Computer Networks

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Material with thanks Mosharaf Chowdhury, and many other colleagues.

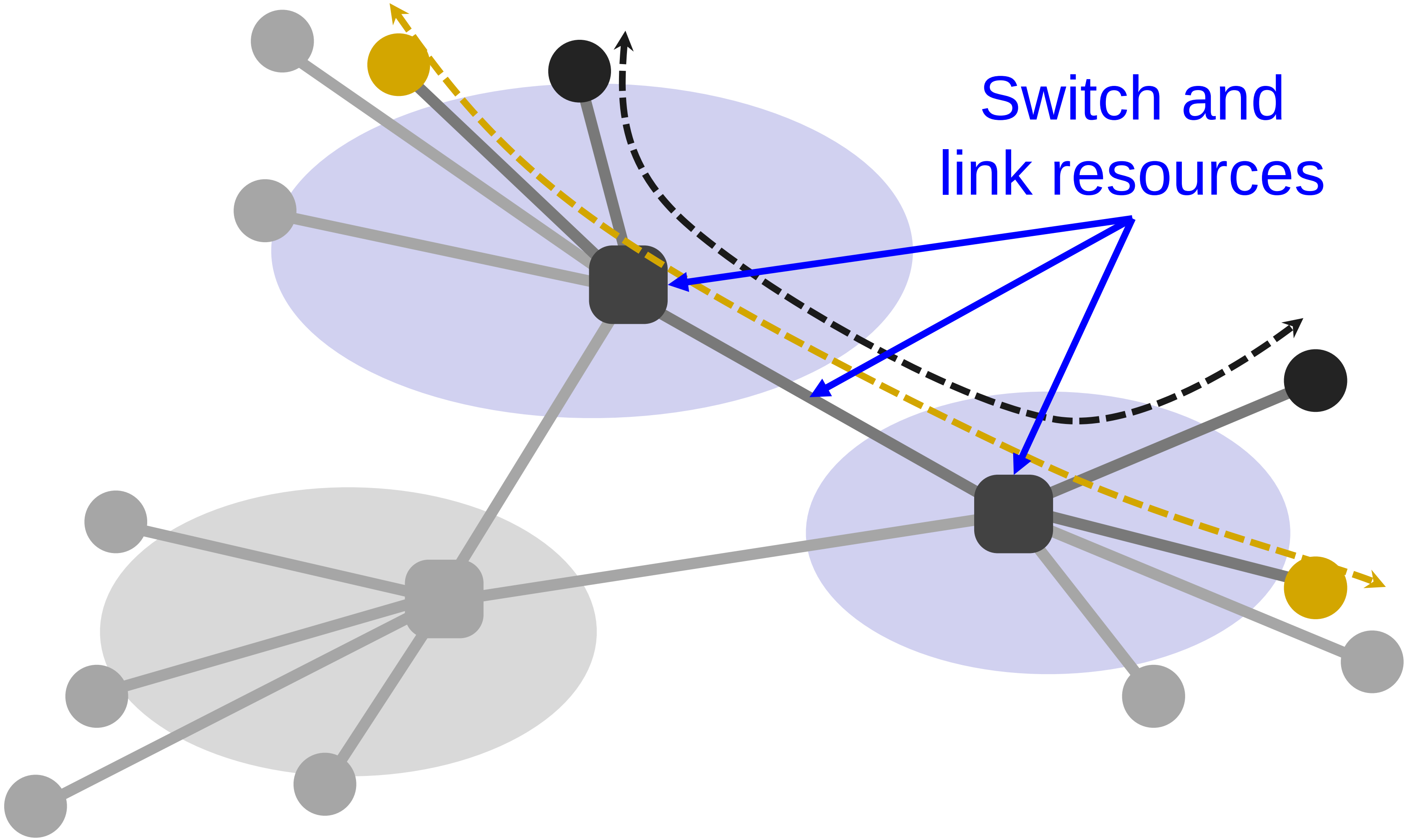
Agenda

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

Switched networks

- End-systems and networks connected by switches instead of directly connecting them
- 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?

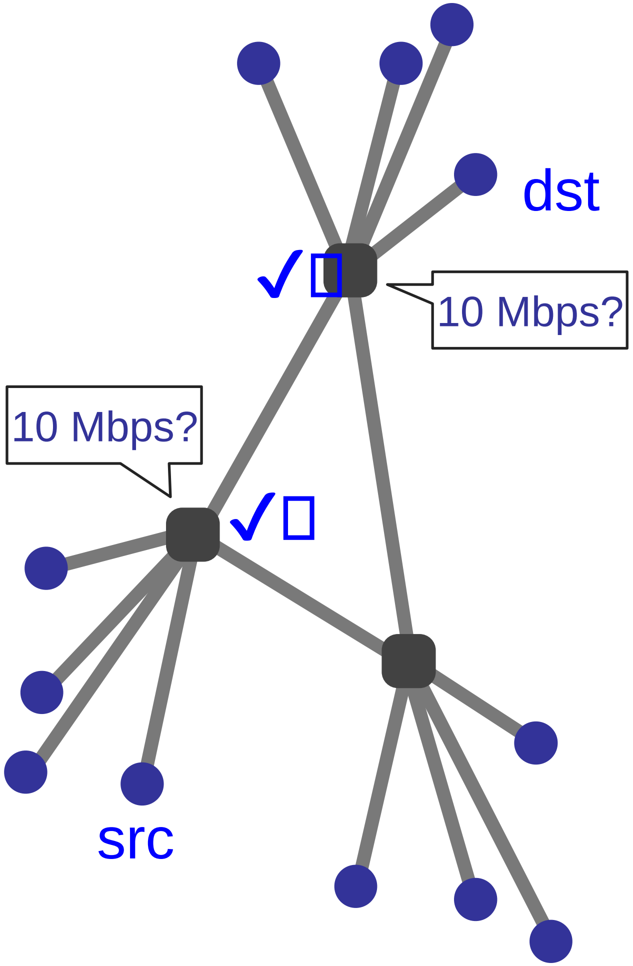


Two ways to share switched networks

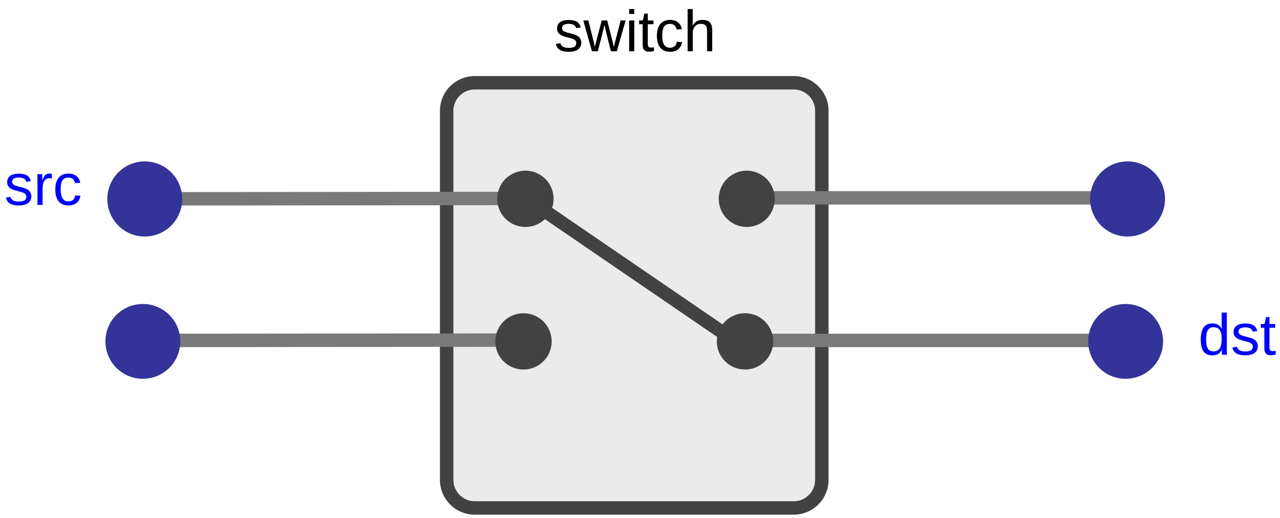
- Circuit switching
  - Resource reserved per connection
  - Admission control: per connection
- Packet switching via statistical multiplexing
  - Packets treated independently, on-demand
  - Admission control: per packet
- Hybrid: virtual circuits
  - Emulating circuit switching with packets (see text)

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



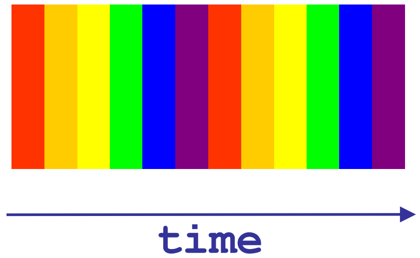
Circuit switching



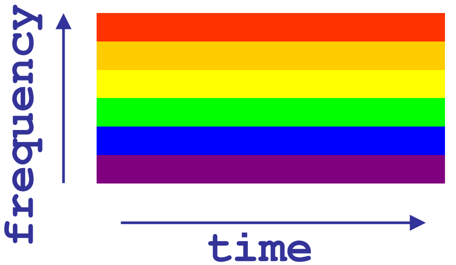
- Reservation establishes a “circuit” within a switch

Many kinds of circuits

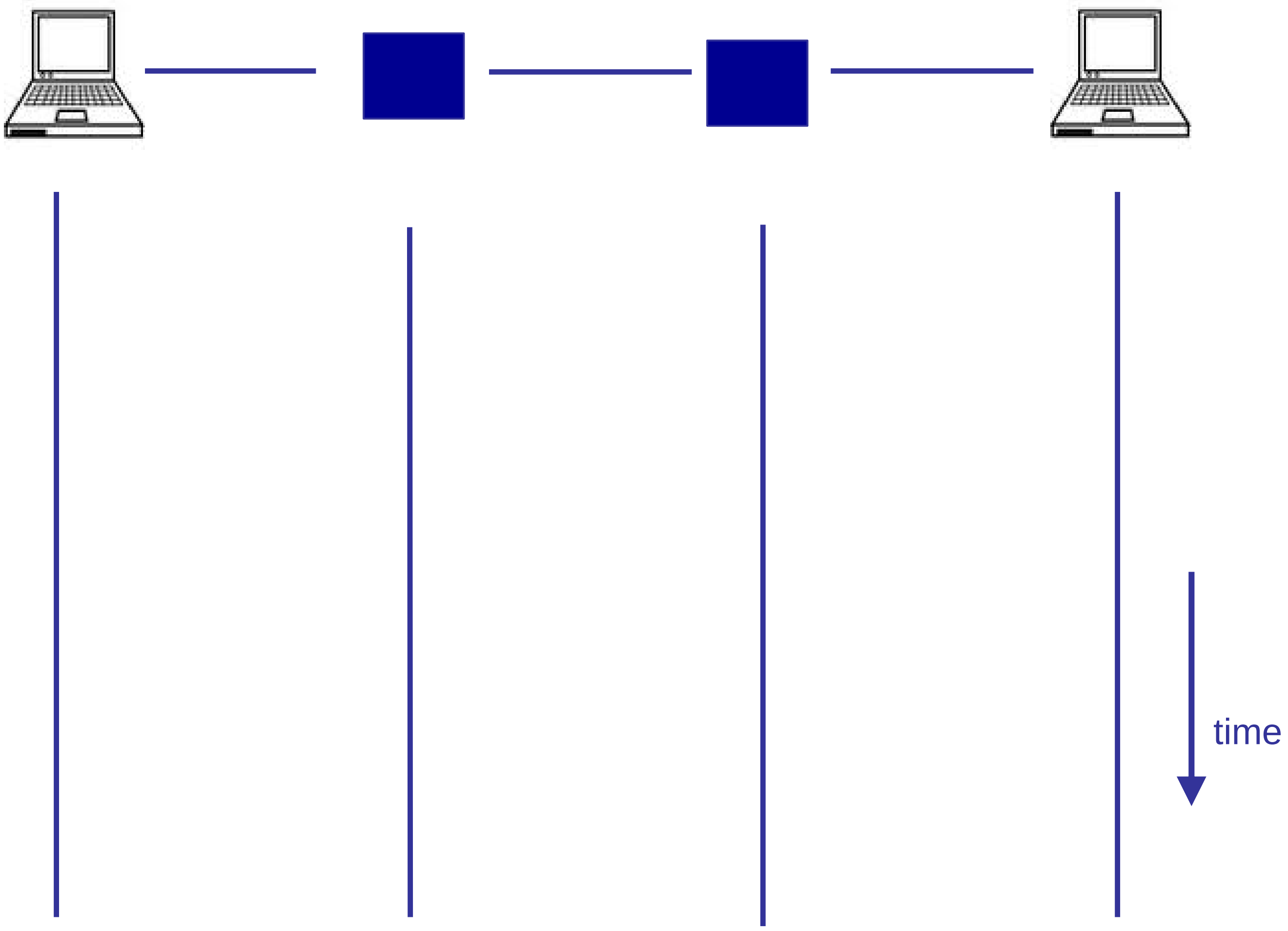
- Time division multiplexing
  - divide time in time slots
  - separate time slot per circuit



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



Timing in circuit switching



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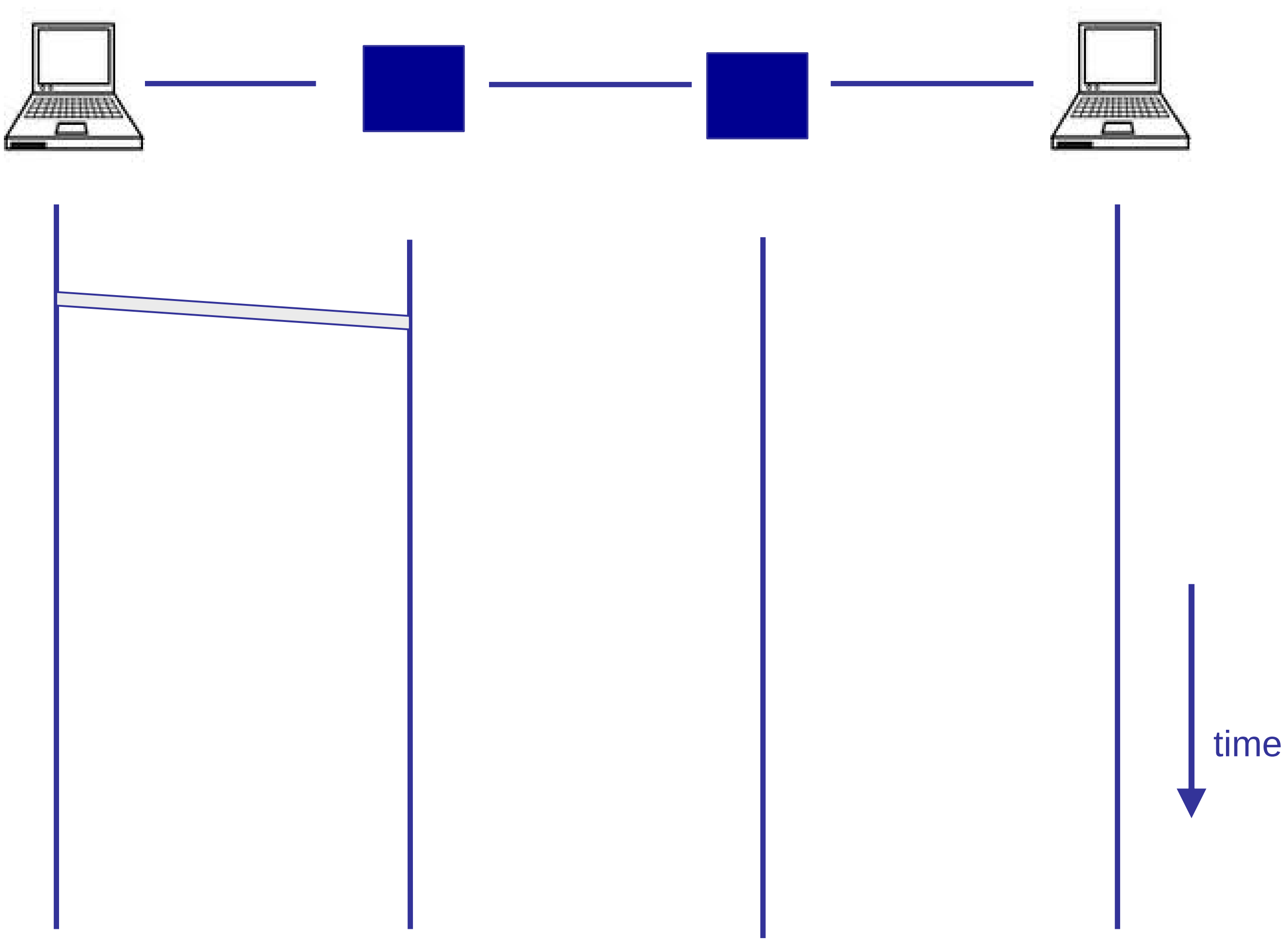

