EECS 489
Computer Networks

Fall 2021

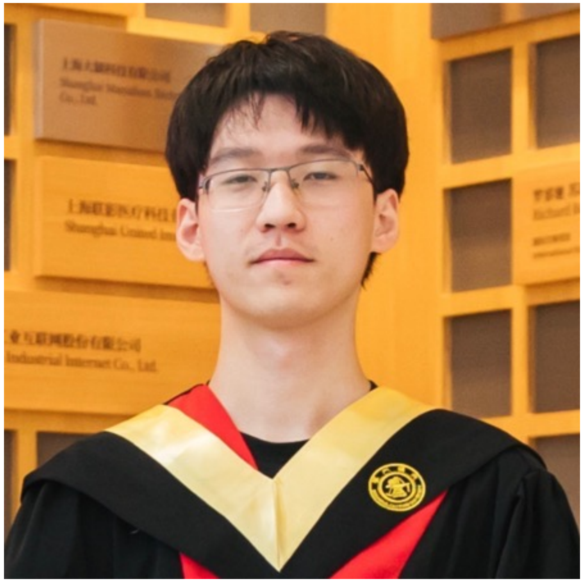
Mosharaf Chowdhury

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?

GSIs



Yinwei Dai

Jiaxing Yang

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

Mosharaf Chowdhury

- @Michigan since 2016
- Research: SymbioticLab.org

- Office hours: Wednesday 2PM – 2:50PM (virtual)
  - Queue: https://officehours.it.umich.edu/queue/421
  - Also, by appointment (pre-scheduled via email)
  - No office hours this week

- Lectures will be recorded (but not discussions)

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

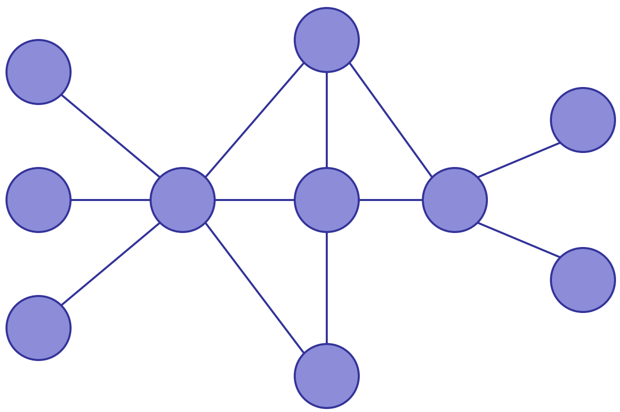
What is missing?

- 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 EEC 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
  - First one is an individual assignment
  - The rest are in groups of 3
- Exams (virtual):
  - Midterm: October 20
  - Final: December 20 8 AM – 10 AM

Grading

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

The ALL-NEW* 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 48 hours
- Participation counts for 0.1 on top of your final grade
  - Max 2.0
- 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

- Course website: http://mosharaf.com/eecs489/
  - Assignments, lecture slides
- Confidential content on canvas
- Piazza for all communication
  - Sign up if you haven't already
  - https://piazza.com/umich/fall2021/eecs489/
- Assignment submission via Github
  - Start forming groups
  - Details will be sent out soon

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

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

Policies on safety

- Masks on, while you are in the class
  - Except for taking quick drinks etc.

- Please strive for us to continue meeting in person instead of going back to zoom
  - We will if/when it’s unsafe

