PADERBORN UNIVERSITY

Computer Networks (WS23/24)

L1: Introduction

Prof. Dr. Lin Wang
Computer Networks Group (PBNet)
Department of Computer Science
Paderborn University

Materials inspired by Laurent Vanbever and Shyam Gollakota

About me

Full Professor at Paderborn University: since November 1, 2023

- Head of the **Computer Networks Group**
- Goal: making networked systems more **scalable** and **sustainable**

https://linwang.info/

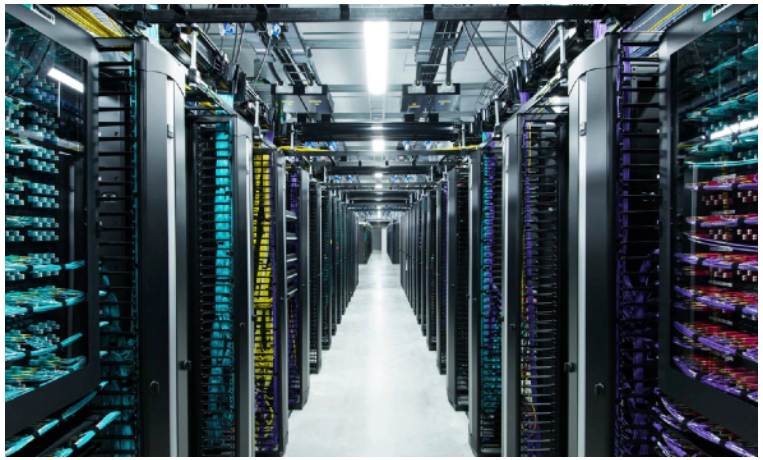
Assistant Professor at Vrije Universiteit Amsterdam: 2018 - 2023

- Led a team in the Computer Systems section

Previous positions

- TU Darmstadt (AYI, 2016 - 2018), SnT Luxembourg (RA, 2015 - 2016), ICT-CAS (PhD, 2012 - 2015), IMDEA Networks Institute (guest, 2012 - 2014), University of Oregon (guest, 2018)

Research @ PBNet



Data center in-network computing

Battery-free computing and networking

Supported by DFG Google intel NWO

People @ PBNet

Prof. Dr. Lin Wang
Head

Dr. Vinod Nigade
Postdoc

Gaosheng Liu
PhD

George Karlos
PhD

Guilherme Apostolo
PhD

Kamran Razavi
PhD

VU Amsterdam

TU Darmstadt

Looking for Postdocs, PhDs, and student assistants...

Course structure

Lectures

- **Two lectures** (Tuesdays and Fridays) per week, two hours each

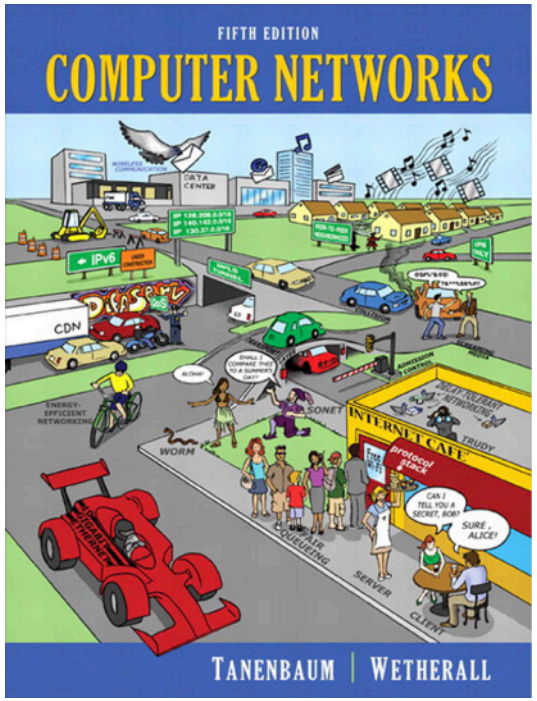
Exercises

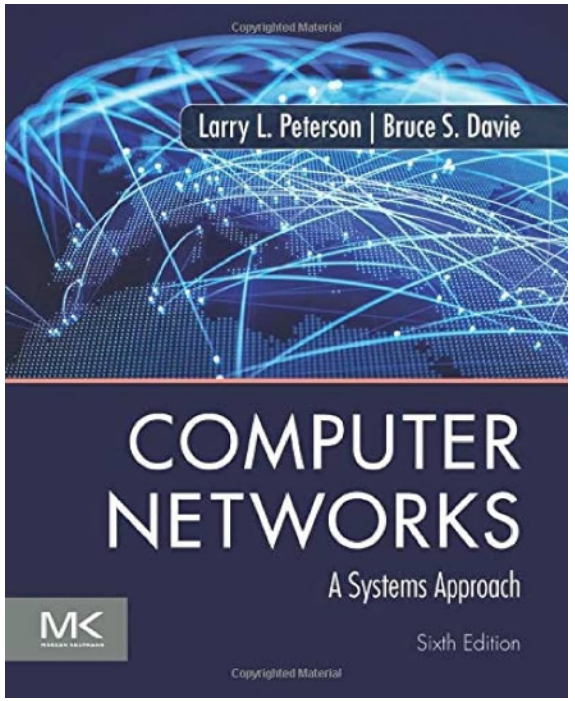
- **Two exercise sessions** per week, three hours each
- Exercises are organized in **two groups**; please attend the sessions accordingly

Projects (TBA)

- Two project assignments
- Implementation in C/C++, and/or Python

Textbooks





https://www.amazon.de/-/en/Andrew-S-Tanenbaum/dp/0132126958
https://book.systemsapproach.org/

Assessment

Exam

- 100% of the final grade
- Closed-book, closed-note, closed-laptop, written exam (90 mins, February 5, 2024)

Exercises are not graded

- But critically important for your exam preparation

Projects

- Bonus grades: passing a project bumps up a level of your final grade
- Only if you pass the final exam

Administrivia

Office hours

- Available by appointment
- Drop me an email at lin.wang@upb.de with title "[CN-WS23/24] Office hours"

Course material

- All teaching material will be released on PANDA
- Slides will be released (hopefully) right before each lecture
- Exercise questions will be released few days before the exercise sesssion

Integrity

Zero tolerance: You should never plagiarize anything in this course (and other courses)

What are considered plagiarism?

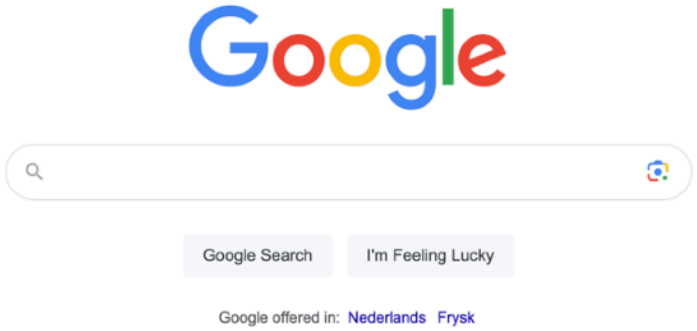
- Copy (part of) a solution from another team or from the Internet
- Buy a solution from any source
- Copy + make changes to any of the above

What happens if someone commits plagiarism

- The case will be reported to the examination committee
- It is up to them to decide on disciplinary actions

Computer Networks

What really happens when you visit google.com?



Can you name or even explain some of the terminologies behind it?

Course goals

After taking this course, you will be able to…

- Explain the basic principles of computer networks and the Internet
- Describe the layered architecture and explain the essential function(s) in each layer
- Apply basic information theory and network protocol specifications to calculate network properties
- Implement network protocols to build own customized networks and networked applications

Non-goals: preparation for Cisco certification, etc., althought relevant

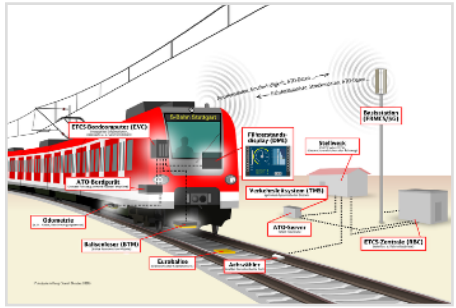
Societal impact

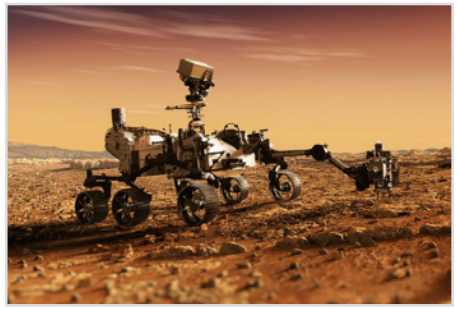
Information source **Online commerce** **Online workspace** **Social media**

The Internet is behind virtuall every service of our modern daily life

Societal impact



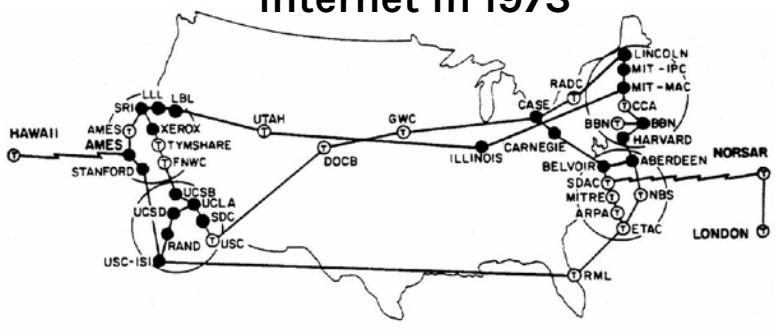


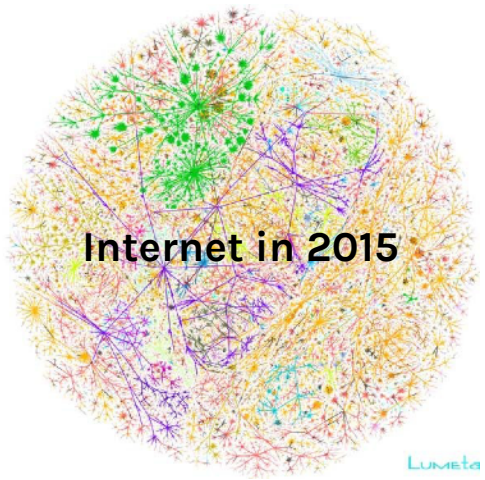



Network innovations can change the world in many different ways

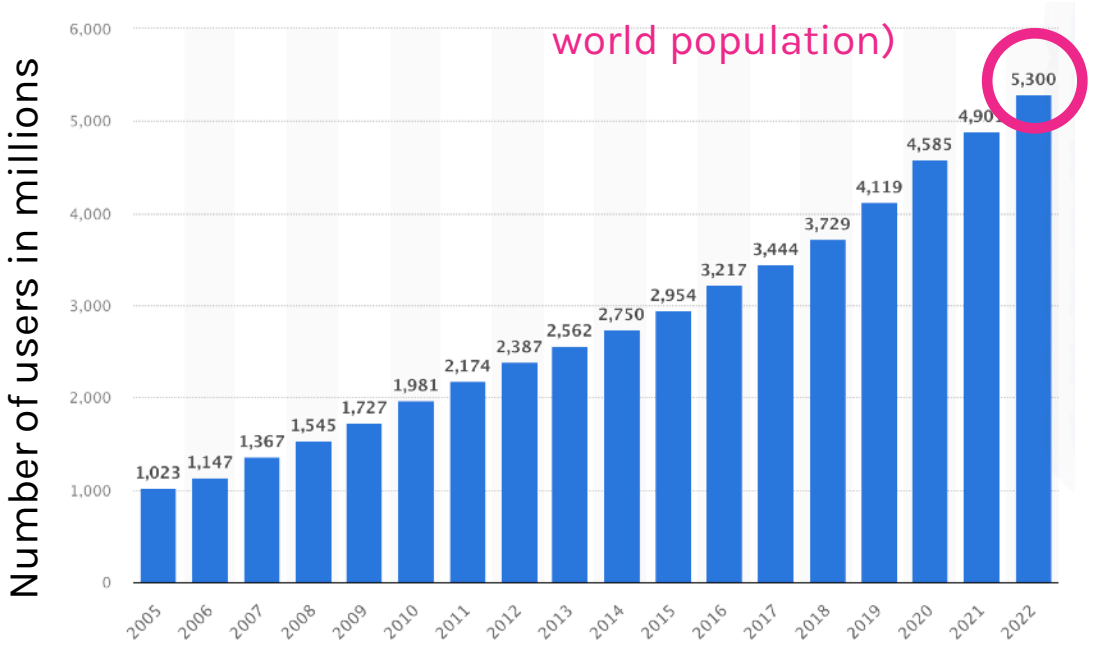
Internet growth

Internet in 1973





5.3 billion users (~65.7% of world population)



https://www.statista.com/statistics/273018/number-of-internet-users-worldwide/

Today's Internet

~30 billion

Estimated number of Internet-connected devices in 2023

~13 exabytes

Estimated **daily** global IP traffic in 2022

How large is one Exabyte?

