Performance of Networked Systems

Lecture 1: Introduction to communication networking

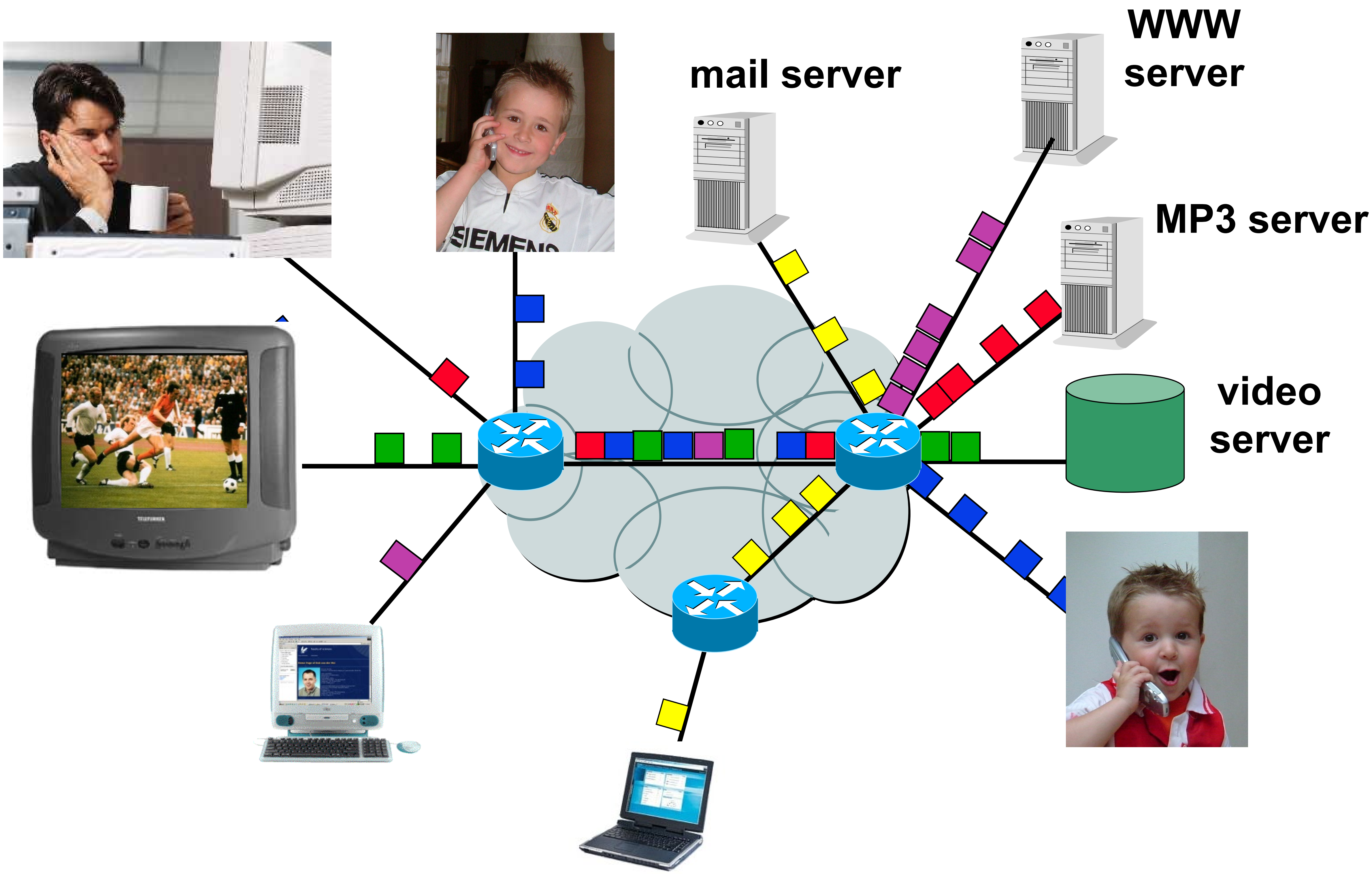
Overview of today's lecture

1. Examples of performance degradation
2. Performance-critical systems
3. Course overview
4. Basics and networking principles
5. Bandwidth versus latency
6. OSI reference model

Background reading material for this week:

I. Grygorik, "High Performance Browser Networking", chapter 1

Perceivable Performance Degradation



Example: Dutch Sports Victory

Semi finals WC Soccer 2010

The Dutch Soccer Frustrations

2010: Arjen Robben and Casillas' toe...

1974: 1-2 loss against West-Germany

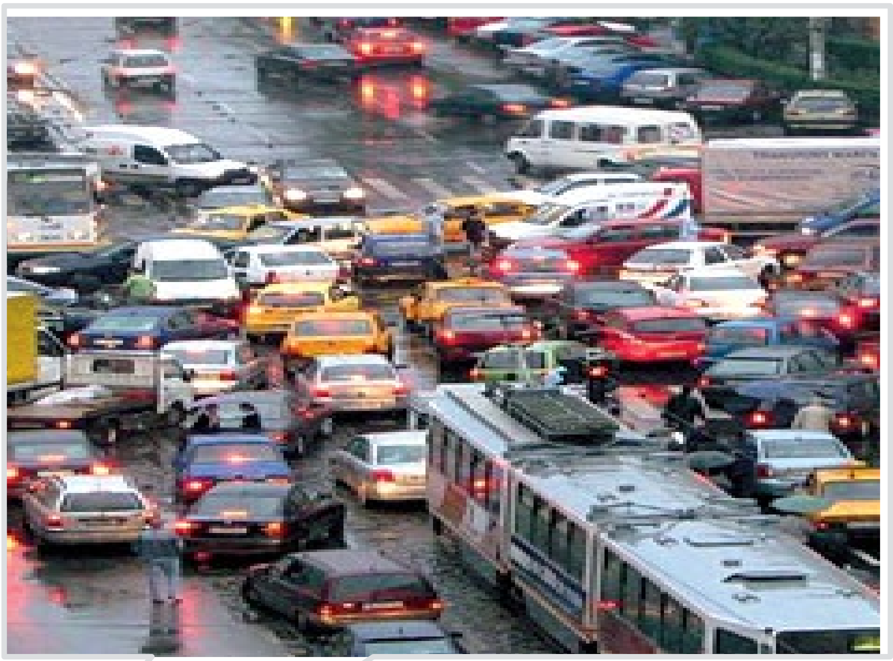
1978: Rob Rensenbrink hits the pole...