LET’S TALK INTERNET

The Internet consists of many end-systems

car navigator

heart pacemaker

smartphone

end-system

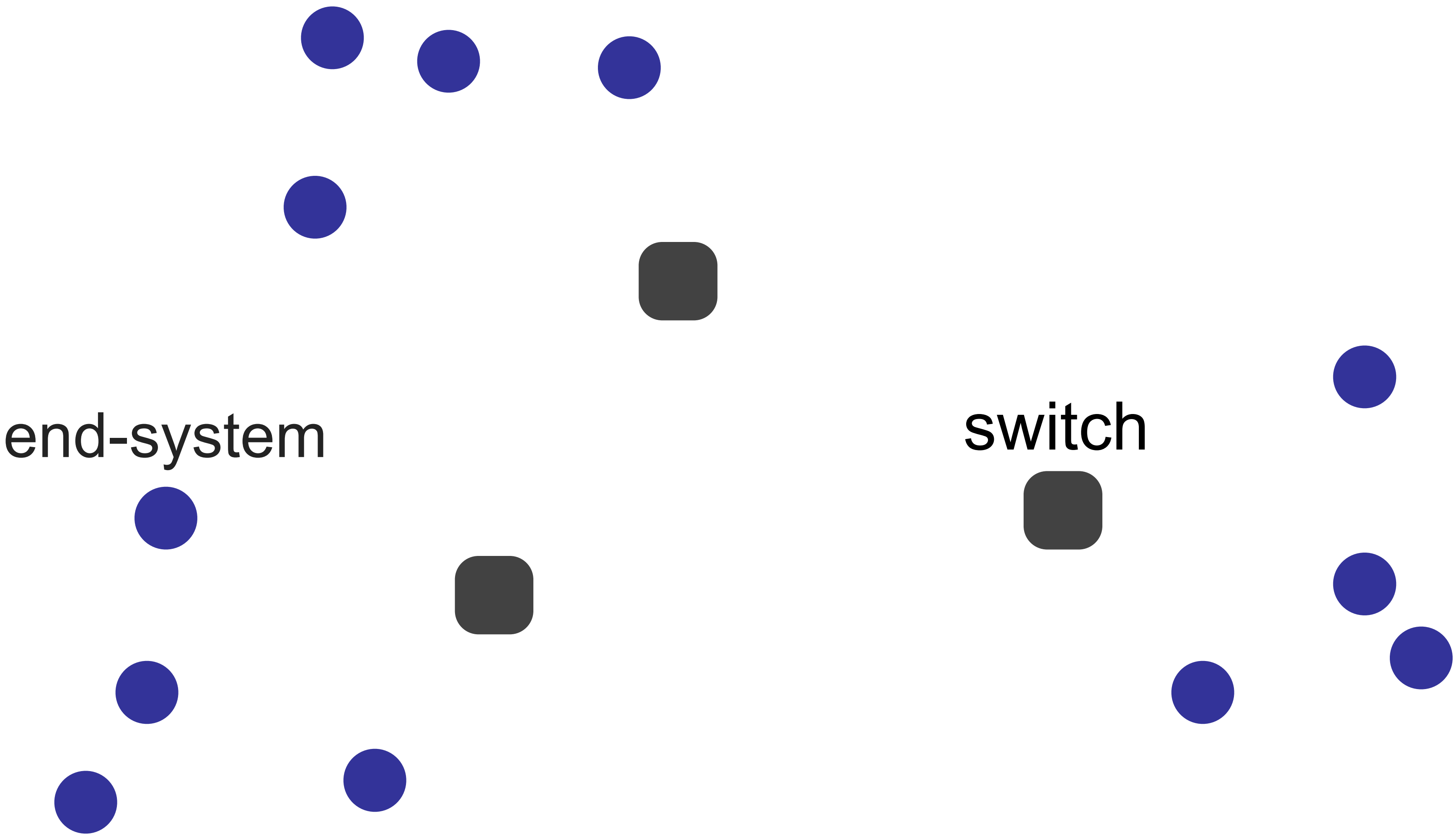
iPad

Linux server

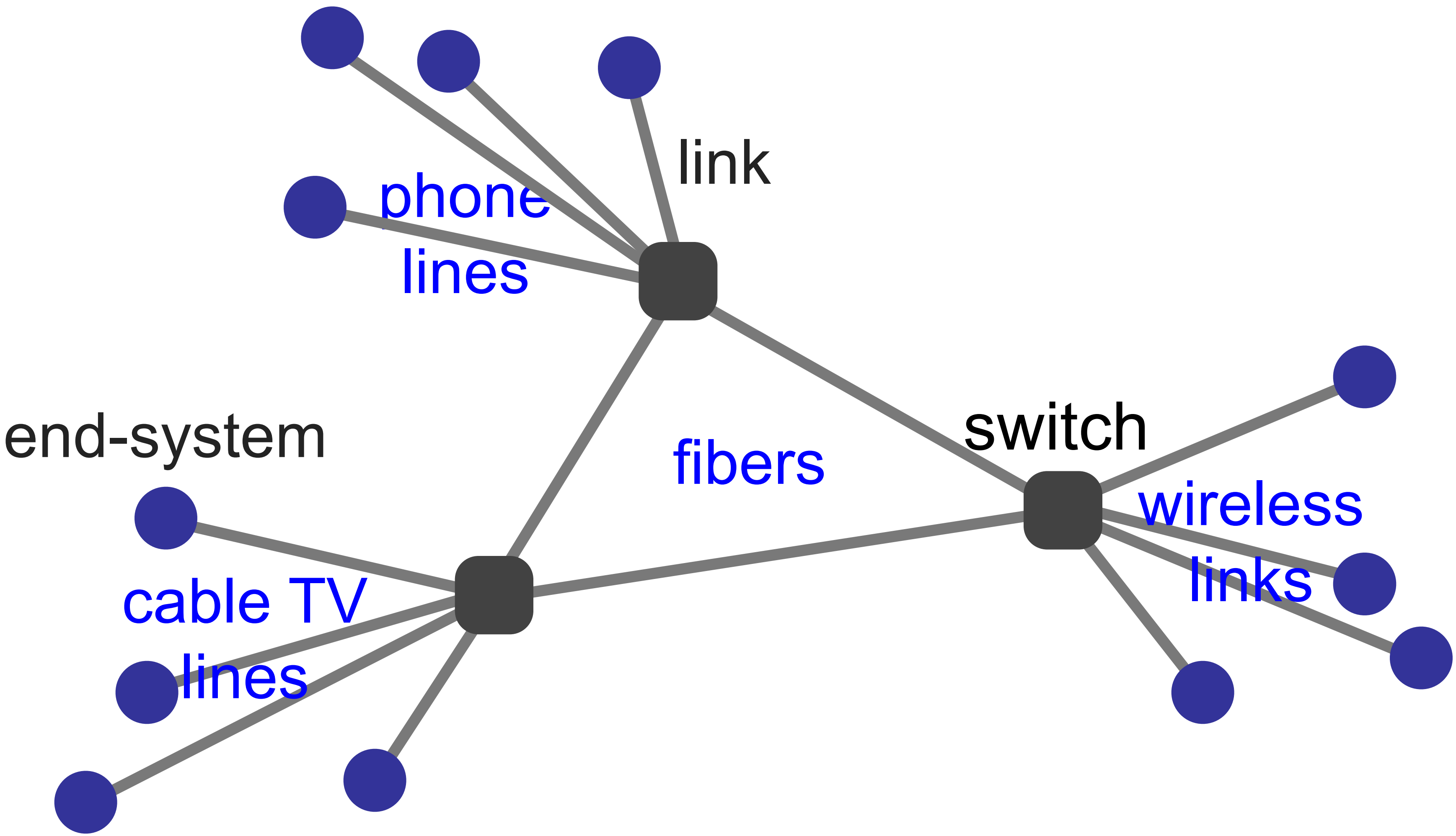
MAC laptop

Windows PC

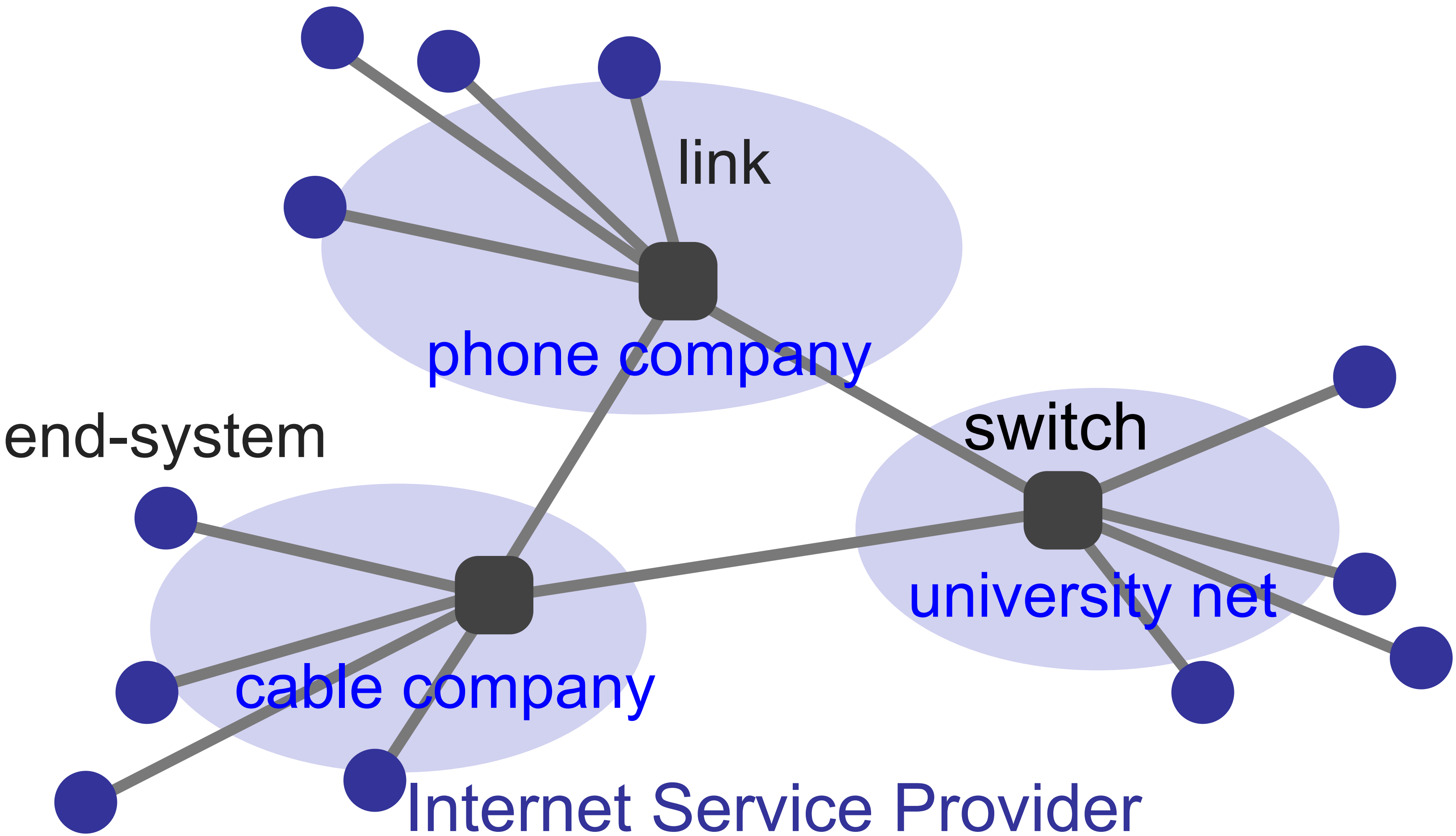
Connected by switches



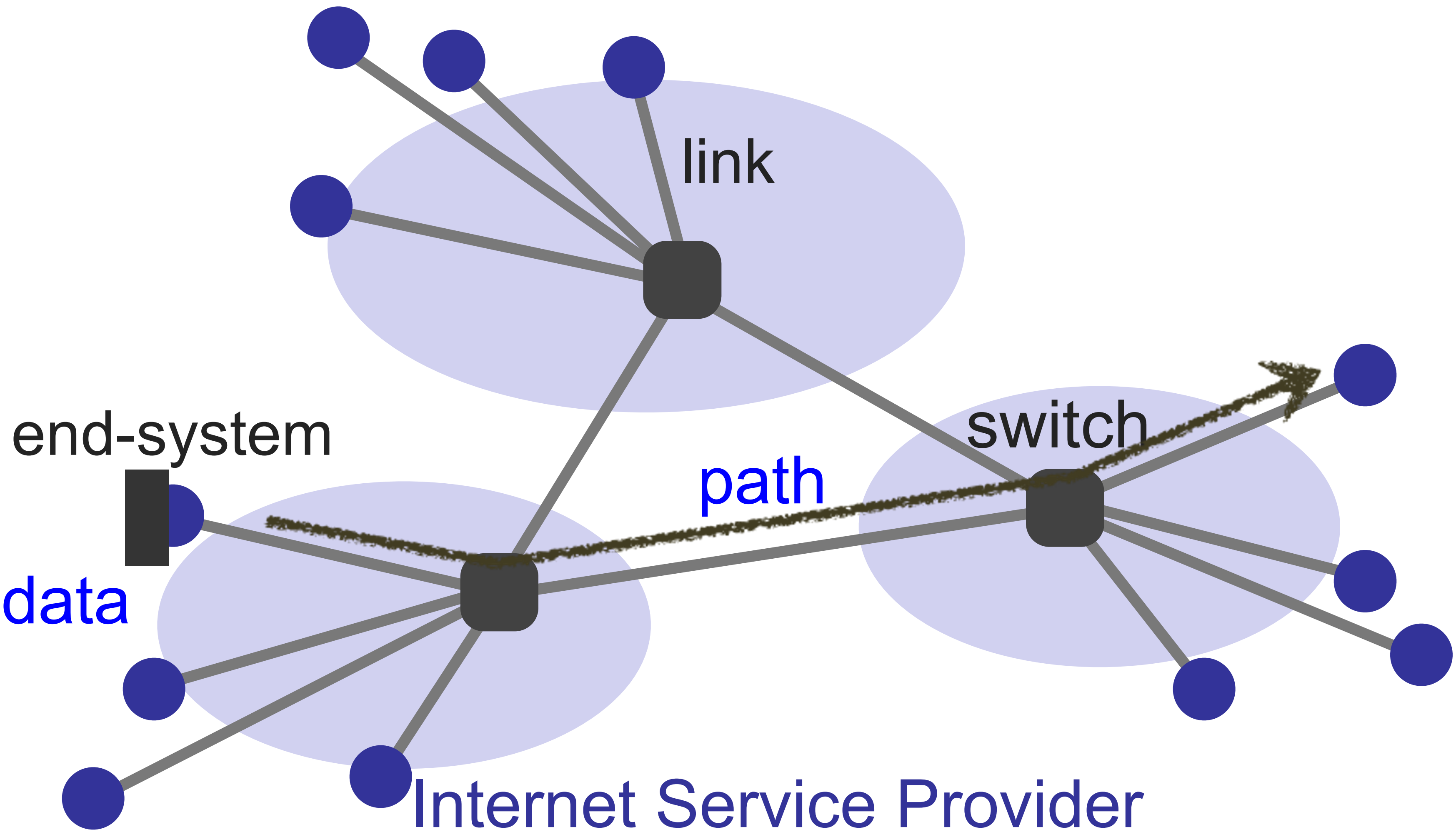
And links


link
phone
lines
end-system
fibers
switch
wireless
links
cable TV
lines

Managed by many parties

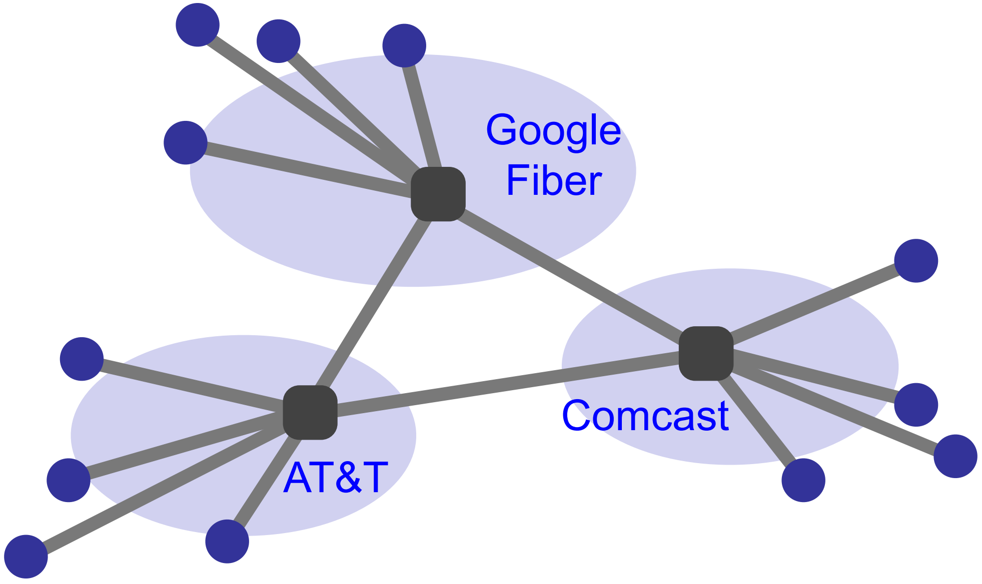


Transfers data



A federated system

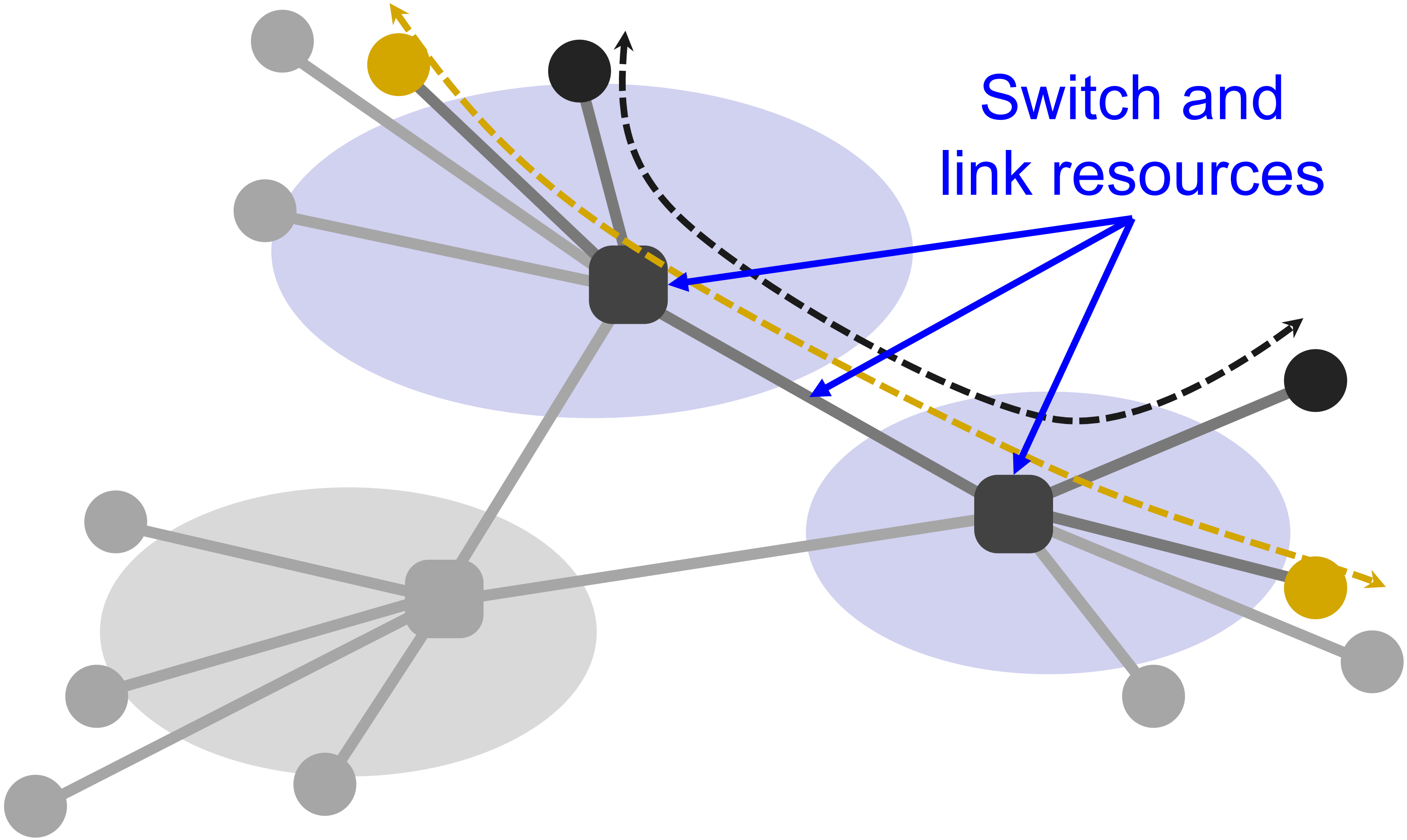
- The Internet ties together different networks **by the IP protocol**
  - *A common interface binds them all together*



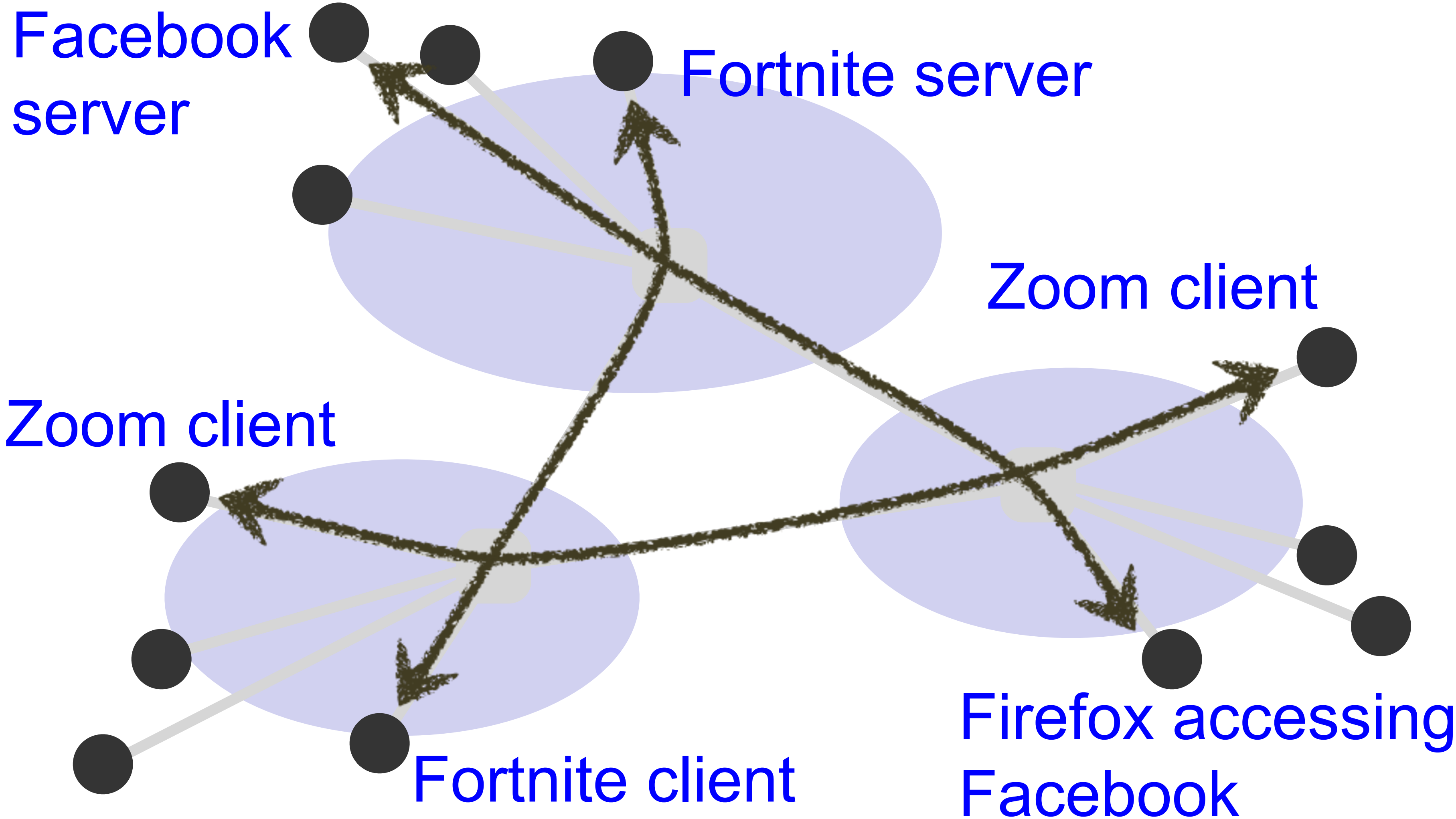
Switched networks

- 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



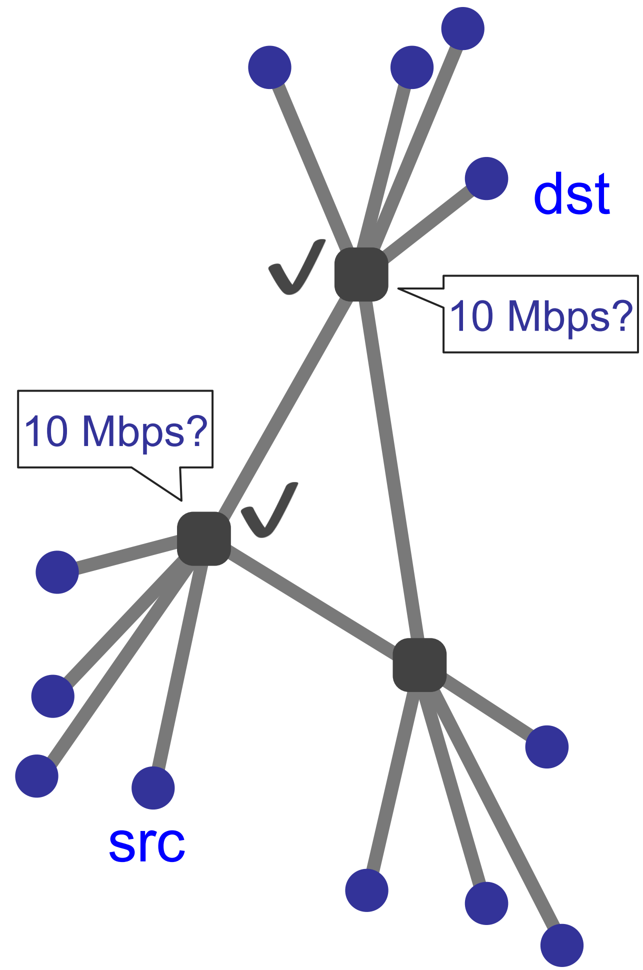
Two ways to share switched networks

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

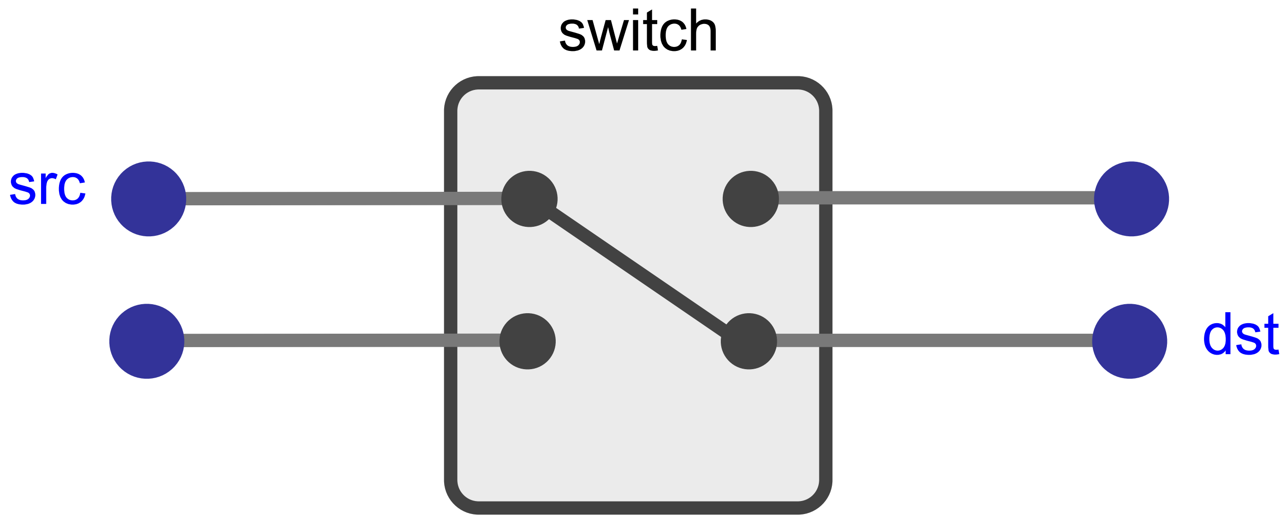
Circuit switching

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

More details in backup



Circuit switching



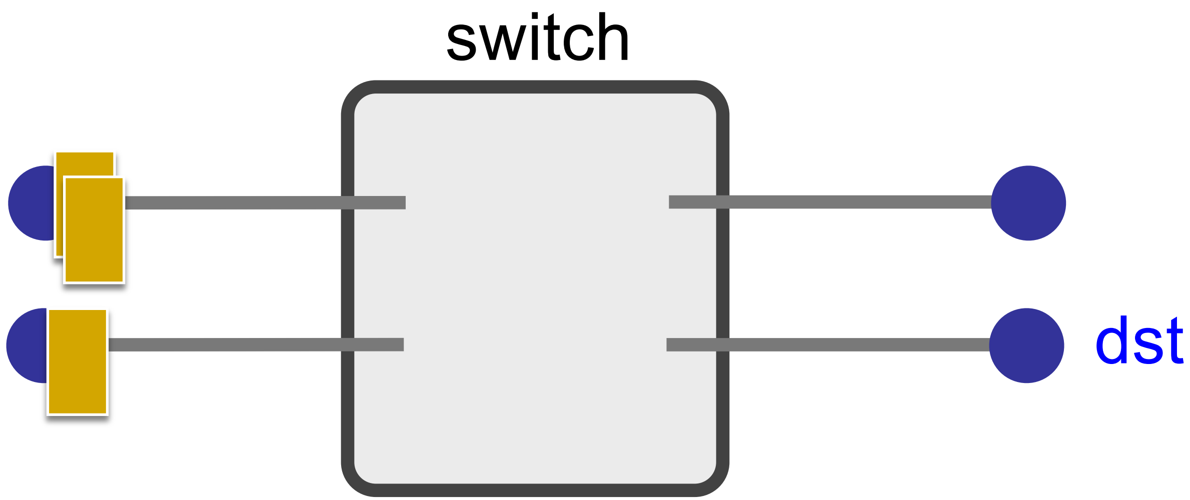
- Reservation establishes a “circuit” within a switch

Circuit switching

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

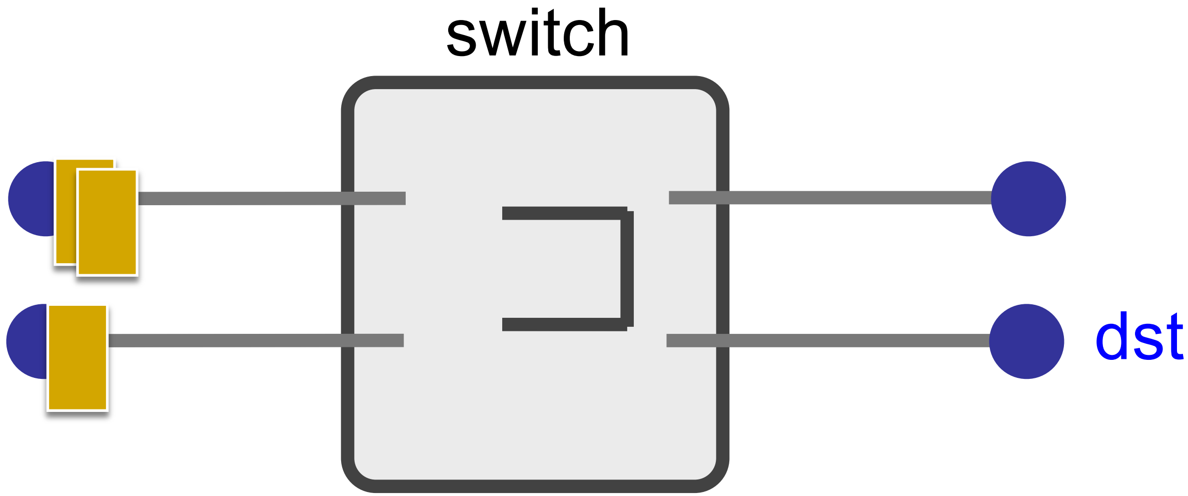
- Cons
  - Complexity of circuit setup/teardown
  - Inefficient when traffic is bursty
  - Circuit setup adds delay
  - Switch fails → its circuit(s) fails

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

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)

