EECS 489
Computer Networks

Winter 2025

Mosharaf Chowdhury

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

Agenda

- Introductions
- Class policies, logistics, and roadmap
- Overview of the basics
  - How is the network shared?
  - How do we evaluate a network?
  - What is a network made of?

Staff

Aditya Singhvi

Efe Akinci

Alex de la Iglesia

- Office hours: See course webpage
- No office hours this week or discussions this week

Mosharaf Chowdhury

- @Michigan since 2016
- Research: SymbioticLab.org

- Office hours: Thursdays 2:45PM – 3:45PM (in-person @ 4820 BBB)

- No office hours this week
- Lectures will be recorded

489 in EECS curriculum

- **EECS 281**
  - High-level logic ⇒ Programs
  - Coding skills learned in 281 are critical for 489 assignments
- *EECS 482*
  - How do machines work?
  - Execute programs, interact with users, etc.
  - Prior 482 experience is not needed

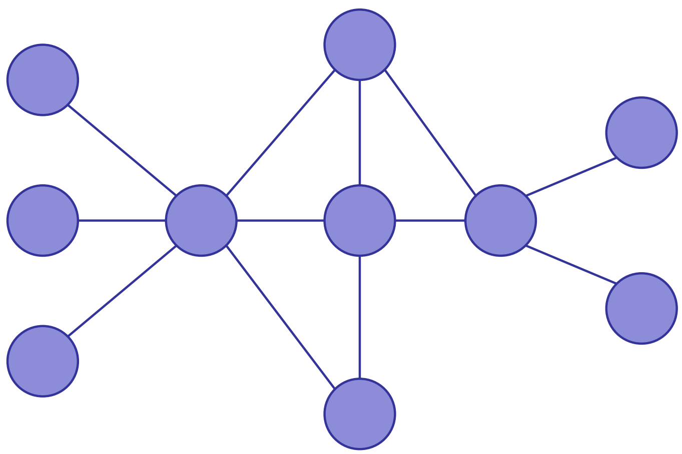
What is missing?

- How do we access *most* services?
  - Examples include search engines, social networks, video streaming, etc.
- How do two machines communicate?
  - When they are directly connected
  - When they are not directly connected

- Using a network

What is a network?

- A system of “links” that interconnect “nodes” in order to move “information” between nodes



- We will focus primarily on the Internet

What is EECS 489 about?

- To learn about (at a high level)
  - How the Internet works
  - Why it works the way it does
  - How to reason about complicated design problems

- What it's not about
  - How to write web services
  - How to design web pages
  - …

Class workload

- Four assignments/projects
  - First one is an individual assignment
  - The rest are done as groups
- Exams:
  - Midterm: Week of February 24 (TBD)
  - Final: April 29, 1:30 PM – 3:30 PM
    - » Final covers only the materials after midterm

Grading

	Allocation
Assignment 1	5%
Assignment 2	15%
Assignment 3	15%
Assignment 4	15%
Midterm	25%
Final	25%

The assignments

- Assignment 1: measure end-to-end throughput and delay of networks (i.e., simple speed test)
- Assignment 2: video streaming from CDNs (i.e., simple Netflix)
- Assignment 3: reliable transport (i.e., how to transfer data over an unreliable network)
- Assignment 4: router design (i.e., how do internal elements of the network work)

All on (emulated) realistic networks using *mininet*

Bonus Quizzes

- ~10 MCQ and solution key for each of the 20 lectures
- Made online sometime after the lecture; live for at least 48 hours
- Completing all counts for a maximum of 2% on top of your final grade
  - How well you do doesn't matter

Enrollment and wait list

- Wait-listed students will be admitted in the order of wait list
- If you’re planning to drop, please do so soon!

Communication protocol

- Website: https://github.com/mosharaf/eecs489/
  - Assignments, lecture slides
- Confidential content on Canvas & Gradescope
- Ed for all communication
  - Sign up at https://edstem.org/us/join/jwtp2b

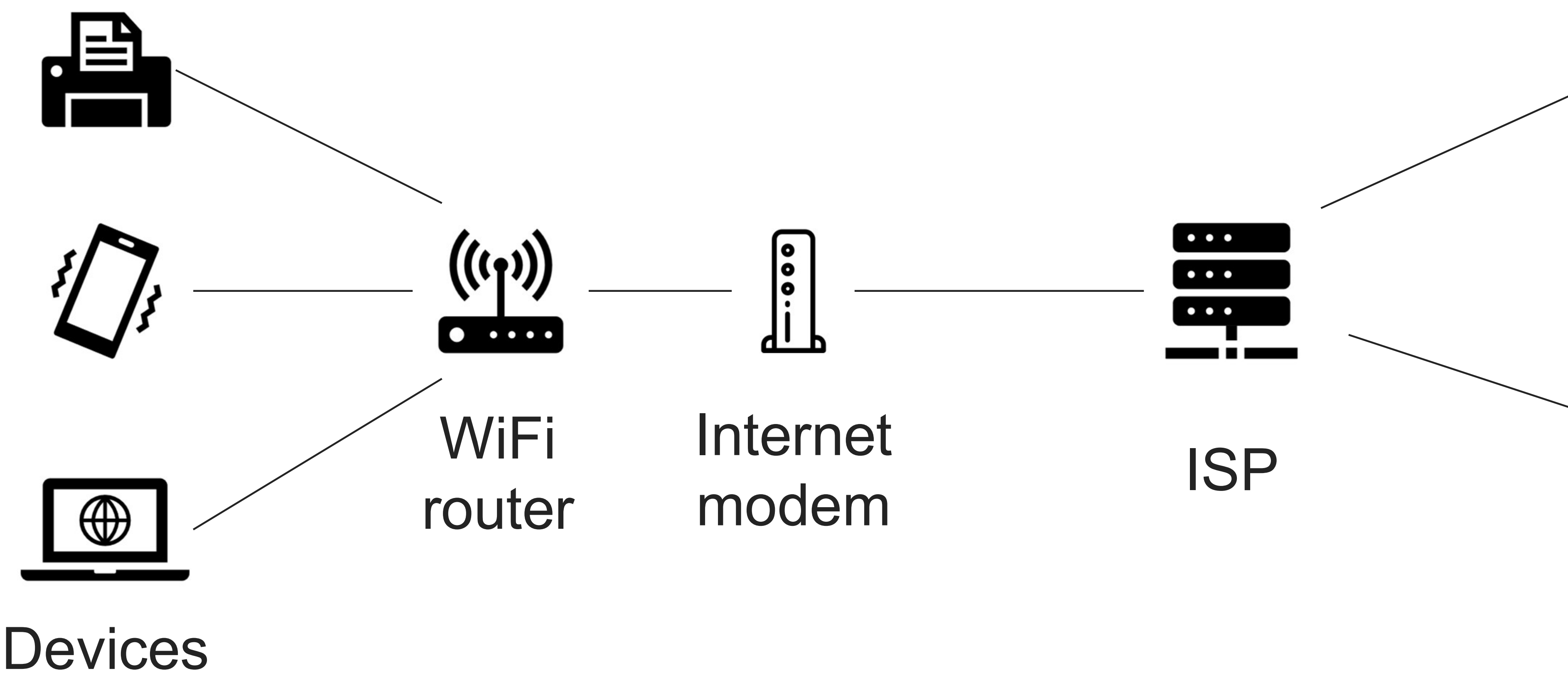
- Assignment submission via g489.eecs.umich.edu

Policies on late submission, re-grade request, cheating …

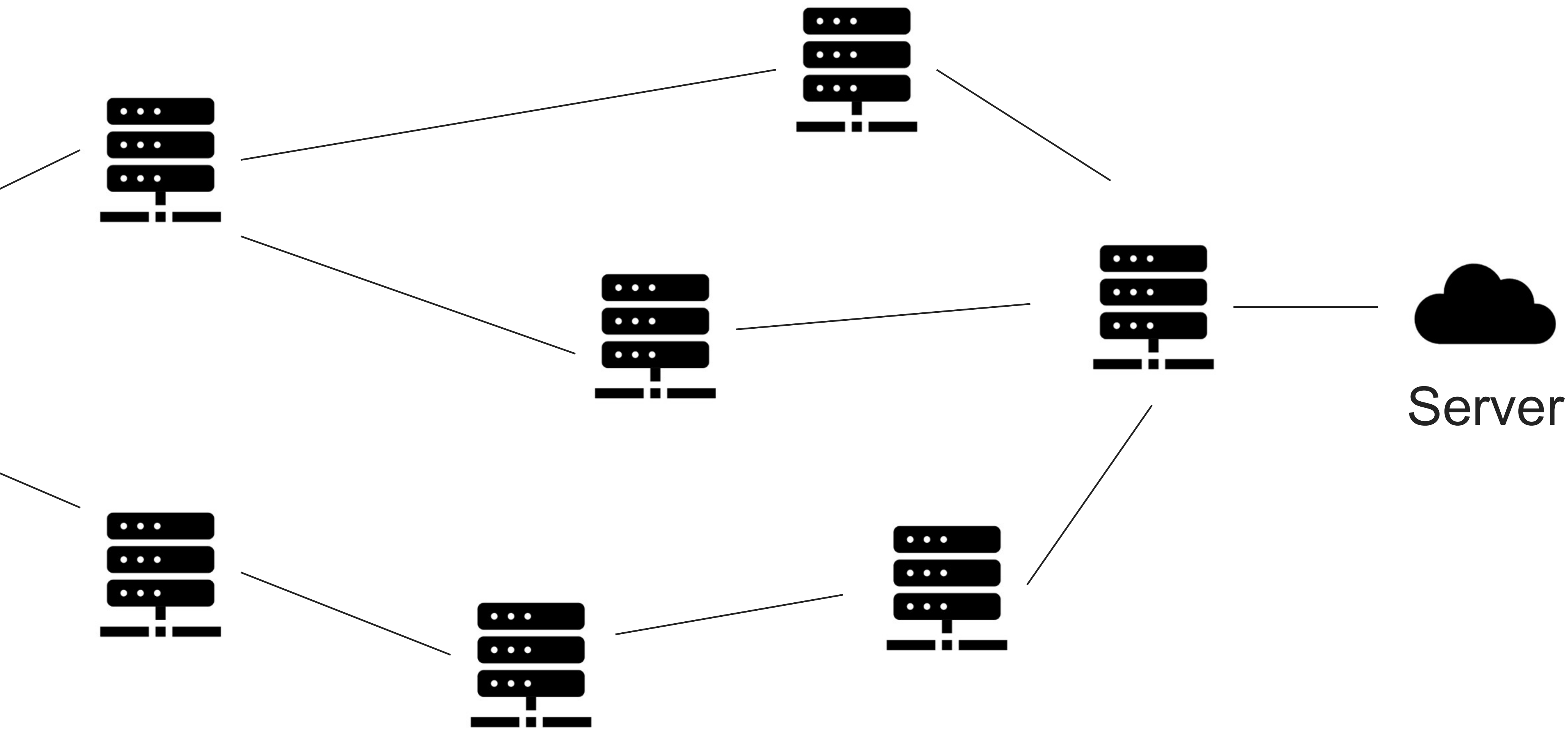
- Detailed description in the course webpage
- Don’t cheat!

LET'S TALK INTERNET

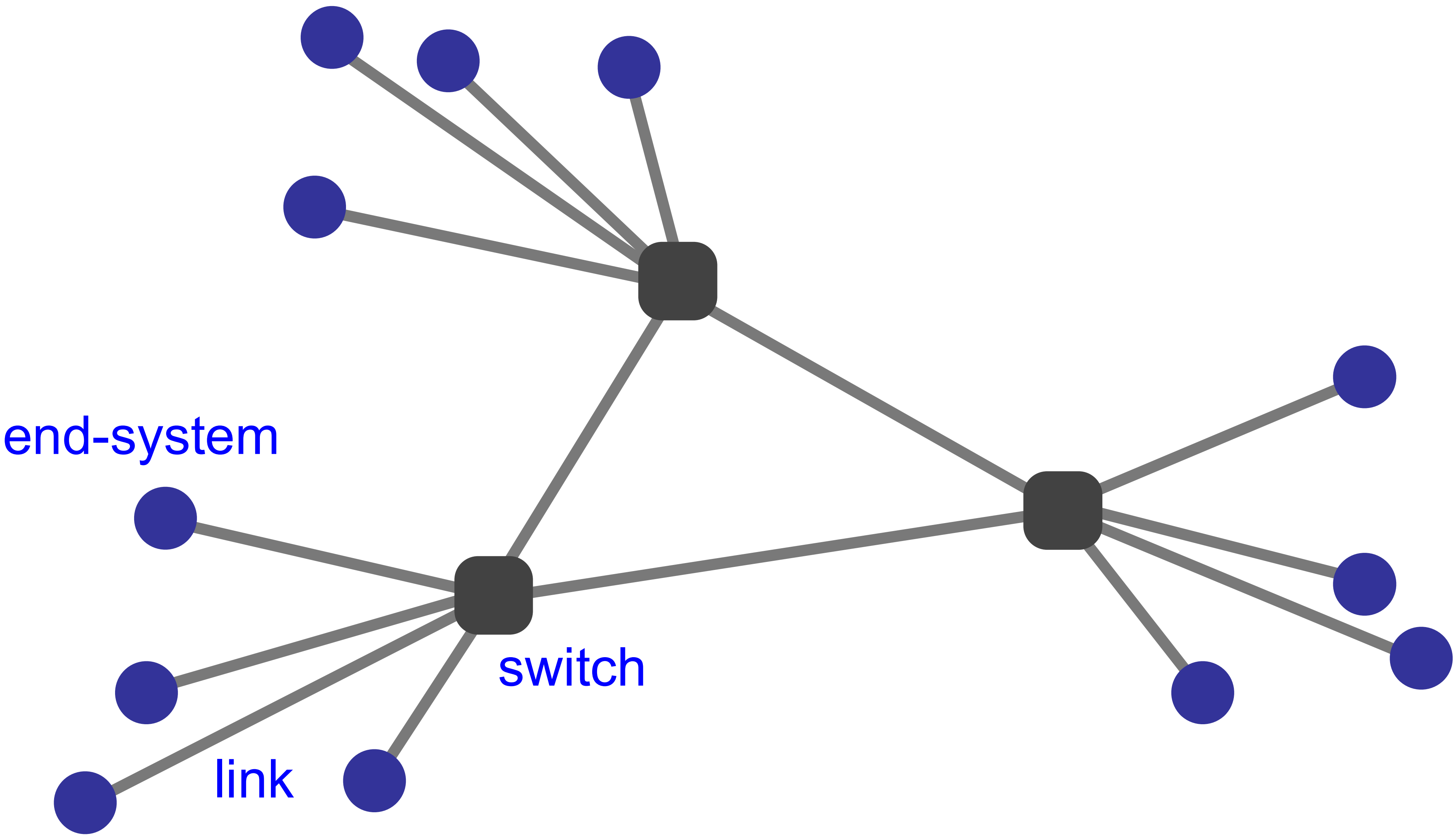
From the home...



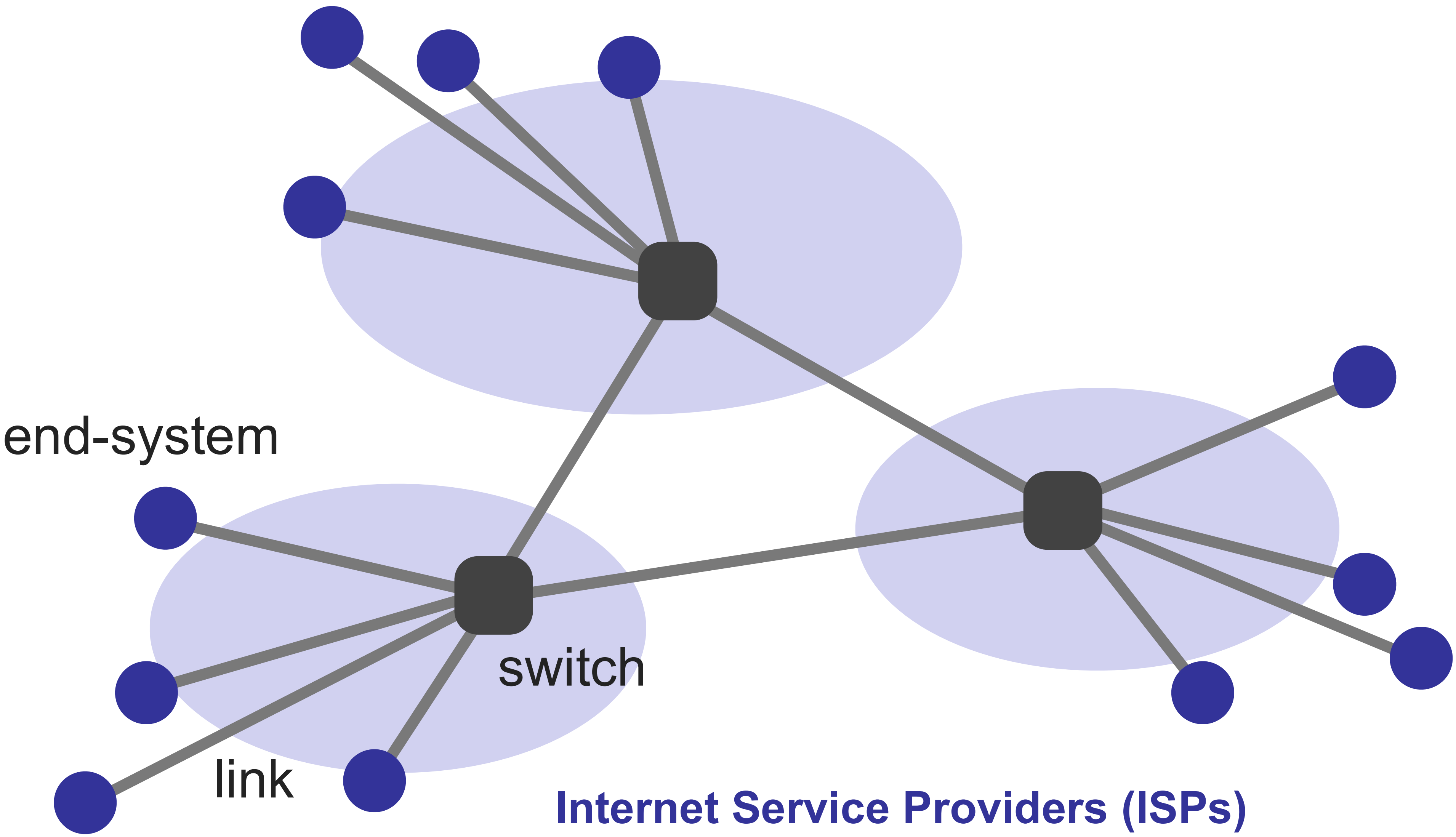
Across the world...