1 Kilobyte

X3

1 Gigabyte

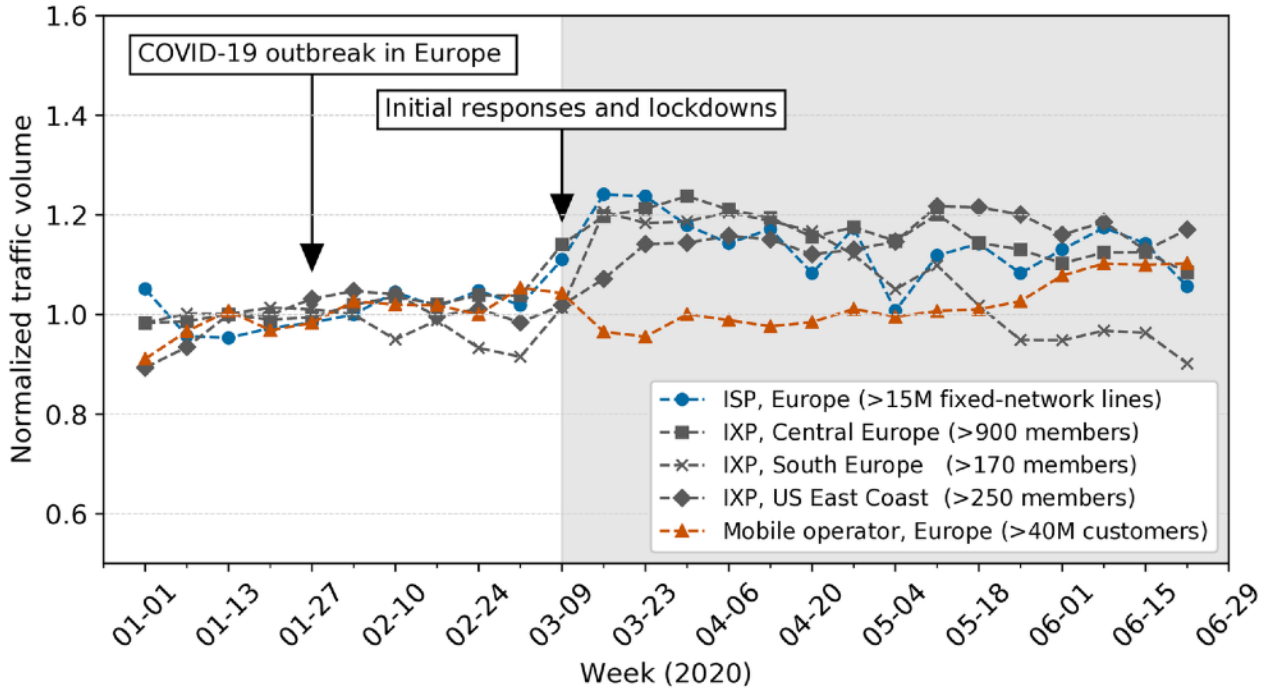
X2

1 Exabyte

Dominant traffic on the Internet

~82%
Internet
traffic

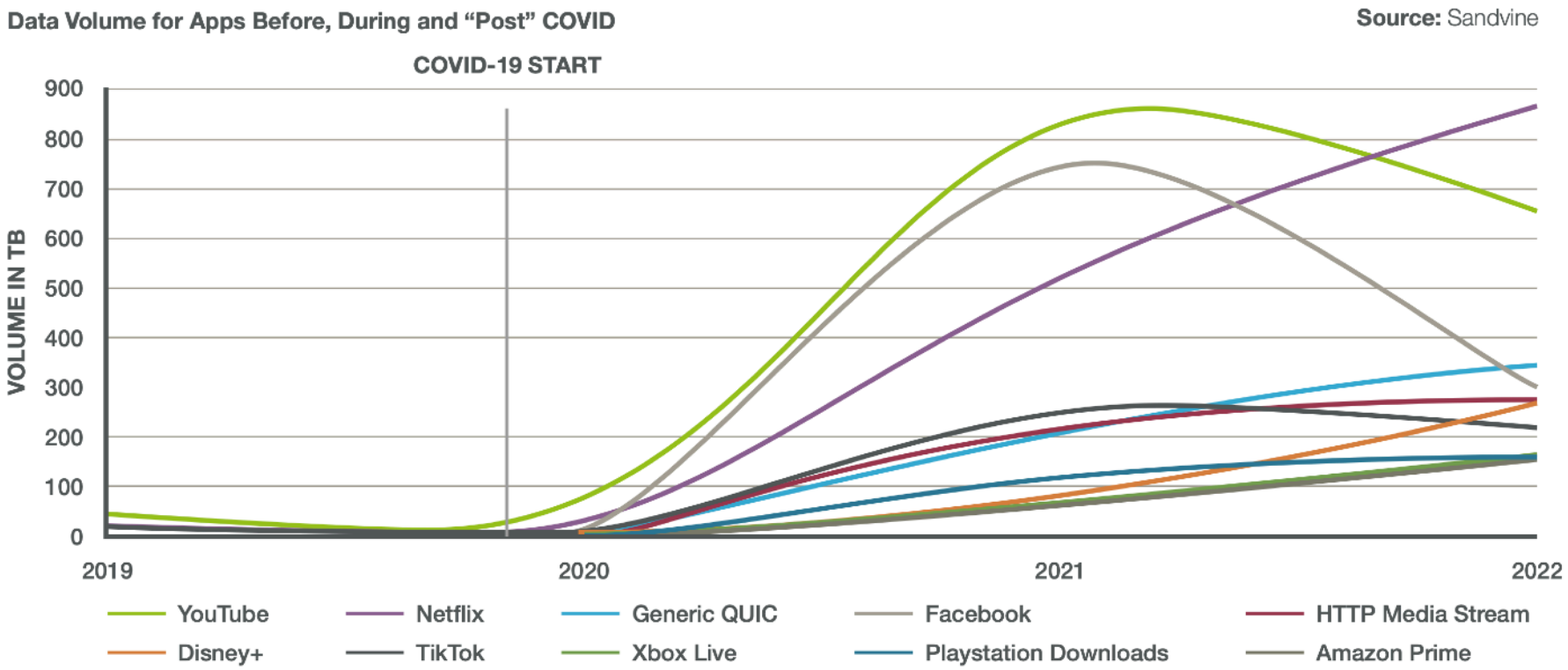
Internet changes during the pandemic



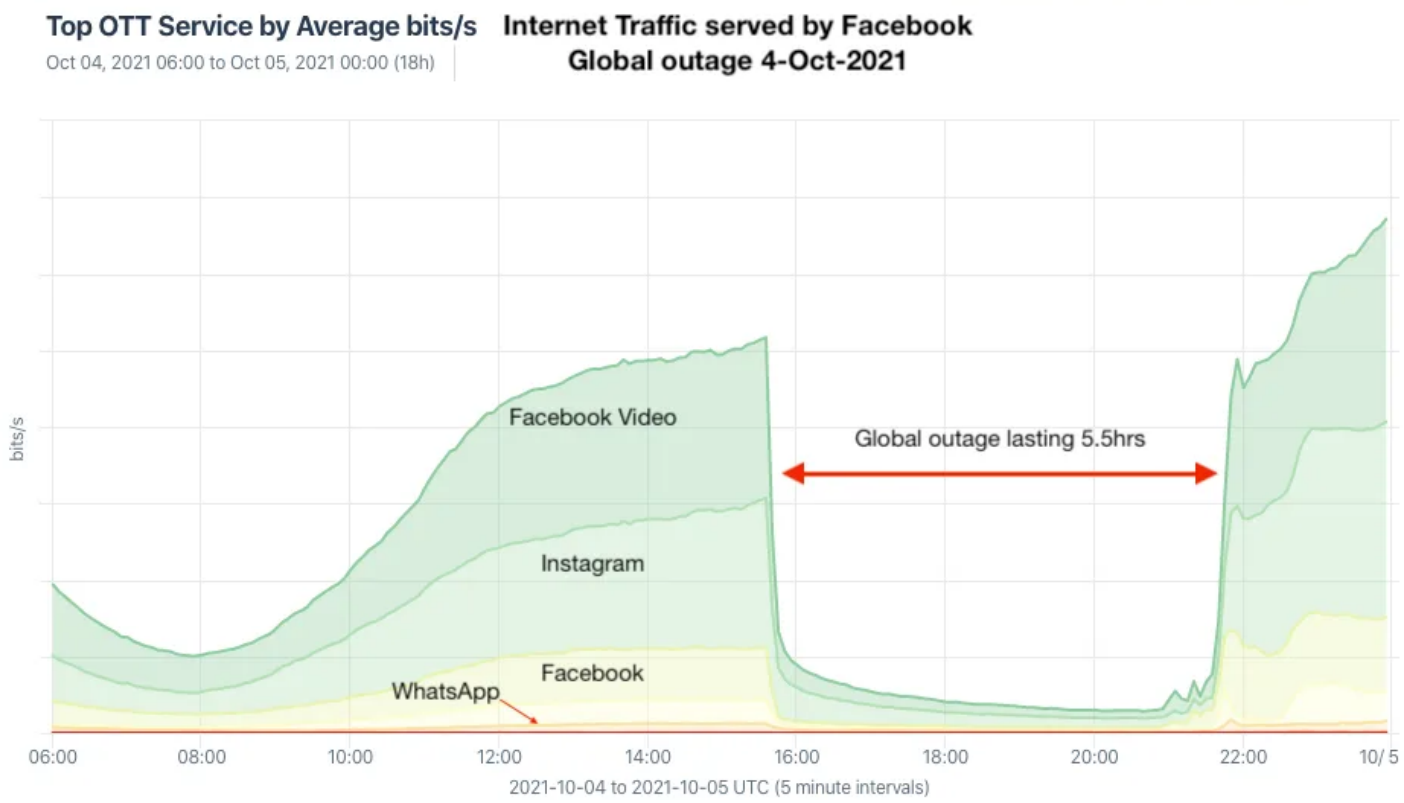
Following the lockdown in March 2020, a traffic increase by **15-20%** was seen on (wired) networks.

https://labs.ripe.net/author/oliver_gasser/the-lockdown-effect-implications-of-the-covid-19-pandemic-on-internet-traffic/

Internet changes during the pandemic

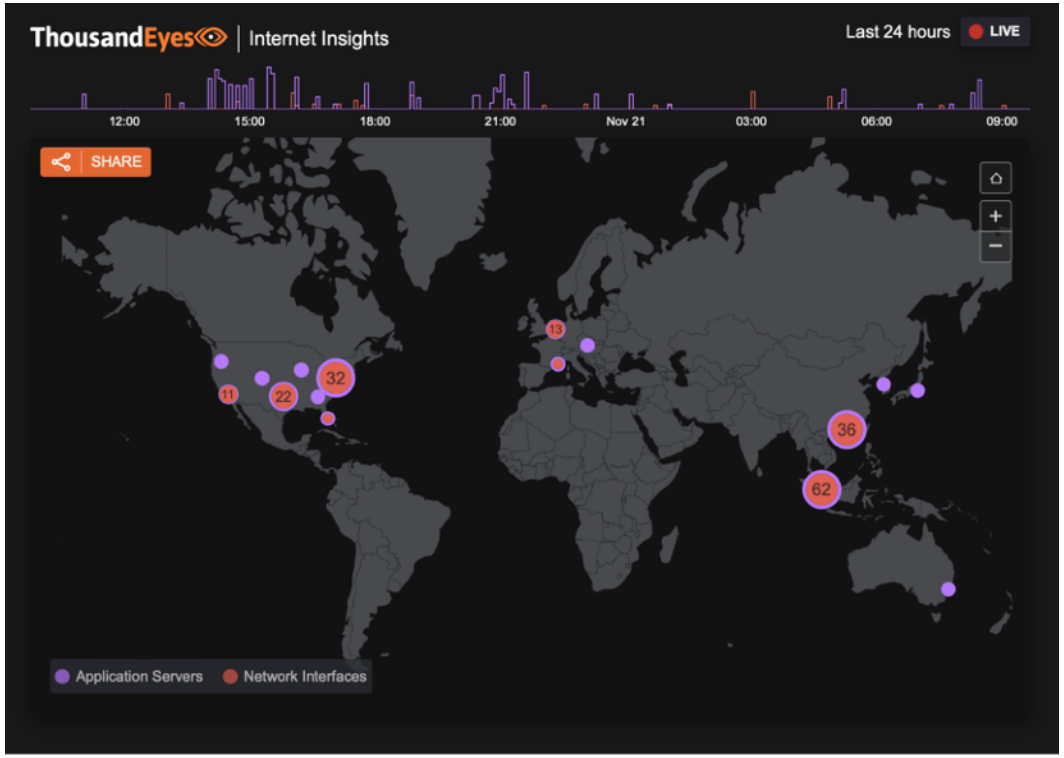


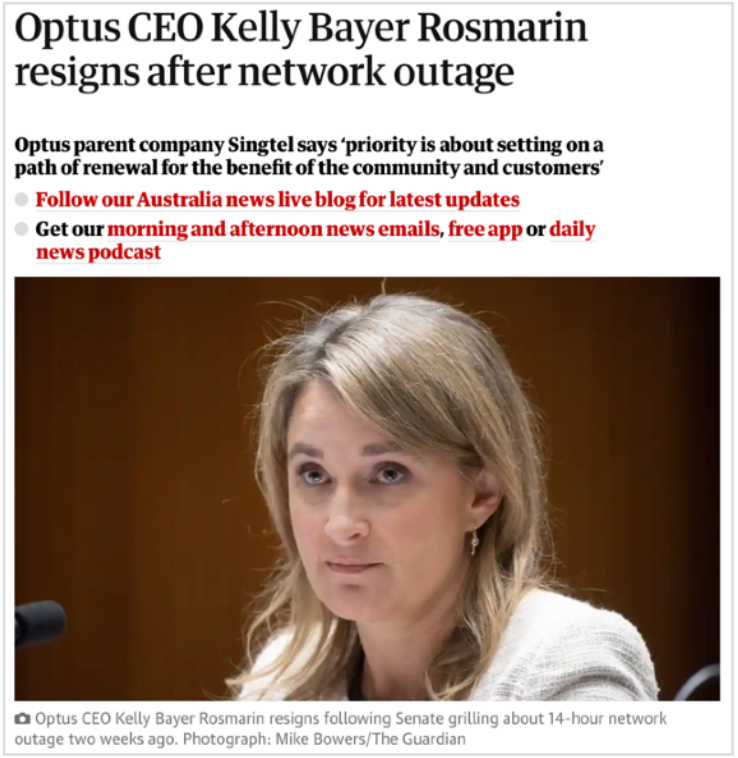
Internet is fragile



https://en.wikipedia.org/wiki/2021_Facebook_outage

Internet outages are normal





Optus CEO Kelly Bayer Rosmarin resigns after network outage

Optus parent company Singtel says 'priority is about setting on a path of renewal for the benefit of the community and customers'

- Follow our Australia news live blog for latest updates
- Get our morning and afternoon news emails, free app or daily news podcast

Optus CEO Kelly Bayer Rosmarin resigns following Senate grilling about 14-hour network outage two weeks ago. Photograph: Mike Bowers/The Guardian

https://www.thousandeyes.com/outages/

"Human factors are responsible for 50% to 80% of network outages"