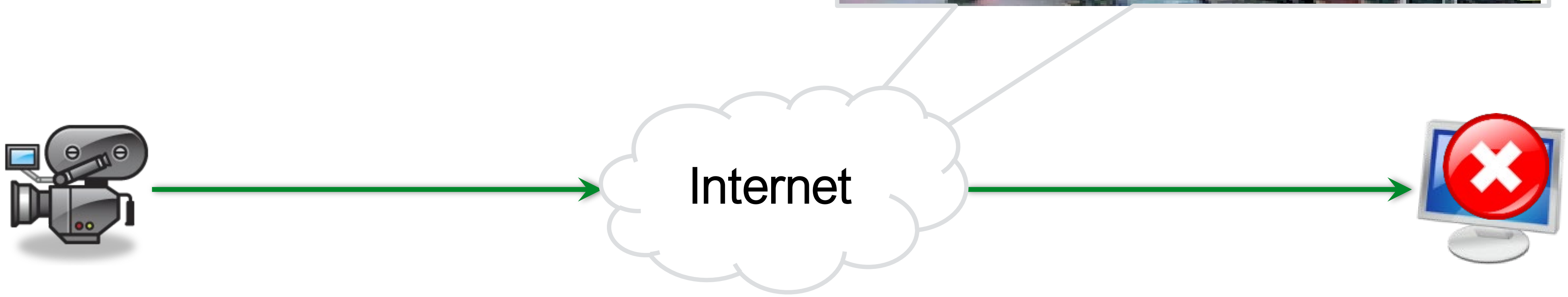
1988: European champion!