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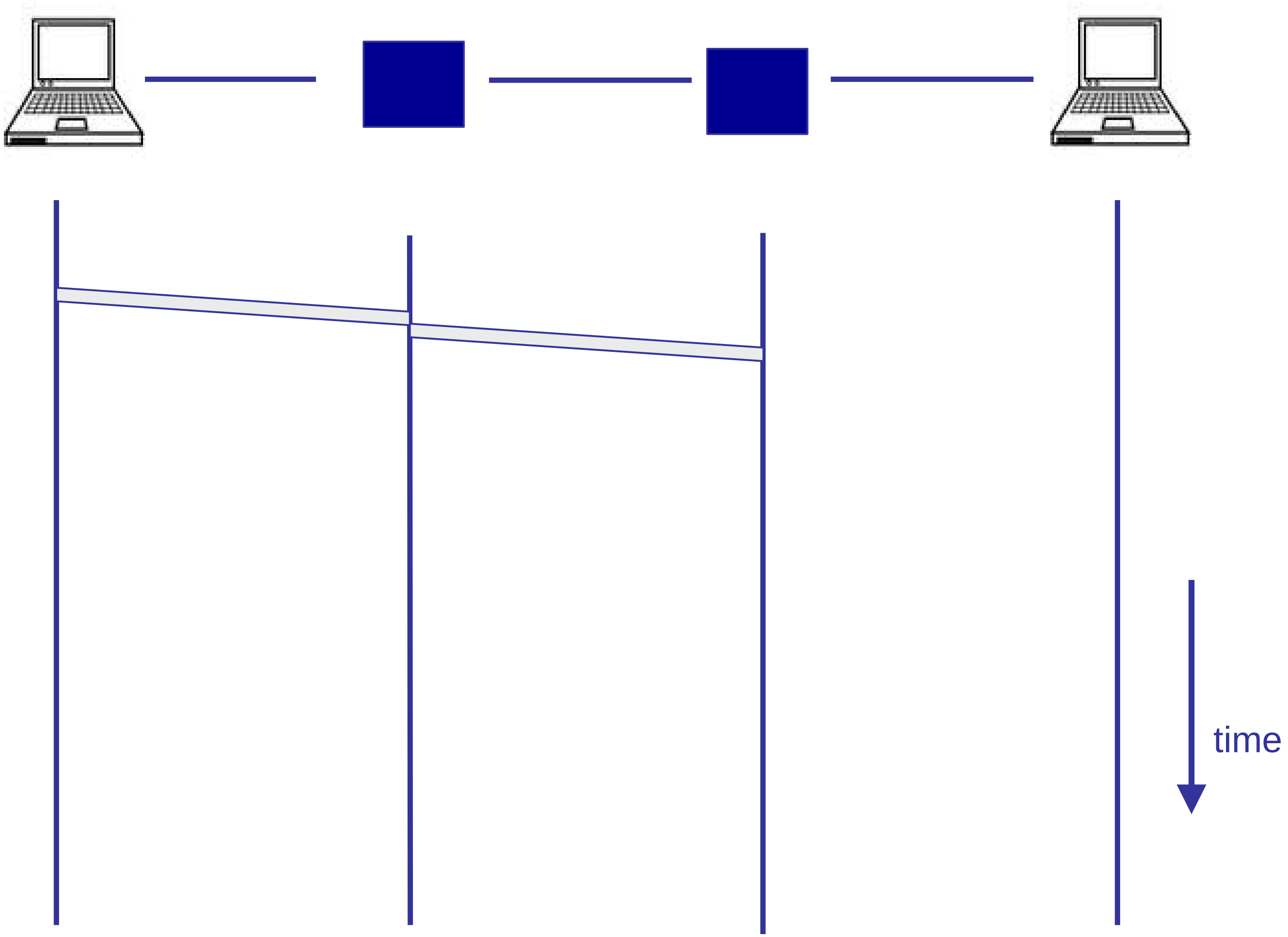

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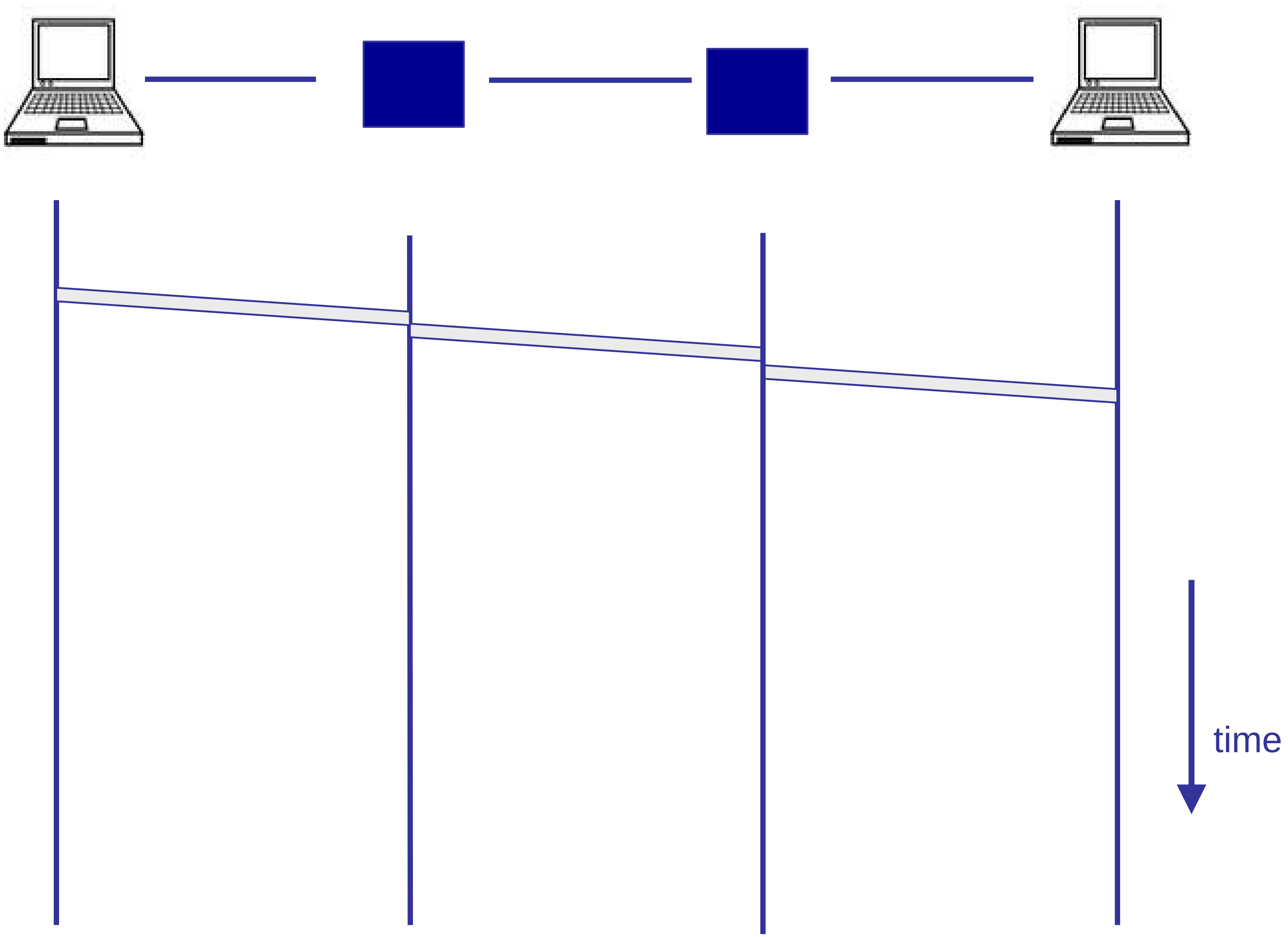

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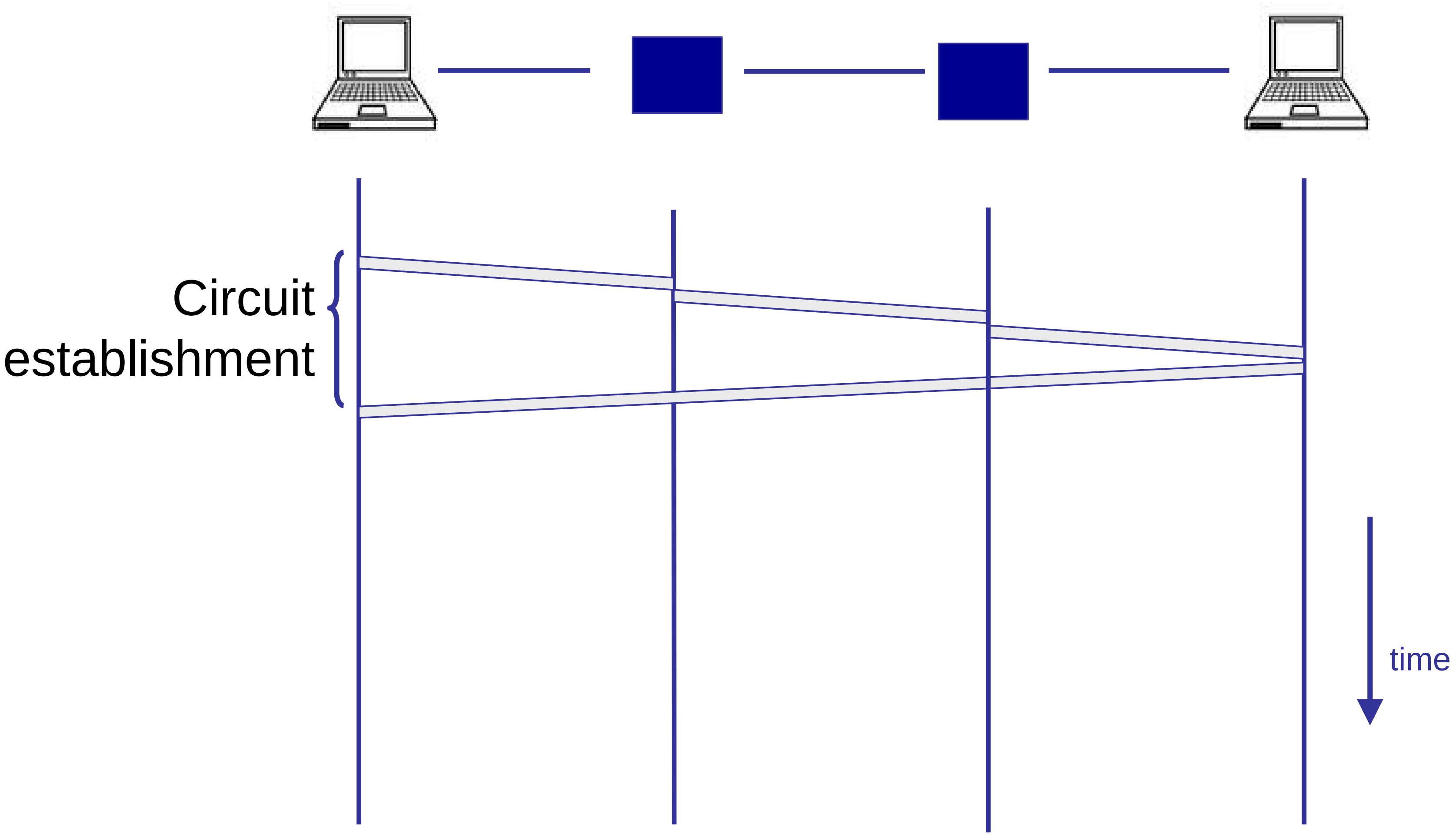

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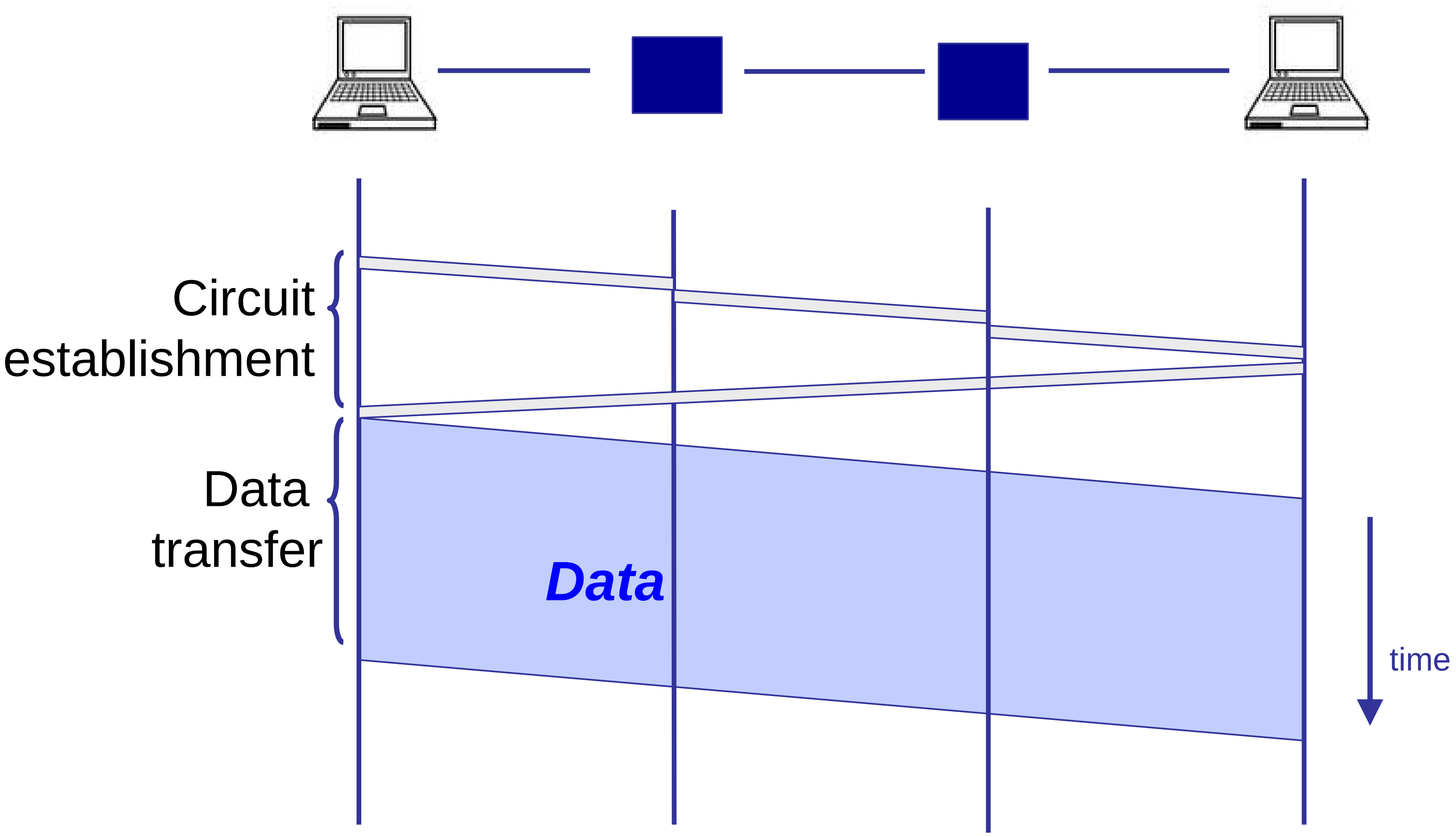