The Internet consists of many end-systems

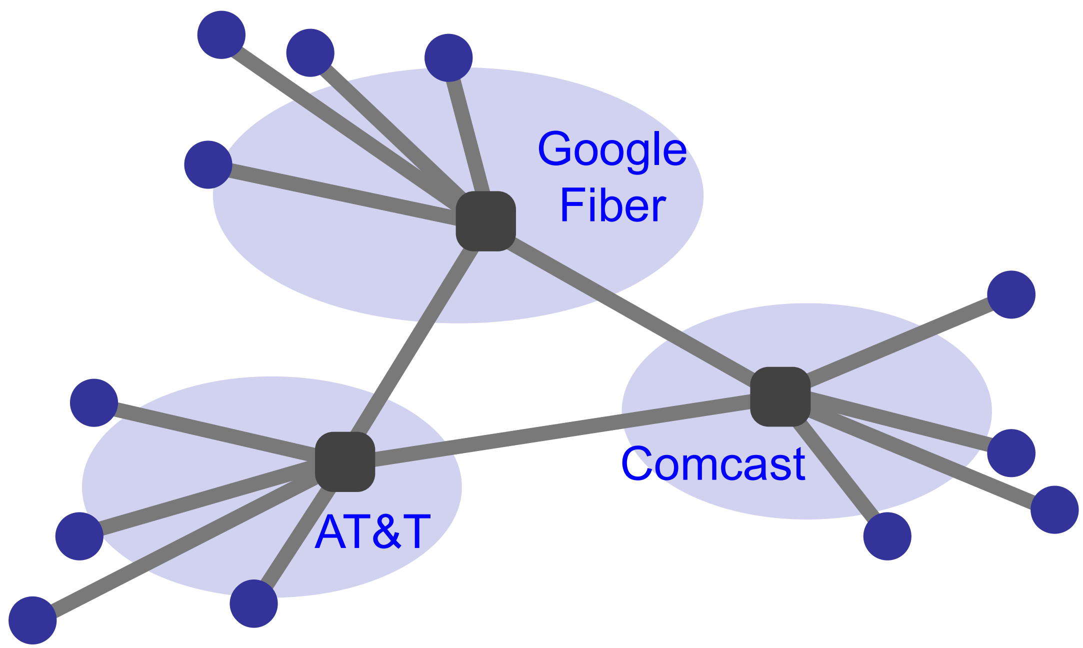


Managed by many parties



A federated system: Logical view

- The Internet ties together different networks **by the IP protocol**
  - *A common interface binds them all together*



A federated system: Physical view

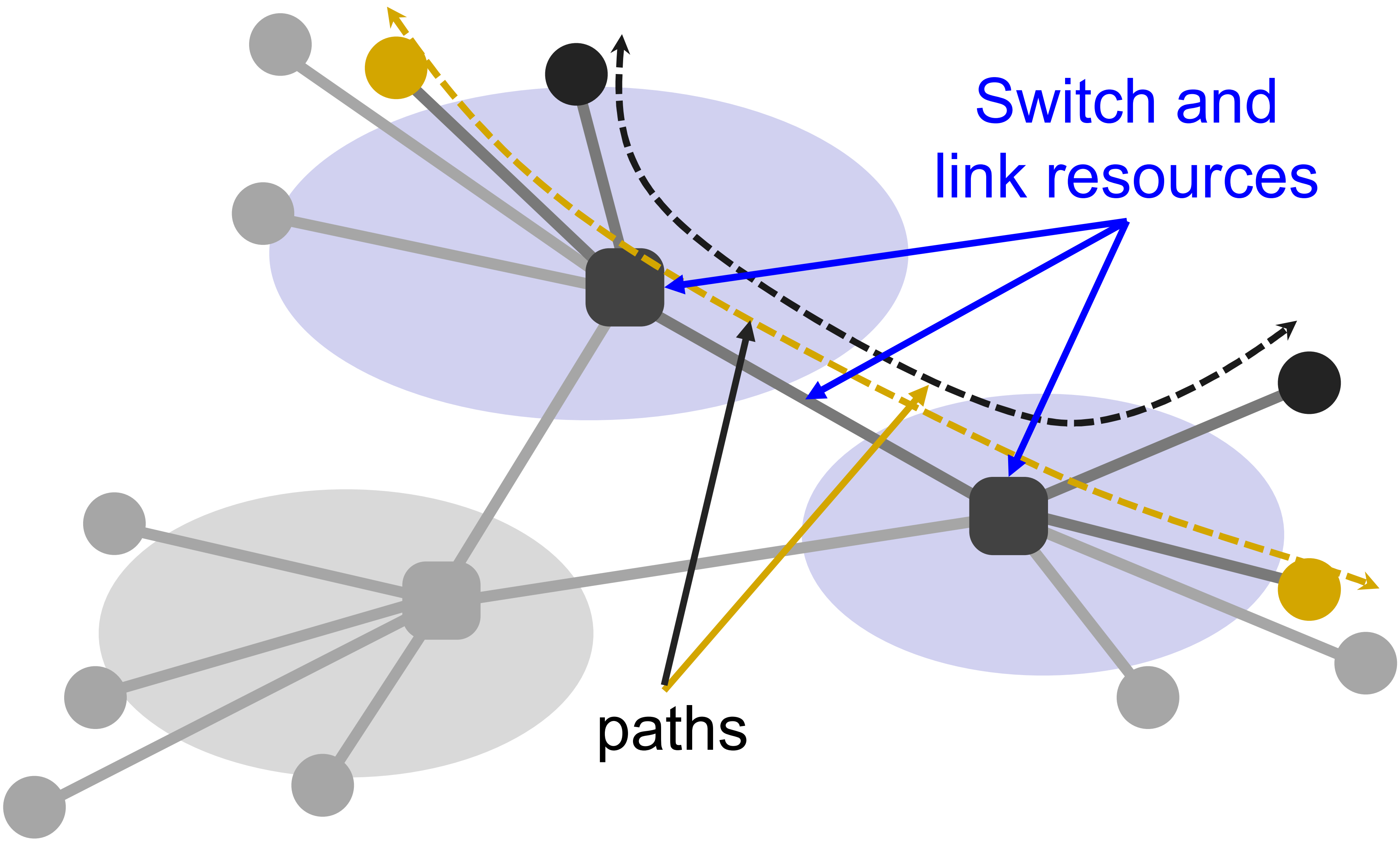
https://kmcd.dev/posts/internet-map-2023/

INTERNET IS A SWITCHED NETWORK (OF NETWORKS)

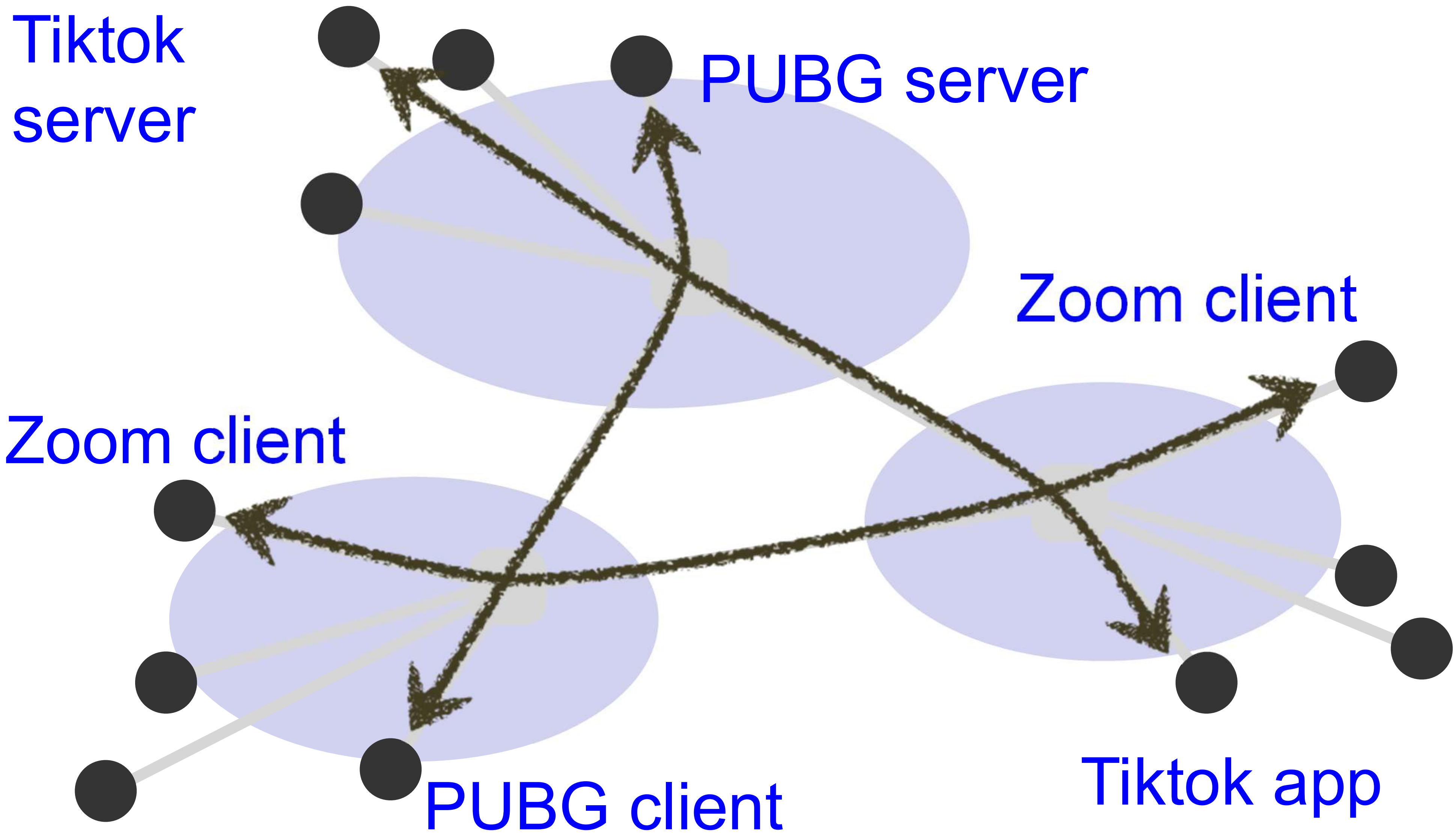
Switched networks

- 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?



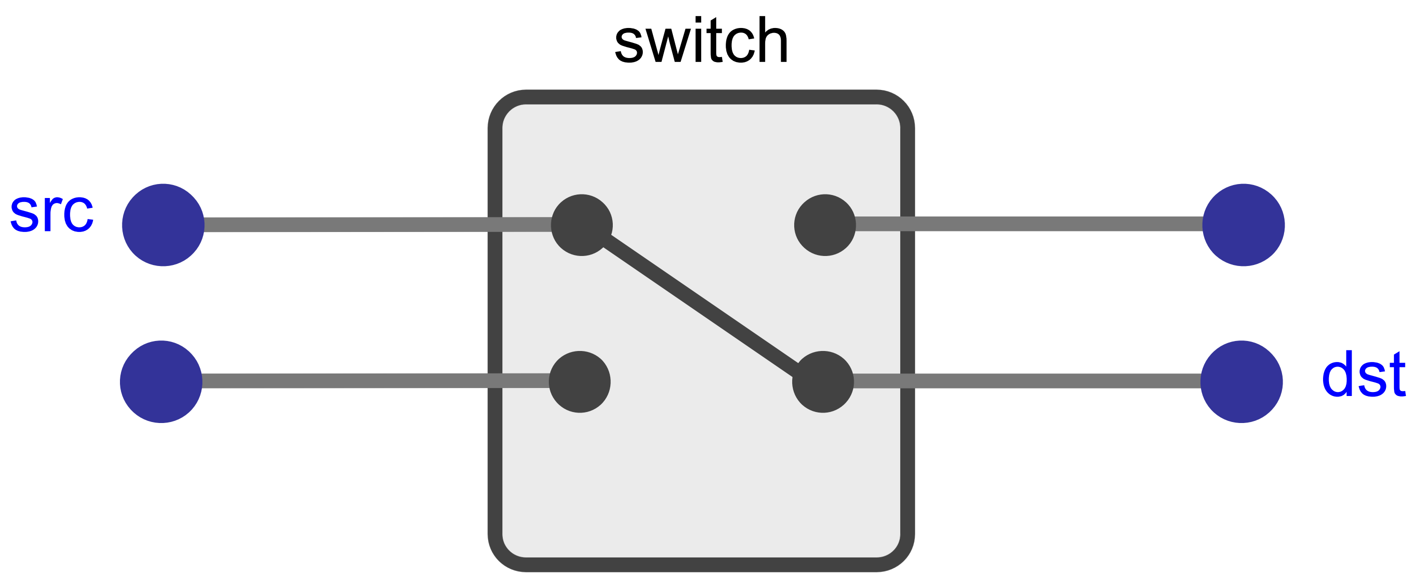
Shared among many services



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

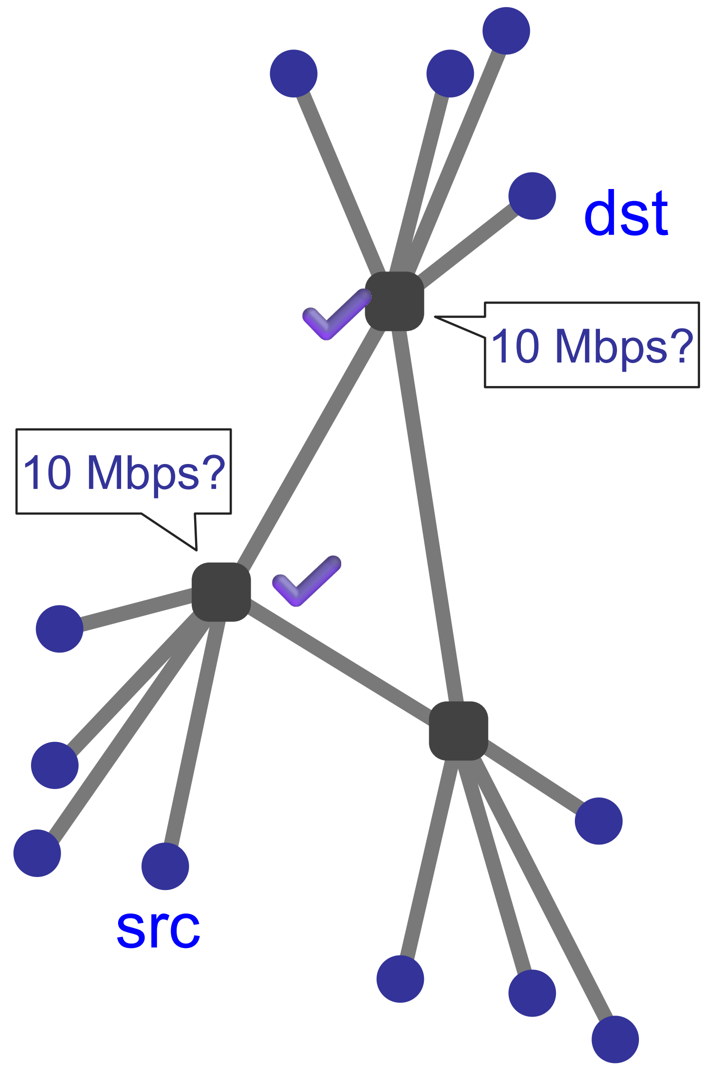
Circuit switching



- Reservation establishes a "circuit" within a switch

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

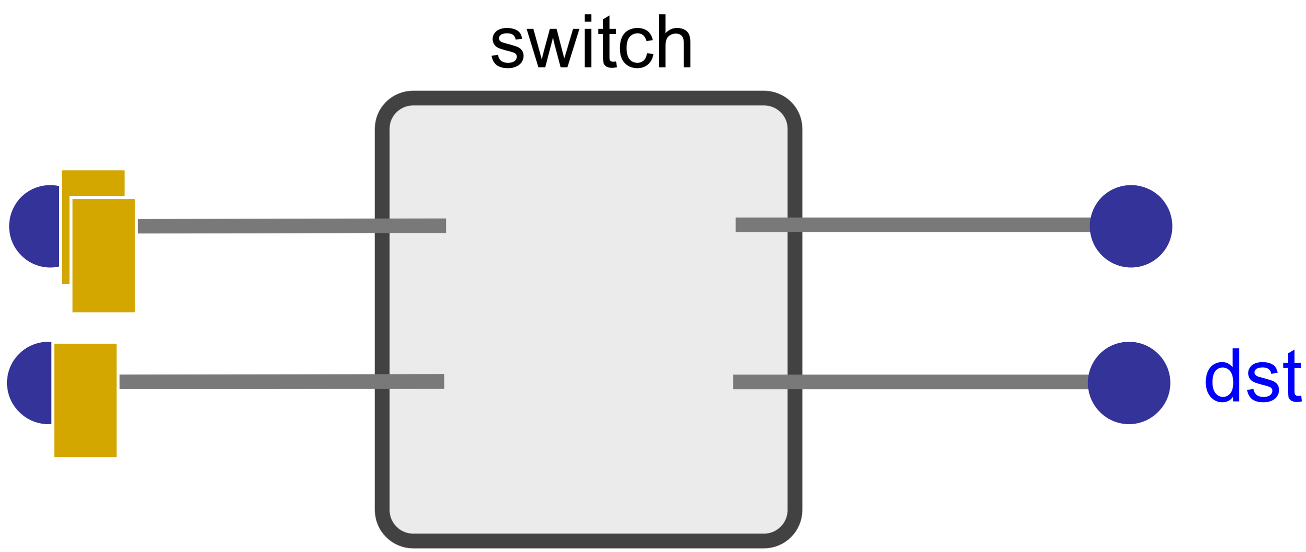


Circuit switching

- Pros
  - Predictable performance
  - Simple/fast switching (once circuit established)

- Cons
  - Complexity and delay from circuit setup/teardown
  - Inefficient when traffic is bursty
  - Switch fails → its circuit(s) fails

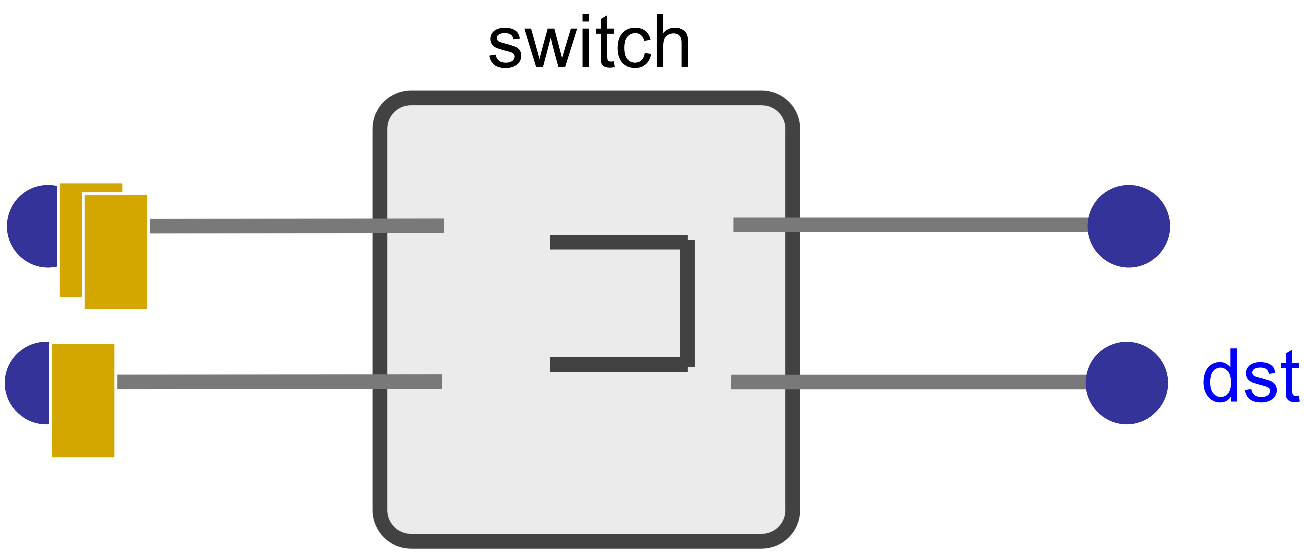
Packet switching



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

MASSIVE Scale

5+ Billion users

>1.1 Billion websites

~350 Billion emails sent per day

>6.9 Billion smartphones

>3 Billion monthly active Facebook users

>1 Billion hours of YouTube watched per day

…

5-MINUTE BREAK!

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?

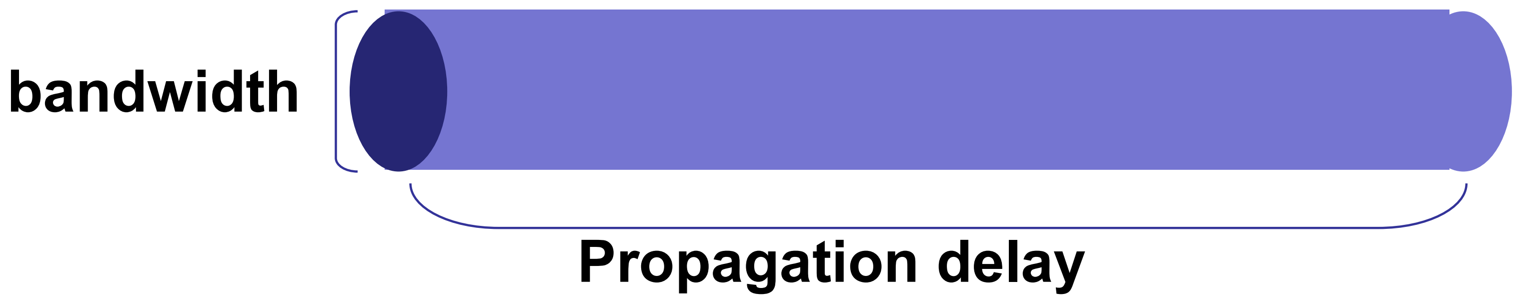
Delay

- 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)

1. Transmission delay

How long does it take to push all the bits of a packet into a link?

