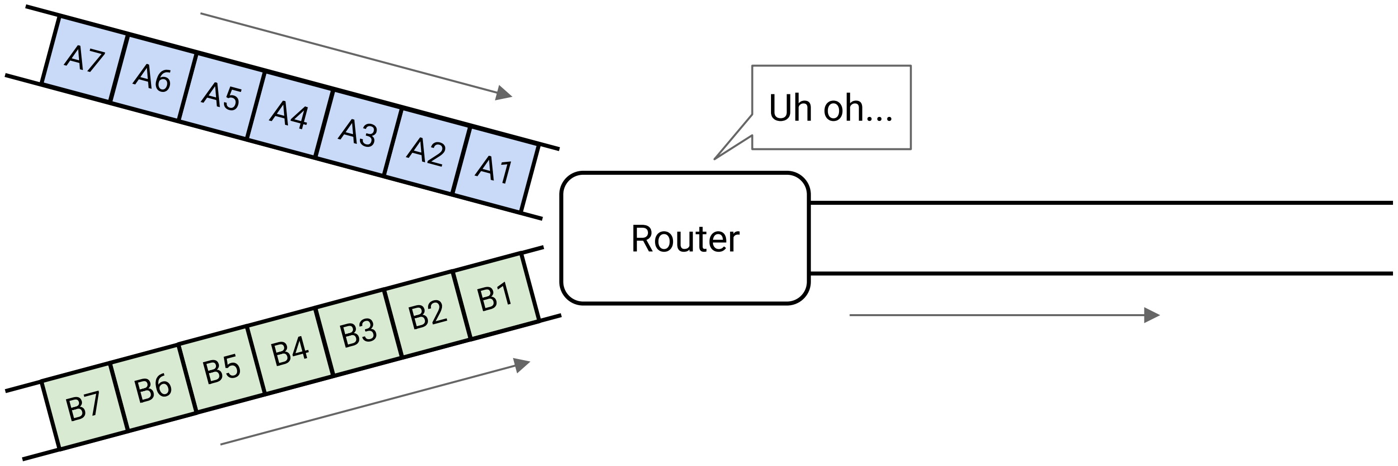
Packet Switching at Routers

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.



Packet Queuing and Life of a Packet

Queues introduce extra delay.

- Packet delay = Transmission Delay + Propagation Delay + Queuing Delay.

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.
  - Packet might be queued or dropped.
- Repeat the last step until:
  - Packet reaches destination.
  - Packet is dropped.

Brief Preview of the Semester

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Brief Preview of the Semester

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Lectures 1–3: Networking Principles.

- Layering and headers.
- Design principles.
- Links, life of a packet.
- Project 1: Traceroute.

Lectures 4–9: Routing (Layer 3).

- Routing: How do routers know where to forward packets?
- Addressing: How do we address end hosts?
- How do you build an industrial-strength router in hardware?
- Project 2: Routing.

Brief Preview of the Semester

Lectures 10–13: Reliability (Layer 4).

- TCP: How do end hosts communicate reliably?
- Congestion control: How do we ensure end hosts don't overload the links?
- Project 3: Transport.

Lectures 14–15: Applications (Layer 7).

- DNS: How do we map names to addresses?
- HTTP: How do we build applications on top of the network?

Lectures 16–17: End-to-End Picture.

- ARP and DHCP: What happens when you join the network for the first time?
- NAT: How do we make sure there's enough addresses for everybody?
- TLS: How do we secure network connections against attackers?

Brief Preview of the Semester

Lectures 18–21: Datacenters.

- How do we build a network to connect servers in high-performance datacenters?
- SDN: Can we centralize control to improve performance?
- Host networking, RDMA: How can we optimize performance at the end hosts?

Lectures 22–23: Beyond Client-Server.

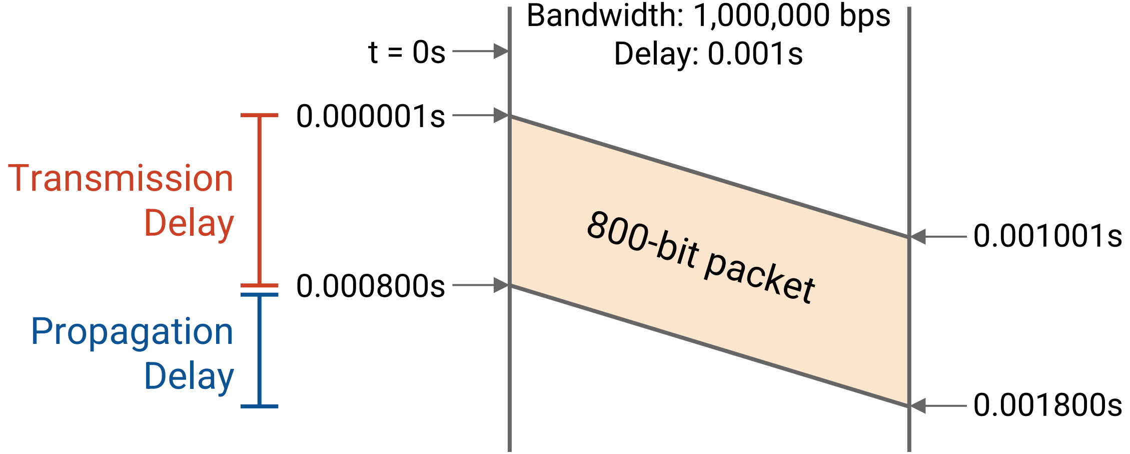
- Multicast: How do we support group communication (e.g. Google Docs)?
- Collectives: How do we design networks to support AI training?

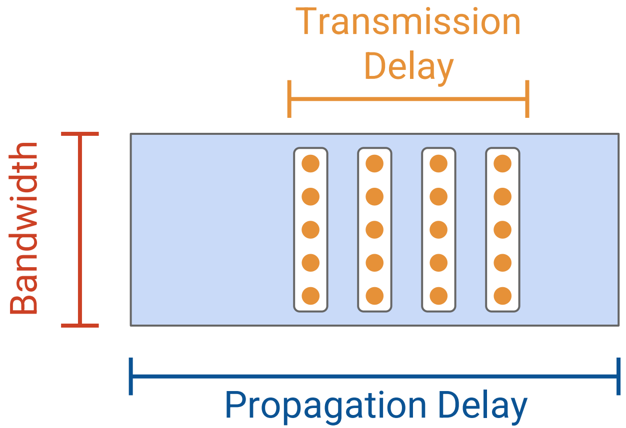
Lectures 24–25: Wireless.

- How do we design wireless communication at Layers 1 and 2?
- How do we design cellular networks?

Summary: Links

- Packet Delay = $\underbrace{\text{(Packet Size / Bandwidth)}}_{\text{Transmission Delay}}$ + Propagation Delay + Queuing 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