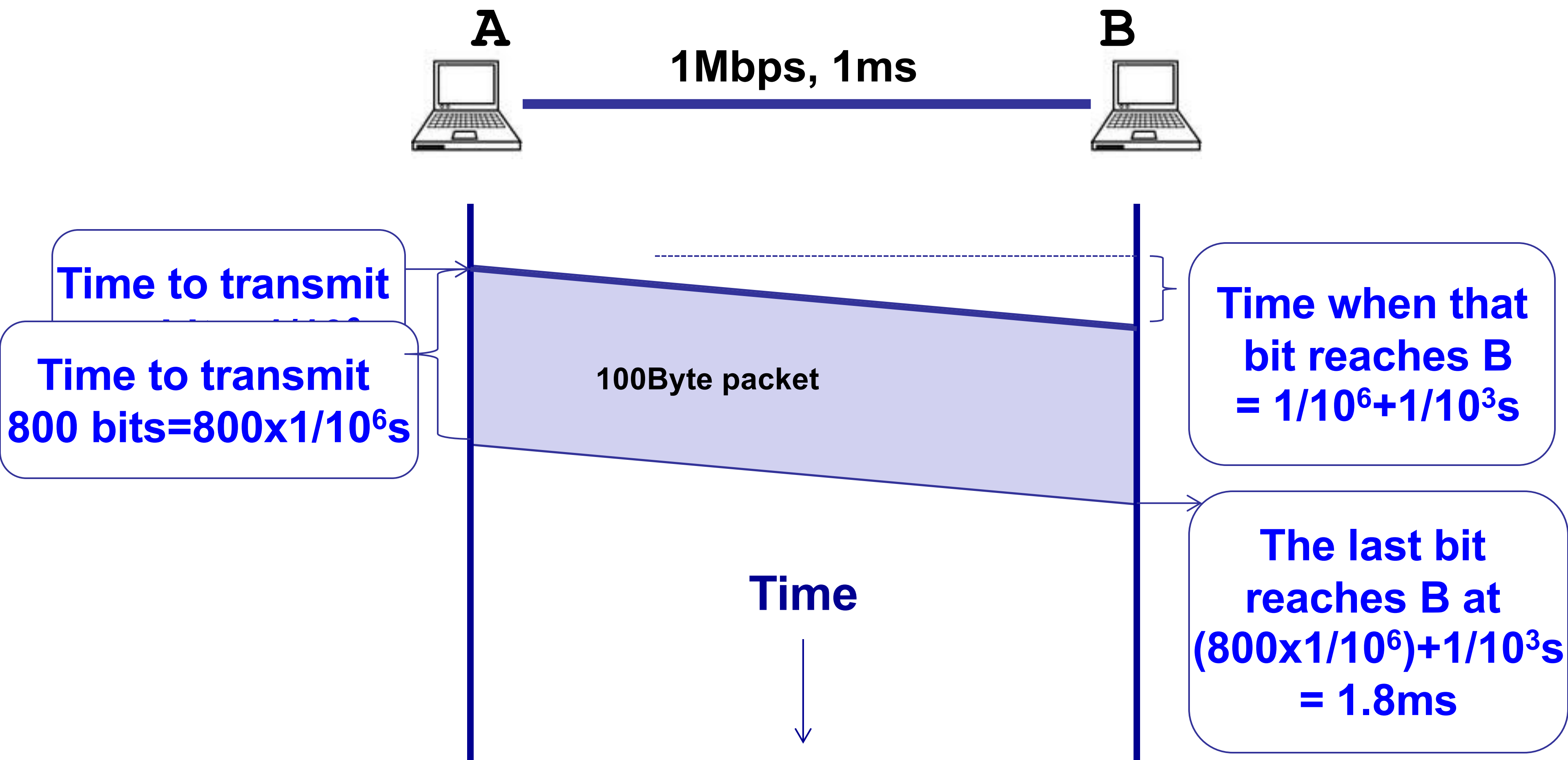
1. Transmission delay

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

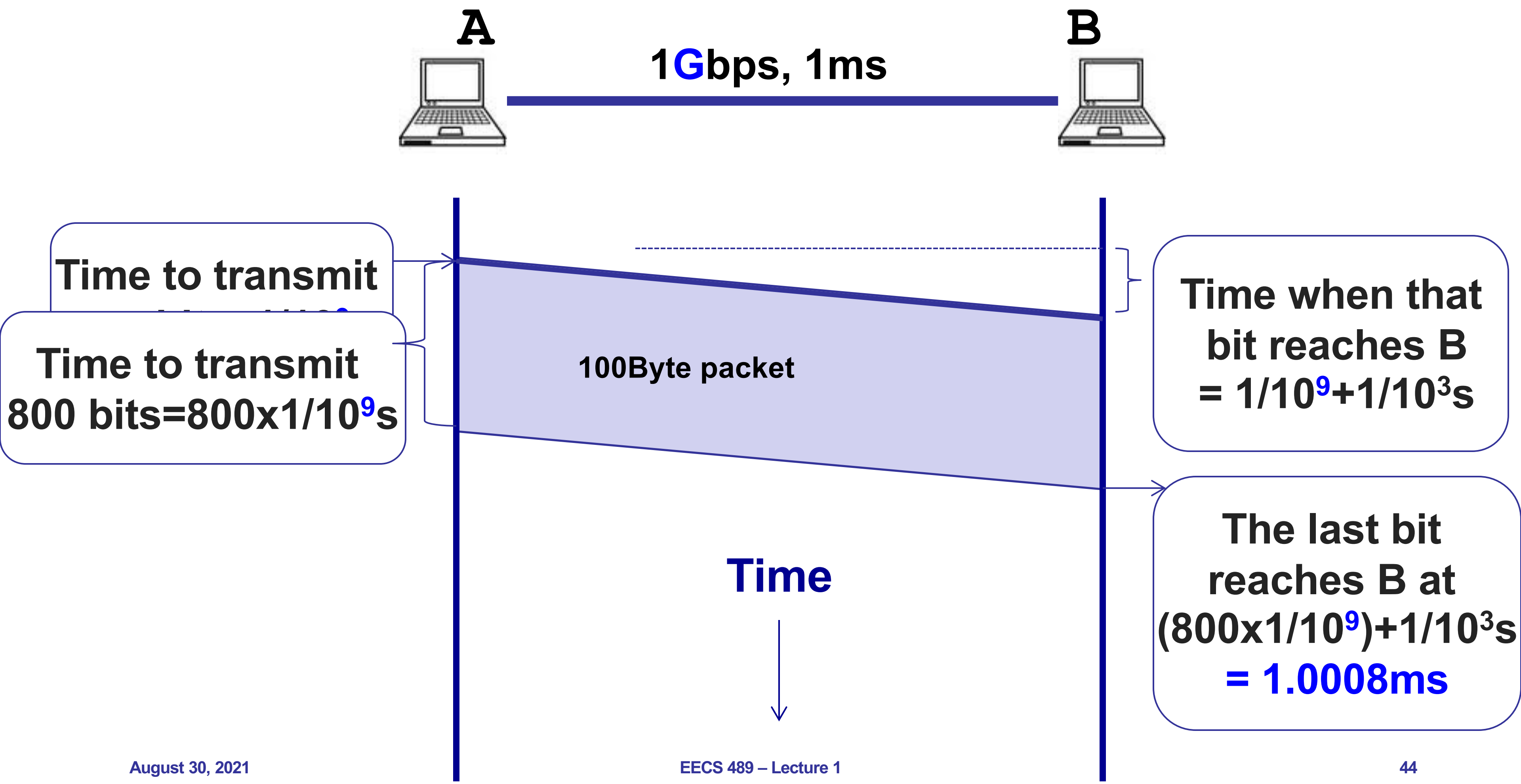
2. Propagation delay

- 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

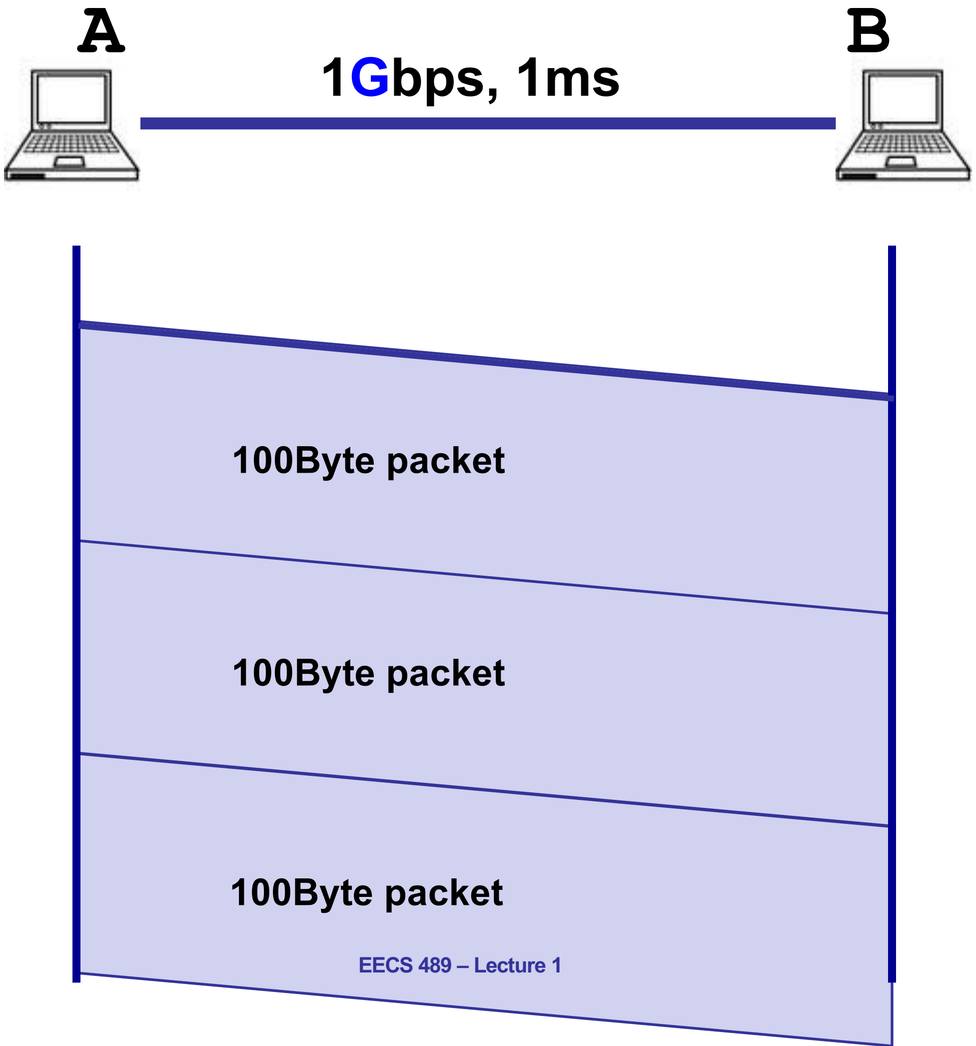
Packet delay
Sending a 100-byte packet



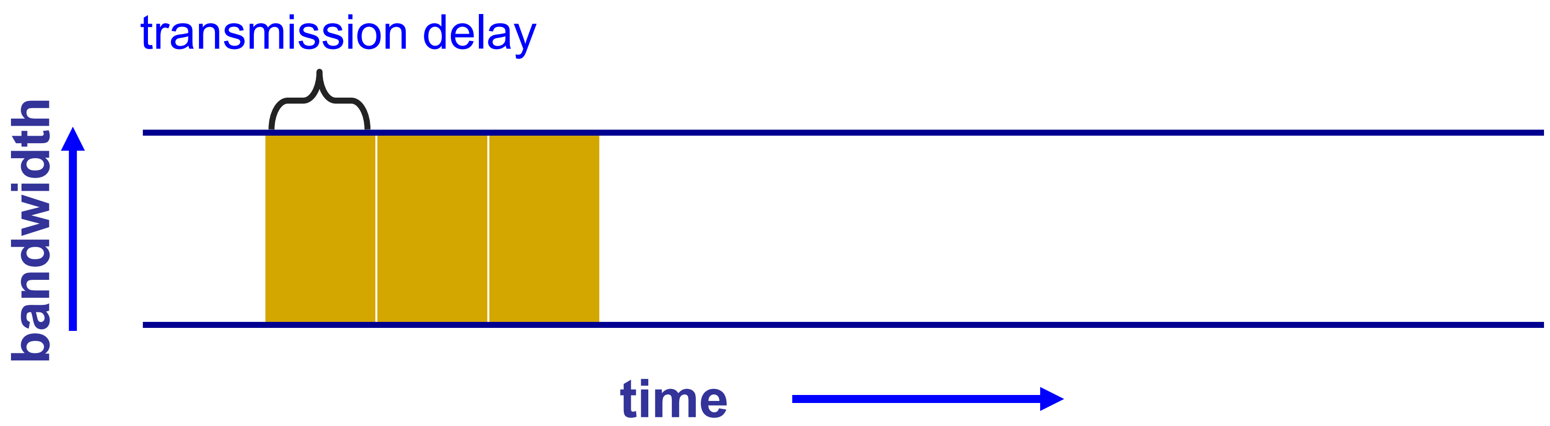
Packet delay
Sending a 100-byte packet



Sending a large file using 100-byte packets



Pipe view of a link

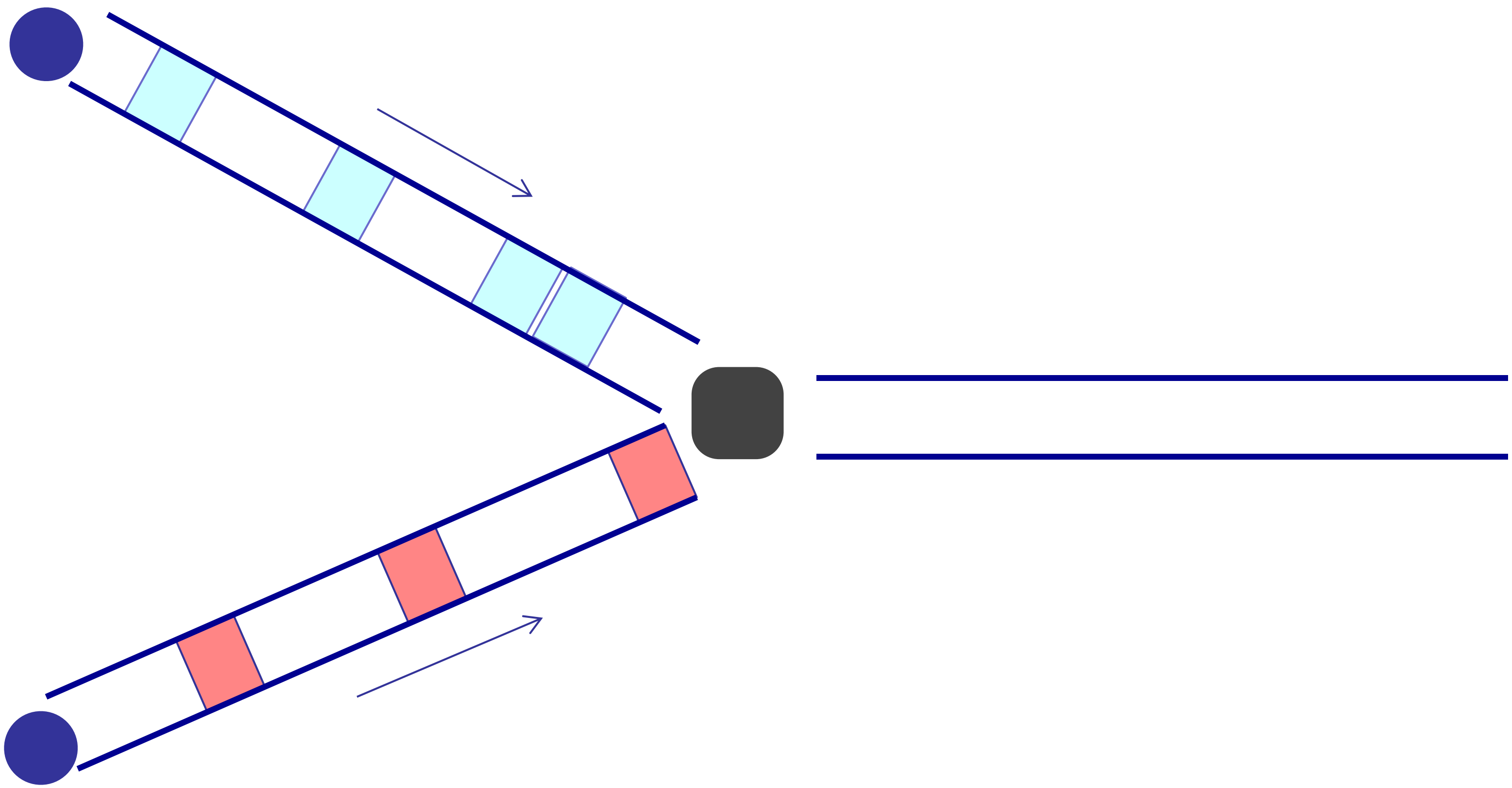


- Transmission delay decreases as bandwidth increases

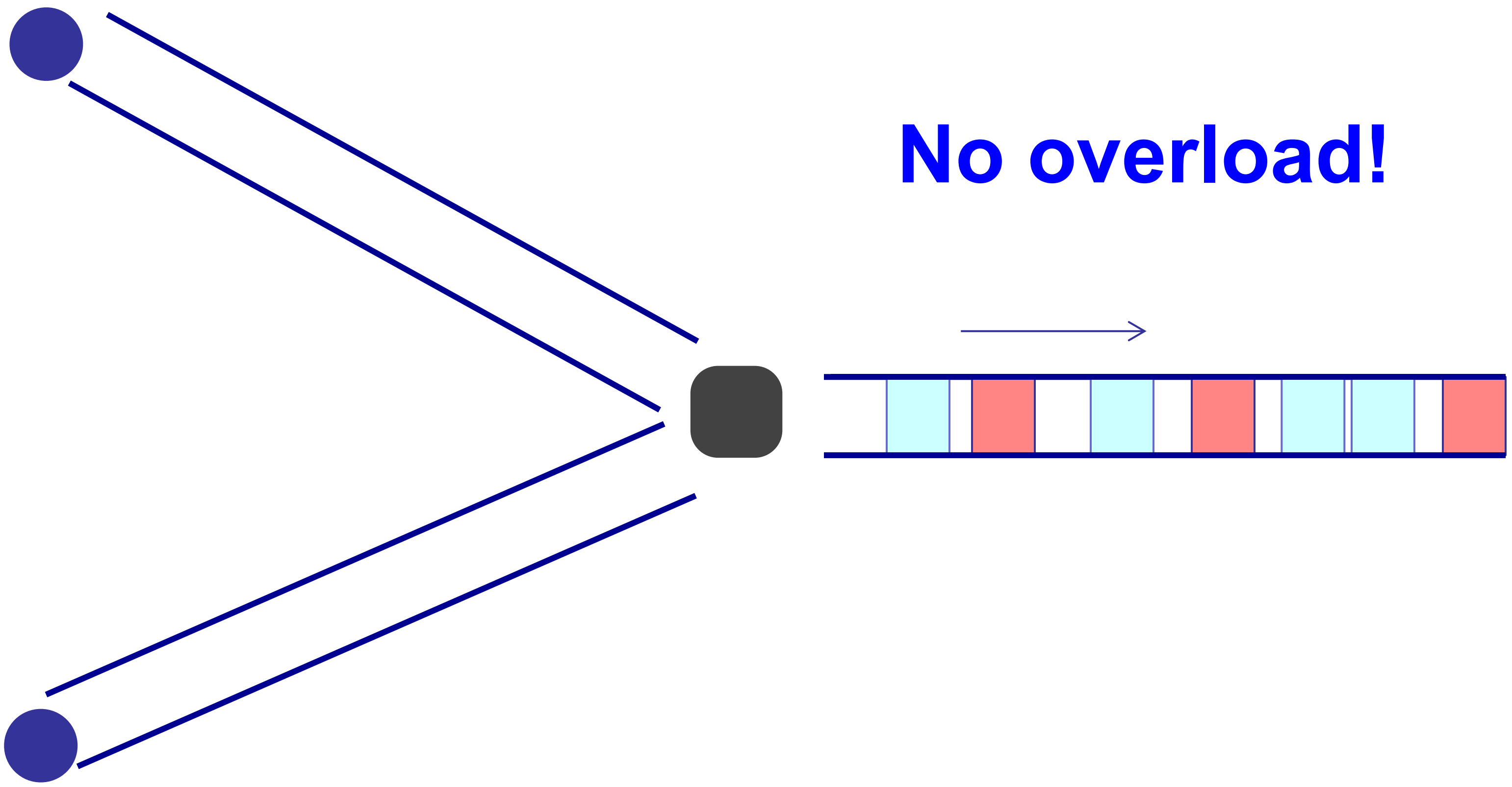
3. Queuing delay

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

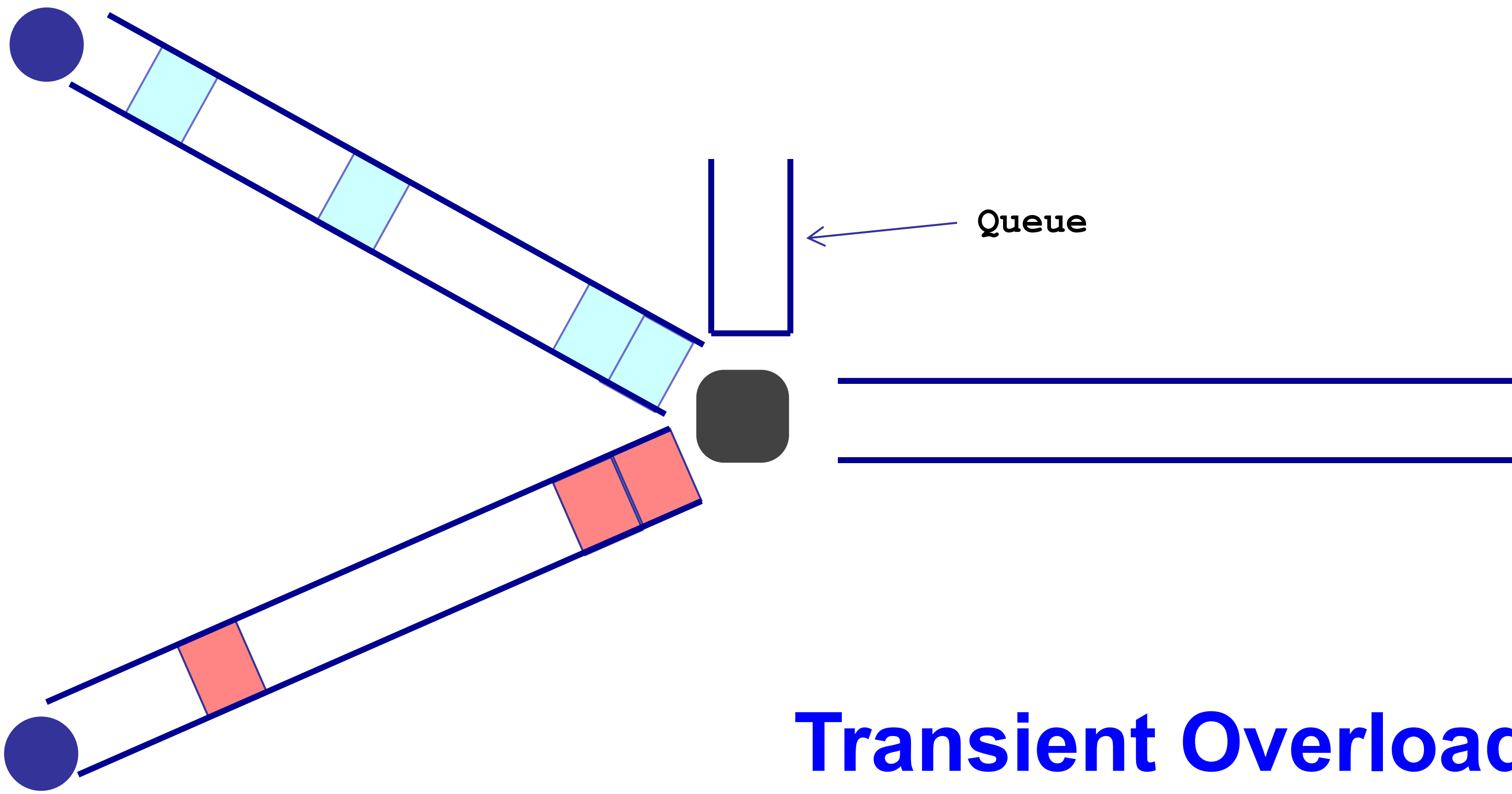