Juniper Networks, What's Behind Network Downtime?, 2008

Networking Basics

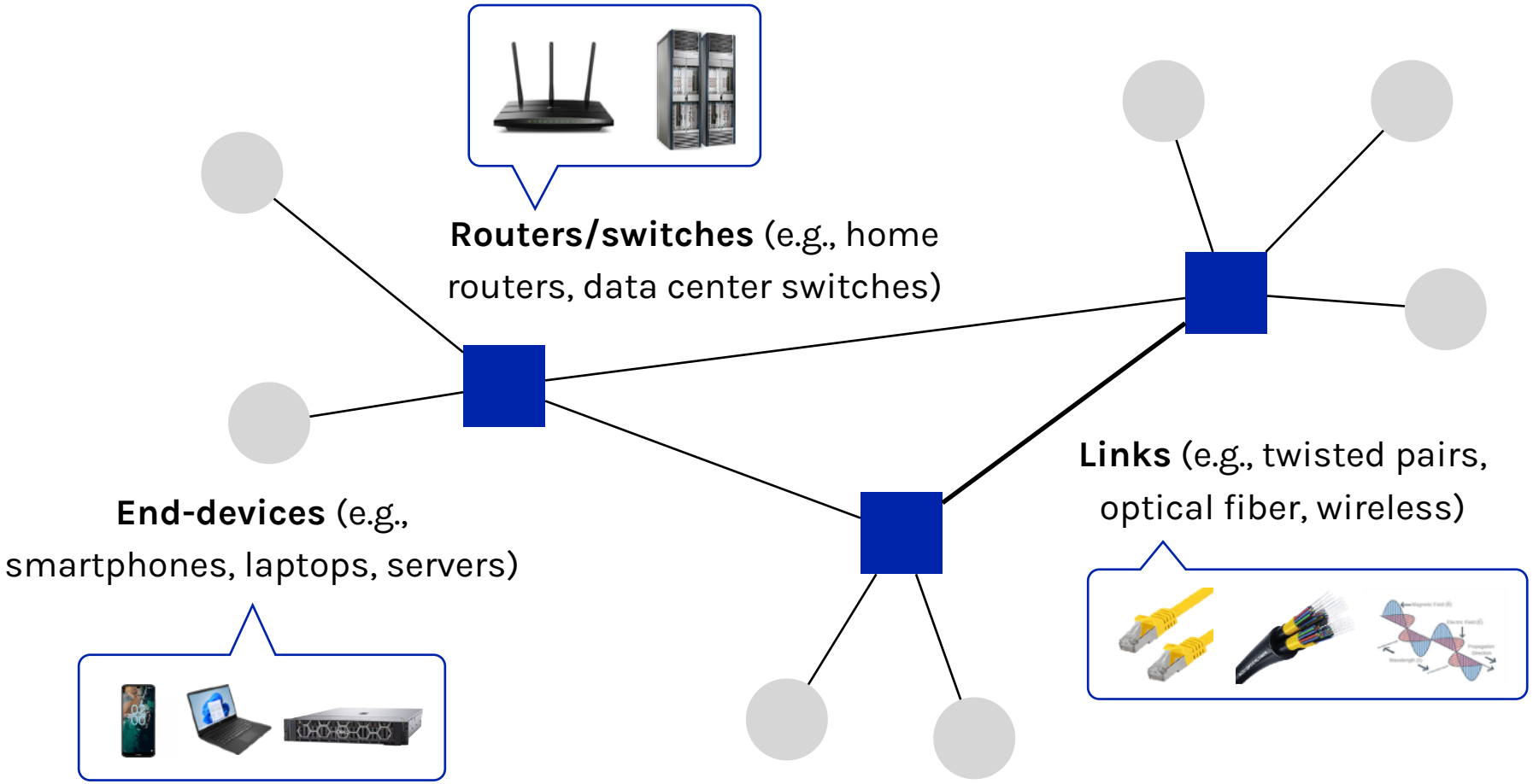
Key questions to answer

1. What is a network made of?
2. How the network is shared?
3. How is it organized?
4. How does communication happen?
5. How do we characterize it?

Key questions to answer

1. **What is a network made of?**
2. How the network is shared?
3. How is it organized?
4. How does communication happen?
5. How do we characterize it?

Basic network components



Key questions to answer

1. What is a network made of?
2. **How the network is shared?**
3. How is it organized?
4. How does communication happen?
5. How do we characterize it?

Requirements for the network topology

Tolerate failures

- More than one path should exist between nodes

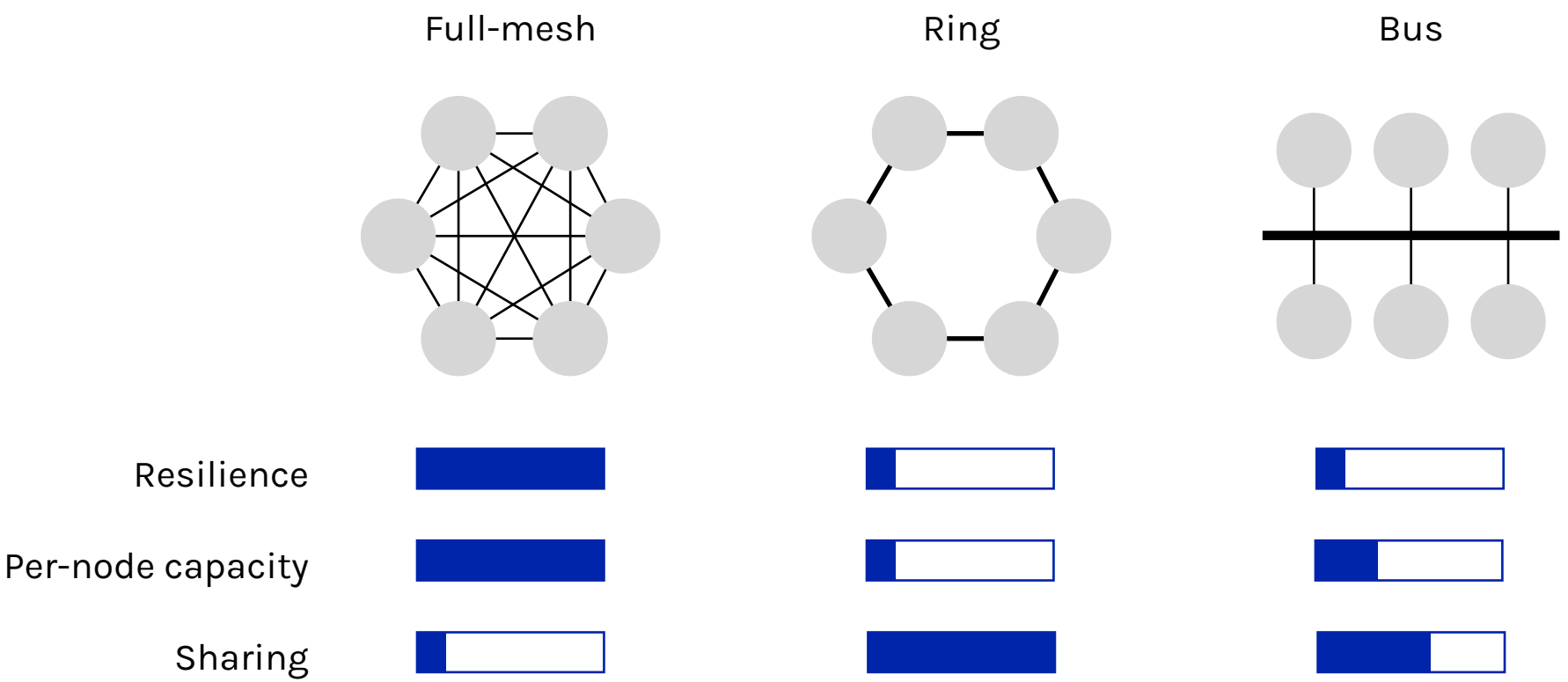
Allow sharing to be feasible and cost-effective

- Number of links should not be too high

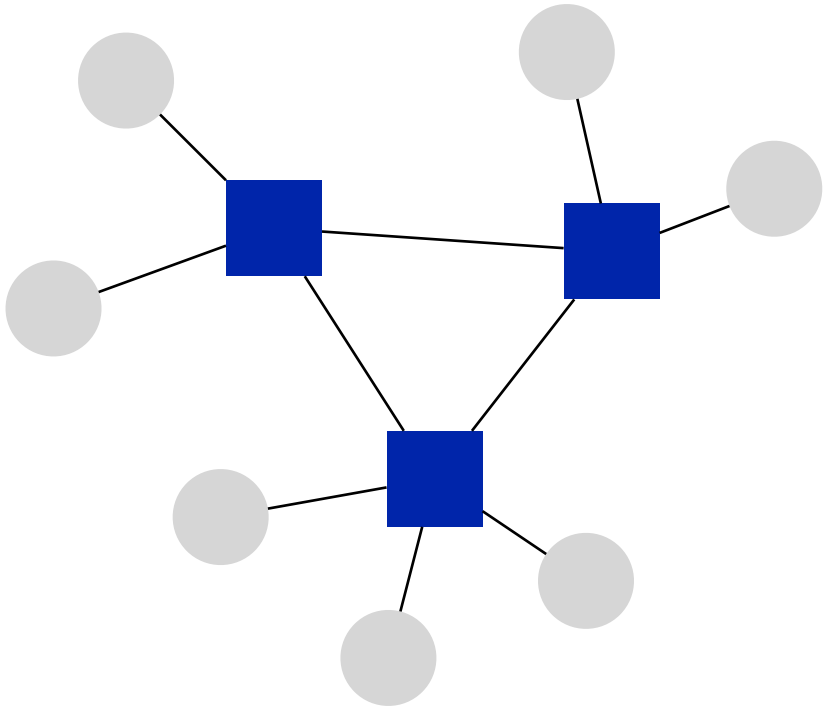
Provide ample capacity

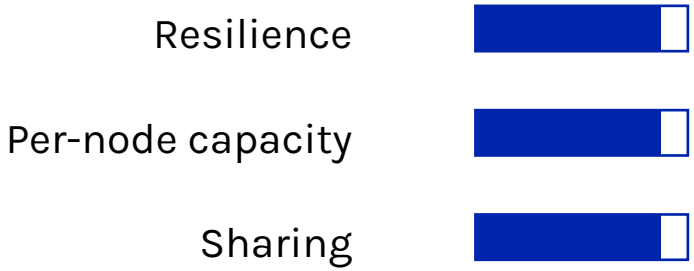
- Number of links should not be too low

Different topology designs



Switched networks

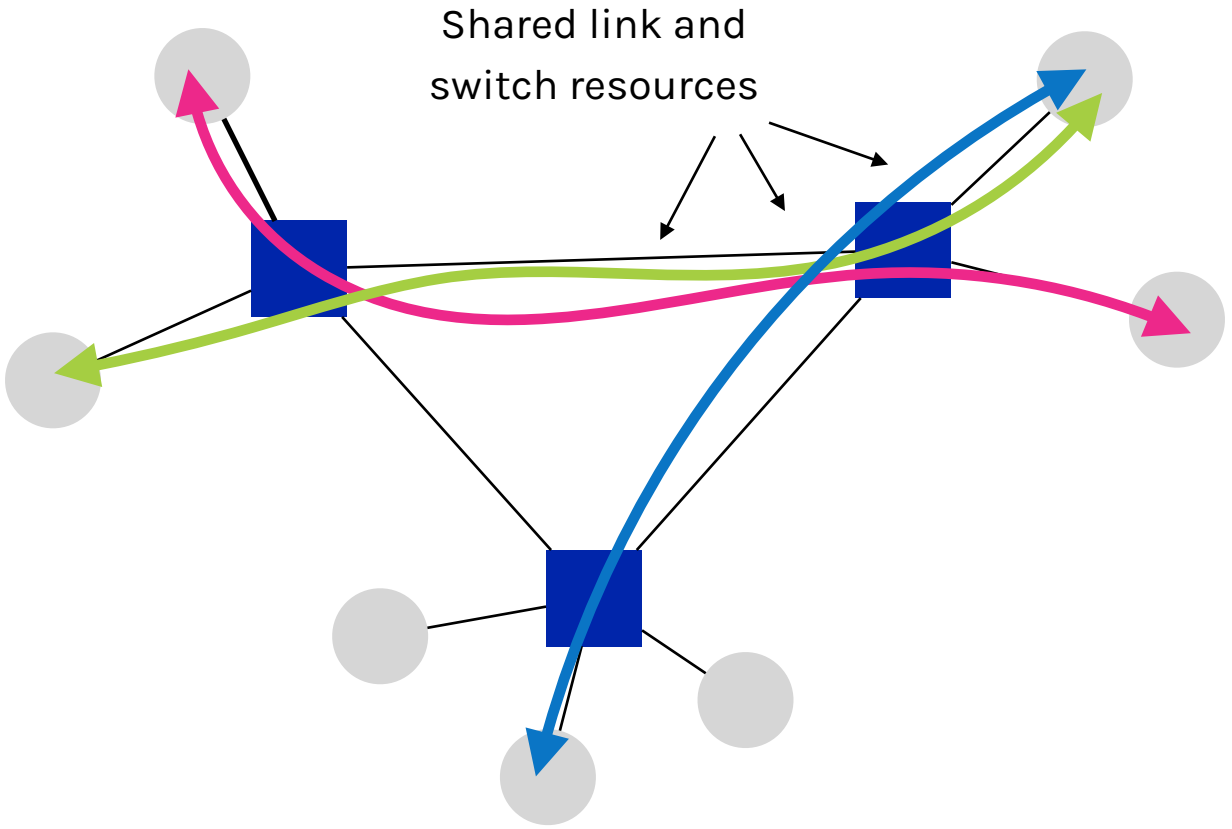




Pro: sharing the per-node capacity can be adapted to fit the network needs

Con: require special devices to perform: forwarding, routing, resource allocation

Sharing on switched networks



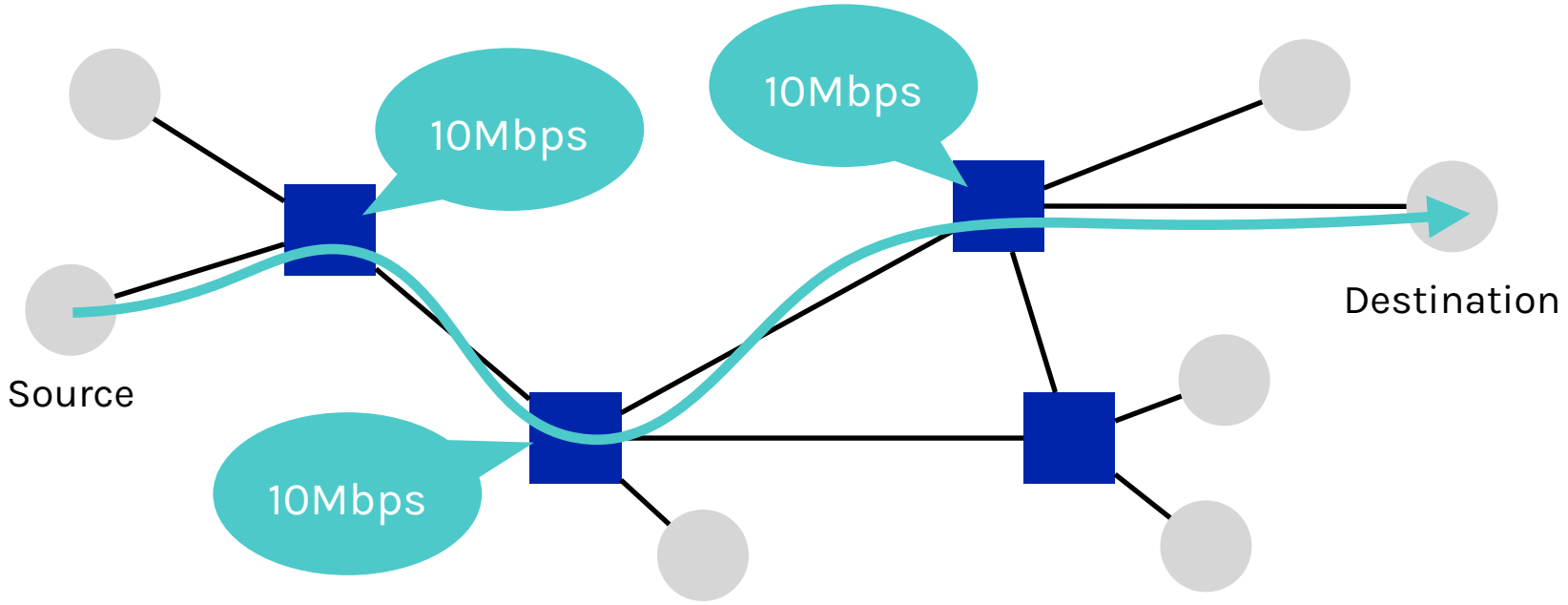
Two approaches to sharing

Circuit switching
(reservation-based)

