

# **EECS 489**

# **Computer Networks**

**Fall 2019**

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*Material with thanks to Aditya Akella, Sugih Jamin, Philip Levis, Sylvia Ratnasamy, Peter Steenkiste, and many other colleagues.*

# Agenda

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- Overview of the basics
  - How is the network shared?
  - How do we evaluate a network?
  - What is a network made of?

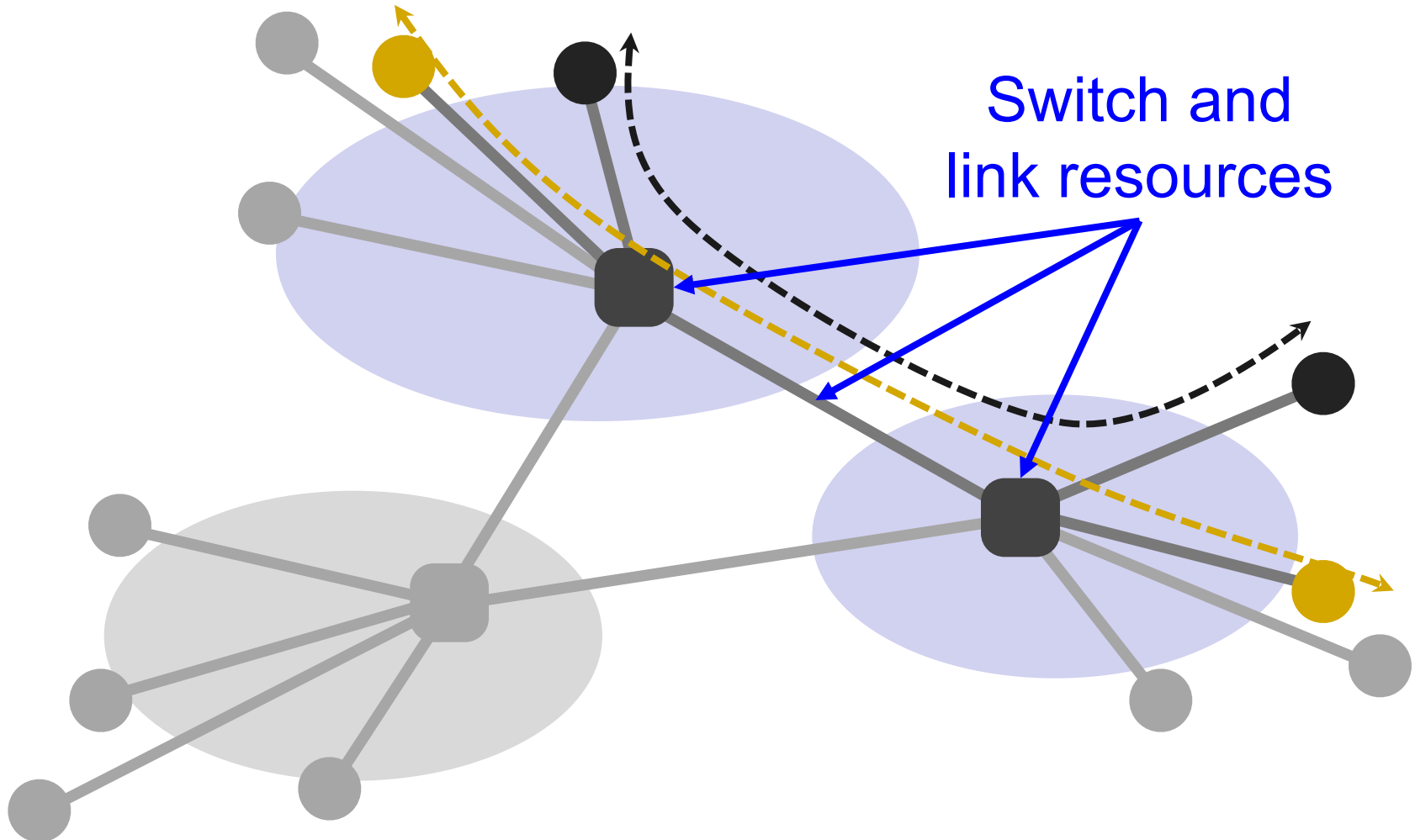
# Switched networks

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- End-systems and networks connected by switches instead of directly connecting them
  - Why?
- Allows us to **scale**
  - For example, directly connecting  $N$  nodes to each other would require  $N^2$  links!

# When do we need to share the network?

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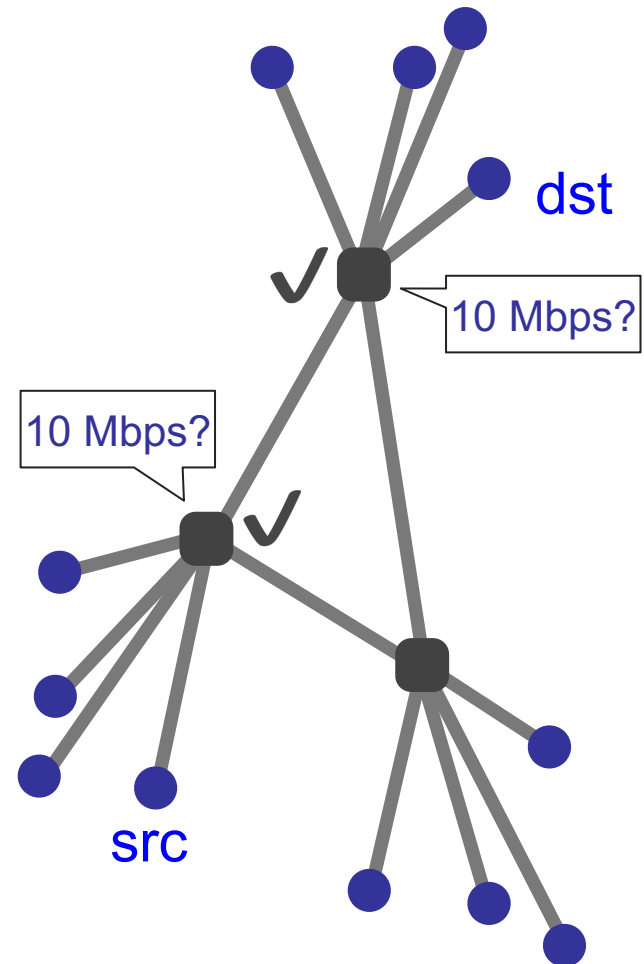
# Two ways to share switched networks

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- Circuit switching
  - Resource **reserved** per connection
  - Admission control: per connection
- Packet switching via statistical multiplexing
  - Packets treated independently, **on-demand**
  - Admission control: per packet

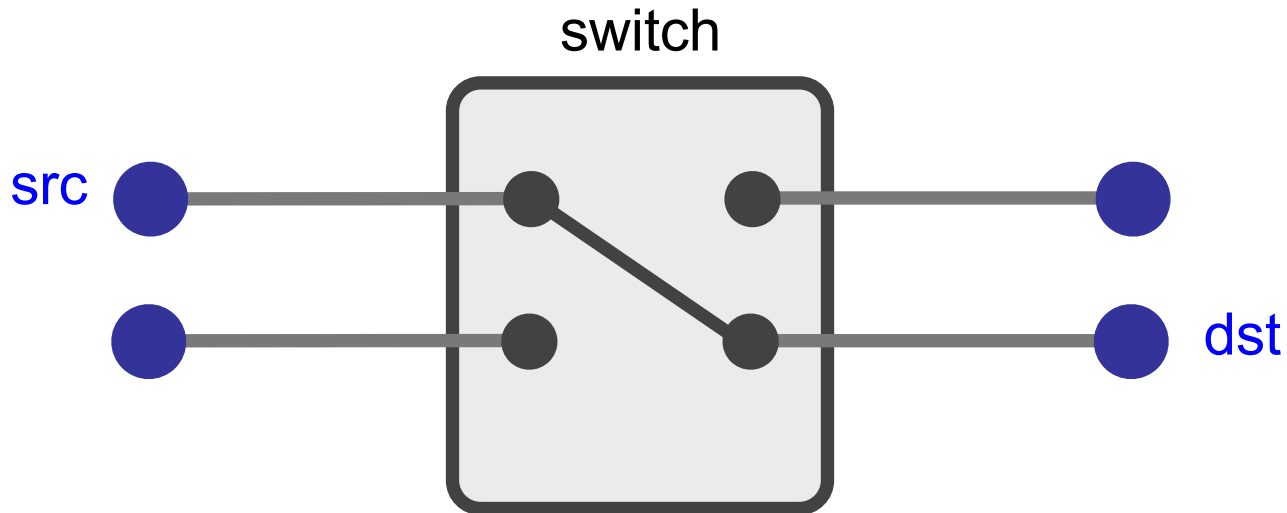
# Circuit switching

1. **src** sends reservation request to **dst**
2. Switches create circuit *after* admission control
3. **src** sends data
4. **src** sends teardown request



# Circuit switching

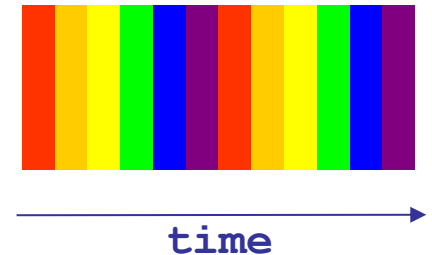
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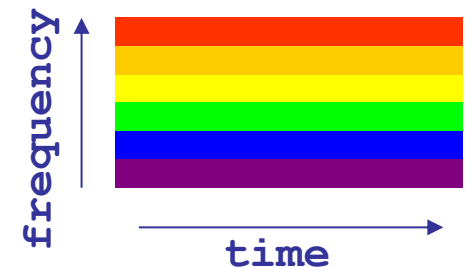
- Reservation establishes a “circuit” within a switch

# Many kinds of circuits

- Time division multiplexing
  - divide time in time slots
  - separate time slot per circuit



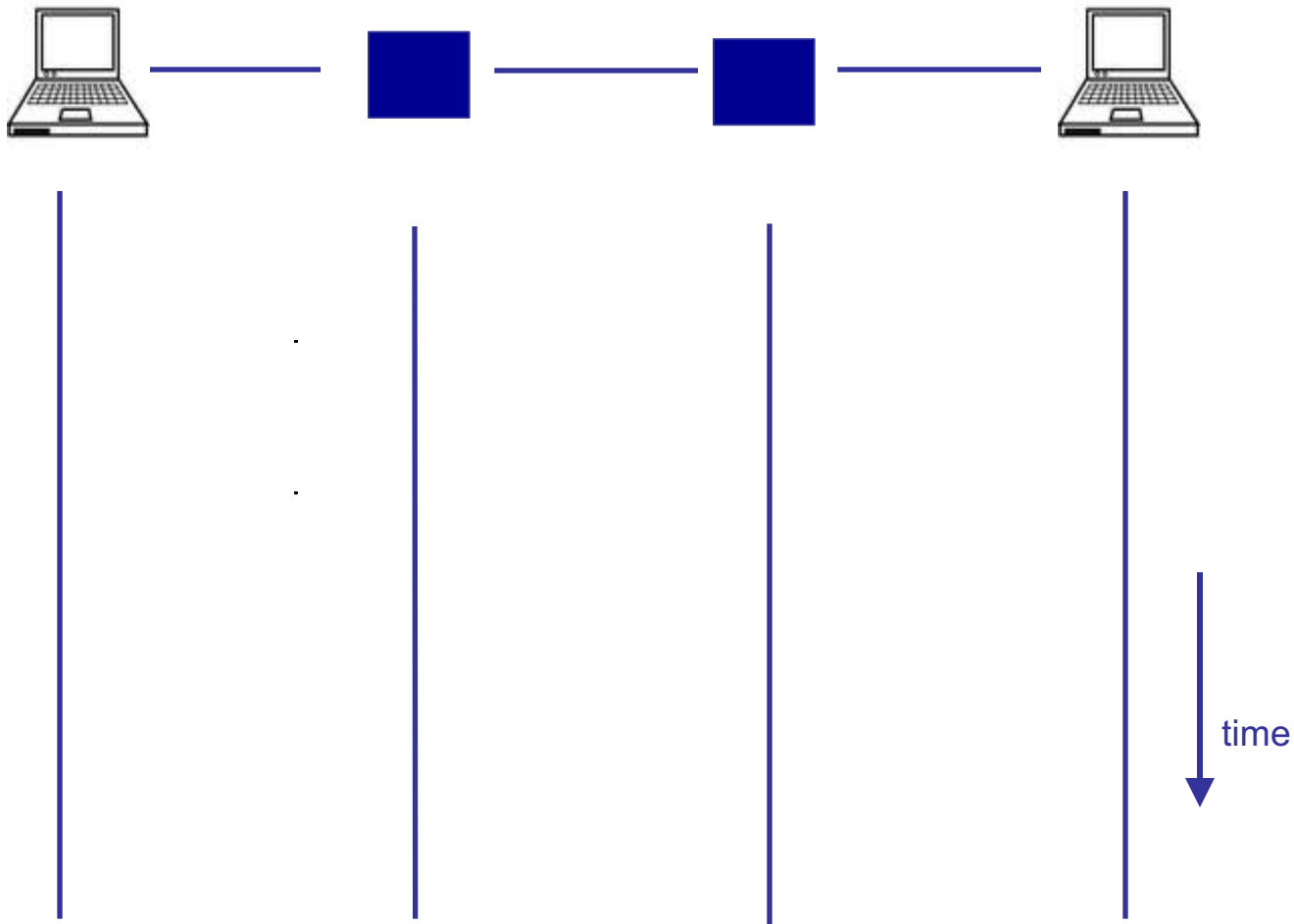
- Frequency division multiplexing
  - divide frequency spectrum in frequency bands
  - separate frequency band per circuit