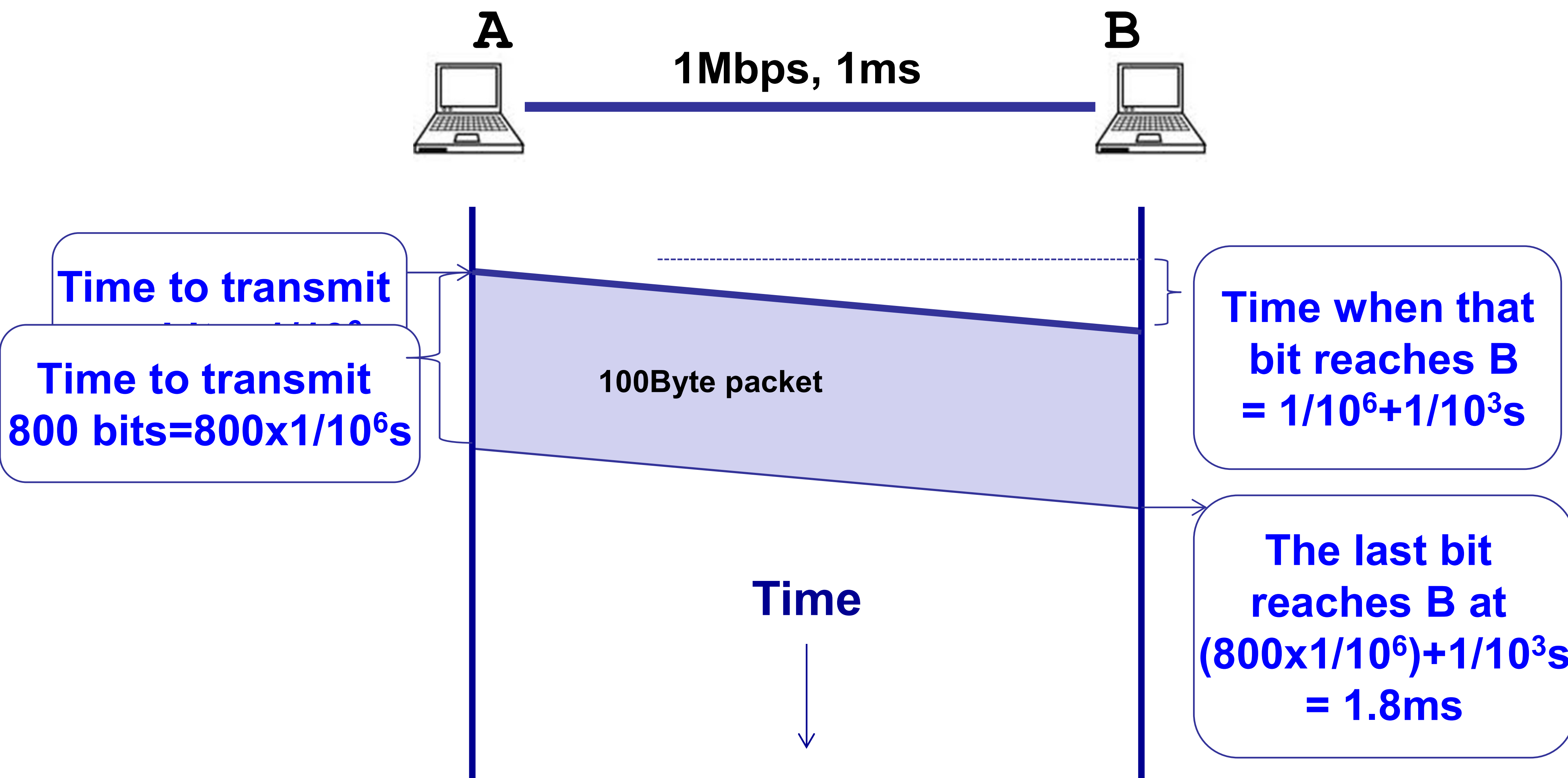
Packet size / Bandwidth of the link

- 1000 bits / 100 Mbits per sec = 10^{-5} sec
- 1000 bits / 1 Gbits per sec = 10^{-6} 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