Packet switching
(on-demand)

Circuit switching

Relies on the Resource Reservation Protocol



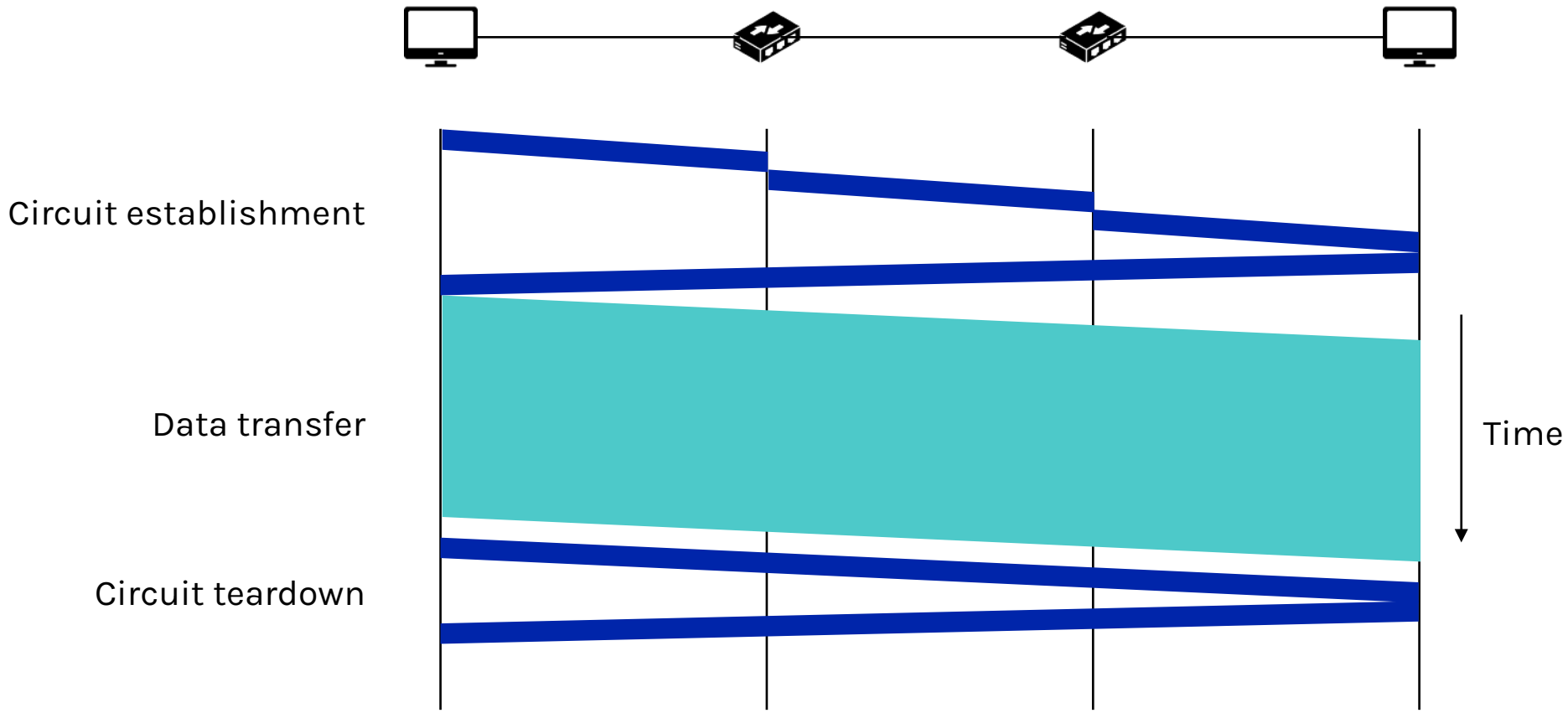
Step 1: source sends a reservation request for 10 Mpbs to destination

Step 2: switches on the path "establish a circuit"