Queueing delay: “pipe” view



Queueing delay: "pipe" view



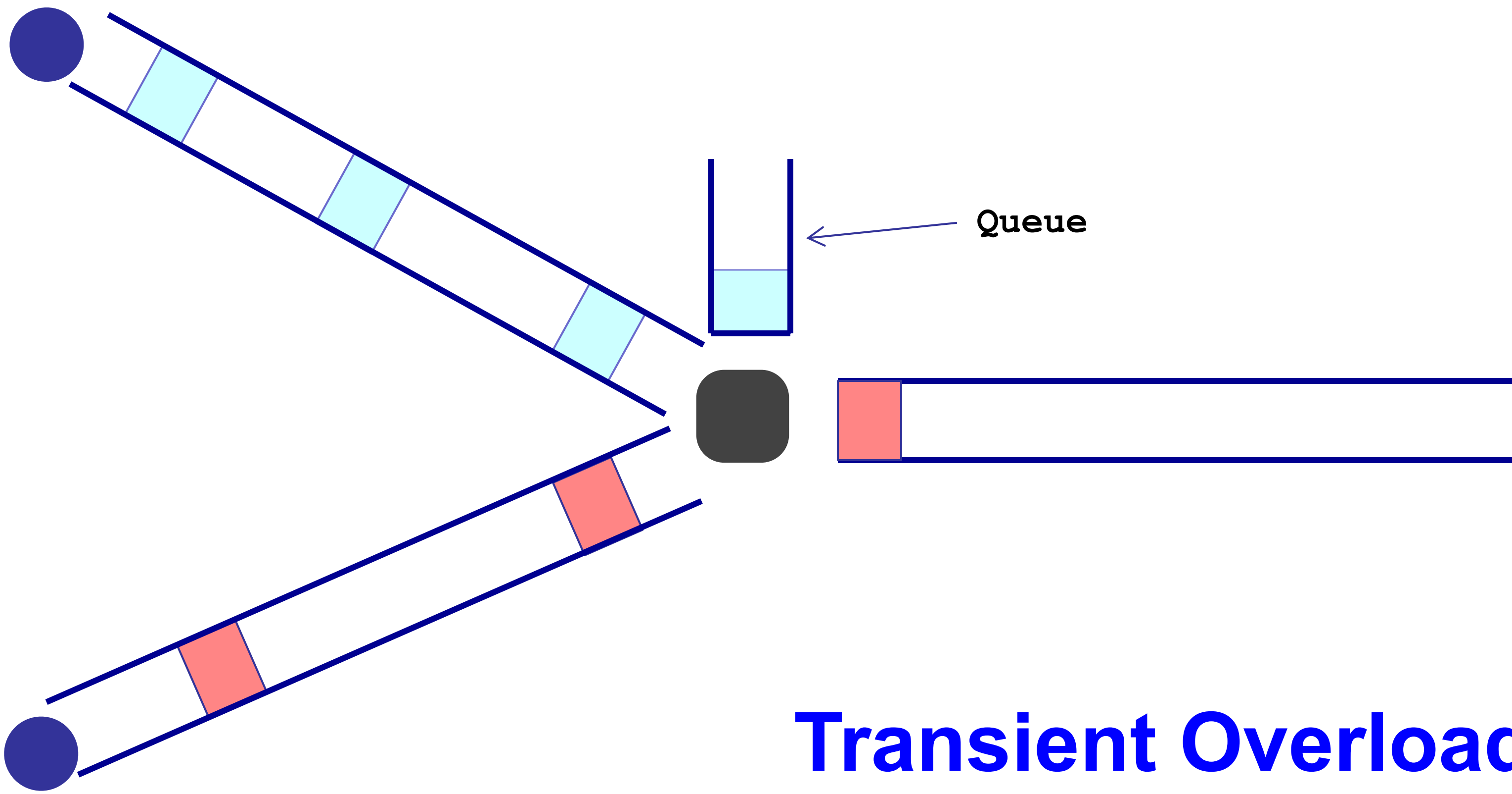
Queueing delay: “pipe” view



Transient Overload

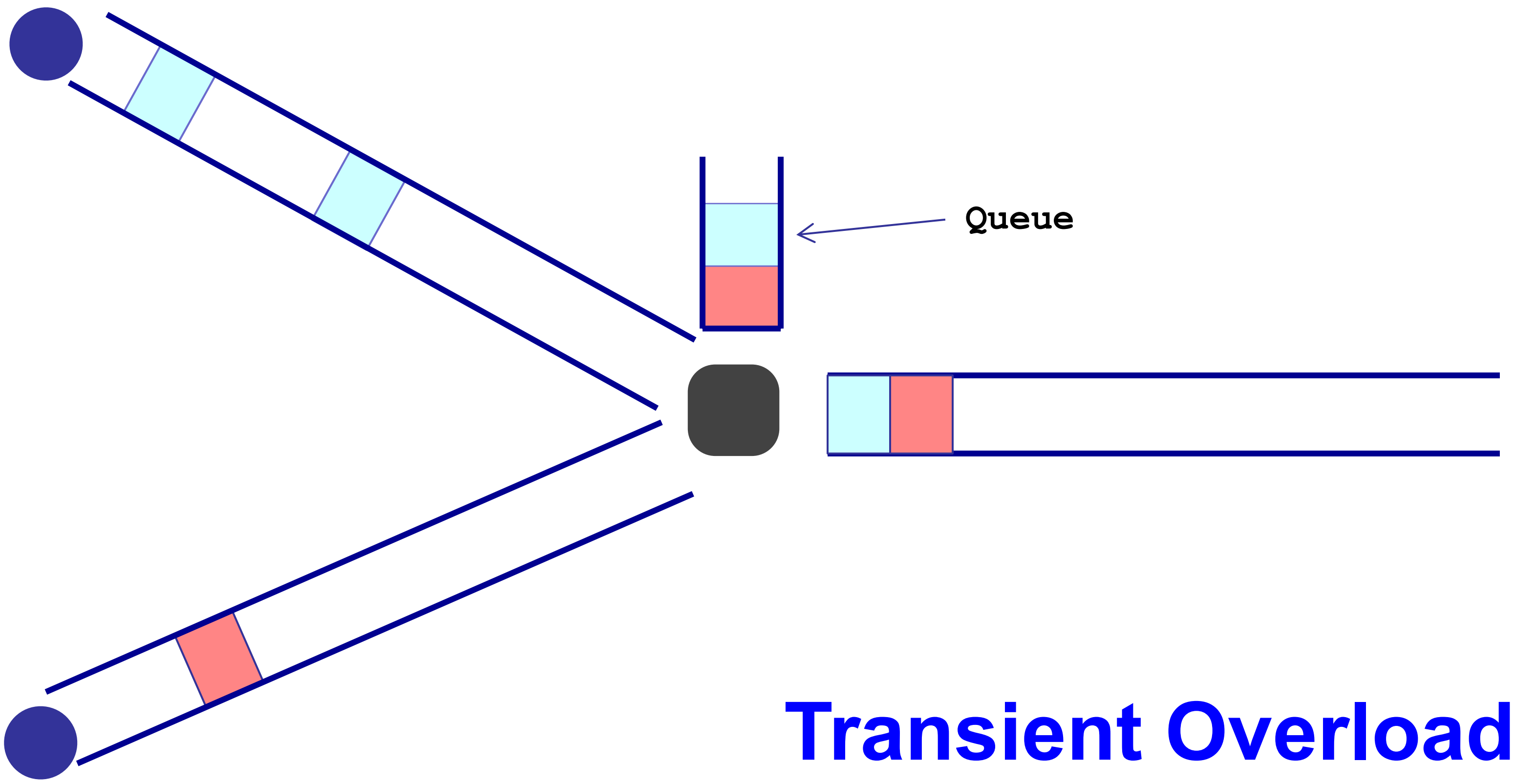
Not a rare event!

Queueing delay: “pipe” view



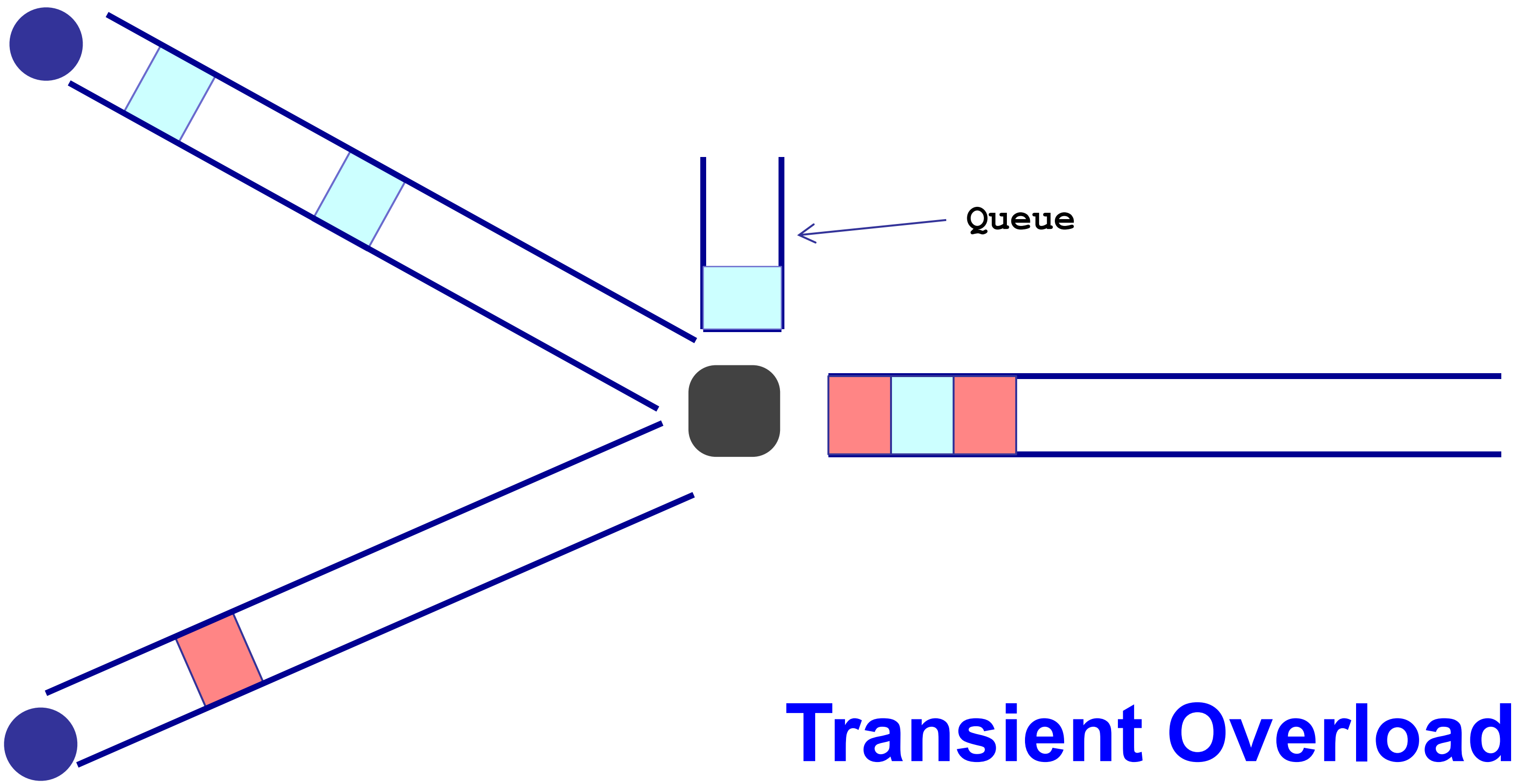
Transient Overload

Queueing delay: "pipe" view



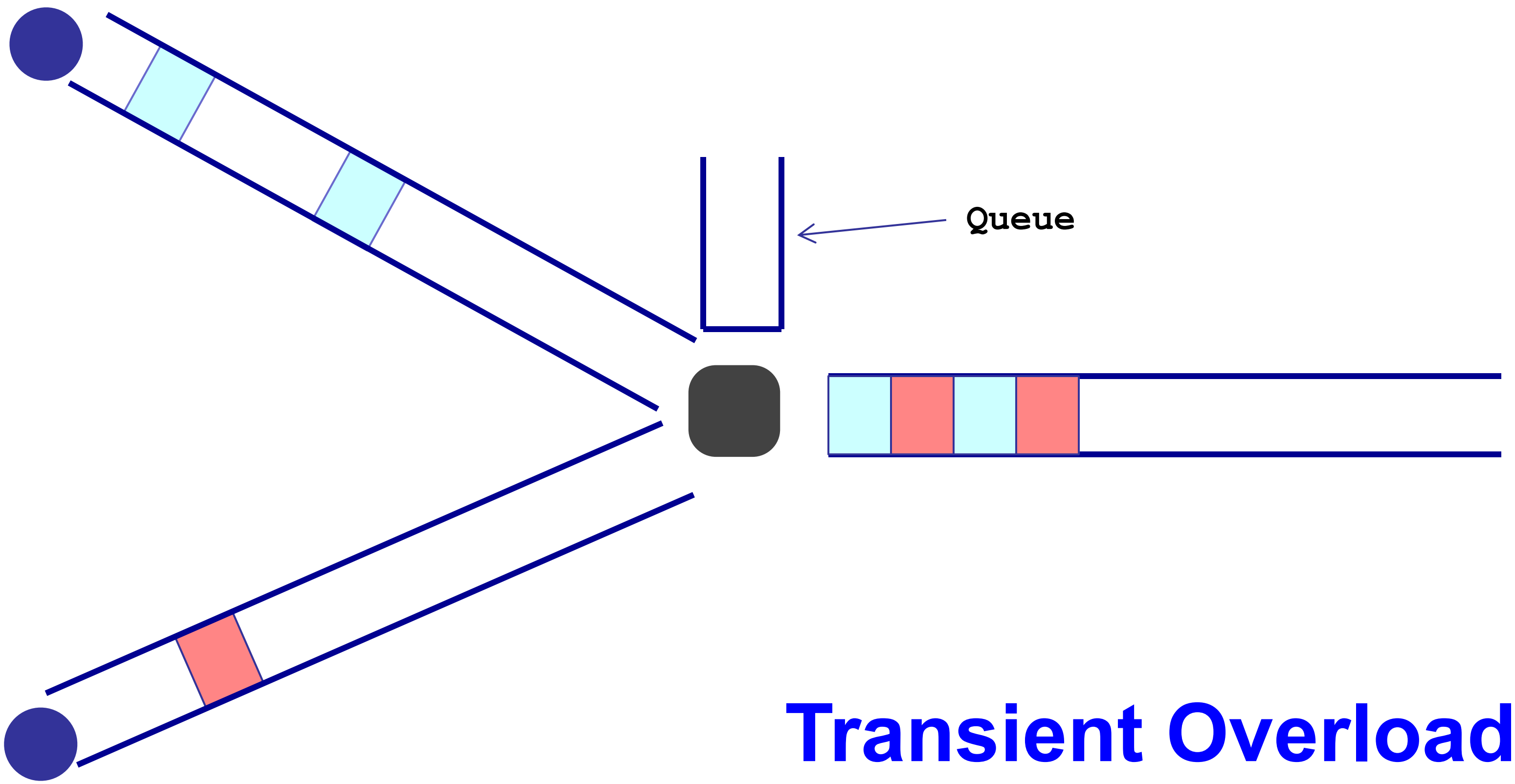
Transient Overload

Queueing delay: “pipe” view



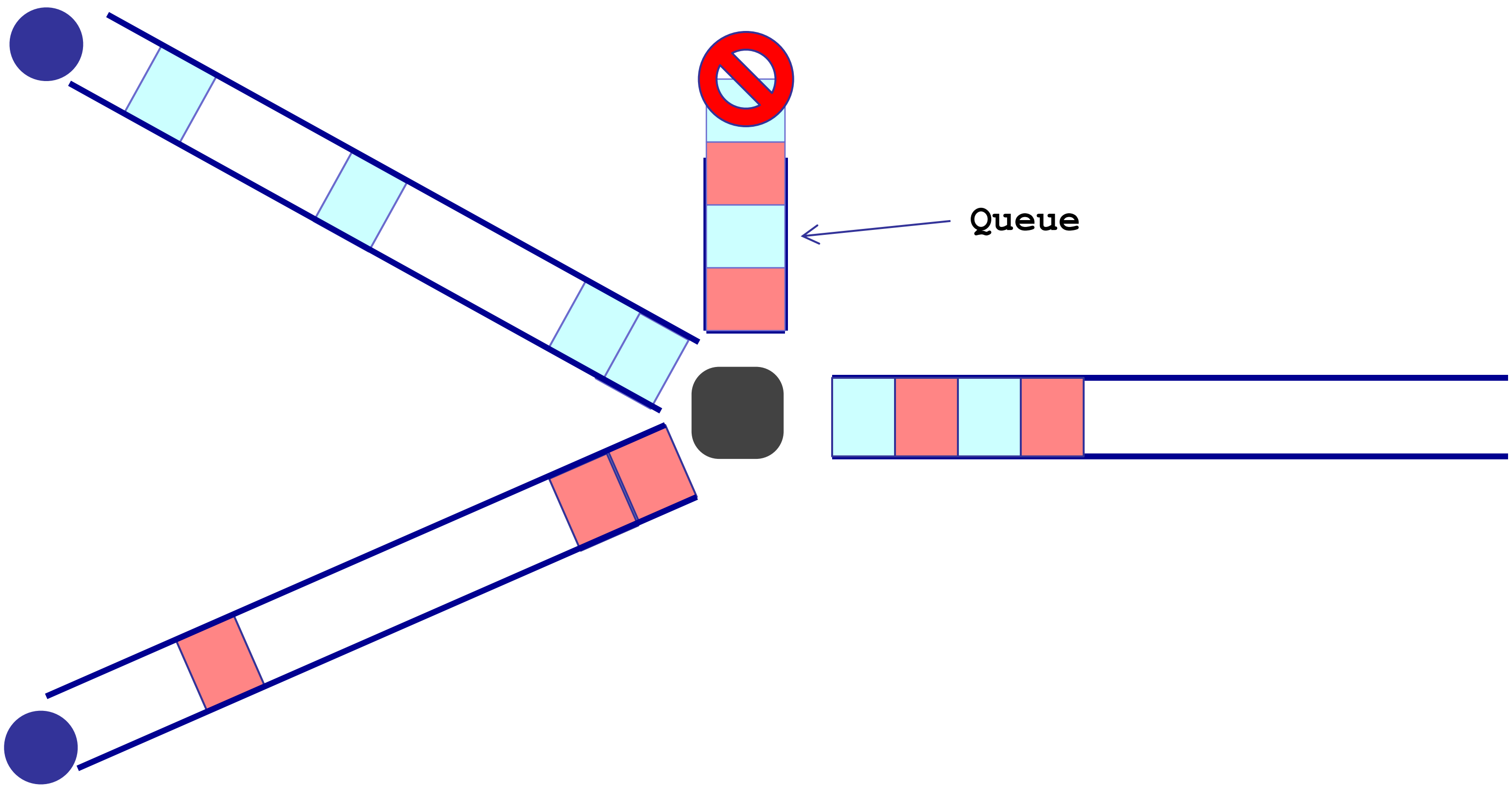
Transient Overload

Queueing delay: “pipe” view



Transient Overload

Persistent overload leads to packet drop/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
- 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)