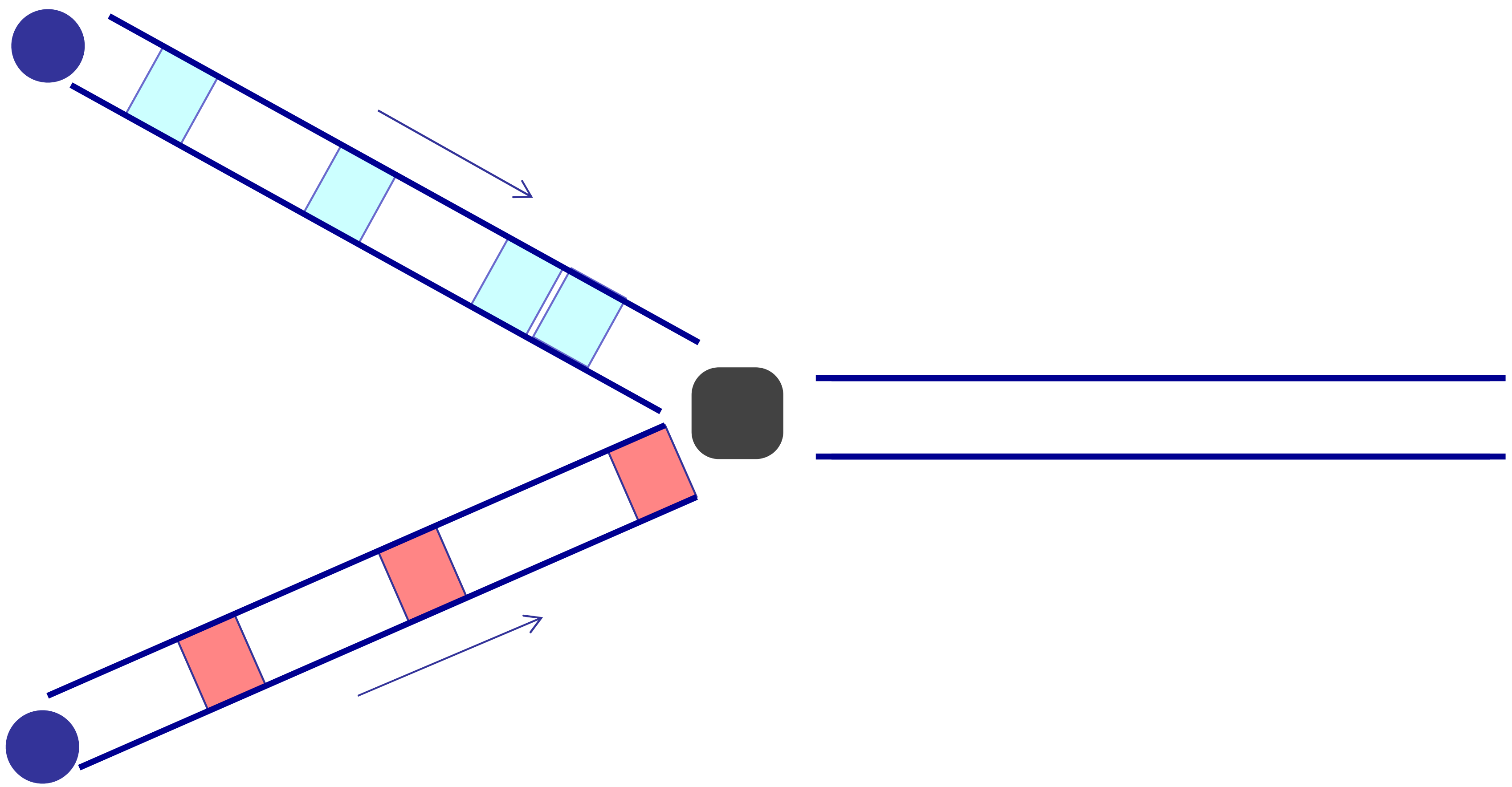
Packet delay
Sending a 100-byte packet



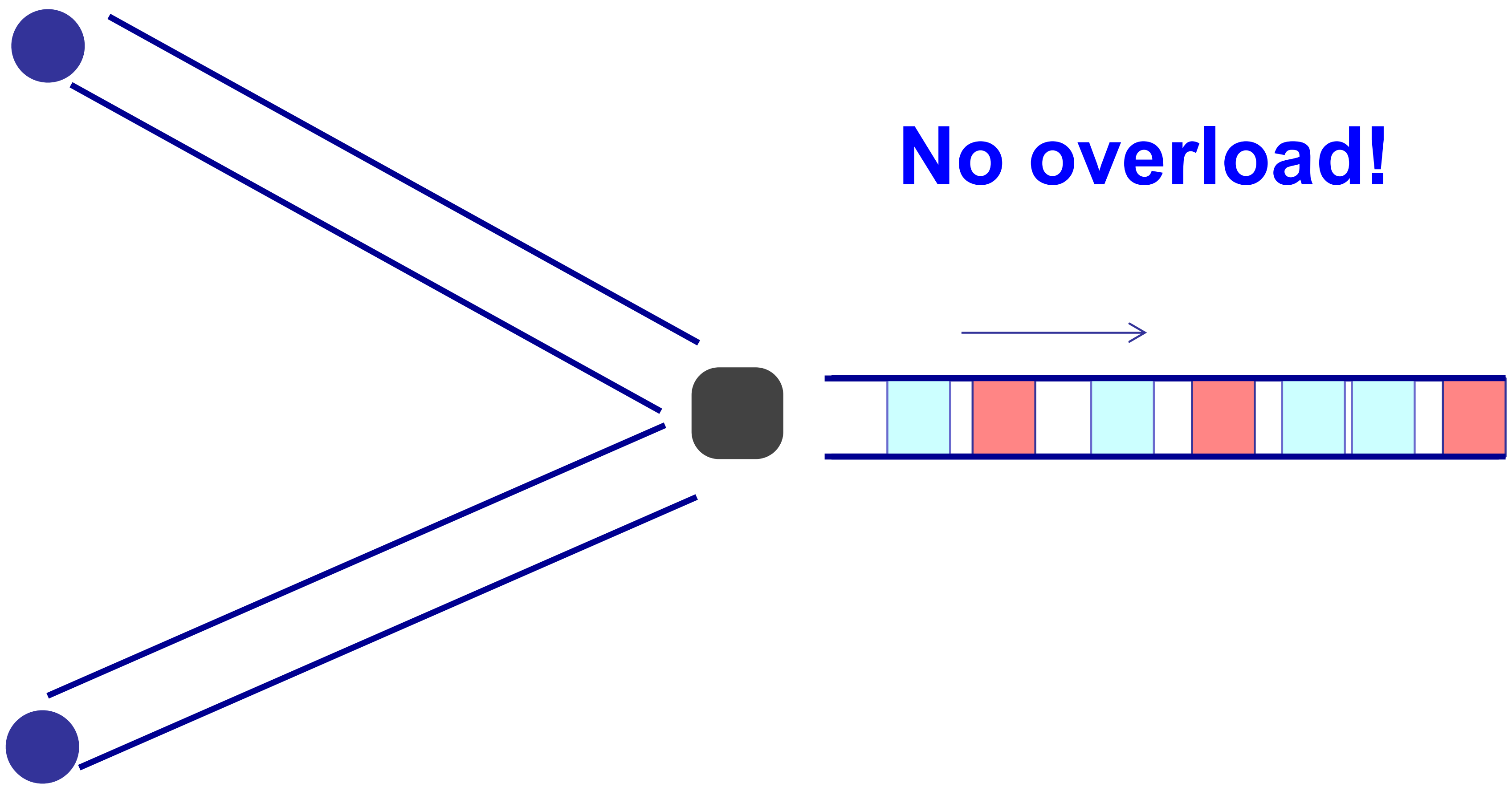
3. Queuing delay

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

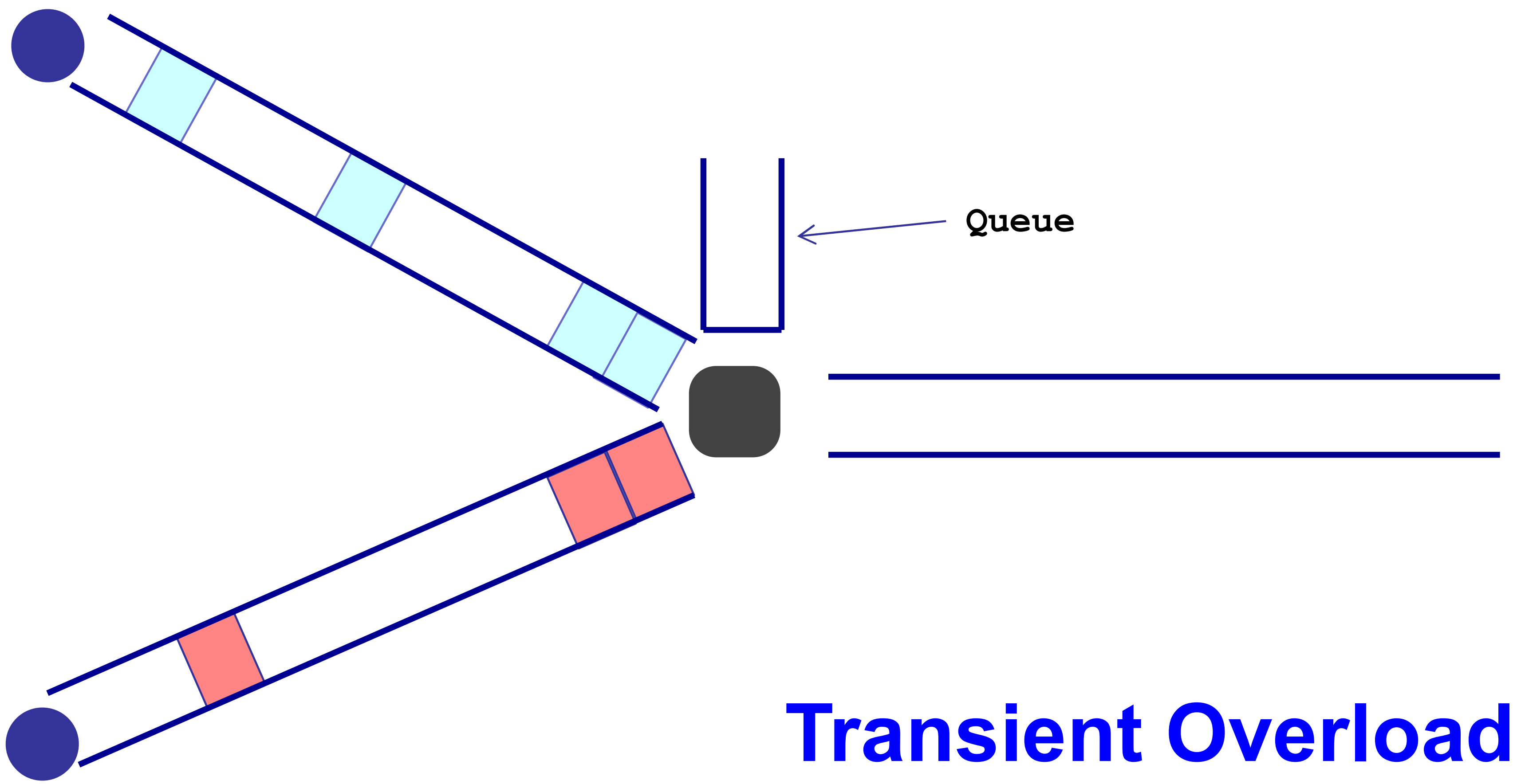
Queueing delay: “pipe” view



Queueing delay: "pipe" view



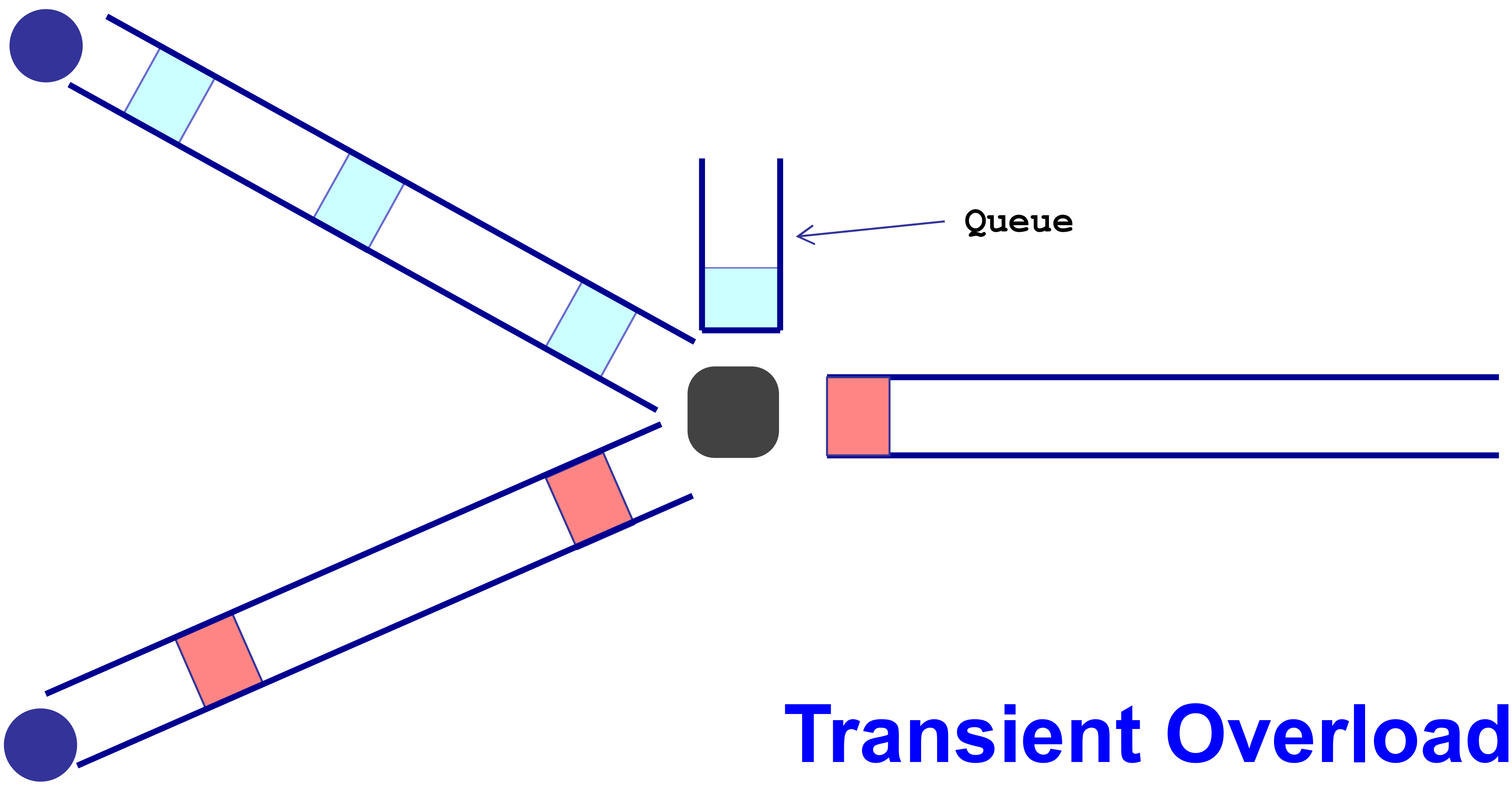
Queueing delay: “pipe” view



Transient Overload

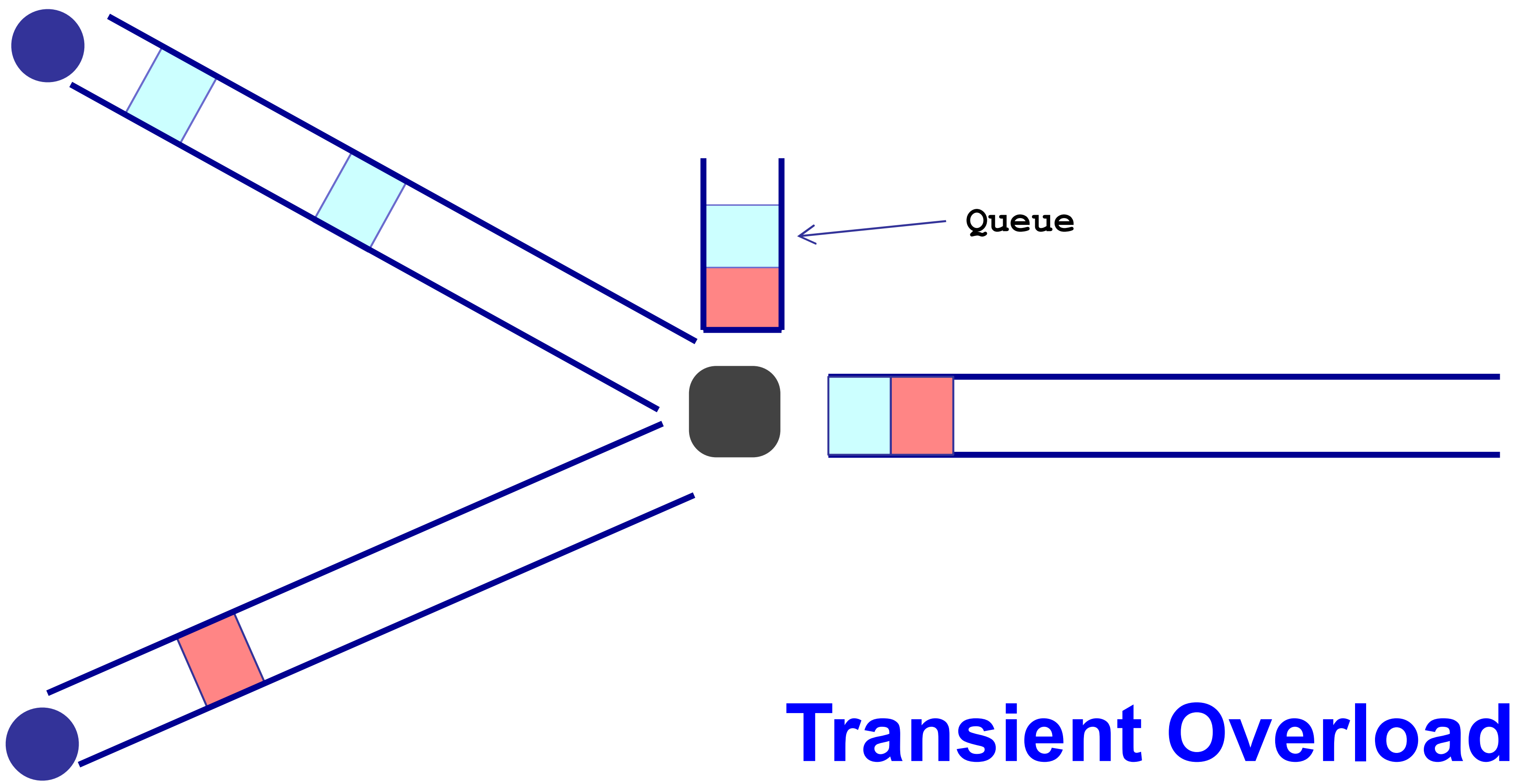
Not a rare event!

Queueing delay: "pipe" view



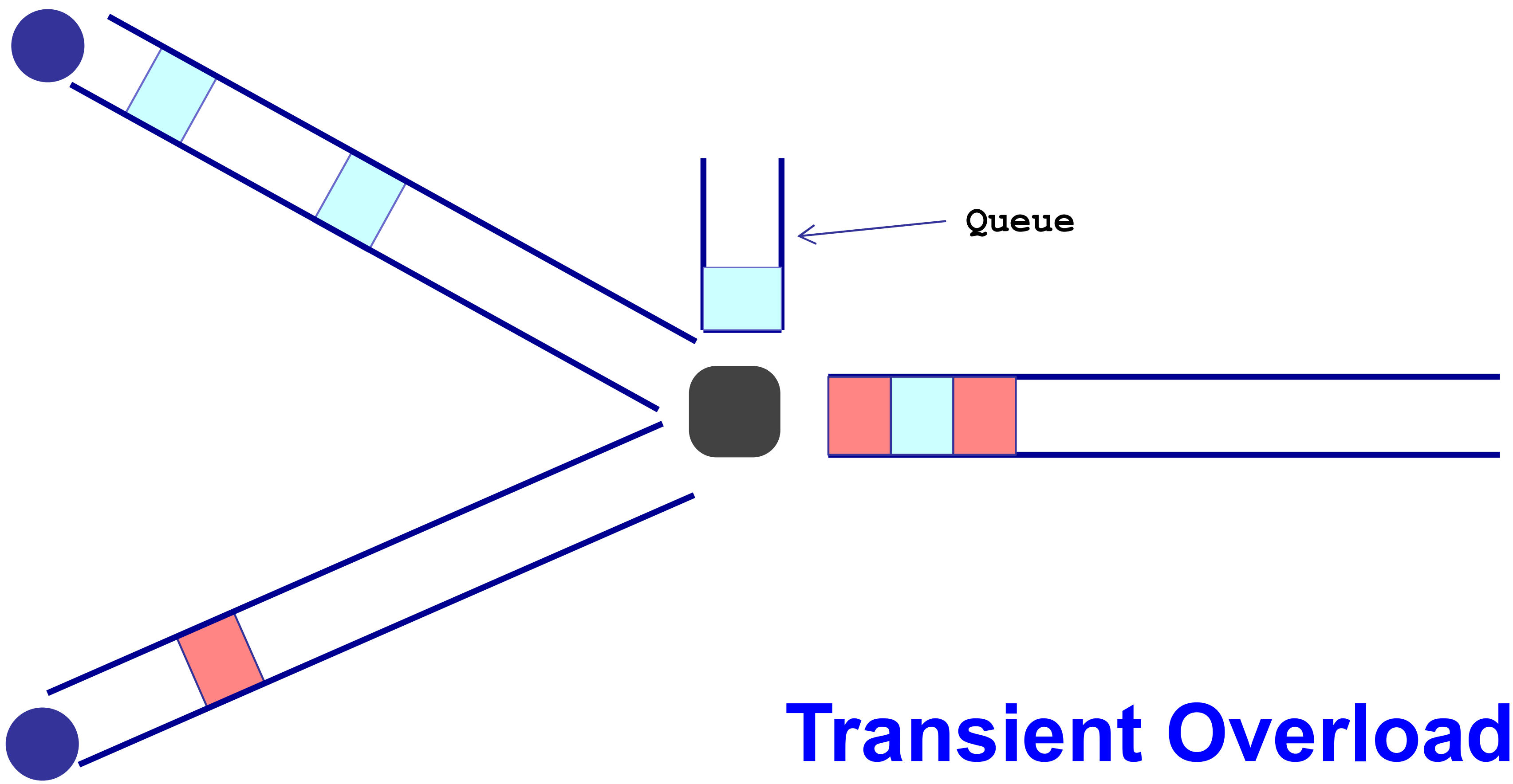
Transient Overload

Queueing delay: “pipe” view



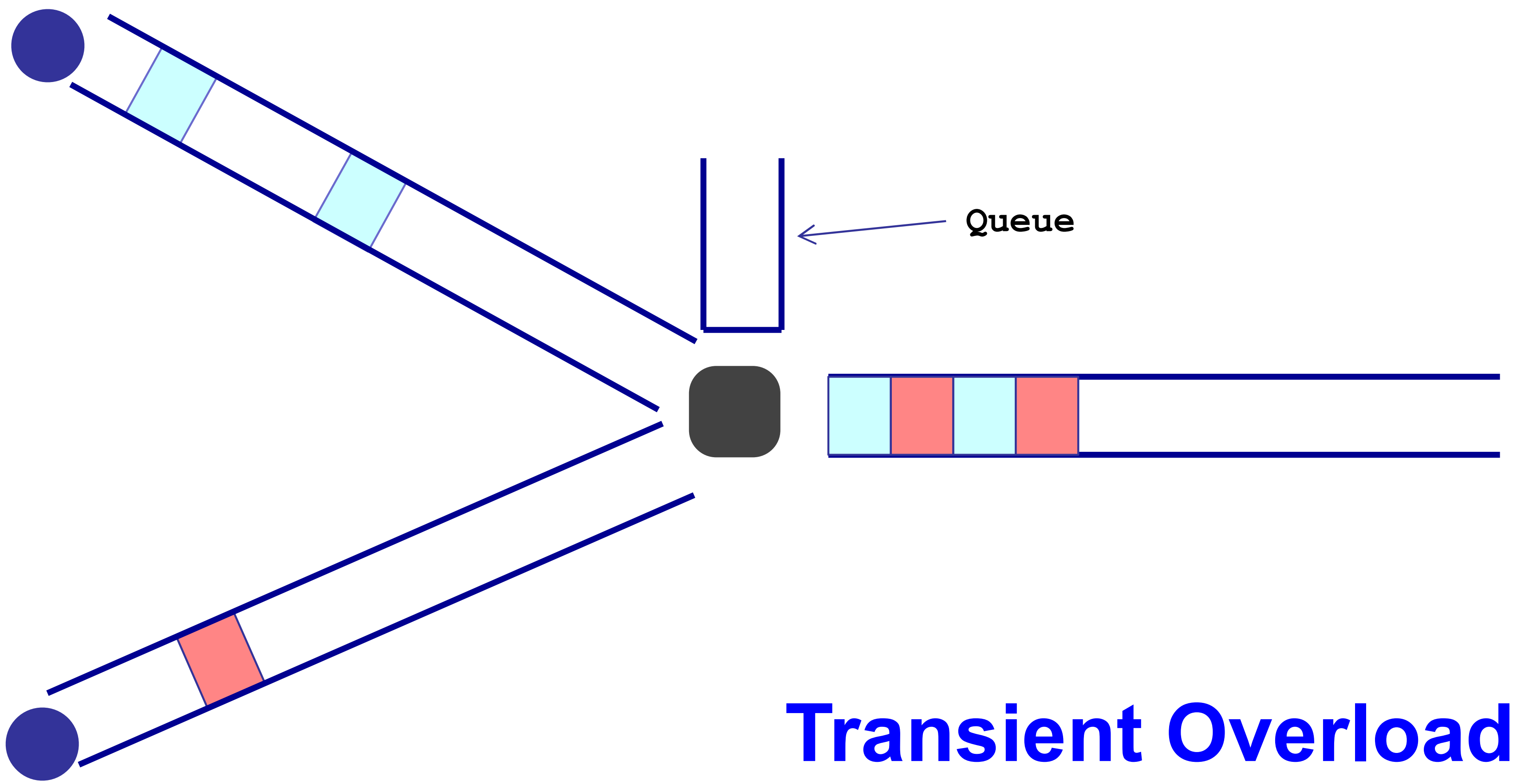
Transient Overload

Queueing delay: "pipe" view



Transient Overload

Queueing delay: “pipe” view



Transient Overload

Queueing delay

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

- Depends on traffic pattern
  - Arrival rate at the queue
  - Nature of arriving traffic (bursty or not?)
  - Bandwidth of outgoing link

- Not easy to compute

Basic queueing theory terminology

- Arrival process: how packets arrive
  - Average rate A
- W: average time packets wait in the queue
  - W for “waiting time” (queuing delay)
- 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

- 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

Round Trip Time (RTT)

- 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

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

Throughput

At what rate is the destination receiving data from the source

Link Throughput

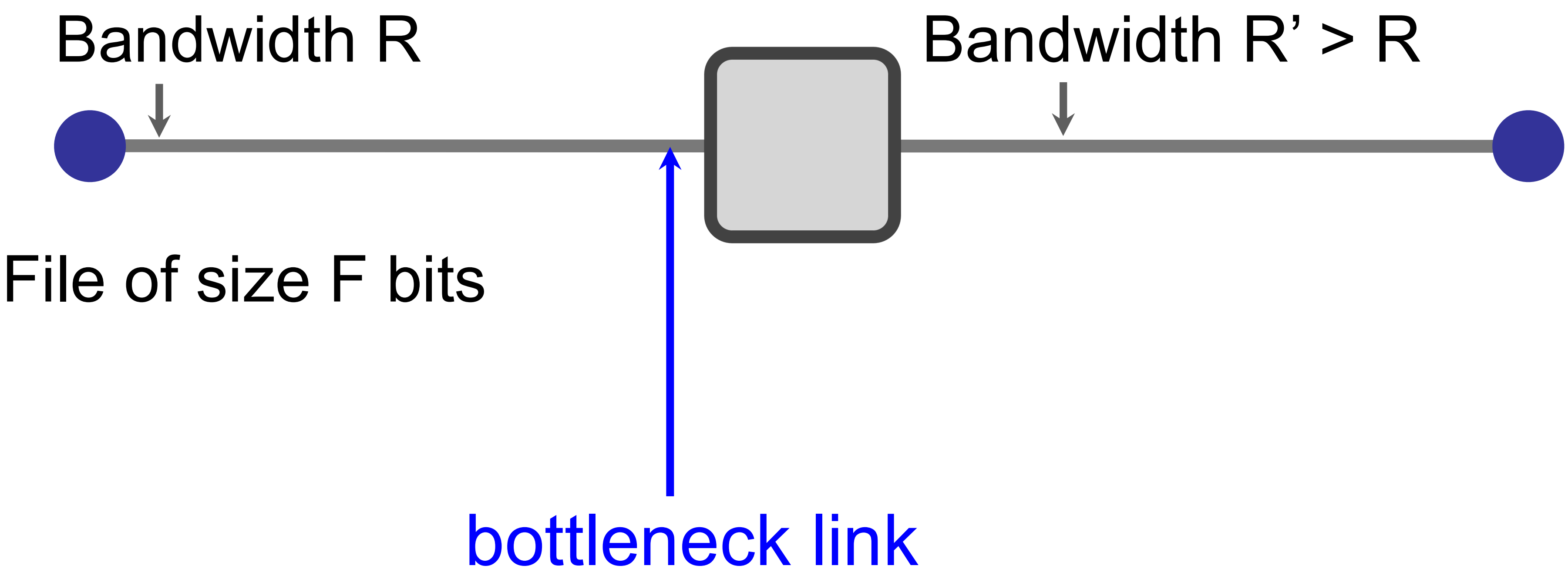
Bandwidth R bits/sec

File of size F bits

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

Average throughput = F/T ≈ R

End-to-end throughput



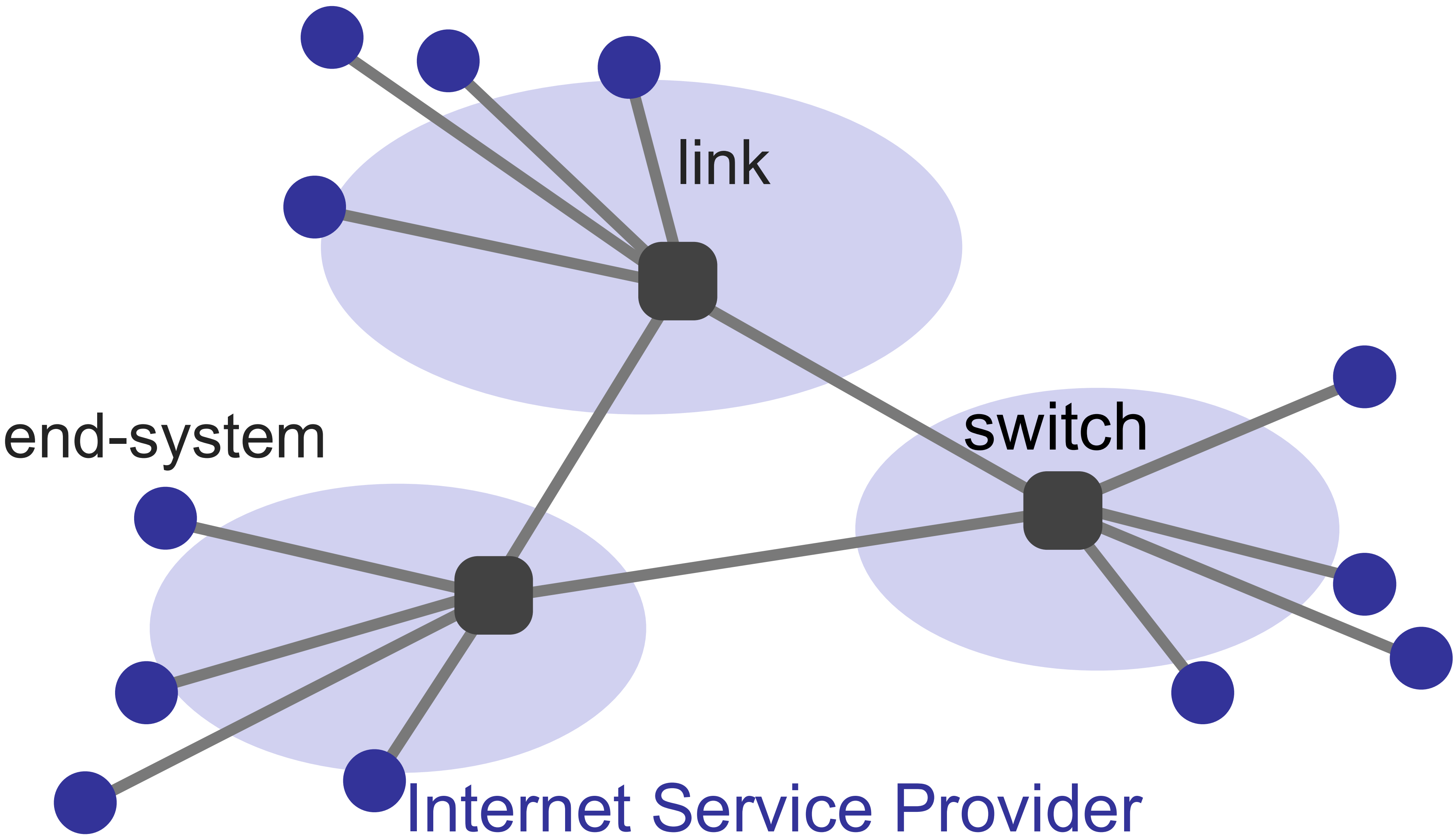
Average throughput = min{R, R’} = R

Summary

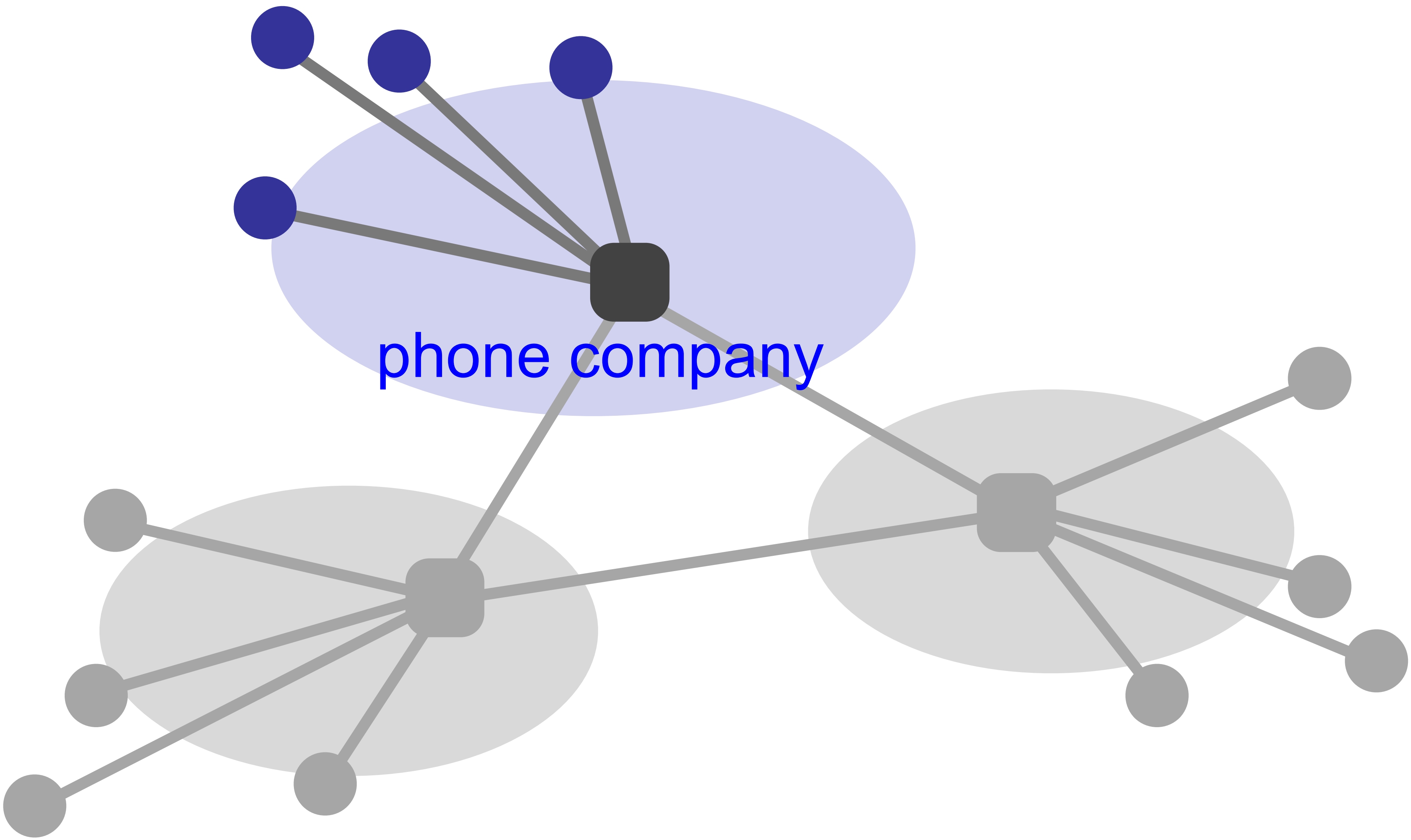
- How is the network shared?
  - On-demand or via reservation
- How do we evaluate a network?
  - Bandwidth, delay, loss, …

WHAT IS THE NETWORK MADE OF?