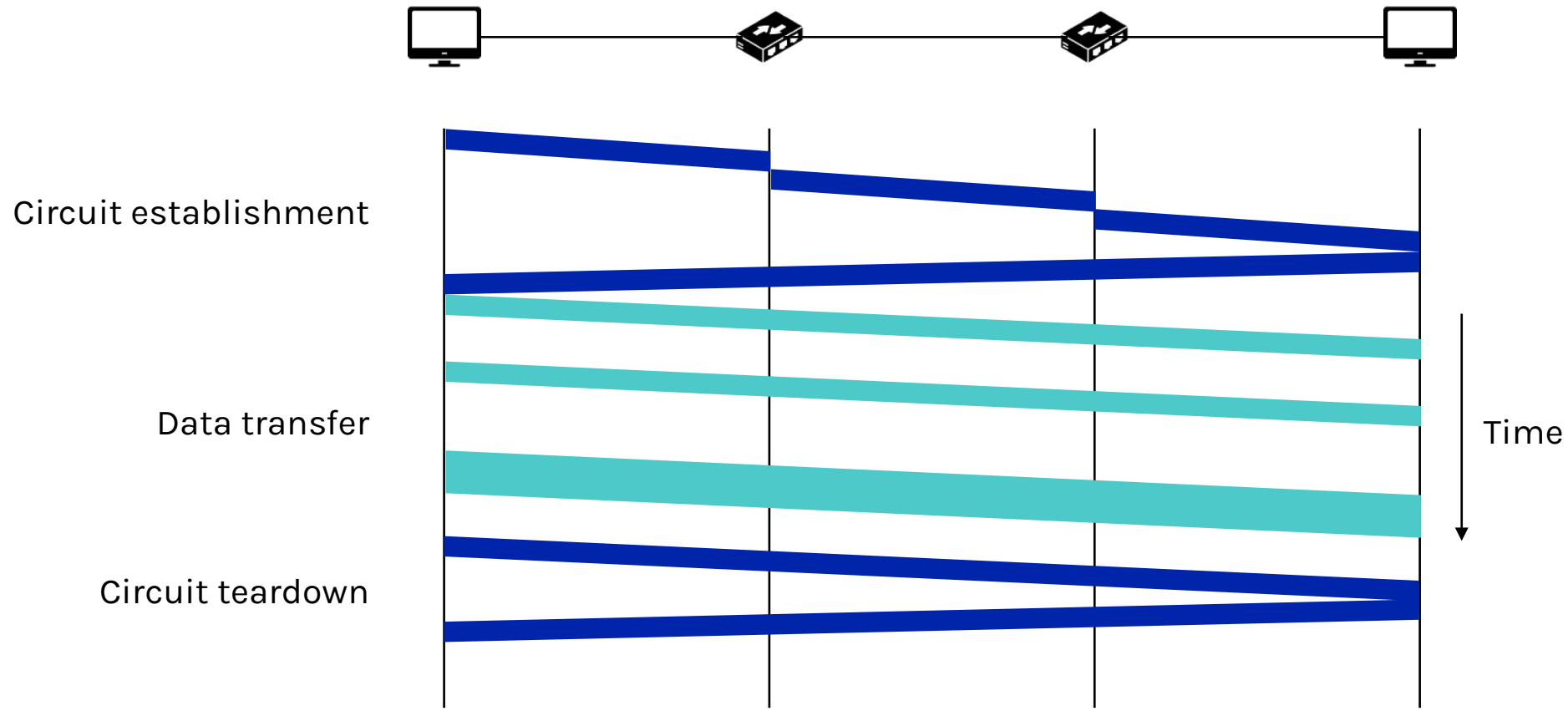
Step 3: source starts sending data

Step 4: source sends a "teardown circuit" message

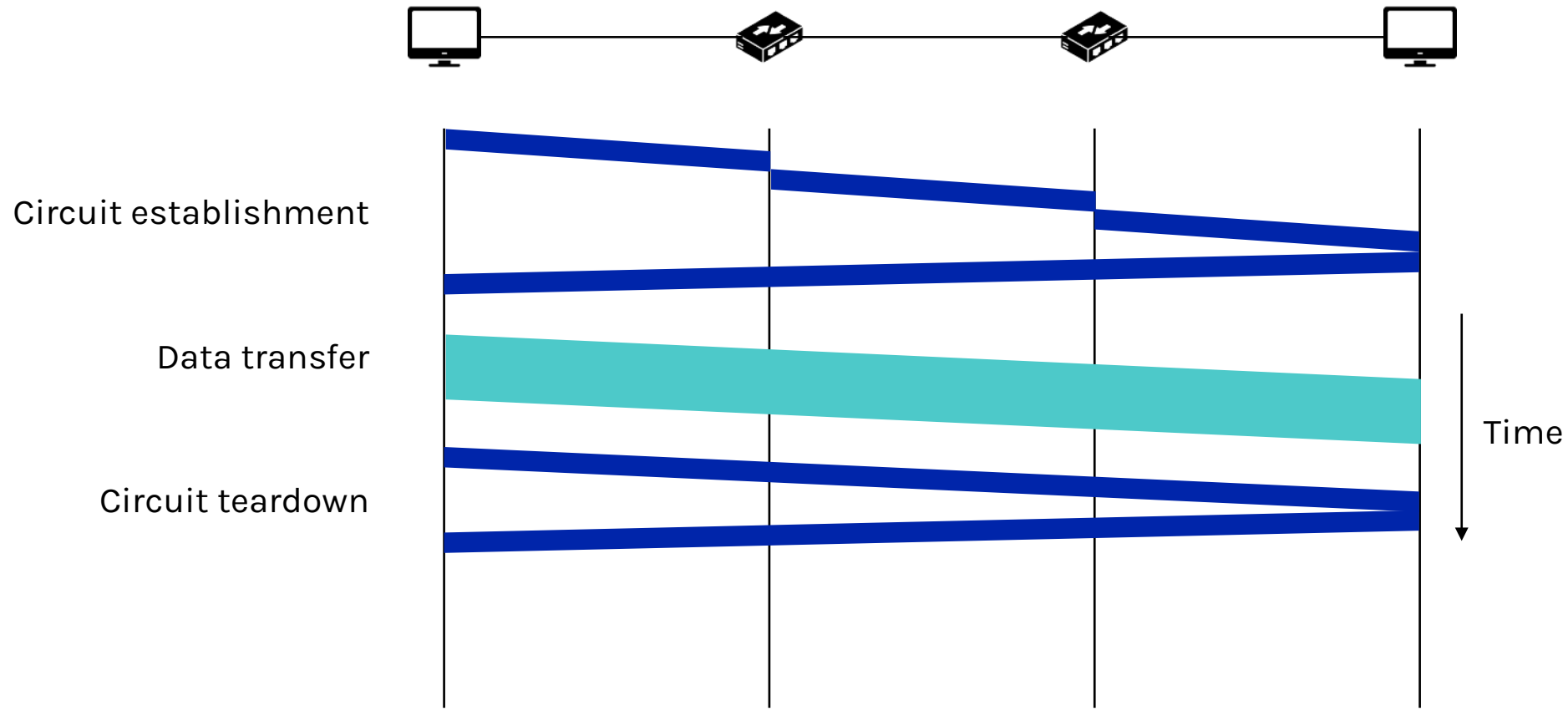
Data transfer with circuit switching



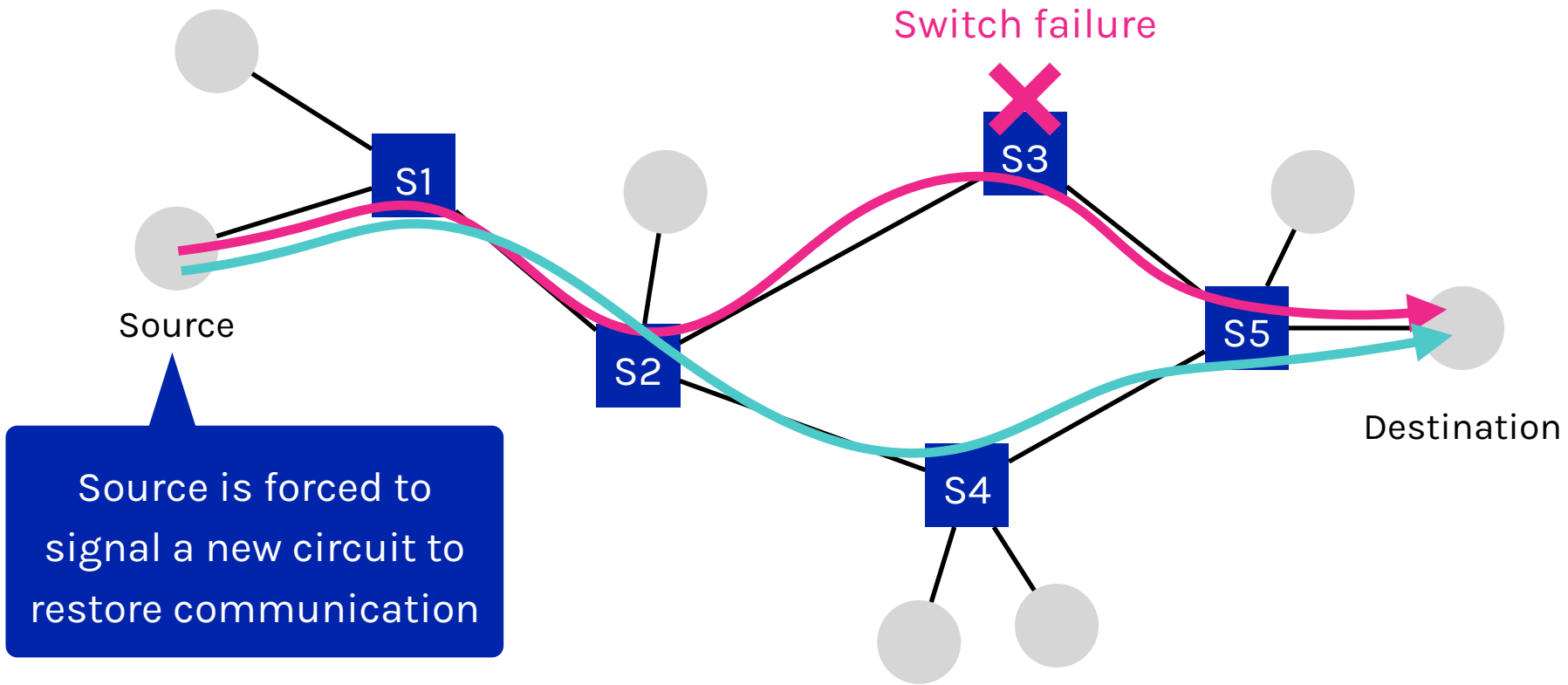
Low utilization when traffic is busty



High overhead for small traffic flows

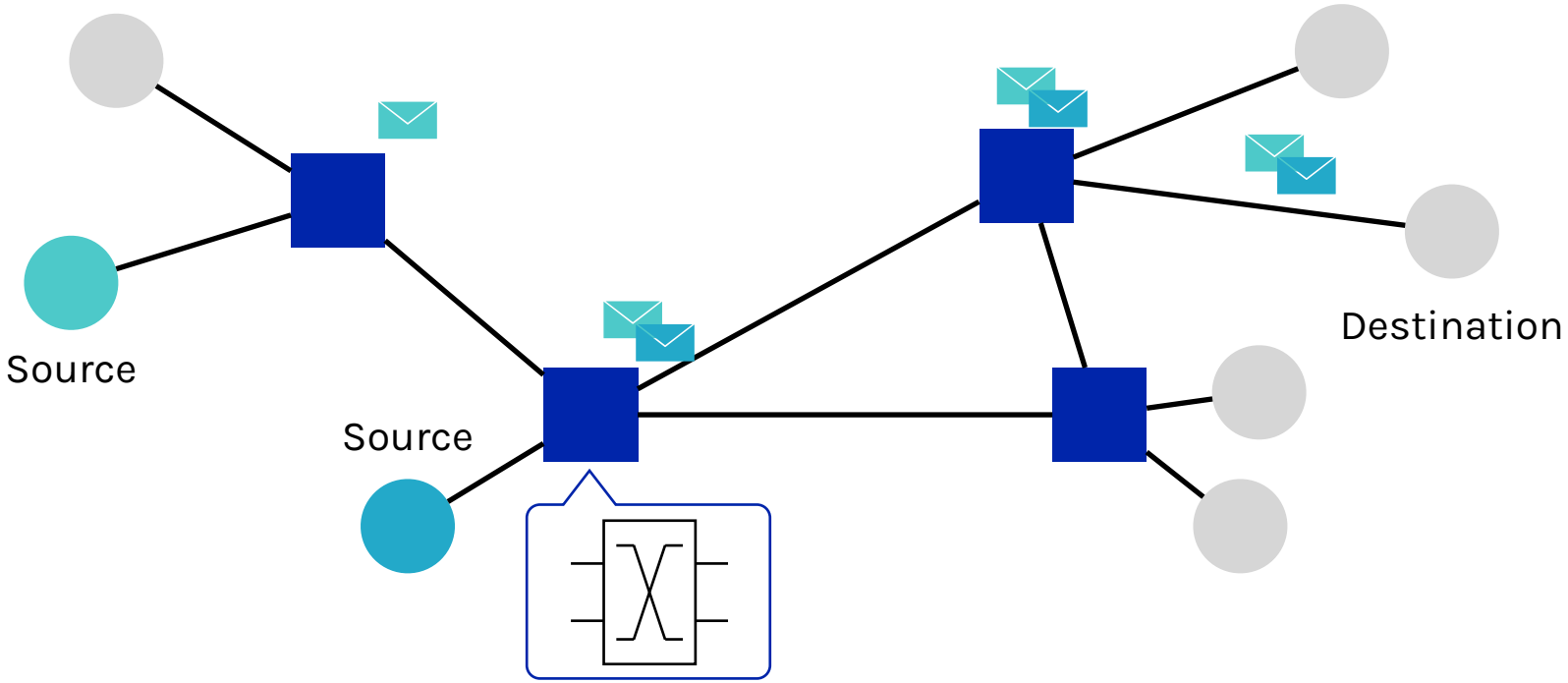


Dealing with failures in circuit switching



Packet switching

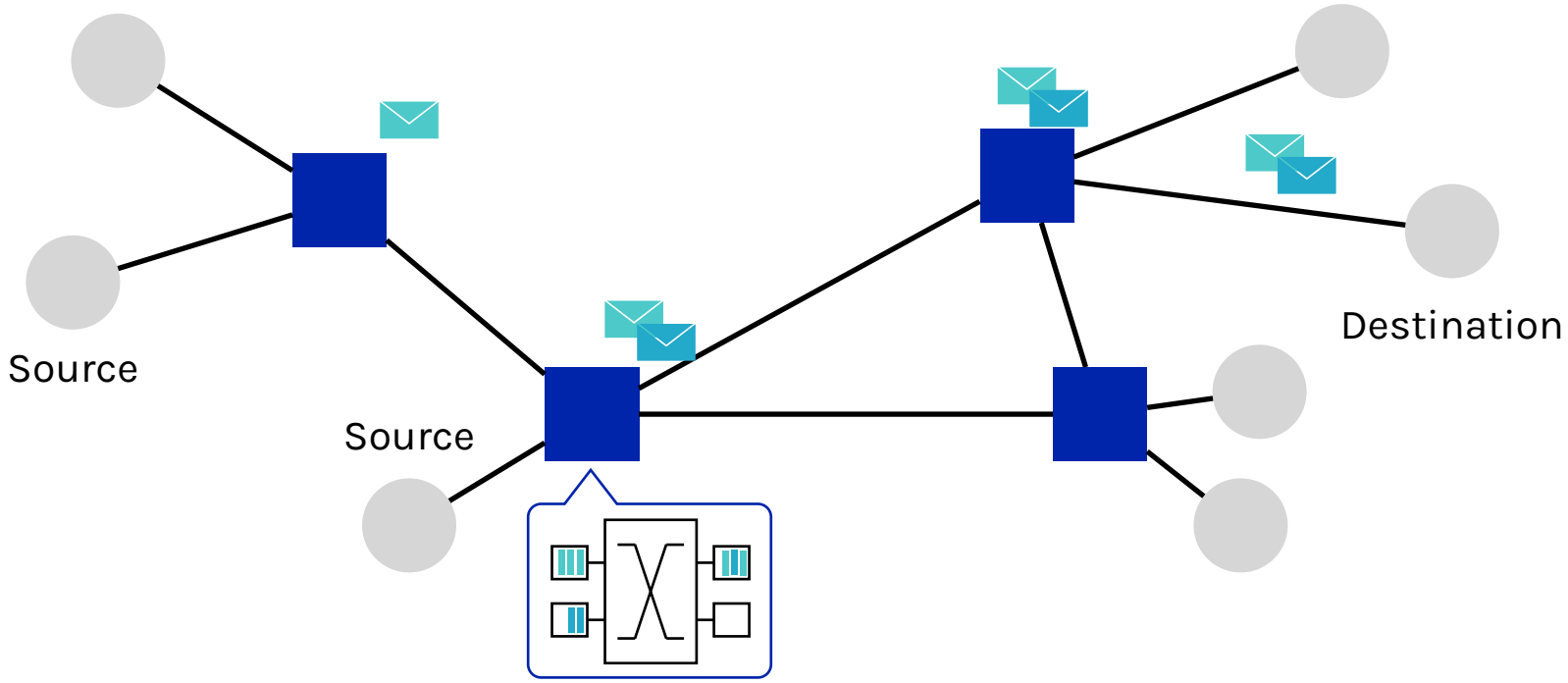
Data transfer through independent packets



Each packet carries its destination used for deciding where to forward the packet

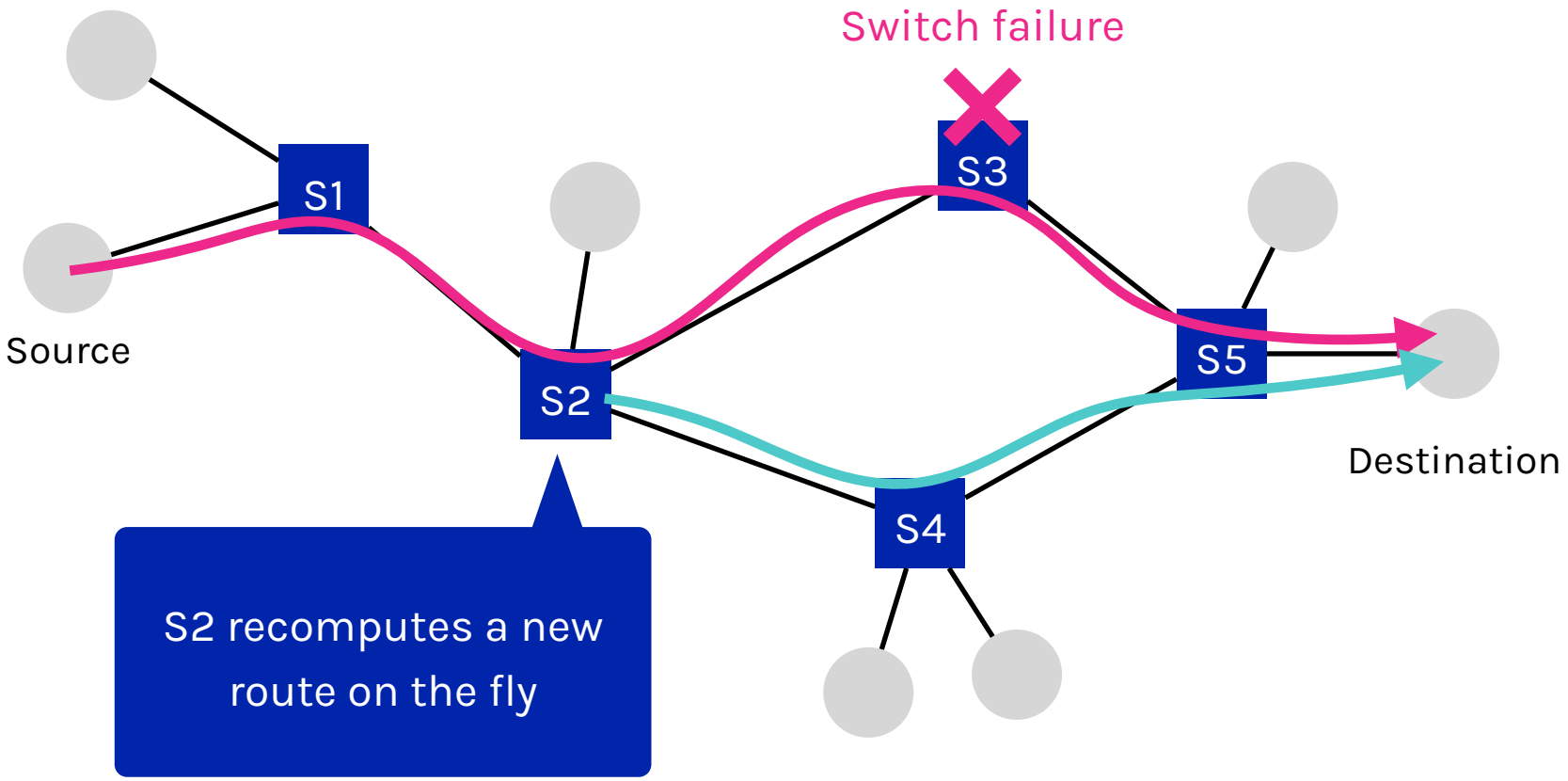
Packet switching

Data transfer through independent packets that may "clash"



Packets are **buffered** to avoid transient overload

Dealing with failures in circuit switching



Circuit switching vs. packet switching

	Advantages	Disadvantages
Circuit switching	- Predictable performance - Simple & fast switching	- Inefficient for short/bursty traffic - Complex circuit setup/teardown - New circuit upon failure
Packet switching	- Efficient use of resources - Simple to implement - Route around failures	- Unpredictable performance - Buffer management and congestion control

Packet switching beats circuit switching

With repsect to resilience and efficiency

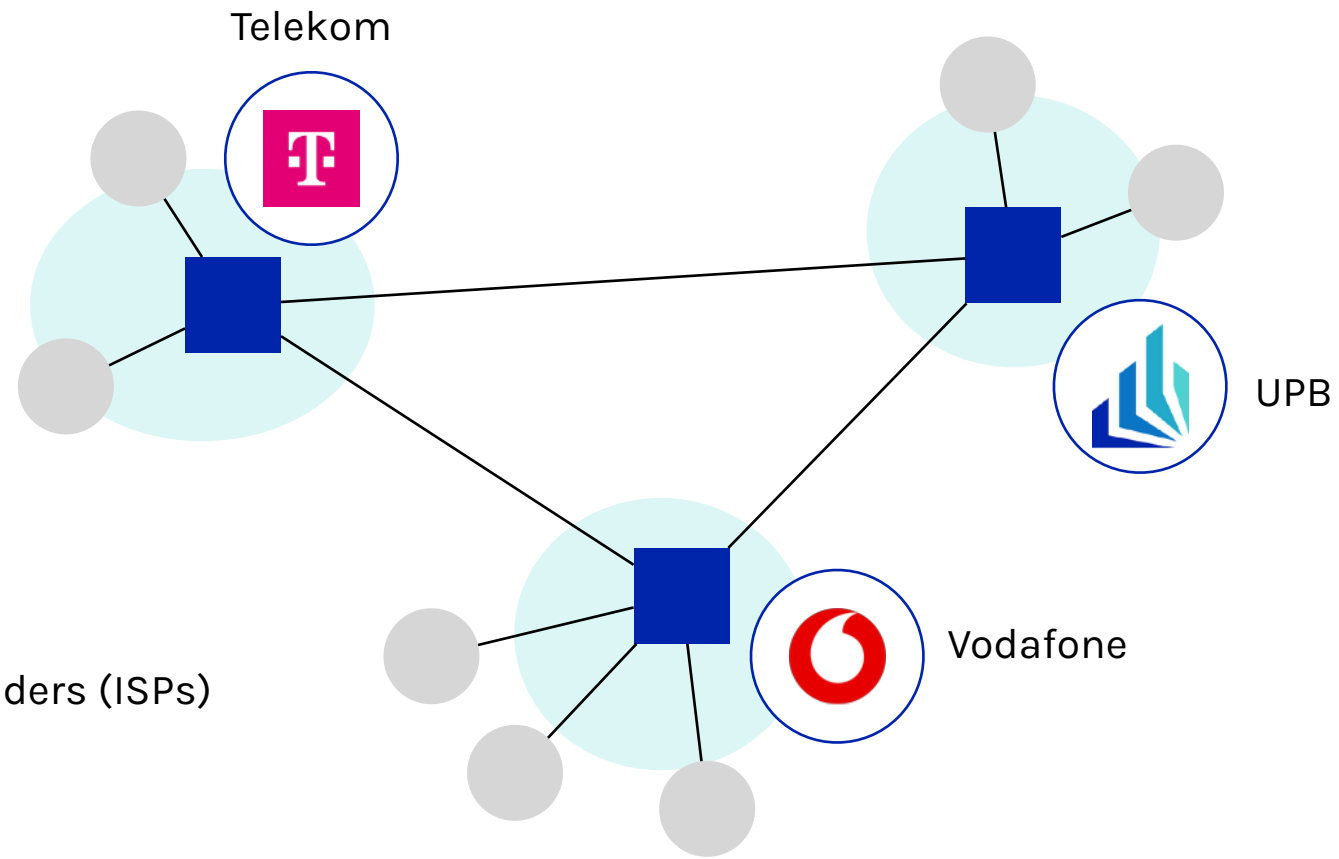
Internet  **packets**

We will focus on packet switching in the rest of this course

Key questions to answer

1. What is a network made of?
2. How the network is shared?
3. **How is it organized?**
4. How does communication happen?
5. How do we characterize it?