- $L = A \times W$

- Compute L: count packets in queue every second

- Why do you care?
  - Easy to compute L, harder to compute W

4. Processing Delay

- 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

Throughput

Transmission rate R bits/sec

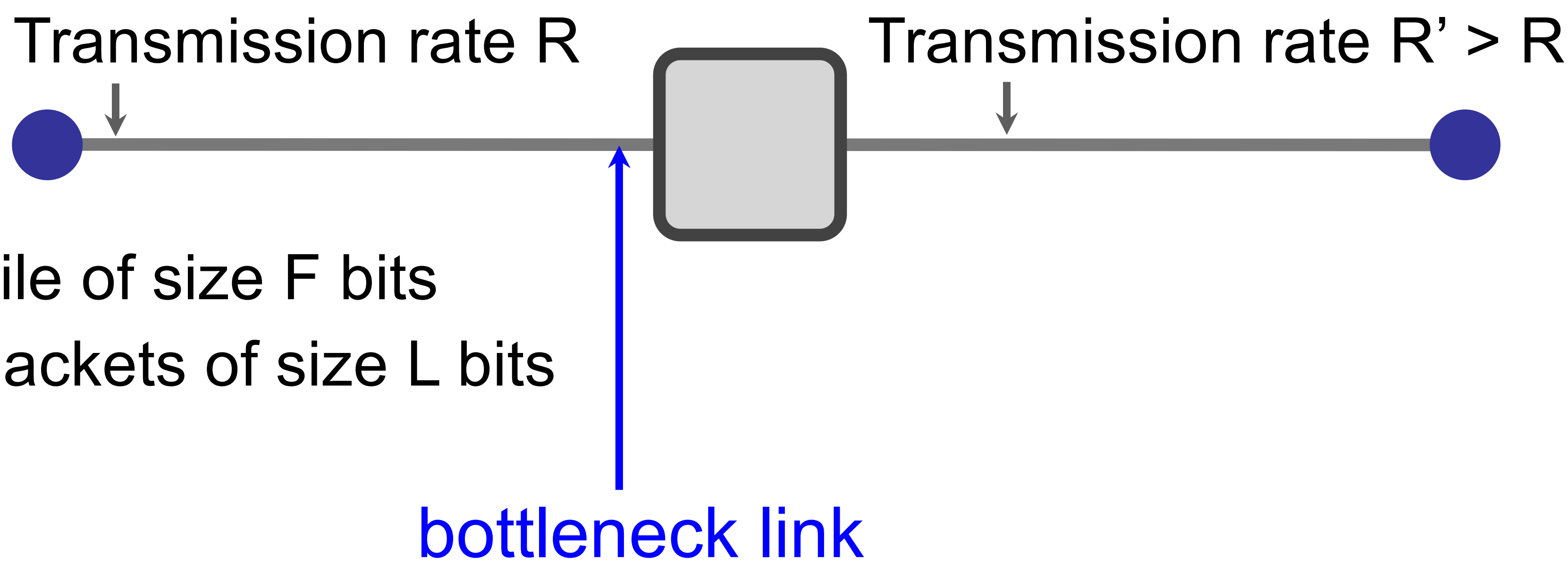
File of size F bits

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

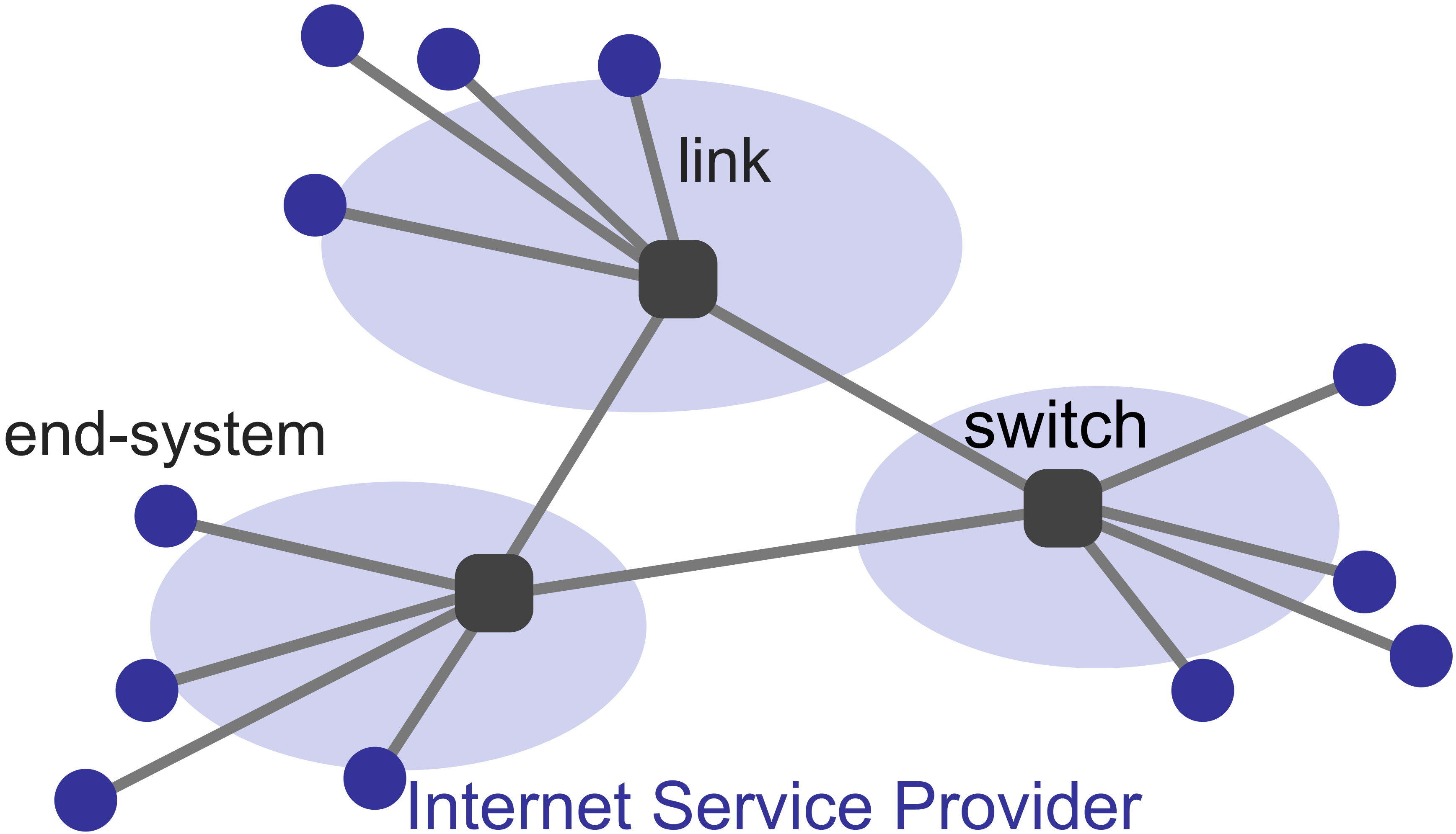
Average throughput = min{R, R’} = R

Summary

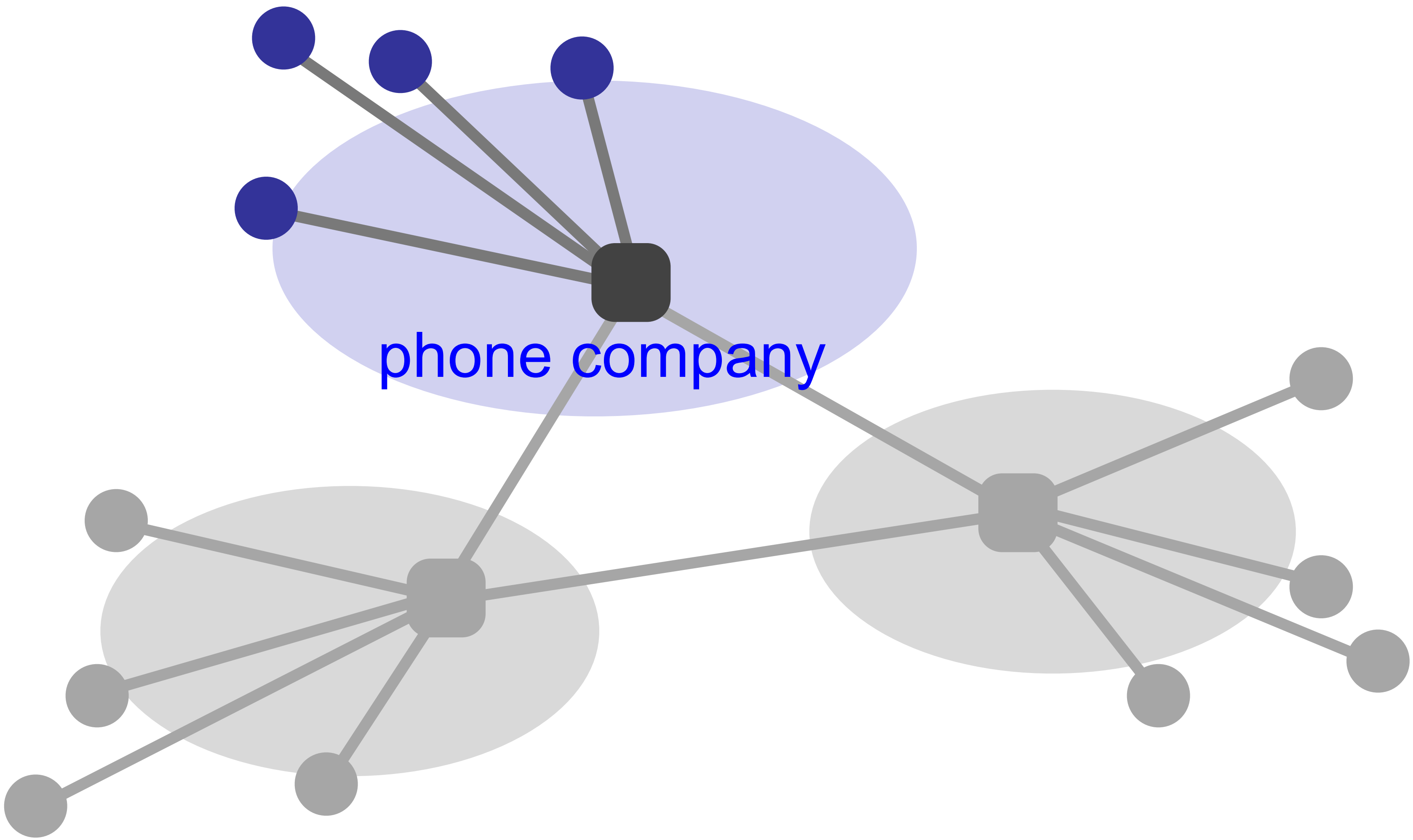
- How is the network shared?
  - On-demand or via reservation
- How do we evaluate a network?
  - Bandwidth, delay, loss, …
- What is a network made of?
  - Whatever physical infrastructure exist
  - See backup slides

WHAT IS THE NETWORK MADE OF?

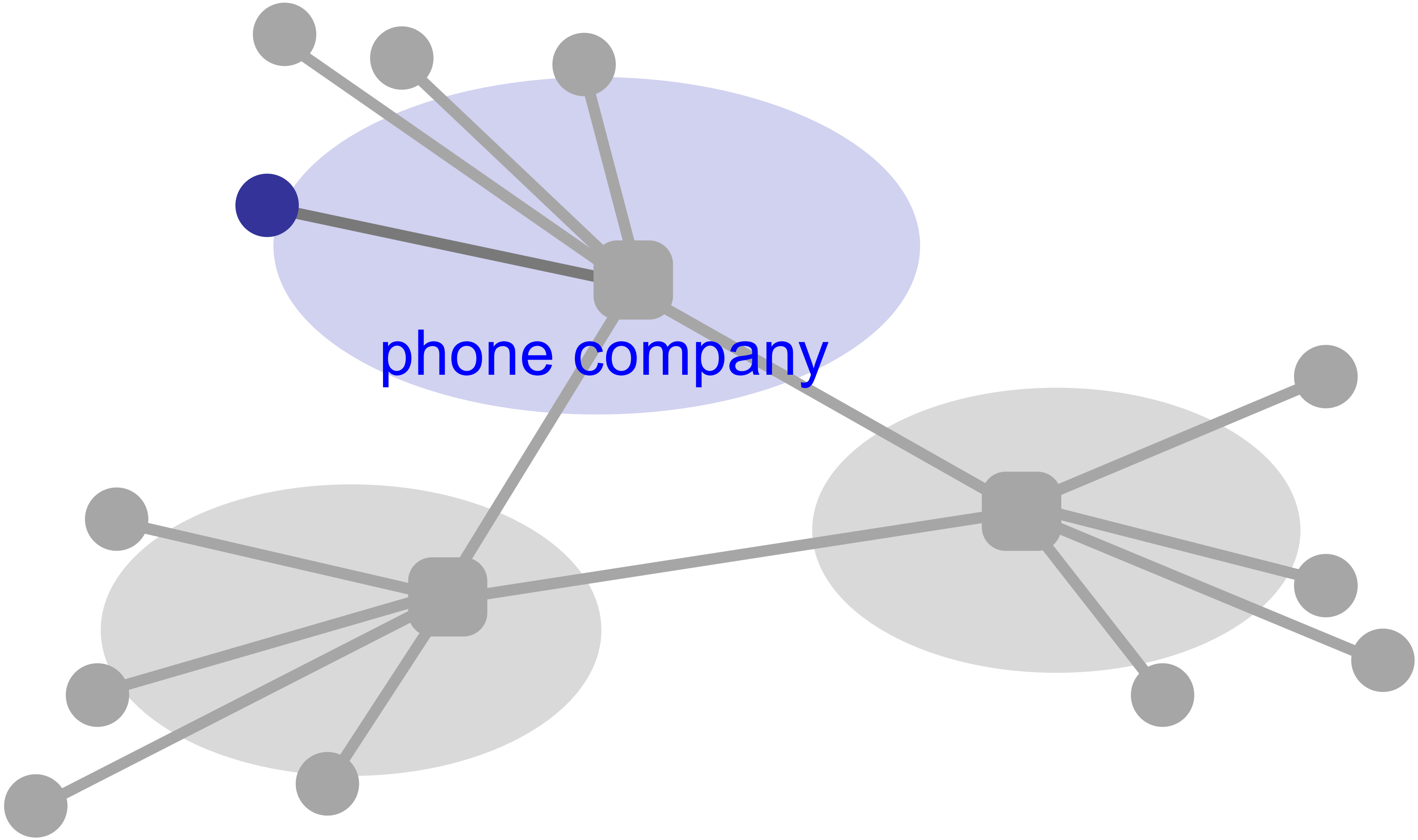
What is a network made of?



What is a network made of?

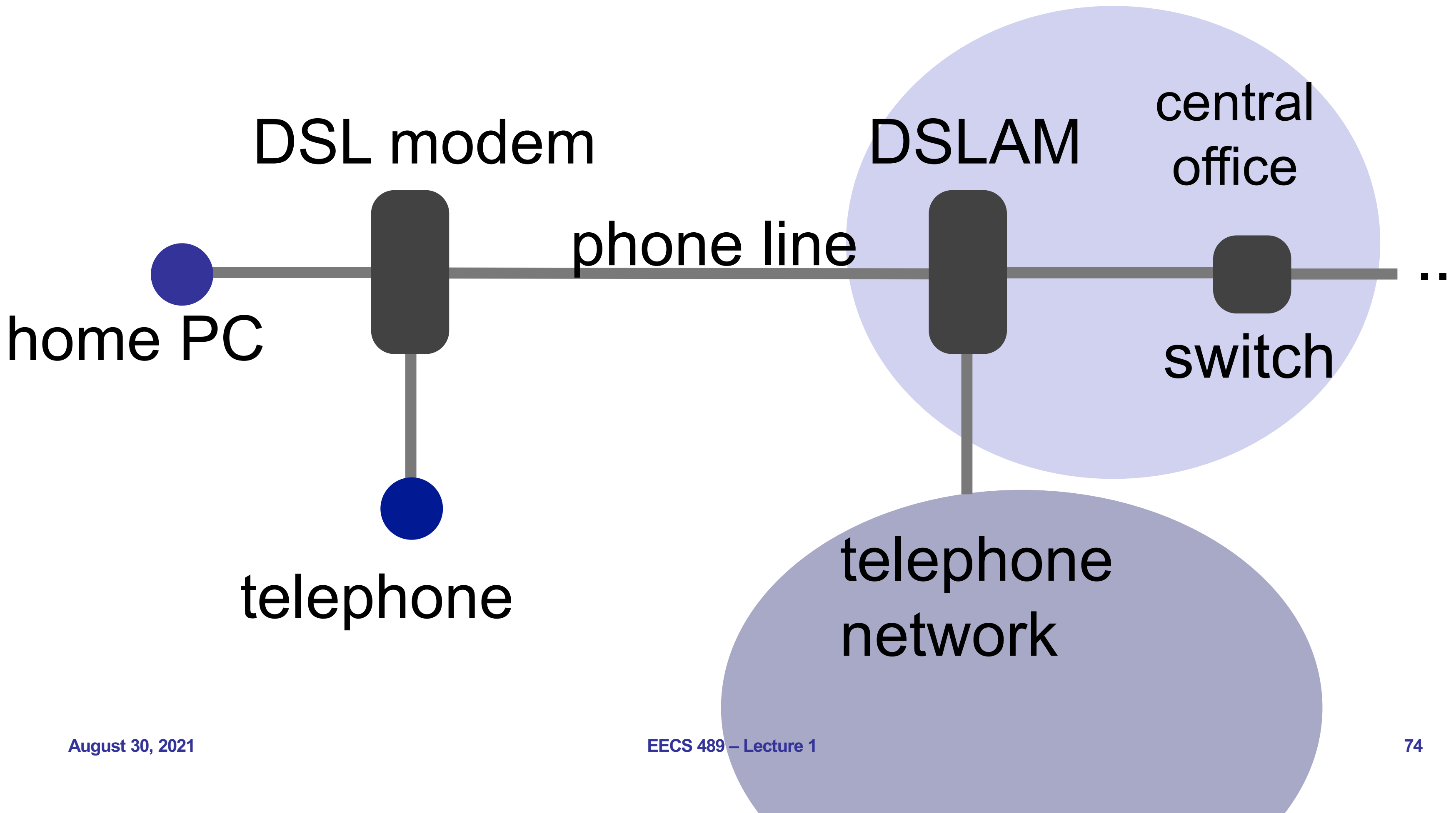


What is a network made of?