What is a network made of?



What is a network made of?



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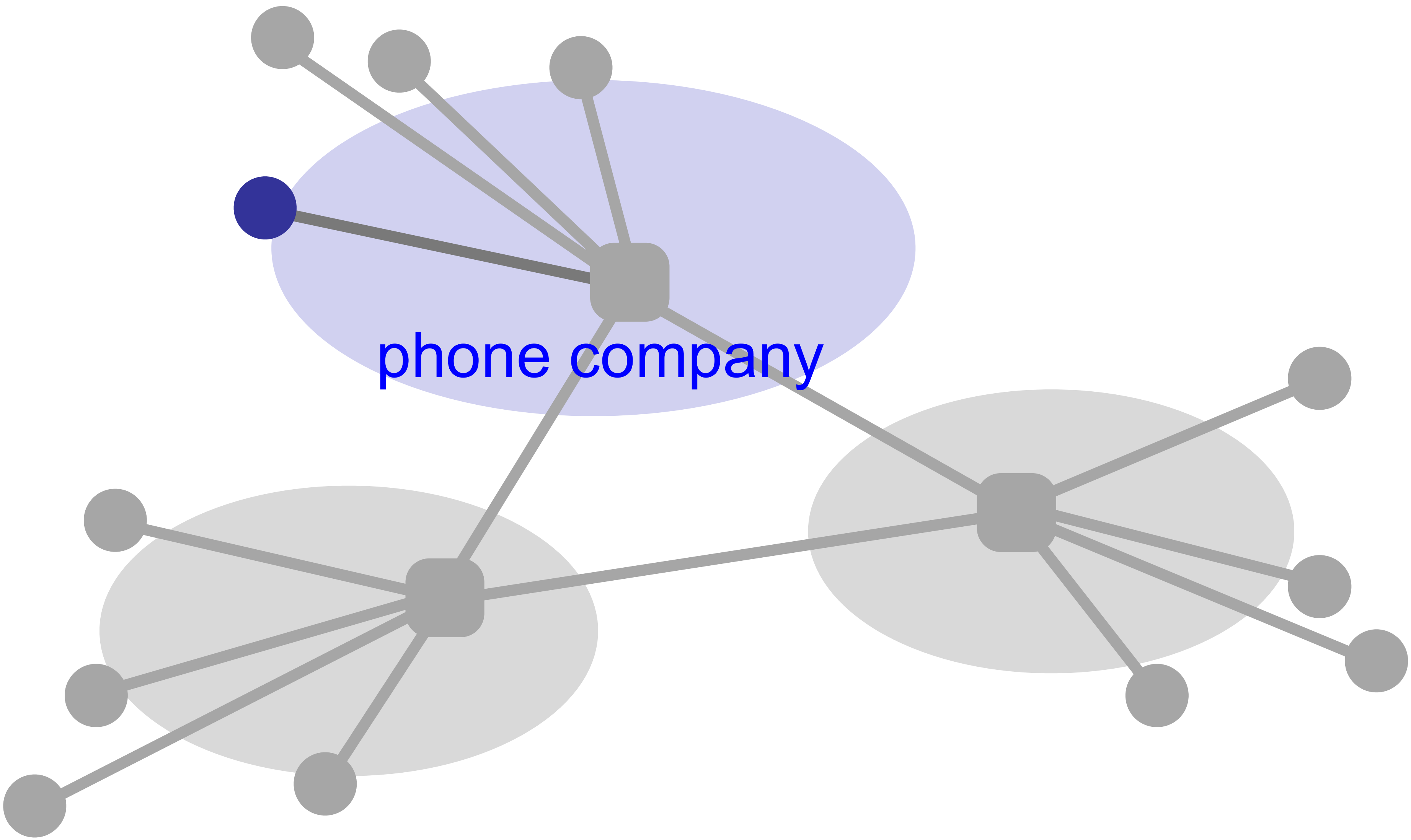
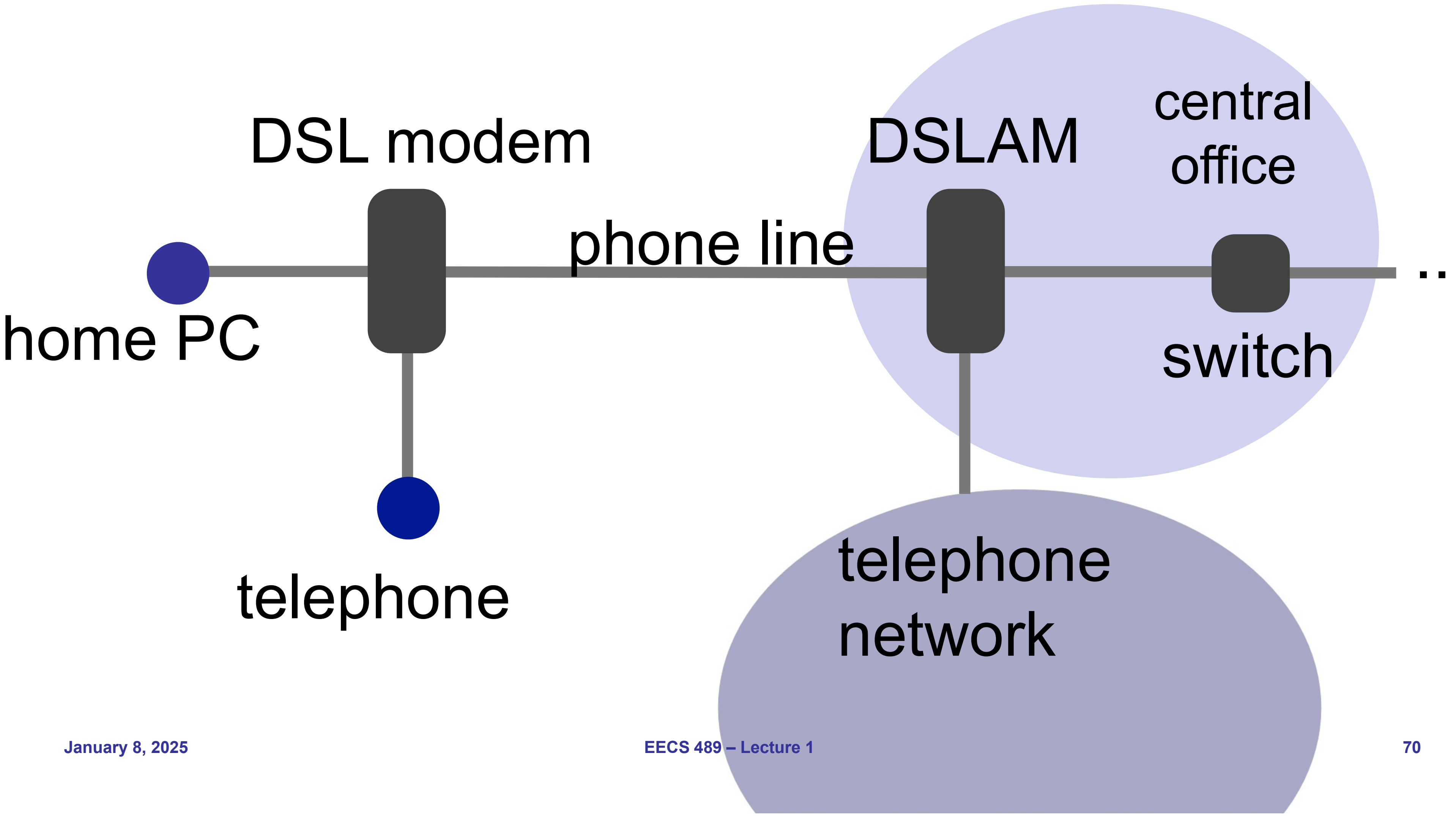


The last hop

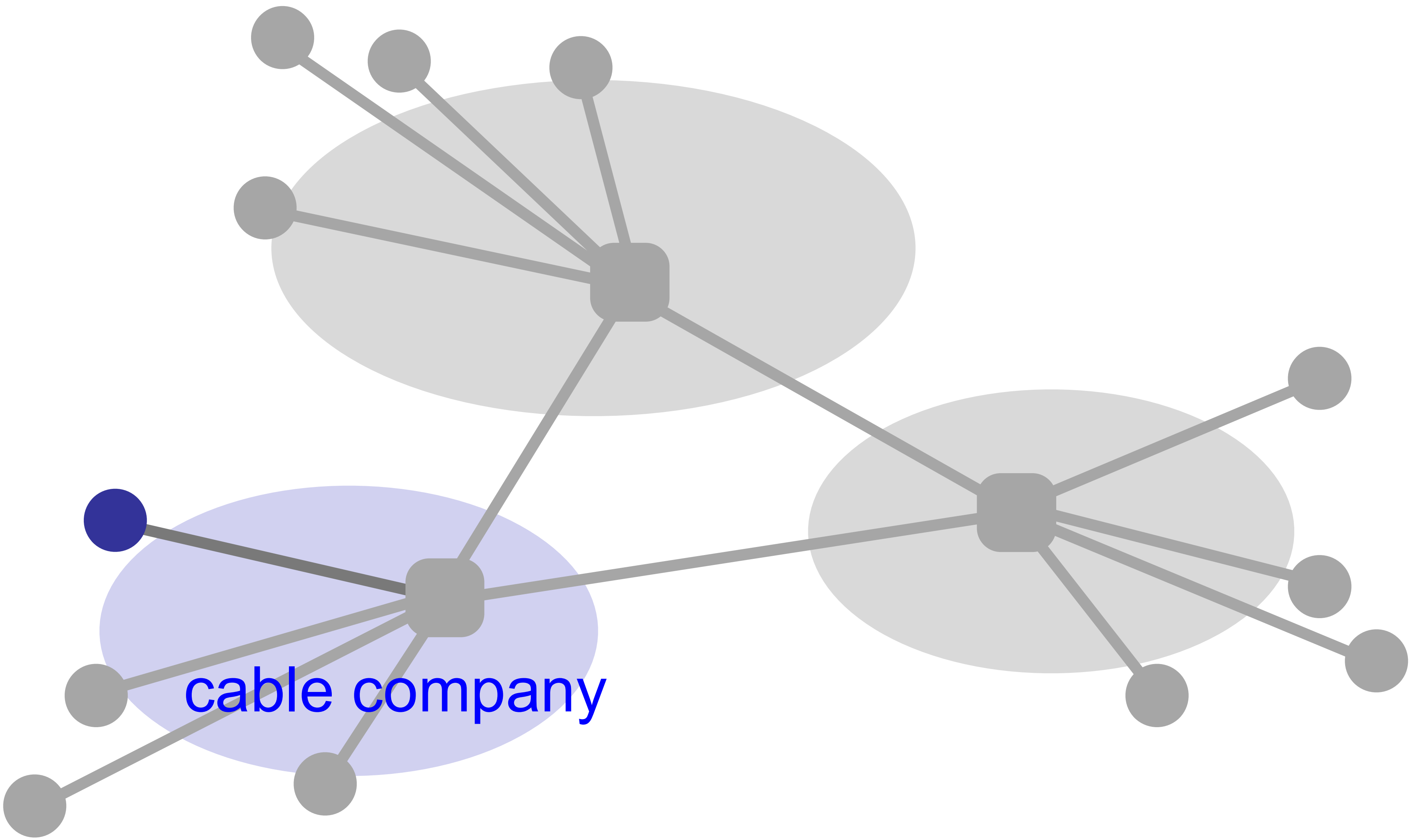
How do we connect?



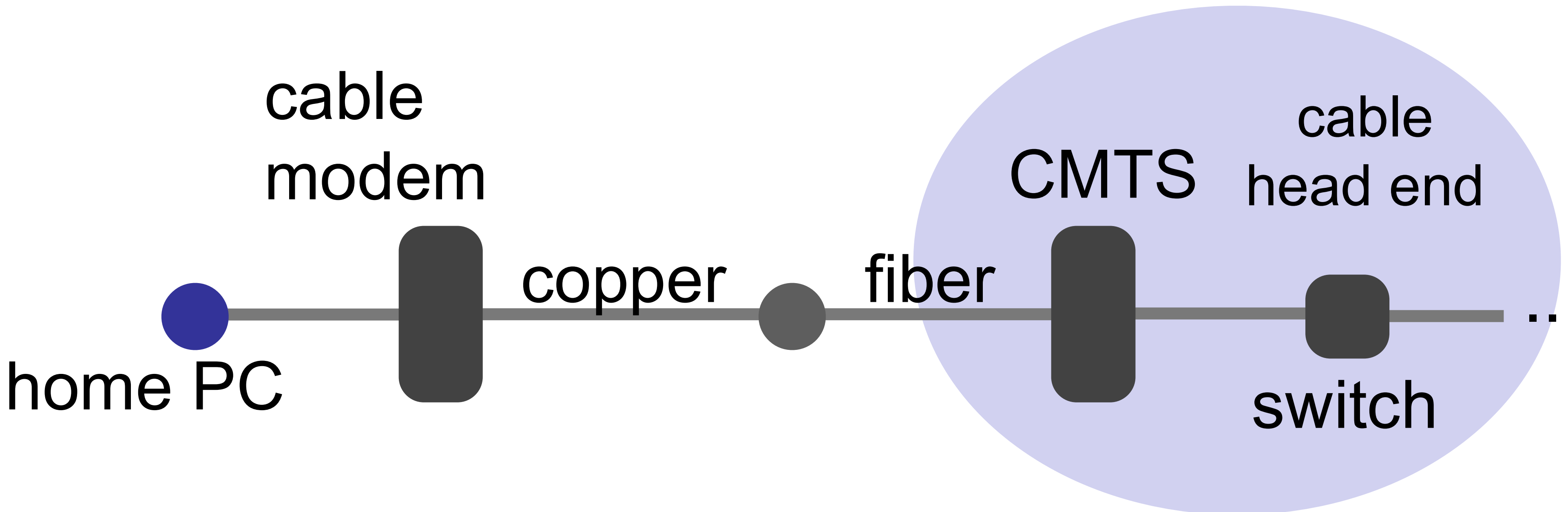
Digital Subscriber Line (DSL)

- 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?



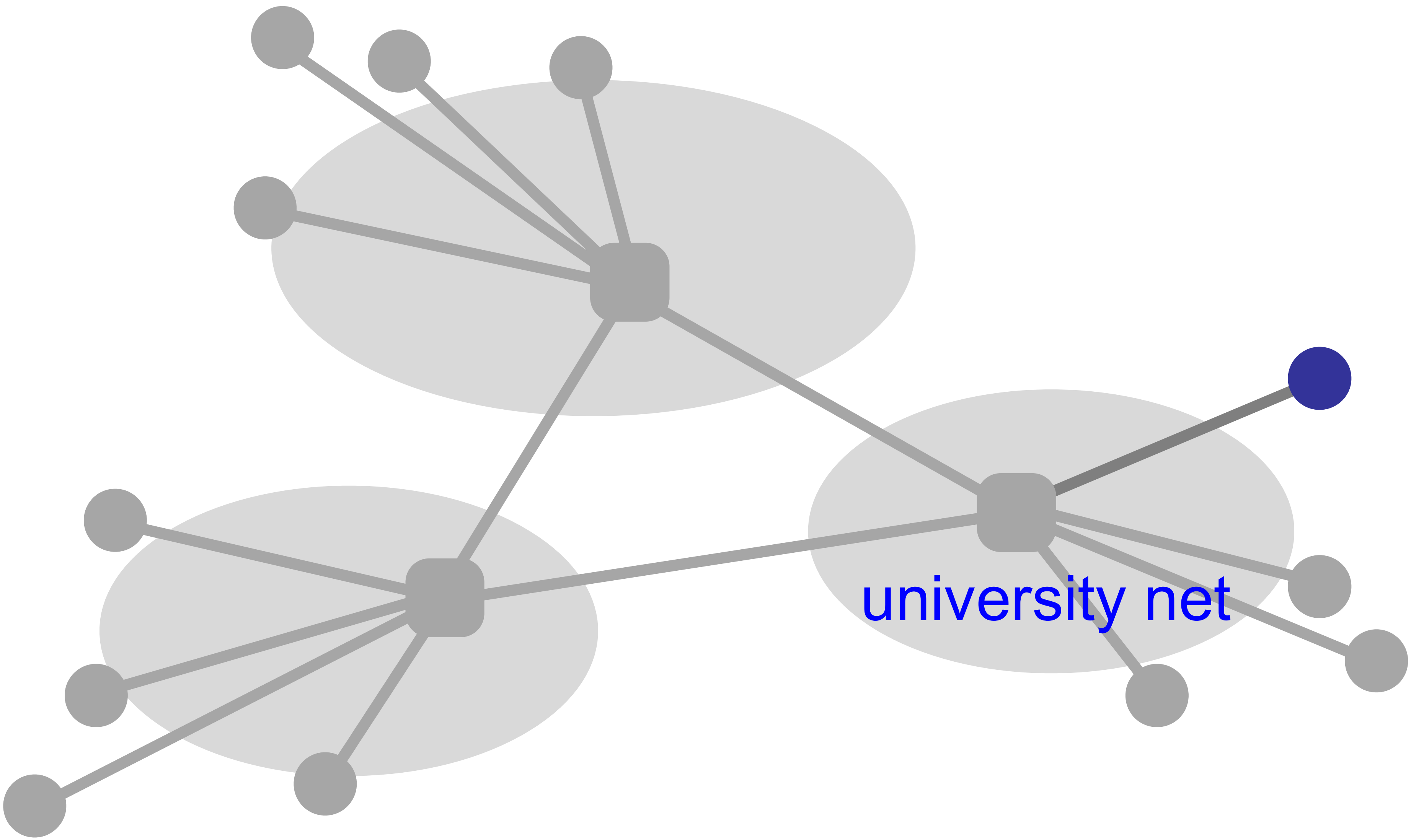
Connecting via cable



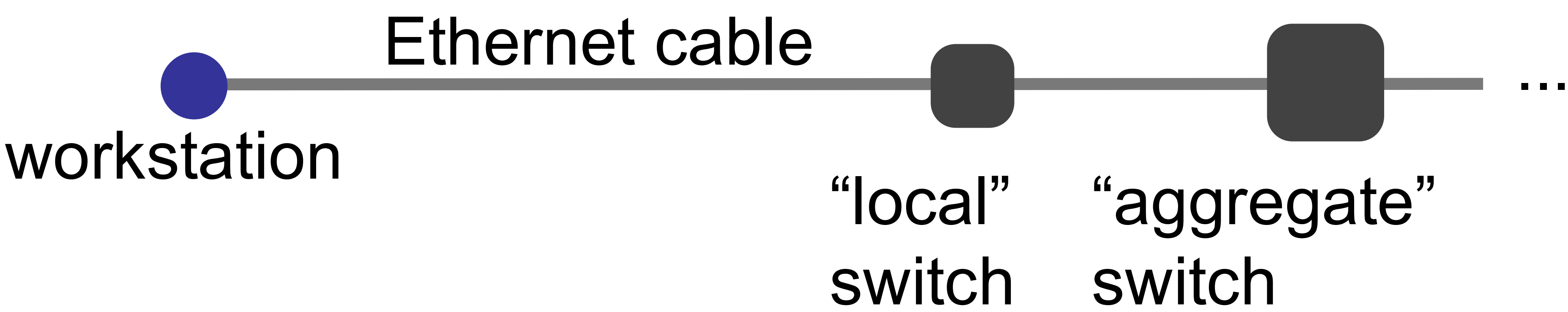
Cable

- 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
...