The Internet is a network of networks



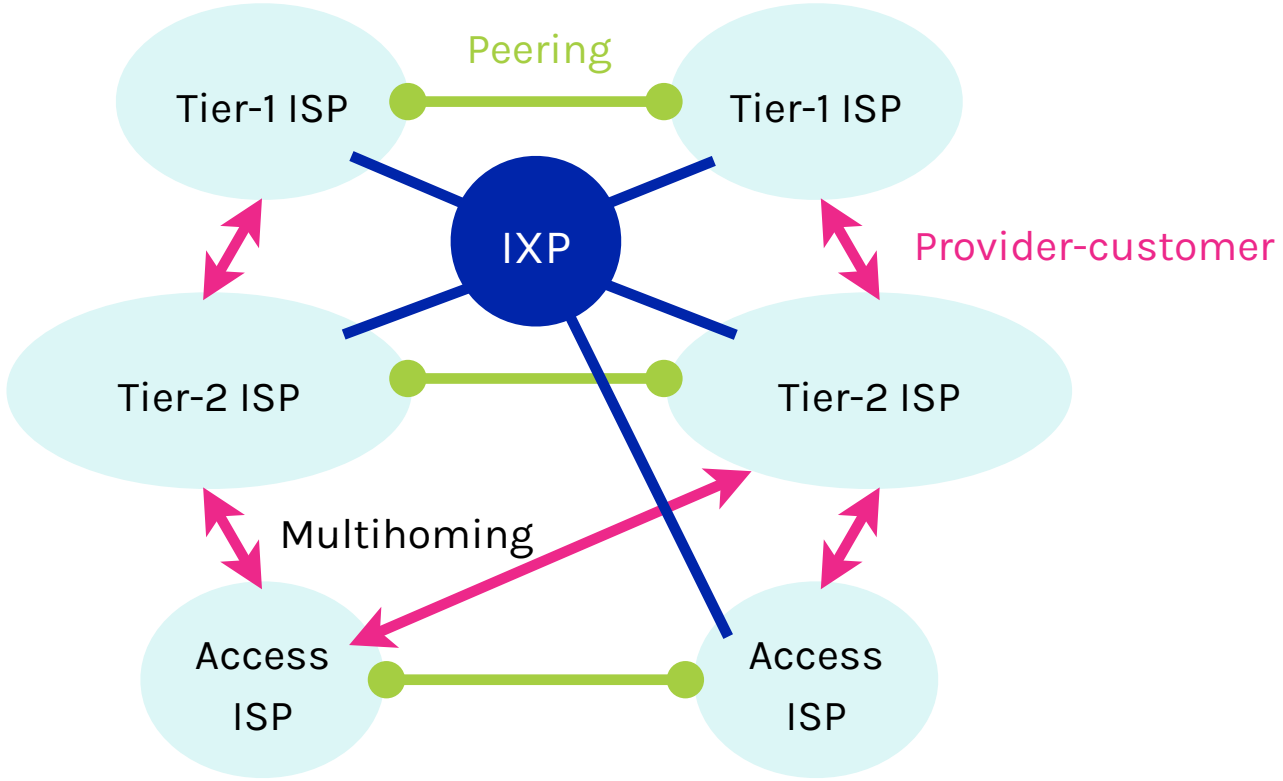
Internet **S**ervice **P**roviders (ISPs)

Internet hierarchy

International
(no provider)

National
(at least one provider)

Local
(at least one provider, no transit)



IXP: Internet Exchange Point

Key questions to answer

1. What is a network made of?
2. How the network is shared?
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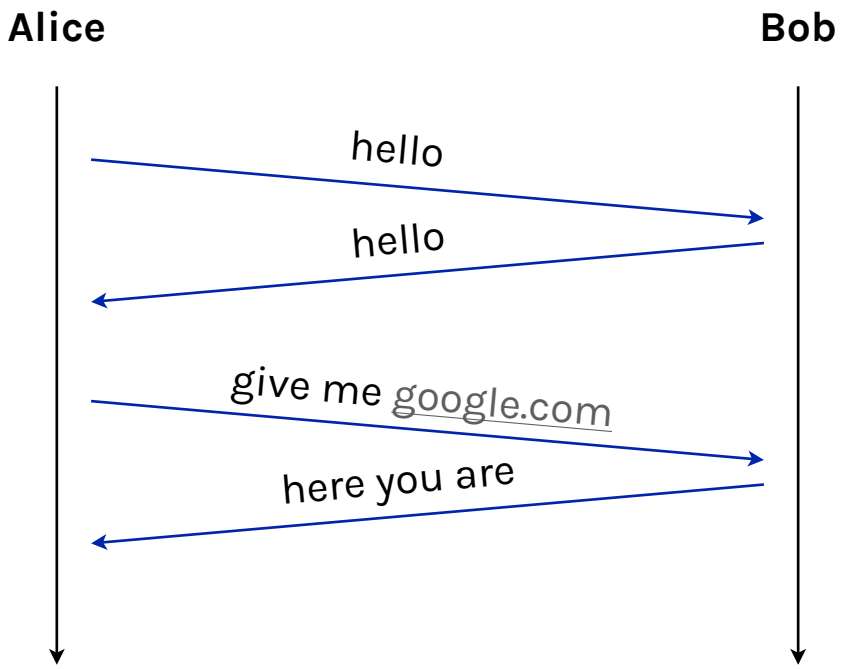
5. How do we characterize it?

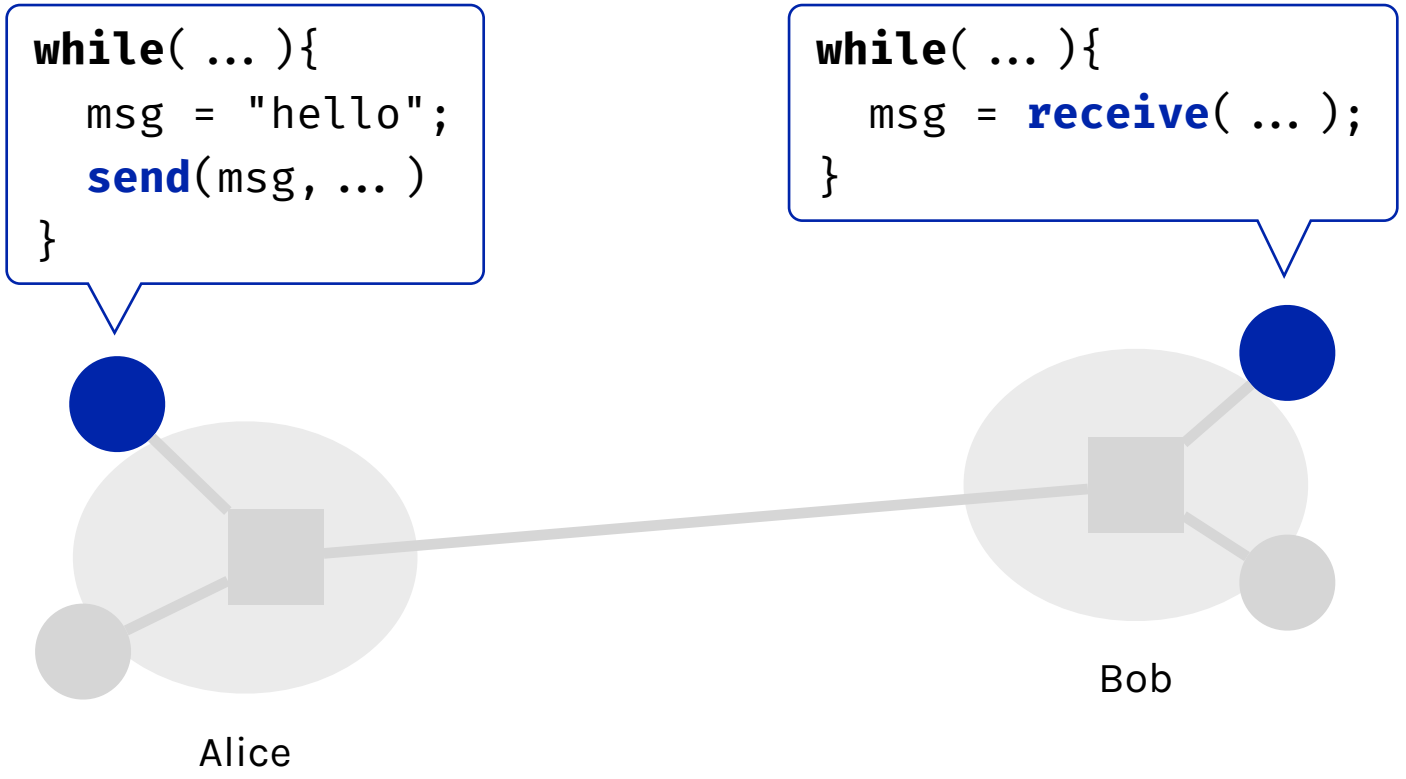
Communication happens with protocols



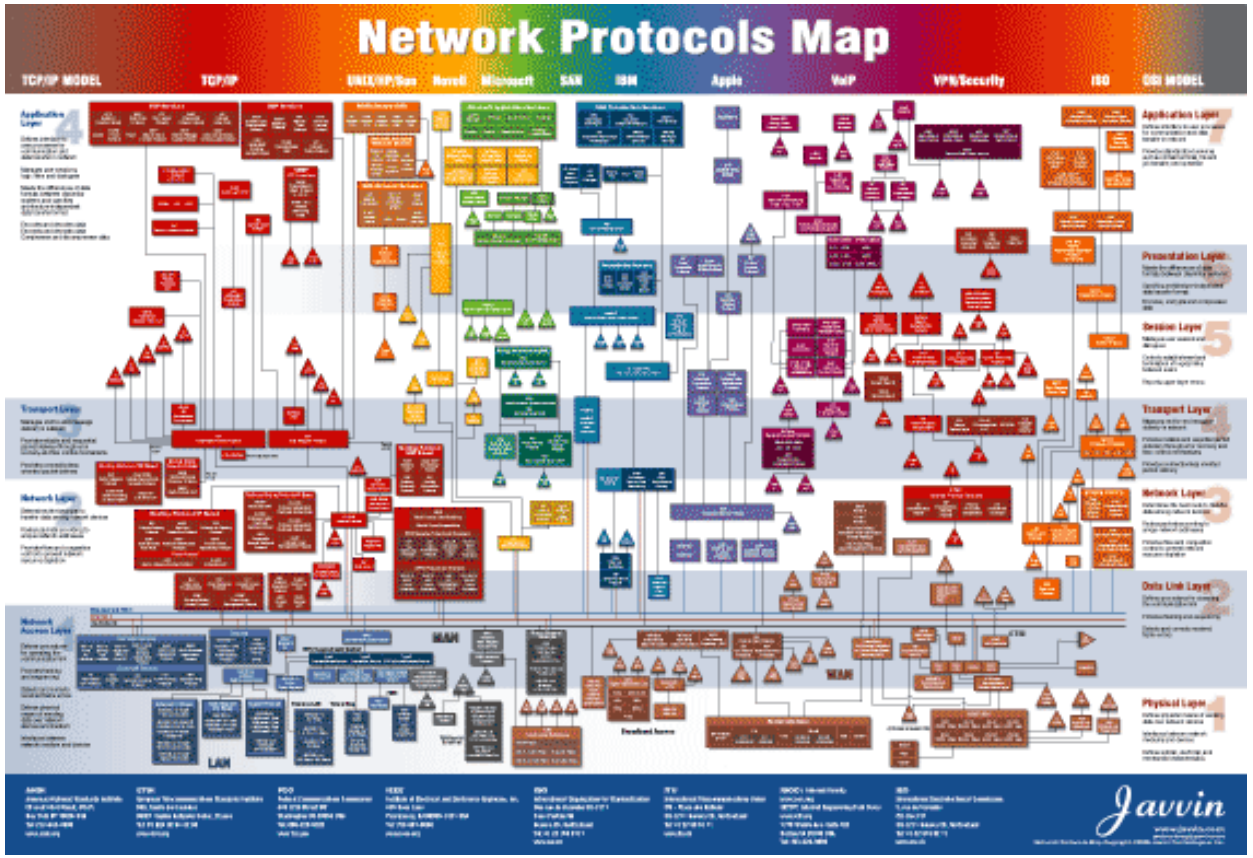
A protocol is like a conversational convention: who should talk next and how they should respond

Each protocol is governed by a specific interface

Called Application Programming Interface (API)



Numerous protocols on the Internet



https://packetlife.net/library/cheat-sheets/

How to organize these protocols?

Modularity to the rescue

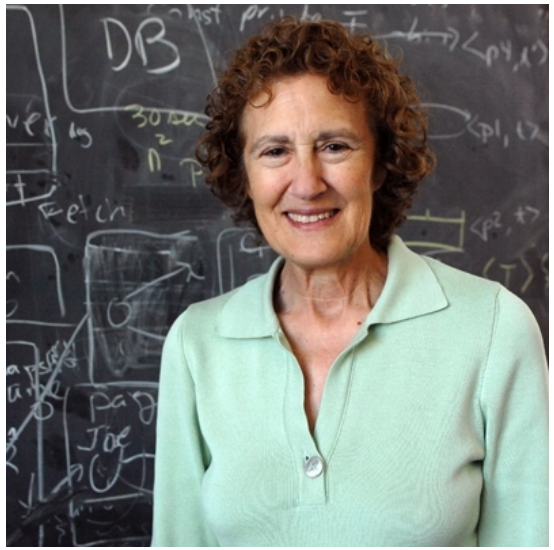
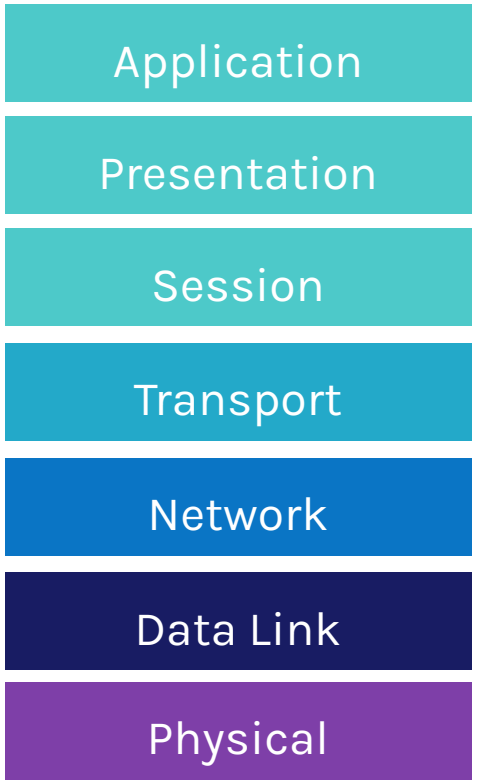


Photo: Donna Coveney

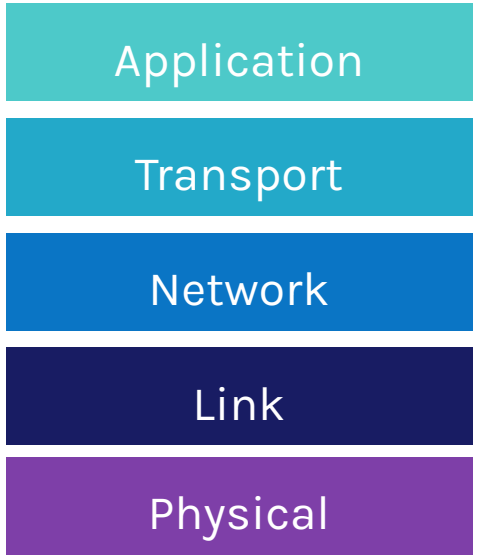
Modularity,
based on abstractions,
is **the** way things get done.