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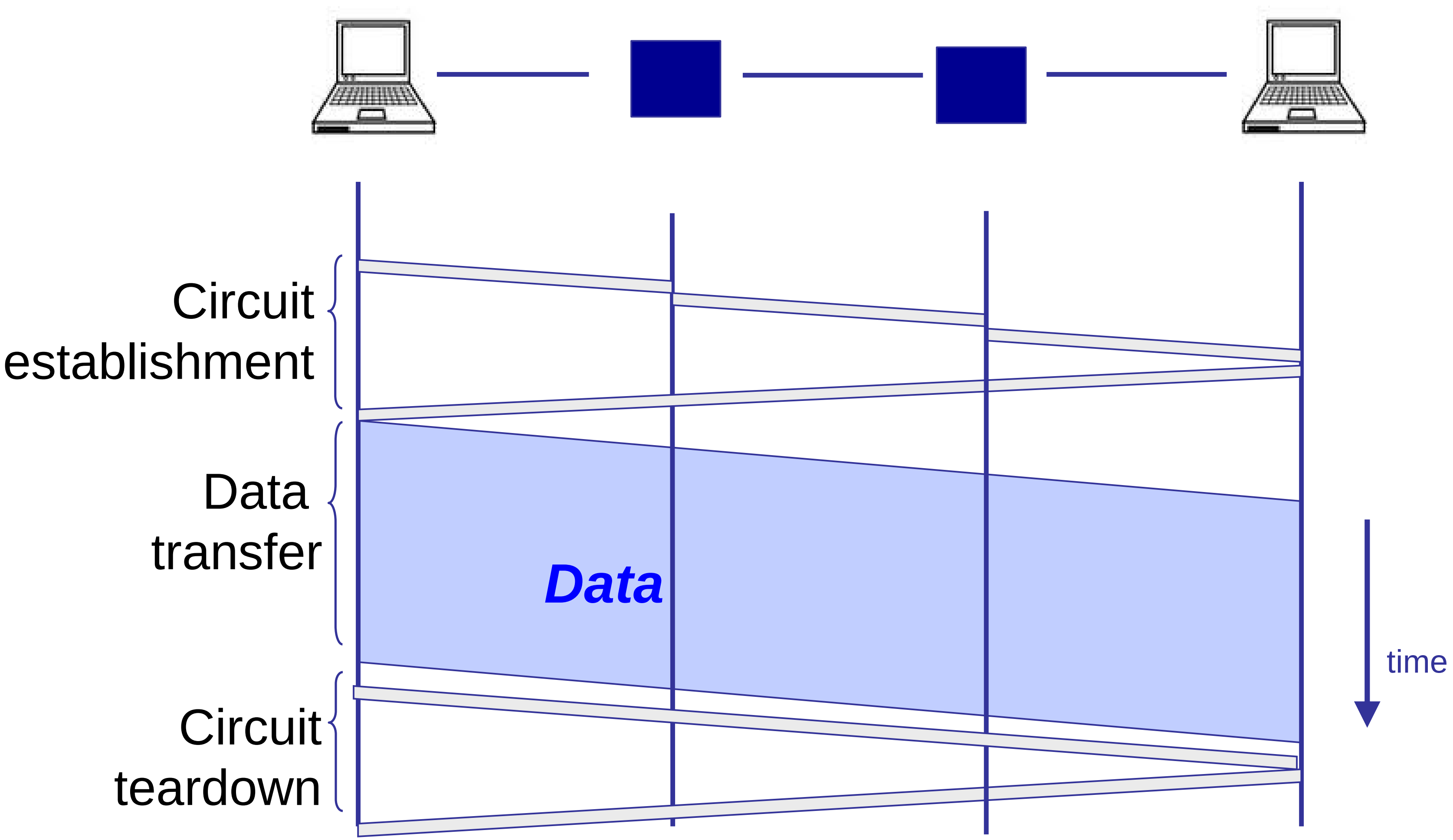
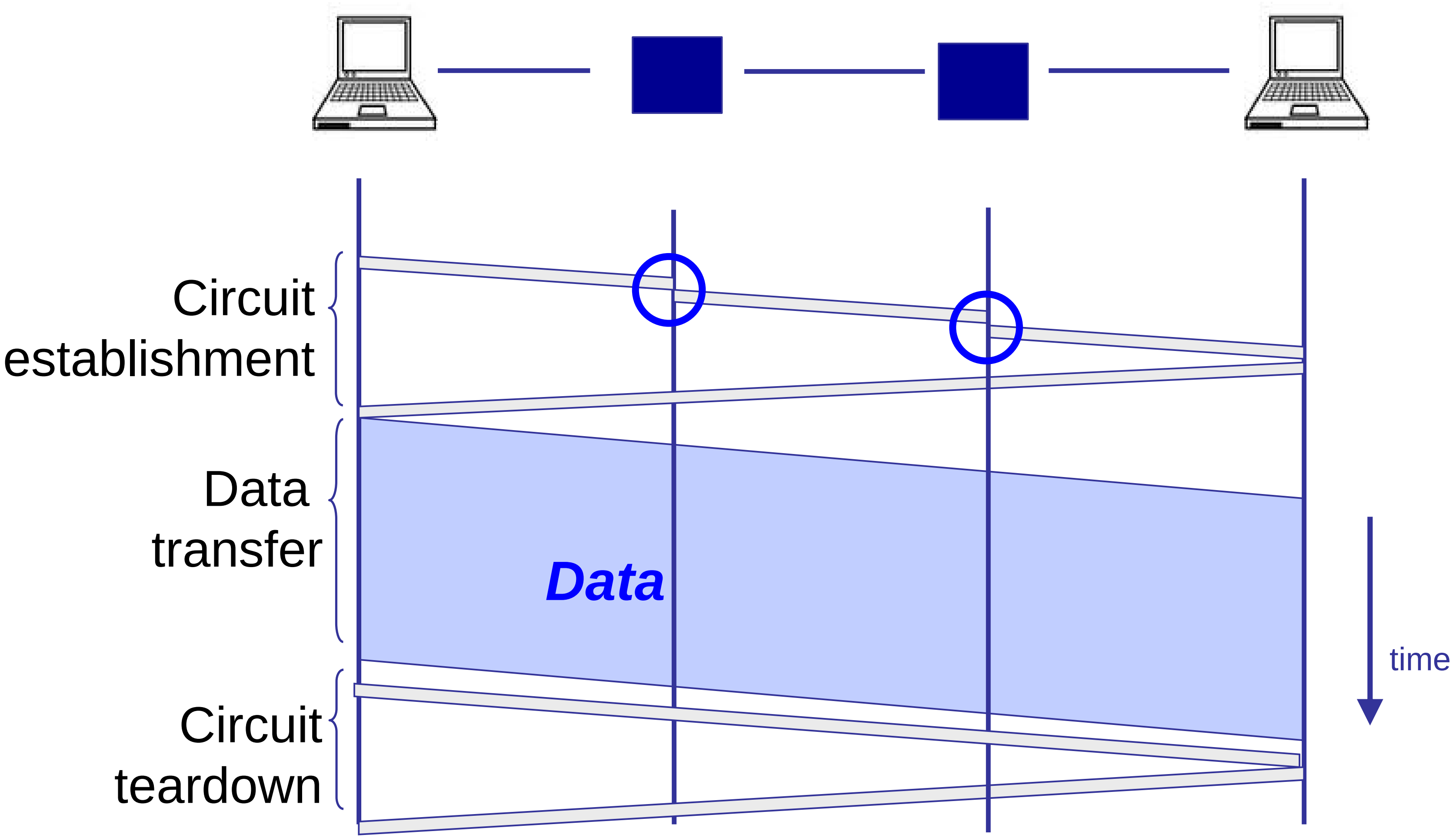
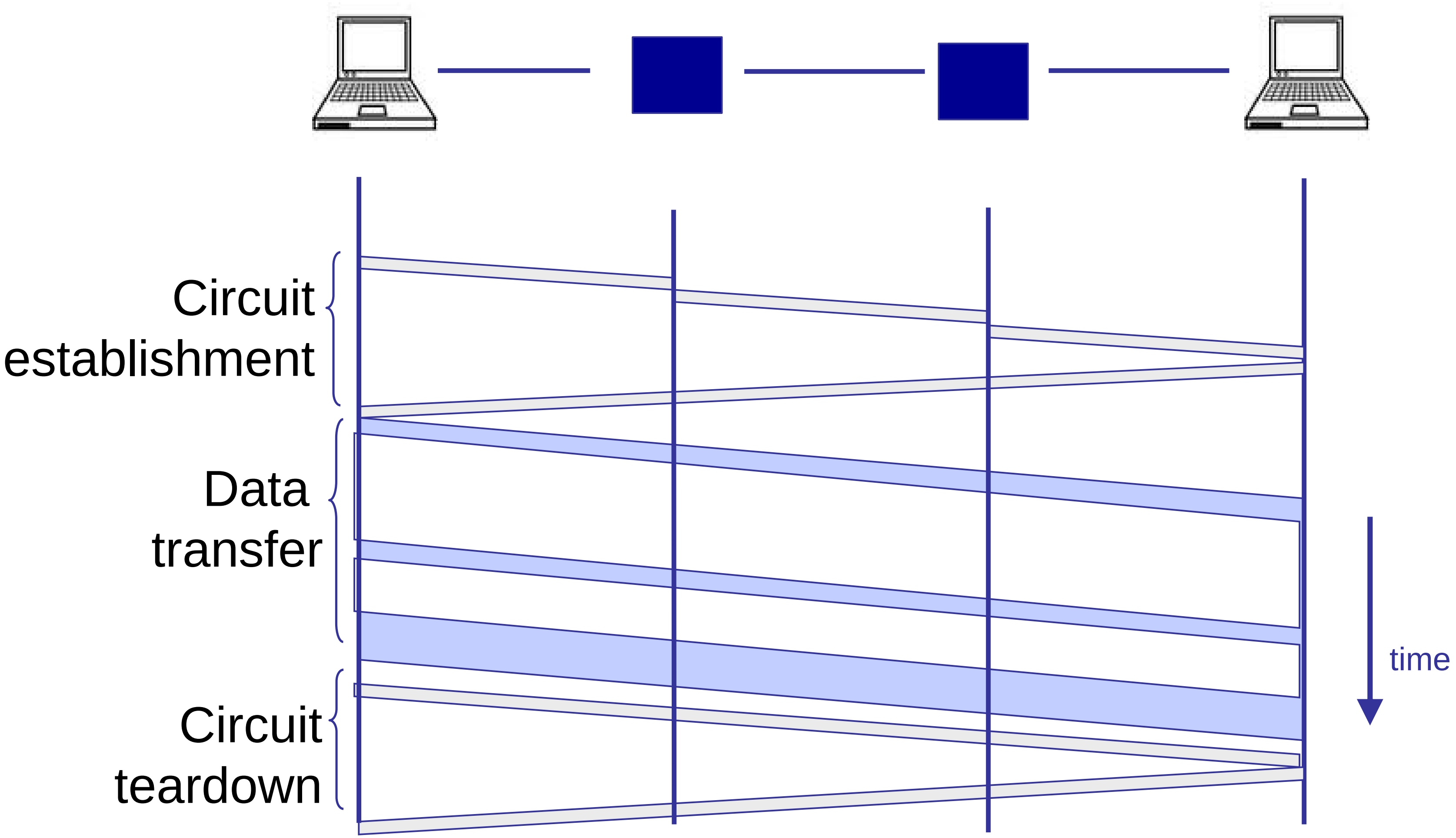


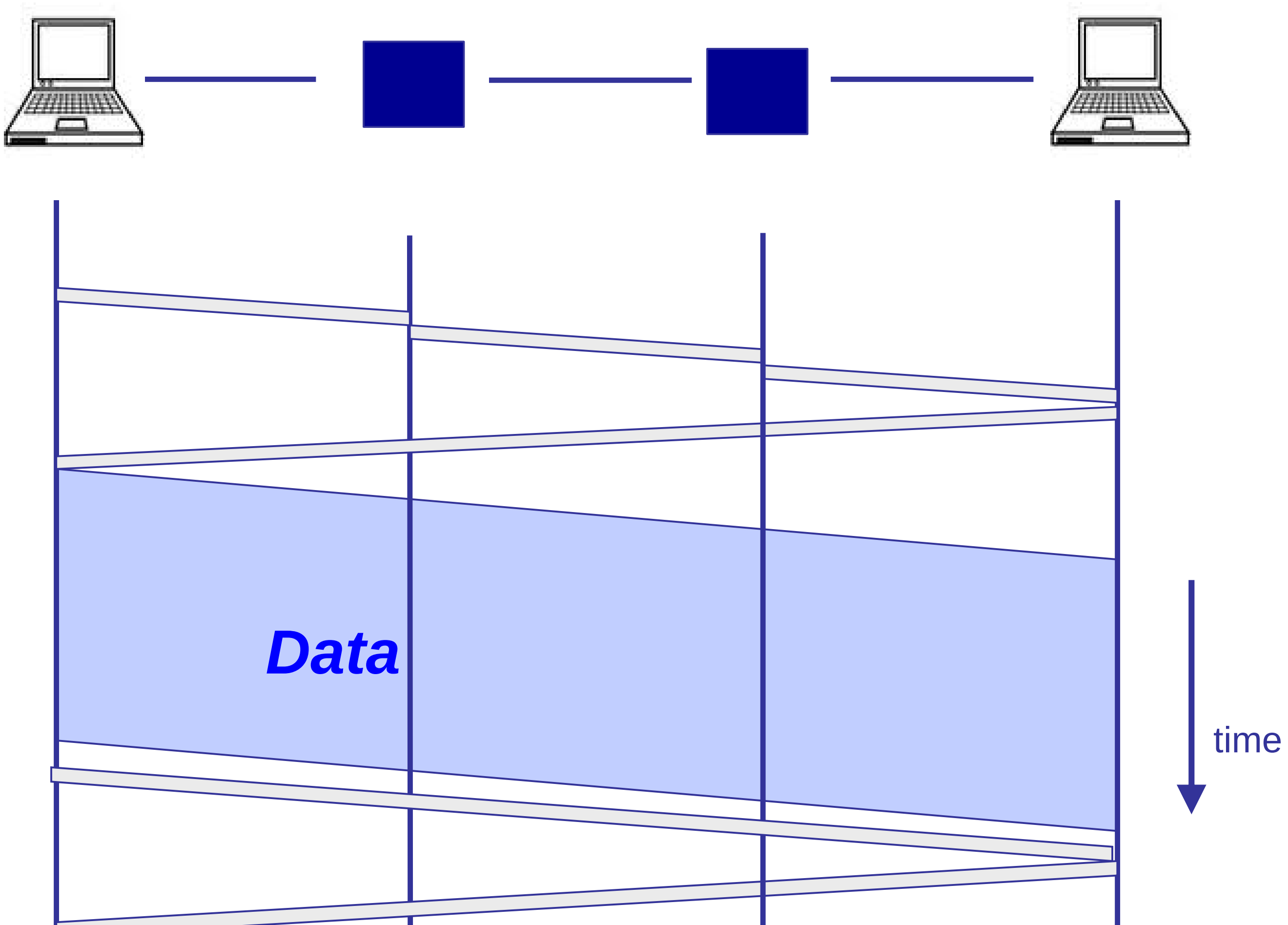
Why the delays?



