Fall 2018-2019: EE471/CS471/CS573
Computer Networks: Principles & Practices
Slide set 02

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Material taken from Jennifer Rexford, Sylvia Ratnasamy, Kurose and Ross, Ion Stoica, Scott Shenker, Dave Anderson and others.

Today

- What is a network made of?
- How is it shared?
- How do we evaluate a network?

What does it take to deliver a webpage to your browser?

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BBC News – Home
http://www.bbc.co.uk/news/
RSS
Apple
Yahoo!
Google Maps
YouTube
Wikipedia
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NEWS
31 August 2011
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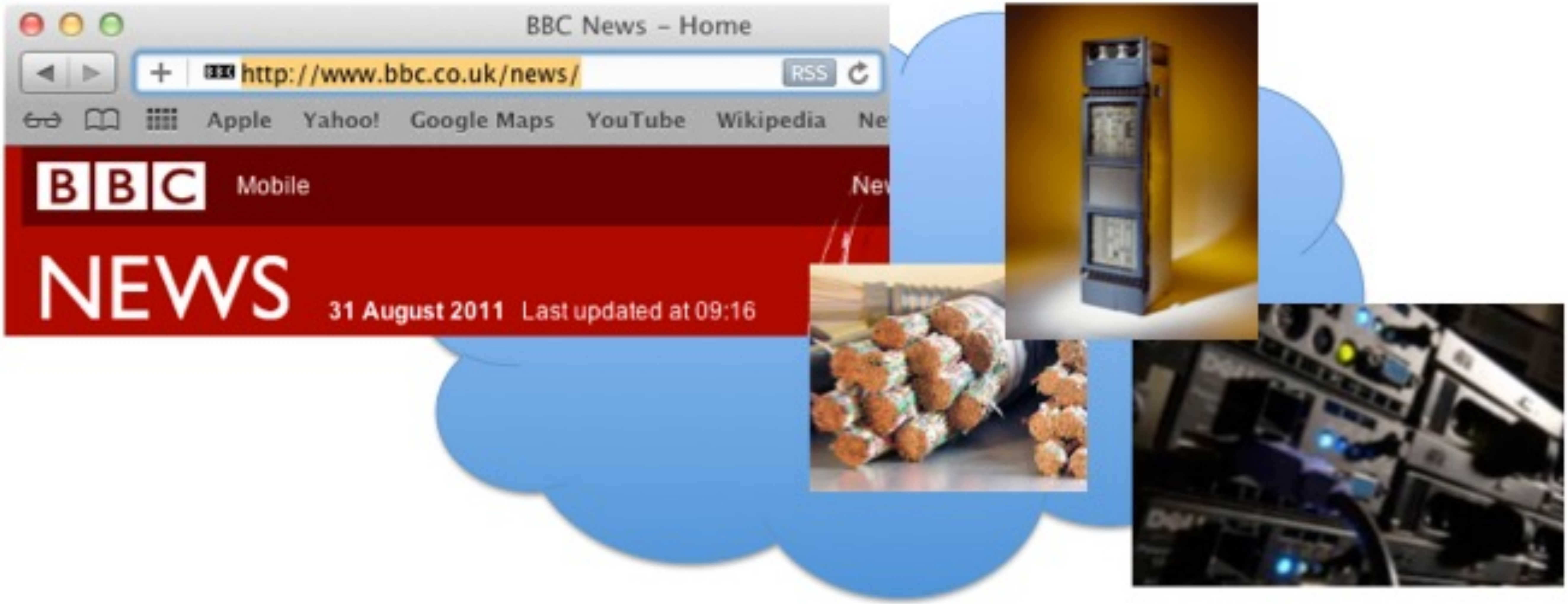
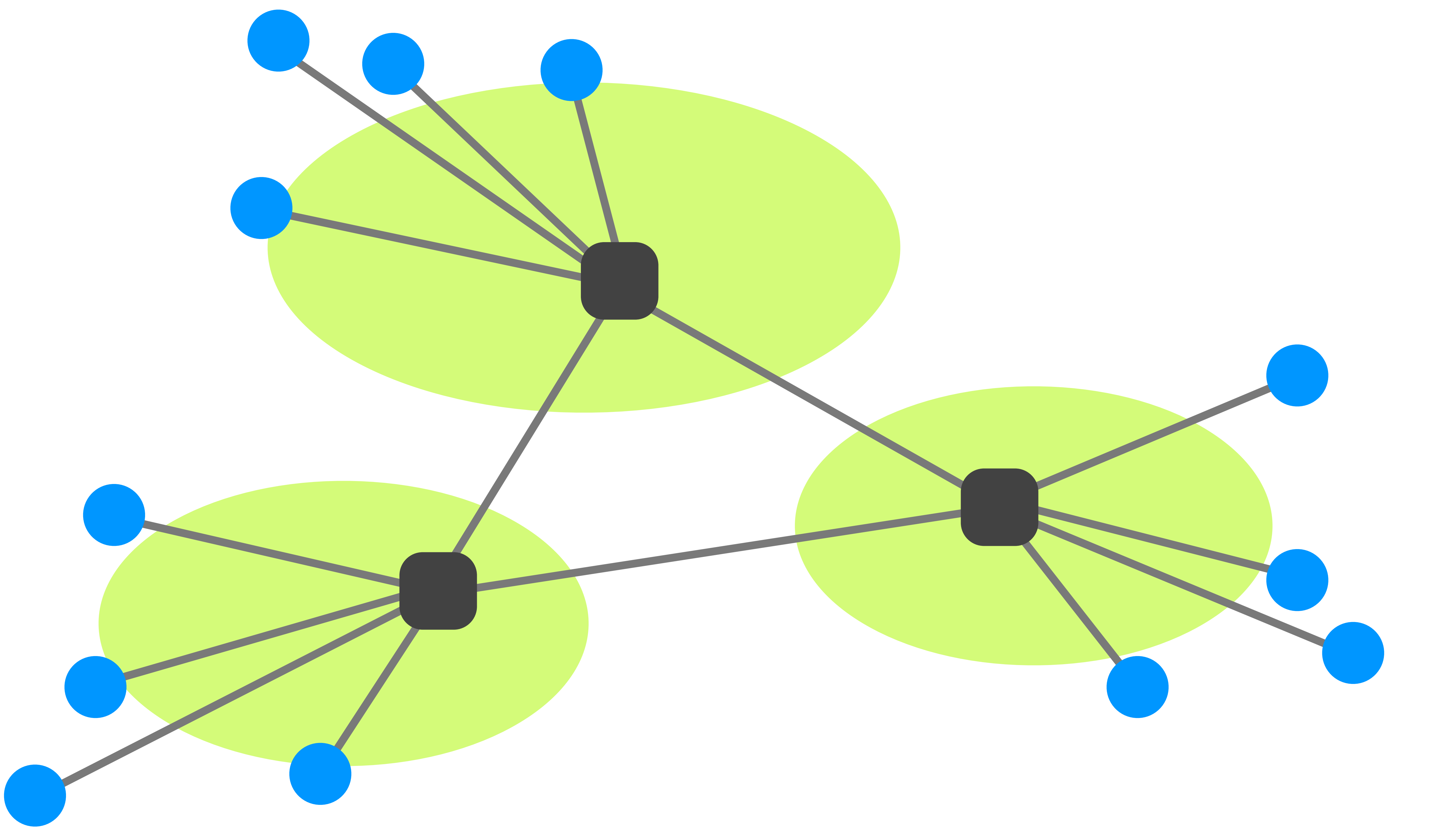


- An **addressing system** to identify computers on the Internet
- A **naming system** to give computers human-readable names
- **Building links**: Ethernet, fiber, wireless, cable TV, etc.
- **Packet switches** – deployed hierarchically (LUMS, PTCL, SingTel)



Today

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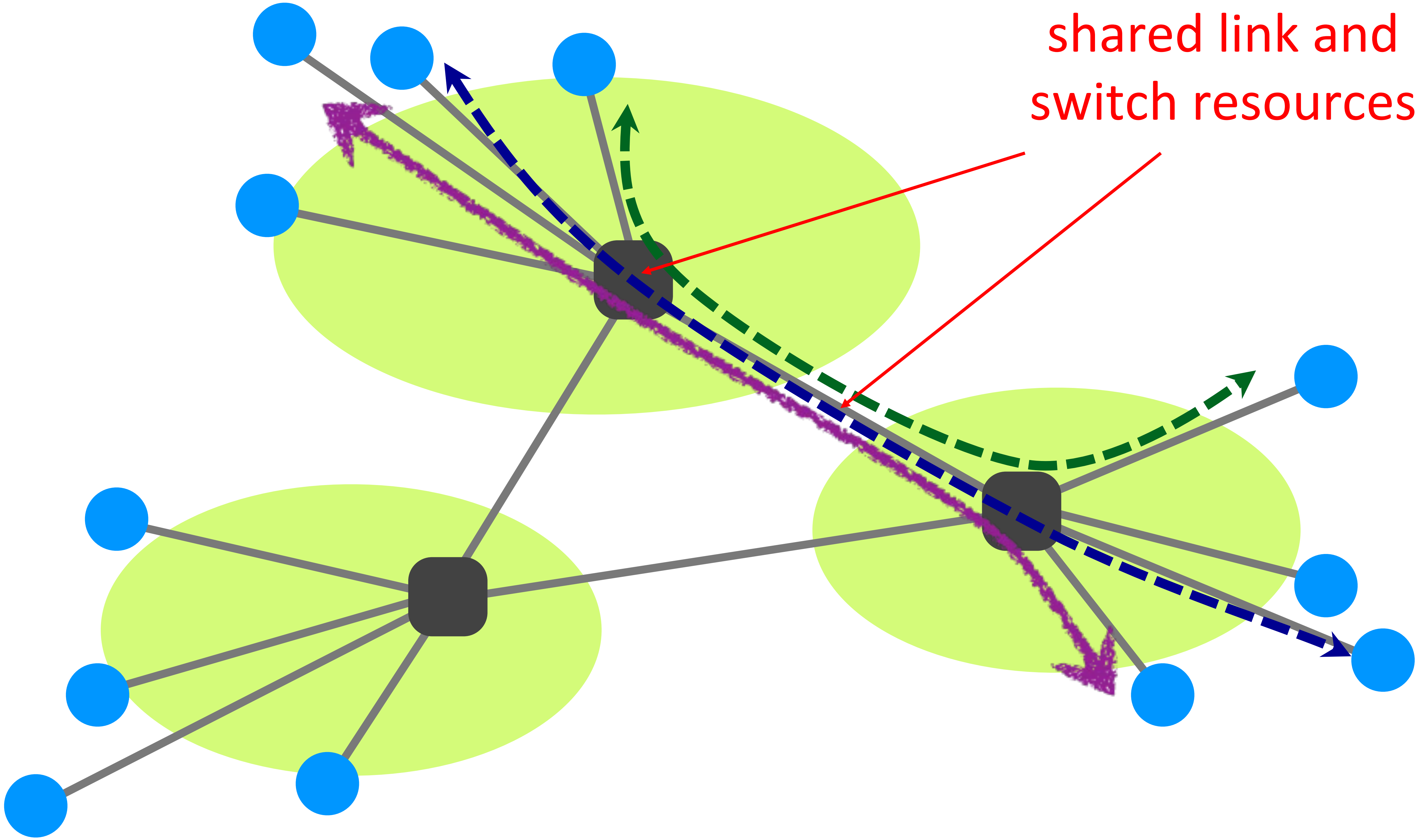

shared link and
switch resources

Two approaches to sharing network resources

- Reservations
  - (with or without multiplexing)
- On demand

How are these implemented?

Two approaches to sharing

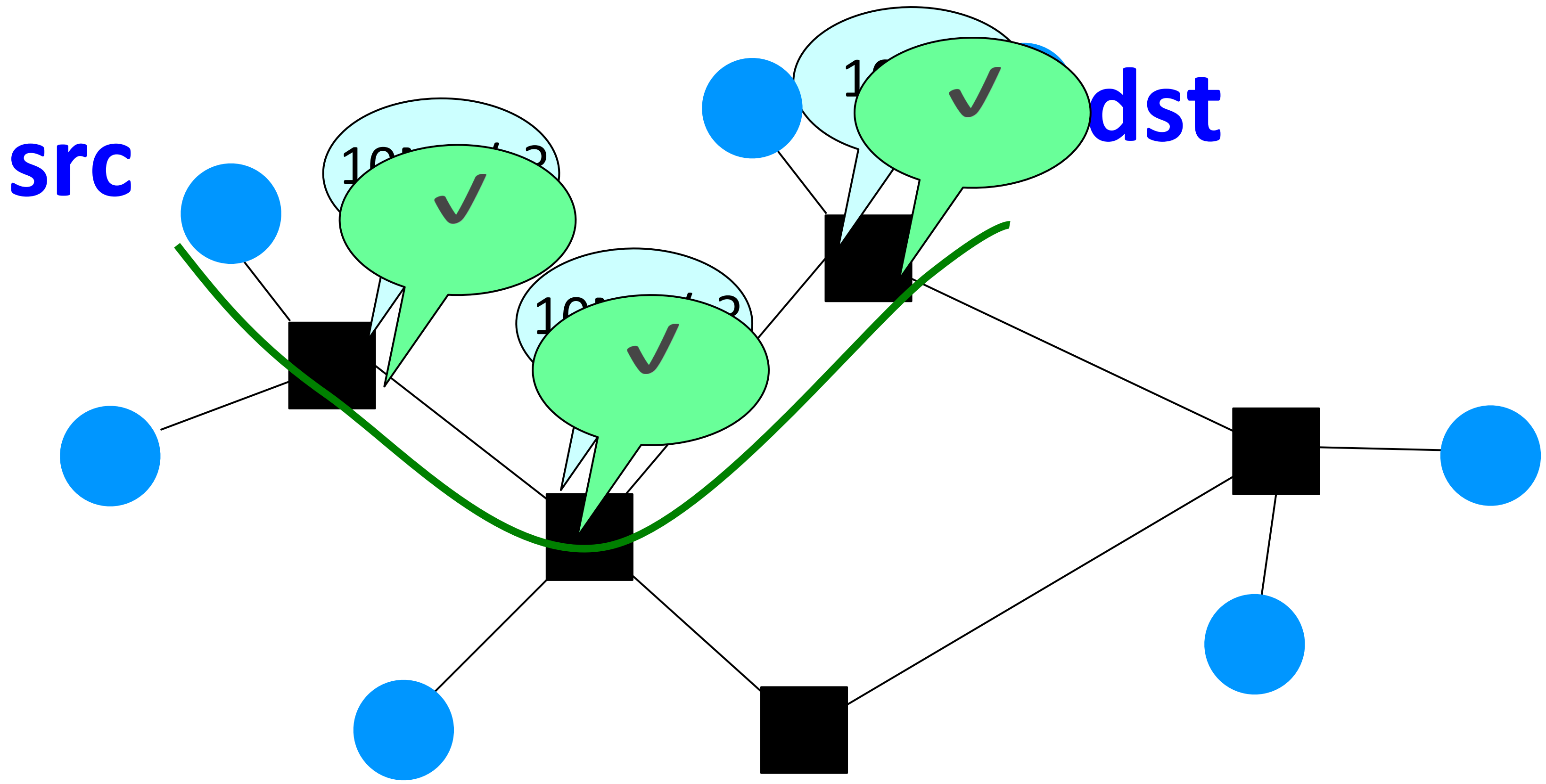
- Reservations → circuit switching
- On demand → packet switching

How are these implemented?