The last hop

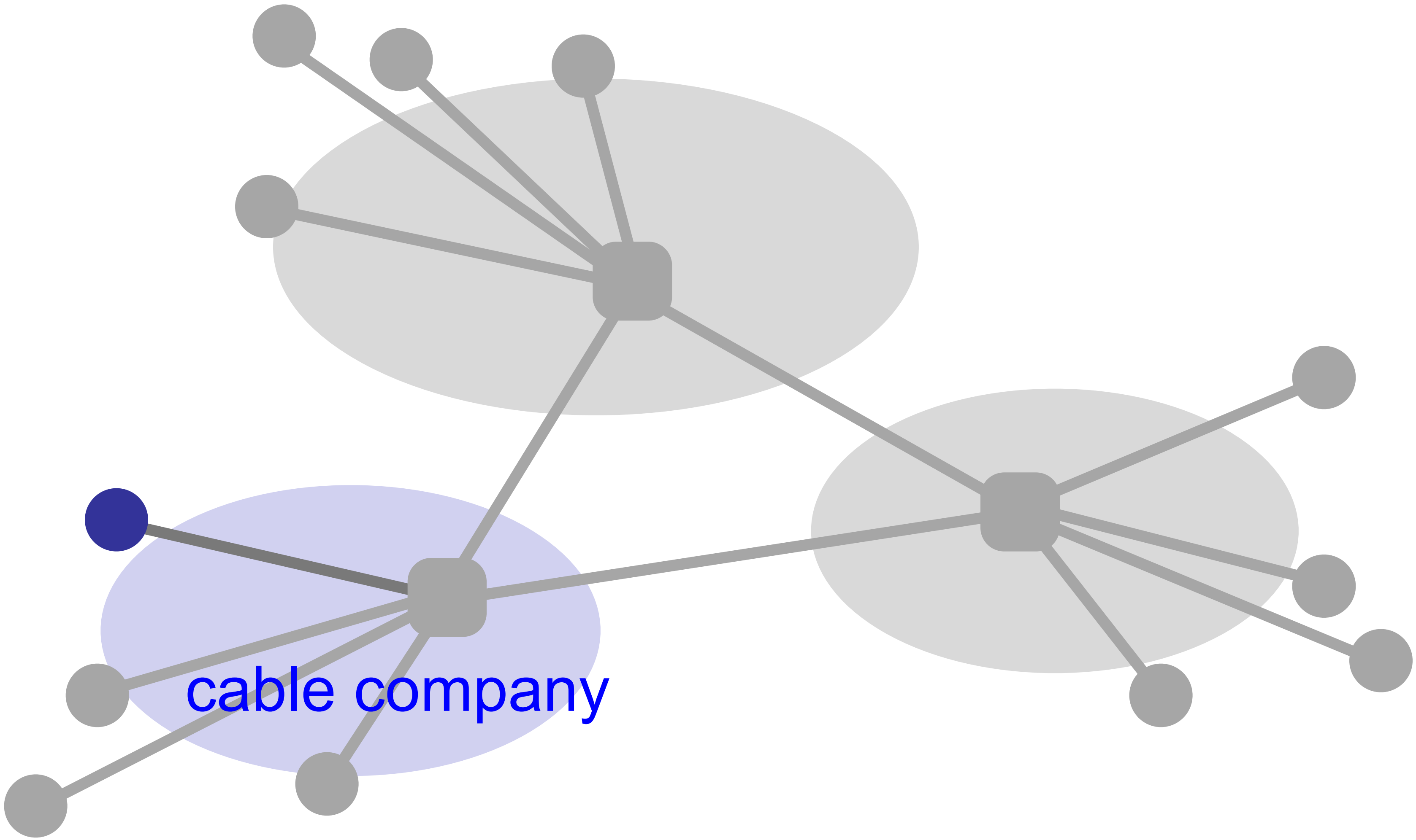
How do we connect?



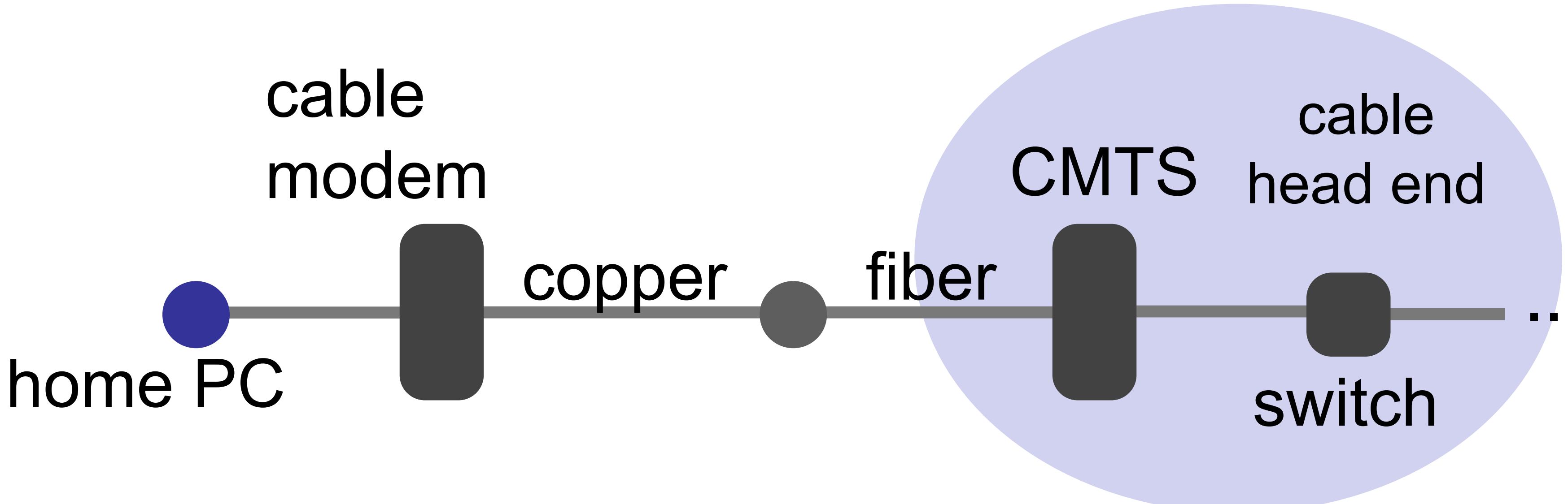
Digital Subscriber Line (DSL)

- 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?



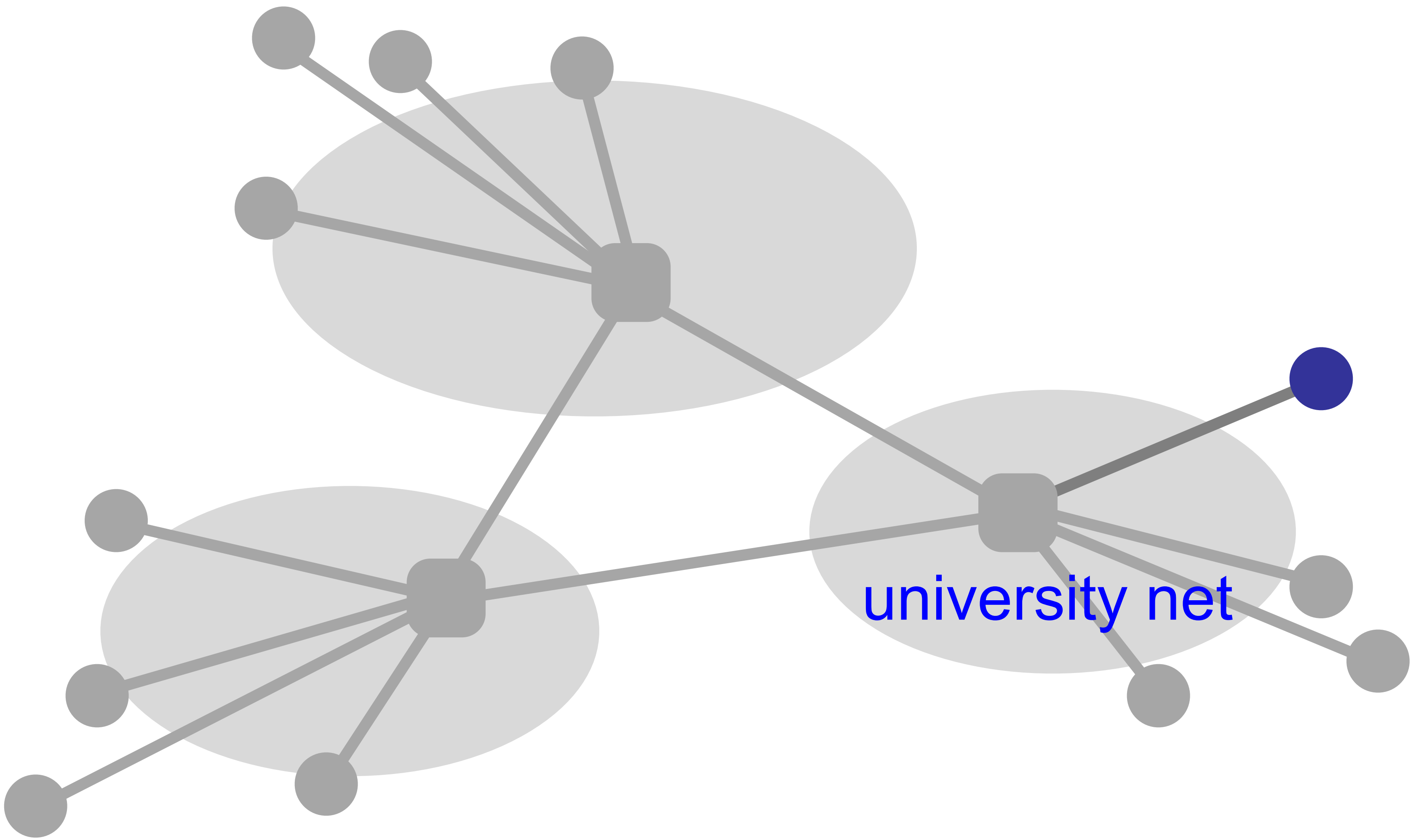
Connecting via cable



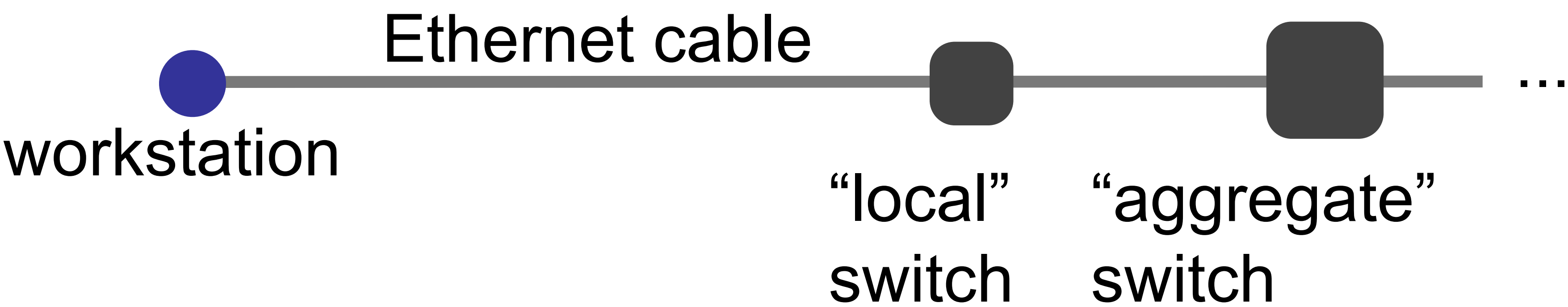
Cable

- 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
…

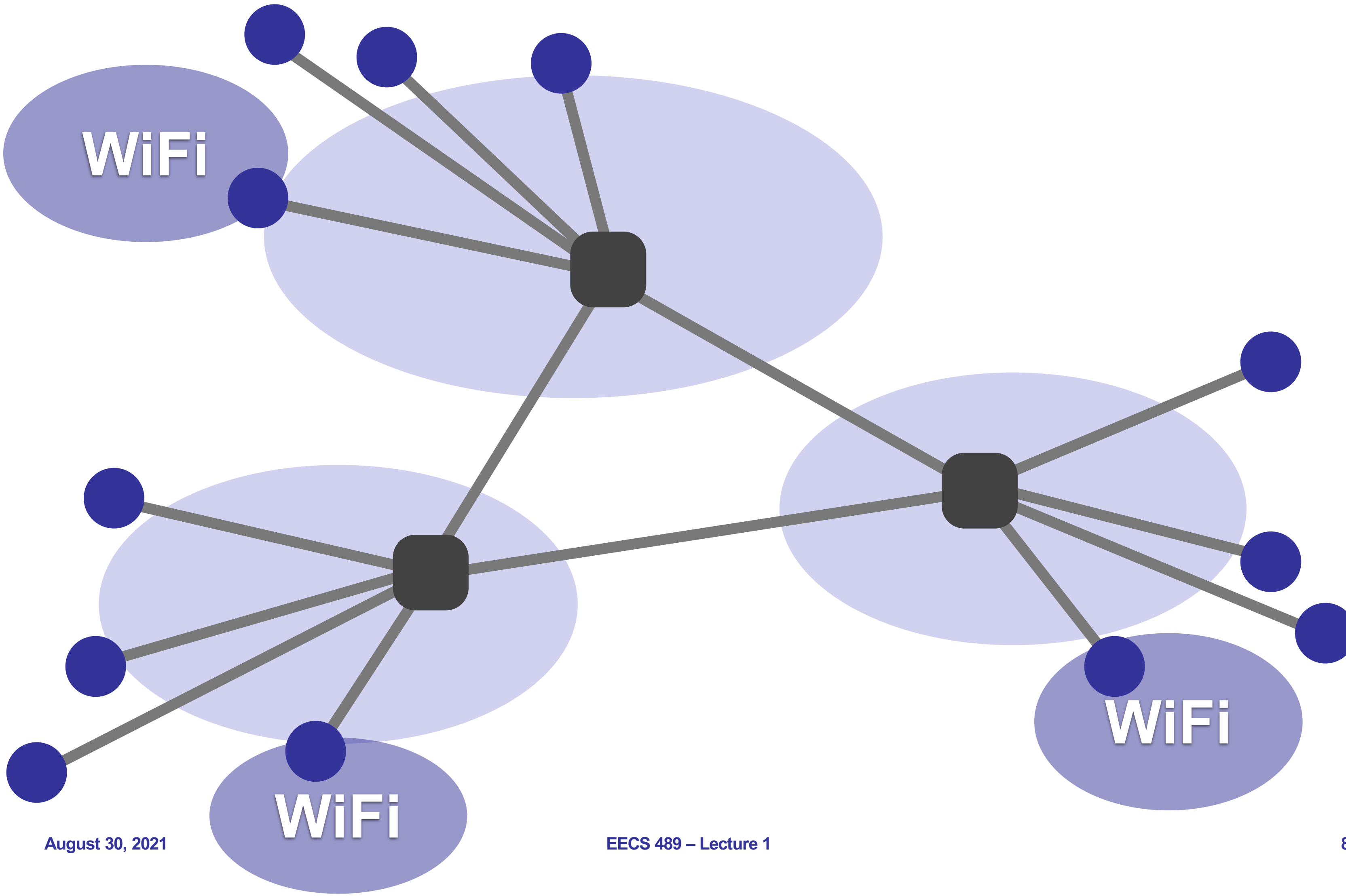
Ethernet

- 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?



MASSIVE Scale

- 4.6 Billion users
- >1.8 Billion websites
- >200 Billion emails sent per day
- >2.5 Billion smartphones
- >2.7 Billion Facebook users
- >1 Billion hours of YouTube watched per day
- Routers that switch 10 Terabits/second
- Links that carry 100 Gigabits/second

Have we found the right solution?

- We don’t really know

- What we do know
  - The early Internet pioneers came up with 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

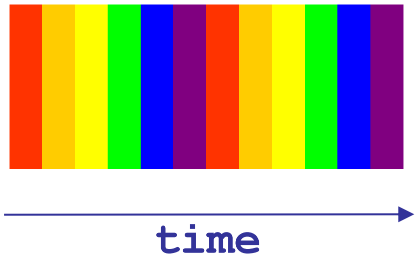
The Internet is a lesson

- 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?

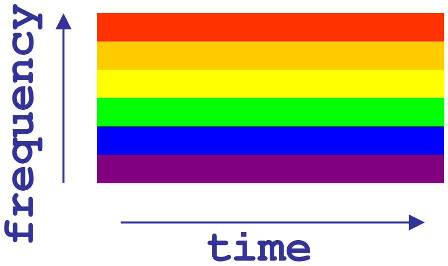
DETAILS ON CIRCUIT SWITCHING

Many kinds of circuits

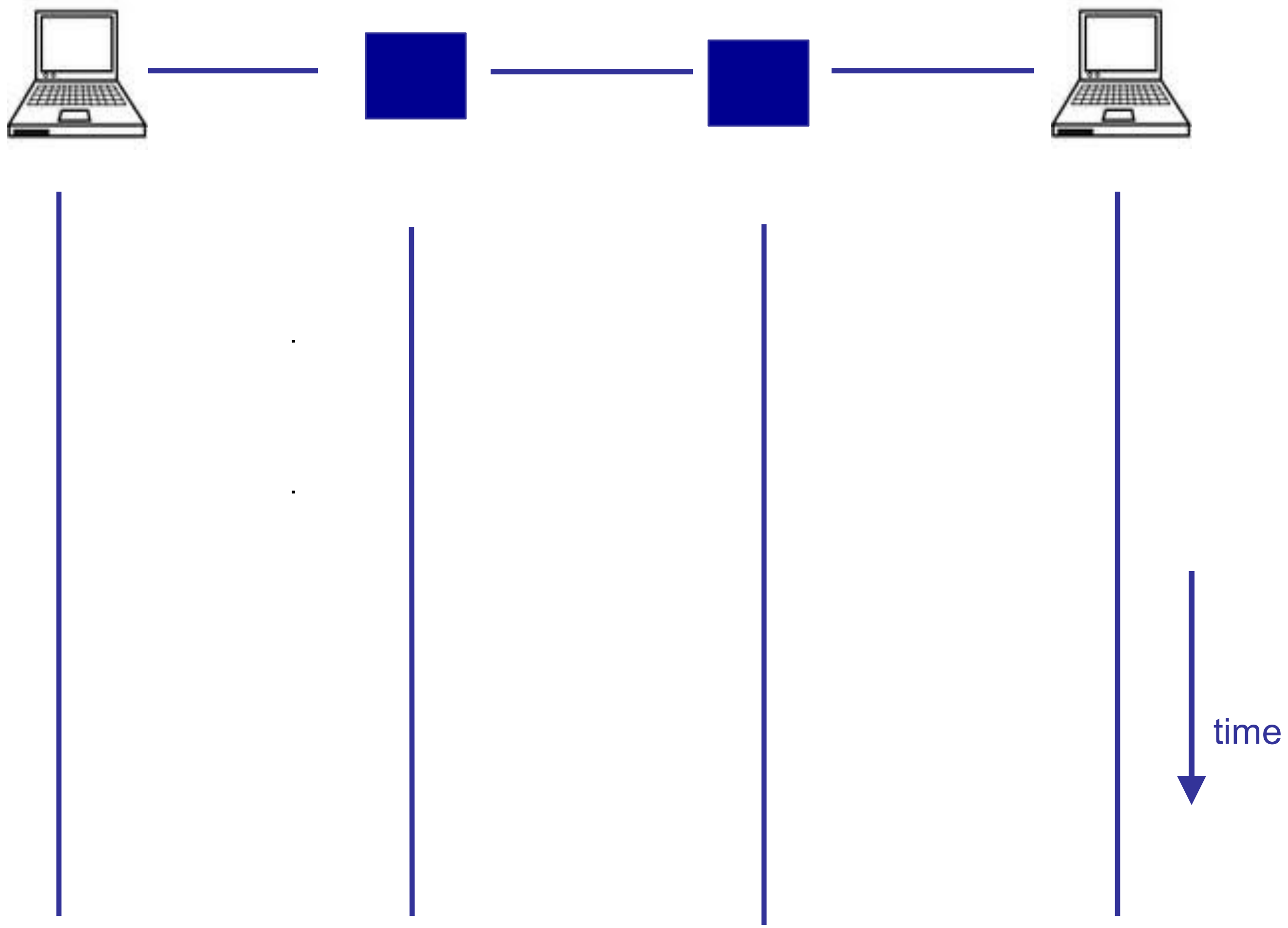
- Time division multiplexing
  - divide time in time slots
  - separate time slot per circuit