Timing in circuit switching



Timing in circuit switching



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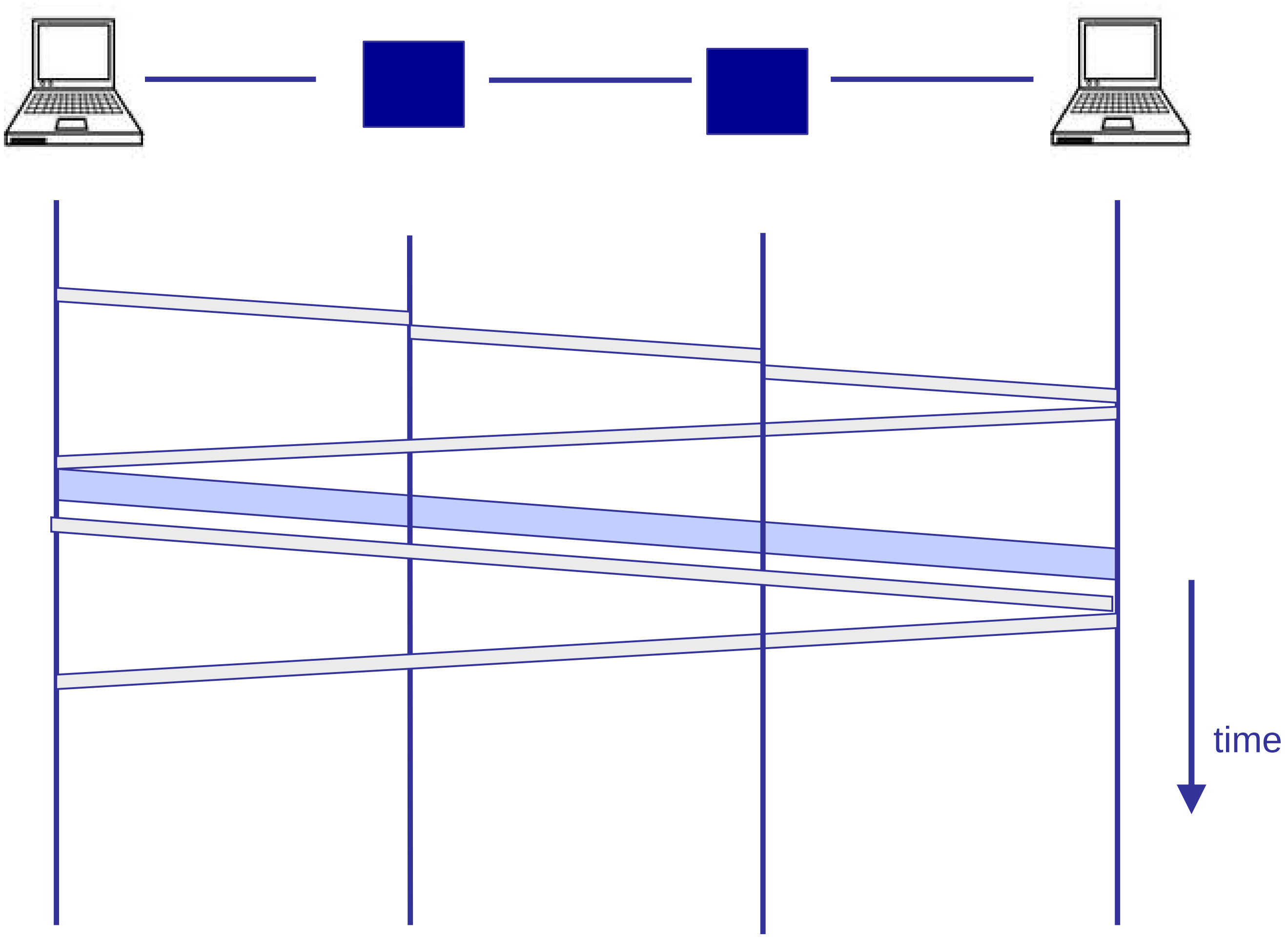
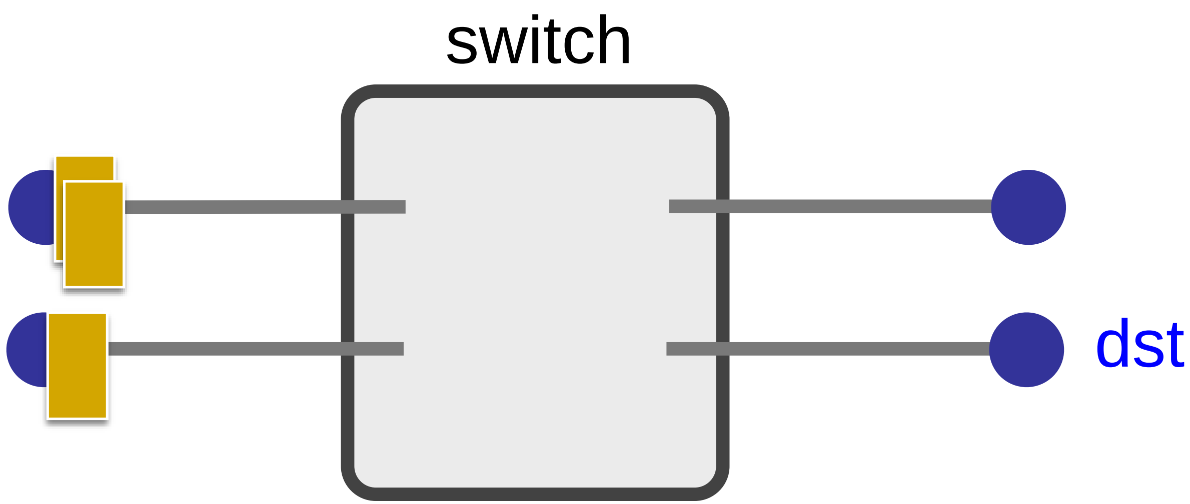


Circuit switching

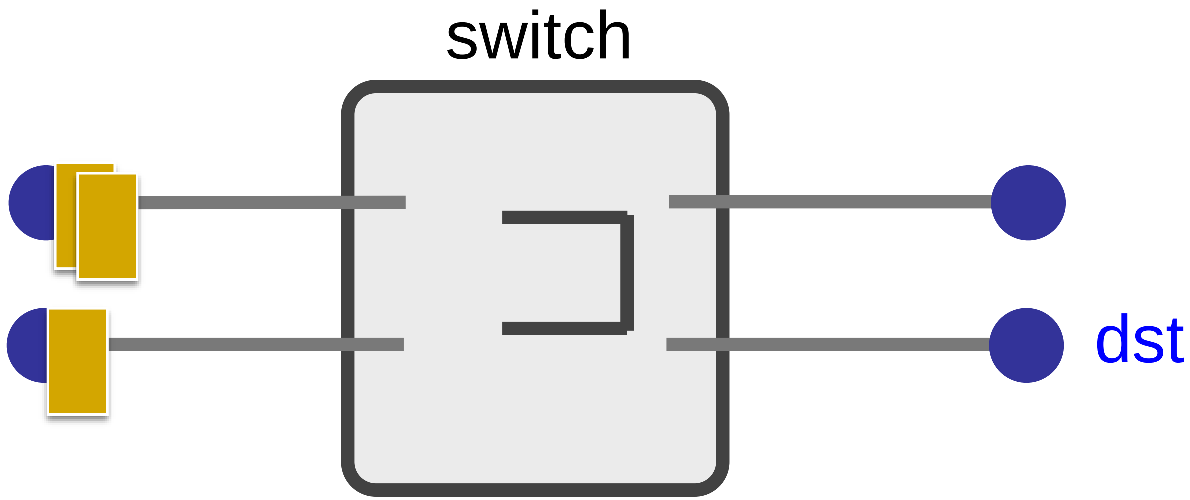
- Pros
  - Predictable performance
  - Simple/fast switching (once circuit established)
- Cons
  - Complexity of circuit setup/teardown
  - Inefficient when traffic is bursty
  - Circuit setup adds delay
  - Switch fails → its circuit(s) fails

Packet switching



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

Packet switching



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

Packet switching

- 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

- 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

HOW DO WE EVALUATE A NETWORK?

Performance metrics

- Delay
- Loss
- Throughput

Delay

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

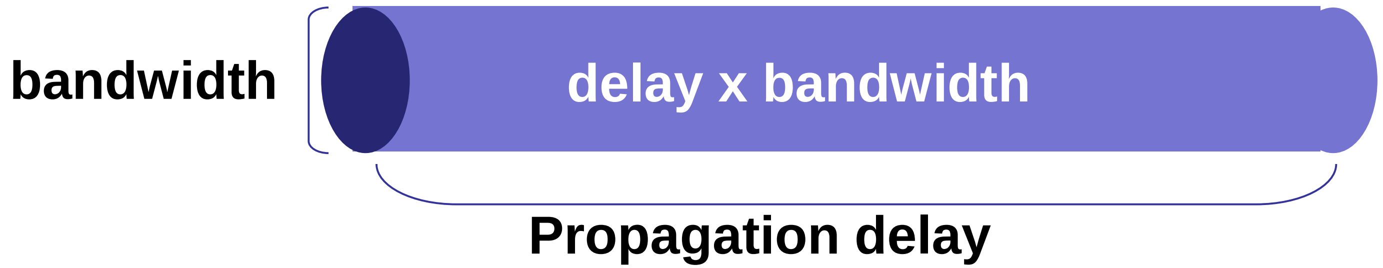
Delay

- 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



- 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 = bandwidth × propagation delay

Examples

- Same city over a slow link:
  - Bandwidth: ~100Mbps
  - Propagation delay: ~0.1msec
  - BDP: 10,000bits (1.25KBytes)

- Cross-country over fast link:
  - Bandwidth: ~10Gbps
  - Propagation delay: ~10msec
  - BDP: 10^8bits (12.5MBytes)

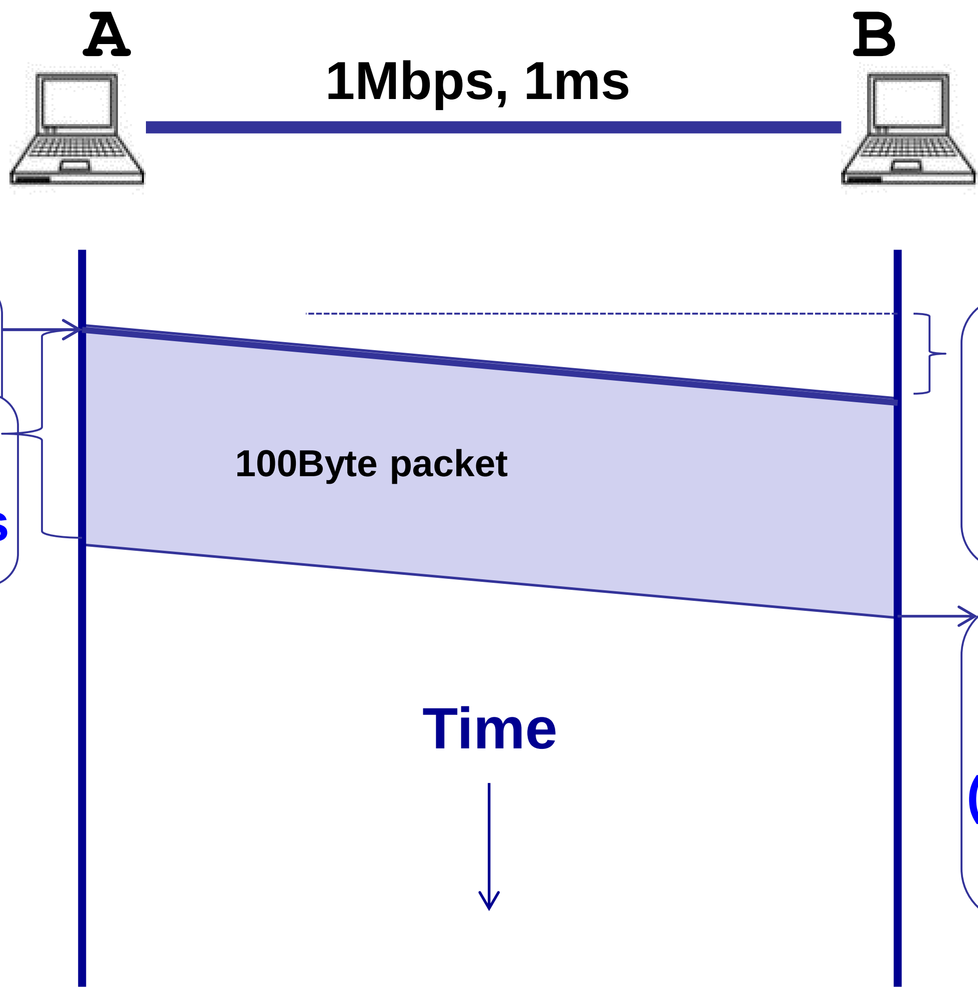
1. Transmission delay

- 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

- 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 / $3*10^8$ meters per sec = 10^{-4} sec

Packet delay
Sending a 100-byte packet



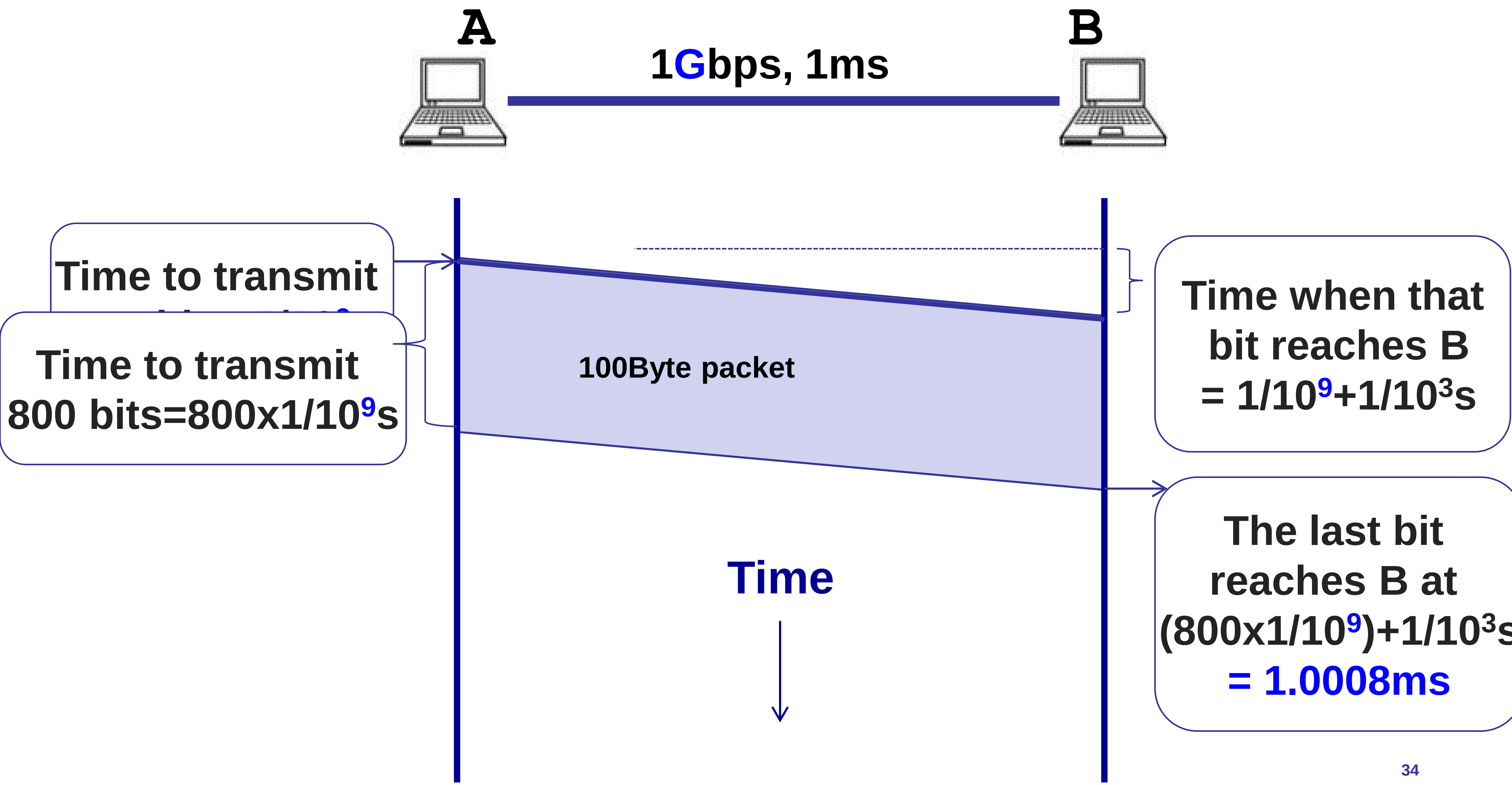
Time to transmit

Time to transmit 800 bits=800x1/10^6s

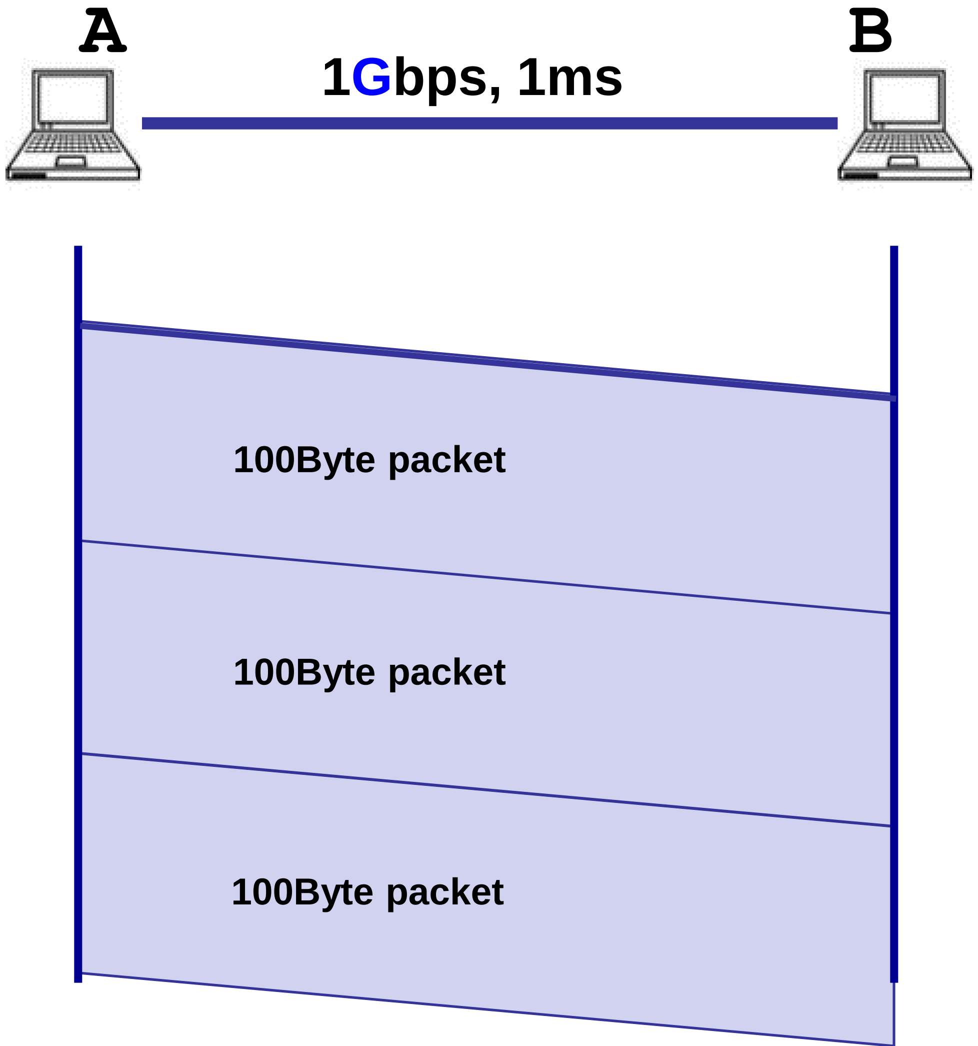
Time when that bit reaches B = 1/10^6+1/10^3s