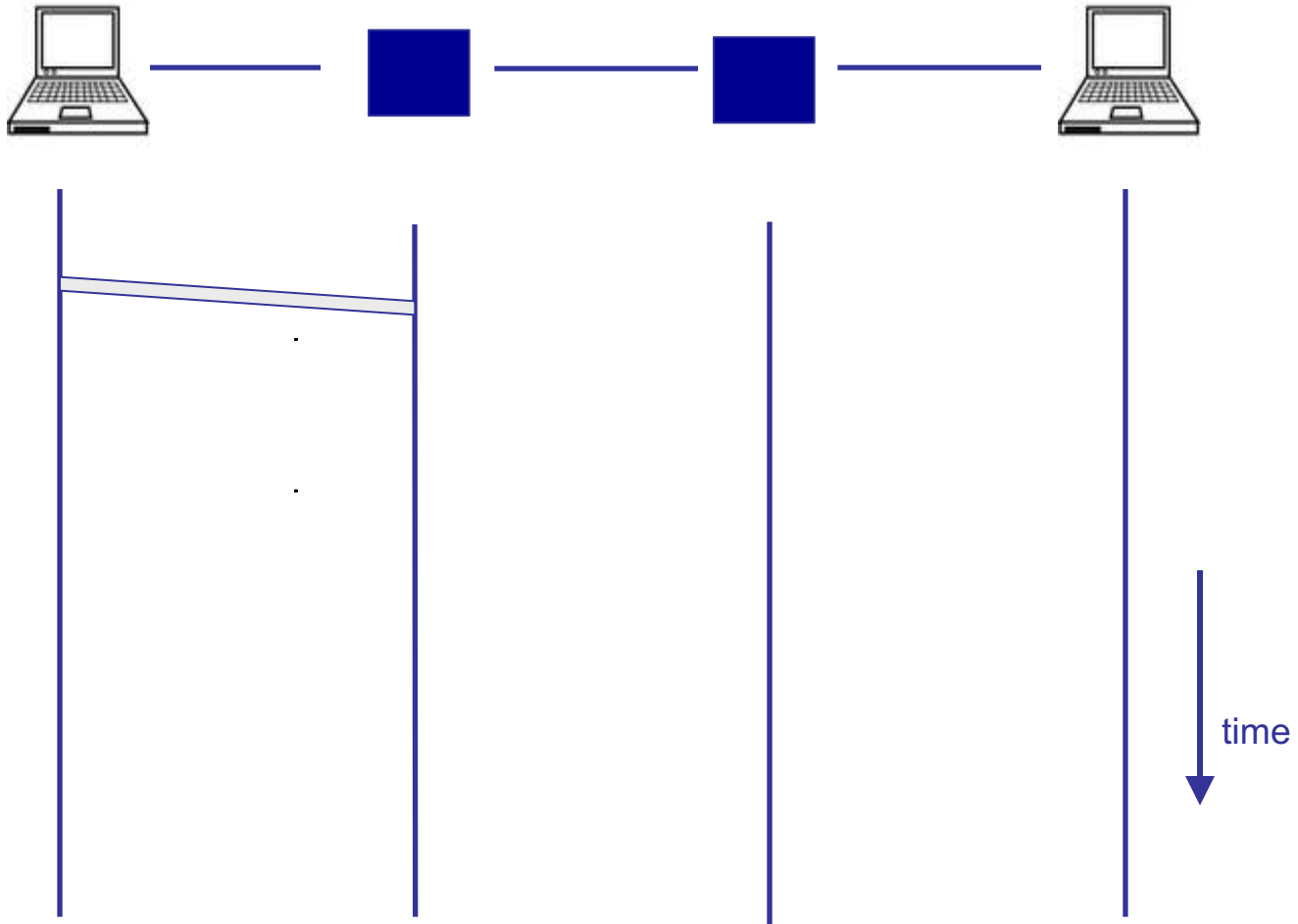


# Timing in circuit switching

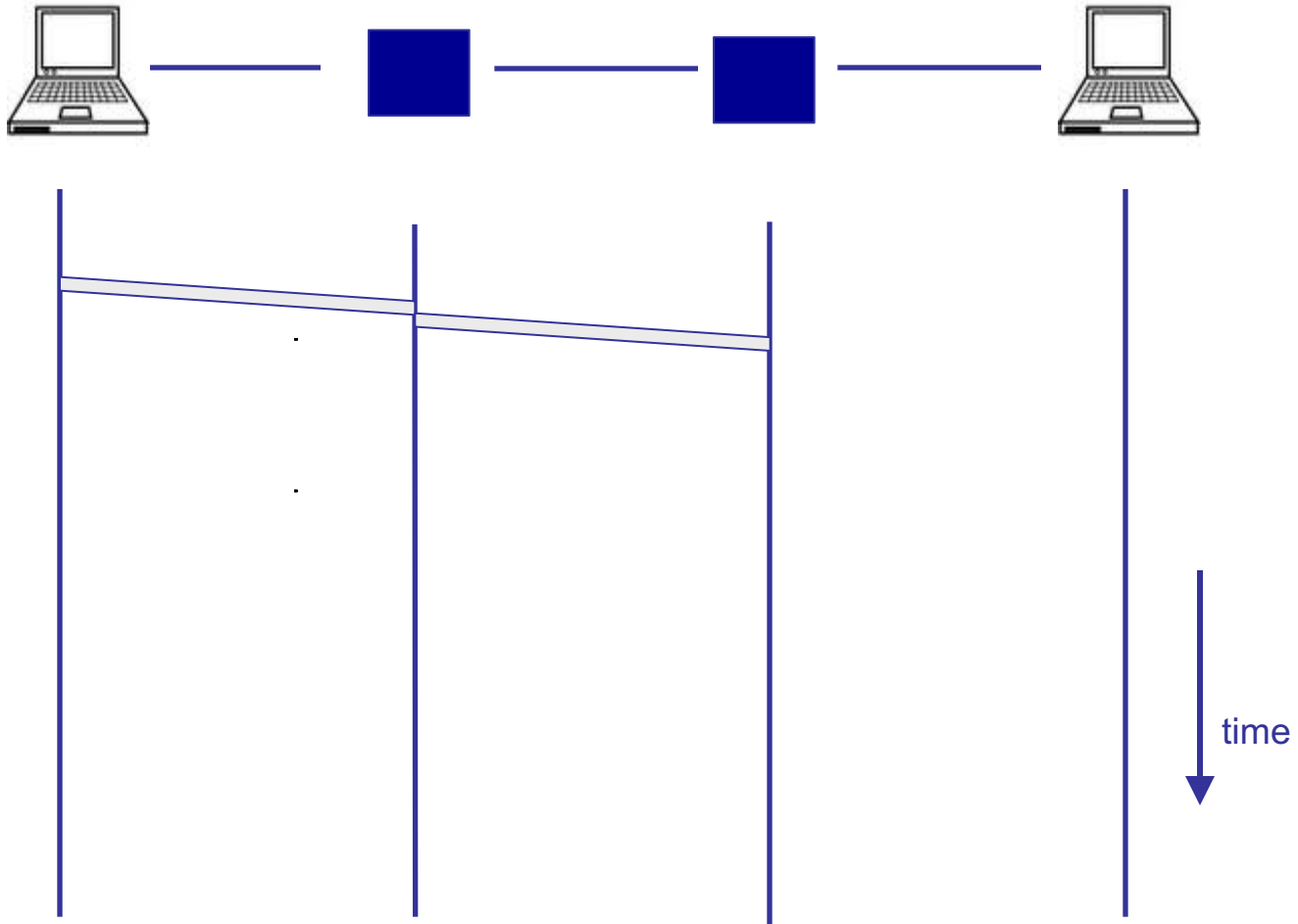
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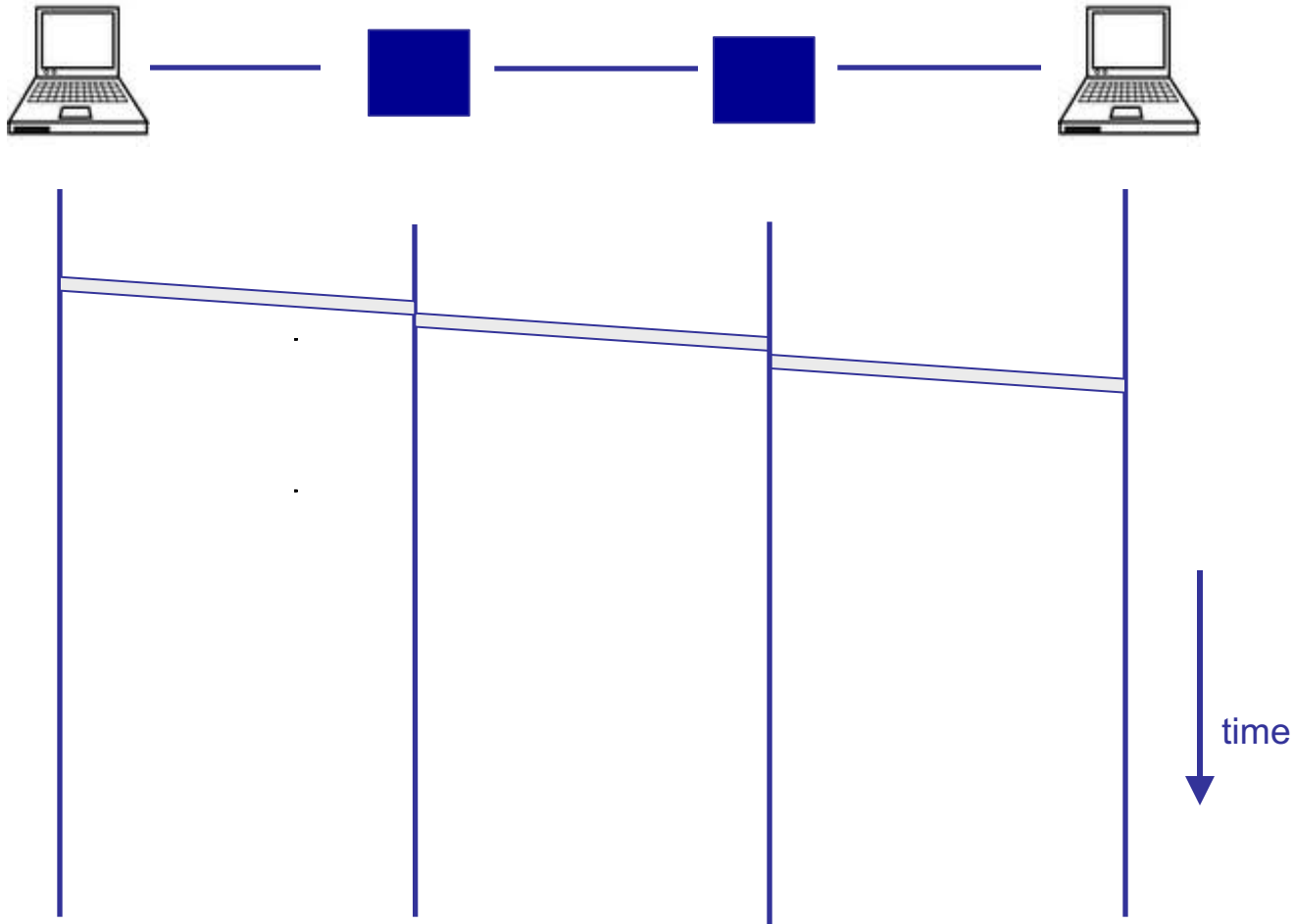
# Timing in circuit switching