Two approaches to sharing

- Packet switching
  - Packets treated on demand
  - **"Admission"** control: per packet
- Circuit switching
  - Resources reserved per active "connection"
  - **"Admission"** control: per connection
- A hybrid: virtual circuits
  - Emulating circuit switching with packets (see text)

Circuit Switching



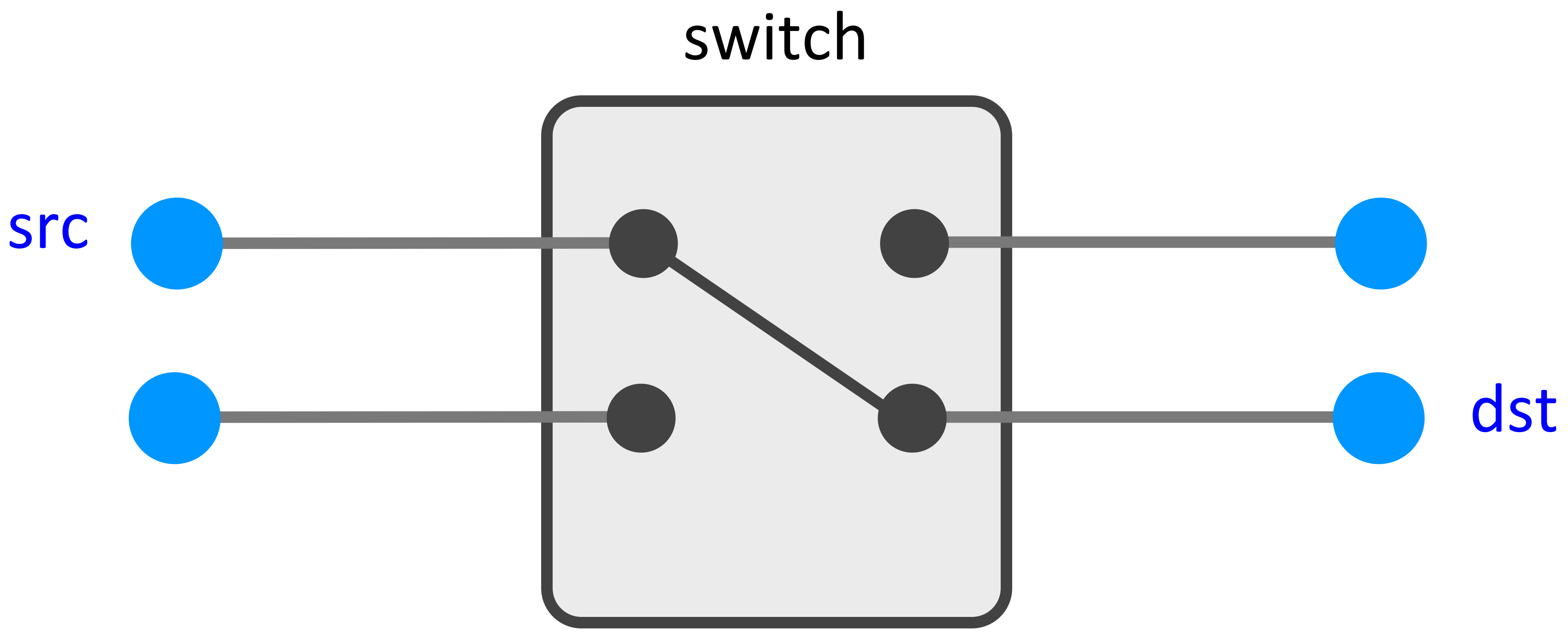
(1)src sends a reservation request to dst

(2) Switches "establish a circuit"

(3) src starts sending data

(4) src sends a "teardown circuit" message

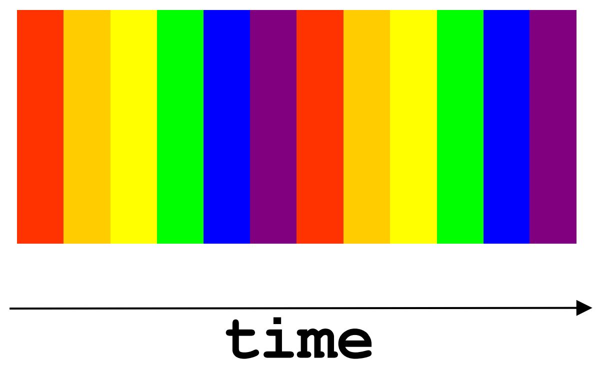
Circuit Switching



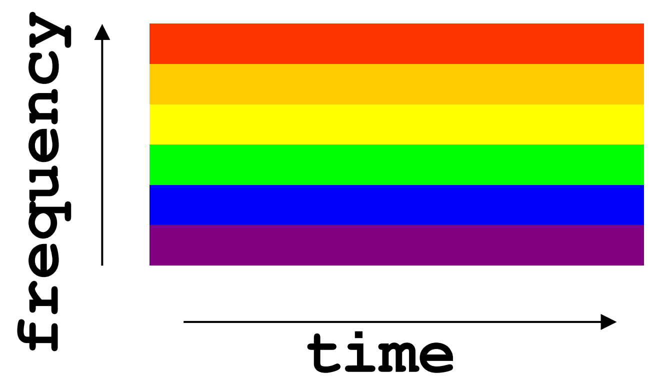
Reservation establishes a “circuit” within a switch

Multiplexing in “**circuits**”

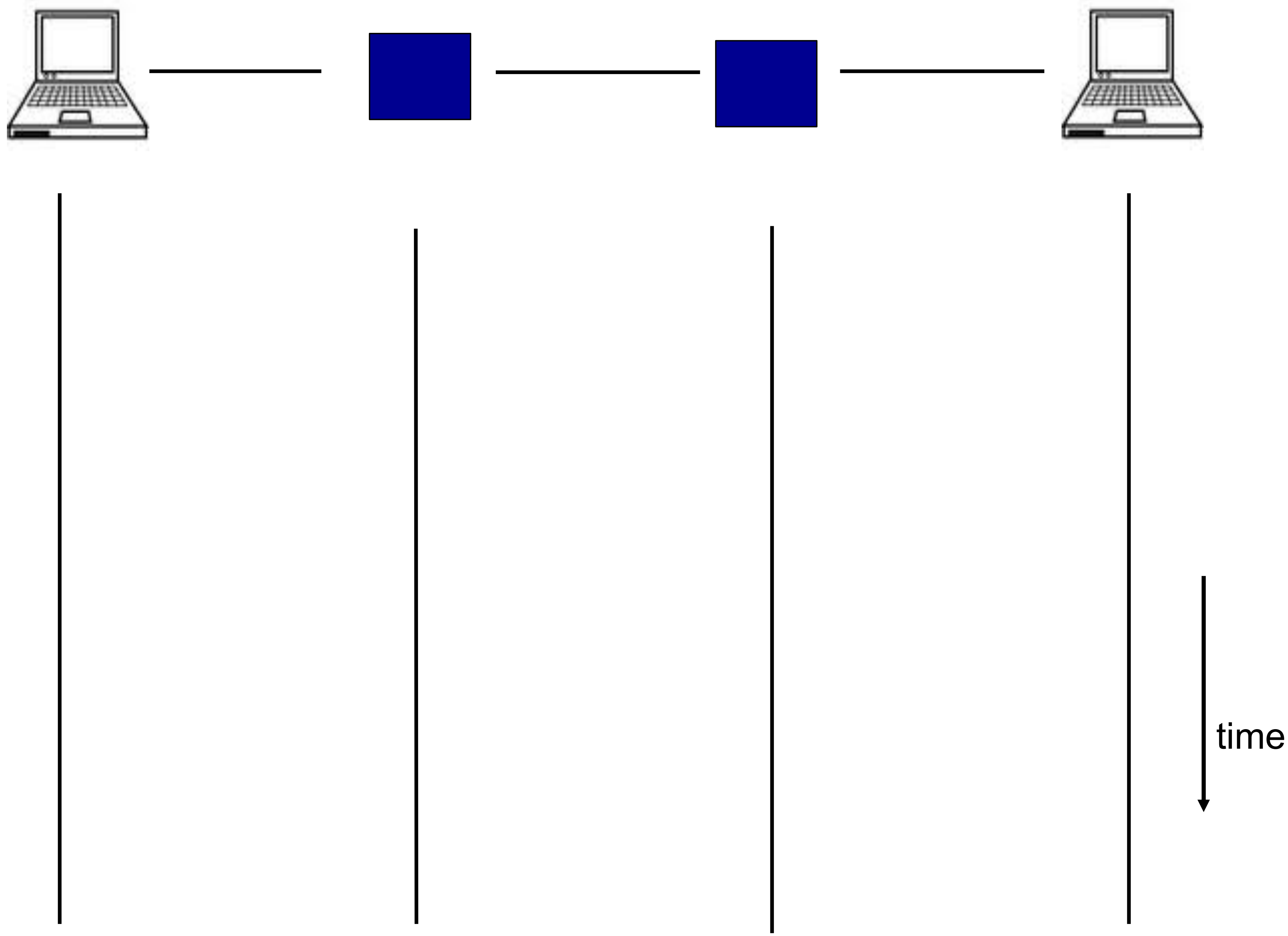
- **Time division multiplexing**
  - divide time in time slots
  - separate time slot per circuit



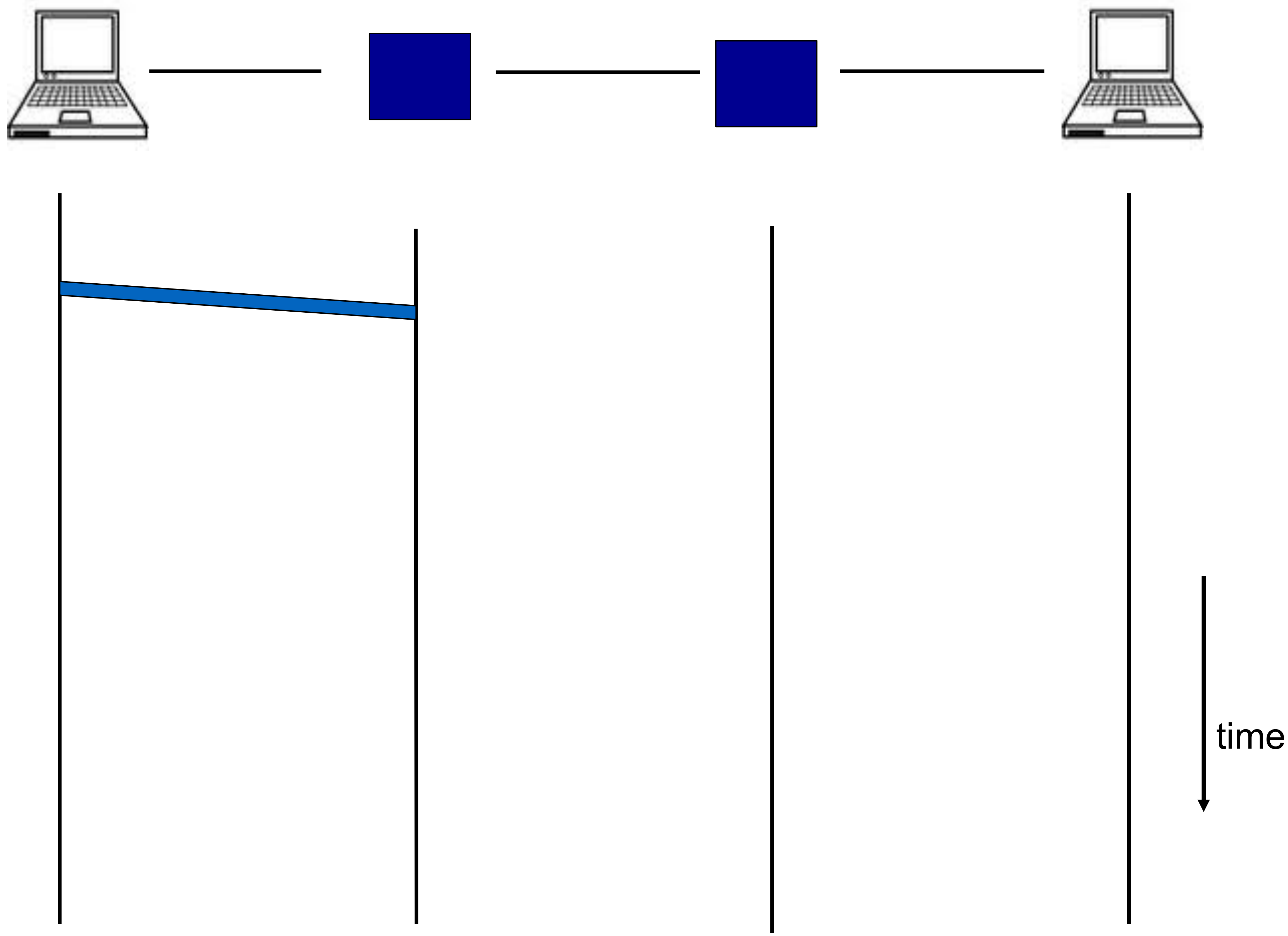
- **Frequency division multiplexing**
  - divide frequency spectrum in frequency bands
  - separate frequency band per circuit