https://youtu.be/q3af4QIh1oc

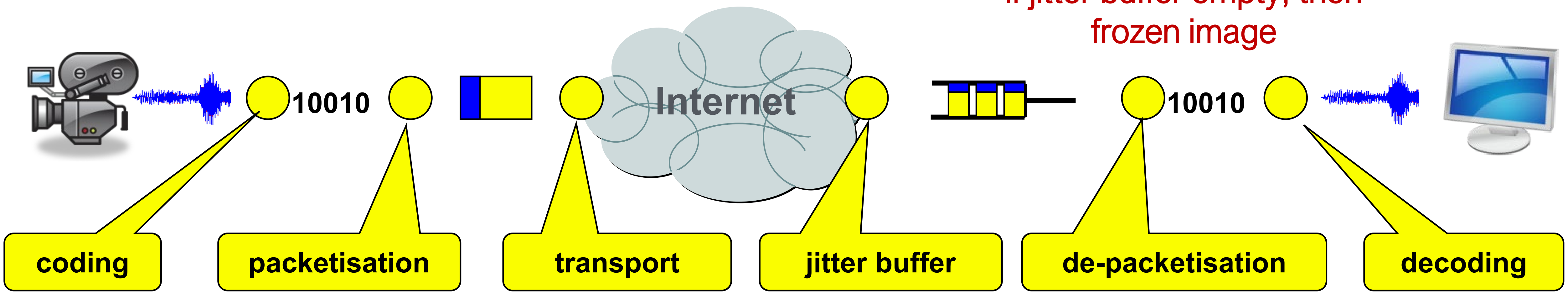
Back to Performance Degradation

congestion in the network…



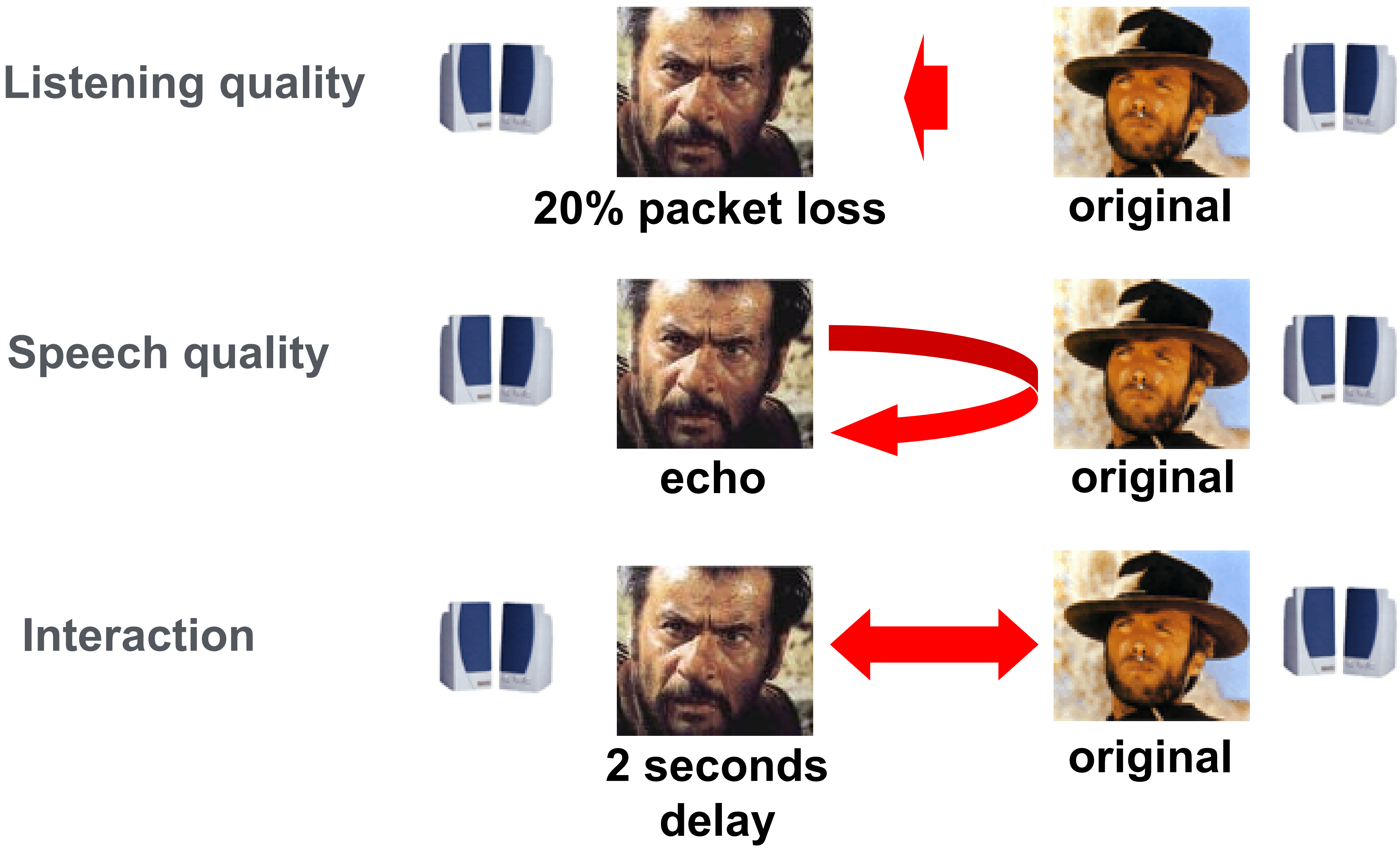


if jitter buffer empty, then frozen image



Voice Quality Degradation

Conversational quality: three components



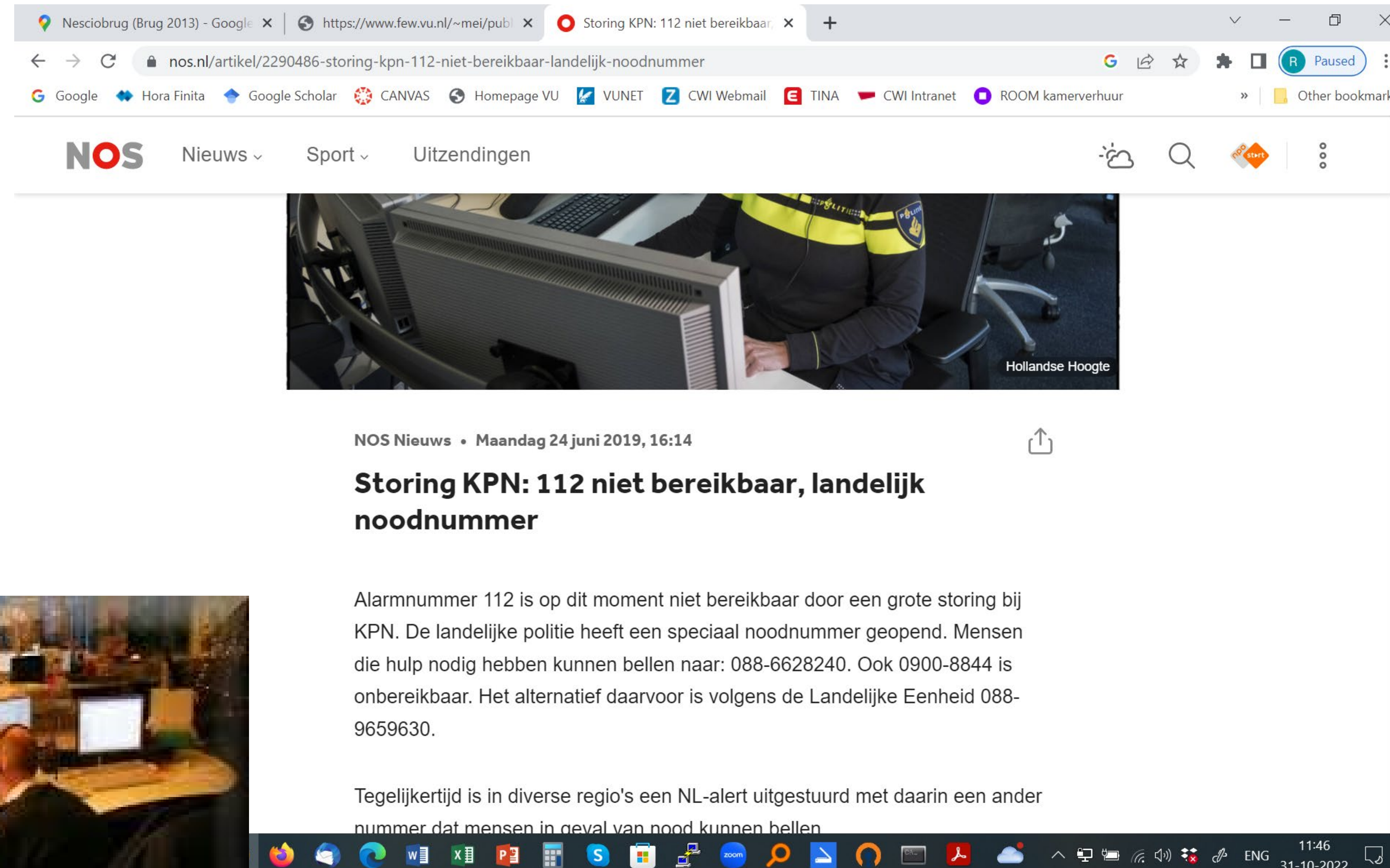
Performance-Critical Systems

Example: airline flight control systems

Impact of failure may be dramatic

Strict requirements on availability and performance of the system

Performance-Critical Systems



Emergency applications pose <u>strict requirements</u> on <u>availability</u> and <u>performance</u>

Performance-Critical Systems

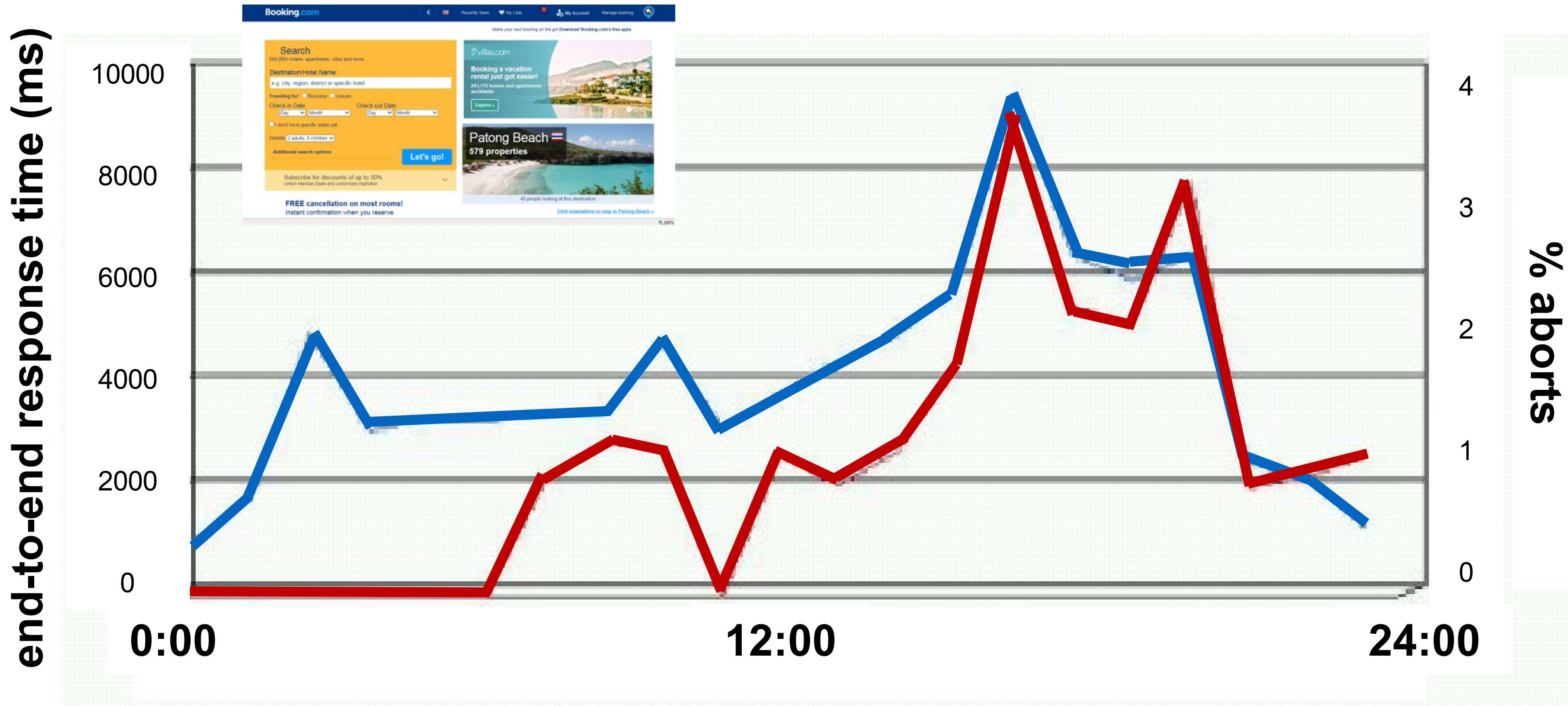
Other examples:

- Cash dispensers
- E-commerce, on-line sales
- On-line stock trade applications
- On-line booking system applications
- Access to railway system