The last bit reaches B at (800x1/10^6)+1/10^3s = 1.8ms

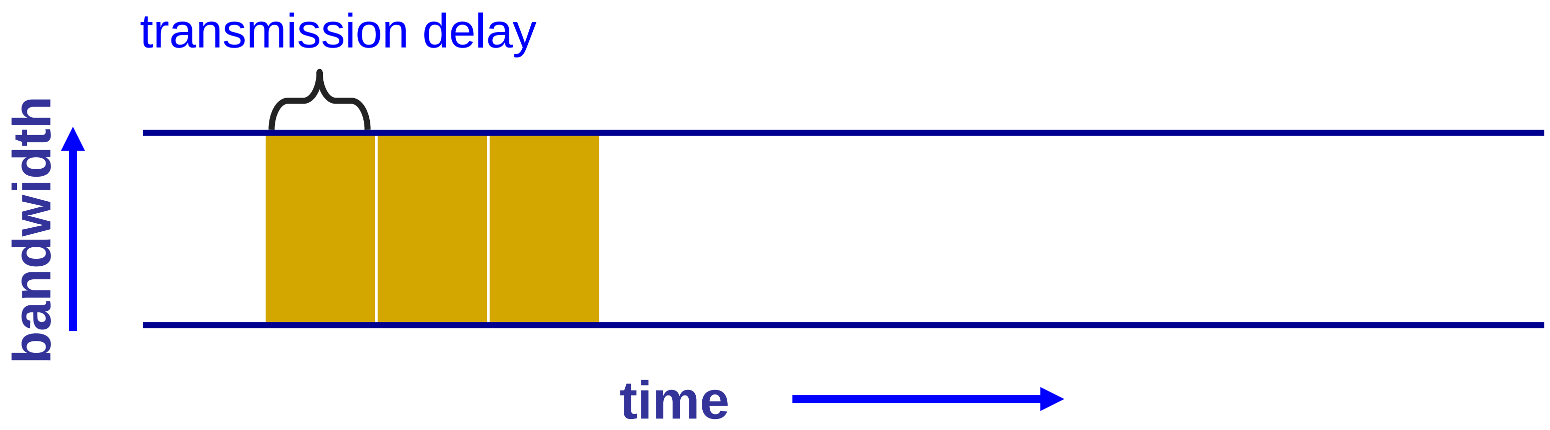
Packet delay
Sending a 100-byte packet



Sending a large file using 100-byte packets



Pipe view of a link

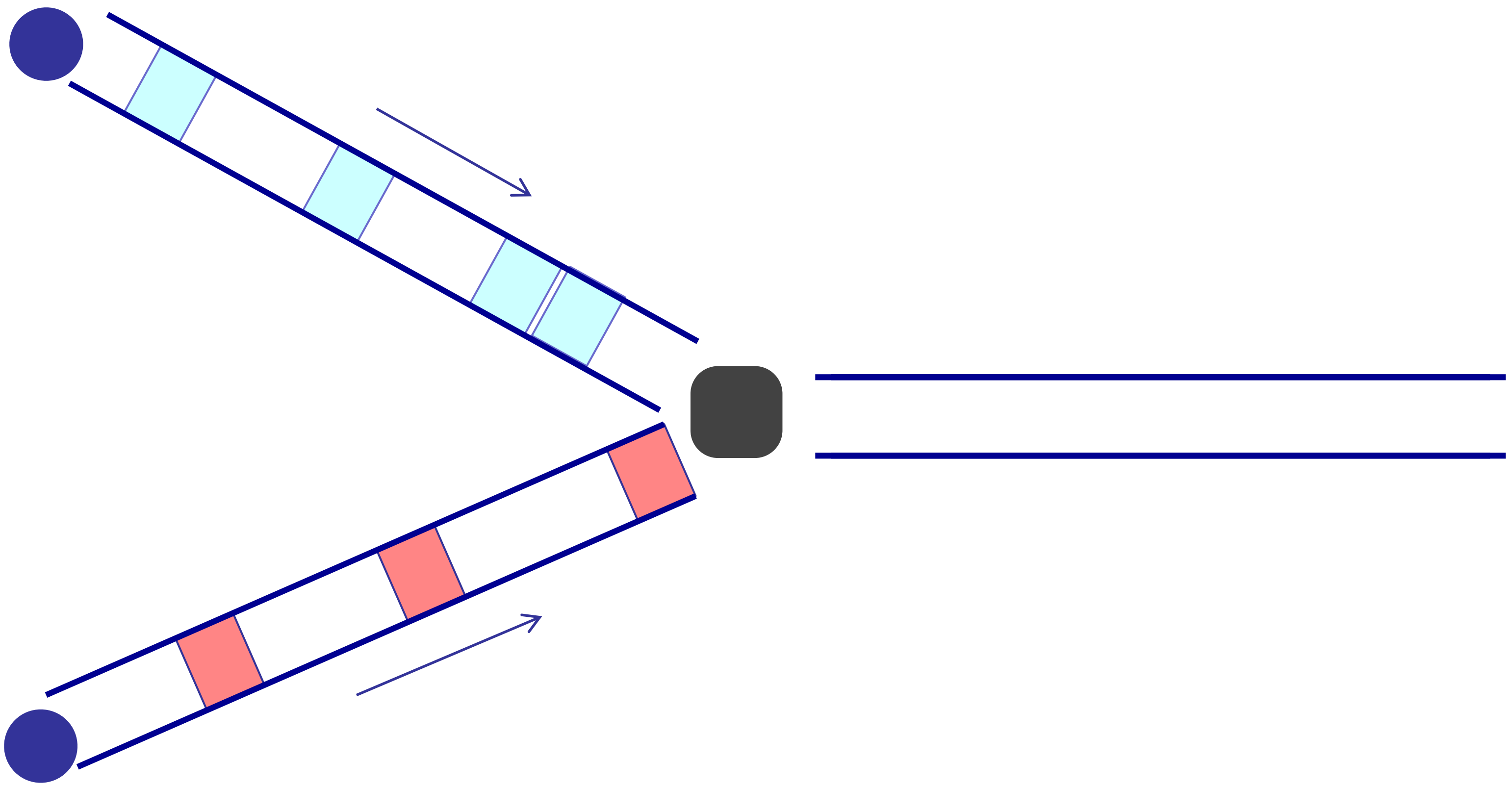


- Transmission delay decreases as bandwidth increases

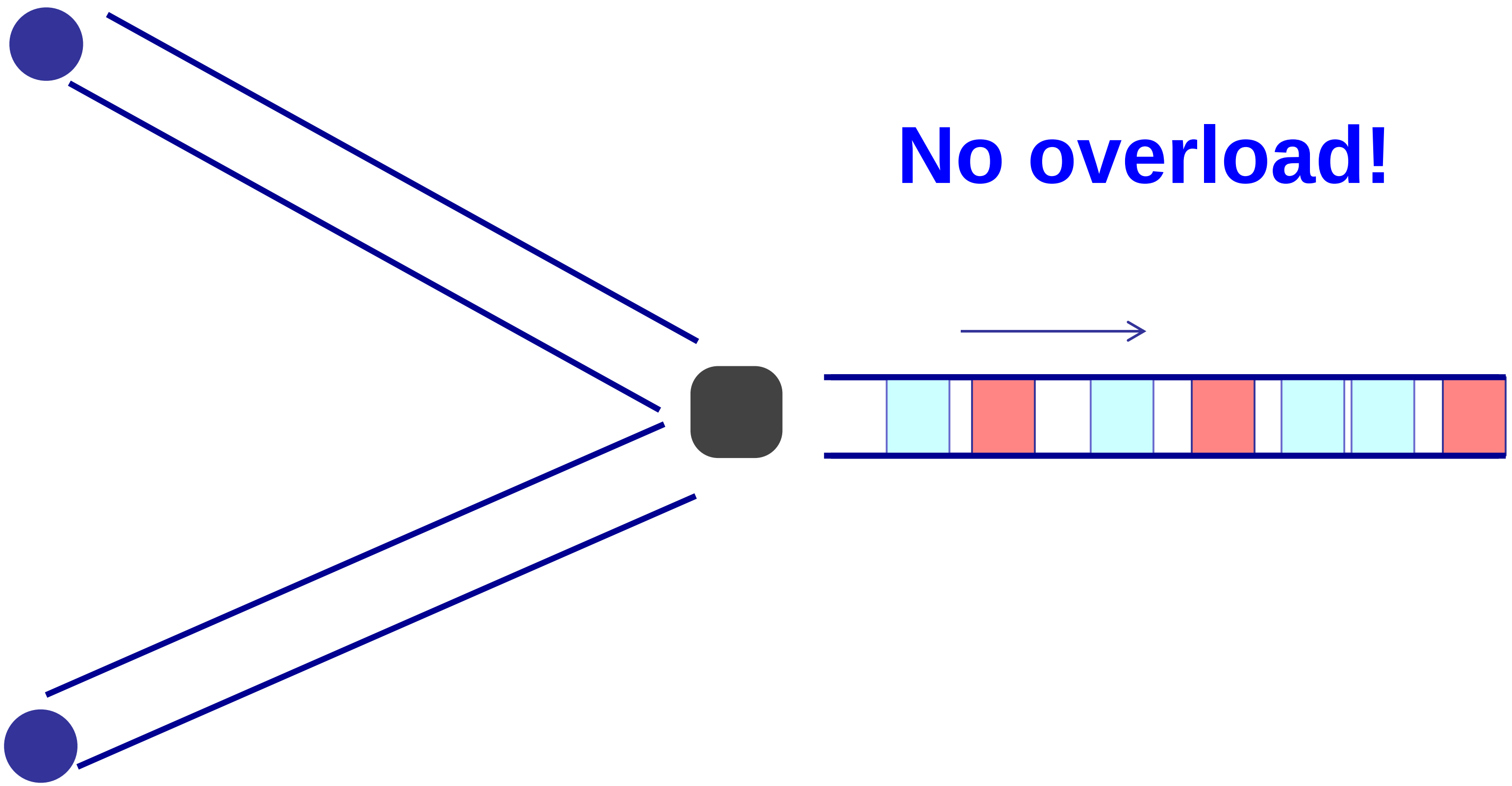
3. Queuing delay

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

Queueing delay: “pipe” view

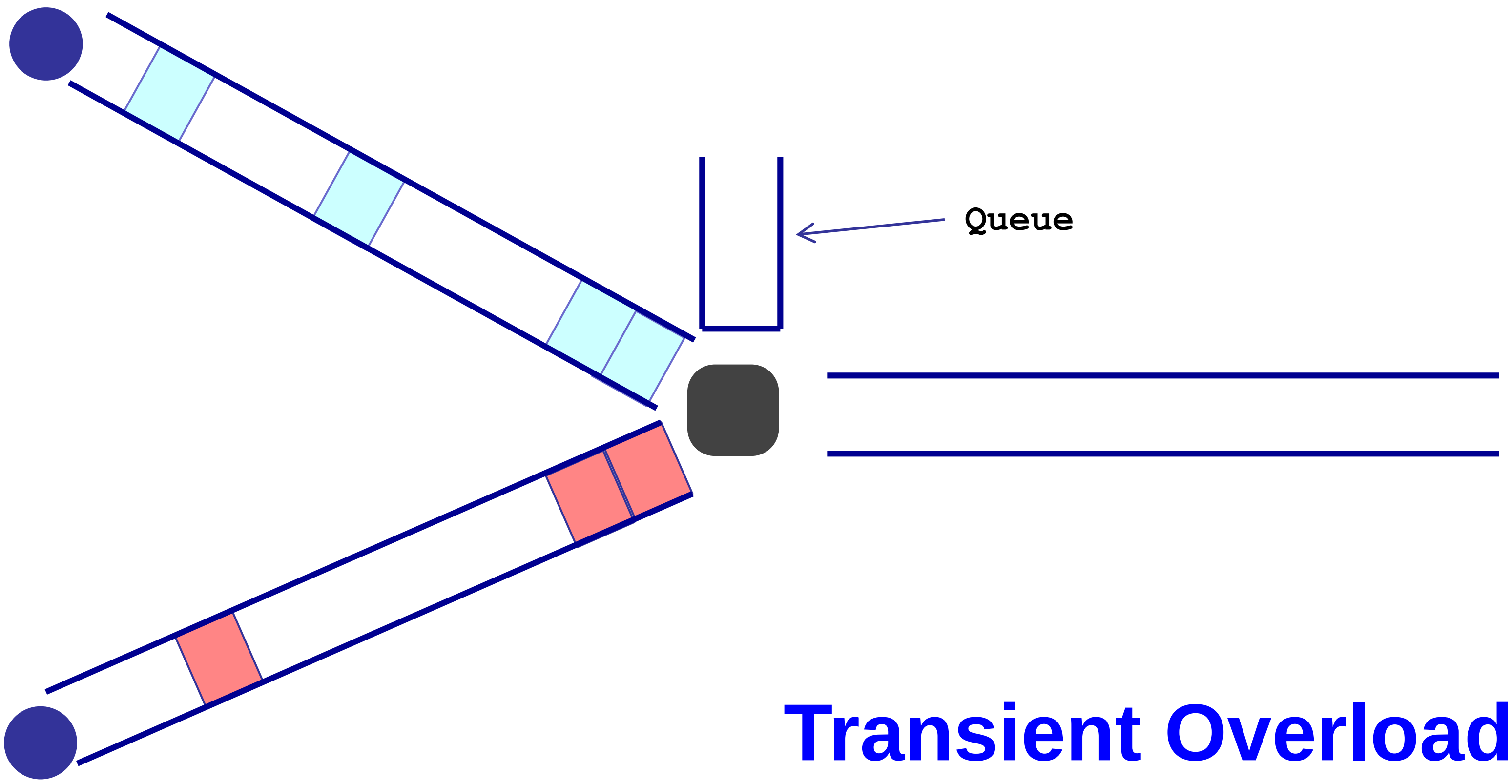


Queueing delay: “pipe” view



No overload!