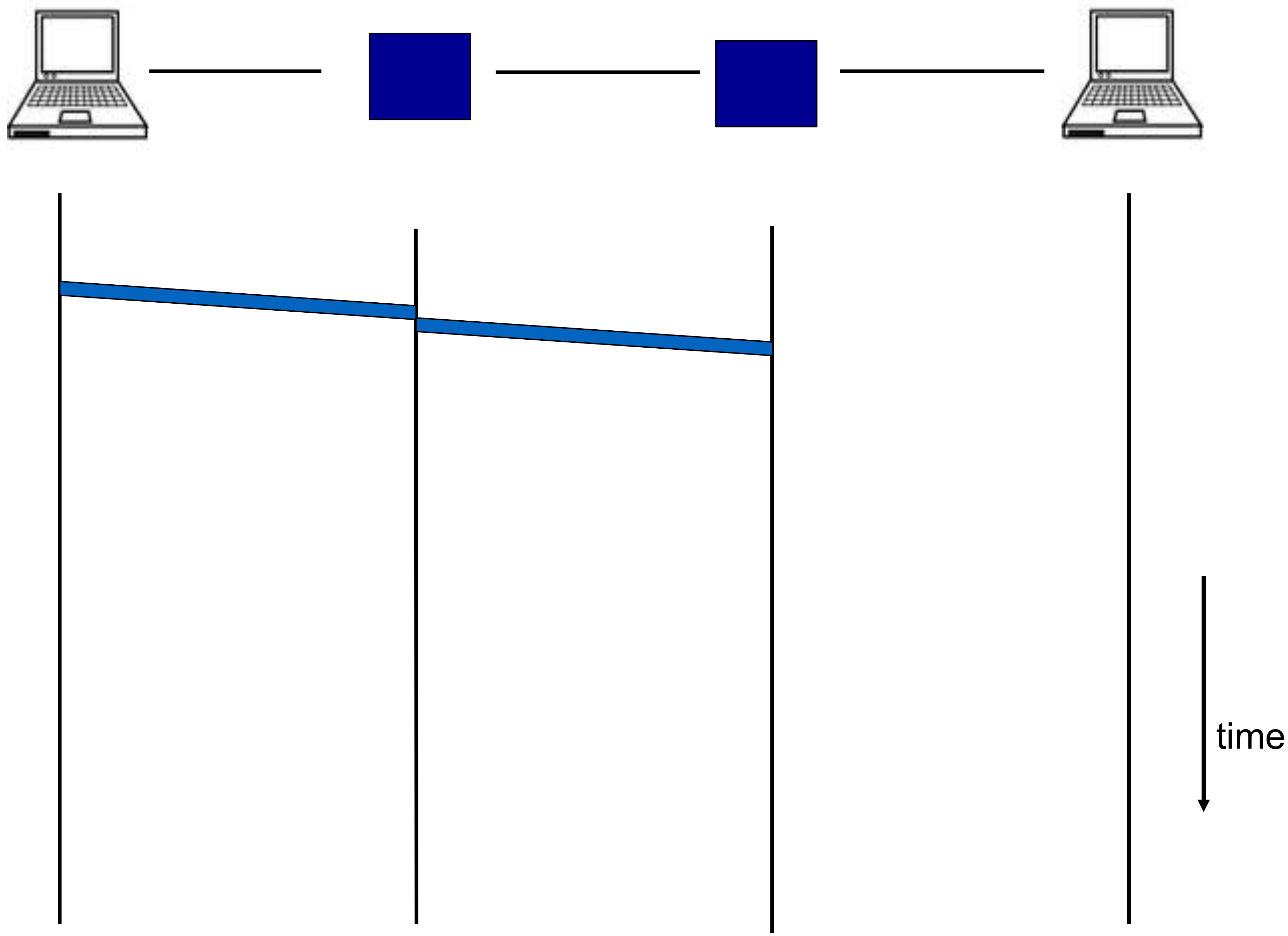
Timing in Circuit Switching



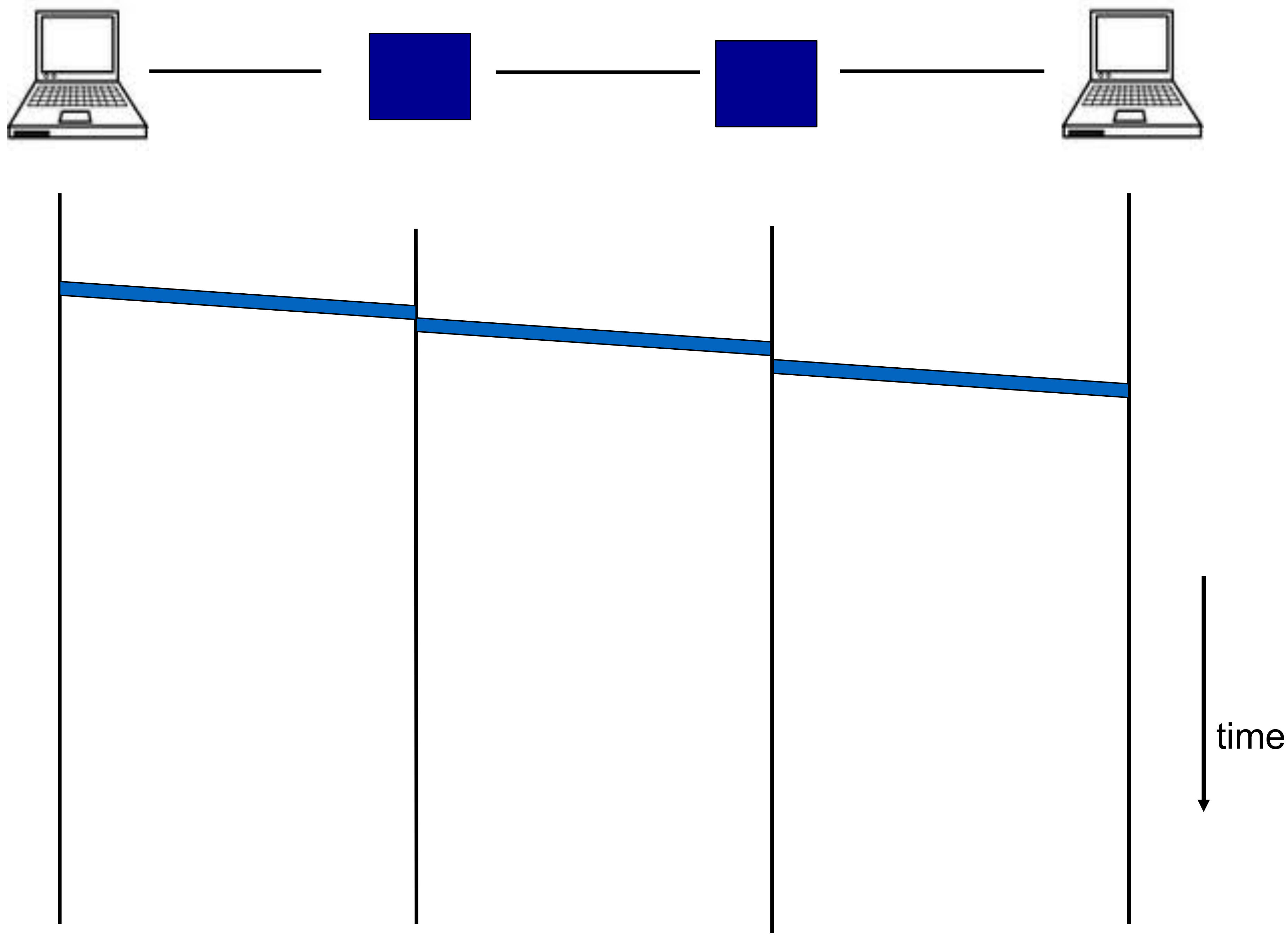
Timing in Circuit Switching



Timing in Circuit Switching



Timing in Circuit Switching



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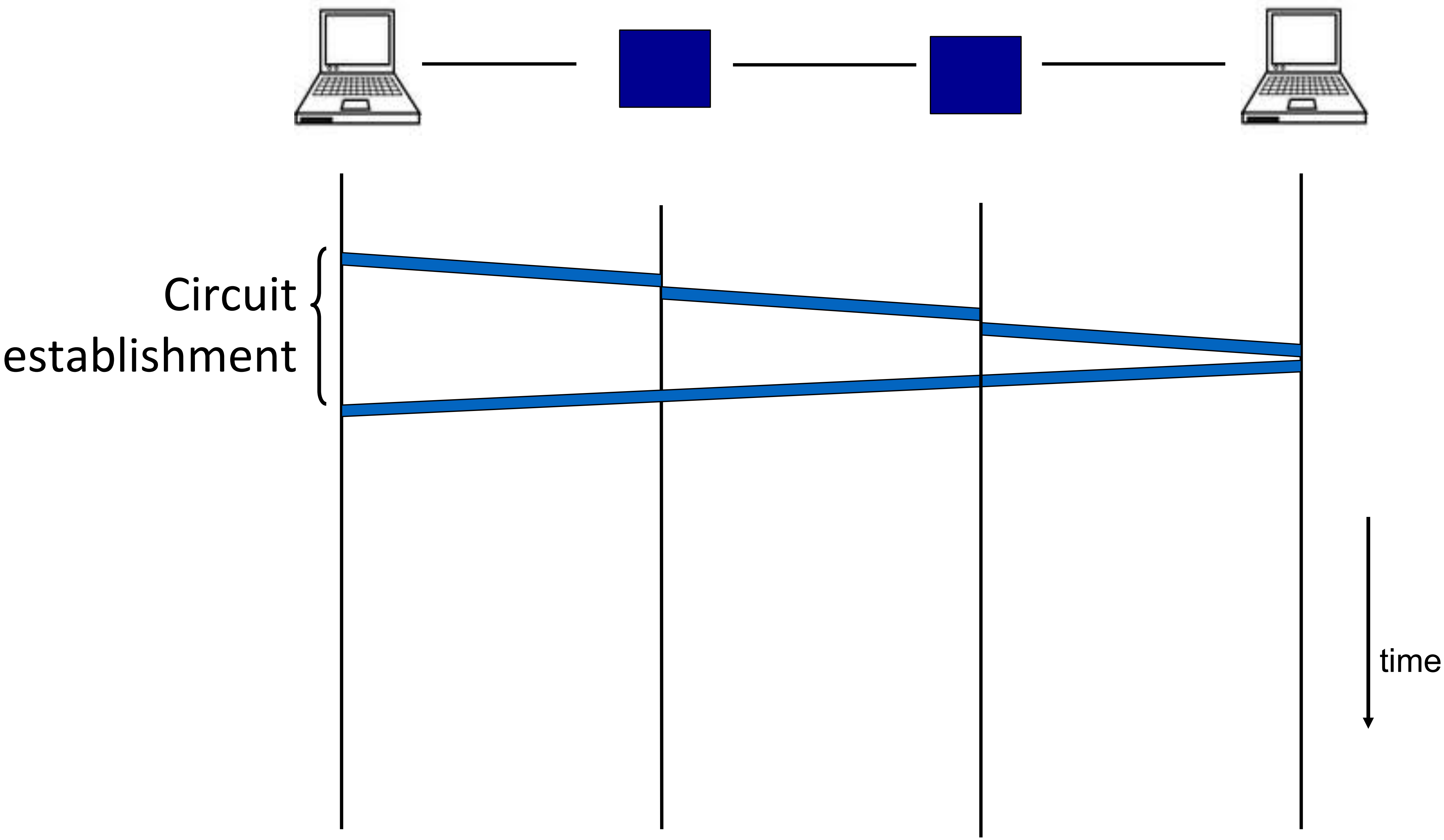
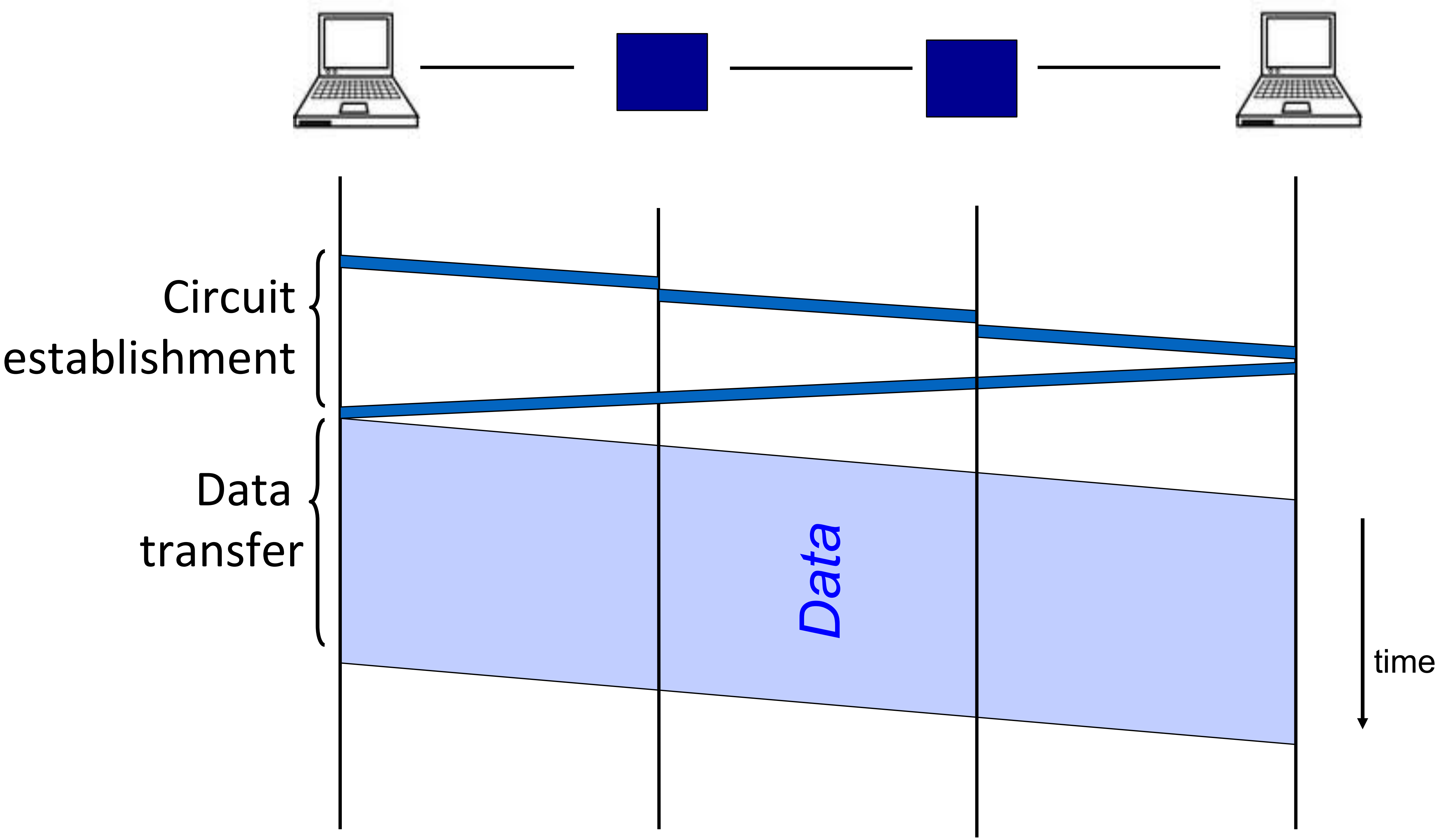