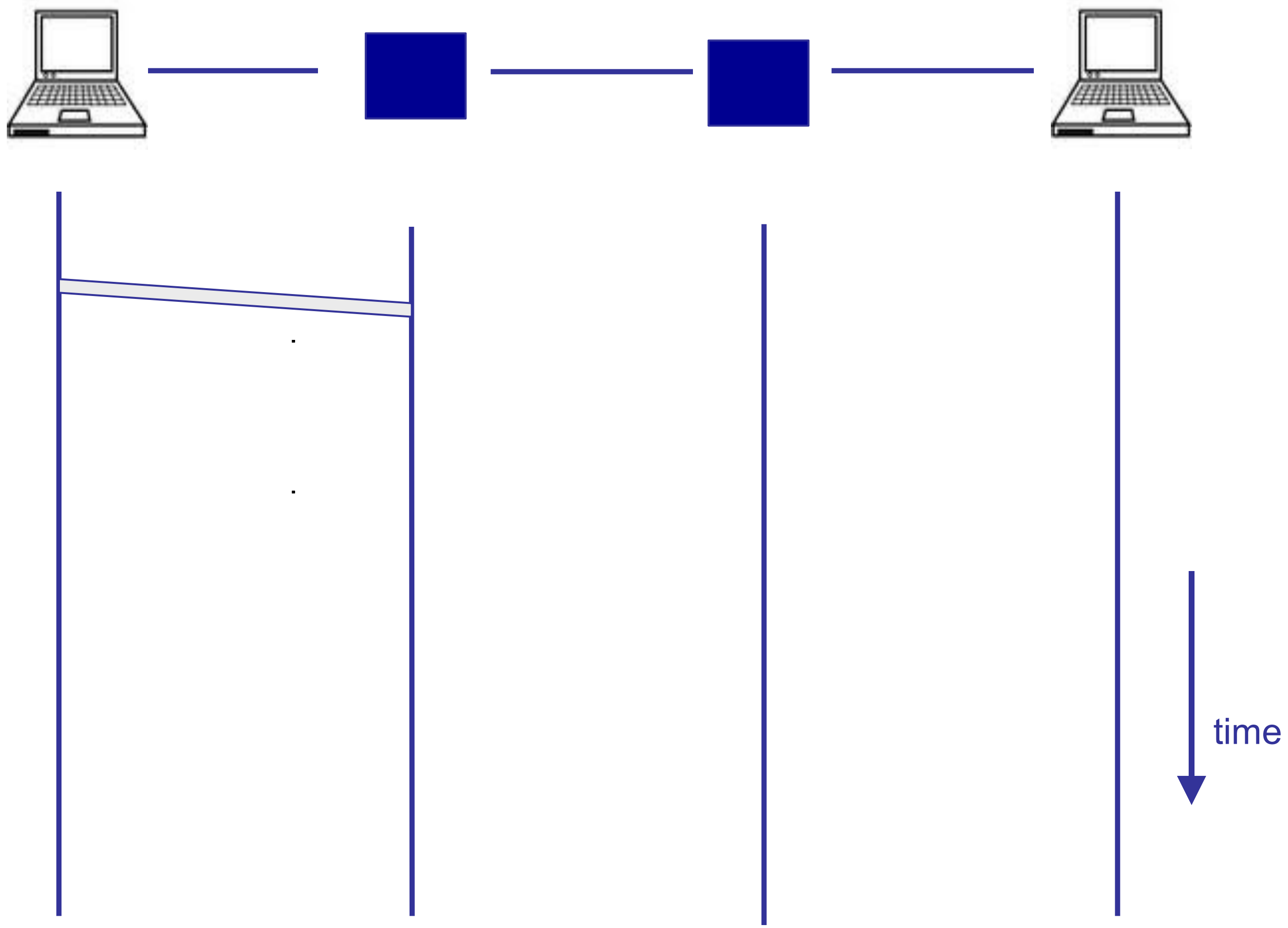
- Frequency division multiplexing
  - divide frequency spectrum in frequency bands
  - separate frequency band per circuit