Real-time applications pose strict requirements on availability and performance

Incidents: Online Banking

Performance Affects Business



Performance directly hits revenues…

About the Course

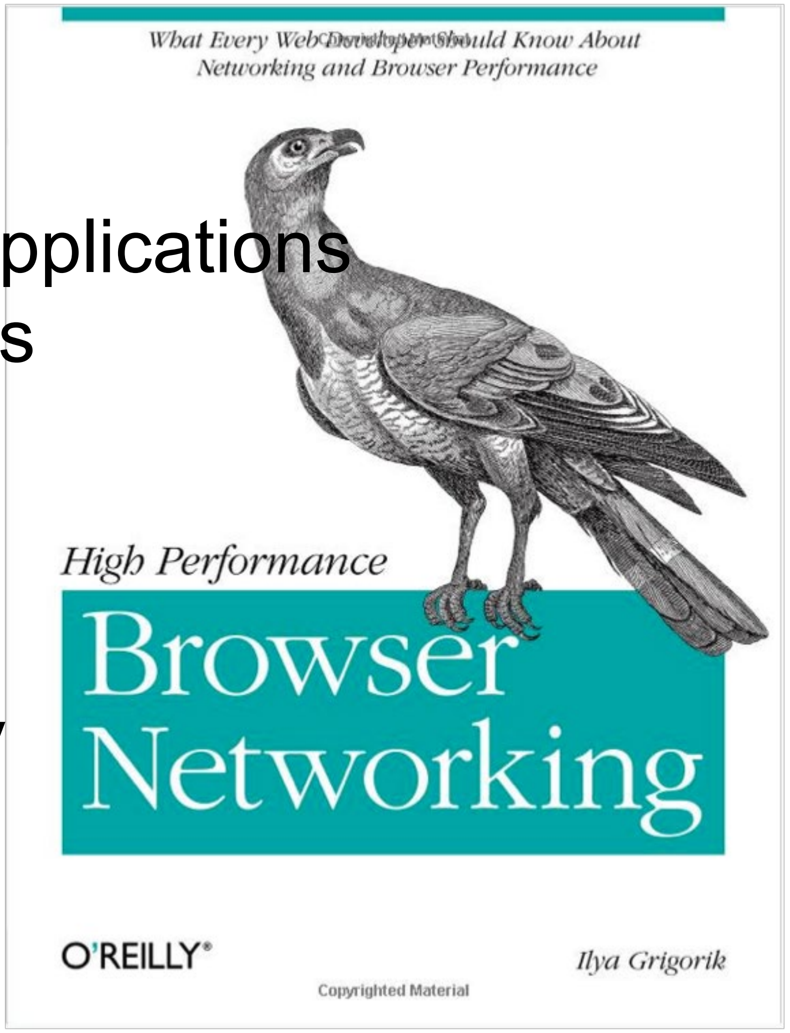
“Performance of Networked Systems”

Class essentially consists of <u>two parts</u>:

1. Performance **engineering** for networked client applications
2. Performance **modelling** for servers and networks

Background reading material:

1. Book “High Performance Browser Networking” by Grigorik (available online via CANVAS)
2. Reader “Stochastic Performance Modeling” by O.J. Boxma
3. Individual papers

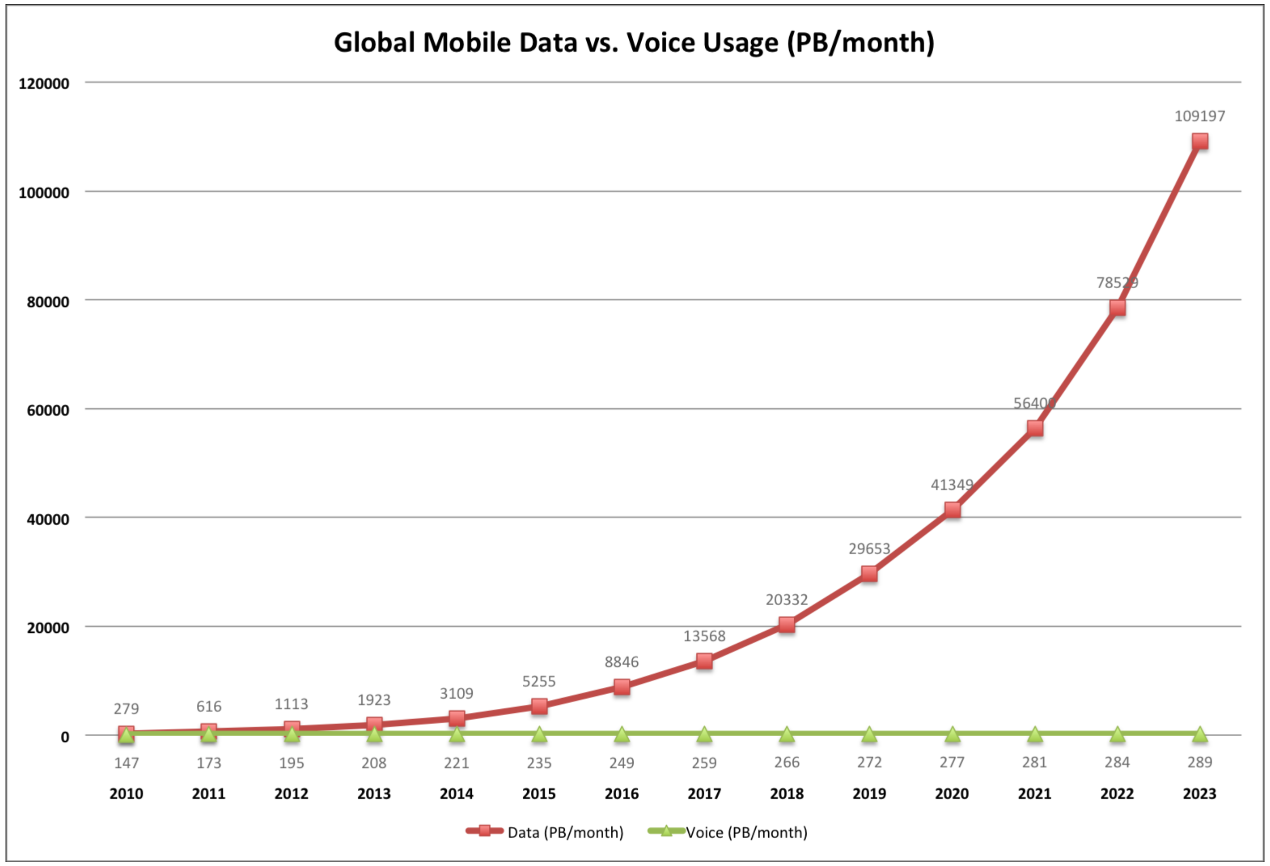


Course Elements

- Lectures (2x per week)
- One homework assignment
- Register groups via CANVAS
- Written exam
- Self study (with the book and the reader)
- Grading: exam (80%) + homework (20%)
  - exam grade must be > 5.5 for passing the course