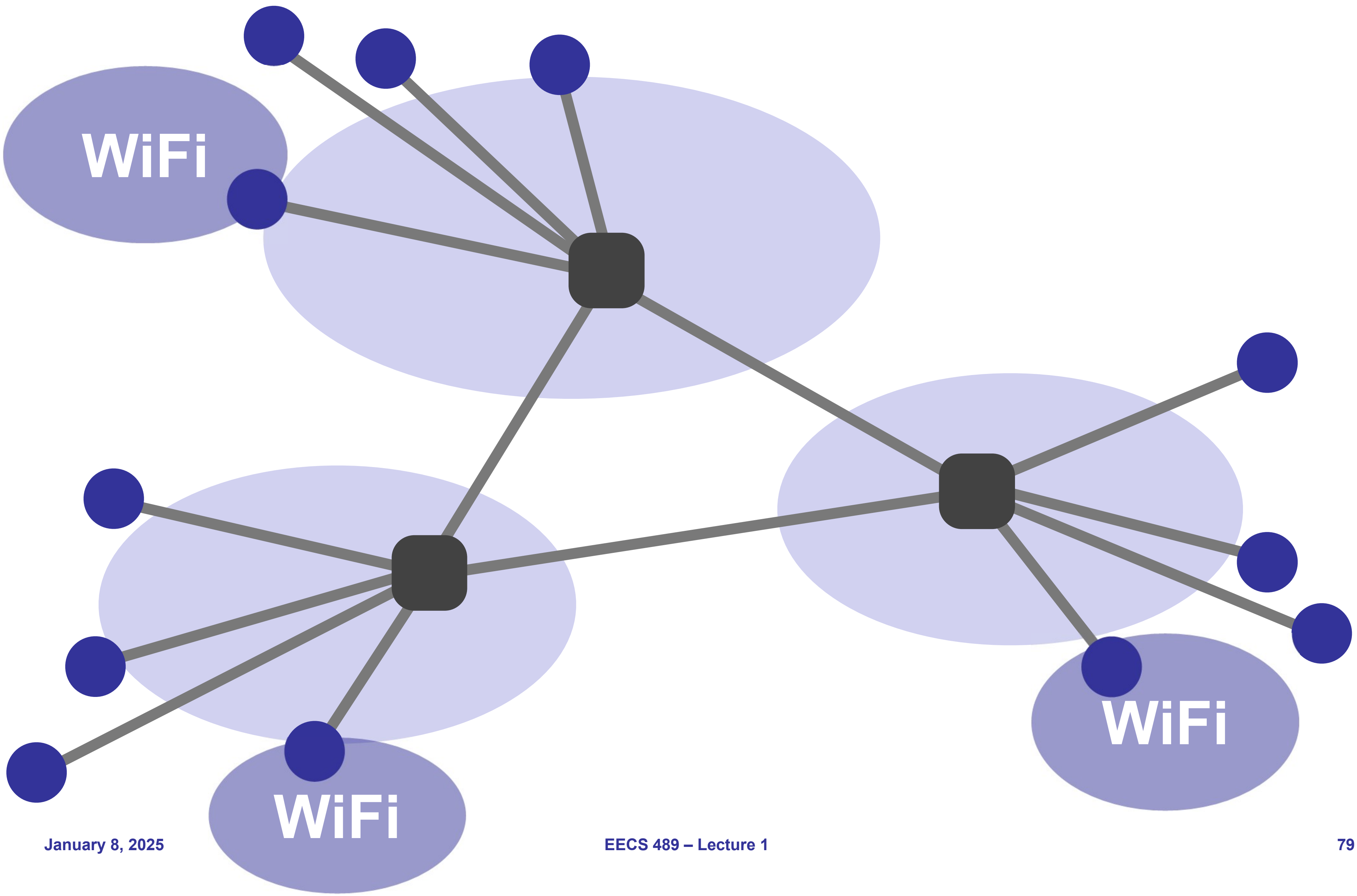
Ethernet

- 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)

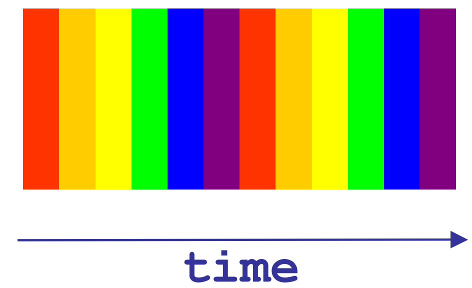
Where is WiFi?



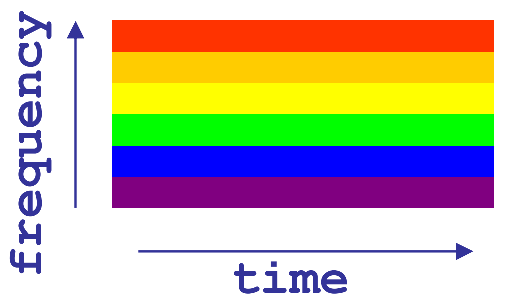
DETAILS ON CIRCUIT SWITCHING

Many kinds of circuits

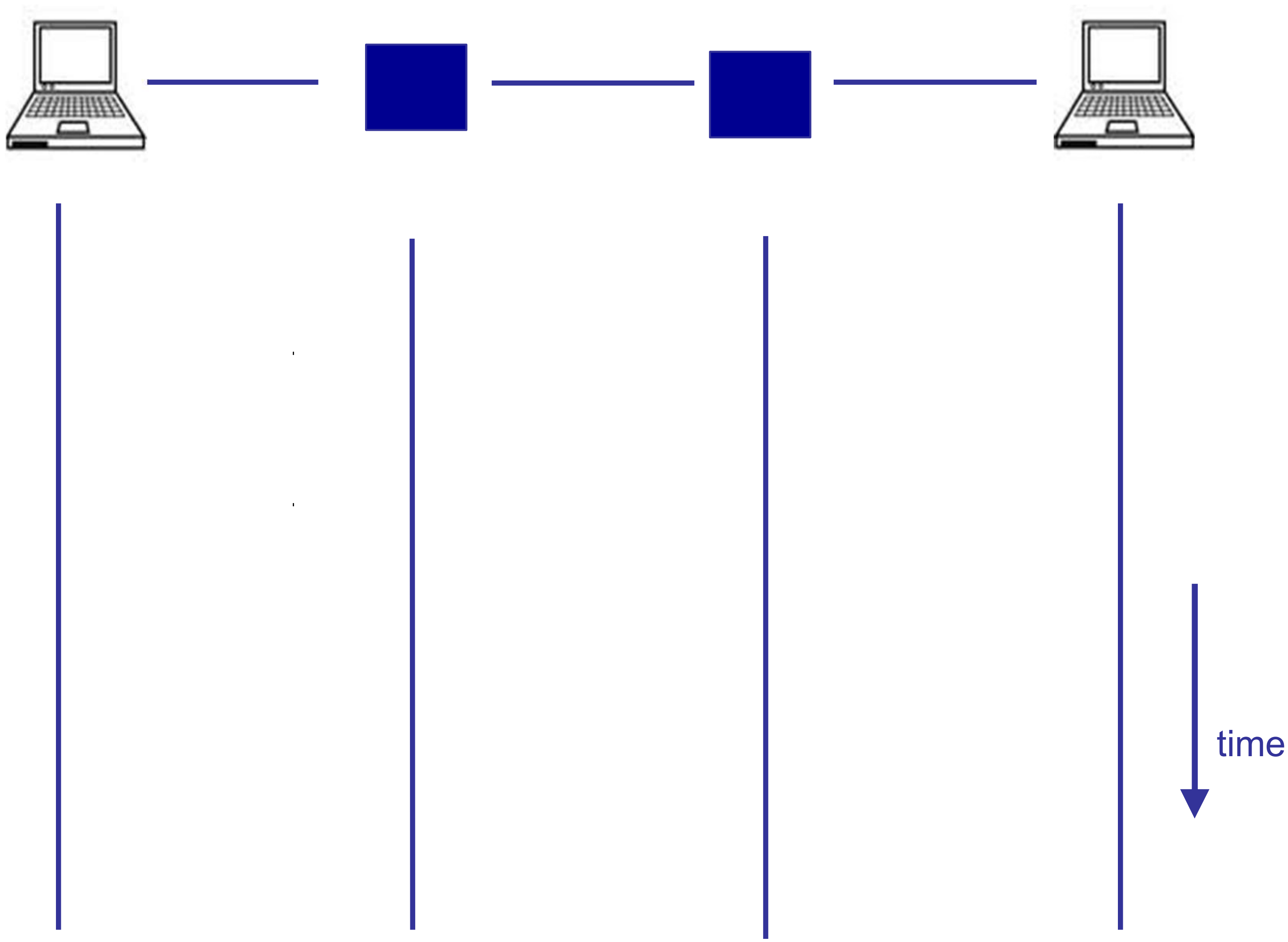
- Time division multiplexing
  - divide time in time slots
  - separate time slot per circuit



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



Timing in circuit switching



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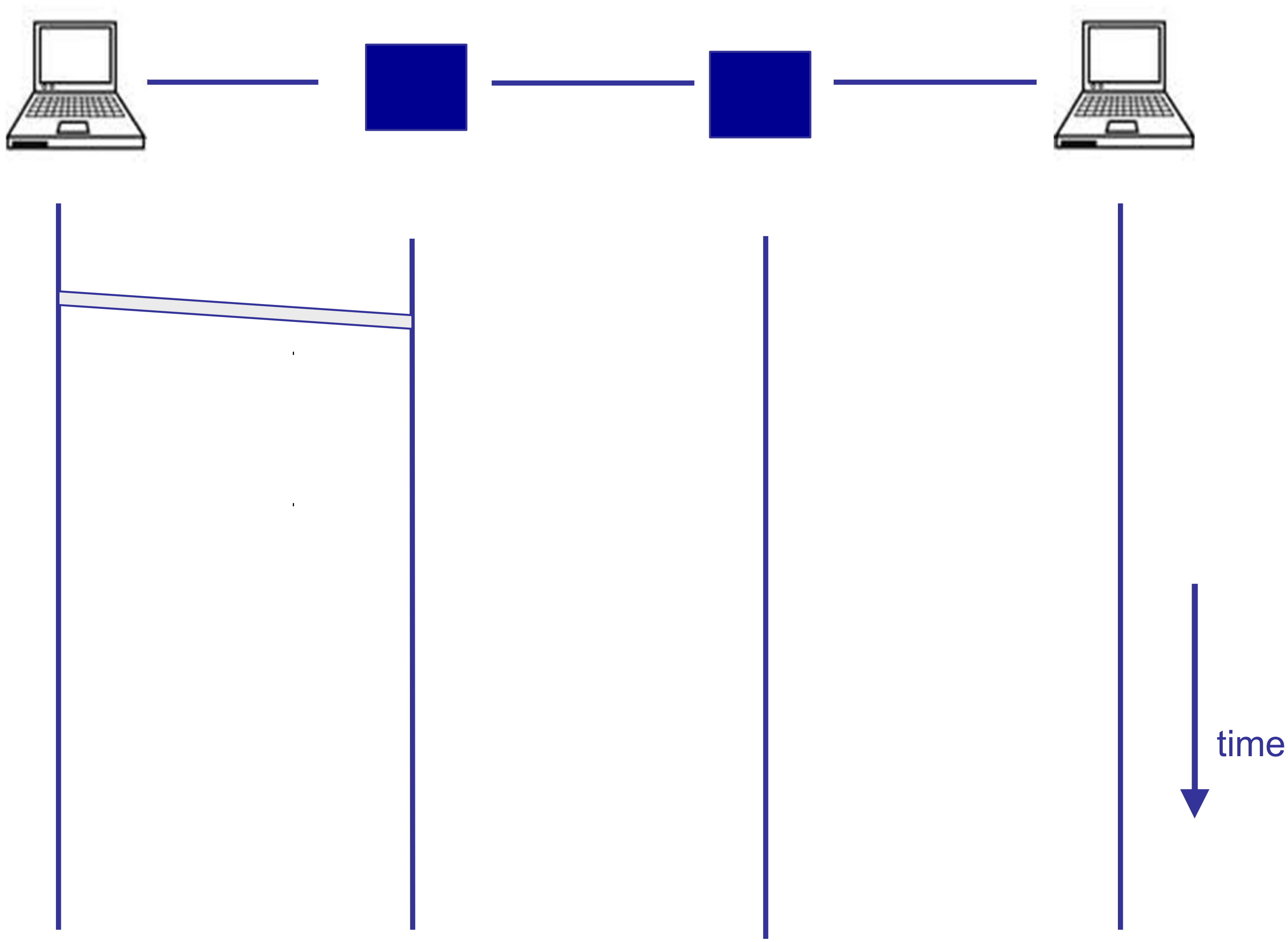

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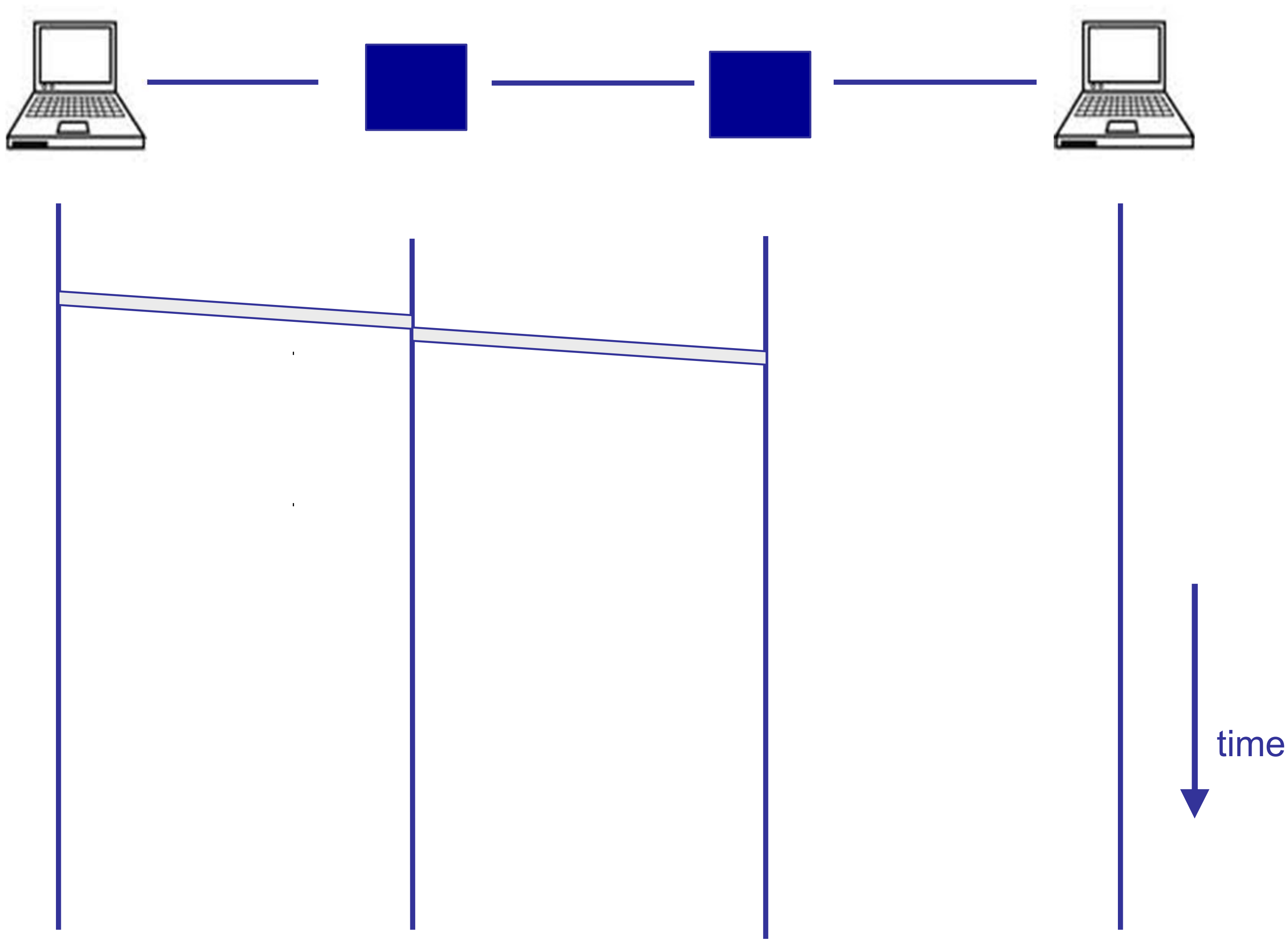