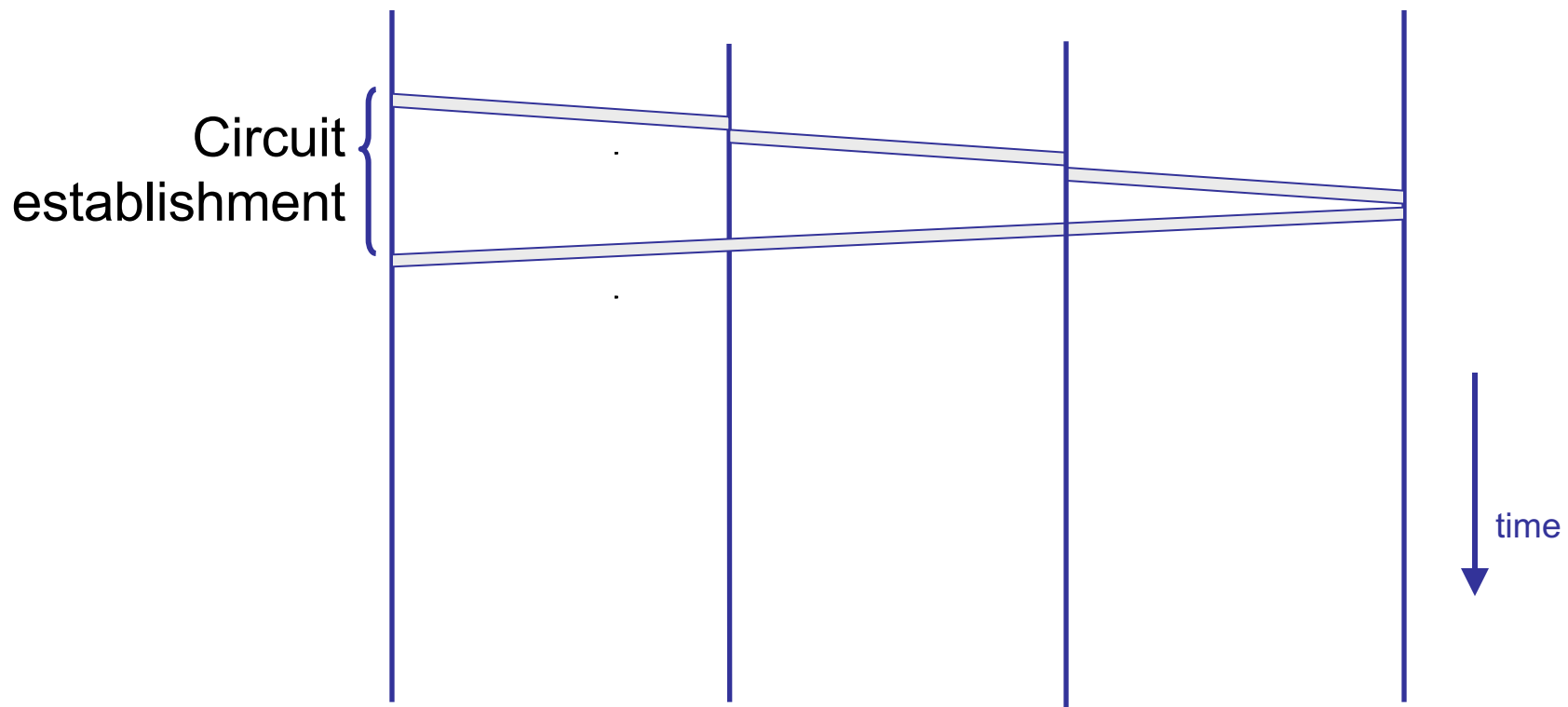
# Timing in circuit switching



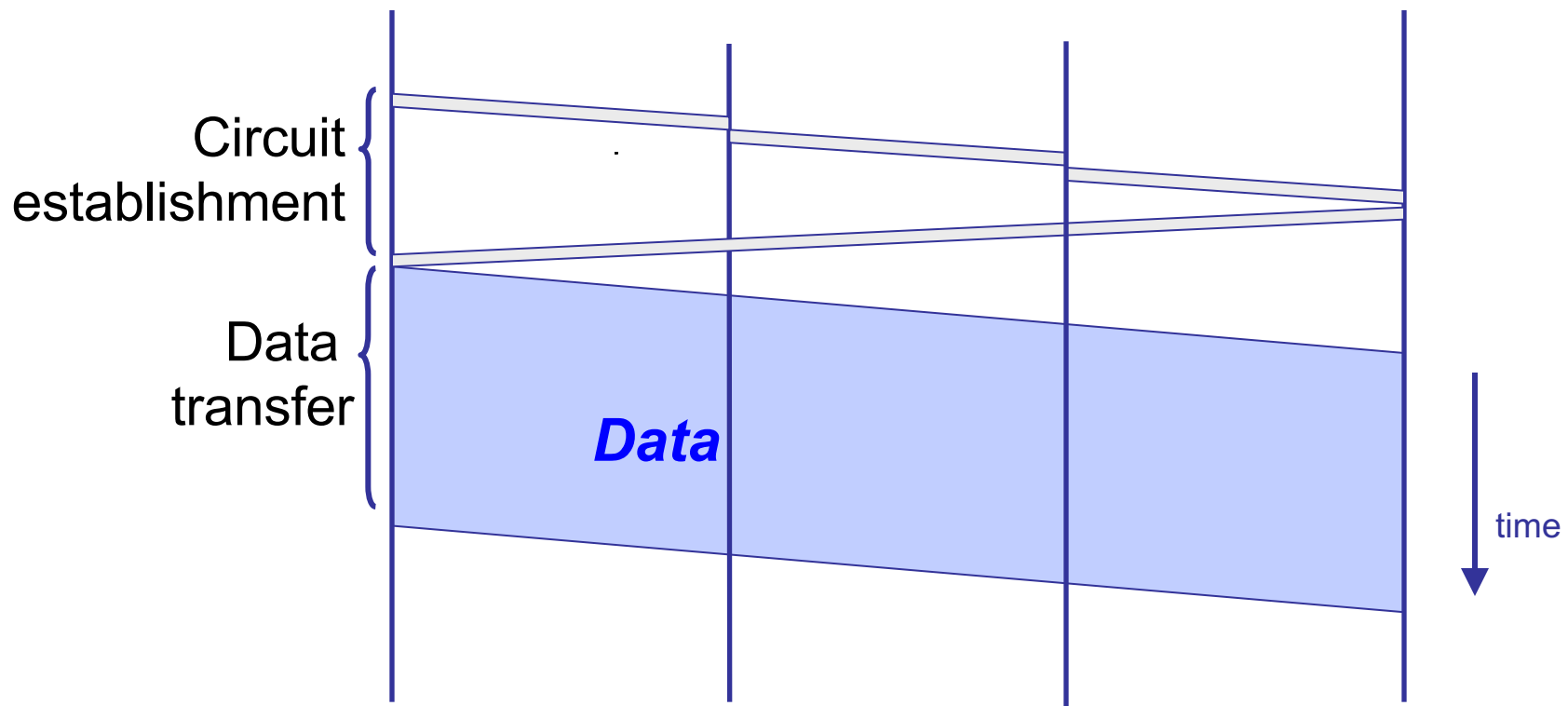
# Timing in circuit switching



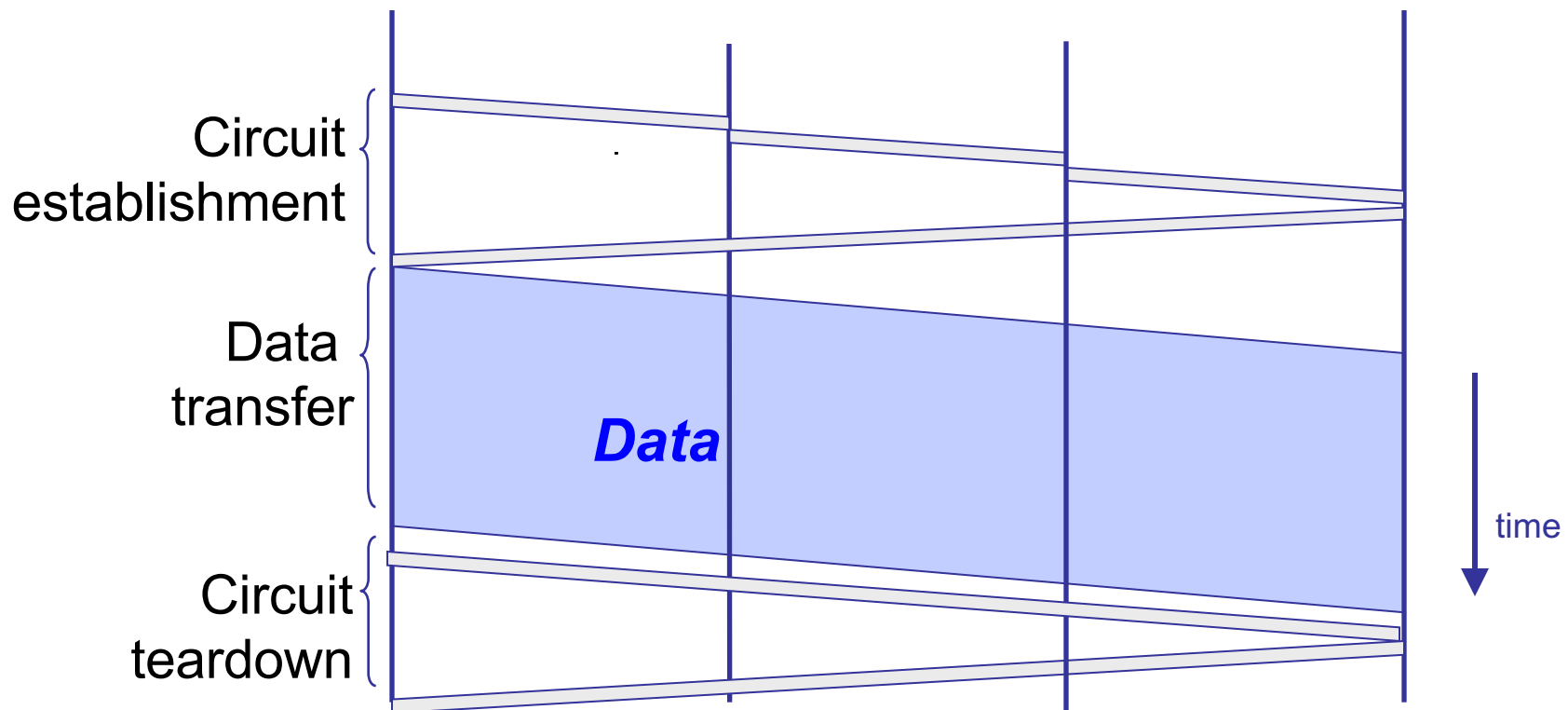
# Timing in circuit switching



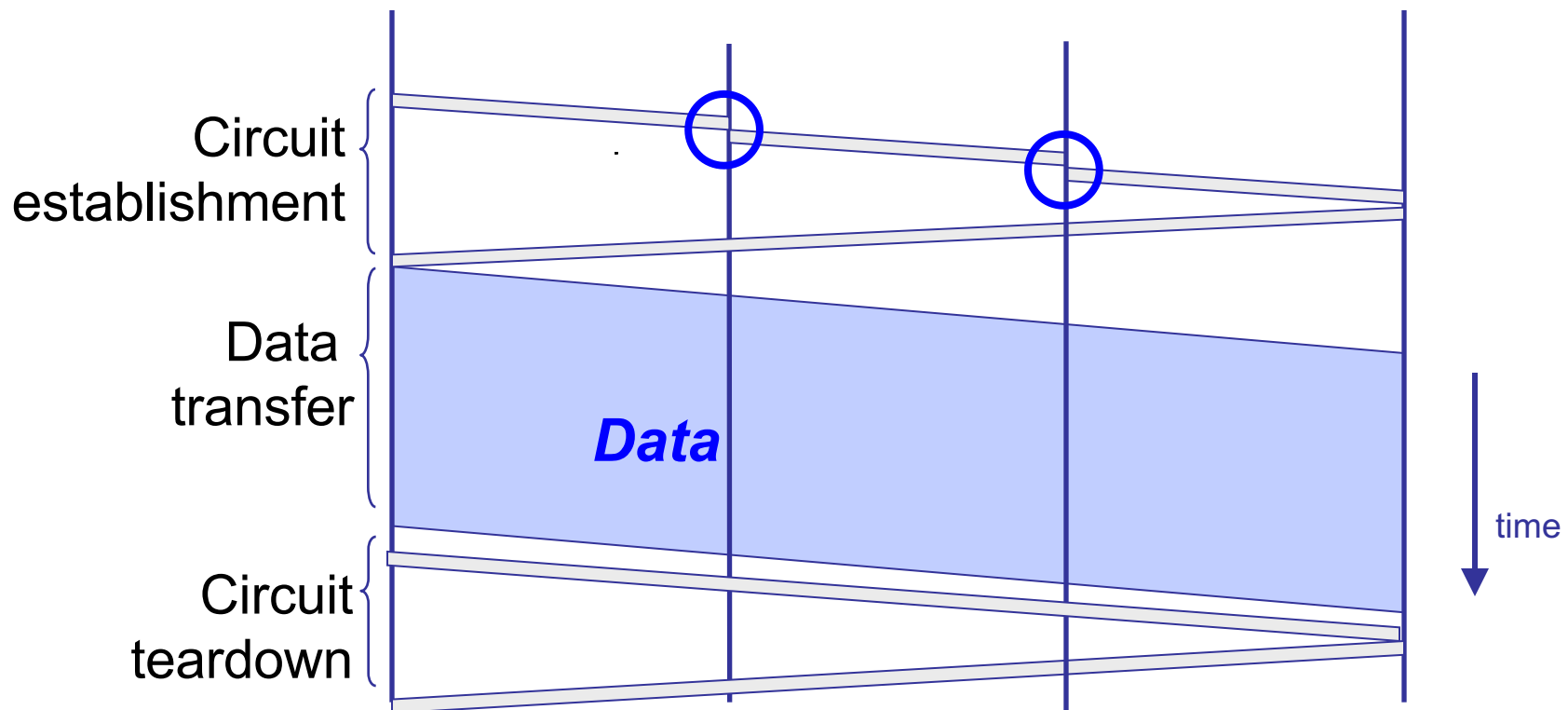
# Timing in circuit switching



# Timing in circuit switching

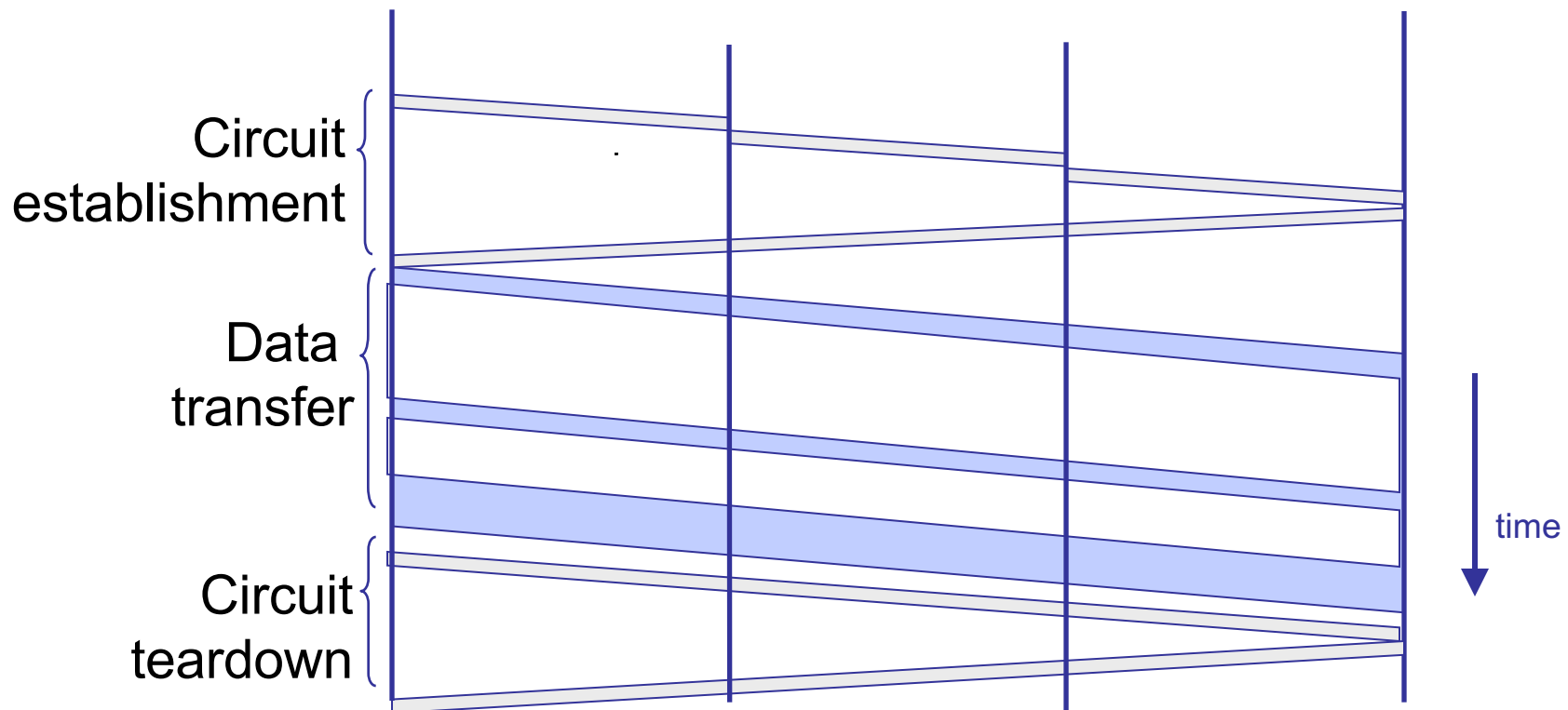


# Why the delays?

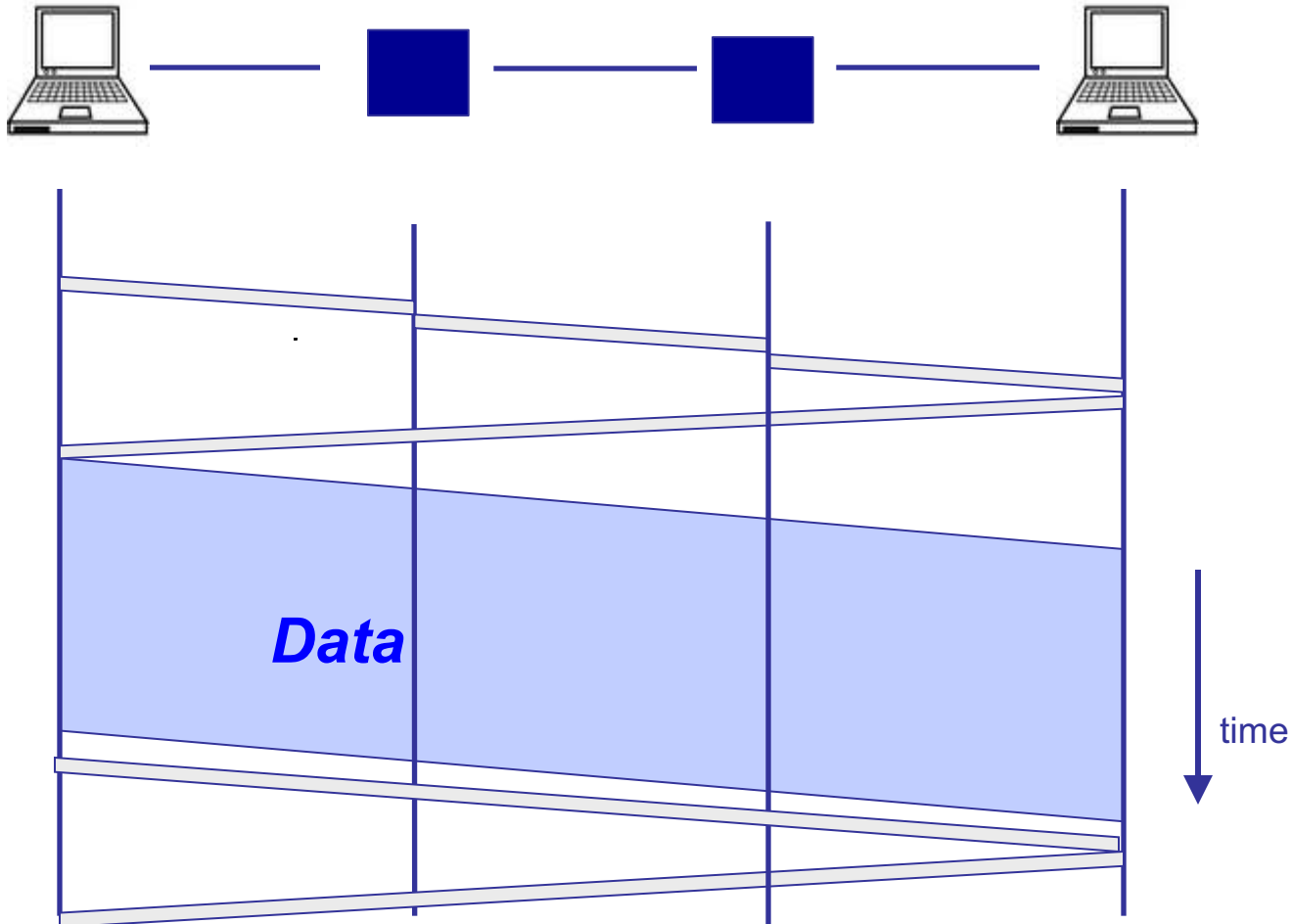




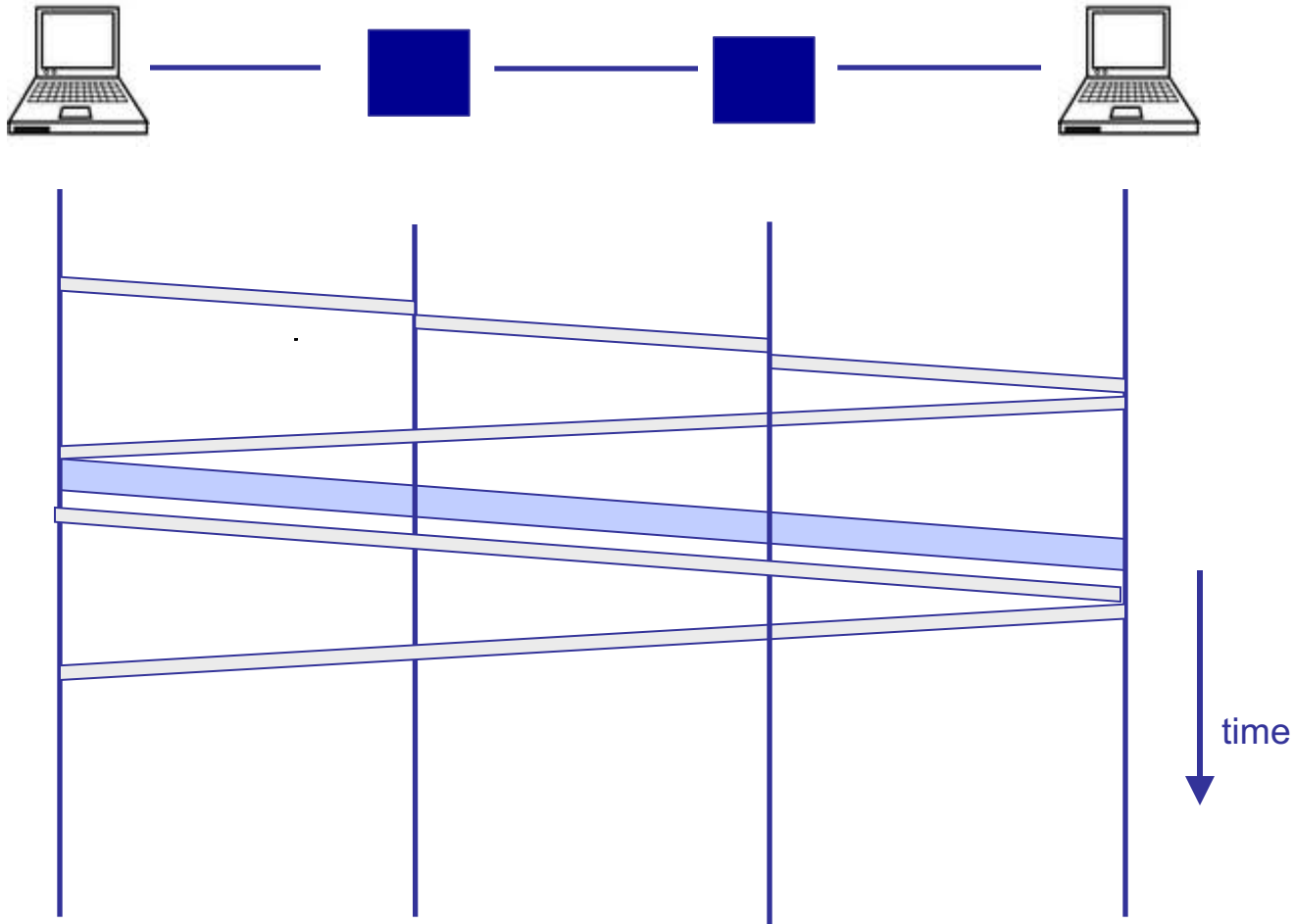
# Timing in circuit switching



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# Timing in circuit switching