Global Monthly Mobile Traffic: voice versus data

2010-2023



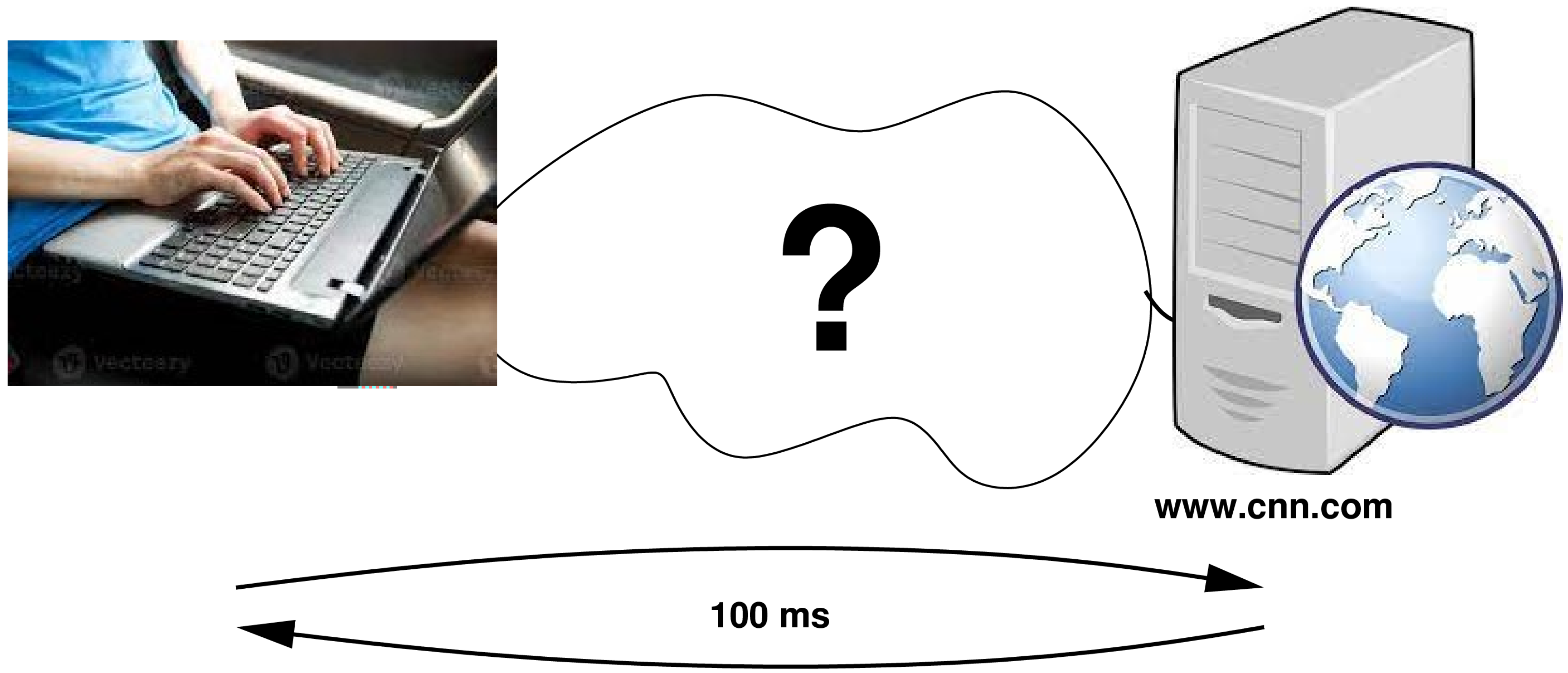
voice traffic volume negligible

https://kk.org/extrapolations/mobile-data-vs-voice-usage/

Total yearly mobile voice and data traffic

- Voice traffic remains fairly constant, and negligible compared to data
- Data grows “exponentially”

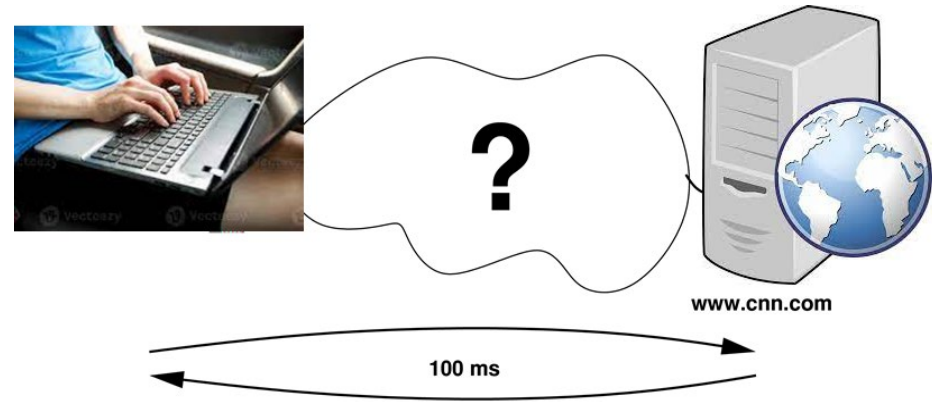
“End-to-End” Performance of Networked Systems

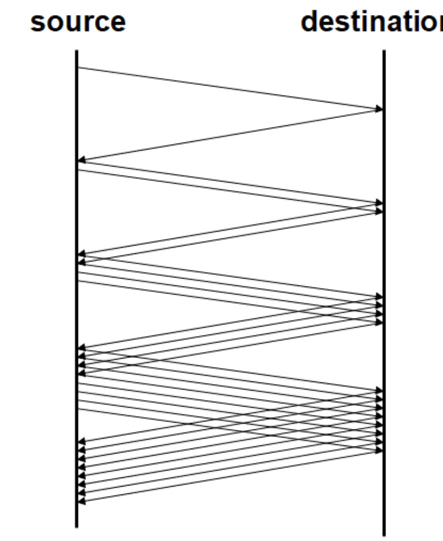


- User - and hence the business - cares about **response time**
- Often called **end-to-end** response time
- How much of it is caused by:
  - the server(s)?
  - the network?
  - the client?
  - the interactions among client, network, and servers?

?

Client, Server and Network Performance





Influence of the client side is often overlooked:

- How much processing is done at the client side?
  - on a mobile device, or a rusty old computer
- The interaction between client and server is often critical
  - over mobile networks

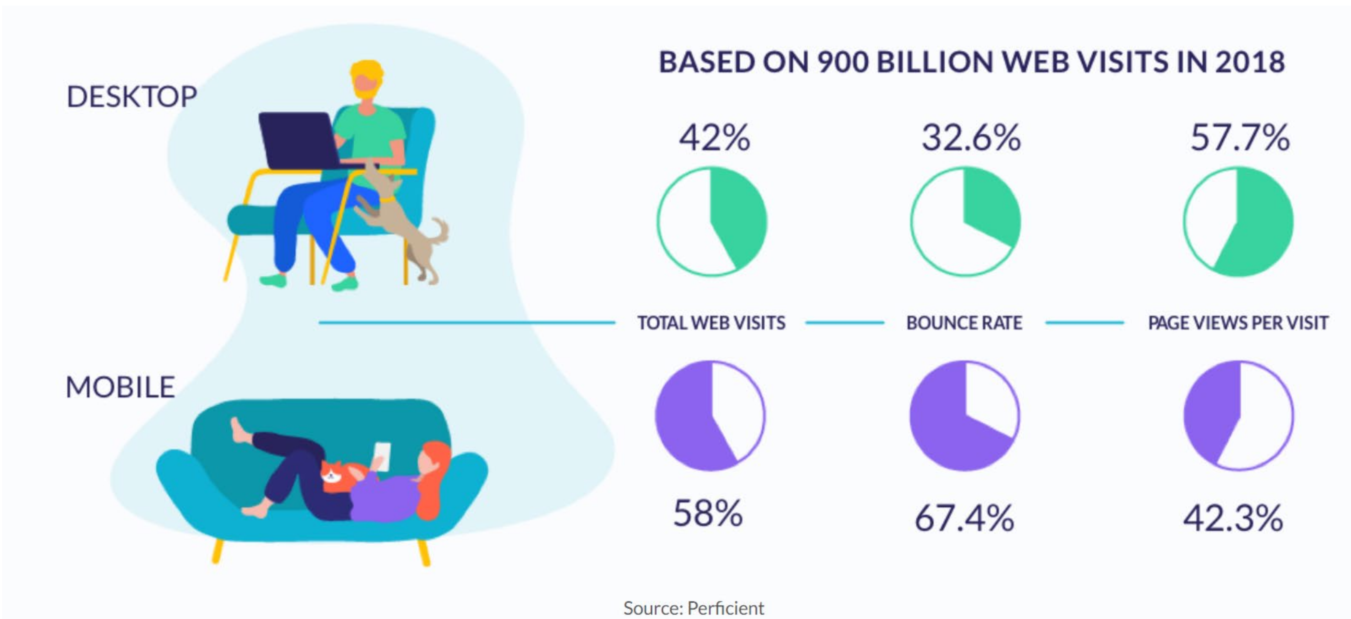
"Network performance" is often misinterpreted and over-rated:

- "I have 10Gb/s access", but what do you really get?
- Network performance often confused with access bandwidth

Classical "performance work" is about capacity planning:

- Focus on server throughout and make sure they can handle the clients' requests (within the SLA), during peak load

Page Load Times
Broadband versus mobile



- **46%** of people say waiting for pages to load is what they dislike most about browsing the web on mobile
- **73%** of mobile users have encountered websites that take too long to load

measurement by Akamai

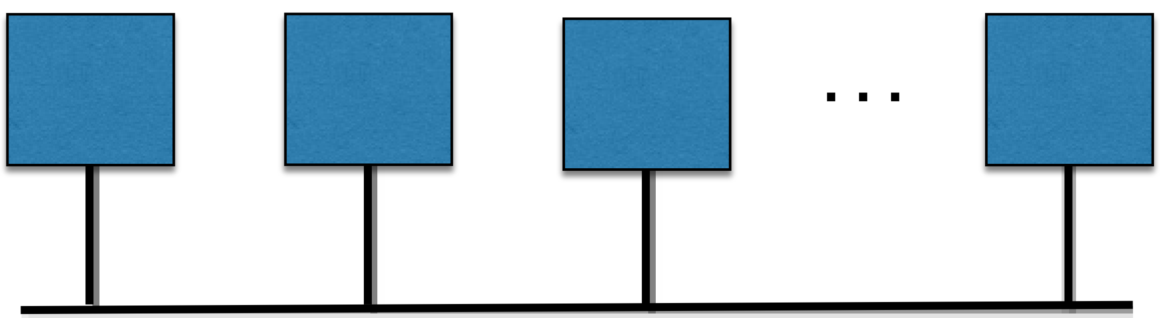
Country/Region	Avg. Page Load Time Broadband (ms)	Avg. Page Load Time Mobile (ms)	Mobile Penalty
Estonia	2297	2972	1.3x
Finland	2740	3826	1.4x
France	3457	3697	1.1x
Germany	2754	2752	1.0x
Greece	3754	4101	1.1x
Hungary	2169	2779	1.3x
Ireland	2581	3299	1.3x
Italy	5312	6636	1.2x
Latvia	2496	3060	1.2x
Lithuania	2254	2981	1.3x
Luxembourg	2717	2892	1.1x
Malta	2887	4645	1.6x
Netherlands	2315	2725	1.2x
Norway	2380	2933	1.2x

To understand what makes up page download times, we need to understand the basics of networking