Timing in Circuit Switching

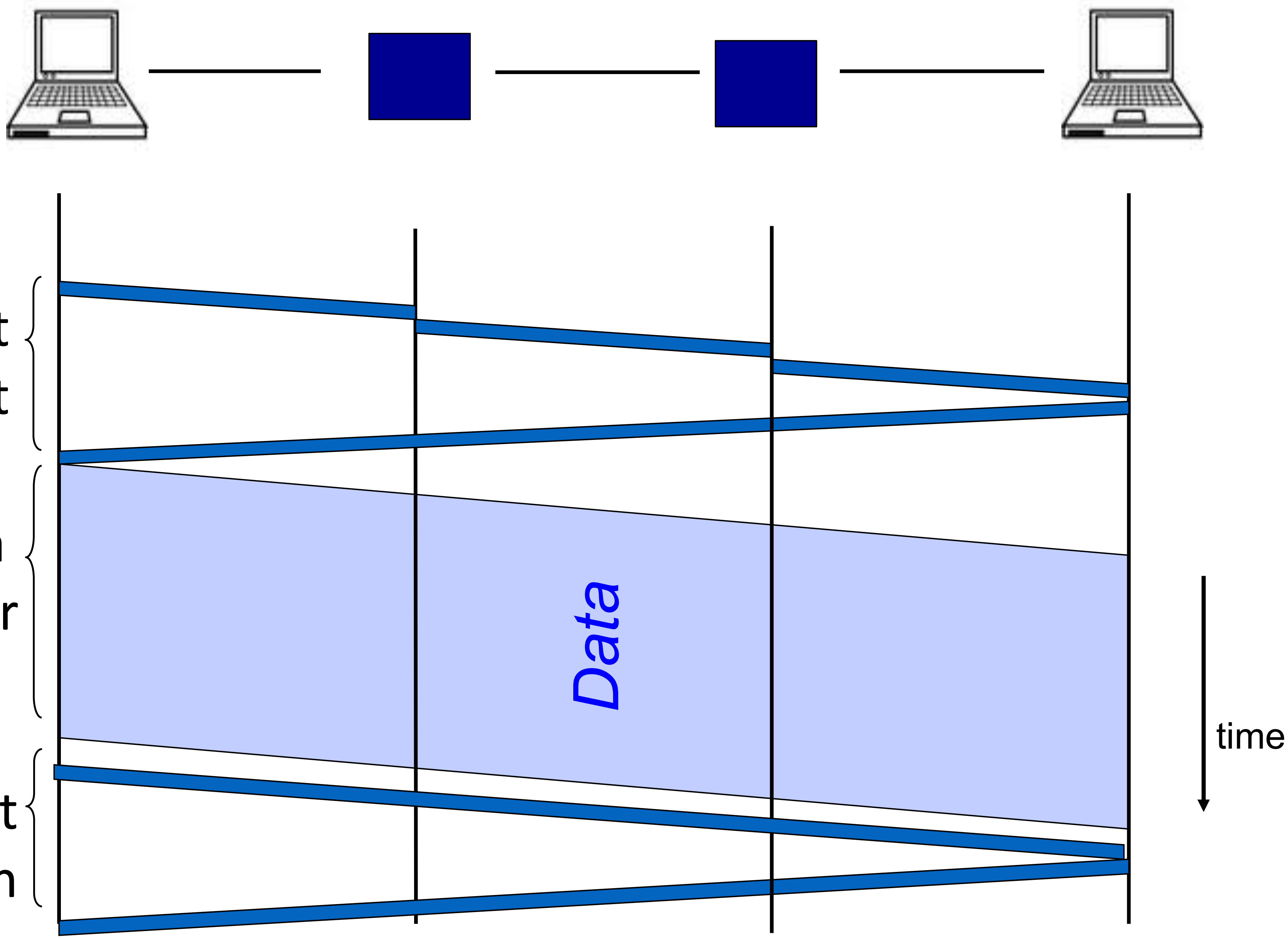


Timing in Circuit Switching

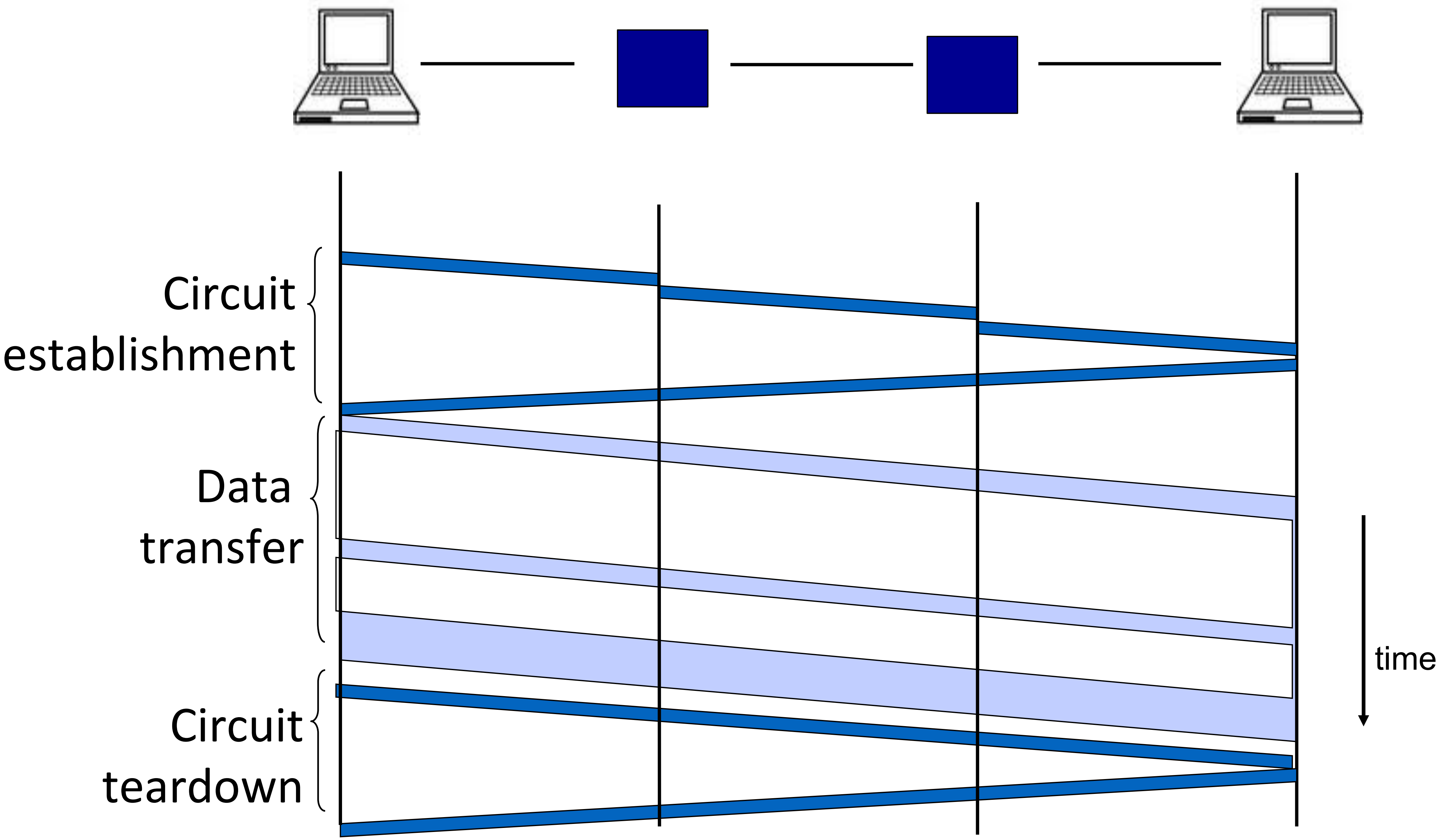
Circuit establishment

Data transfer

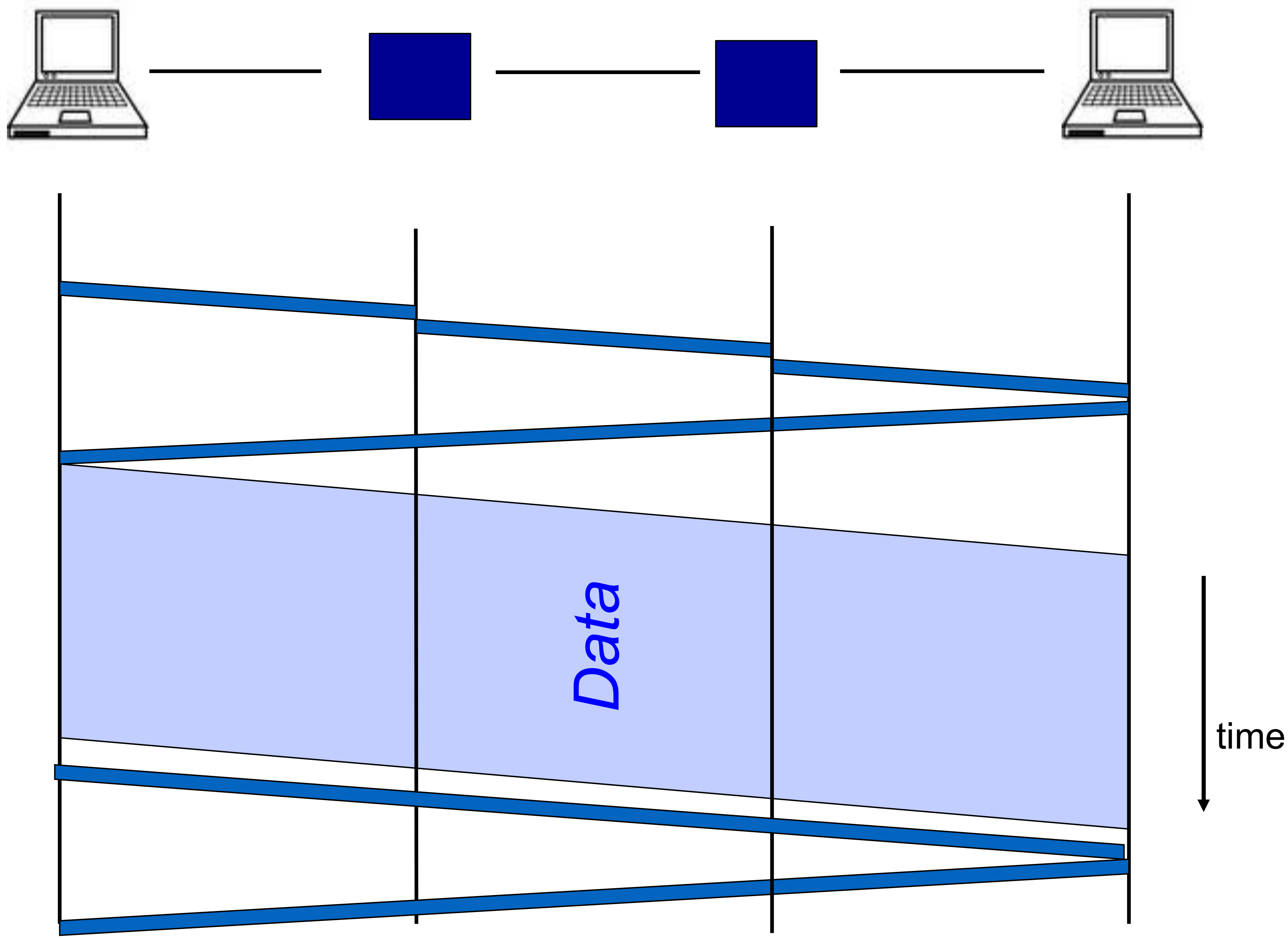
Circuit teardown



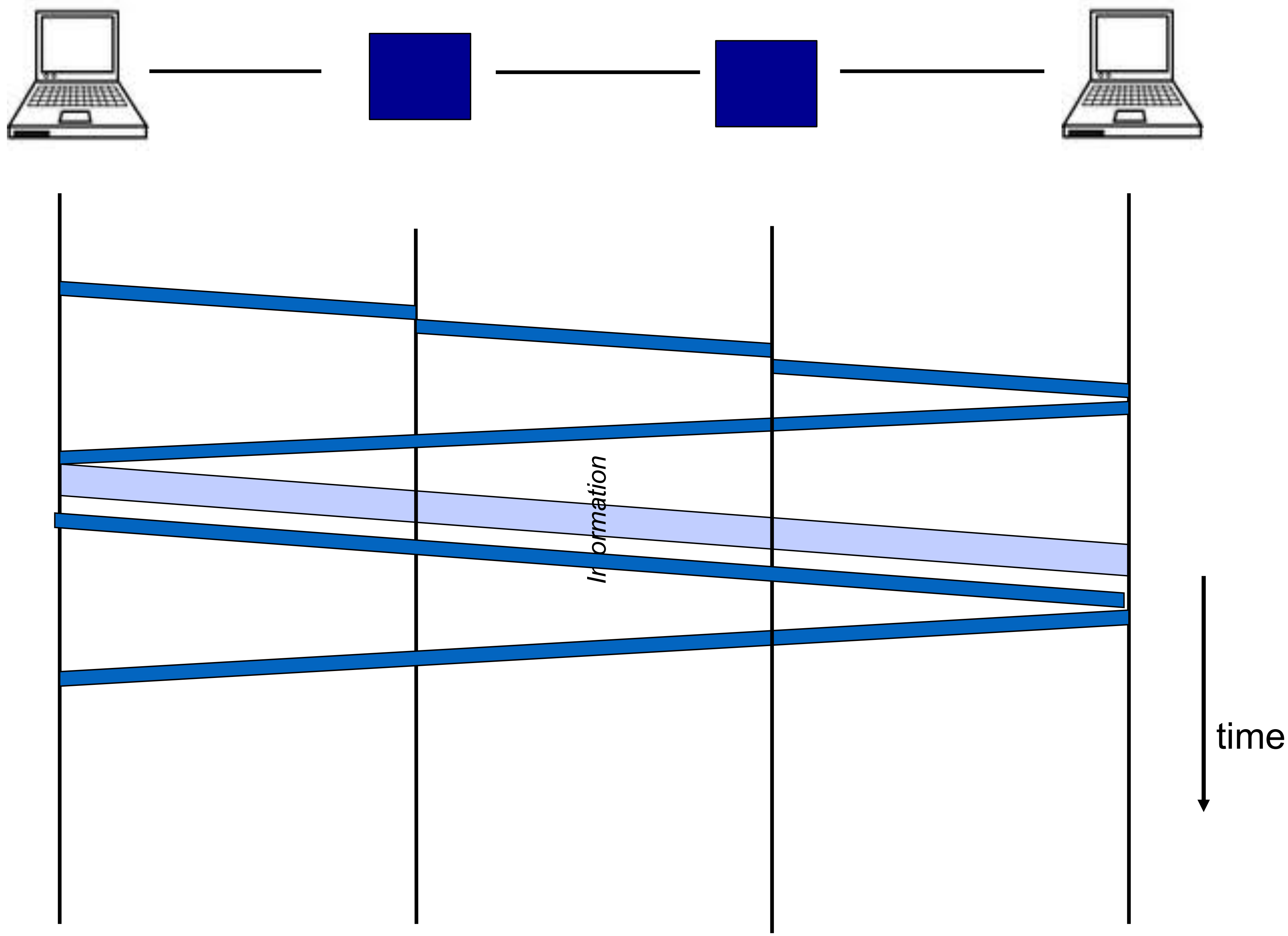
Timing in Circuit Switching



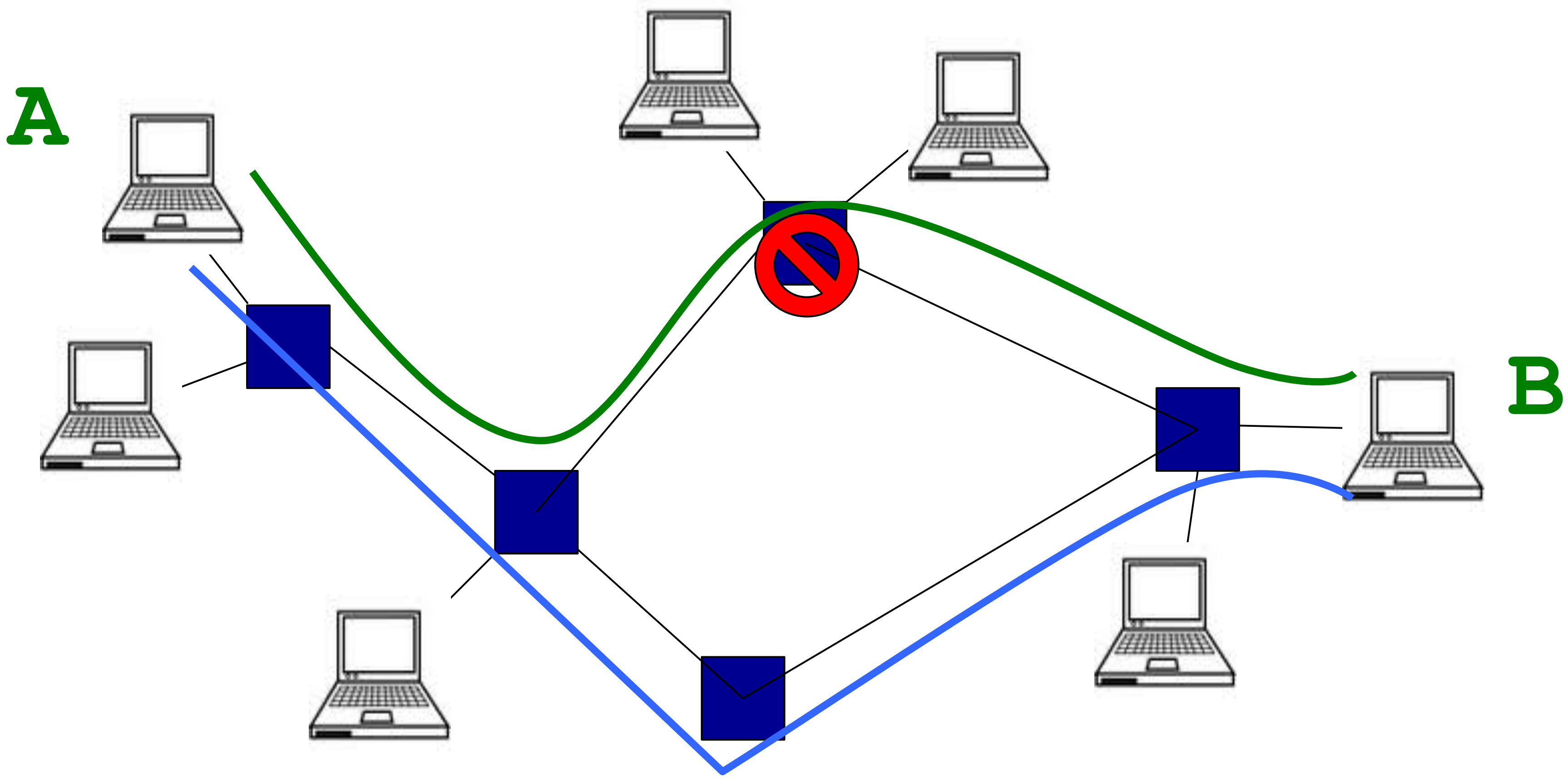
Timing in Circuit Switching



Timing in Circuit Switching



Circuit Switching

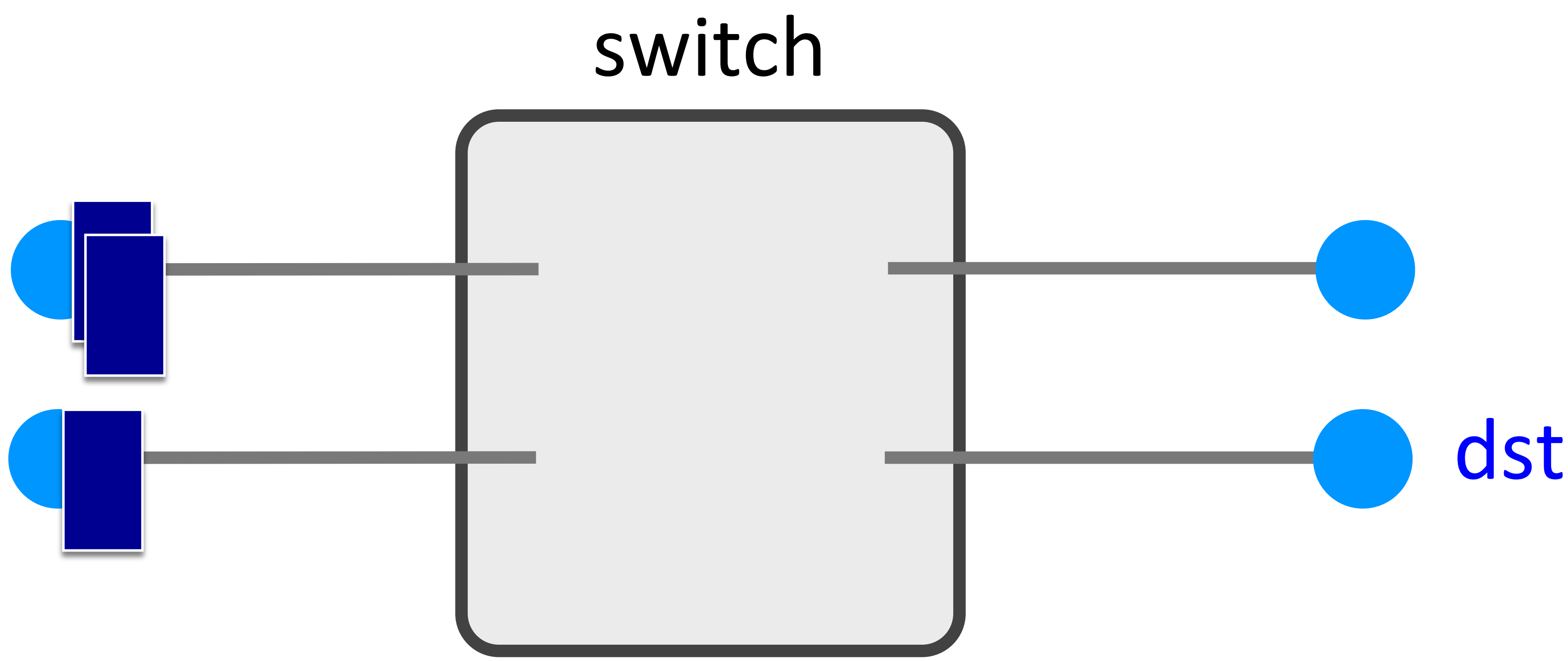


Circuit switching doesn't "route around trouble"