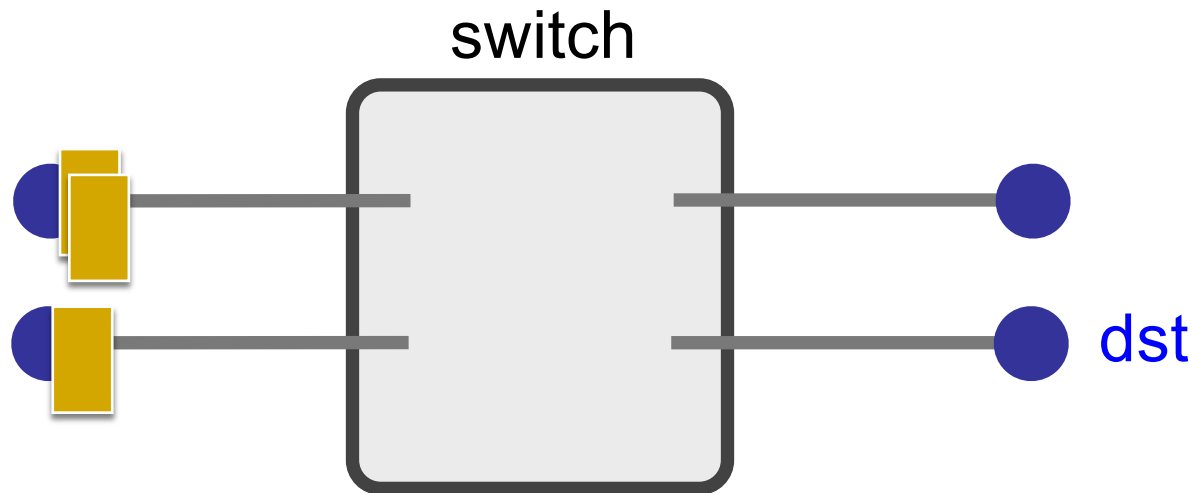
# Circuit switching

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- Pros
  - Predictable performance
  - Simple/fast switching (once circuit established)
- Cons
  - Complexity of circuit setup/teardown
  - Inefficient when traffic is bursty
  - Circuit setup adds delay
  - Switch fails → its circuit(s) fails

# Packet switching

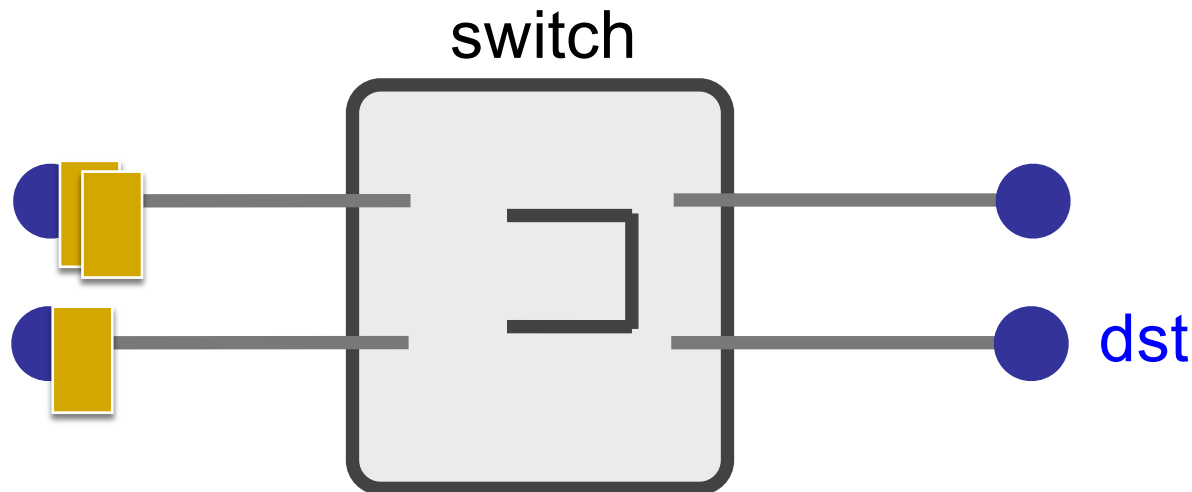
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- Each packet contains destination (**dst**)
- Each packet treated independently

# Packet switching

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- Each packet contains destination (**dst**)
- Each packet treated independently
- **With buffers to absolve transient overloads**

# Packet switching

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- Pros

- Efficient use of network resources
- Simpler to implement
- Robust: can “route around trouble”

- Cons

- Unpredictable performance
- Requires buffer management and congestion control

# Statistical multiplexing

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- Allowing more demands than the network can handle
  - Hoping that not all demands are required at the same time
  - Results in unpredictability
  - Works well except for the extreme cases



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**5-MINUTE BREAK!**

# Announcements

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- Discussion sections start this week
  - Check course webpage for times, dates, locations
- If you're planning to drop, please do so soon!

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# **HOW DO WE EVALUATE A NETWORK?**

# Performance metrics

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- Delay
- Loss
- Throughput

# Delay

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- How long does it take to send a packet from its source to destination?

# Delay

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- Consists of four components

- Transmission delay
- Propagation delay
- Queuing delay
- Processing delay

} due to link properties

} due to traffic mix and  
switch internals

# A network link

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- Link bandwidth
  - Number of bits sent/received per unit time (bits/sec or bps)
- Propagation delay
  - Time for one bit to move through the link (seconds)
- Bandwidth-Delay Product (BDP)
  - Number of bits “in flight” at any time
- $BDP = \text{bandwidth} \times \text{propagation delay}$

# BDP Examples

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- Same city over a slow link:
  - Bandwidth:  $\sim 100\text{Mbps}$
  - Propagation delay:  $\sim 0.1\text{msec}$
  - BDP:  $10,000\text{bits}$  ( $1.25\text{KBytes}$ )
- Cross-country over fast link:
  - Bandwidth:  $\sim 10\text{Gbps}$
  - Propagation delay:  $\sim 10\text{msec}$
  - BDP:  $10^8\text{bits}$  ( $12.5\text{MBytes}$ )



# 1. Transmission delay

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- How long does it take to push all the bits of a packet into a link?
- Packet size / Transmission rate of the link
  - E.g., 1000 bits / 100 Mbits per sec =  $10^{-5}$  sec

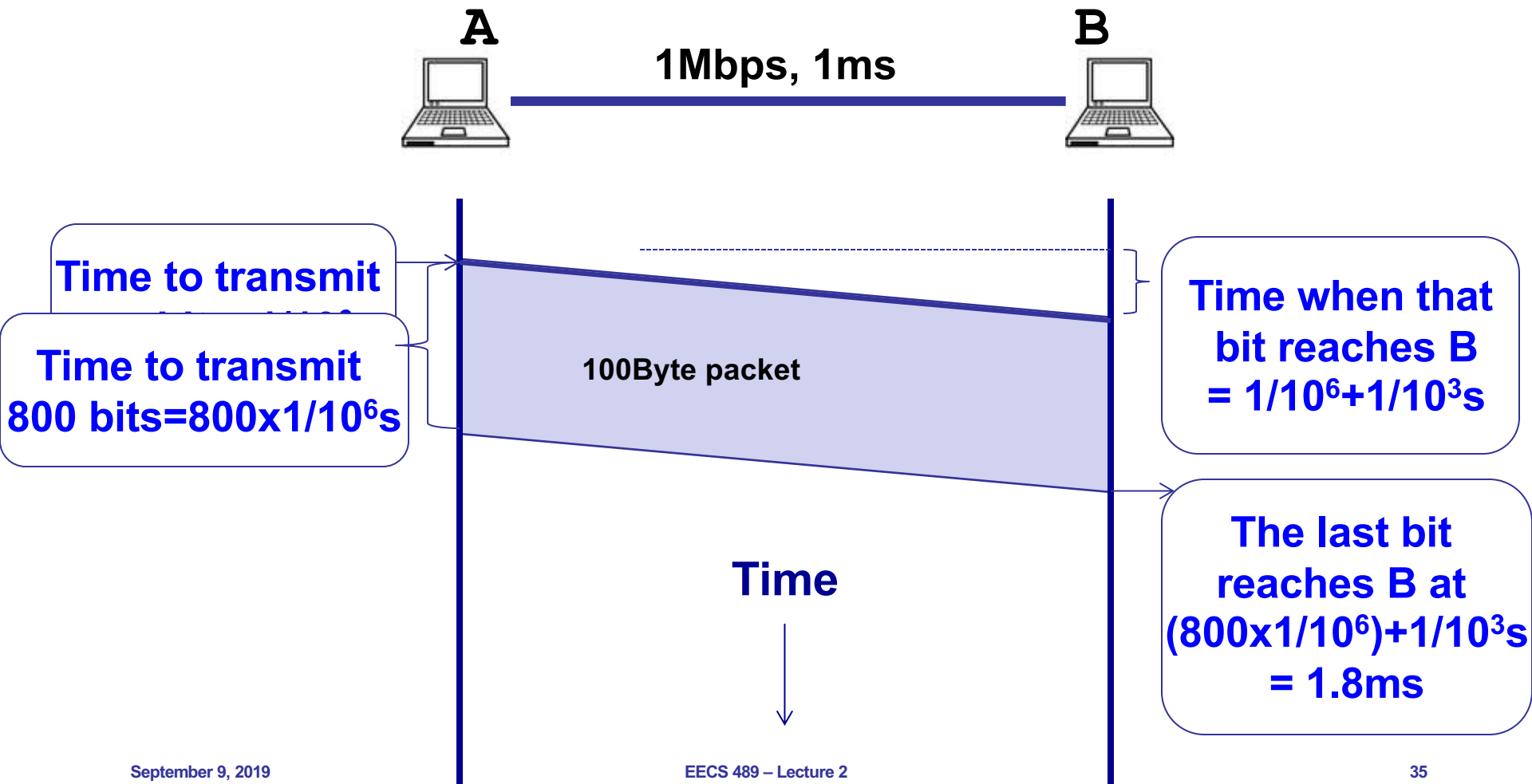
## 2. Propagation delay

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- How long does it take to move one bit from one end of a link to the other?
- Link length / Propagation speed of link
  - E.g., 30 kilometers /  $3 \times 10^8$  meters per sec =  $10^{-4}$  sec