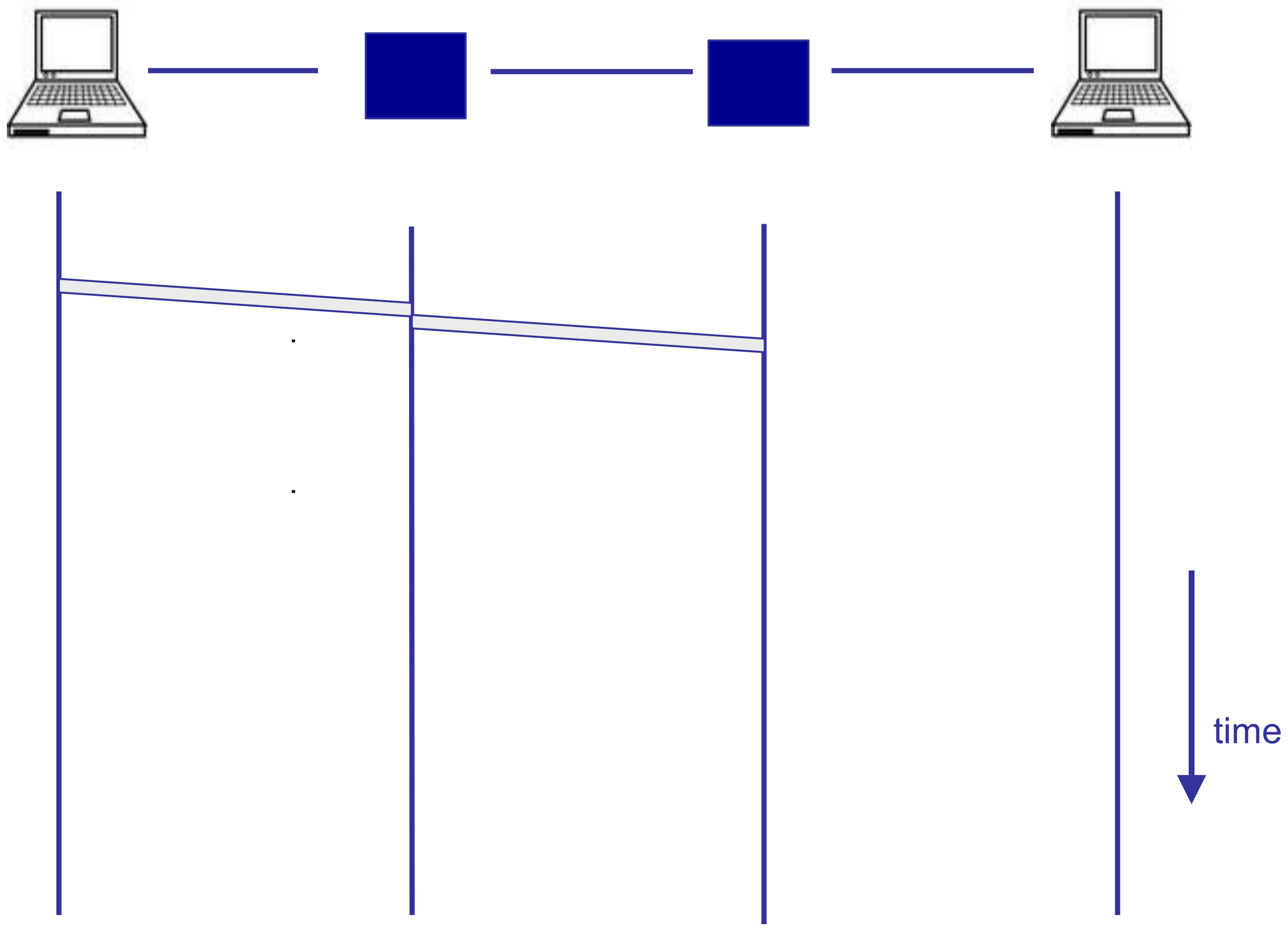
Timing in circuit switching



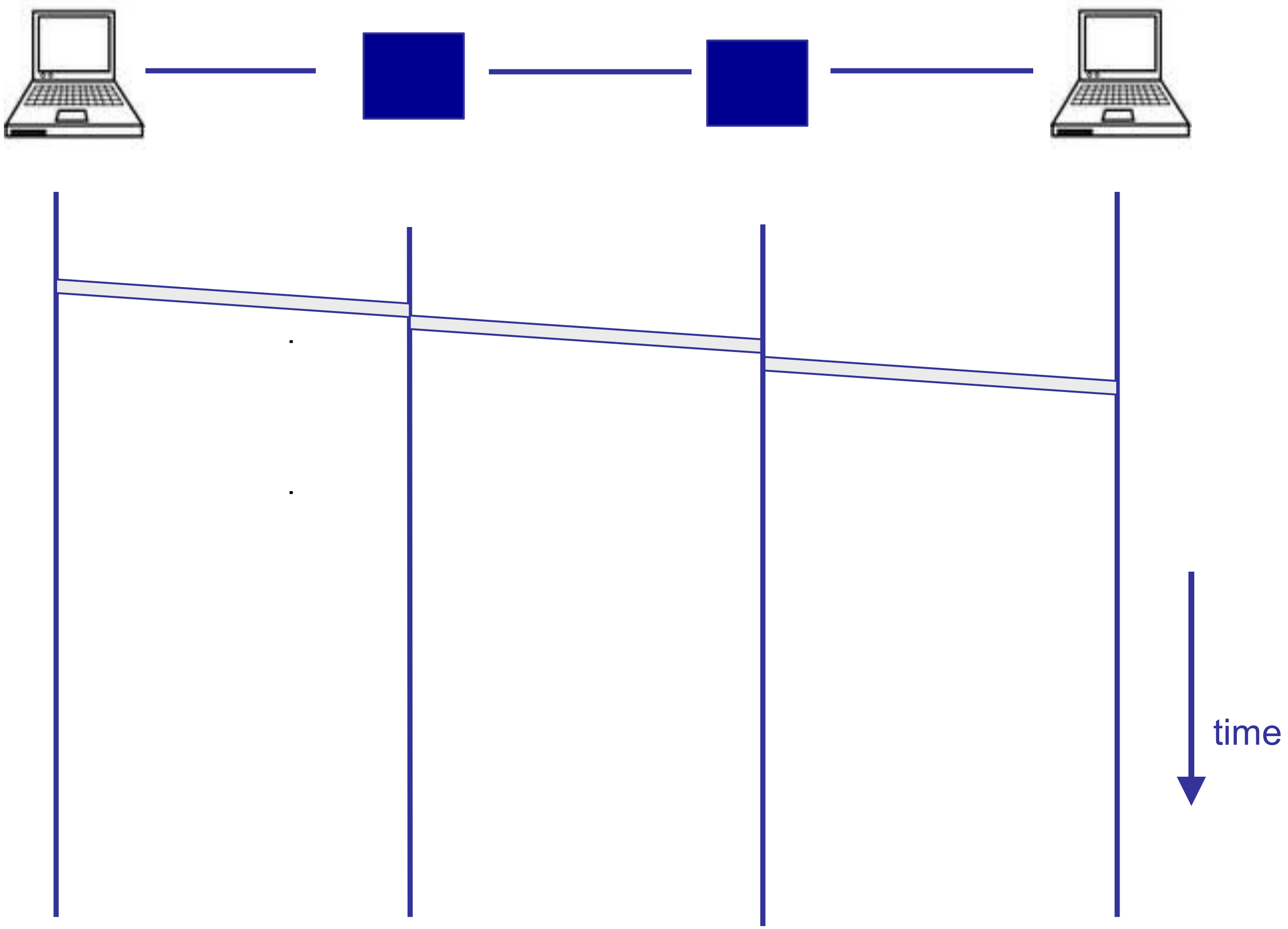
Timing in circuit switching



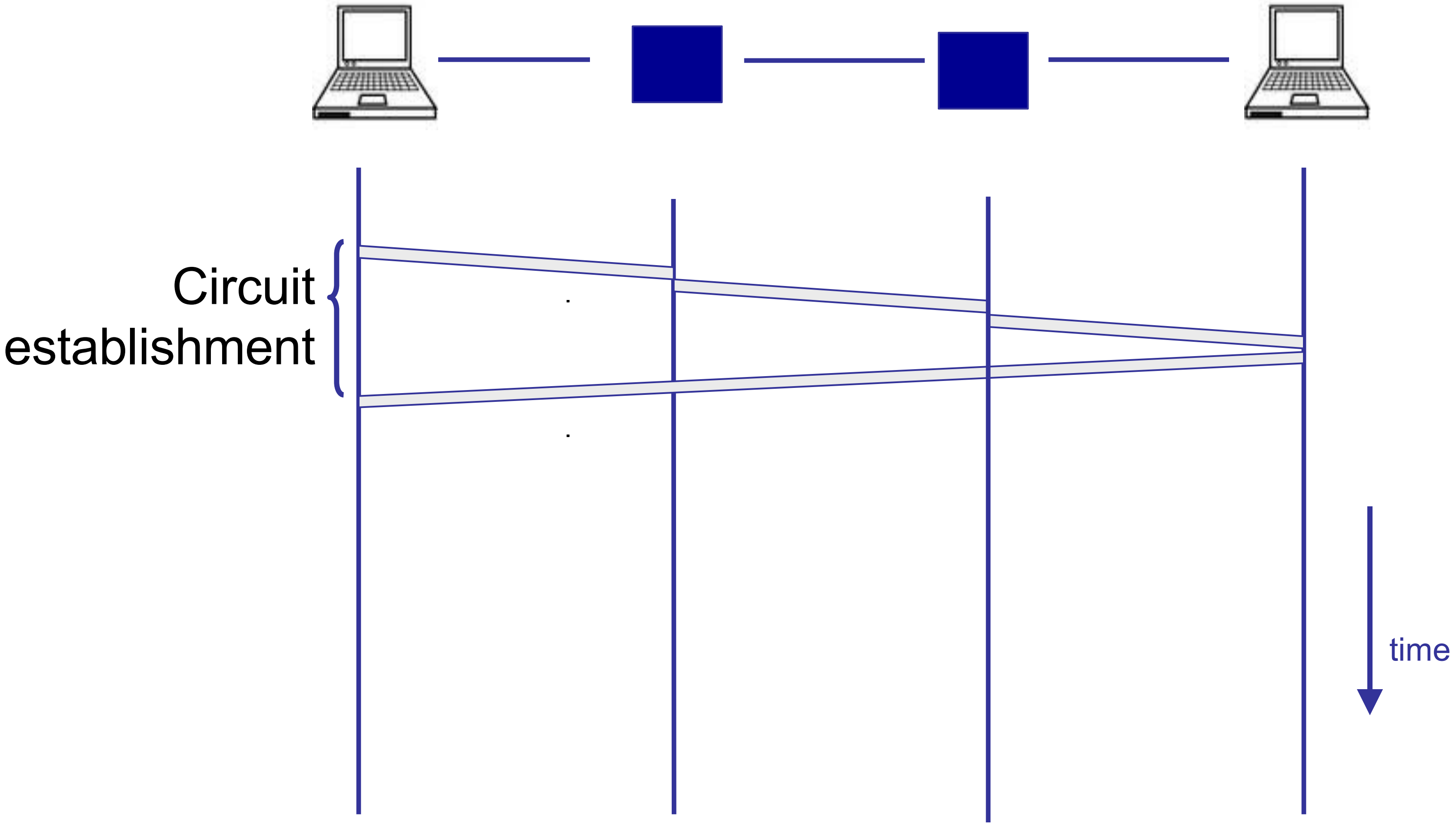
Timing in circuit switching



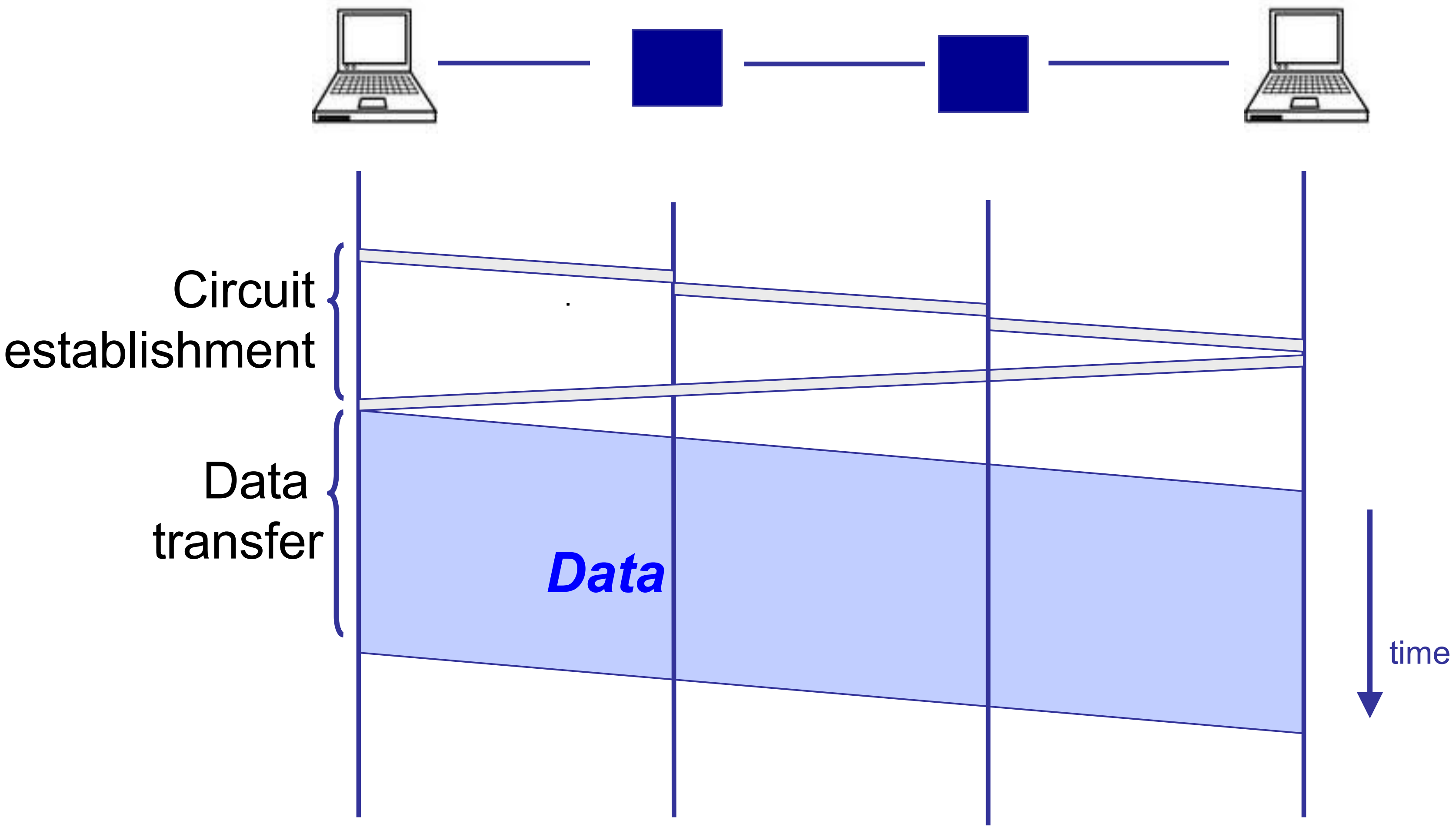
Timing in circuit switching



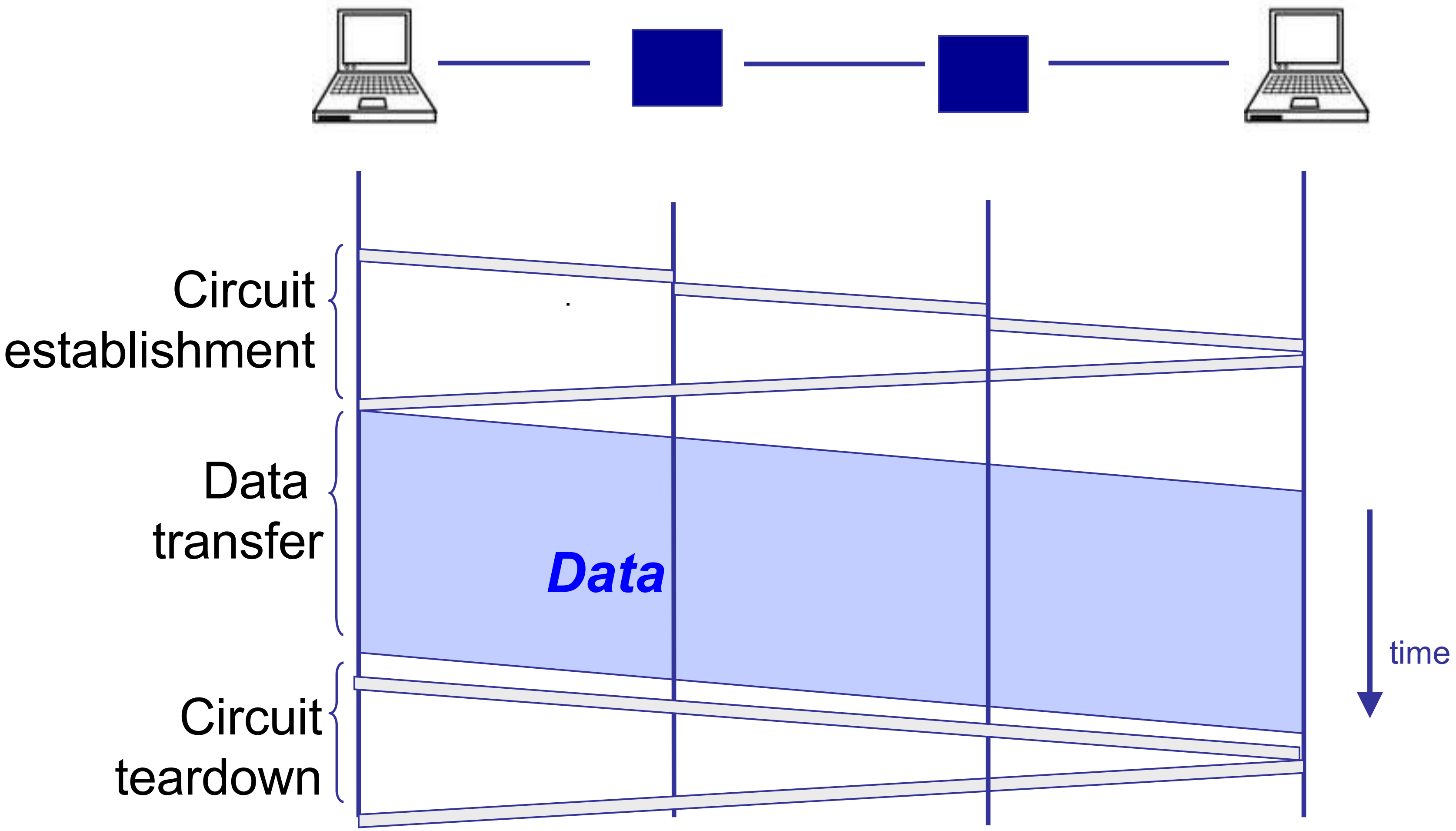
Timing in circuit switching



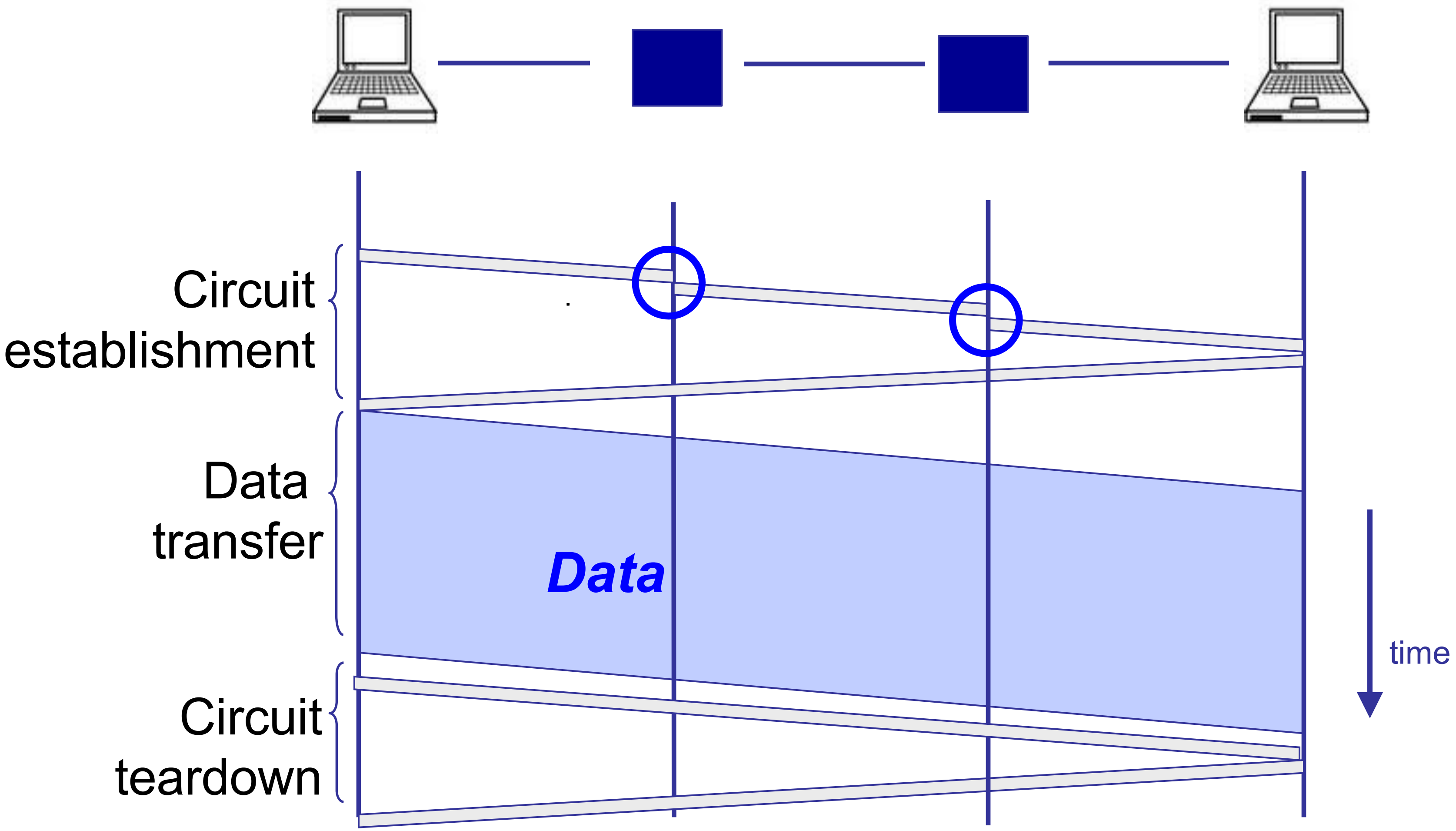
Timing in circuit switching



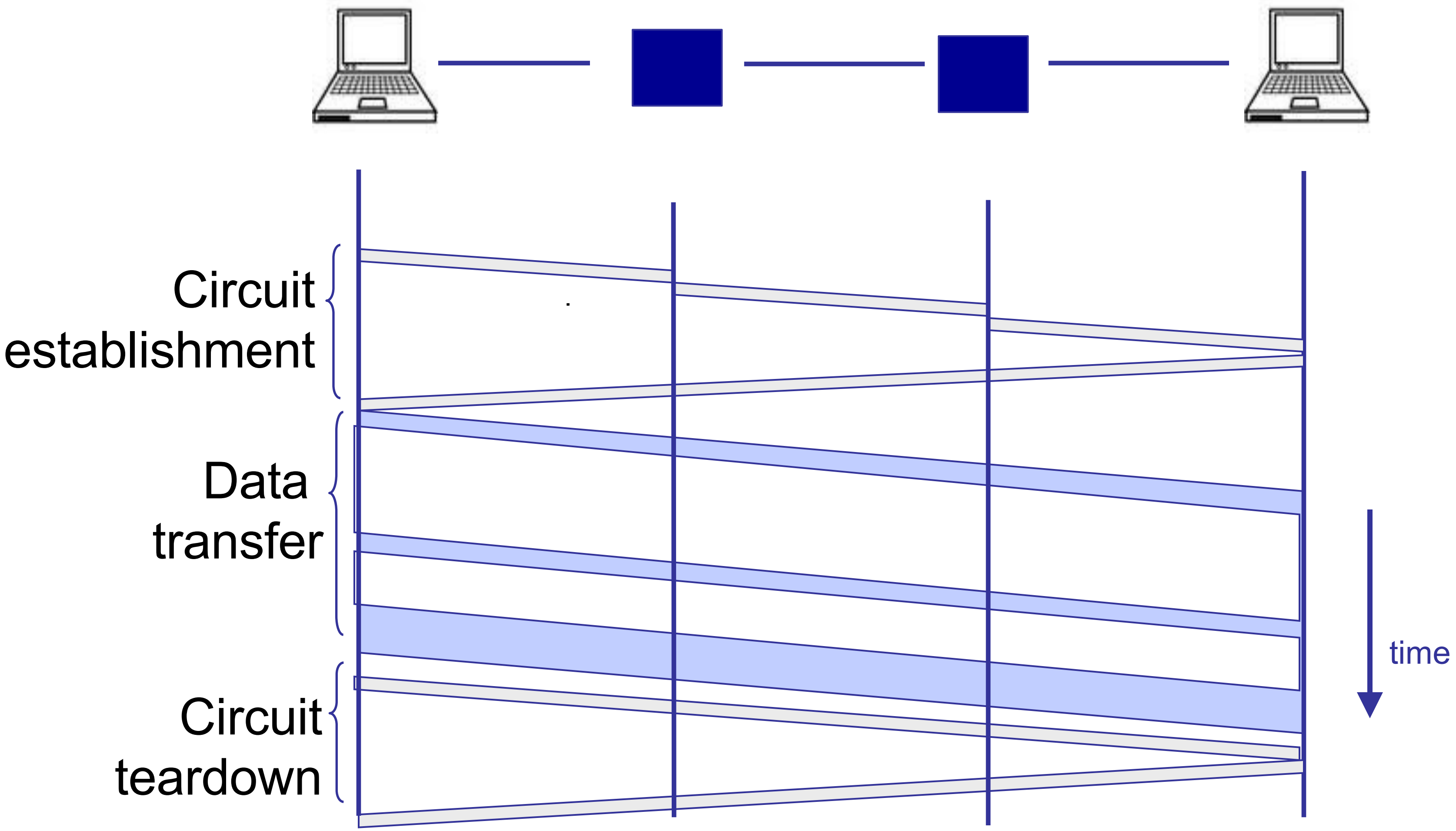
Timing in circuit switching



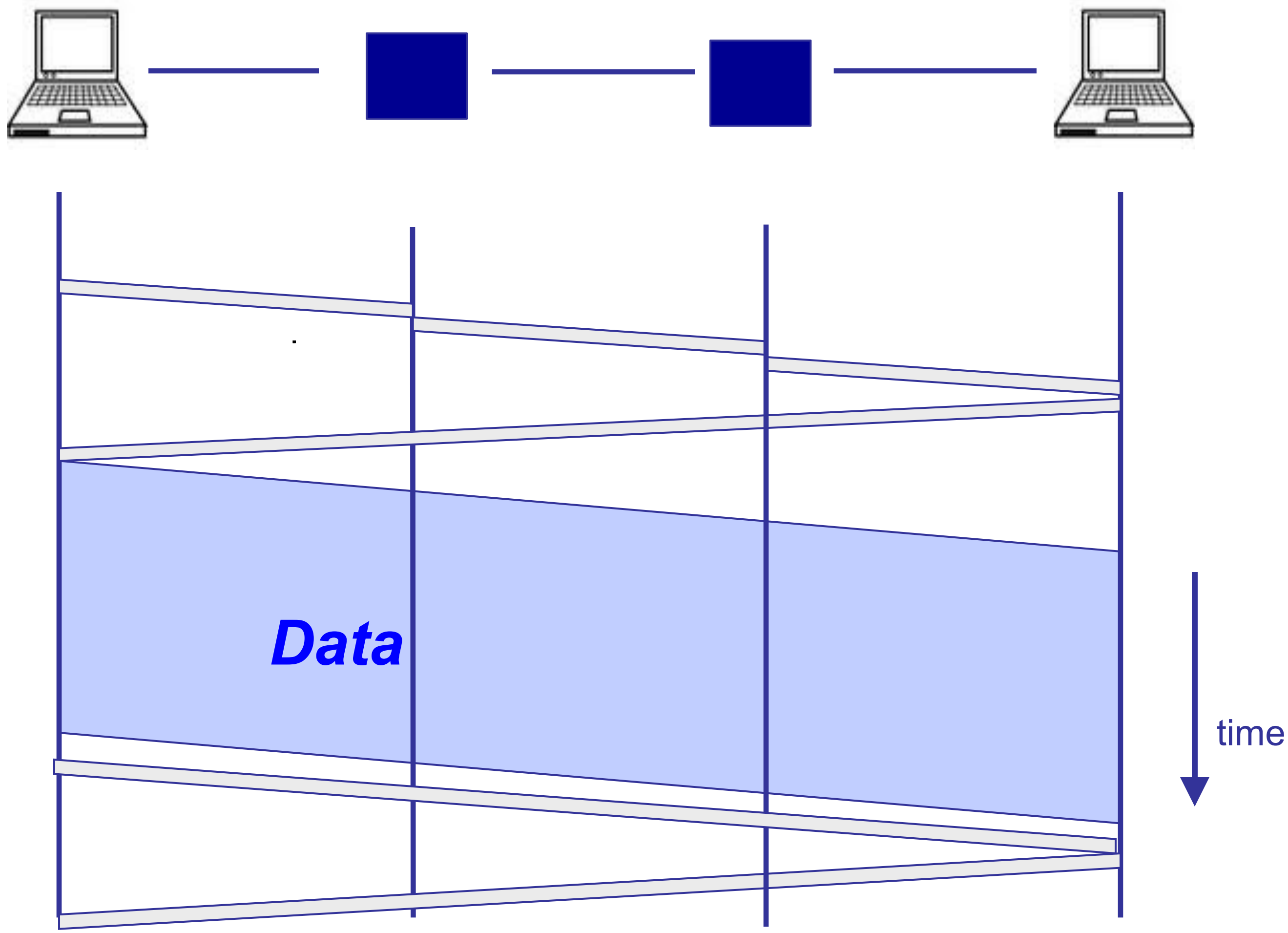
Why the delays?



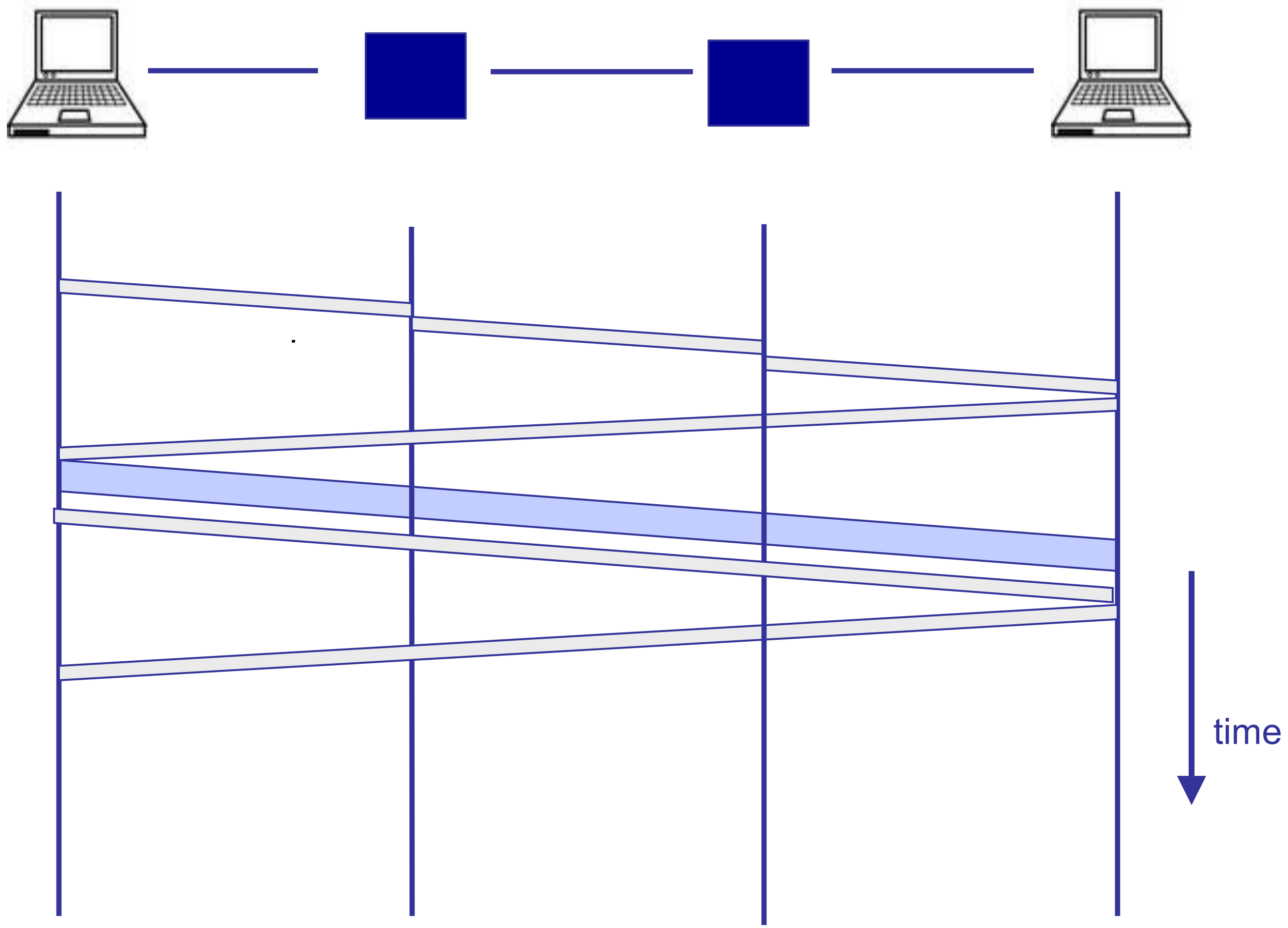
Timing in circuit switching



Timing in circuit switching



Timing in circuit switching



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 $\times$ 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)