Circuit Switching

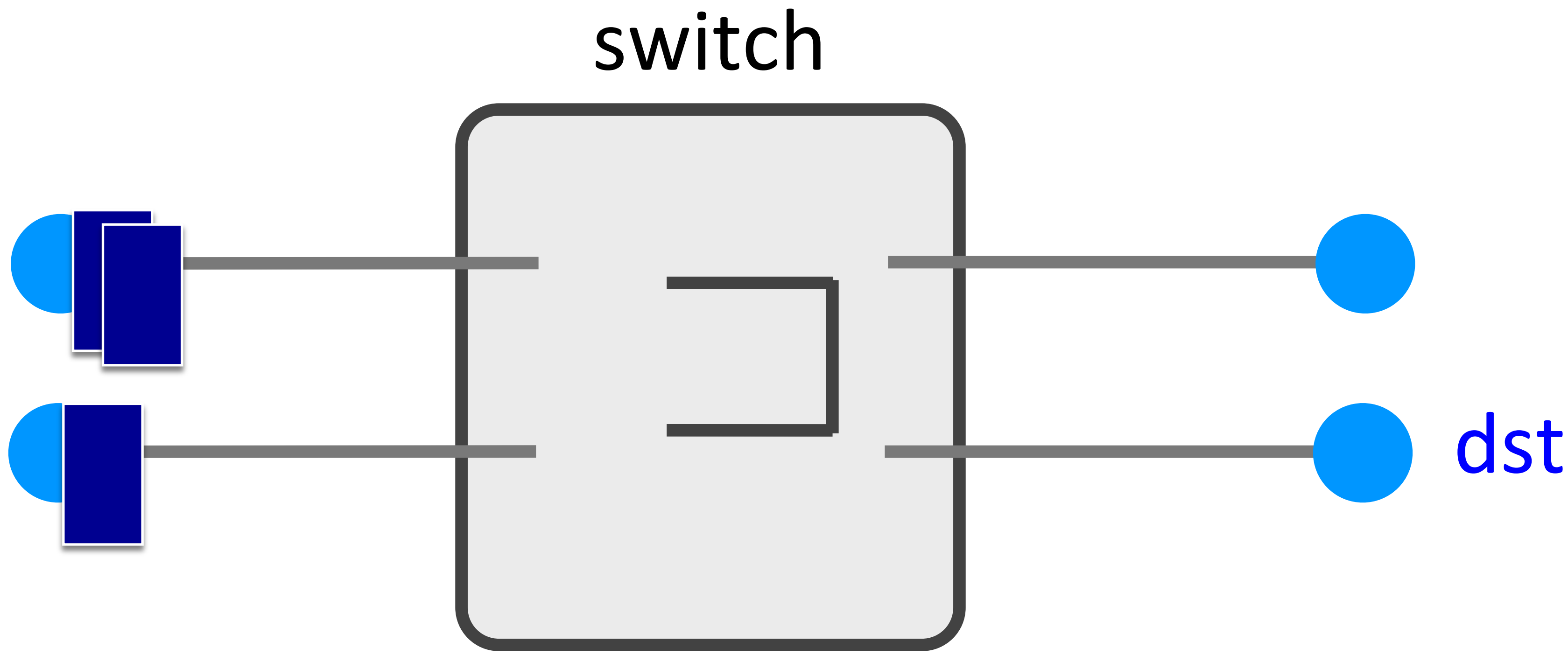
- **Pros**
  - predictable performance
  - simple/fast switching (once circuit established)
- **Cons**
  - complexity of circuit setup/teardown
  - inefficient when traffic is bursty
  - circuit setup adds delay
  - switch fails → its circuit(s) fails

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 absorb transient overloads

Packet Switching

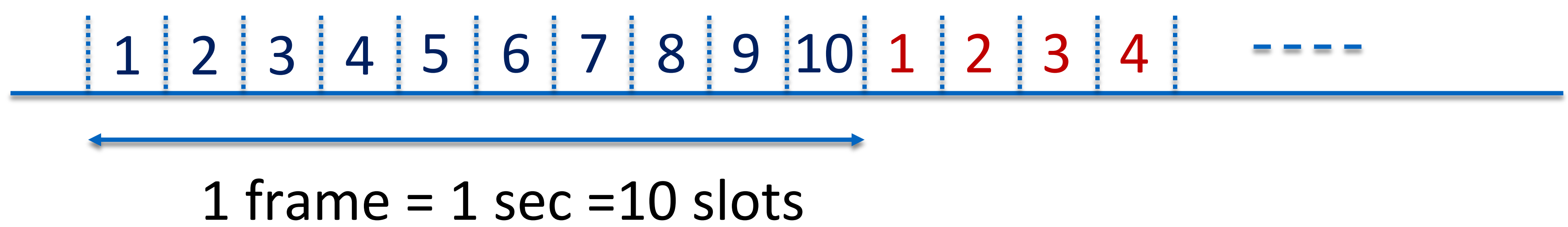
- **Pros**
  - efficient use of network resources
  - simpler to implement
  - robust: can “route around trouble”

- **Cons**
  - unpredictable performance
  - requires buffer management and congestion control

- *On-demand or reserve?*

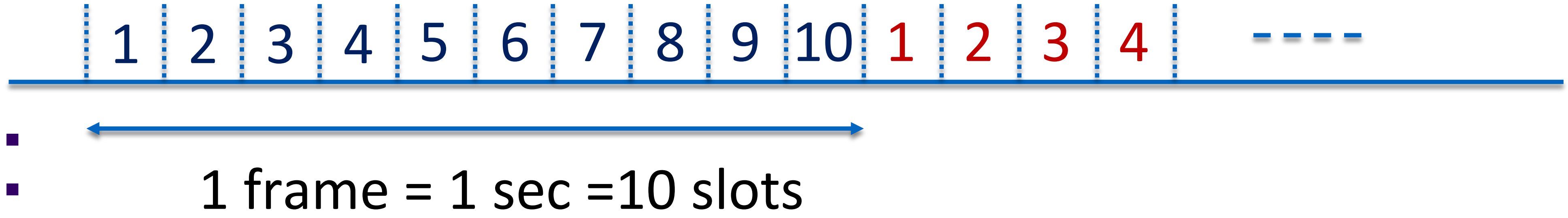
Example:

- 1Mb/s link
- Divide into 10 “slots” (1, 2, 3, …)
  - Slots get repeated after a “frame” (say 1sec)



- Sharing/multiplexing mechanics:
  - Slot duration: 1/10 second (or 100ms)
  - One sender sends at full rate (1Mb/s) in a slot
  - A sender can send 100K bits per slot

Example:



- Circuit switching:
  - **Max:** 10 users can be supported, one per slot
  - Avg. data rate for any user is 100Kb/s
  - What if each user active only 10% of time?
- Packet switching
  - Say each user active only 10% of time
  - P(user active) = 0.1
  - Now try accommodating more users (say 35)
  - P (> 10 users active) = 0.0004 (approx.)

Packet vs. Circuit switching

- Two clear benefits:
  - A lot more users can be supported
    - Statistically multiplexed
  - A single user can occupy all empty slots and hence quickly send data
  - **Ex:** Only one user has 1Mb of data to send
    - Circuit switching: 10 frames (or 10 secs)
    - Packet switching: As quick as 1 sec

Today

- What is a network made of?
- How do we evaluate a network?

Recap and moving forward

- Internet Structure
  - *End hosts (clients and servers)*
  - *switches, links (edge and core), ISPs*
  - *Protocols, Standards, and RFCs*
  - *Fundamental goal? Connect everyone to everyone else!*
- Connection Paradigms
  - *Circuit switching (with and without MUXing)*
  - *Packet switching (with Statistical multiplexing)*
- Network Performance Metrics
  - *Delay, Loss, Throughput*

Performance Metrics

- Delay
- Loss
- Throughput

Delay

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

Loss

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

Throughput

- ***At what rate is the destination receiving data from the source? (end 2 end)***
  - ***Different from the link transmission rate (more later!)***

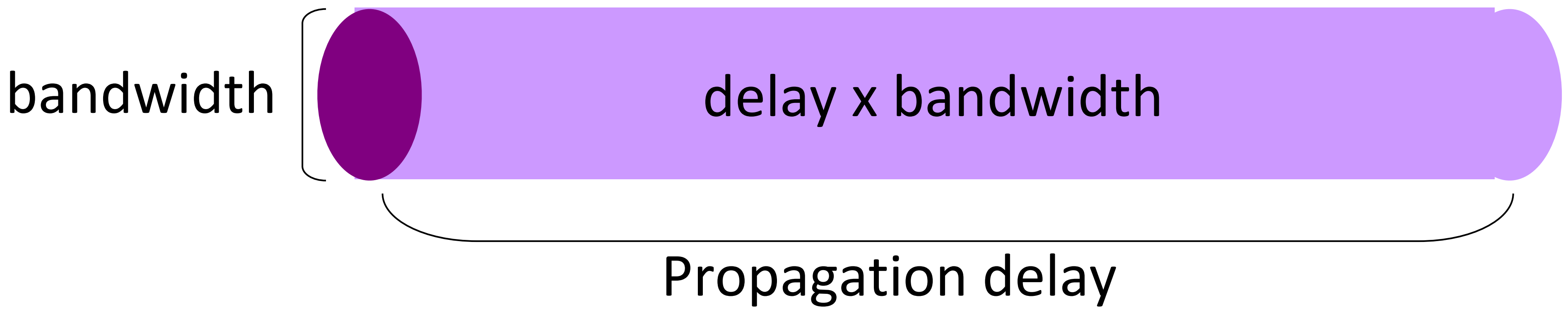
Delay

- 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 [dictates transmission delay]
  - 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

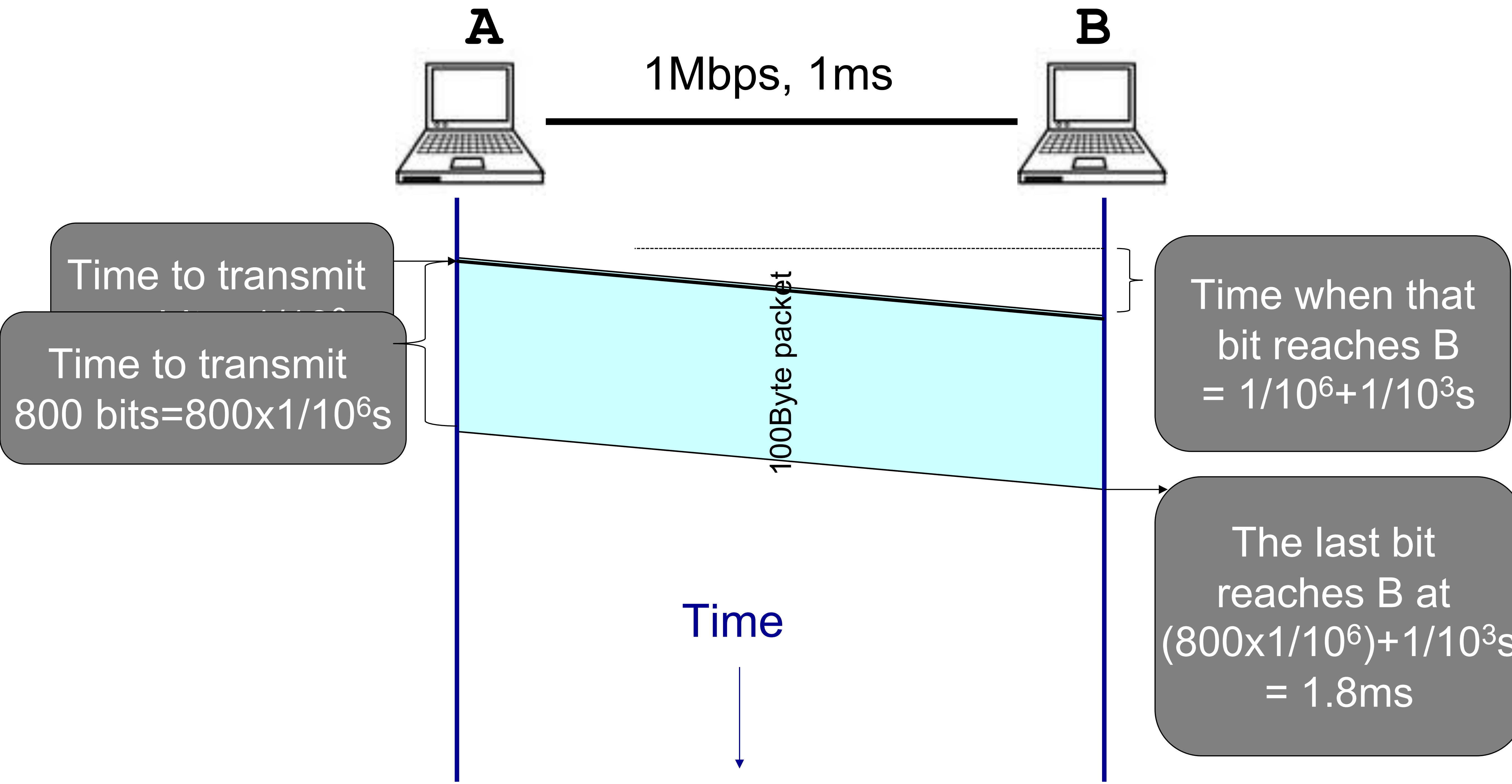
- How long does it take to push all the bits of a packet into a link?
  - *Not dependent on the length of the link!*
- Packet size / Transmission rate of the link
  - *e.g. 1000 bits / 100 Mbits per sec = 10^{-5} sec*

2. Propagation delay

- How long does it take to move one bit from one end of a link to the other?
  - *No matter what speed the link is operating on!*
- Link length / Propagation speed of link
  - *E.g. 30 kilometers / 3 x 10^8 meters per sec = 10^{-4} sec*

Packet Delay

Sending 100B (=800bits) packets from A to B?