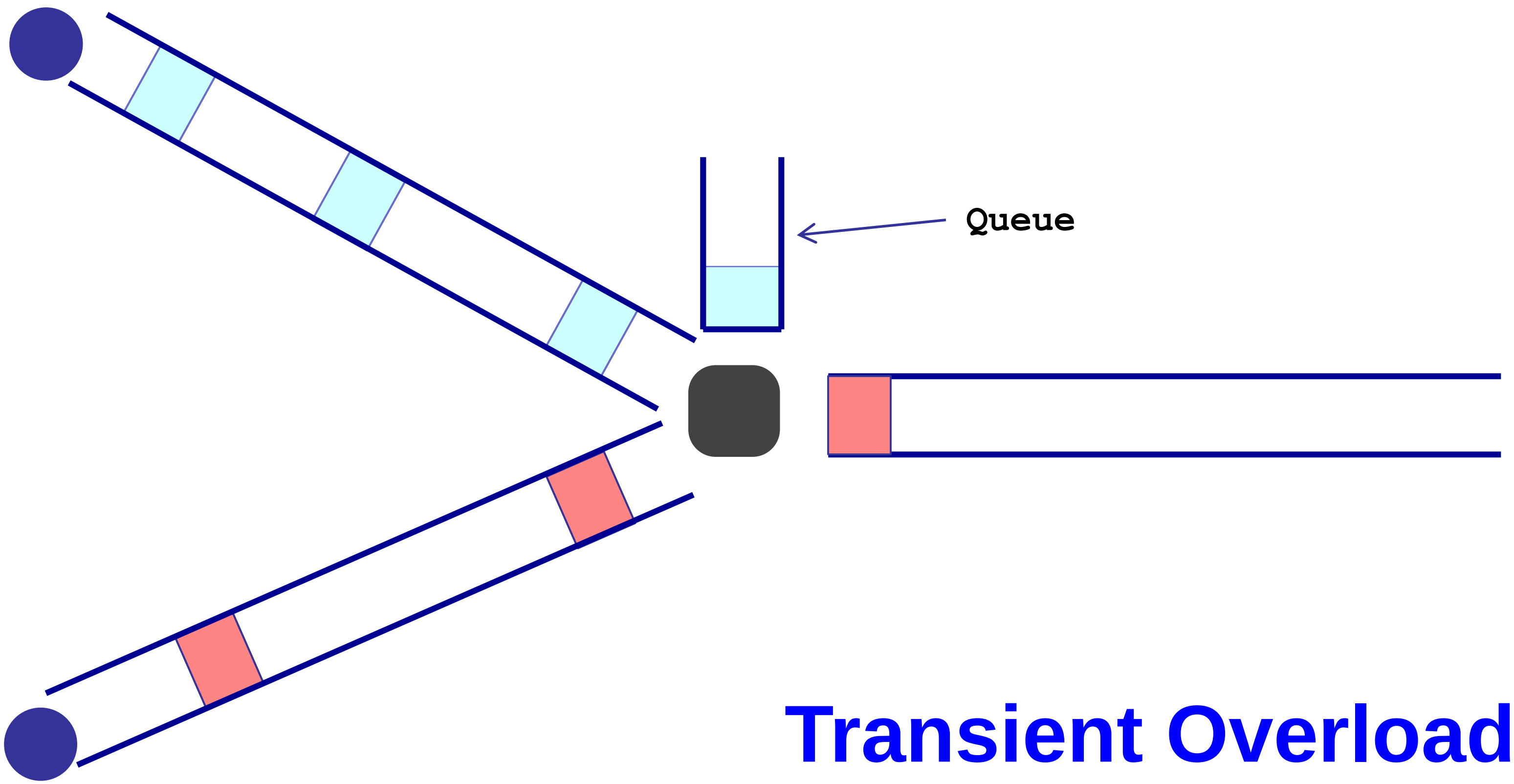
Queueing delay: “pipe” view



Transient Overload

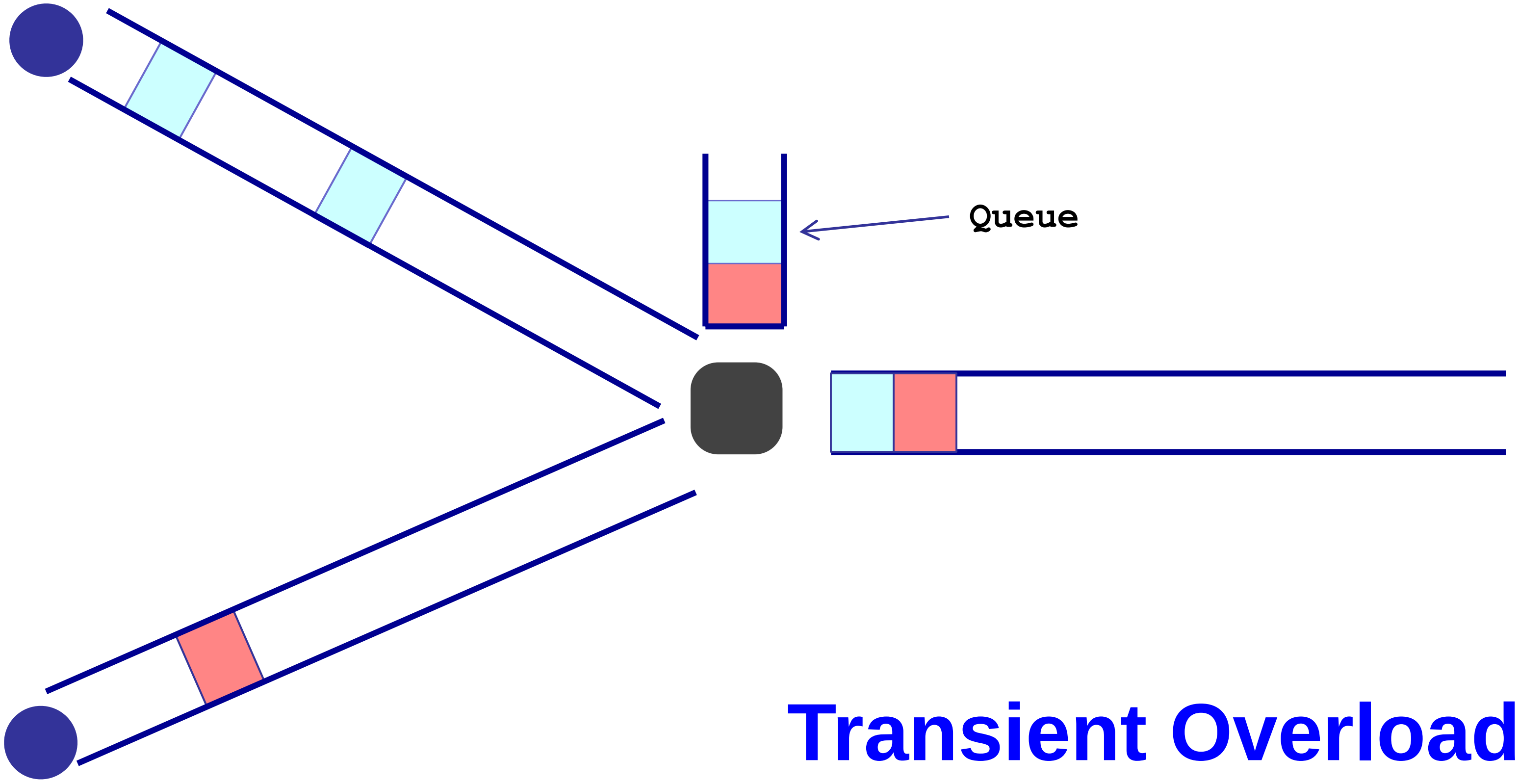
Not a rare event!

Queueing delay: “pipe” view



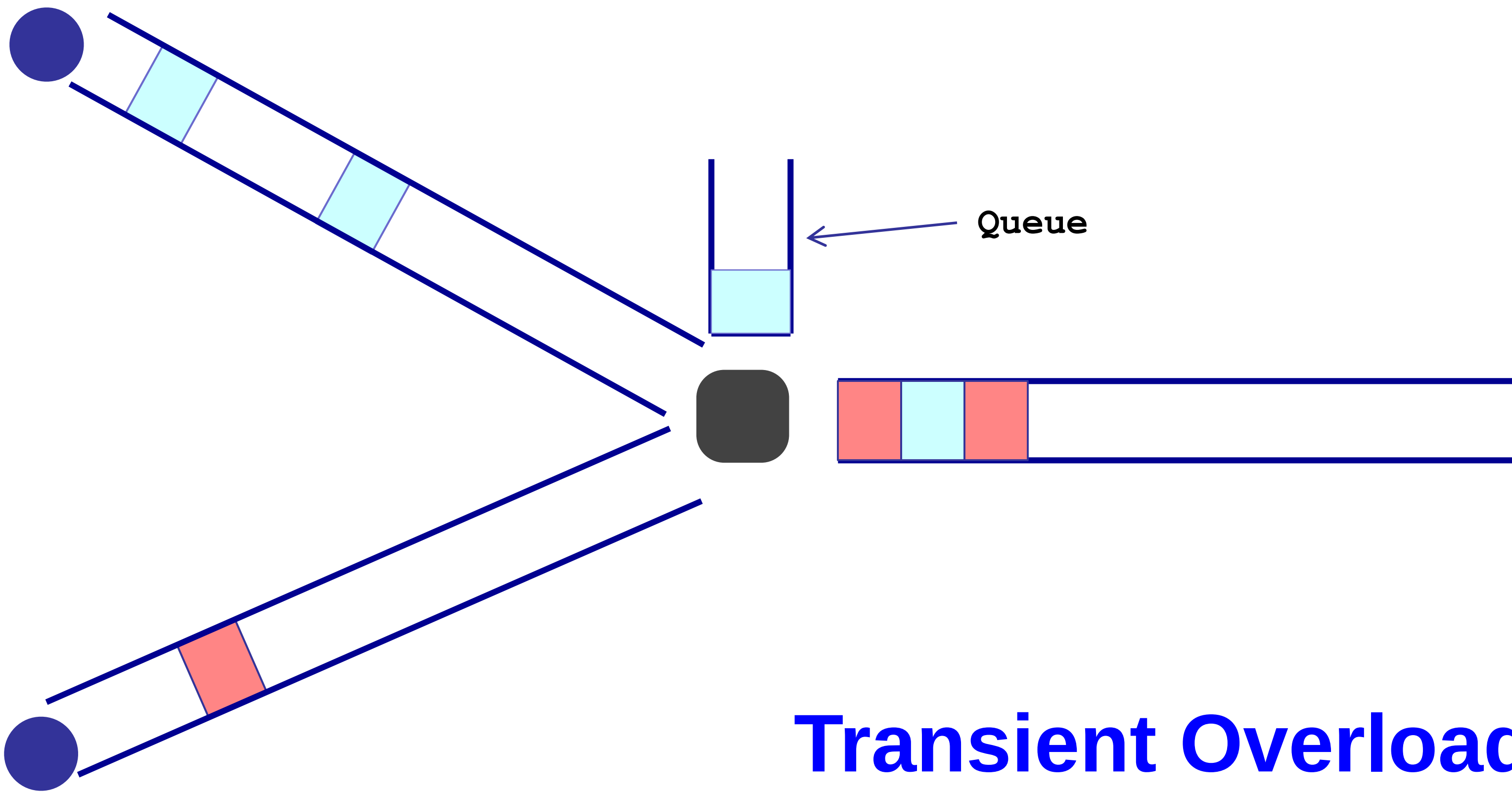
Transient Overload

Queueing delay: "pipe" view



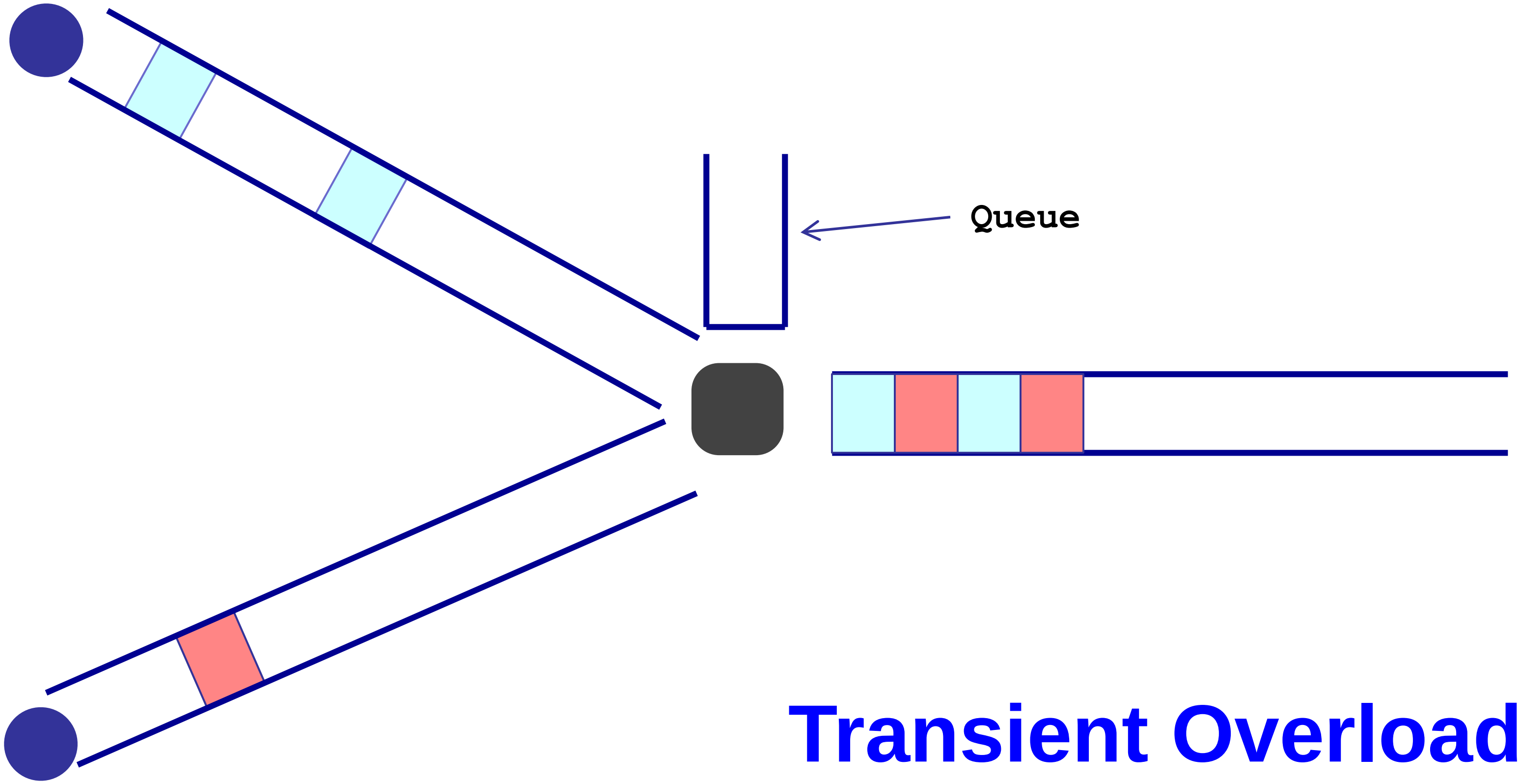
Transient Overload

Queueing delay: “pipe” view



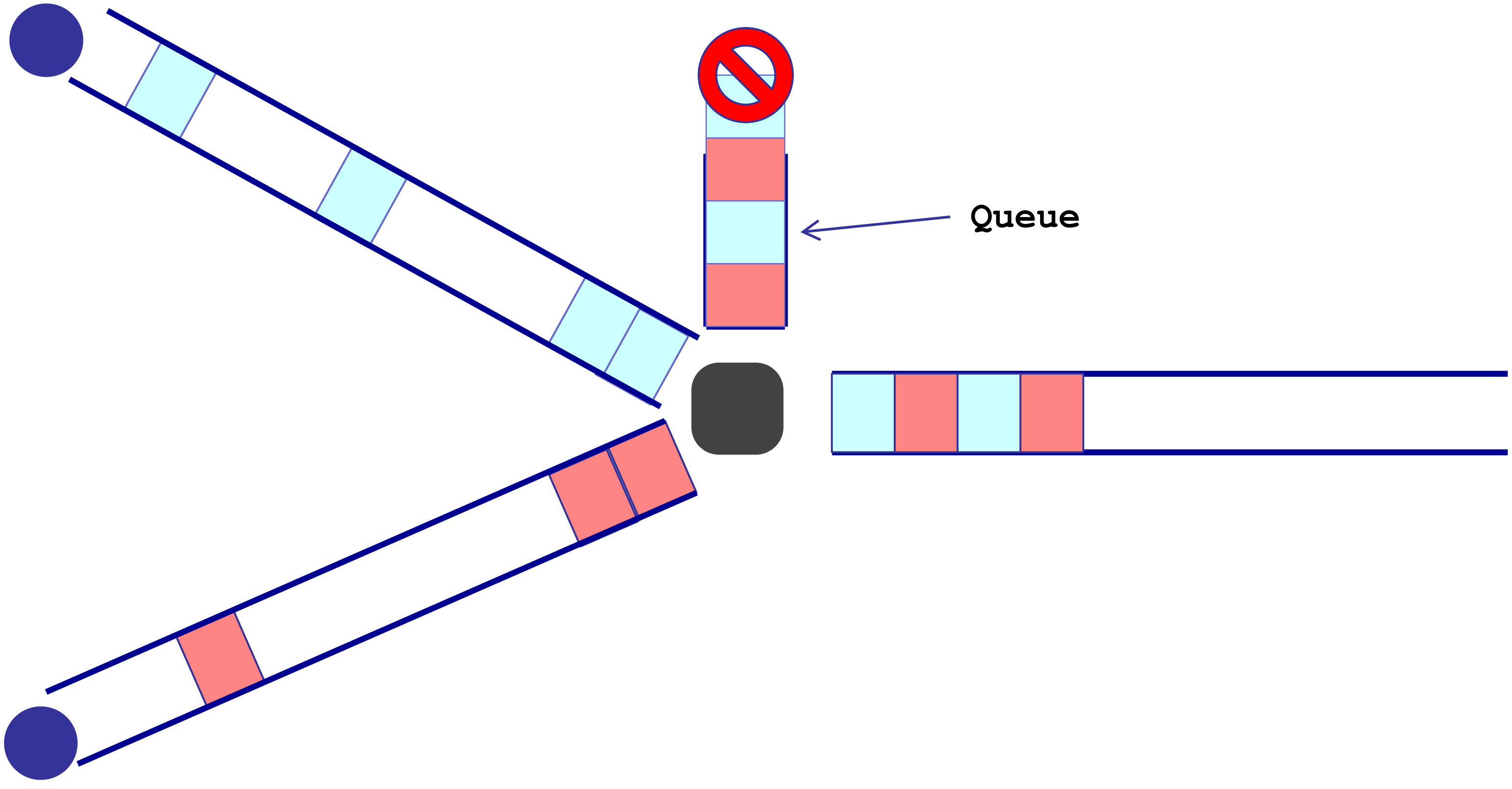
Transient Overload

Queueing delay: “pipe” view



Transient Overload

Persistent overload leads to packet loss



Queueing delay

- 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

- 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

- Arrival process: how packets arrive
  - Average rate A
  - Peak rate P
- 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)