Basics of Networking

- point-to-point

- multiple access

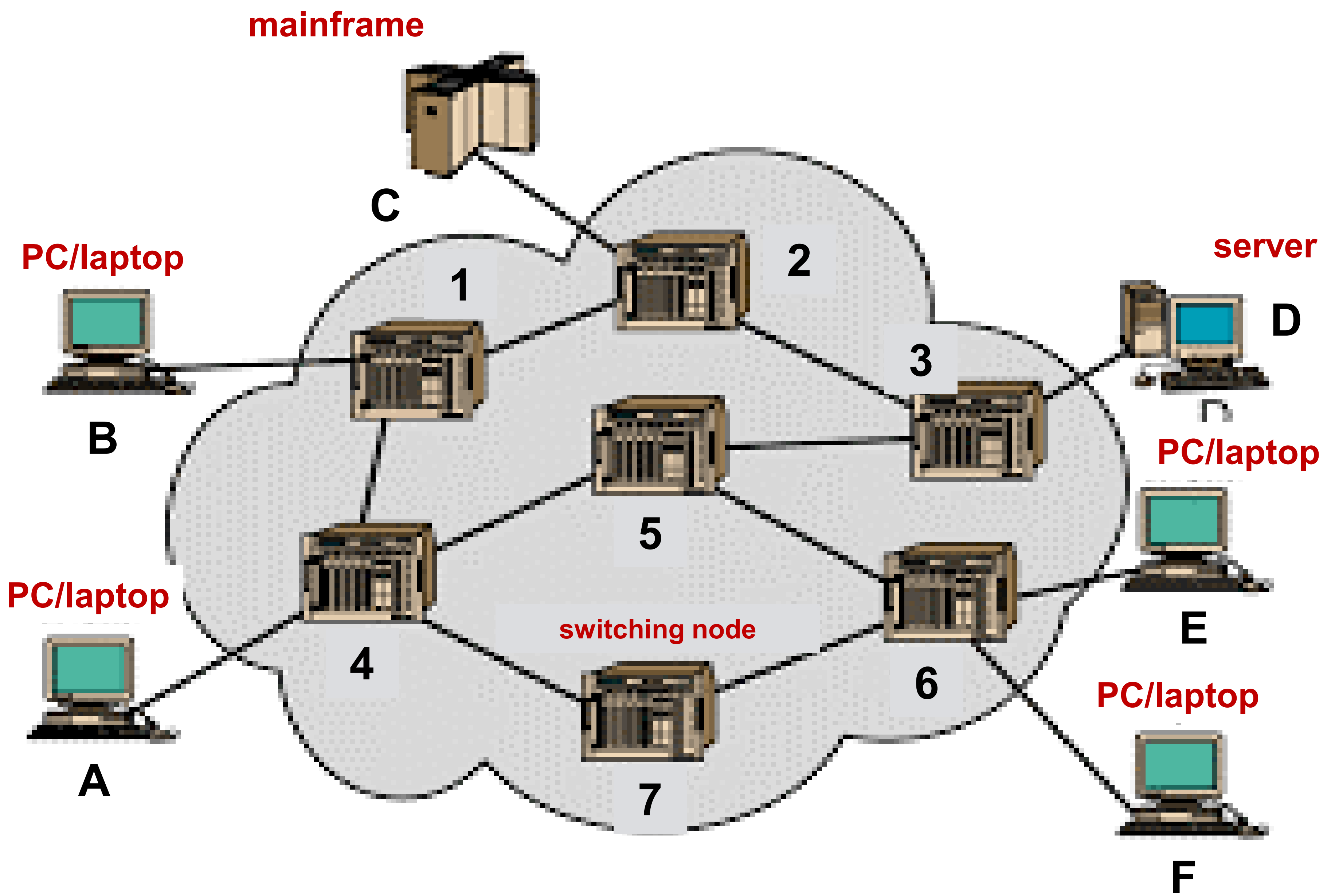


shared network

Nodes:
- laptops, phones, servers, routers, switches, printers

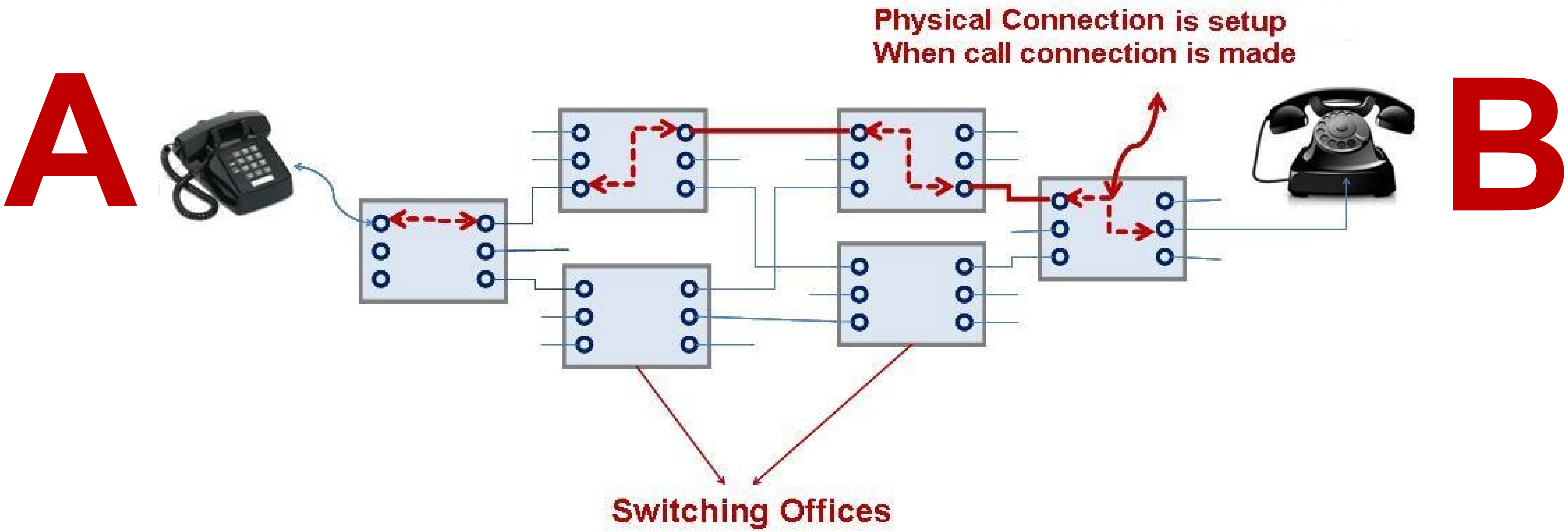
Connections:
- copper cable, optical fiber, wireless

Switched Networks



- Switches connect multiple links, with possibly more switches
- Fundamentally different ways to connect: **circuit vs. packet switching**

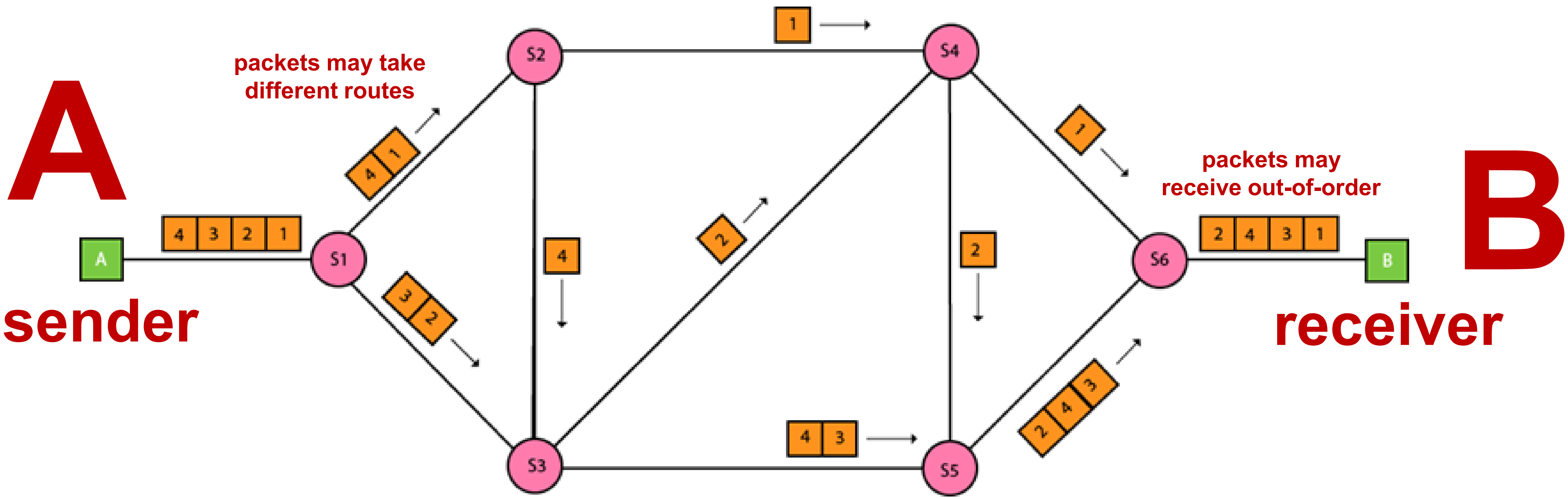
Circuit Switching



Circuit Switched networks set up a connection between A and B (with fixed bandwidth)