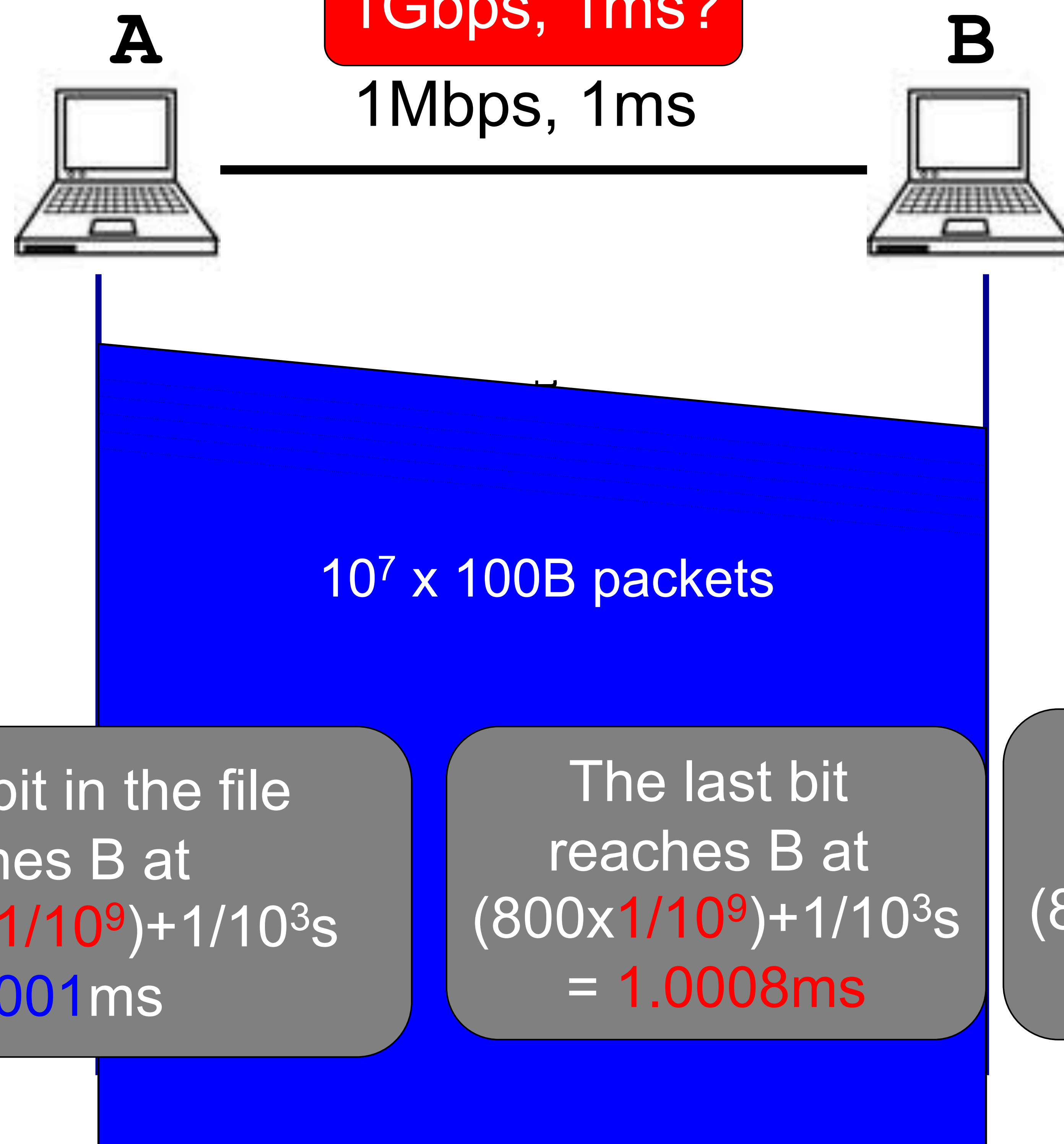


1GB file in 100B packets

y

Sending 100B=800bits packets from A to B?

1Gbps, 1ms?



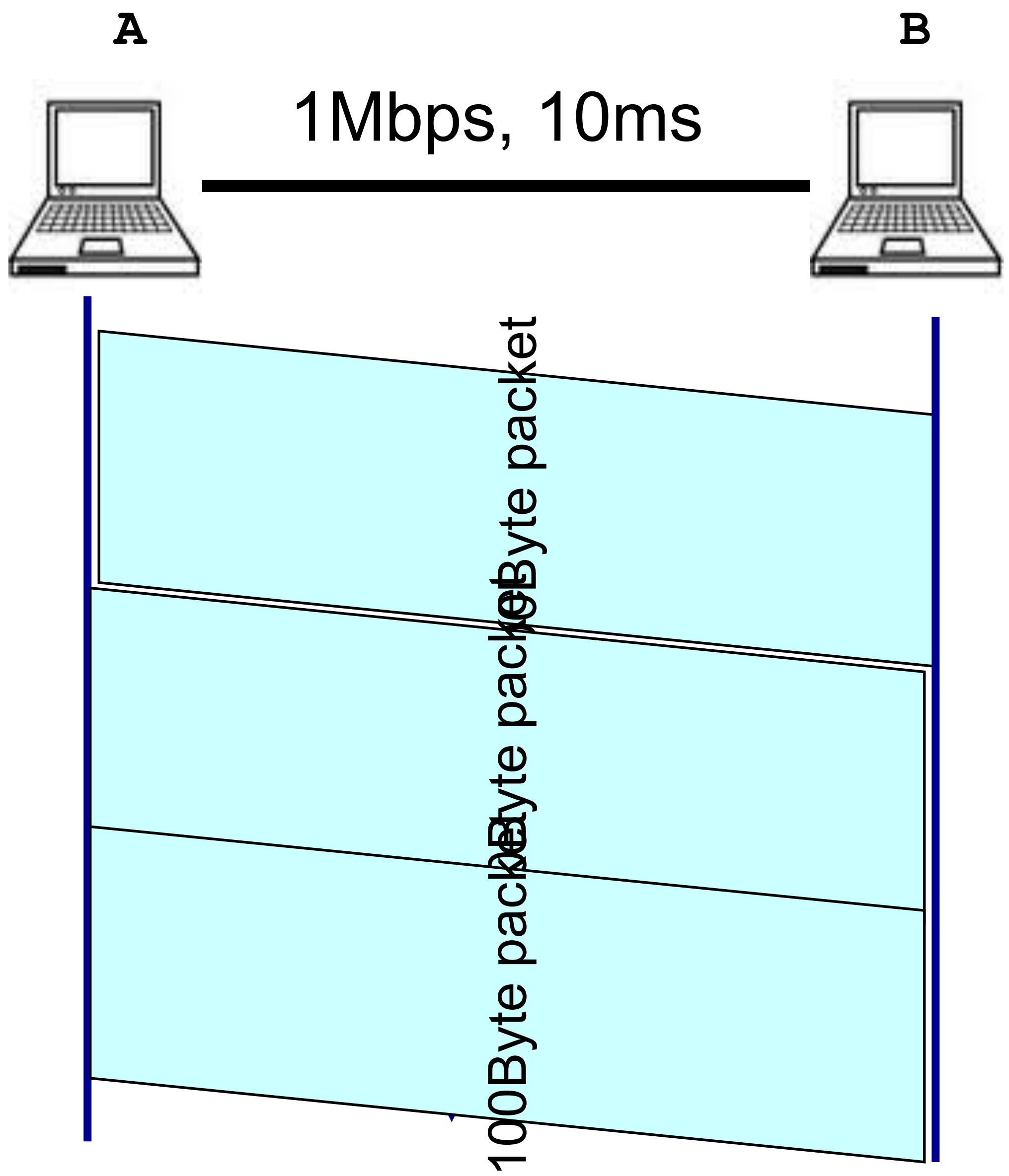
The last bit in the file reaches B at $(10^7 \times 800 \times 1/10^9) + 1/10^3$s = 8001ms

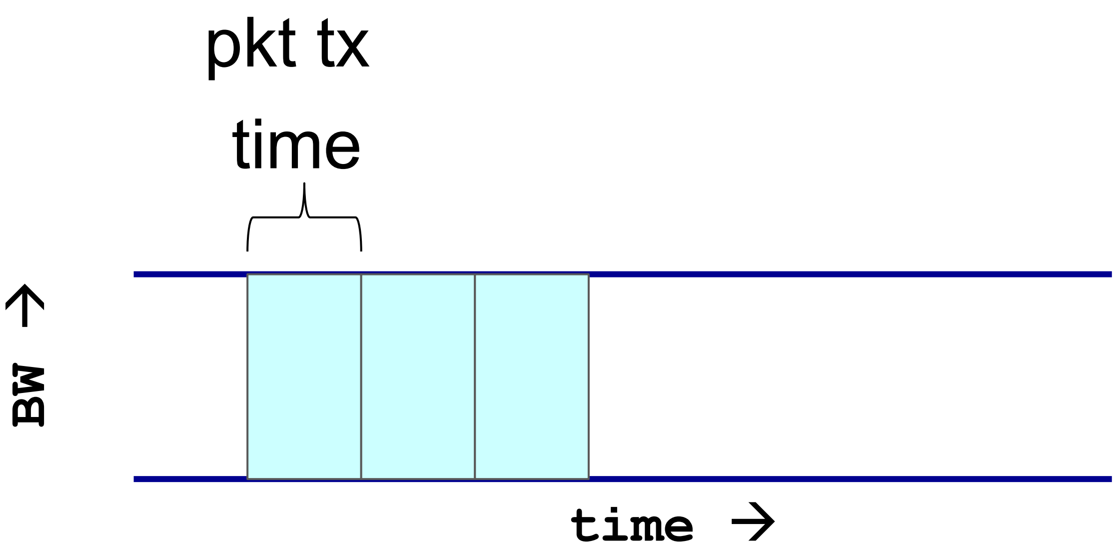
The last bit reaches B at $(800 \times 1/10^9) + 1/10^3$s = 1.0008ms

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

Packet Delay: The "pipe" view

Sending 100B packets from A to B?

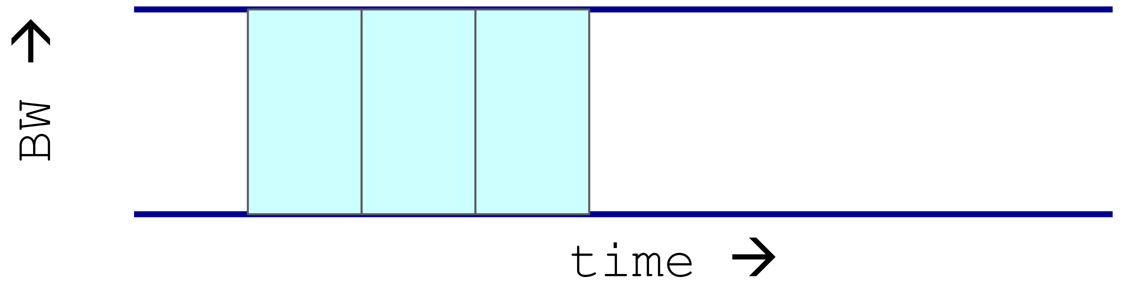




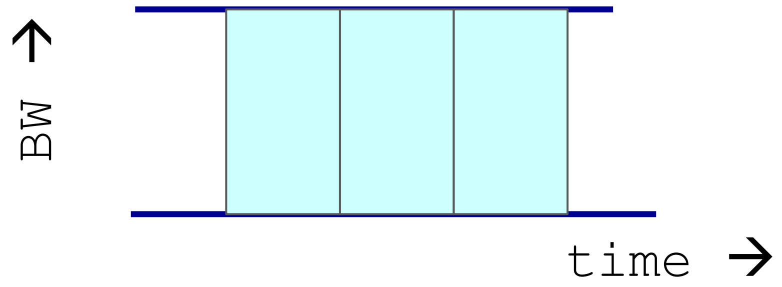
Packet Delay: The “pipe” view

Sending 100B packets from A to B?

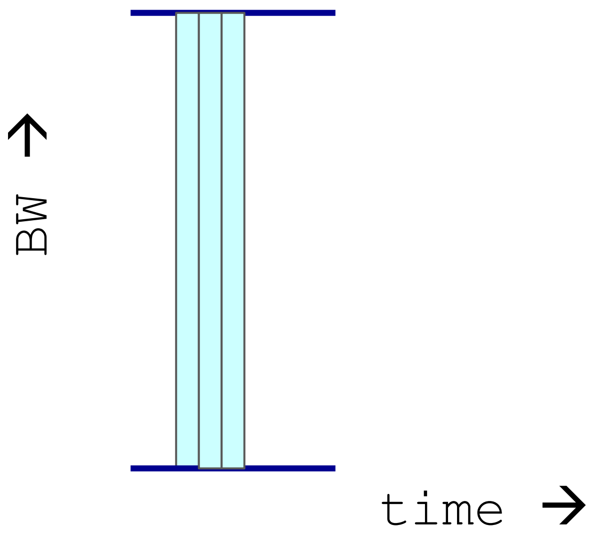
1Mbps, 10ms (BDP=10,000)



1Mbps, 5ms (BDP=5,000)



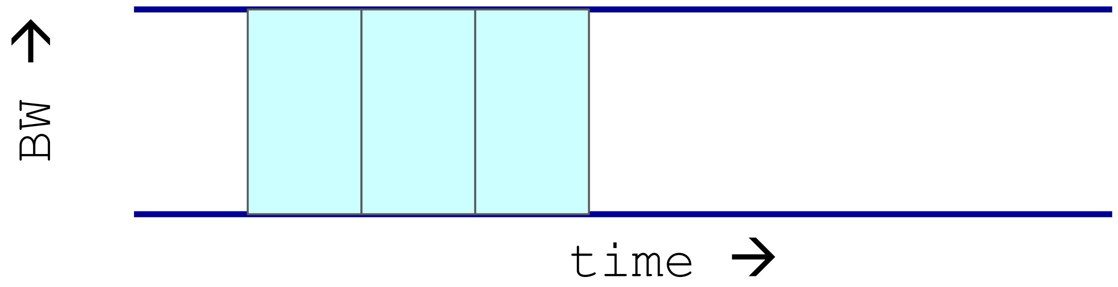
10Mbps, 1ms (BDP=10,000)



Packet Delay: The "pipe" view

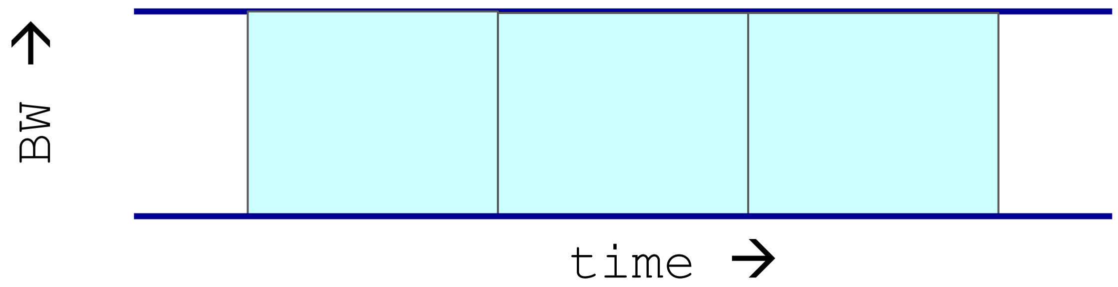
Sending ~~100B~~ packets from A to B?

1Mbps, 10ms (BDP=10,000)



200B?

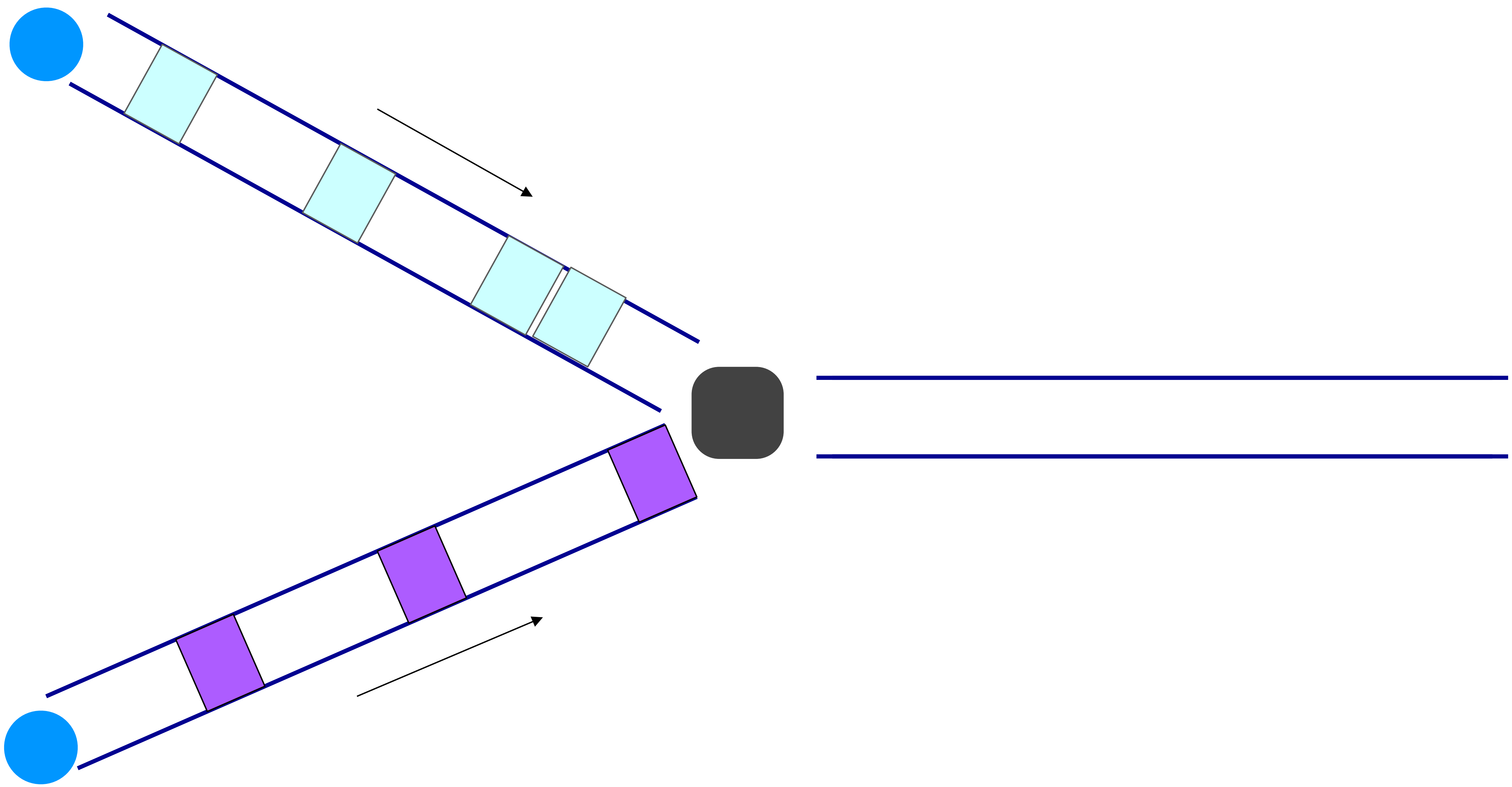
1Mbps, 10ms (BDP=10,000 *units?*)