— *Barbara Liskov*, MIT

Layered architecture of network protocols



OSI model



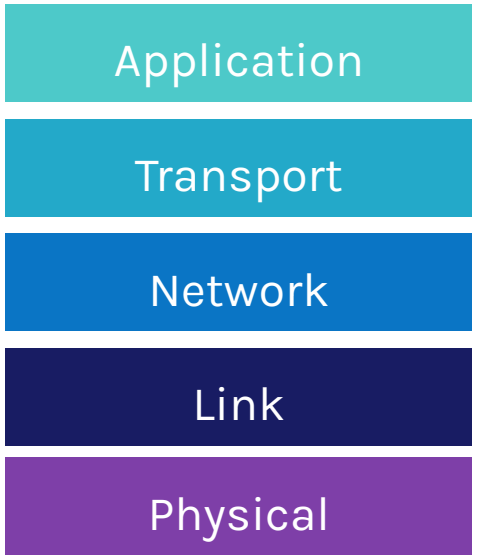
Intenet protocol stack

Internet protocols standardized by IETF

We reject kings, presidents, and voting. We believe in rough consensus and running code.
- David Clark

Andrew L. Russel. 'Rough Consensus and Running Code' and the Internet-OSI Standards War. IEEE Annals of the History of Computing, vol. 28(3), pp. 48-61, 2006.

Each layer provides a service to the upper layer



Network access

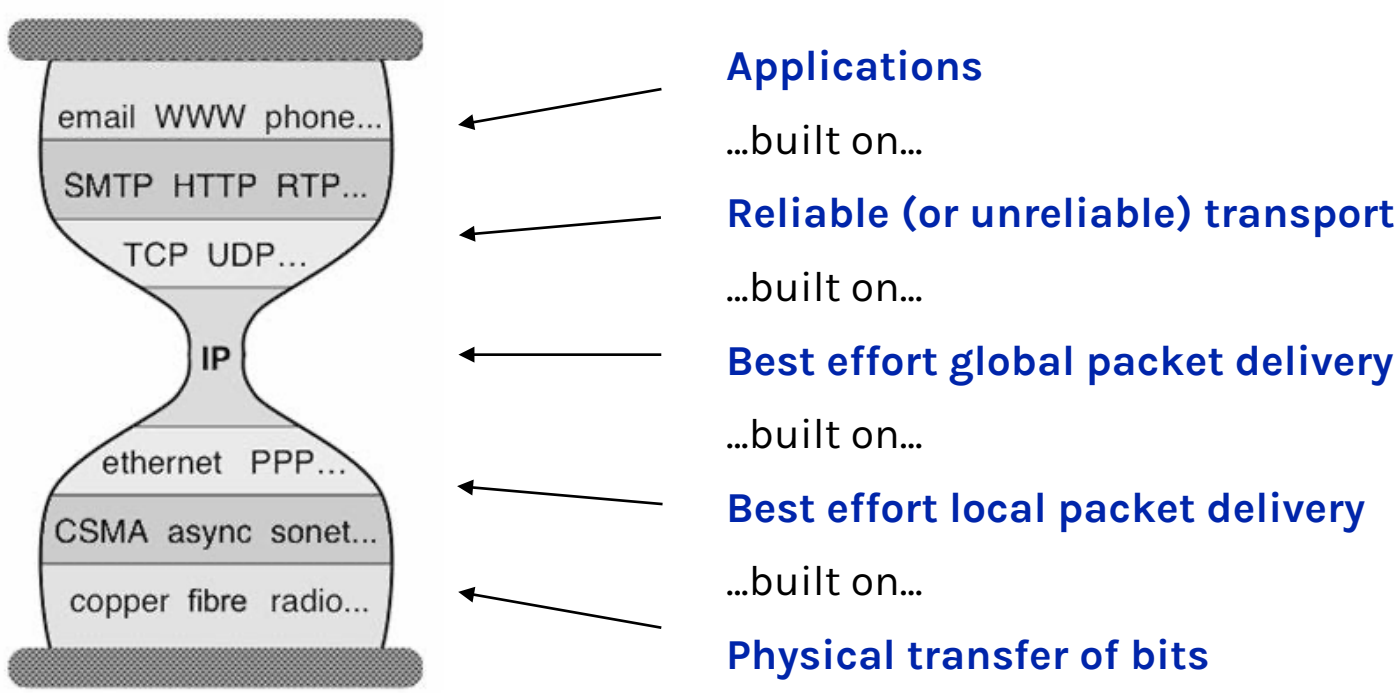
End-to-end delivery (reliable & unreliable)

Global best-effort delivery

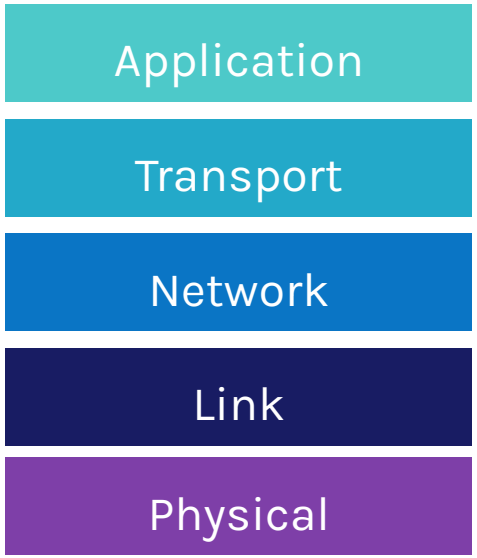
Local best-effort delivery

Physical transfer of bits

The Internet hourglass



Each layer has a unit of data



Exchanges **messages** between processes

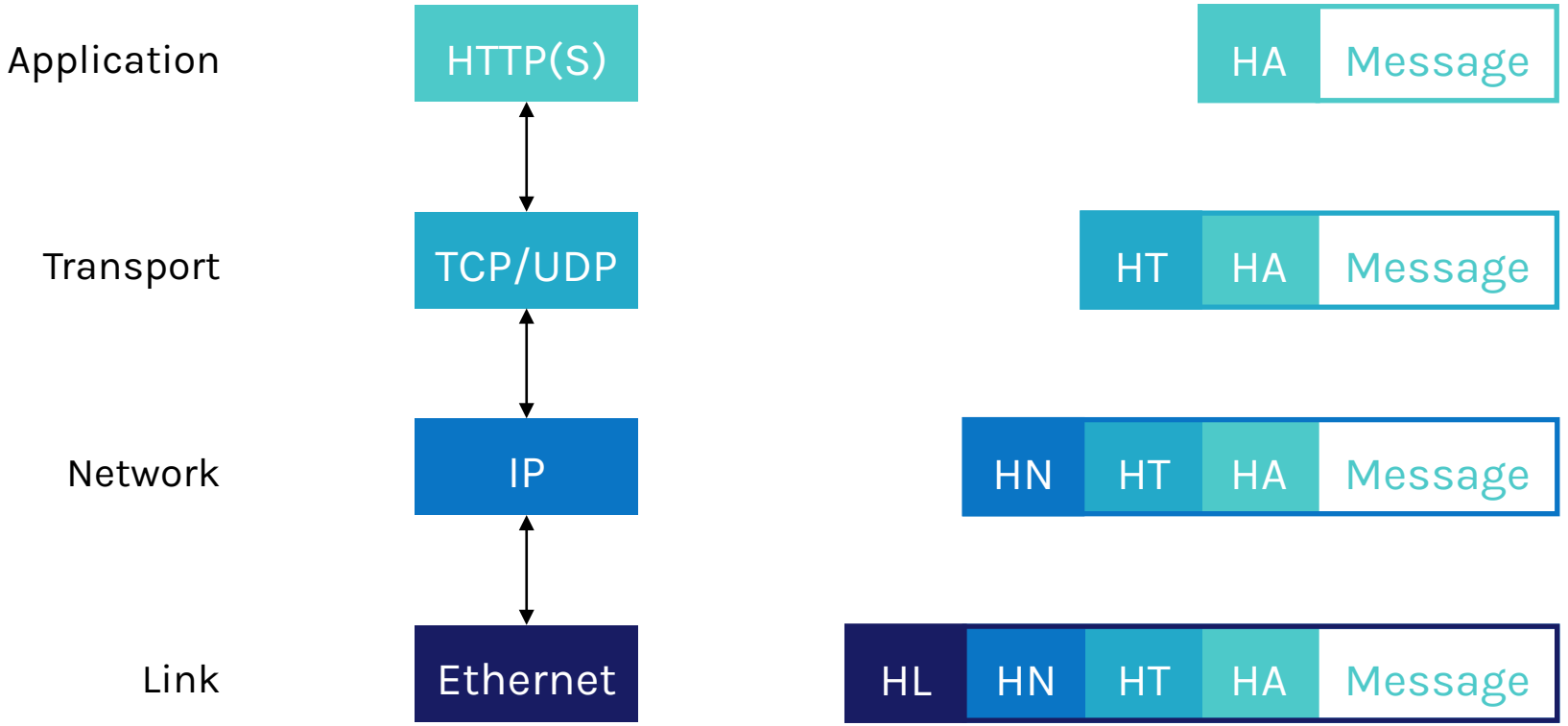
Transports **segments** between end-systems

Moves **packets** around the network

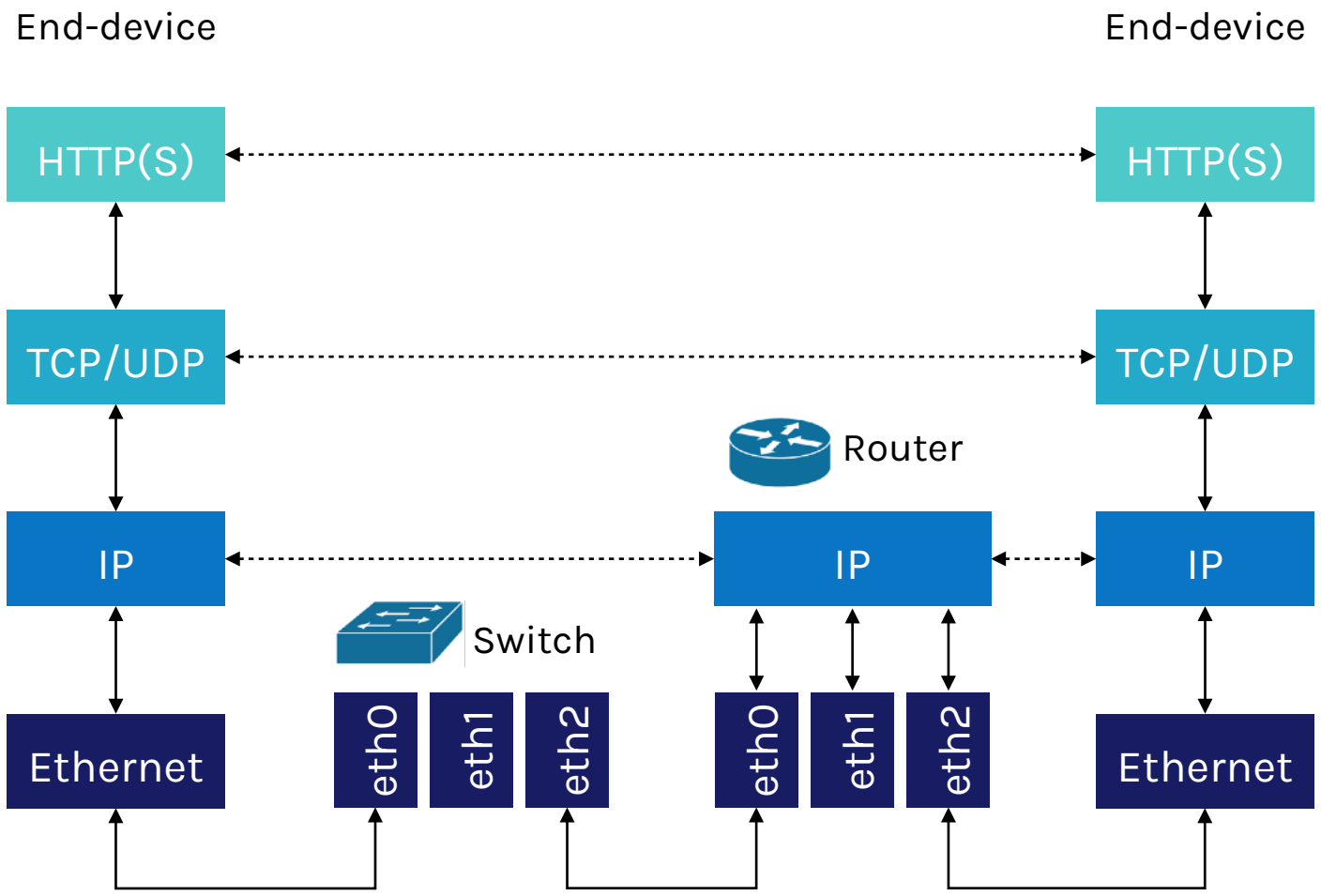
Moves **frames** across a network link

Moves **bits** across a communication medium

Encapsulation



Layers on network devices



Key questions to answer

1. What is a network made of?
2. How the network is shared?
3. How is it organized?
4. How does communication happen?
5. **How do we characterize the network?**

Network performance metrics

Delay

How long does it take for a packet to reach the destiantion?