- L = A x W
- Compute L: count packets in queue every second
  - How often does a single packet get counted? W times
- Why do you care?
  - Easy to compute L, harder to compute W

4. Processing Delay

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

End-to-end delay

transmission

propagation

queueing
processing

transmission

propagation

queueing
processing

transmission

propagation

Loss

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

Throughput

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

Throughput

Transmission rate R bits/sec

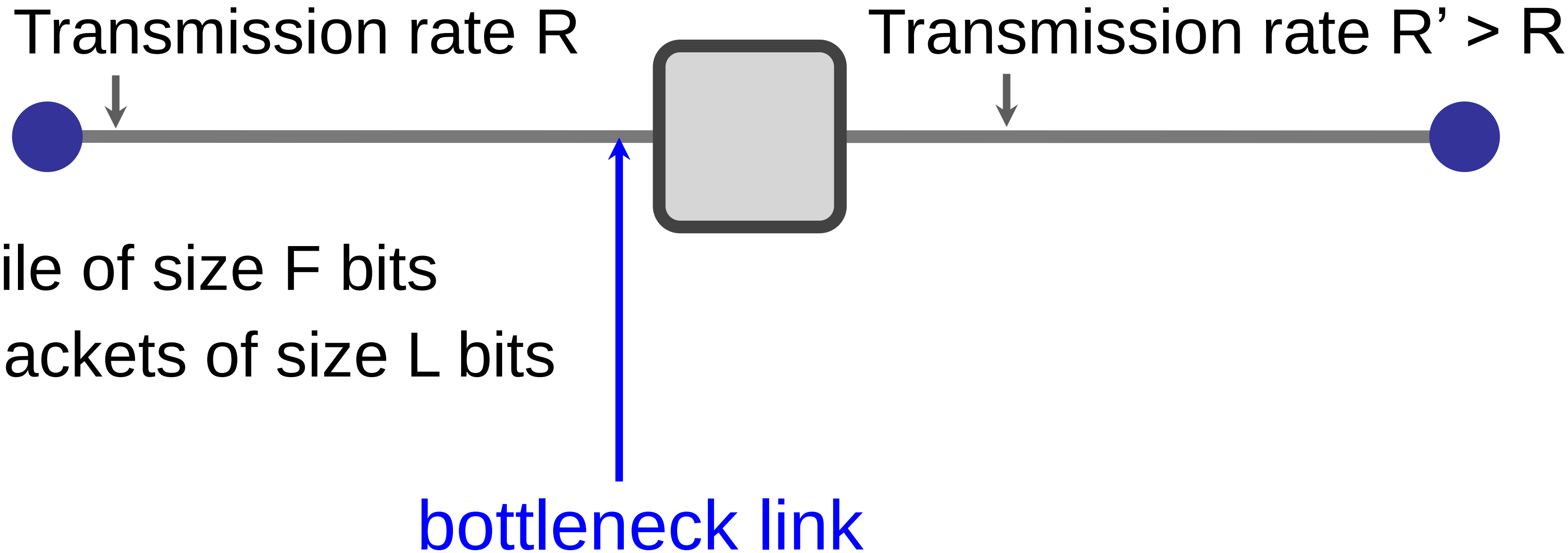
File of size F bits

Packets of size L bits

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

Average throughput = F/T ≈ R

End-to-end throughput



File of size F bits

Packets of size L bits

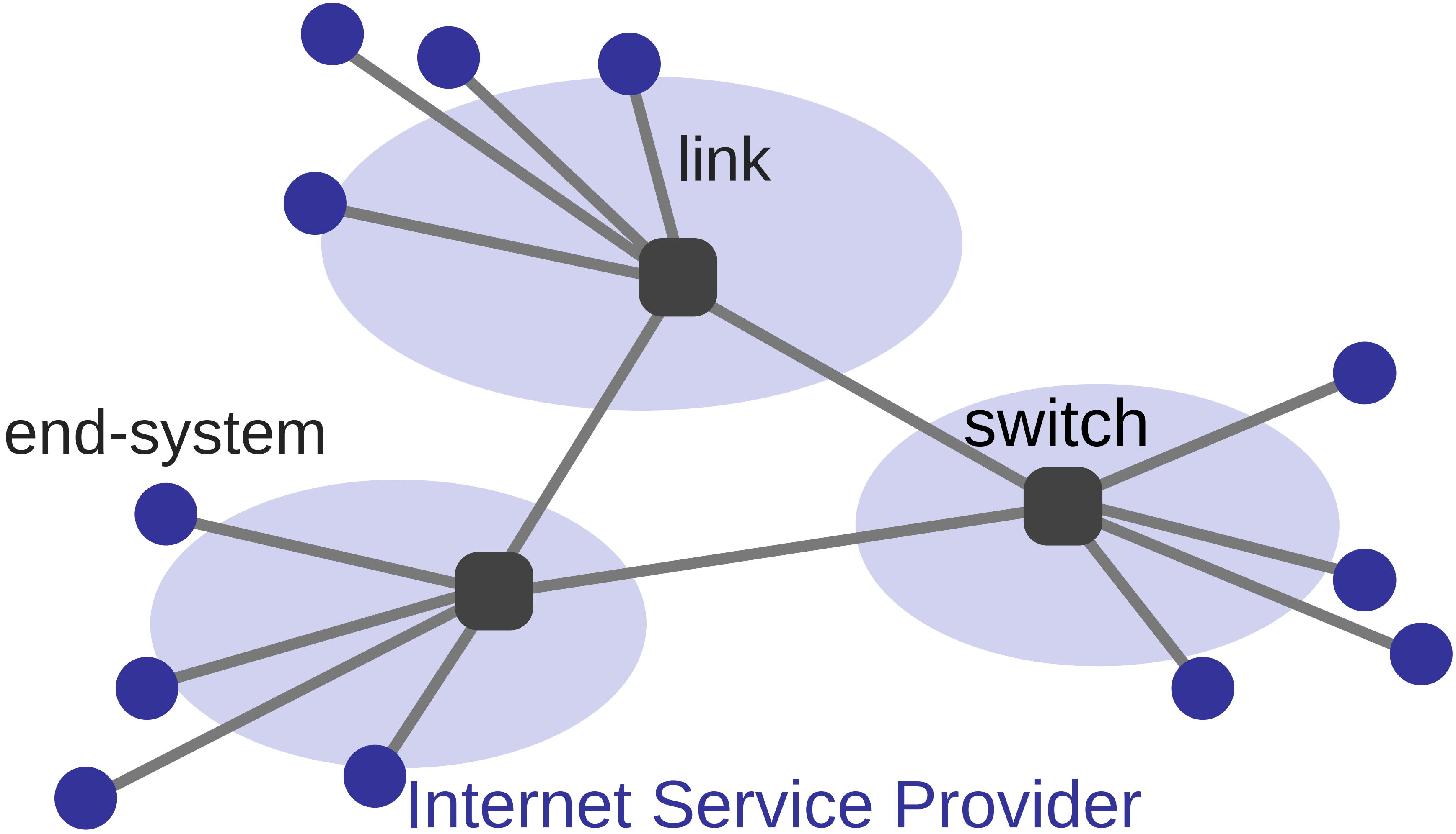
Average throughput = min{R, R’} = R

Summary

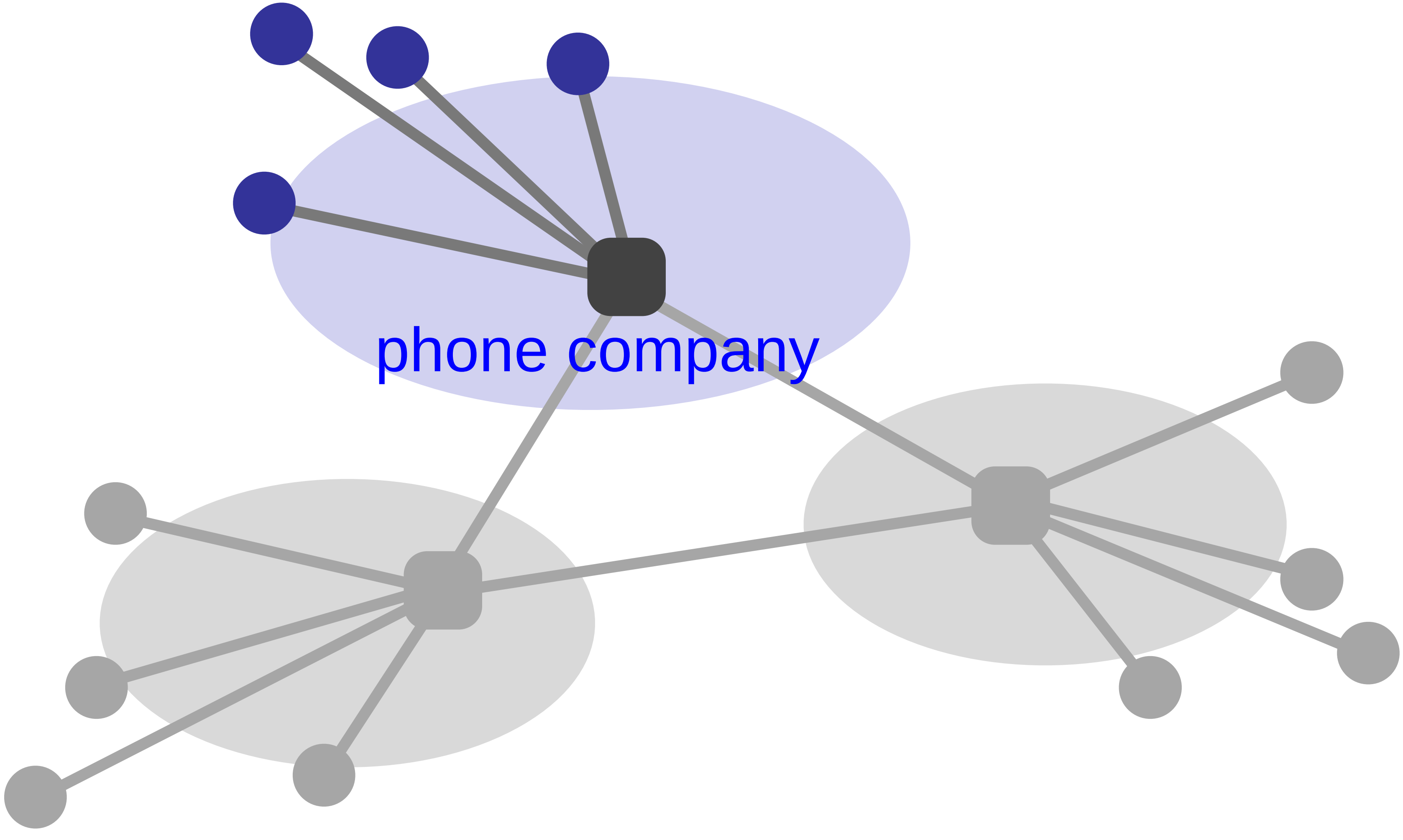
- How is it shared?
  - On-demand or via reservation
- How do we evaluate a network?
  - Bandwidth, delay, loss, BDP, …
- What is a network made of?
  - Whatever physical infrastructure exist
  - See backup slides

WHAT IS THE NETWORK MADE OF?

What is a network made of?



What is a network made of?