3. Queuing delay

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

Queuing delay: “pipe” view



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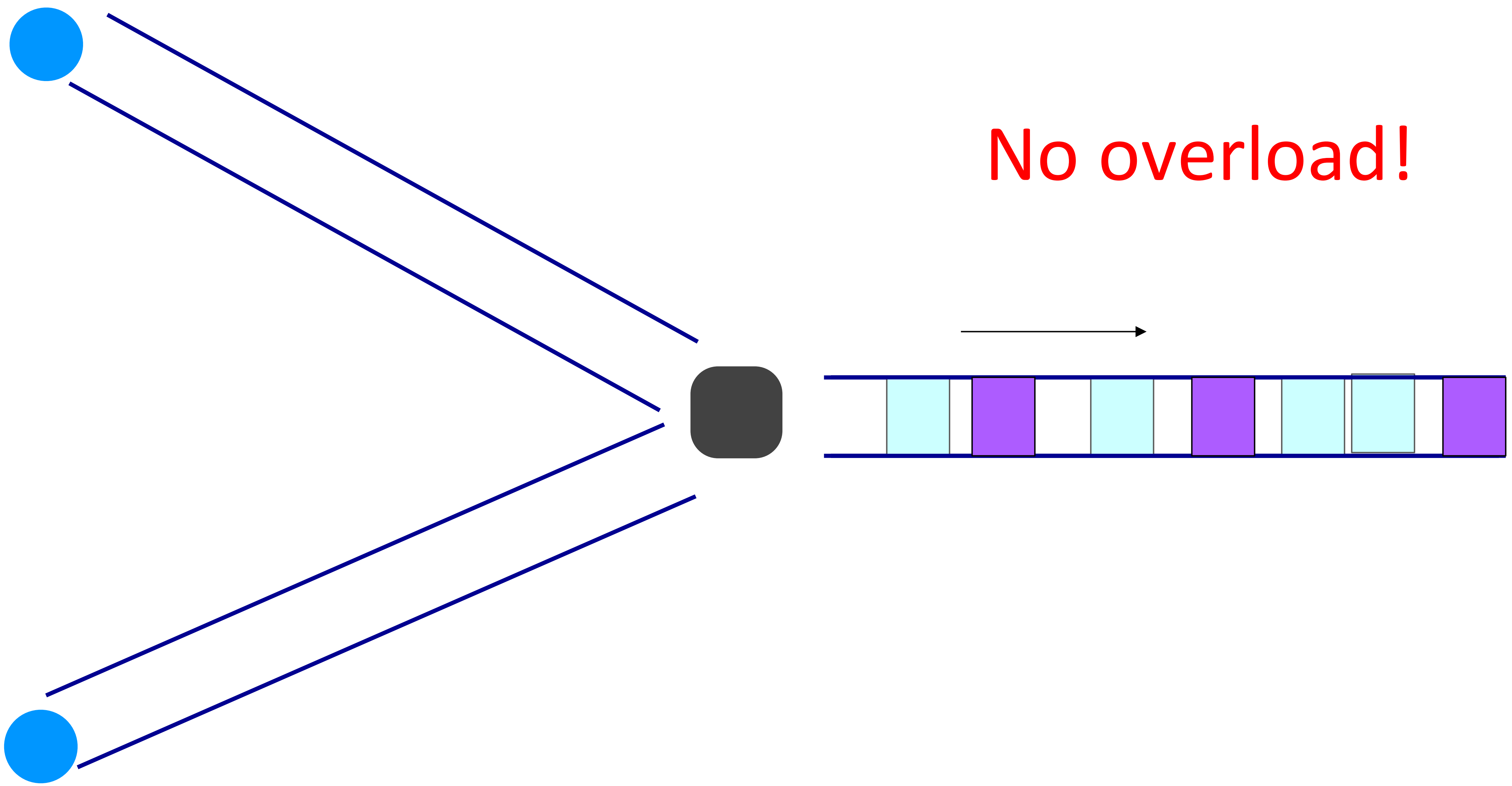

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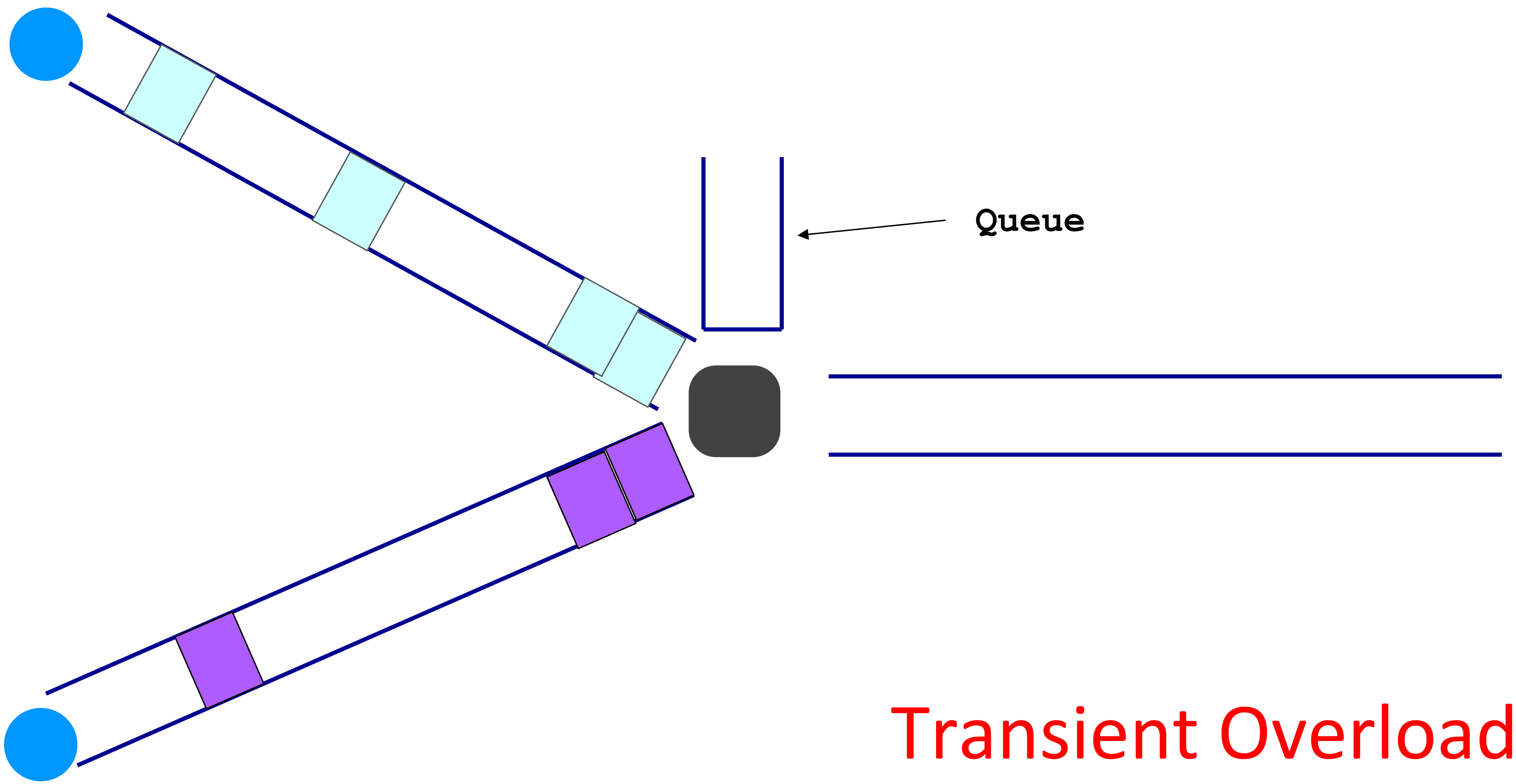
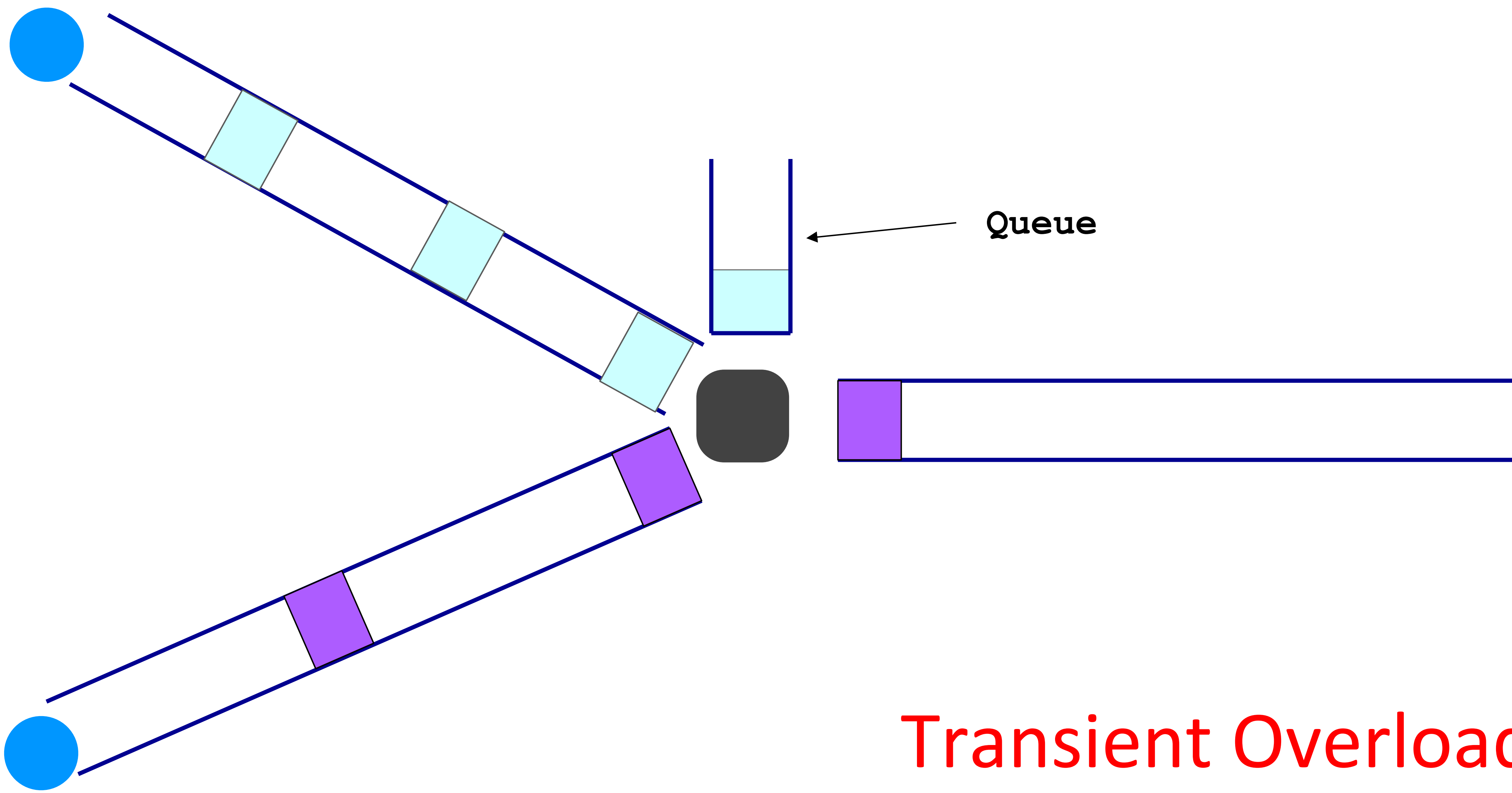


Transient Overload

Not a rare event!

Queuing delay: “pipe” view



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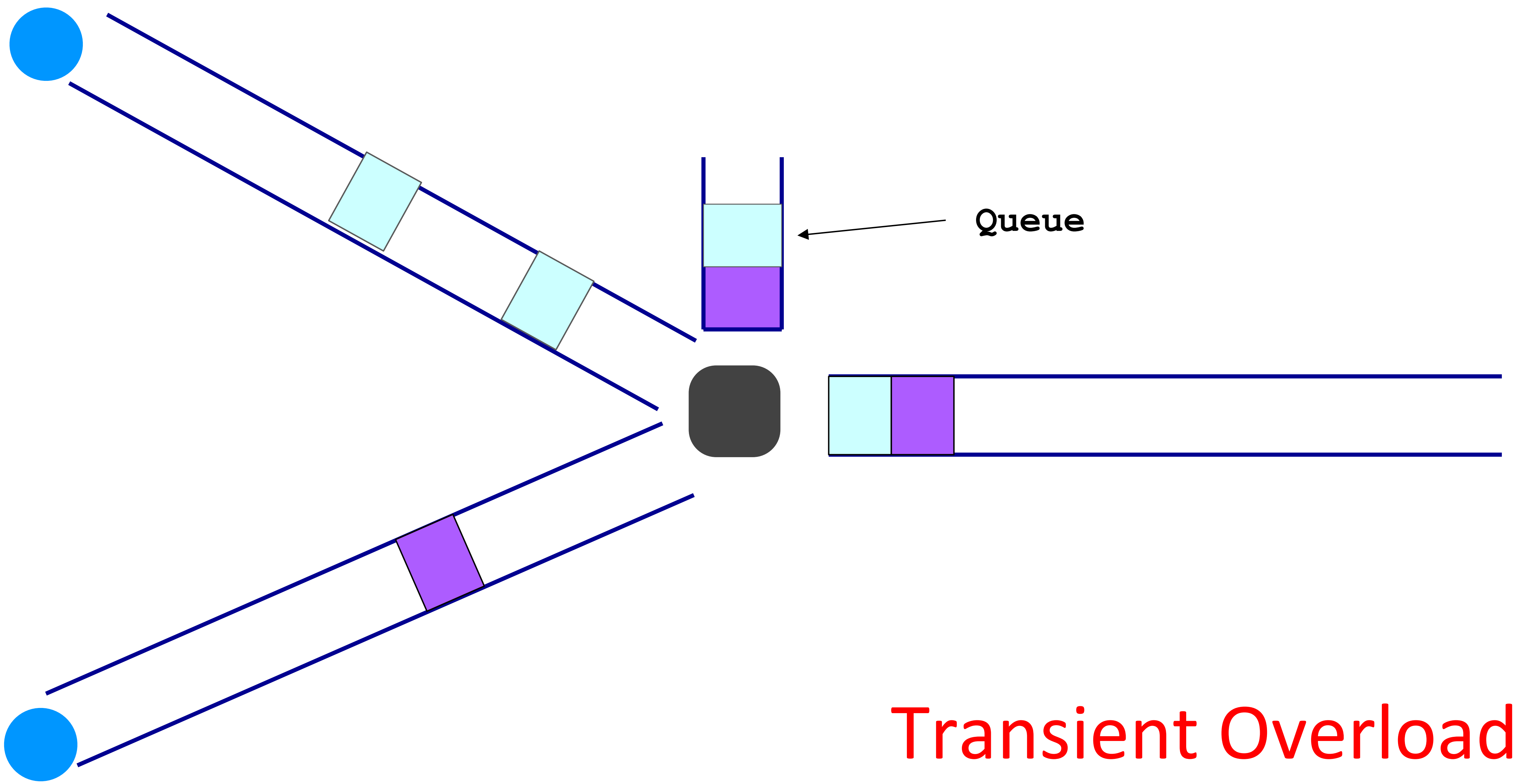