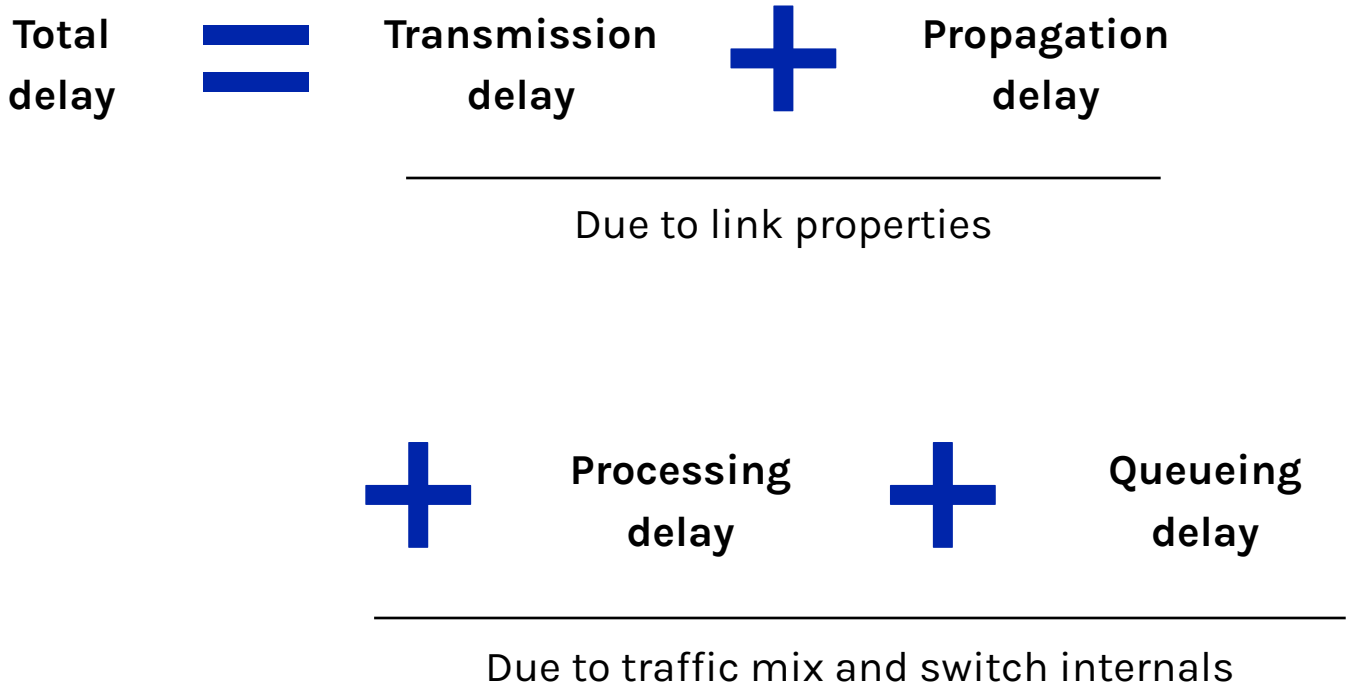
Loss rate

What fraction of packets sent to a destination are dropped?

Throughput

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

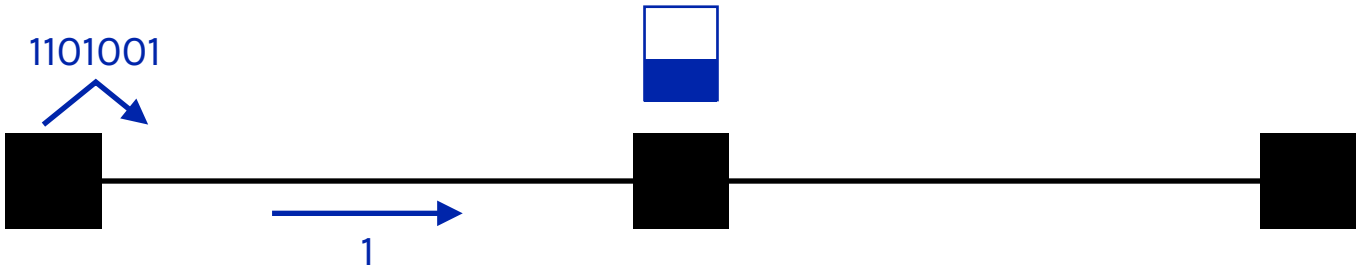
Different types of delay



Delay calculation

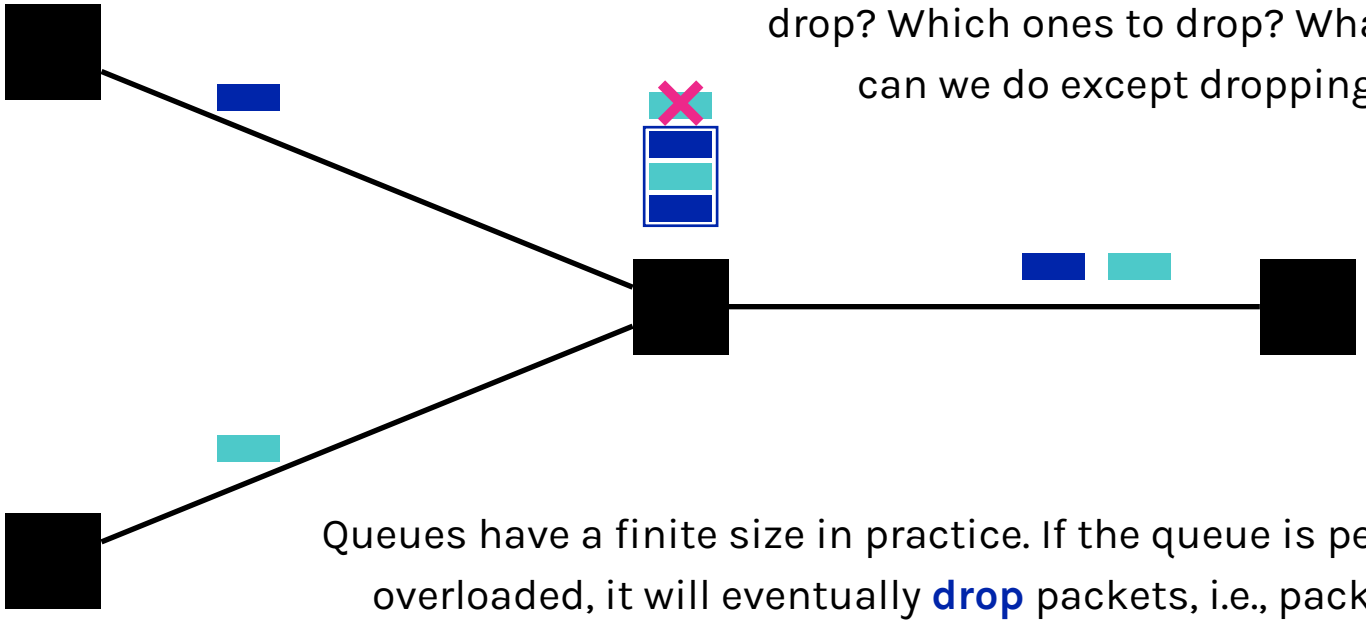
Transmission delay: amount of time required to push all of the bits onto the link, e.g., 1000 bits / 100 Gbps = 10 ns

Queueing delay: the time a packet has to sit in a buffer before being processed, depending on the traffic pattern (burstiness)



Propagation delay: amount of time required for a bit to travel to the end of the link, e.g., 30 km / 2×10^8 m/s = 150 µs

Loss rate



Questions to think about: When to drop? Which ones to drop? What else can we do except dropping?

Queues have a finite size in practice. If the queue is persistently overloaded, it will eventually **drop** packets, i.e., packet loss.

Throughput

The instantaneous rate at which a host receives data

(need to consider the bottleneck link)

File size:

$s = 10$ MB

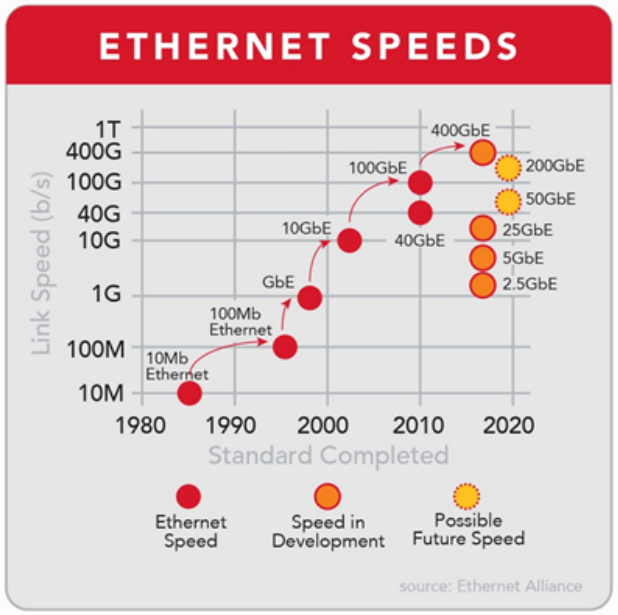
$R_1 = 8$ Mbps

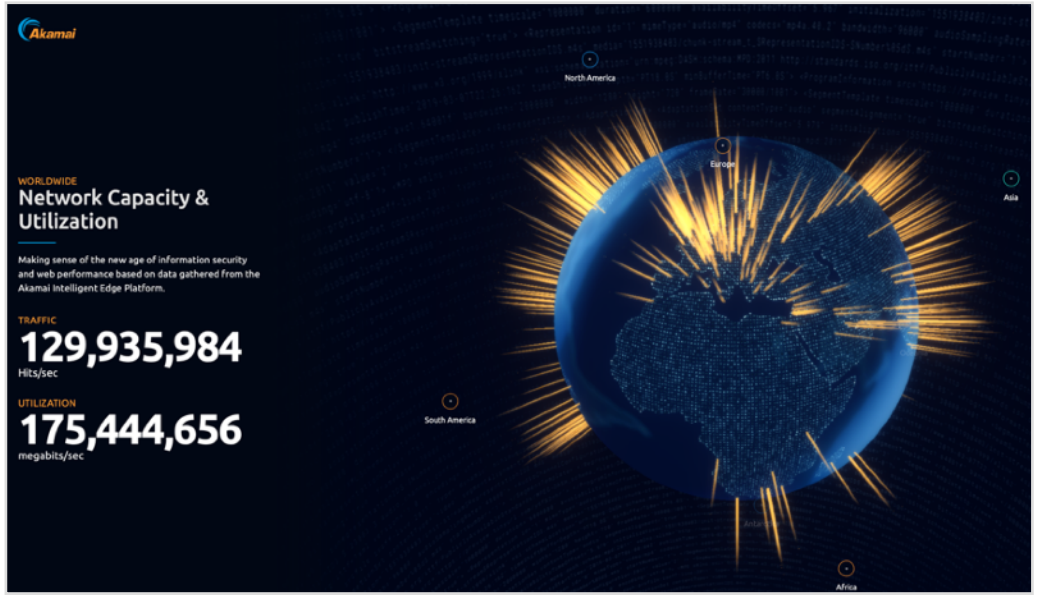
$R_2 = 5$ Mbps

$$\text{Throughput} = \min\{R_1, R_2\}, \text{time} = \frac{s}{\min\{R_1, R_2\}} = \frac{80 \text{ Mb}}{5 \text{ Mbps}} = 16 \text{ sec}$$

Network performance improvement

Throughput ↑ delay ↓ (propagation delay ≈, due to speed of light)





Content Distribution Networks (CDN), Edge Computing

https://www.ciena.com/insights/articles/Carrier-Ethernet-Speeds-Standards-and-Services.html

Summary

What is a network made of?

- End-devices
- Switches/routers
- Links

How the network is shared?

- Circuit switching vs. packet switching

How the network is organized?

- ISPs, IXP, peering

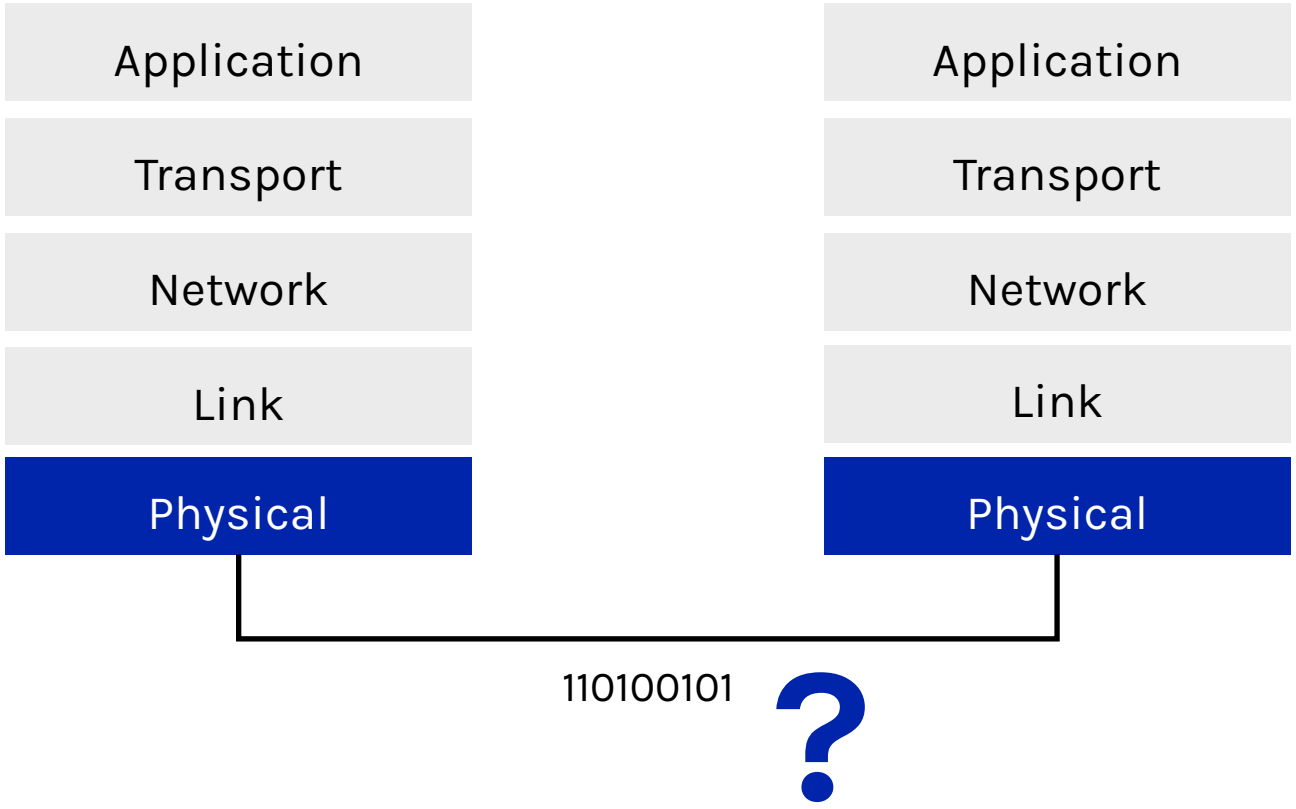
How does communication happen?

- Protocols
- Layered architecture

How do we characterize a network?

- Delay
- Loss rate
- Throughput

Next time: network physical layer



Further reading material

Andrew S. Tanenbaum, David J. Wetherall. Computer Networks (5th edition).

- Section 1: Introduction

Larry Peterson, Bruce Davie. Computer Networks: A Systems Approach.

- Section 1.5.1: Bandwidth and Delay

James F. Kuros, Keith W. Ross. Computer Networking: A Top-Down Approach.

- Chapter 1: Computer Networks and the Internet