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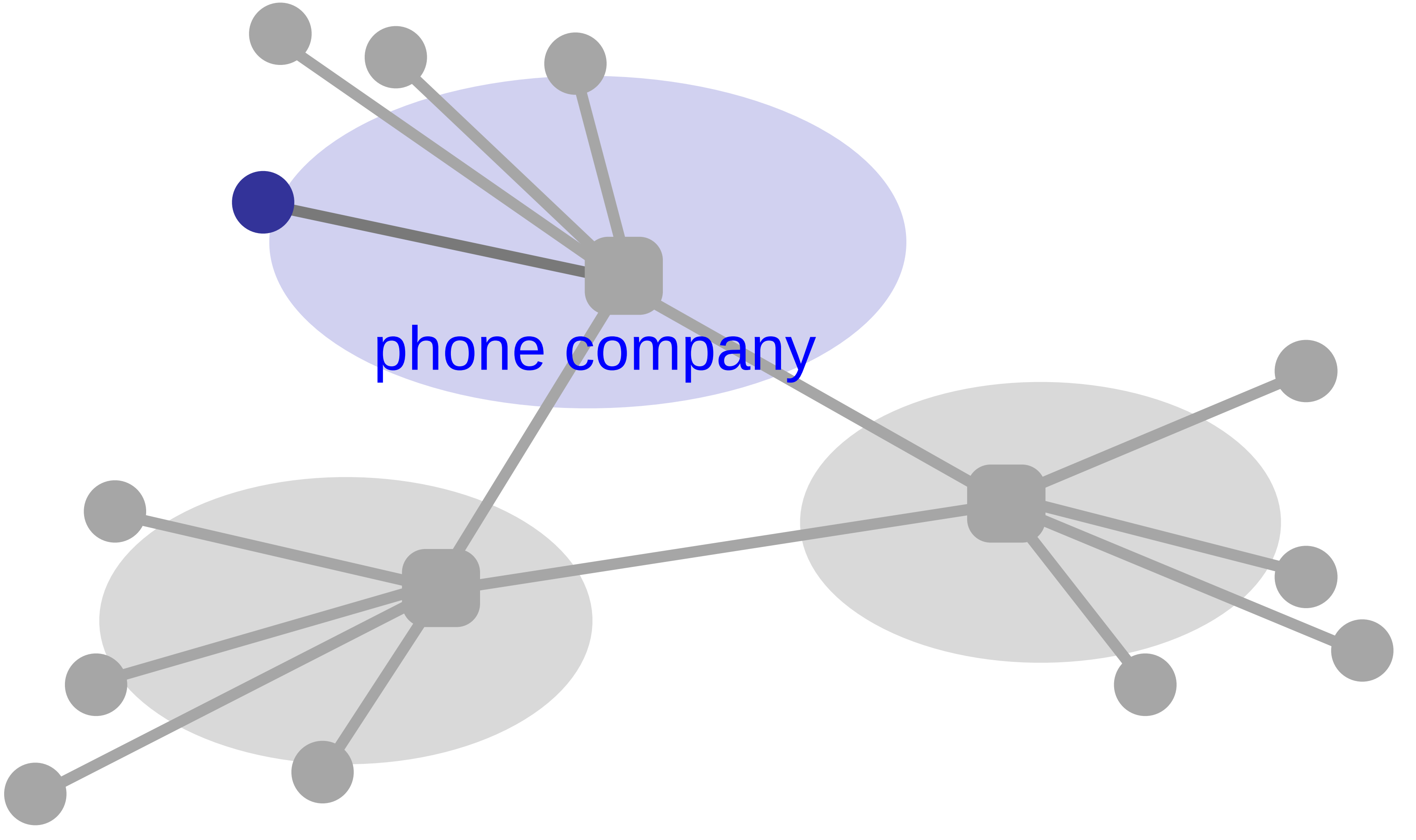
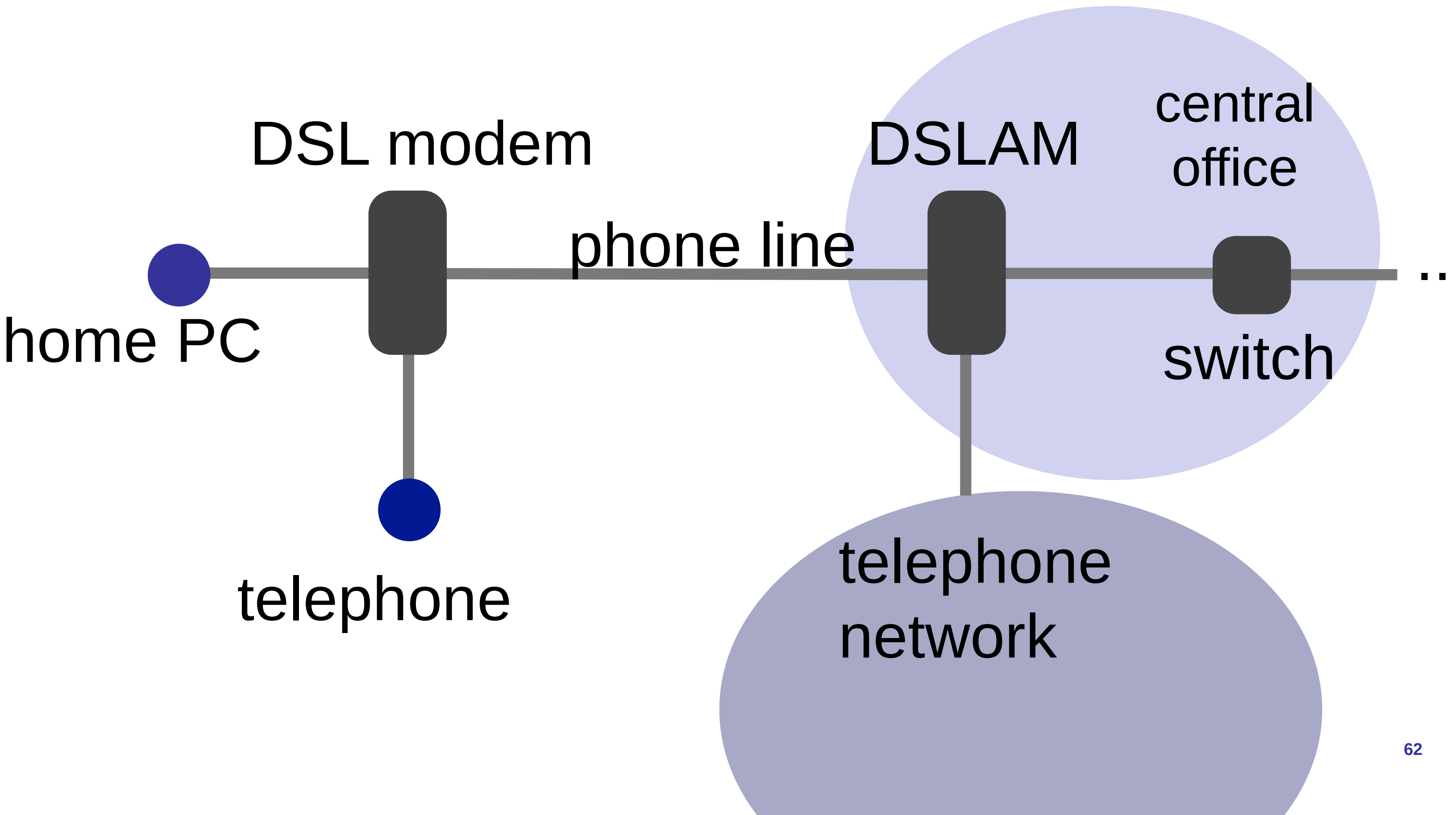


The last hop

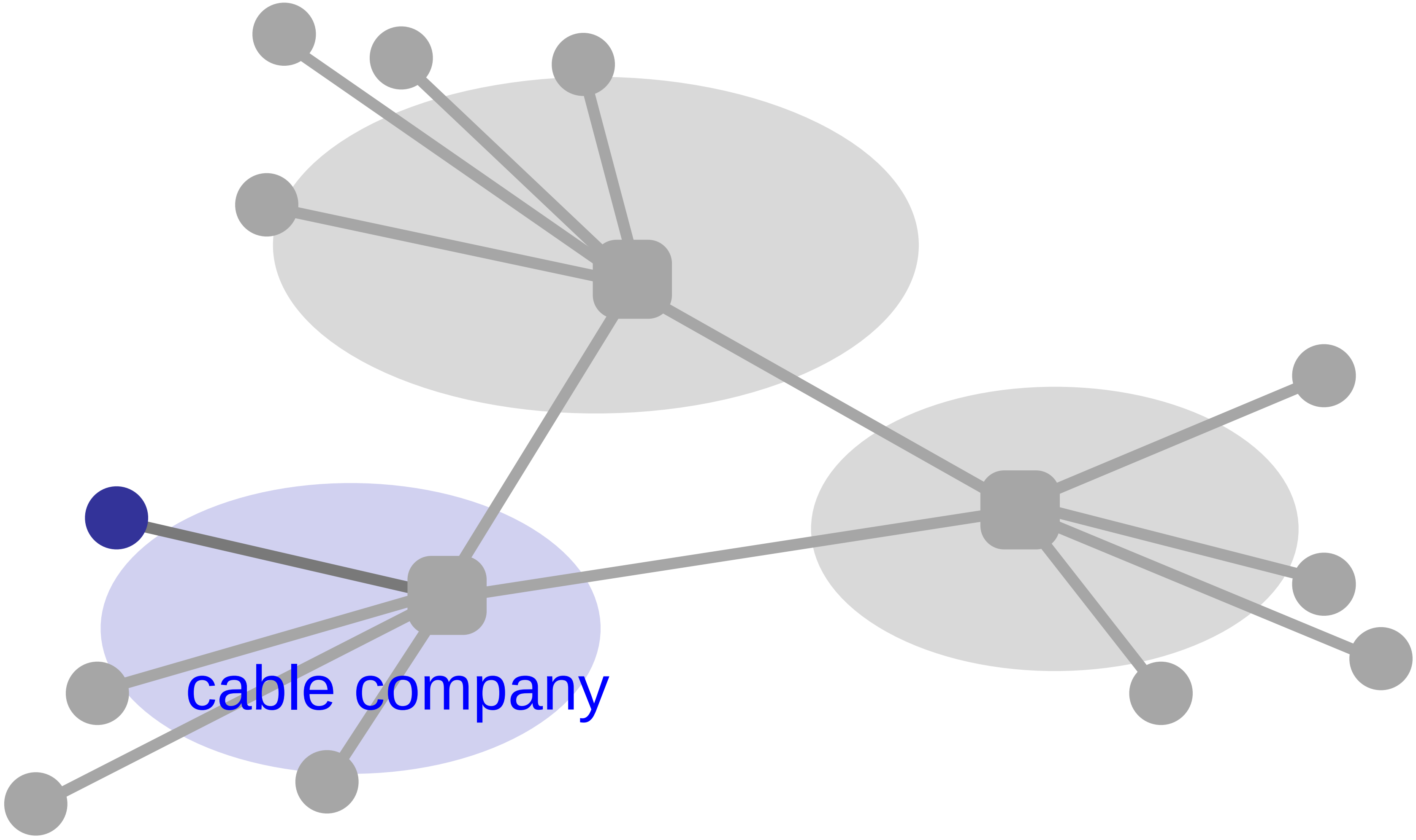
How do we connect?



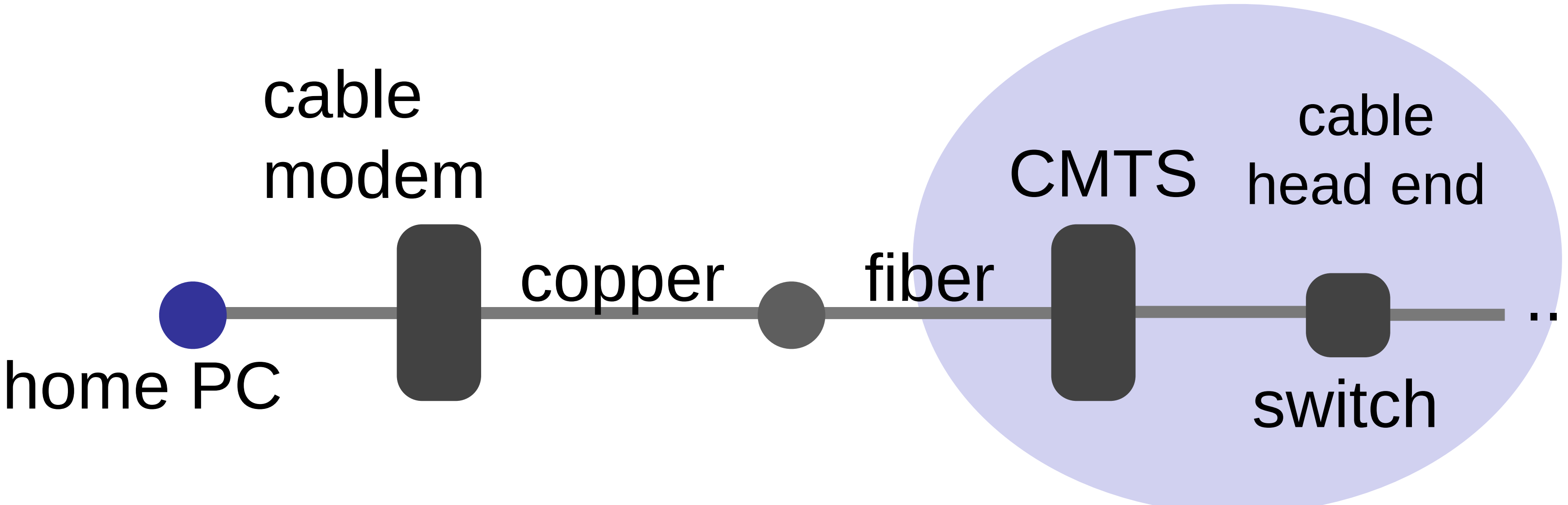
Digital Subscriber Line (DSL)

- 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?



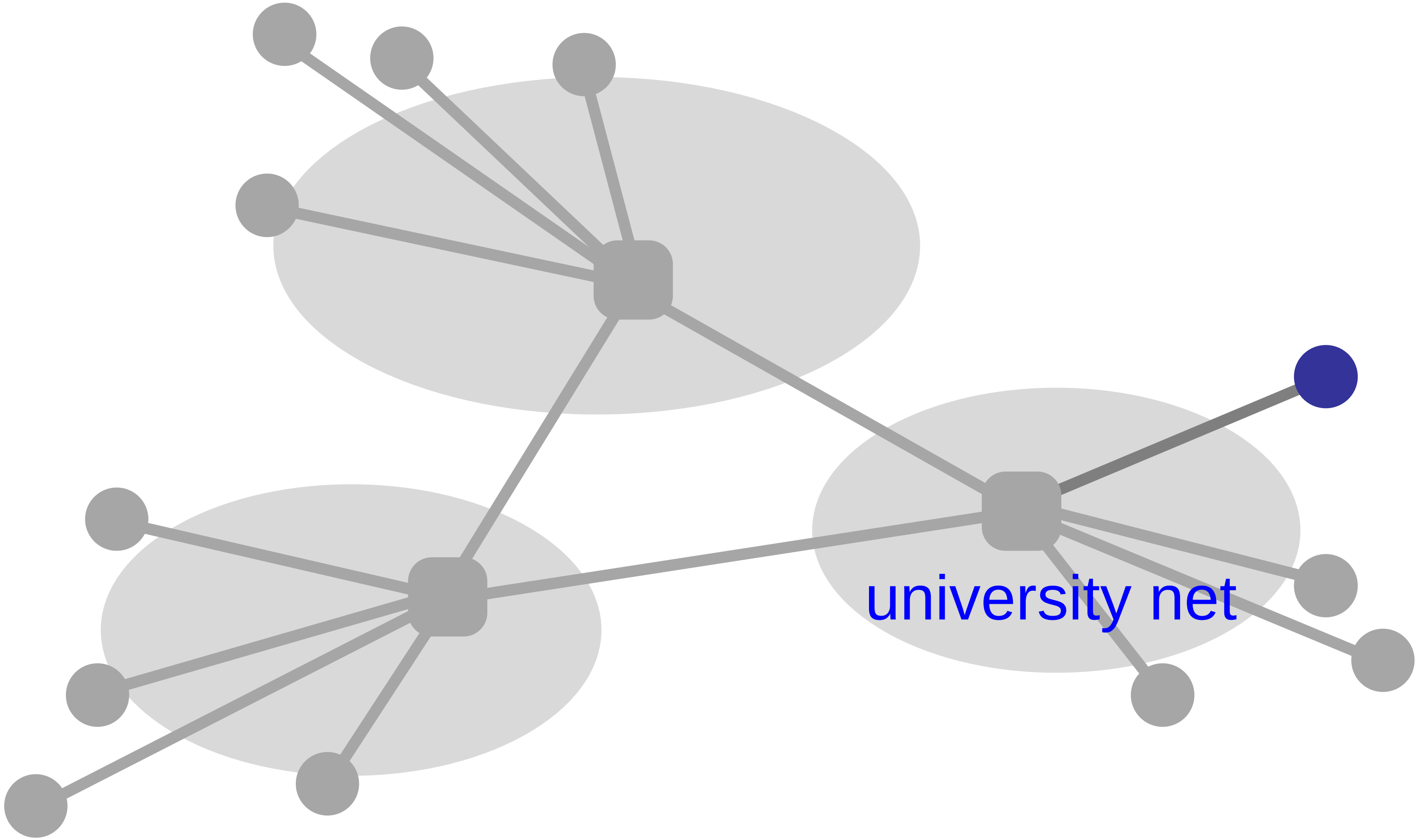
Connecting via cable



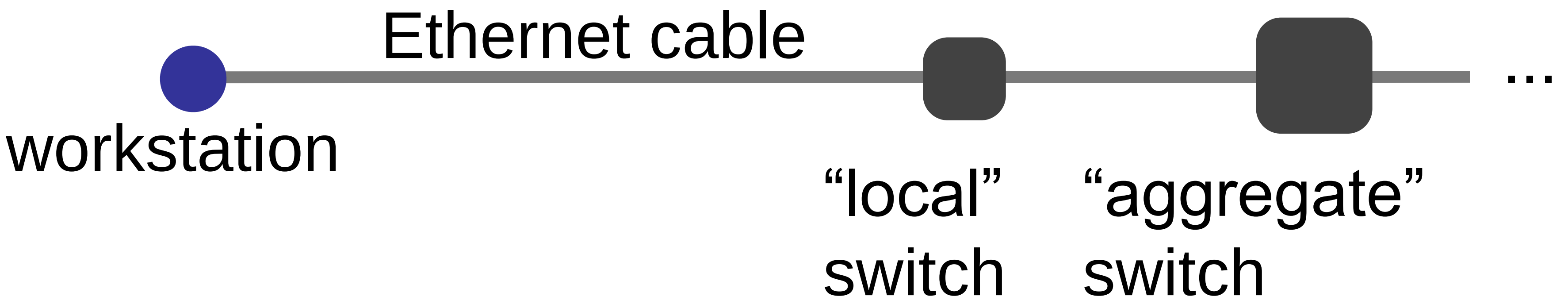
Cable

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

Any other means?



Ethernet


Ethernet cable
workstation
“local” switch
“aggregate” switch
...

Ethernet

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

Many other ways

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

Where is WiFi?