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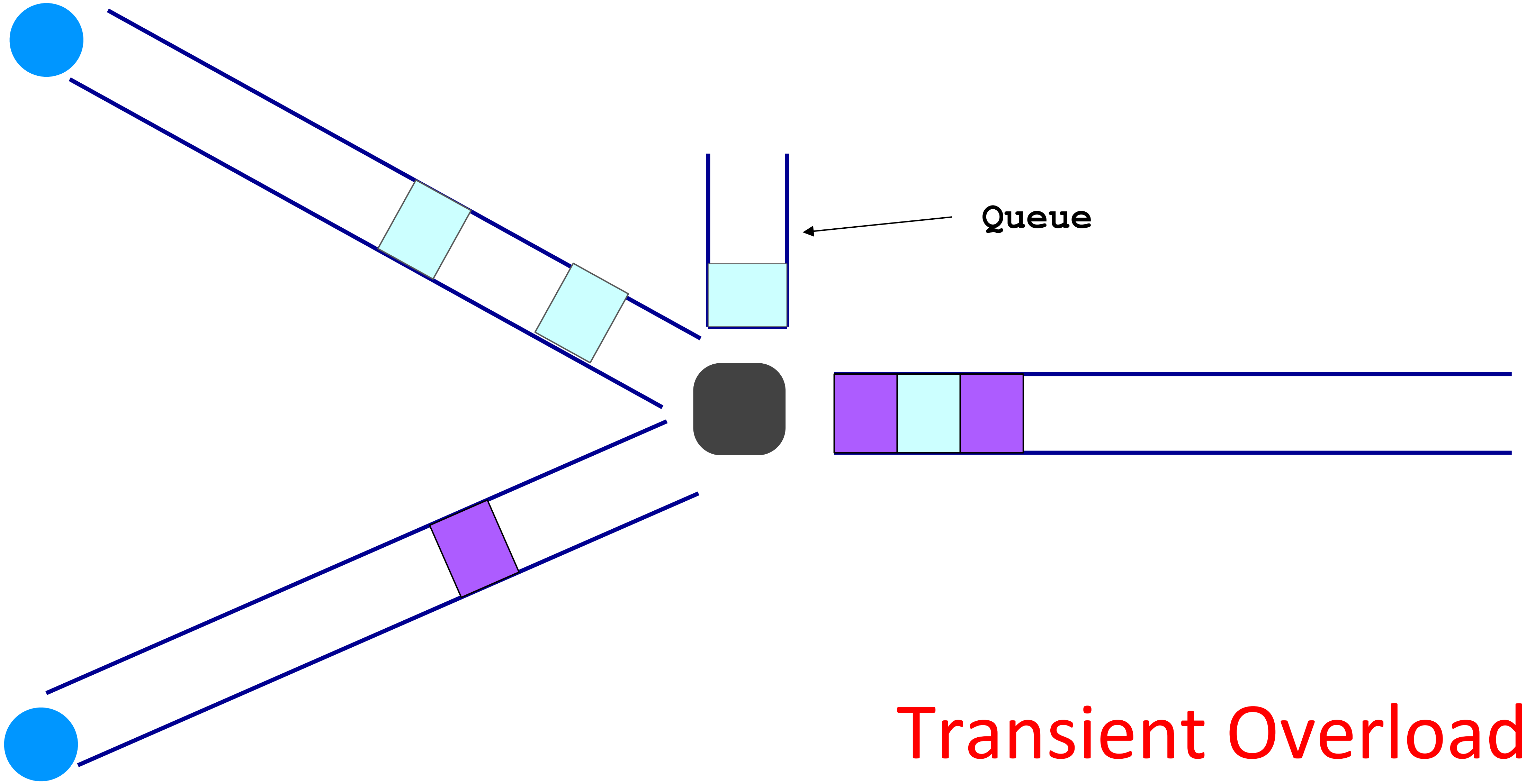

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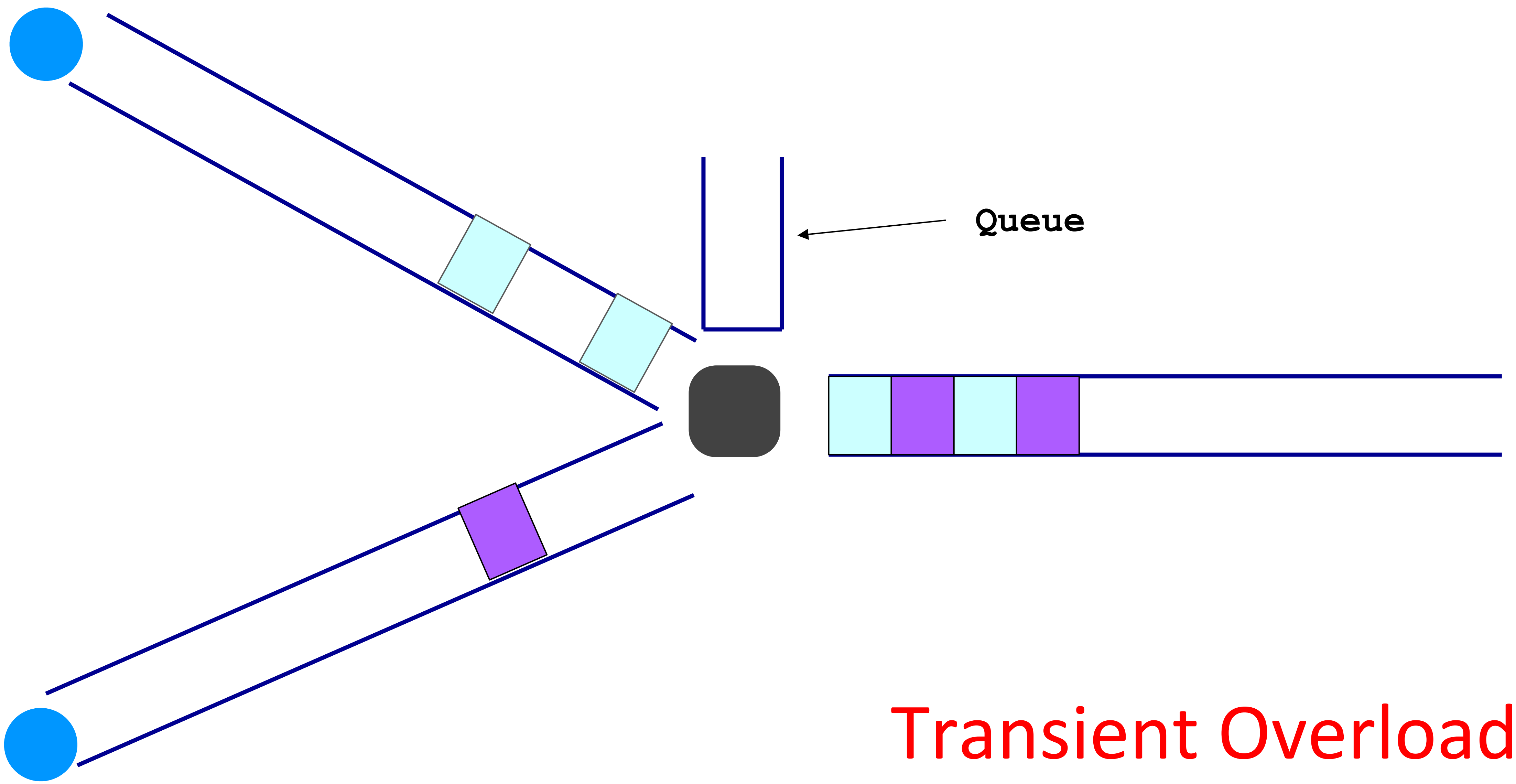

Transient Overload

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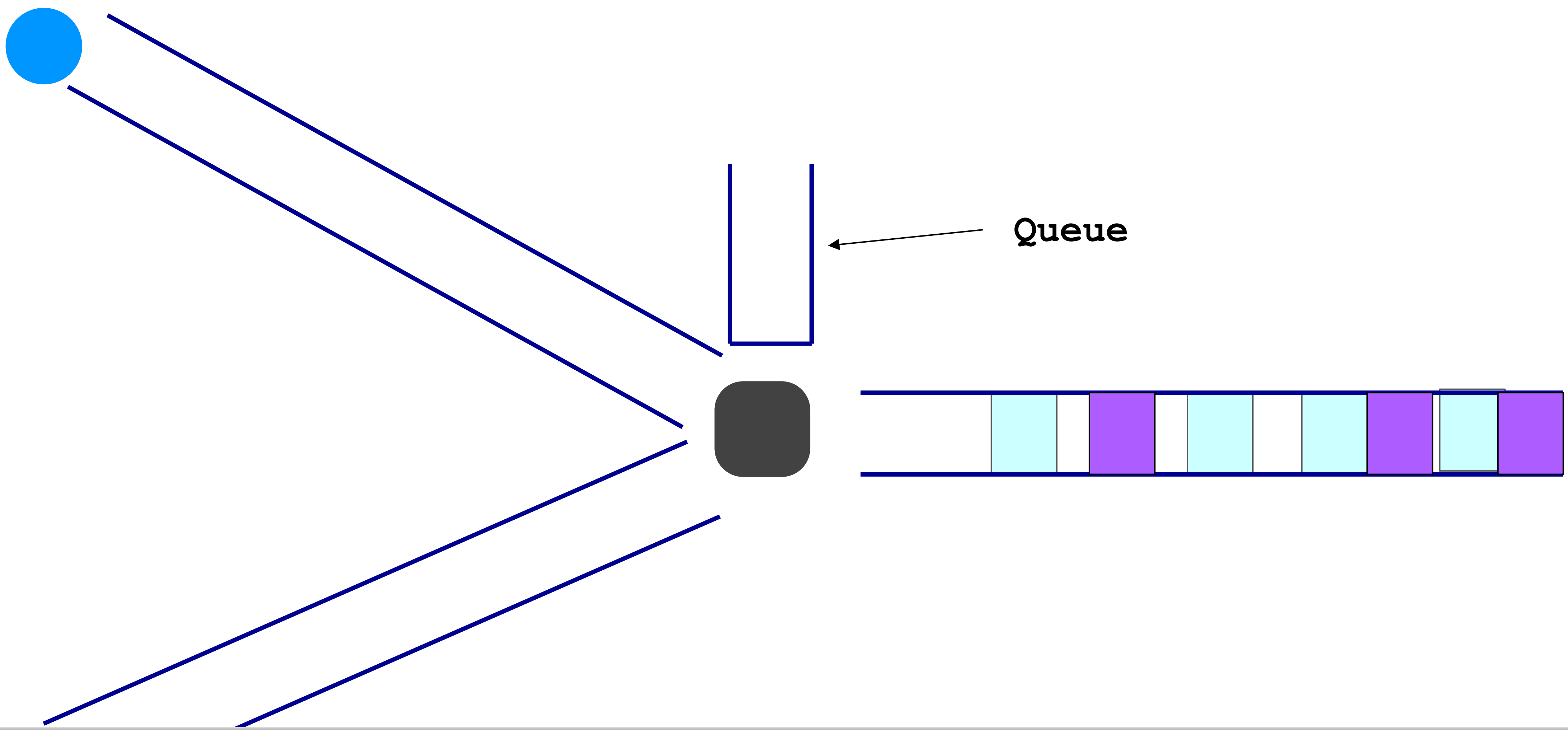
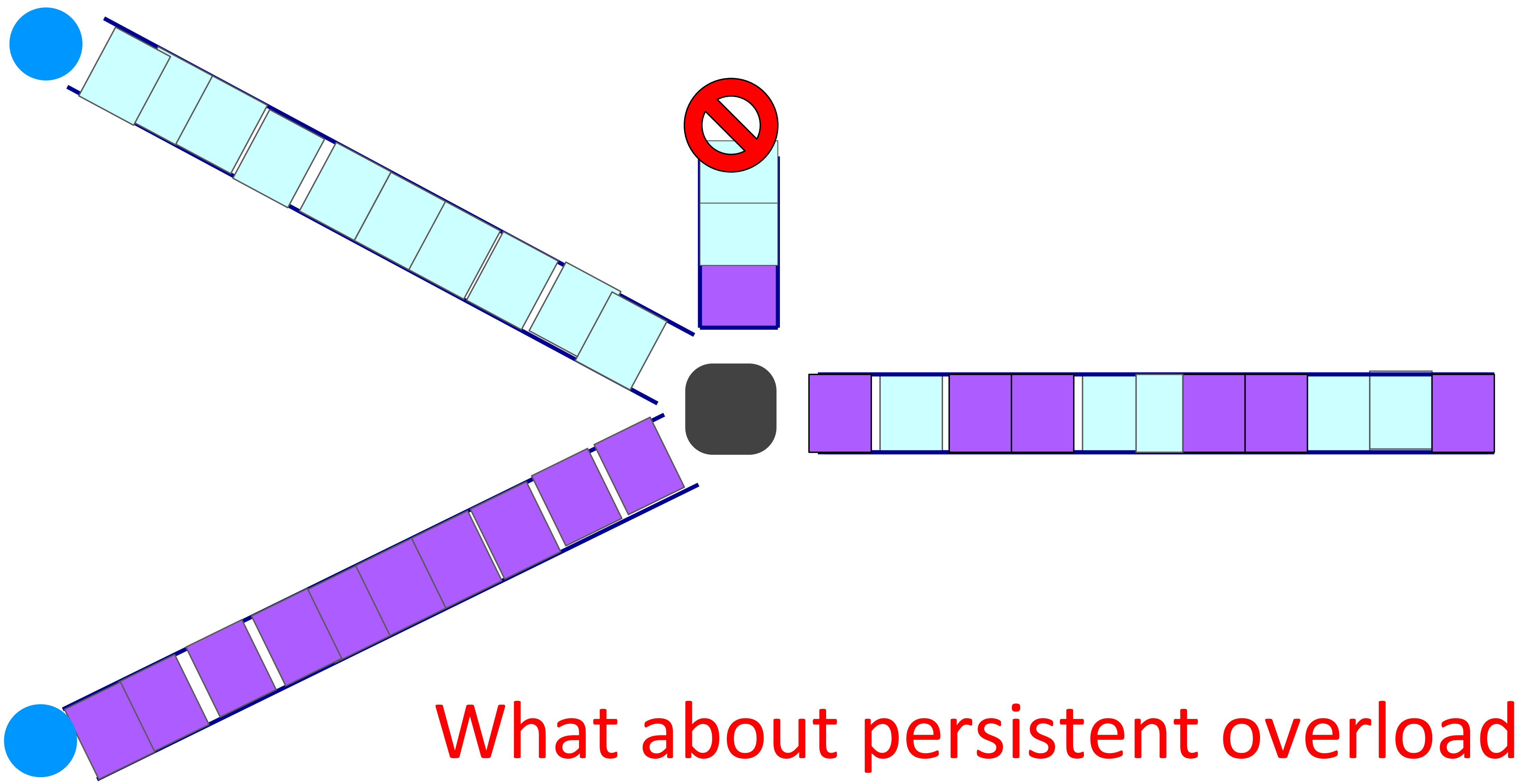
Queuing delay: "pipe" view



Queues absorb transient bursts but introduce queuing delay

Queuing delay: “pipe” view



What about persistent overload?

Will eventually drop packets (“loss”)

Queuing 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

Queuing 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 Queuing Theory Terminology

- Arrival process: how packets arrive
  - Average rate λ (in packets per unit time)
  - 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" (in packets)

Little’s Law (1961)

$$L = \lambda \times W$$

- Compute L: count packets in queue every second
  - How often does a single packet get counted? W times

- Example:
  - Arrival rate is 100,000 packets/sec
  - Avg time a packet spends in buffer is 1ms
  - Then avg queue size is 100 packets.

Queueing Process

A(t) = cumulative #bits arrived until time t
D(t) = cumulative #bits departed until time t

Both A(t) and D(t) are non-decreasing functions
A(t) is always greater than or equal to D(t)

Queue size Q(t) is the difference between A(t) and D(t)
Q(t) is always non-negative

4. Processing Delay

- *How long does the switch take to process a packet?*
  - typically assume this is negligible at macro level

Thank you!