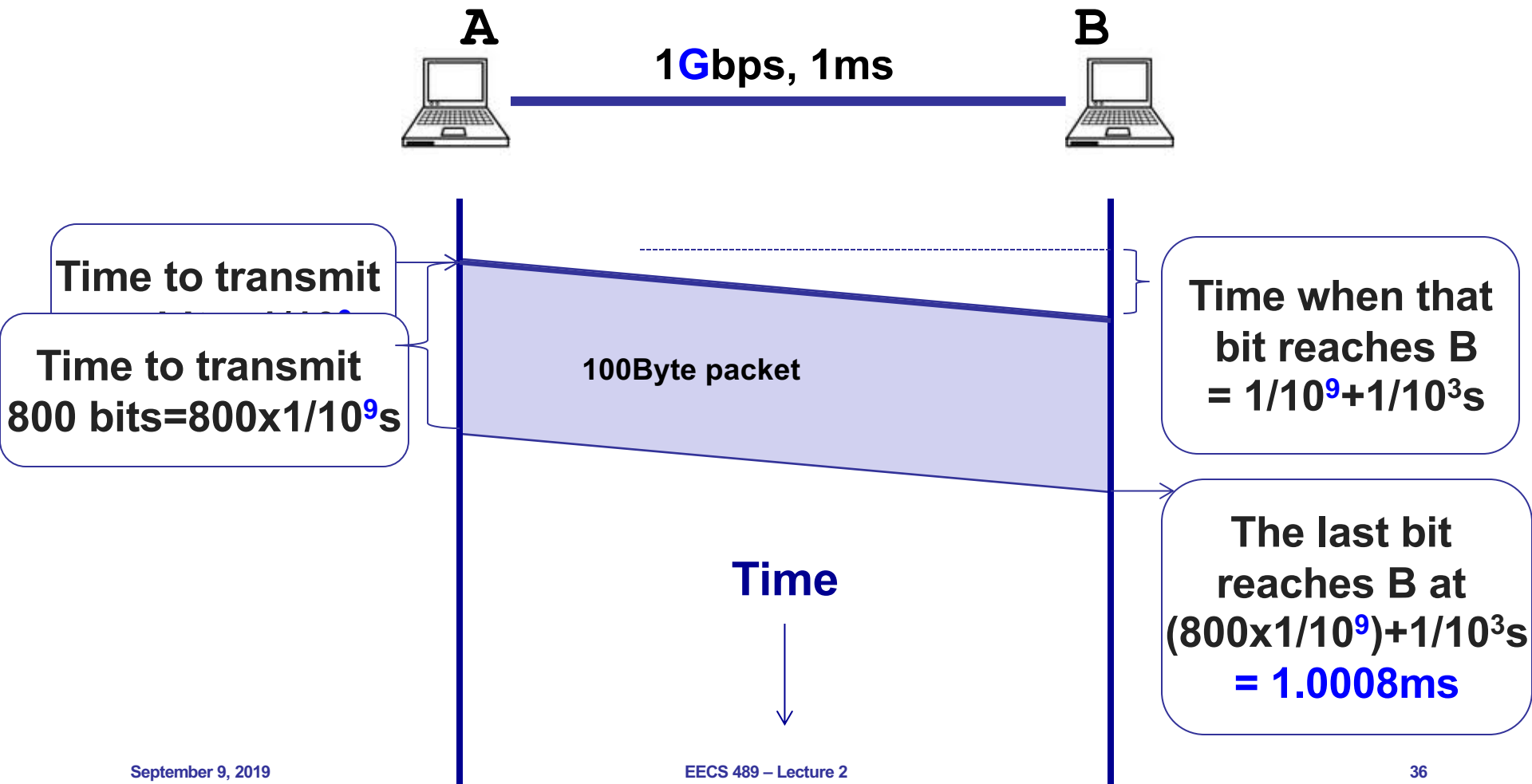
# Packet delay

## Sending a 100-byte packet

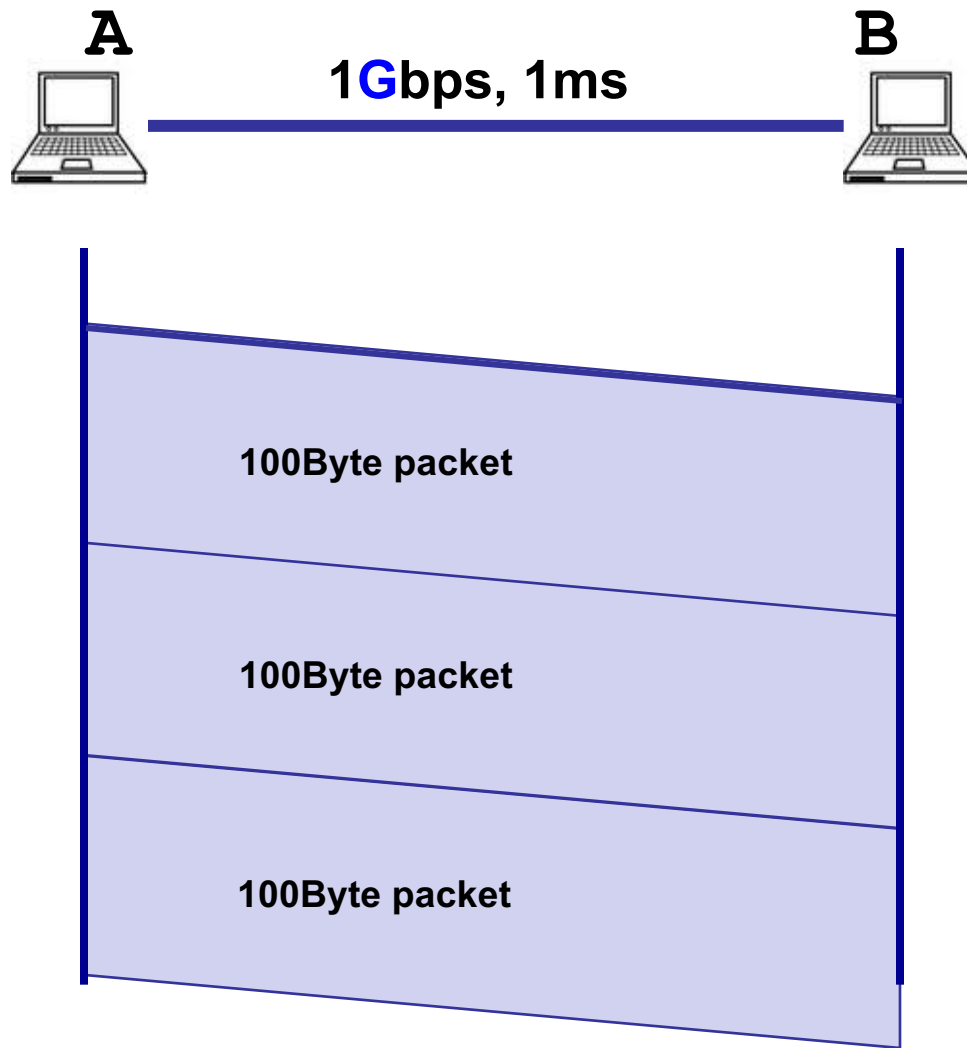


# Packet delay

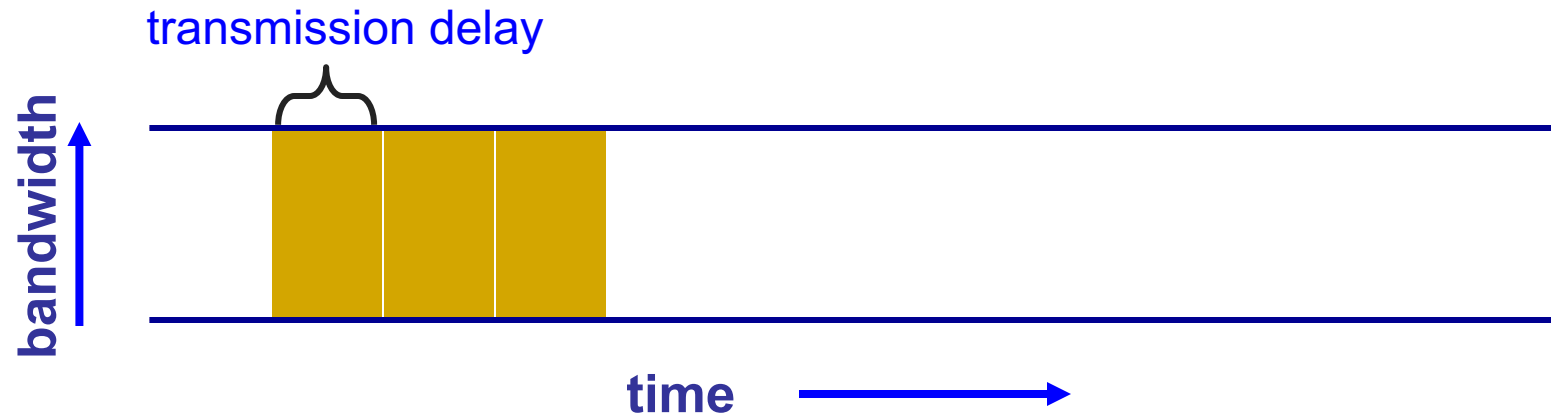
## Sending a 100-byte packet



# Sending a large file using 100-byte packets



# Pipe view of a link



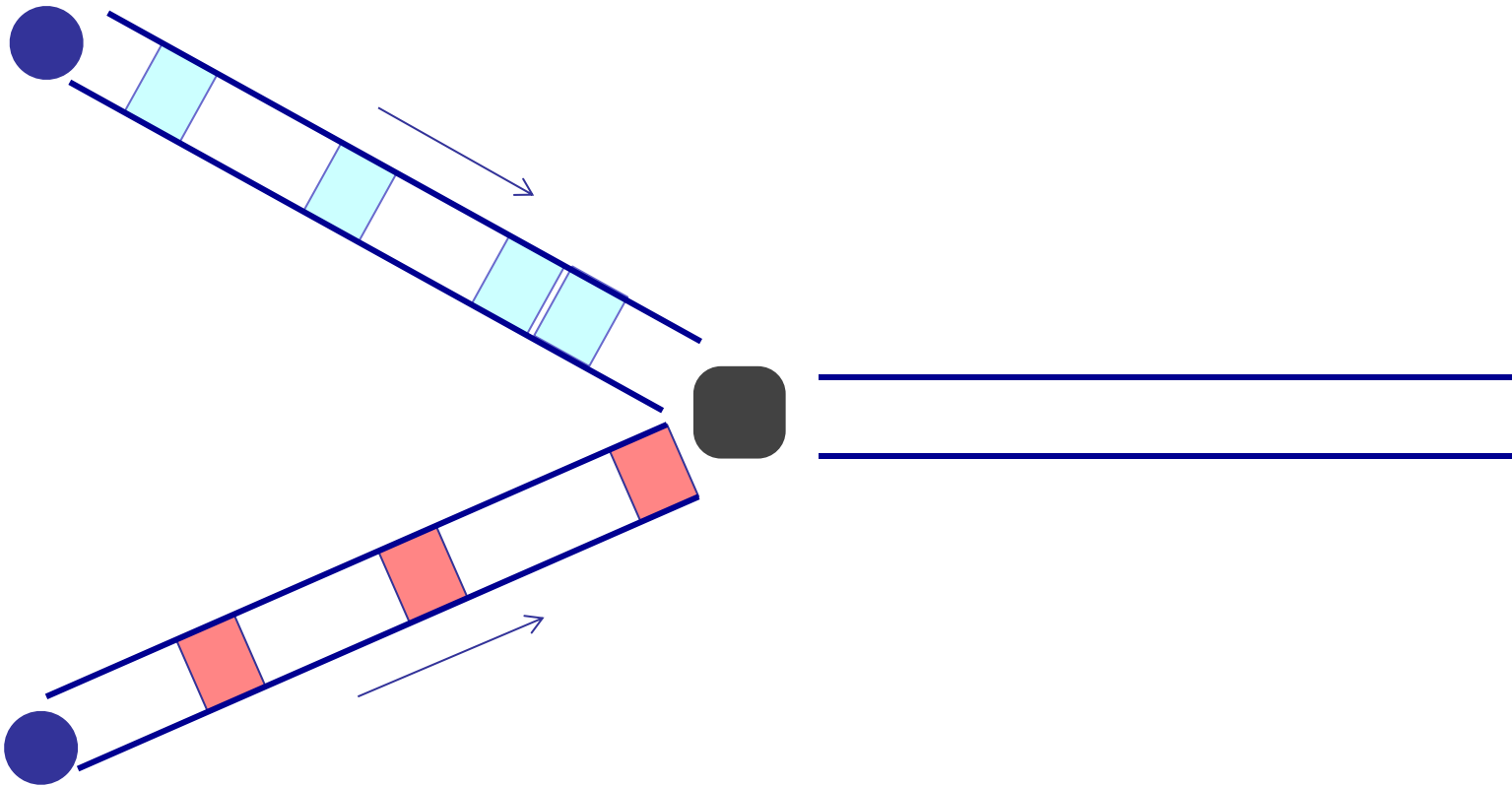
- Transmission delay decreases as bandwidth increases

# 3. Queuing delay

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- How long does a packet have to sit in a buffer before it is processed?

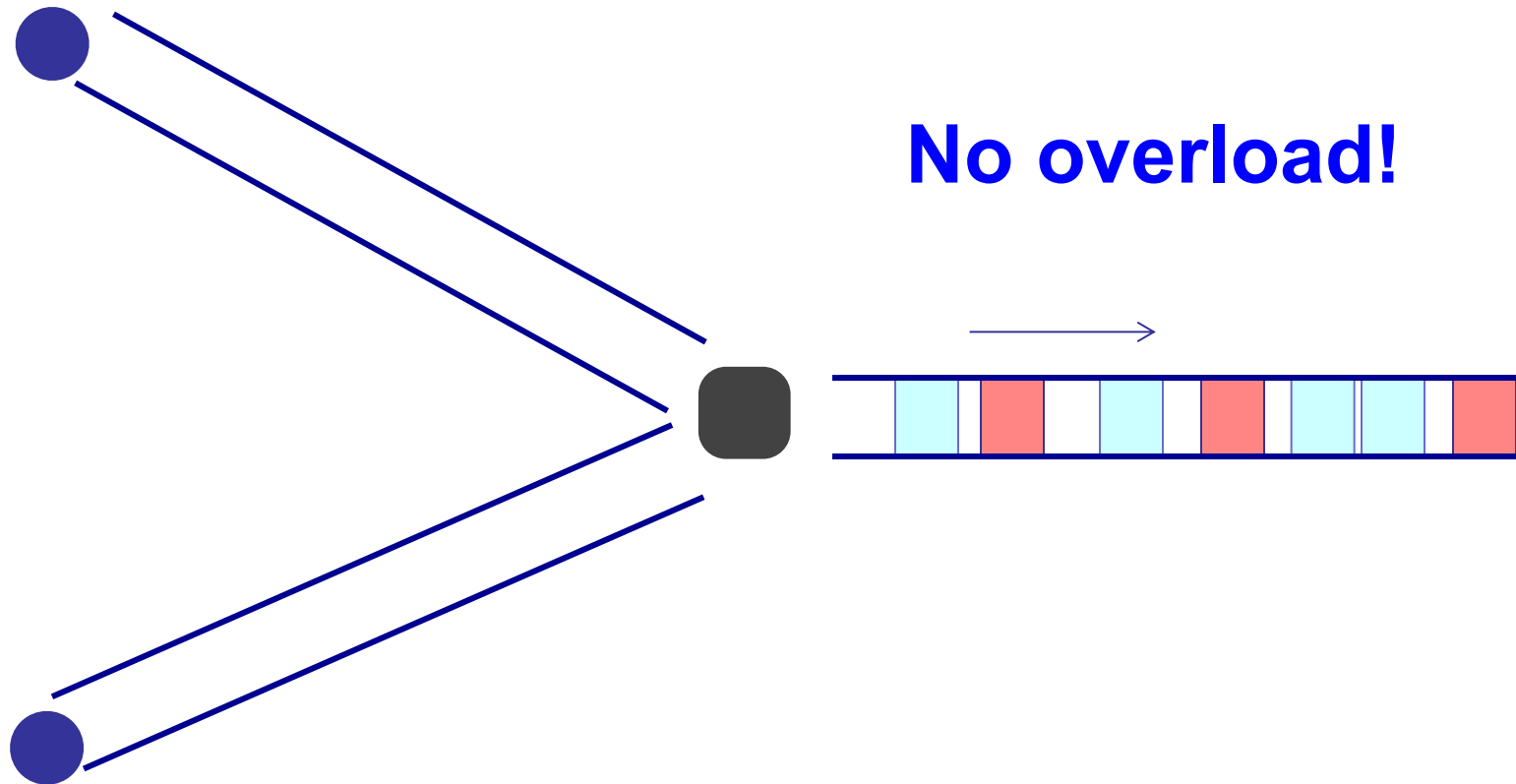
# Queueing delay: “pipe” view



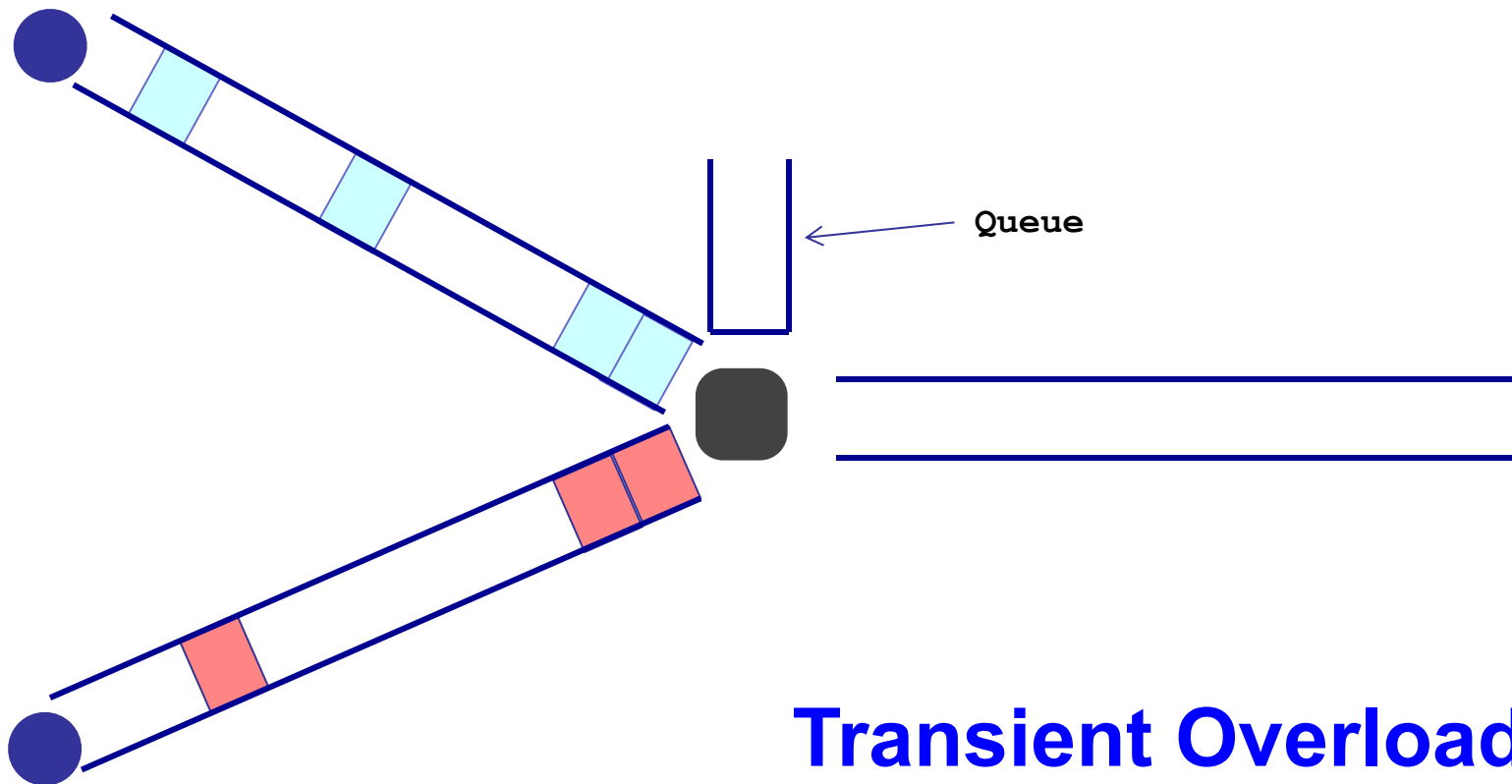


# Queueing delay: “pipe” view

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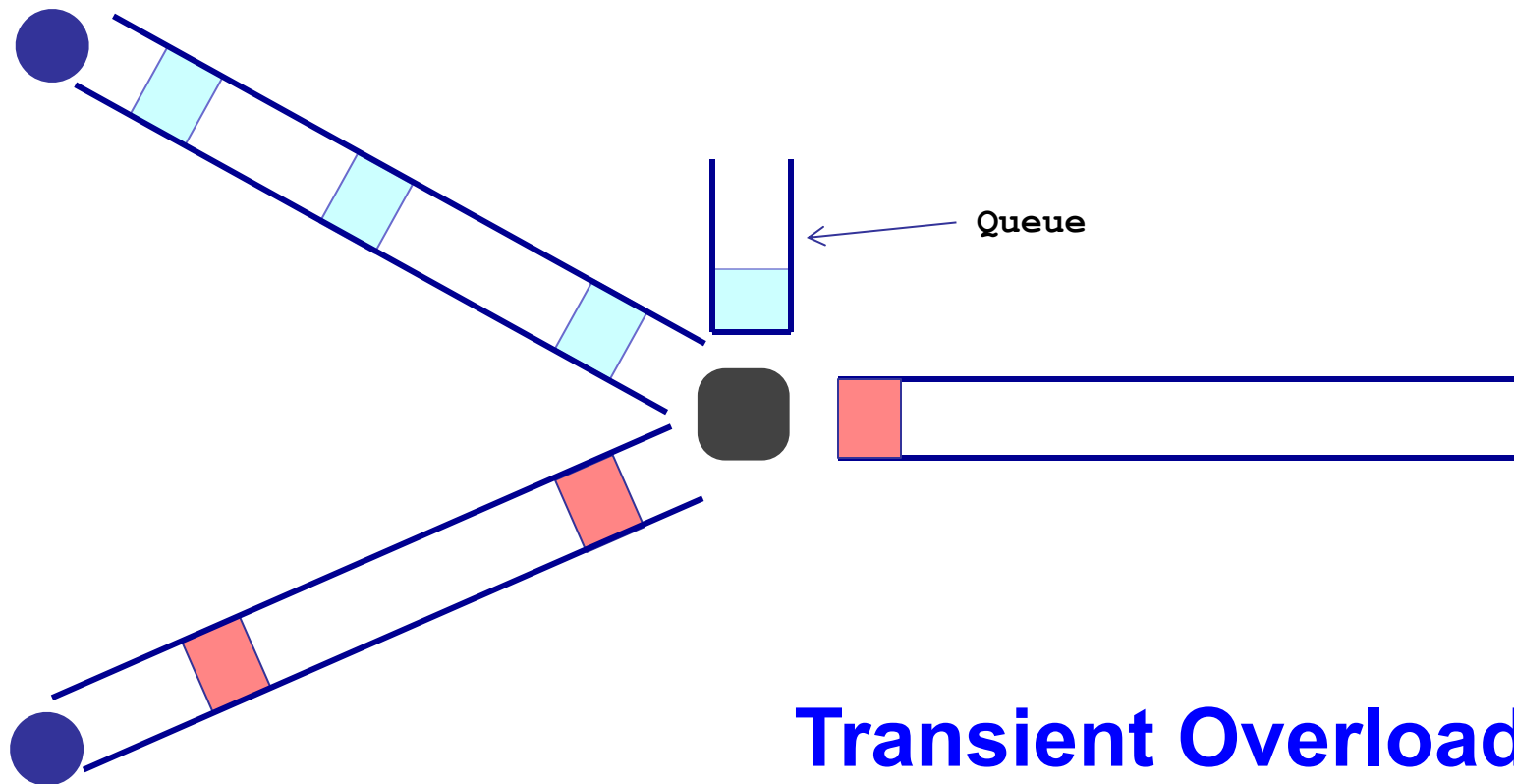