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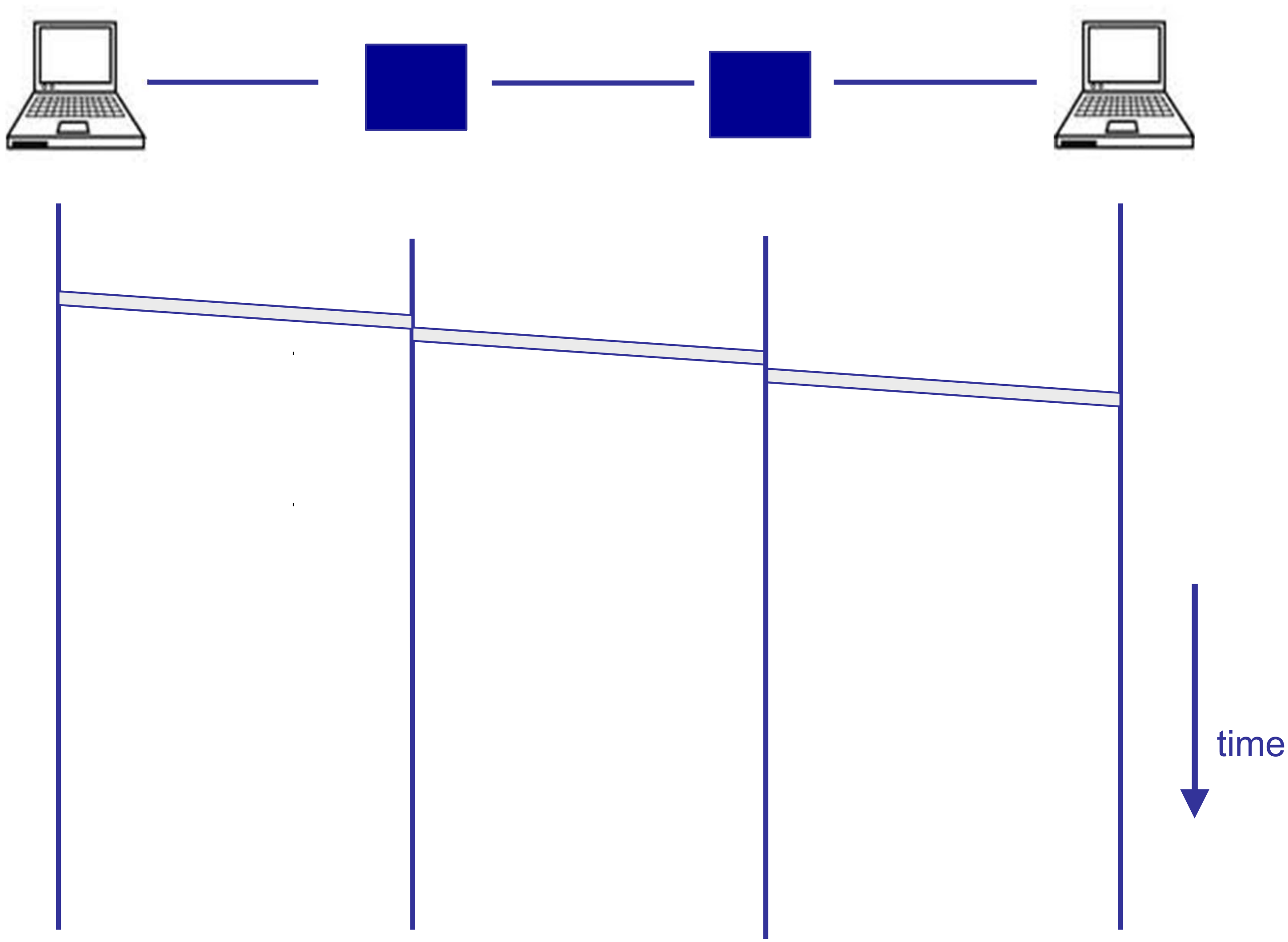

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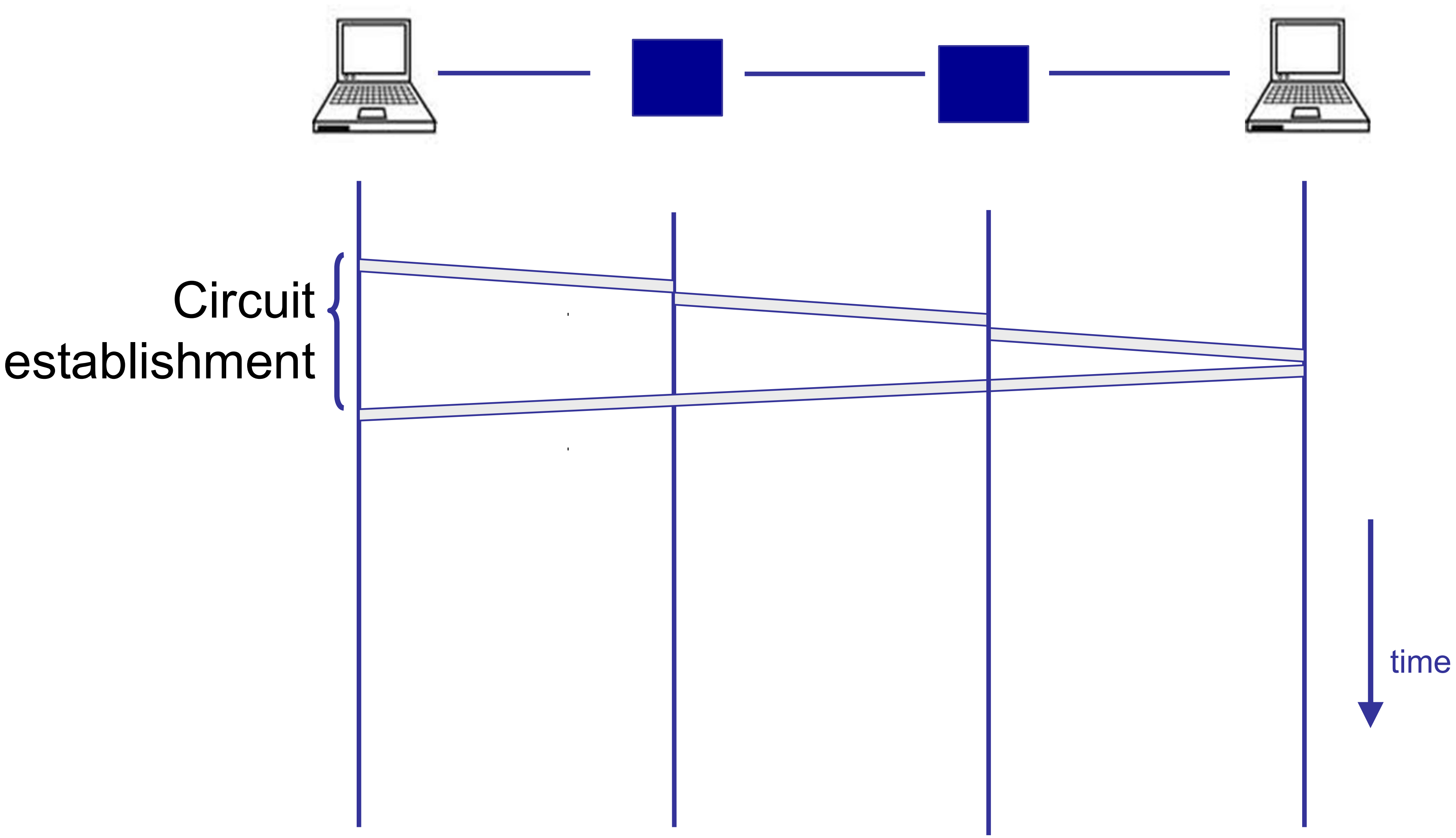

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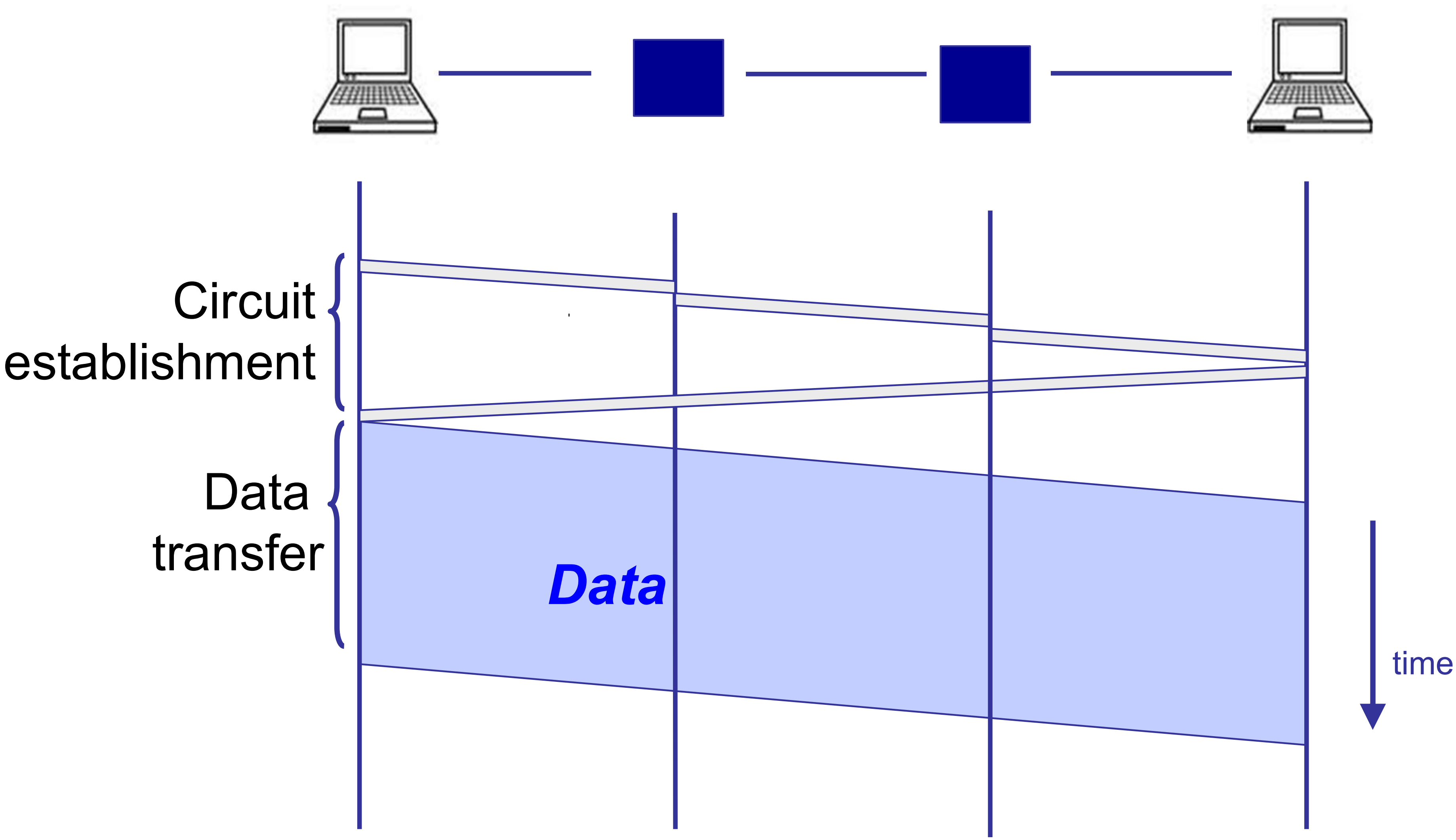

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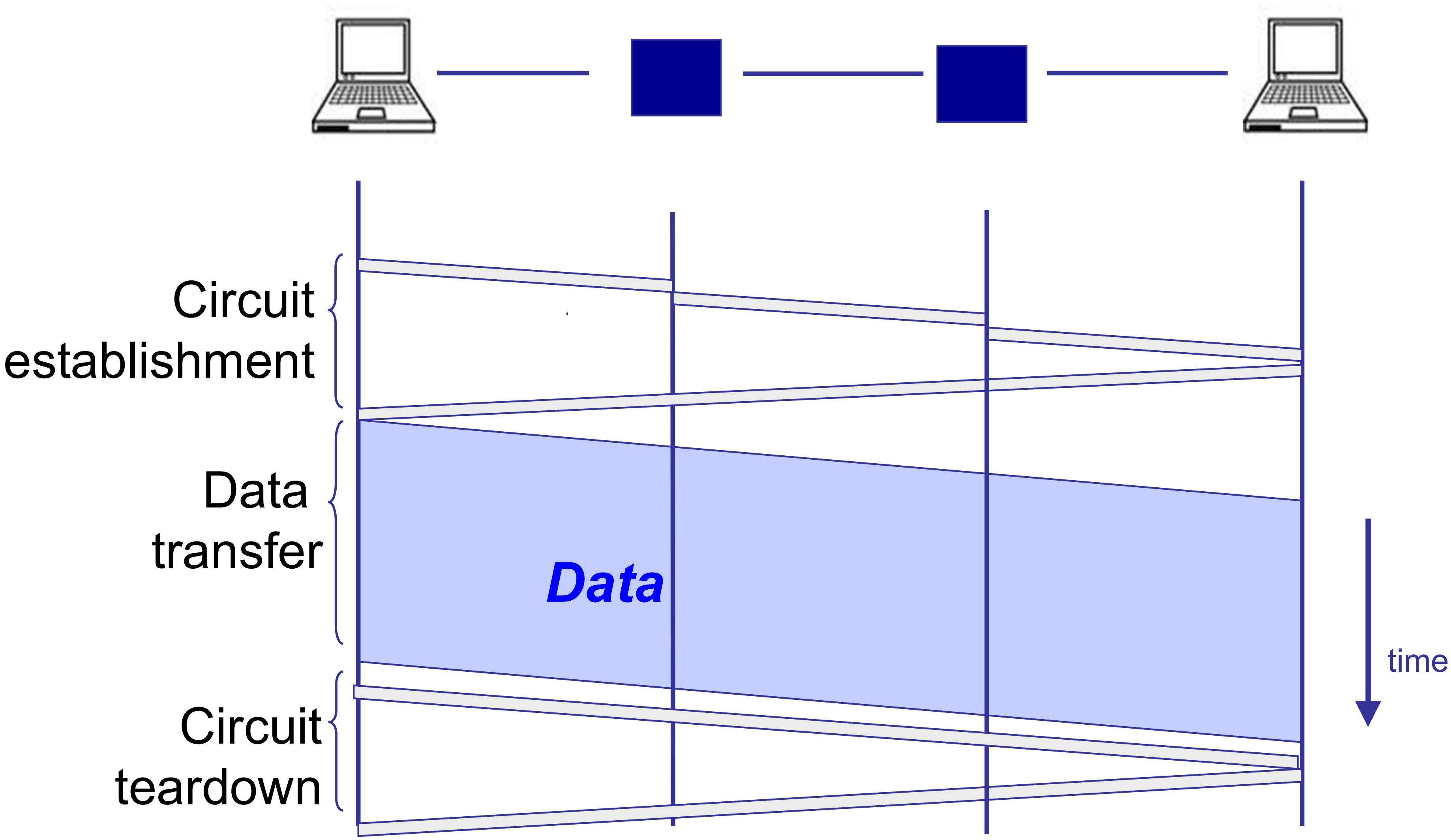
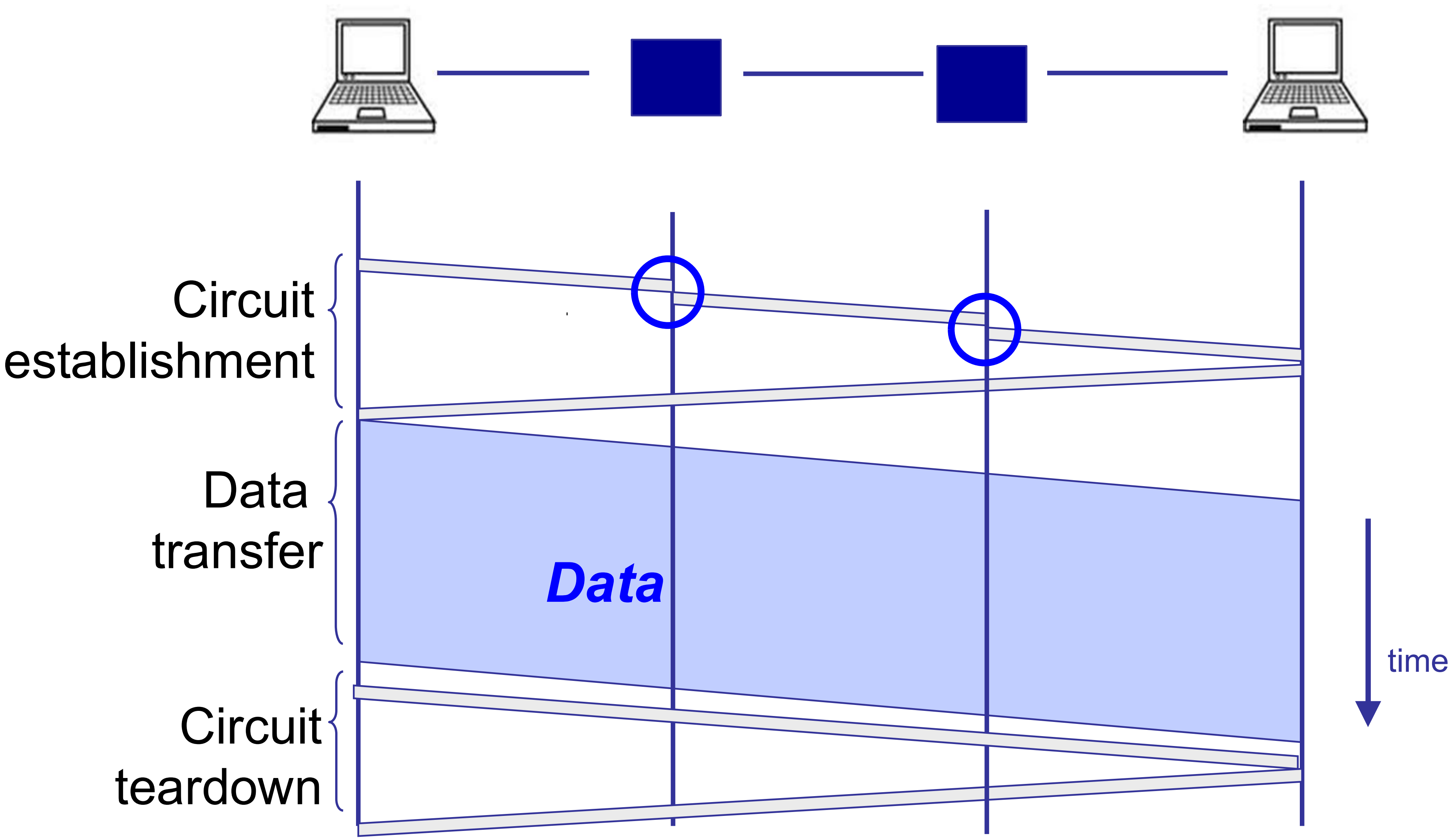


Why the delays?