# Queueing delay: “pipe” view

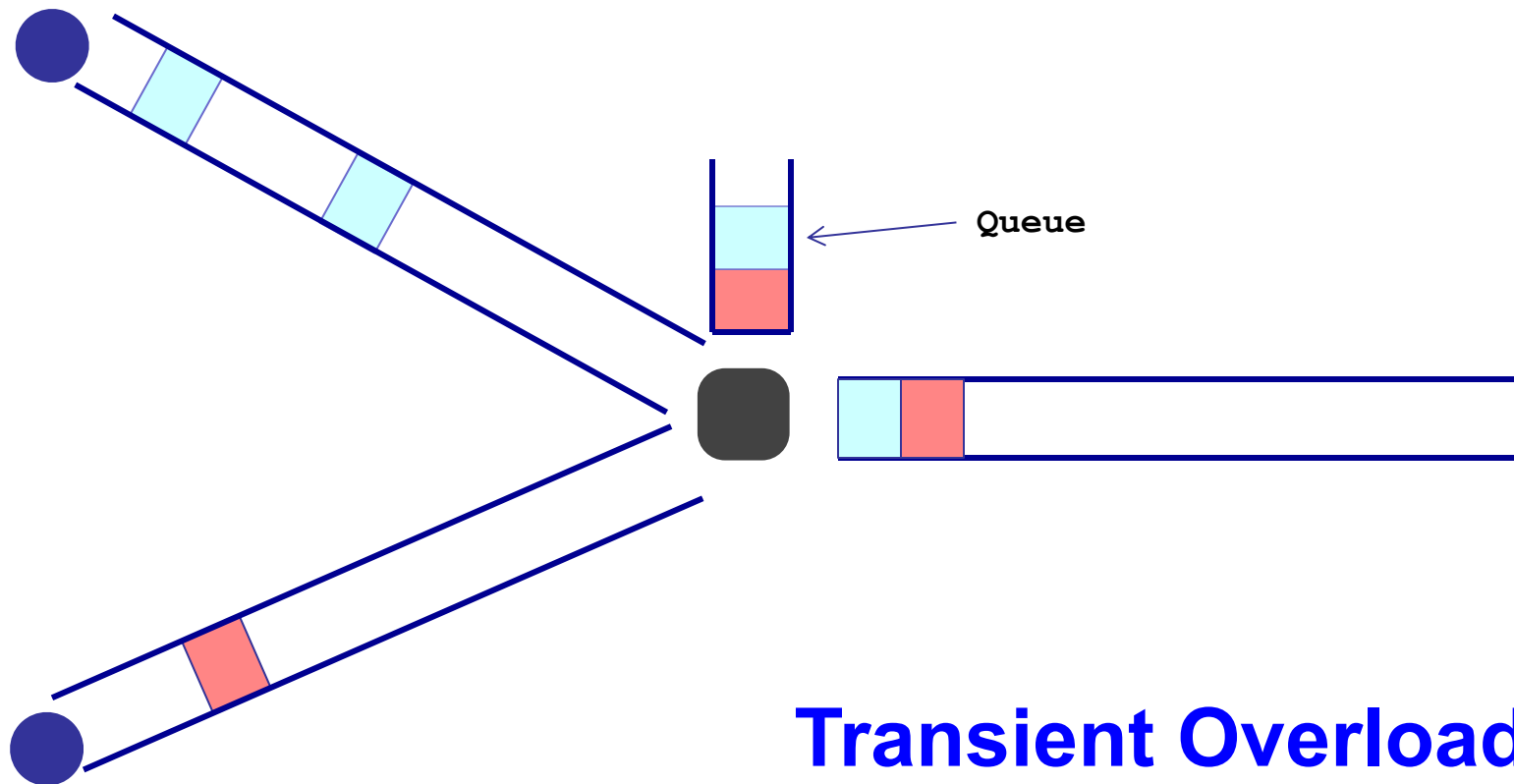


**Transient Overload**  
**Not a rare event!**

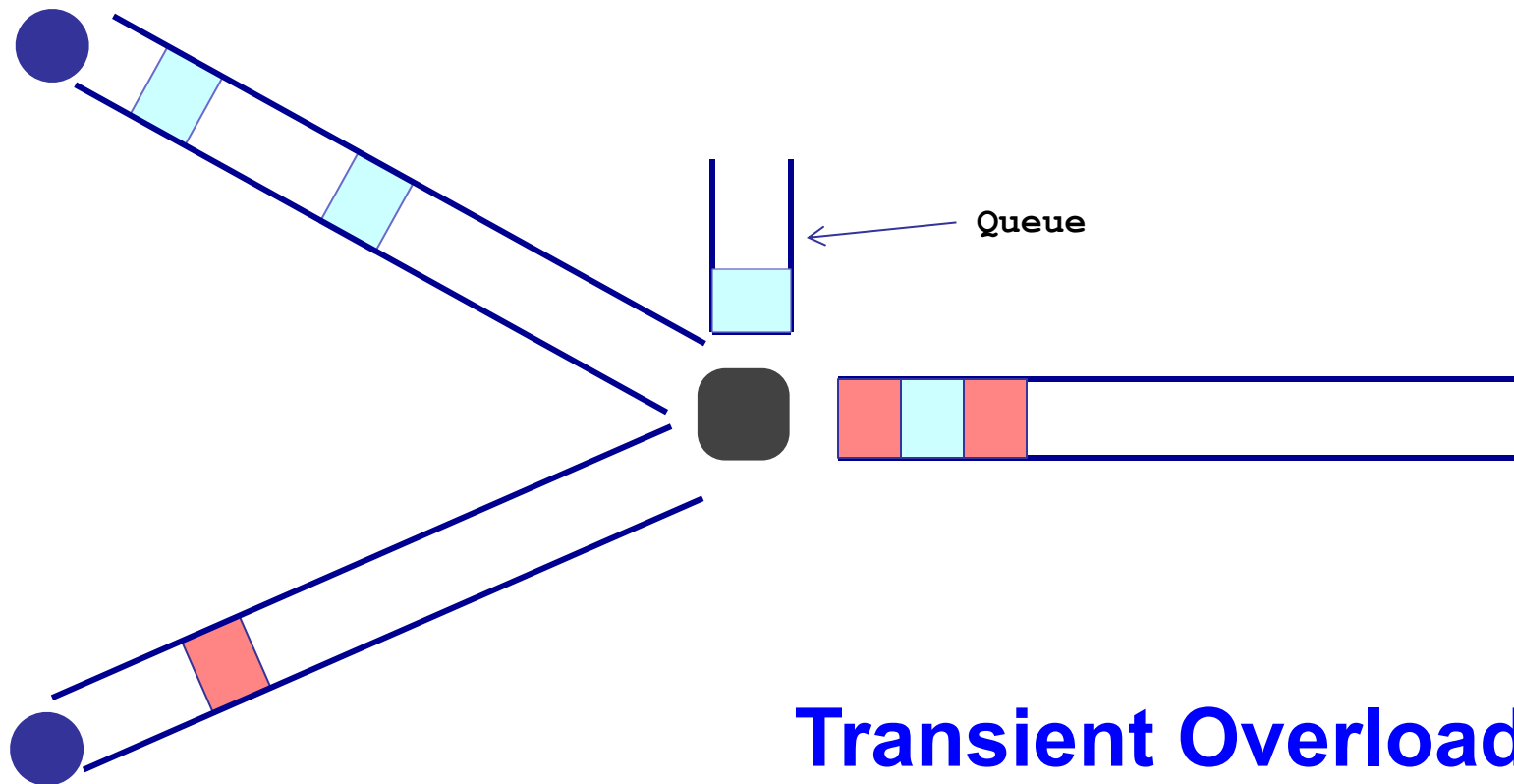
# Queueing delay: “pipe” view



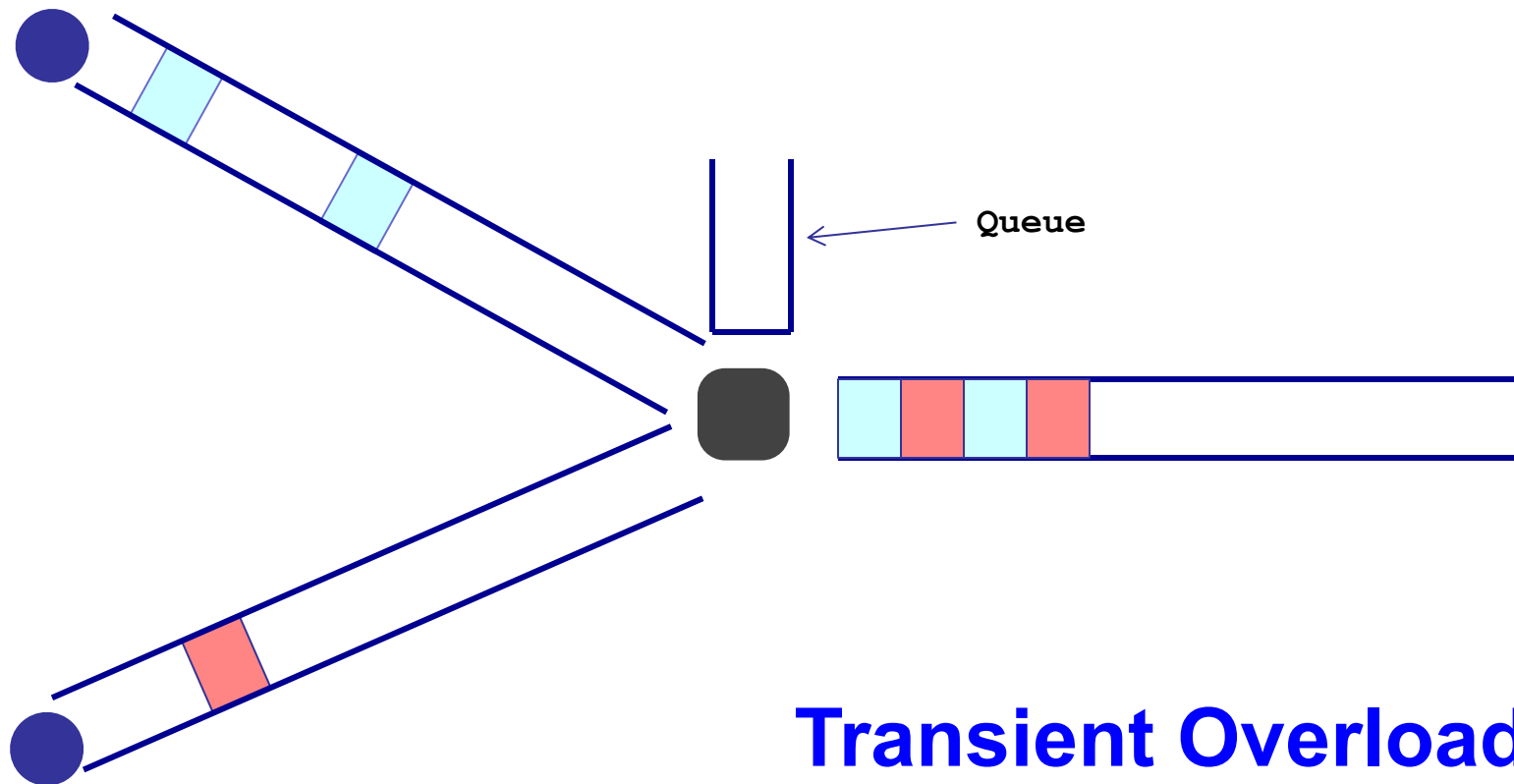
# Queueing delay: “pipe” view



# Queueing delay: “pipe” view

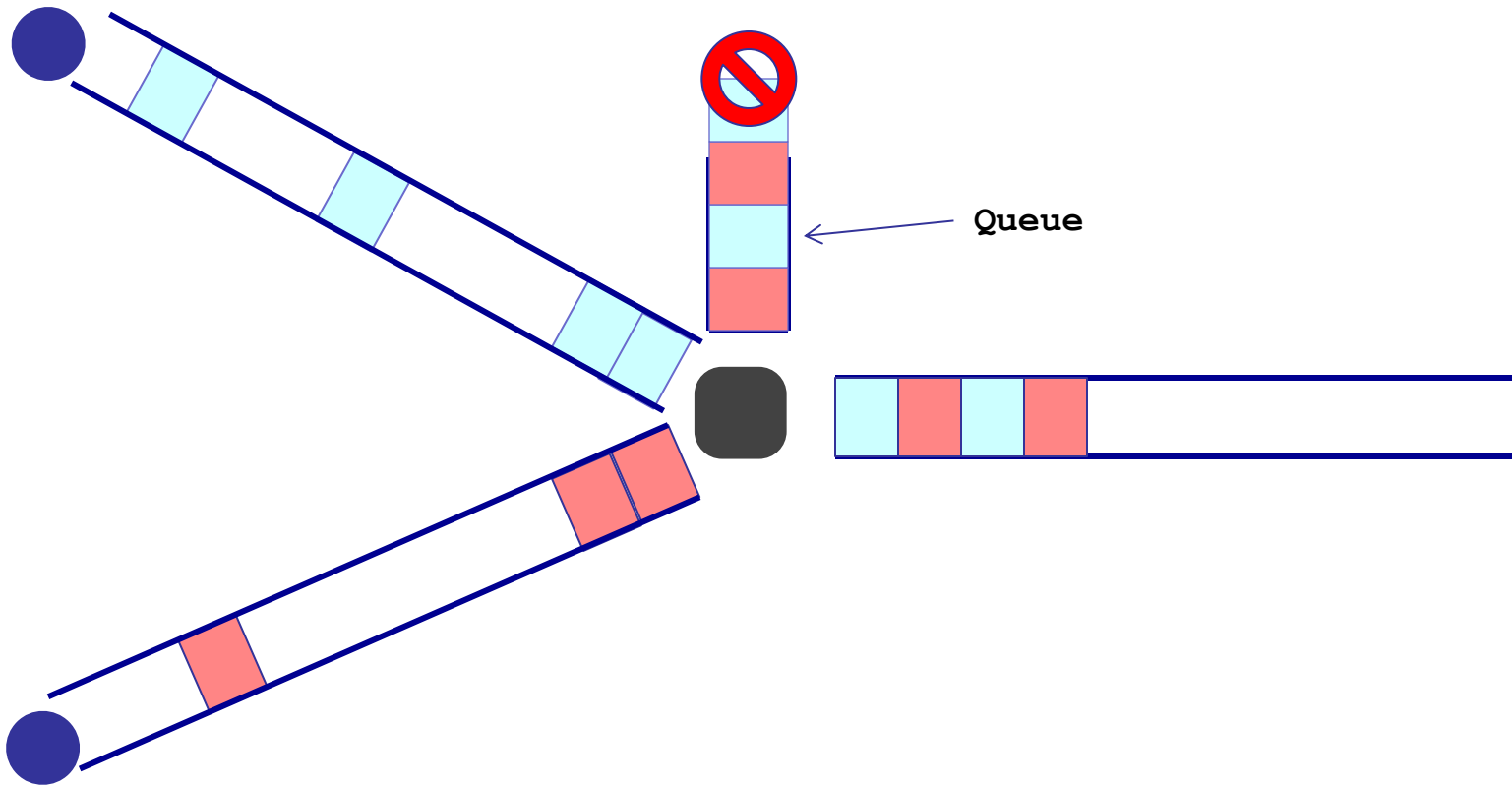


# Queueing delay: “pipe” view



# Persistent overload leads to packet drop/loss

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# Queueing delay

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- How long does a packet have to sit in a buffer before it is processed?
- Depends on traffic pattern
  - Arrival rate at the queue
  - Nature of arriving traffic (bursty or not?)
  - Transmission rate of outgoing link



# Queueing delay

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- How long does a packet have to sit in a buffer before it is processed?
- Characterized with statistical measures
  - Average queuing delay
  - Variance of queuing delay
  - Probability delay exceeds a threshold value

# Basic queueing theory terminology

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- Arrival process: how packets arrive
  - Average rate  $A$
- $W$ : average time packets wait in the queue
  - $W$  for “waiting time”
- $L$ : average number of packets waiting in the queue
  - $L$  for “length of queue”

# Little's Law (1961)

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- $L = A \times W$
- Compute L: count packets in queue every second
- Why do you care?
  - Easy to compute L, harder to compute W

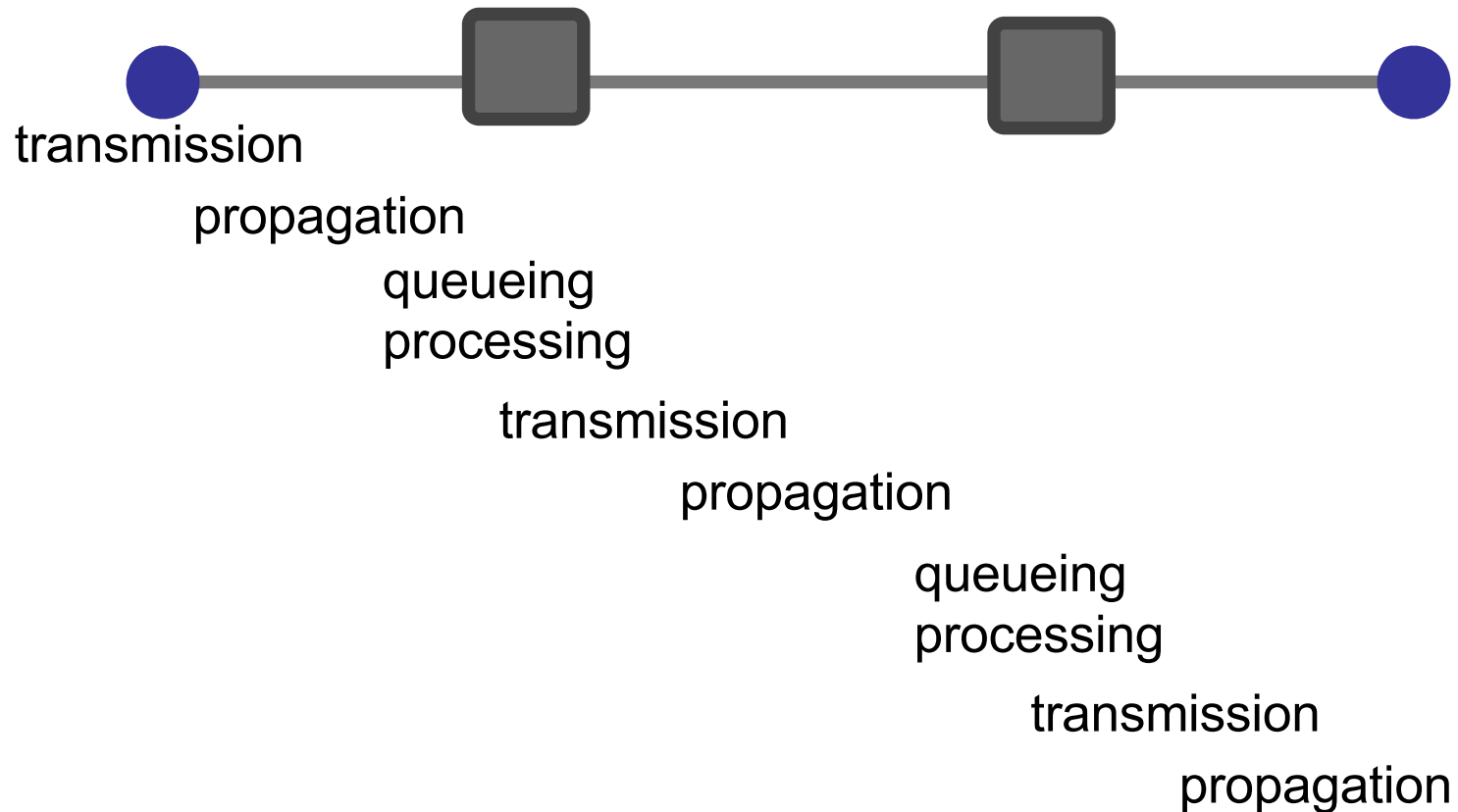
# 4. Processing Delay

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- How long does the switch take to process a packet?
  - Negligible

# End-to-end delay

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# Round Trip Time (RTT)

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- Time for a packet to go from a source to a destination and to come back
- Why do we care?
  - Measuring delay is hard from one end
- $RTT/2$  equals *average* end-to-end delay
  - Why not exact?

# Loss

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- What fraction of the packets sent to a destination are dropped?

# Throughput

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



# Throughput

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Transmission rate  $R$  bits/sec



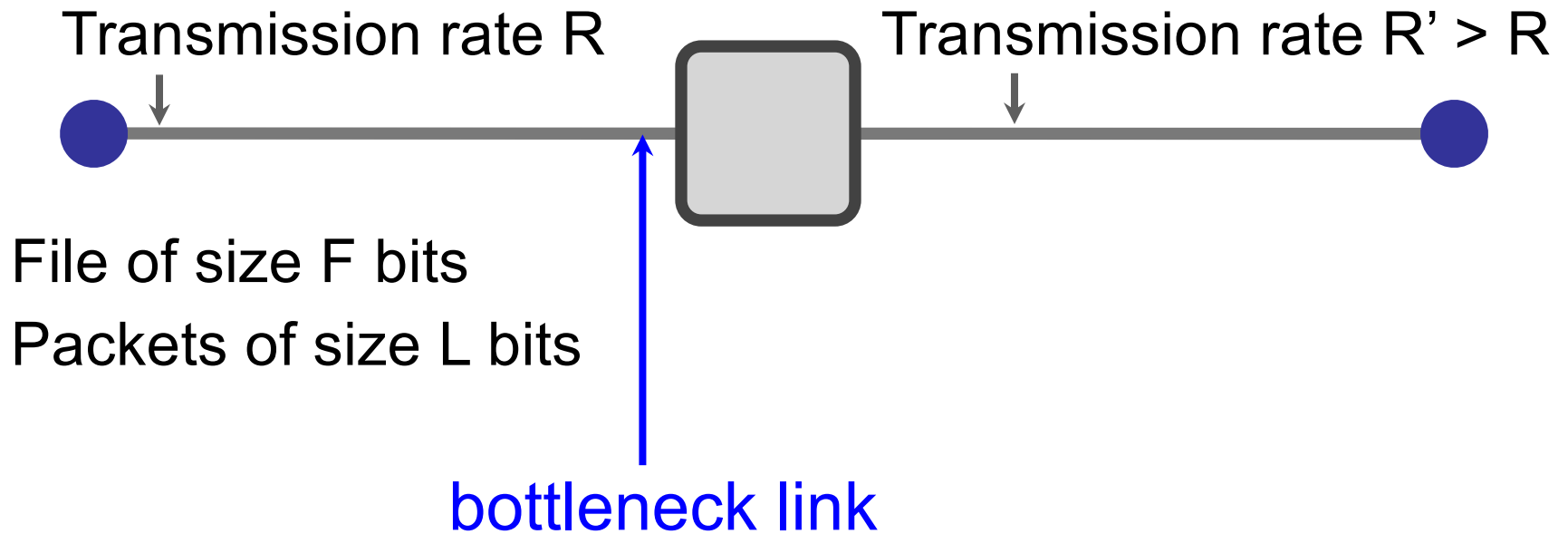
File of size  $F$  bits

Packets of size  $L$  bits

Transfer time ( $T$ ) =  $F/R$  + propagation delay

Average throughput =  $F/T \approx R$

# End-to-end throughput



$$\text{Average throughput} = \min\{R, R'\} = R$$

# Summary

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- How is it shared?
  - On-demand or via reservation
- How do we evaluate a network?
  - Bandwidth, delay, loss, BDP, ...
- What is a network made of?
  - Whatever physical infrastructure exist
  - See backup slides

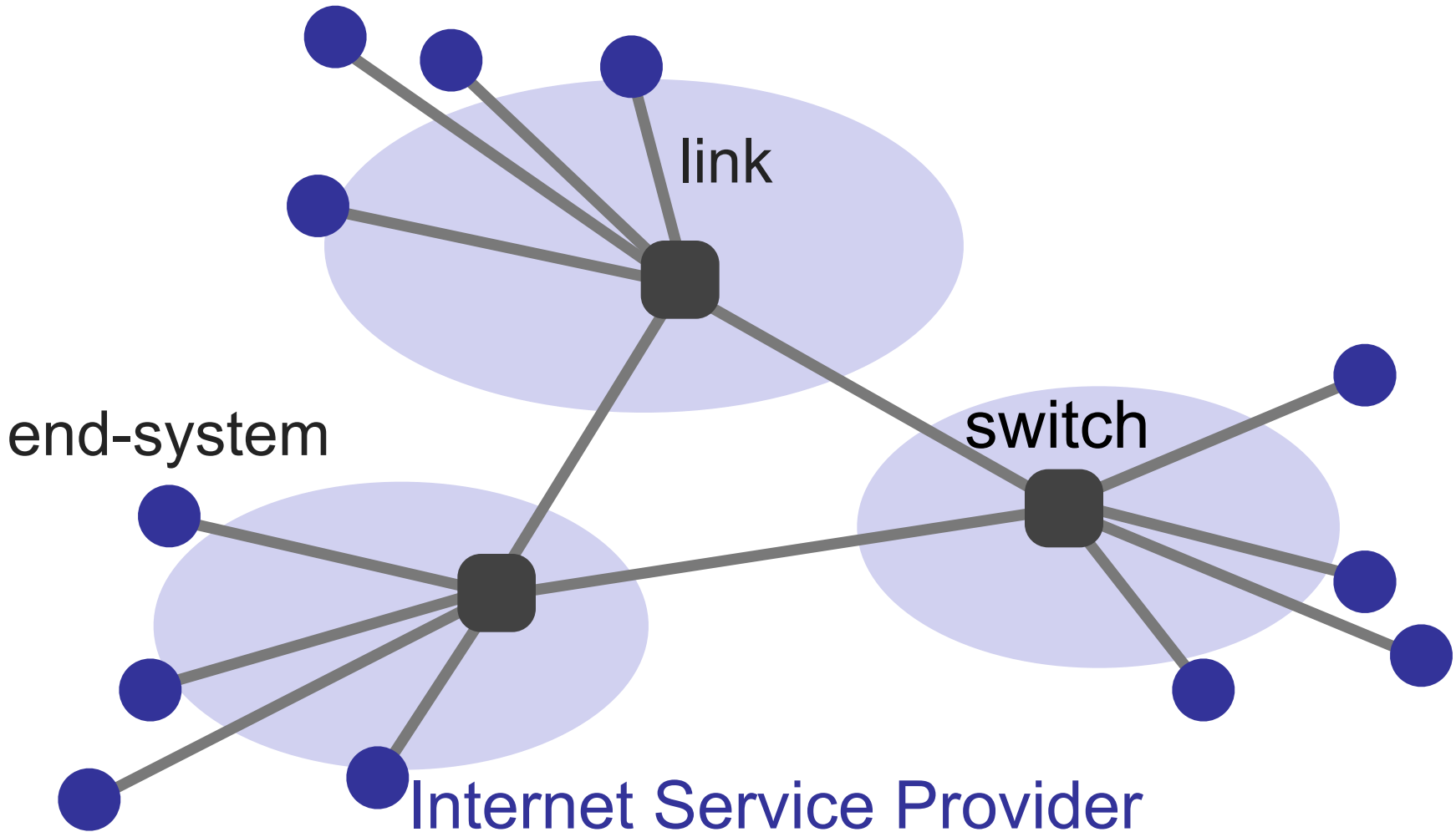


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# WHAT IS THE NETWORK MADE OF?

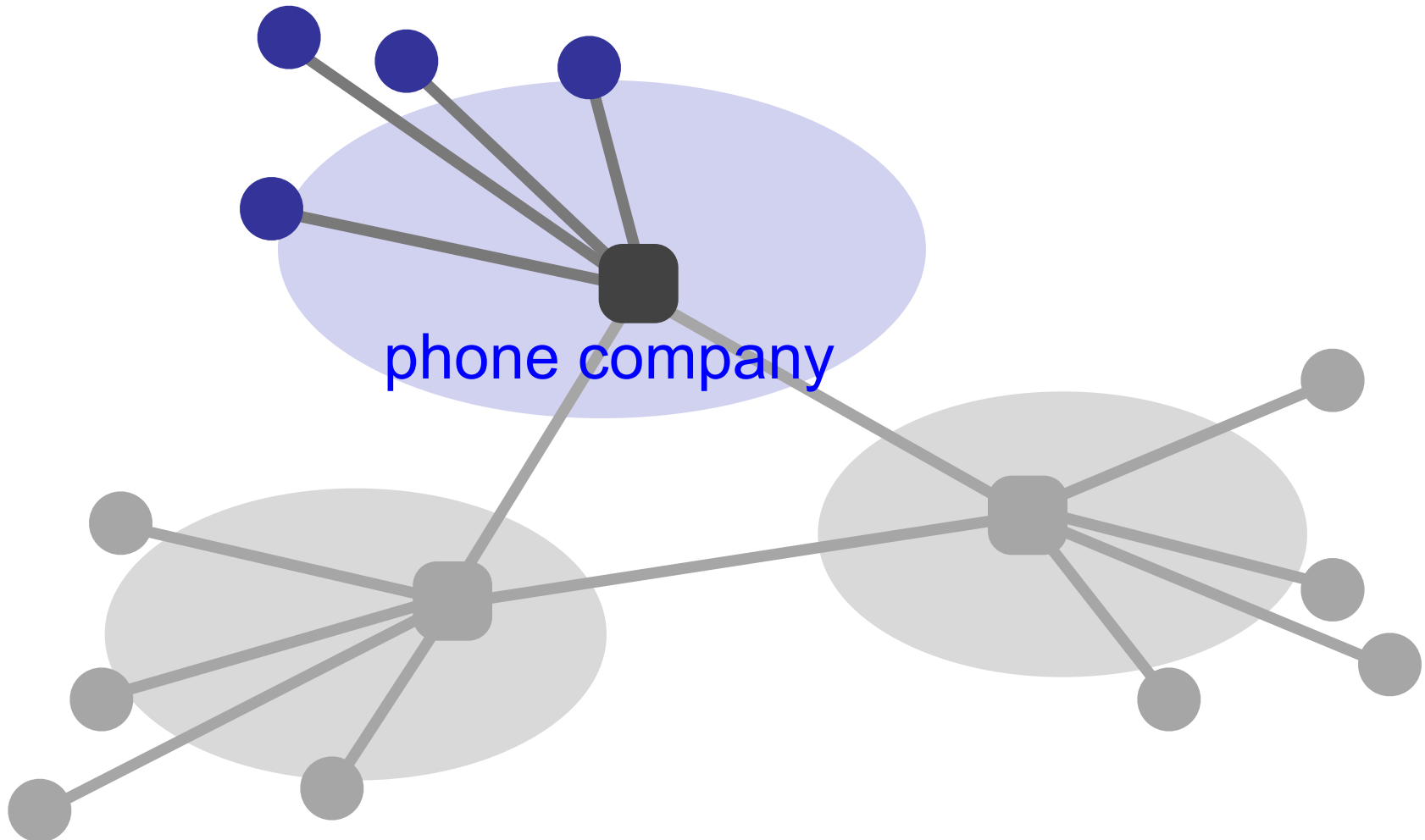
# What is a network made of?

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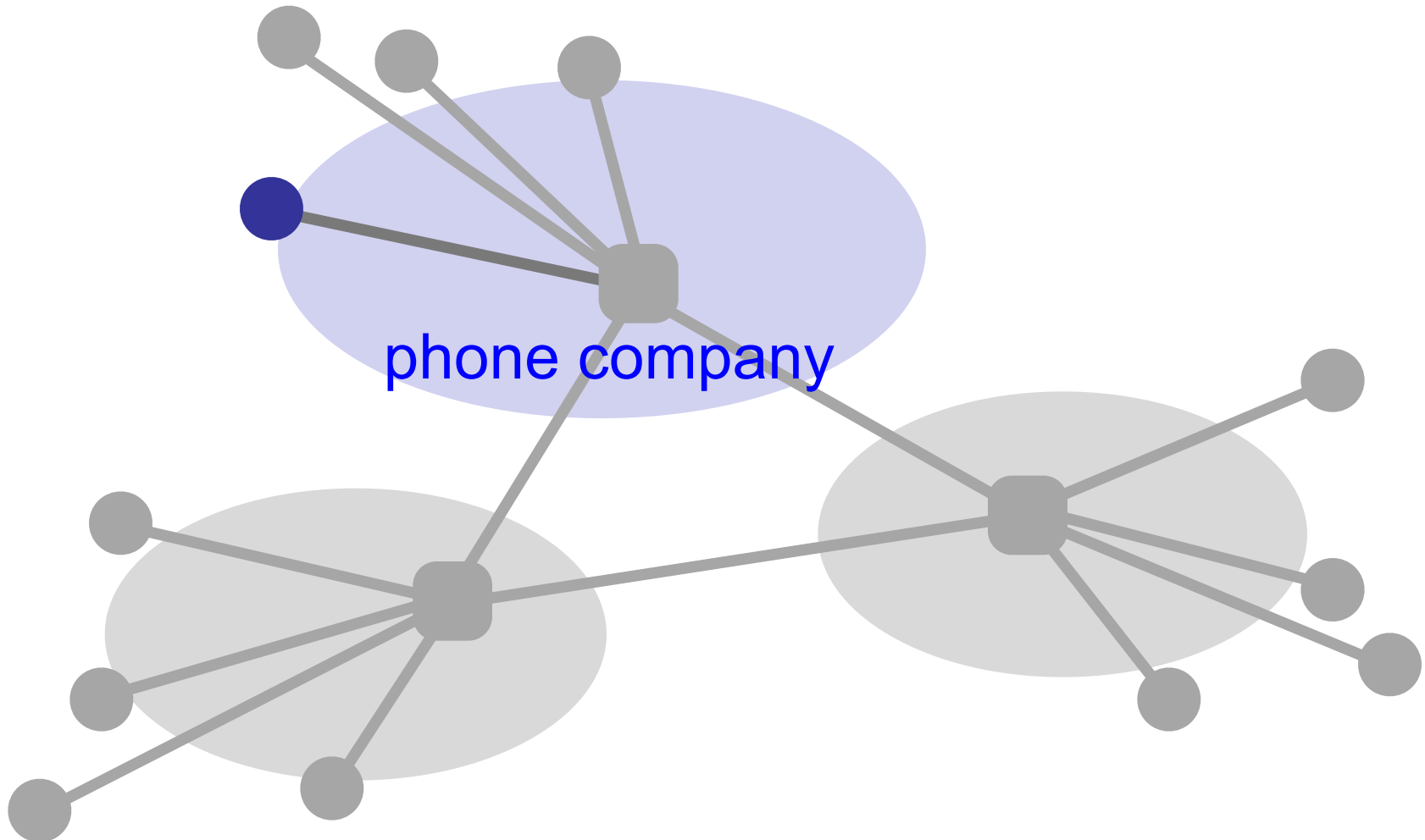
# What is a network made of?