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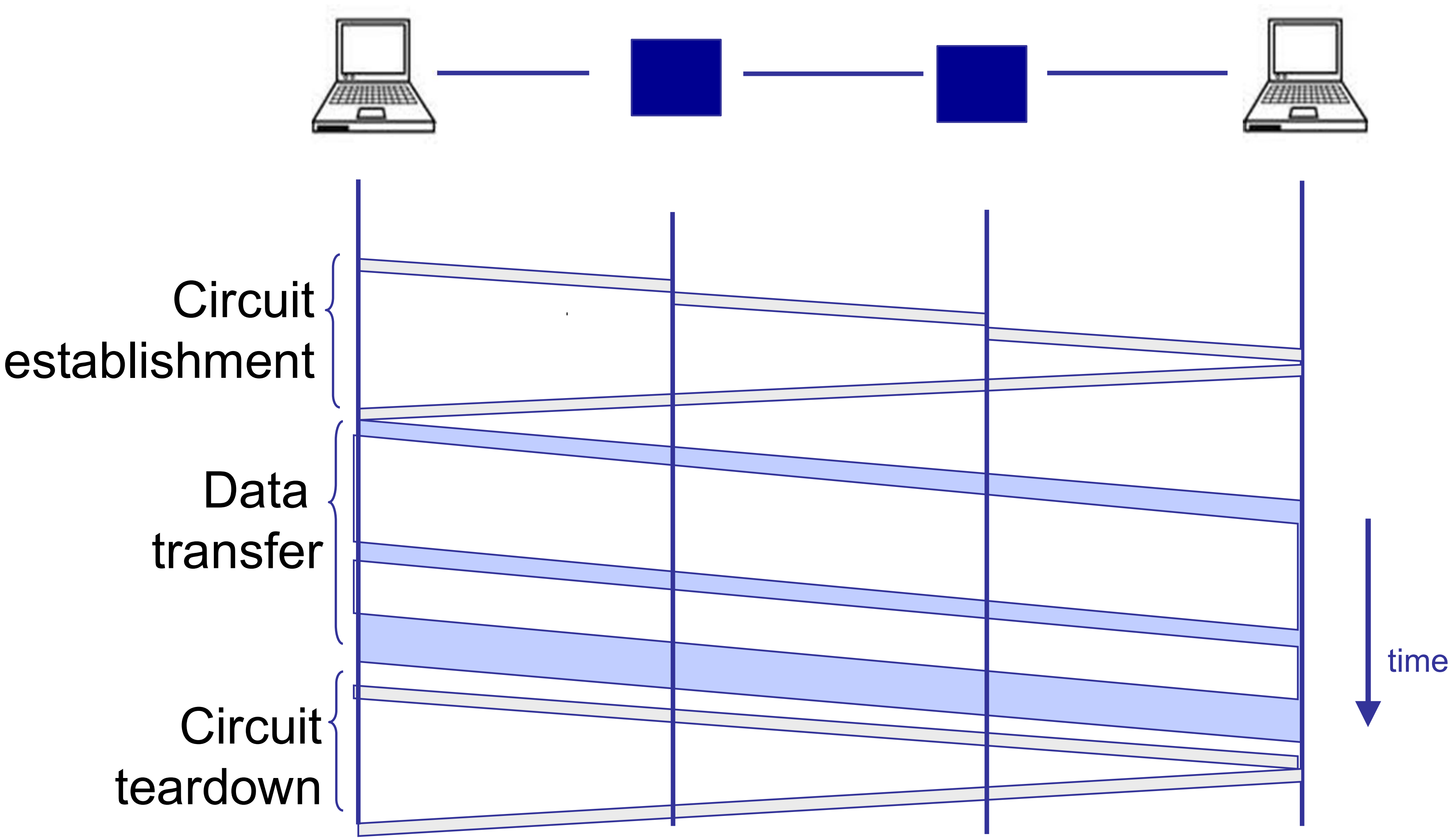

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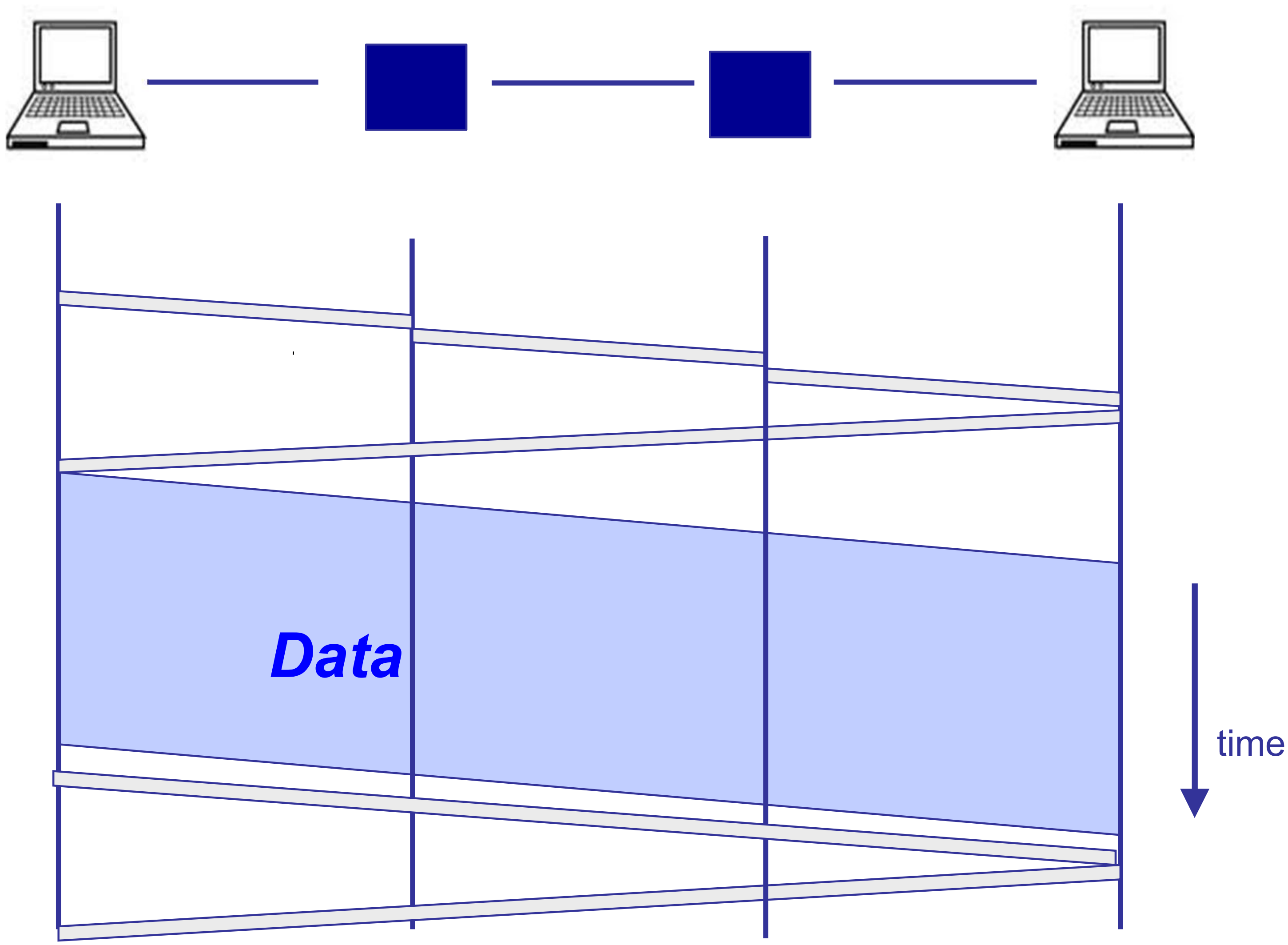

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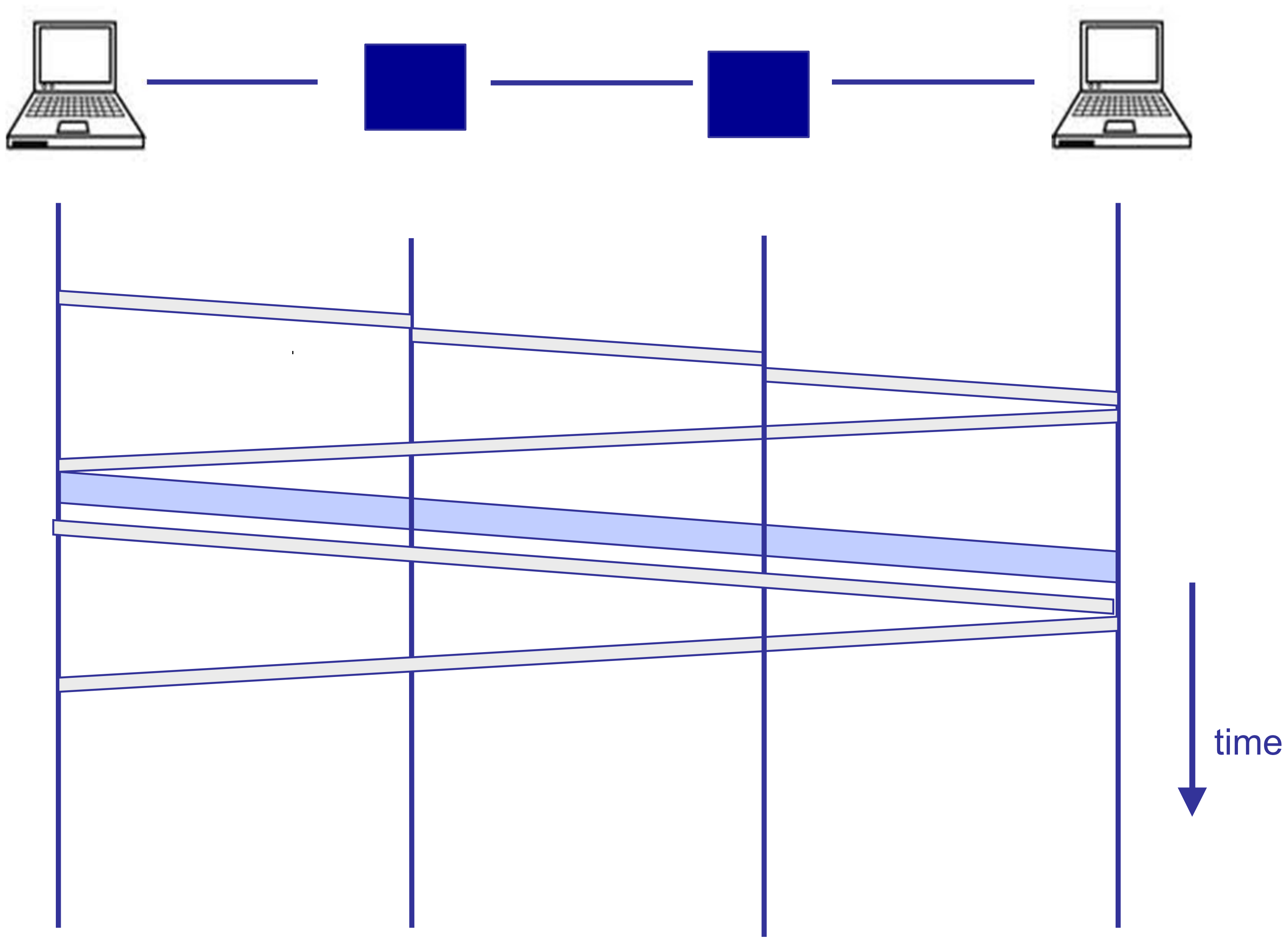


Have we found the right solution?

We don’t really know

What we do know

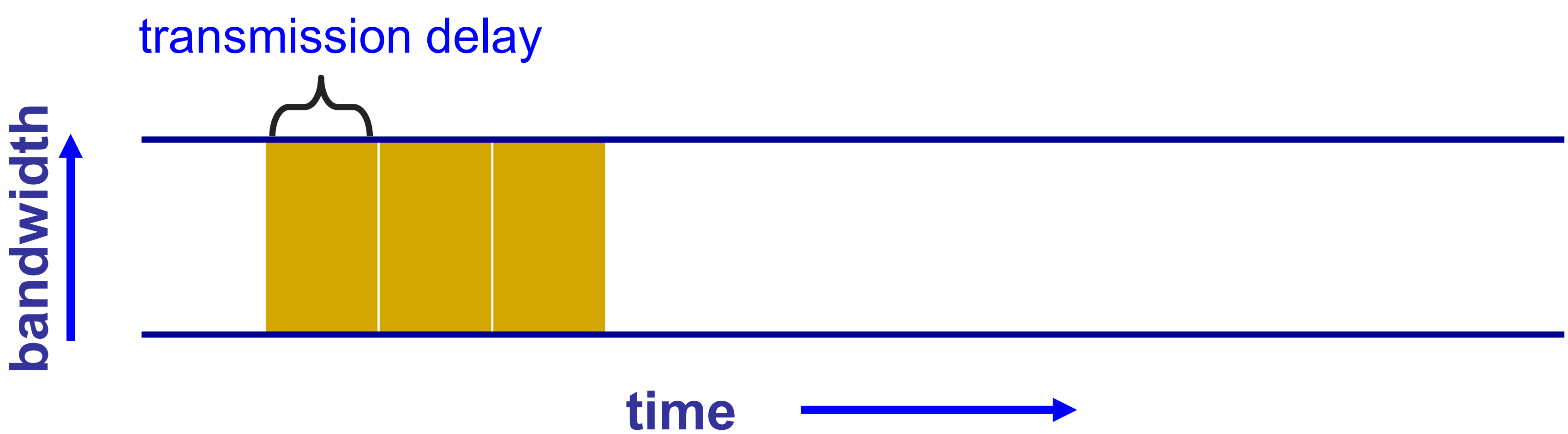
- The early Internet pioneers produced a solution that was successful beyond all imagining
- Several enduring architectural principles and practices emerged from their work

Still, it is just one design with many questions

The Internet is a lesson

- In how to reason through the design of a <u>very</u> complex system
  - What are our goals and constraints?
  - What's the right prioritization of goals?
  - How do we decompose a problem?
  - Who does what? How?
  - What are the interfaces between components?
  - What are the tradeoffs between design options?

Pipe view of a link



- Transmission delay decreases as bandwidth increases

A network link: BDP

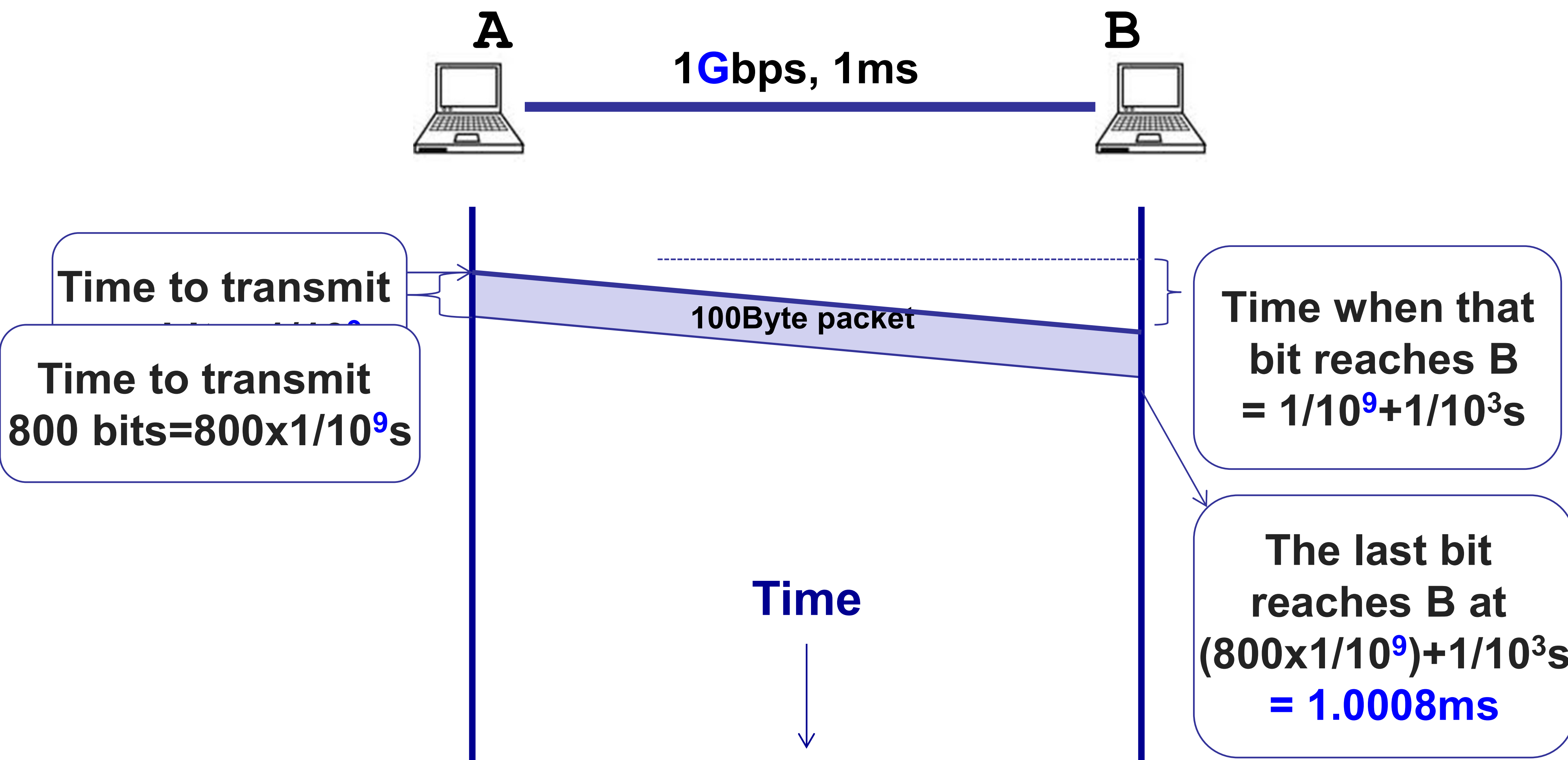
- Link bandwidth
  - Number of bits sent/received per unit time (bits/sec or bps)
- Propagation delay
  - Time for one bit to move through the link (seconds)
- Bandwidth-Delay Product (BDP)
  - Number of bits “in flight” at any time
- BDP = bandwidth × propagation delay

BDP Examples

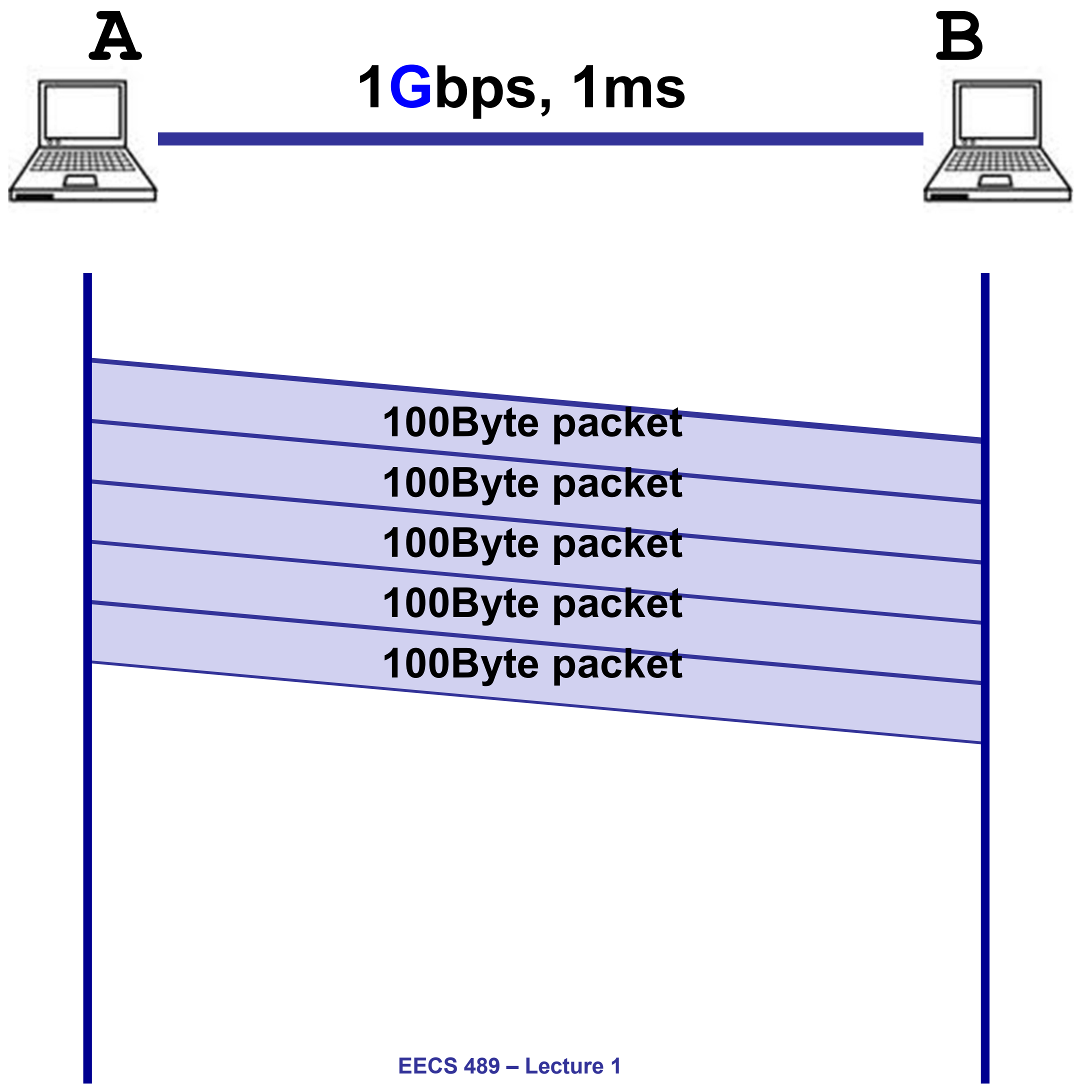
- Same city over a slow link:
  - Bandwidth: ~100Mbps
  - Propagation delay: ~0.1msec
  - BDP: 10,000bits (1.25KBytes)

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

Packet delay
Sending a 100-byte packet



Sending a large file using 100-byte packets



Persistent overload leads to packet drop/loss