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# What is a network made of?

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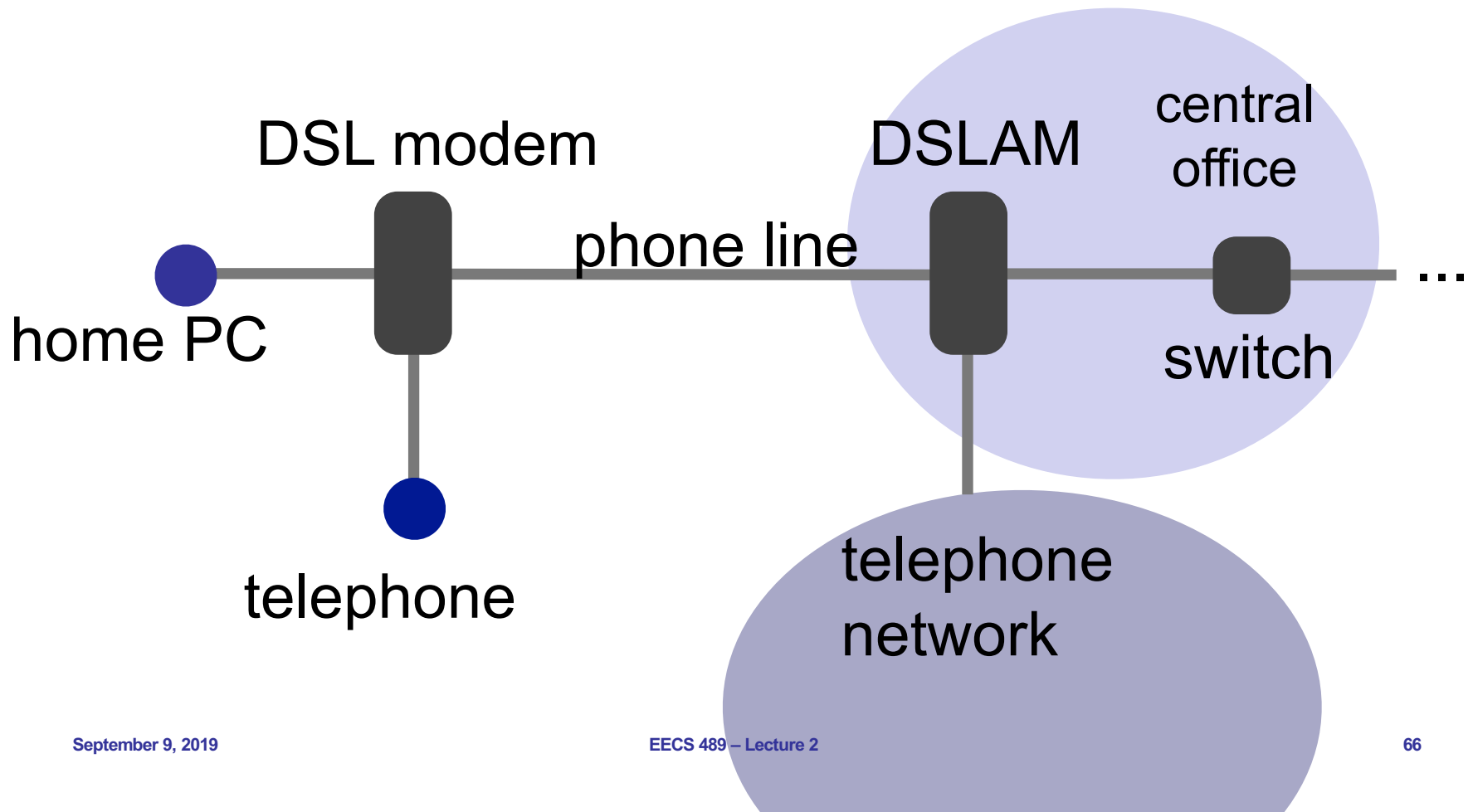
# The last hop

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# How do we connect?

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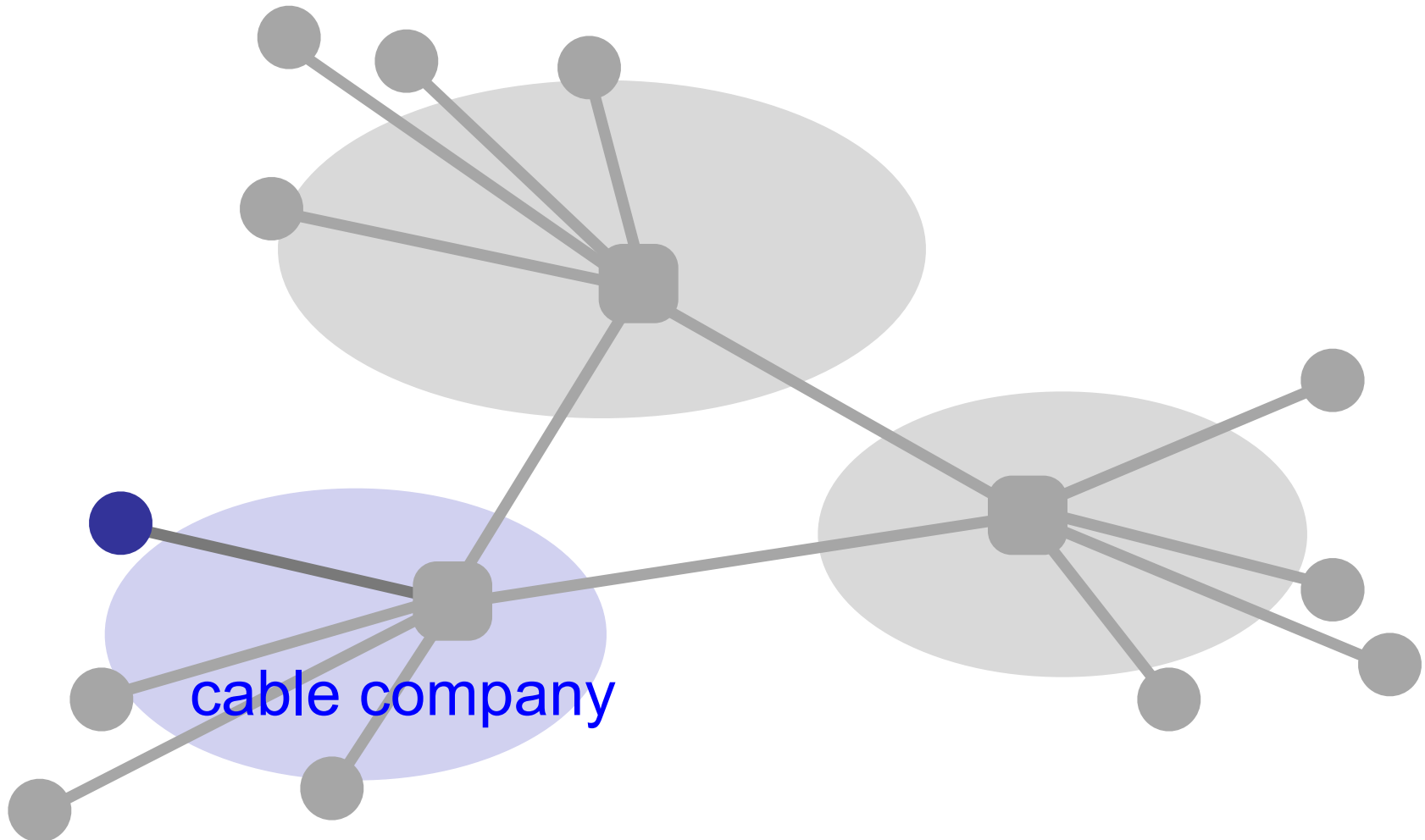
# Digital Subscriber Line (DSL)

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- Twisted pair copper
- 3 separate channels
  - downstream data channel
  - upstream data channel
  - 2-way phone channel
- up to 25 Mbps downstream
- up to 2.5 Mbps upstream

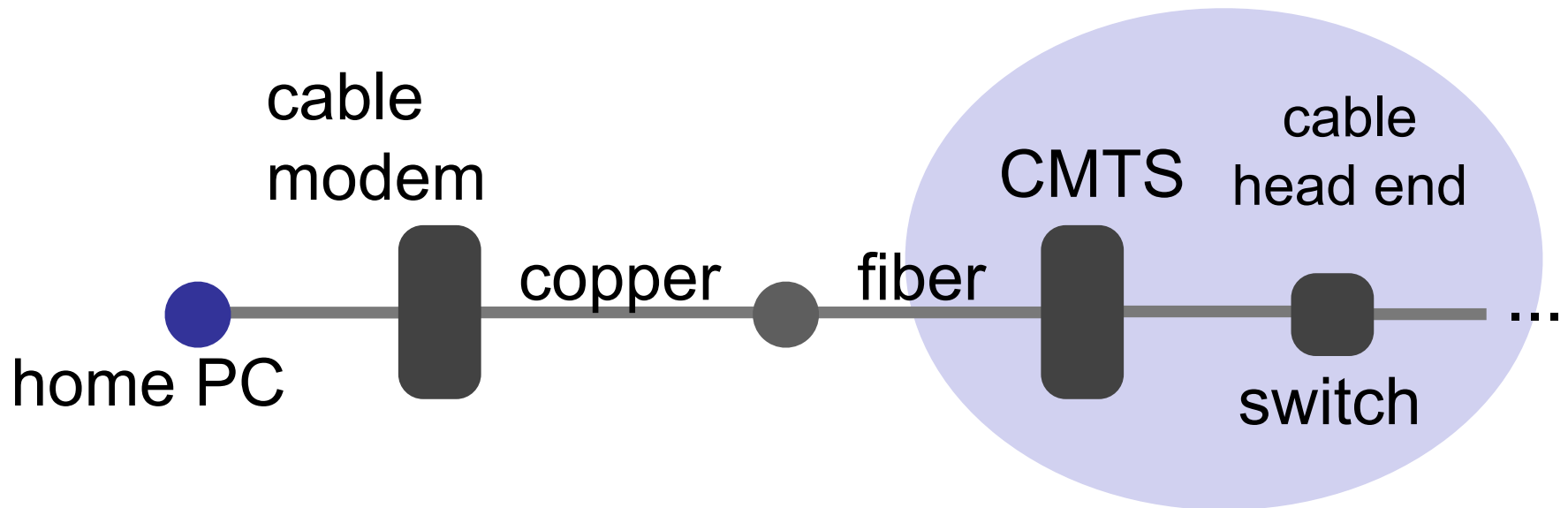
# How about an cable provider as an ISP?

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# Connecting via cable

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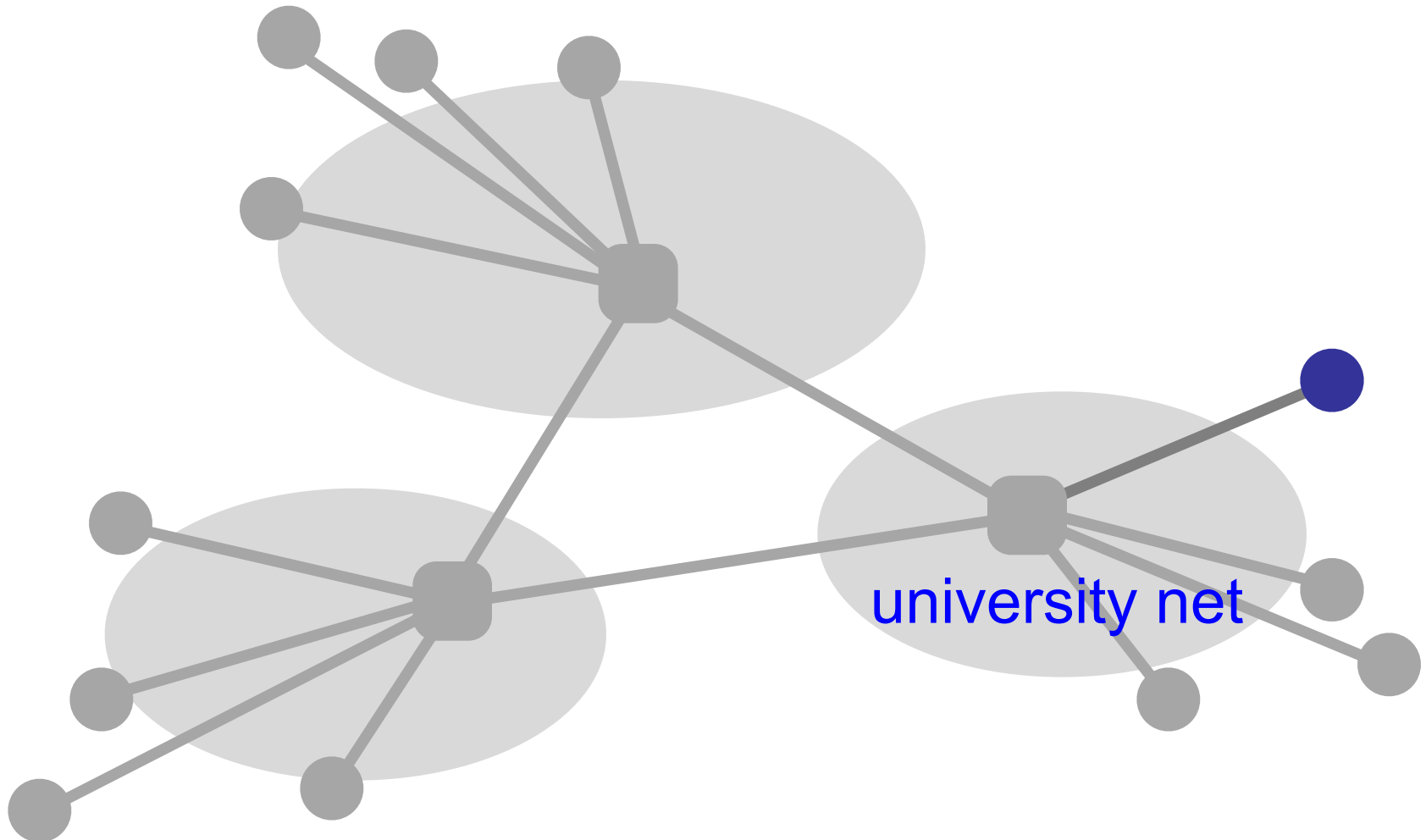
# Cable

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- Coaxial copper & fiber
- Up to 42.8 Mbps downstream
- Up to 30.7 Mbps upstream
- Shared broadcast medium

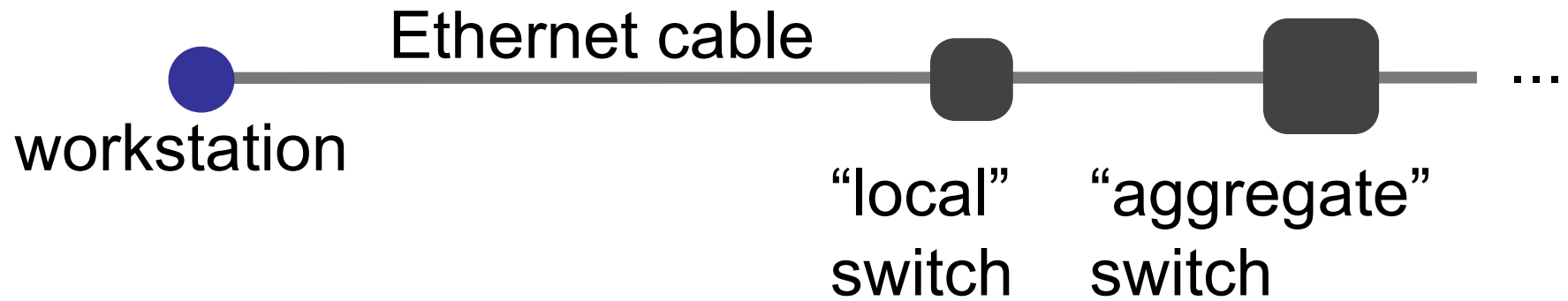
# Any other means?

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# Ethernet

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# Ethernet

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- Twisted pair copper
- 100 Mbps, 1 Gbps, 10 Gbps (each direction)

# Many other ways

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- Cellular (smart phones)
- Satellite (remote areas)
- Fiber to the Home (home)
- Optical carrier (Internet backbone)

# Where is WiFi?

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