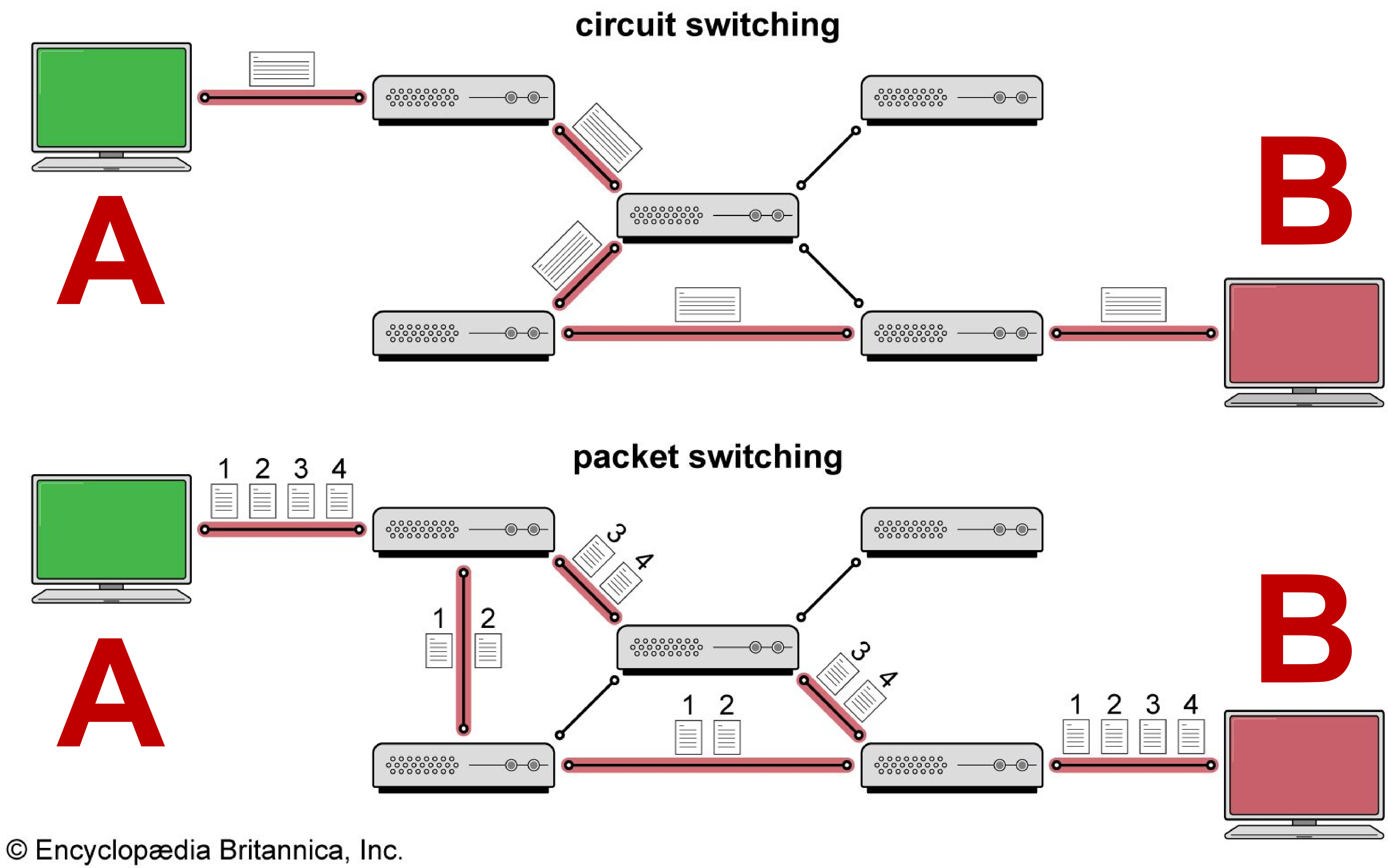
Examples: Plain Old Telephony Service (“POTS”), GSM

Packet Switching

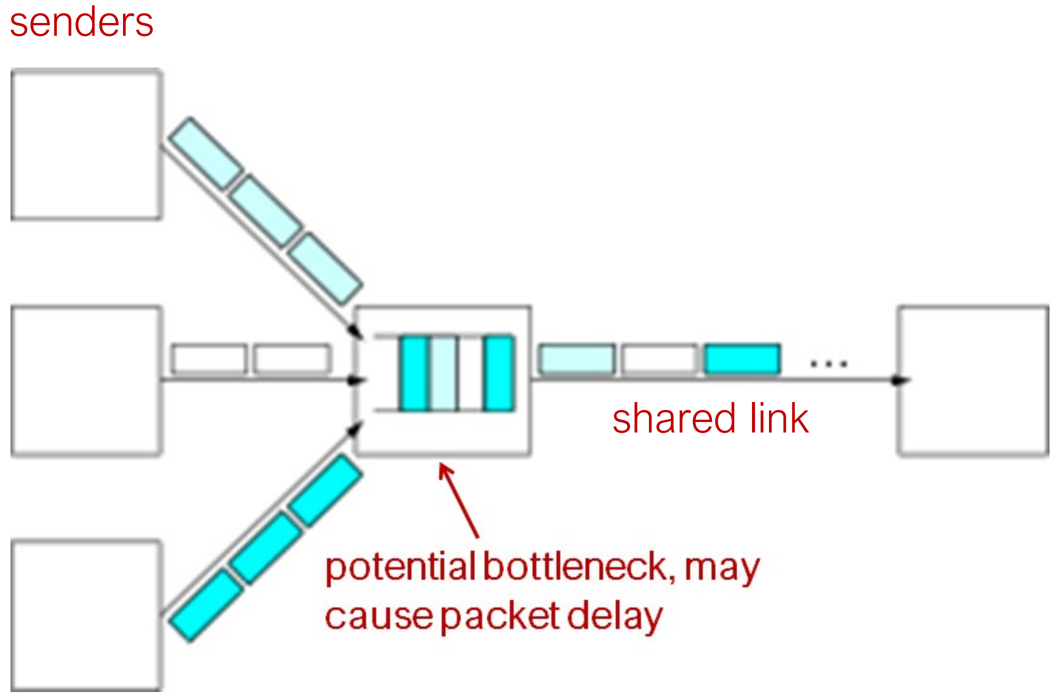


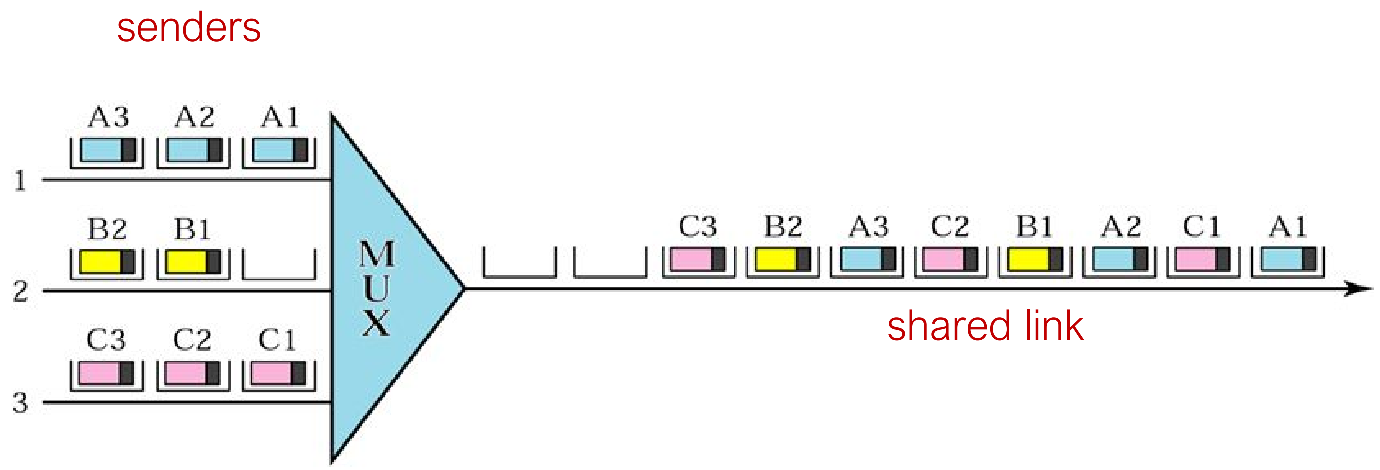
- Computer networks transmit **individual packets**
- Telephone networks have become packet-switched, too

Circuit Switching vs. Packet Switching



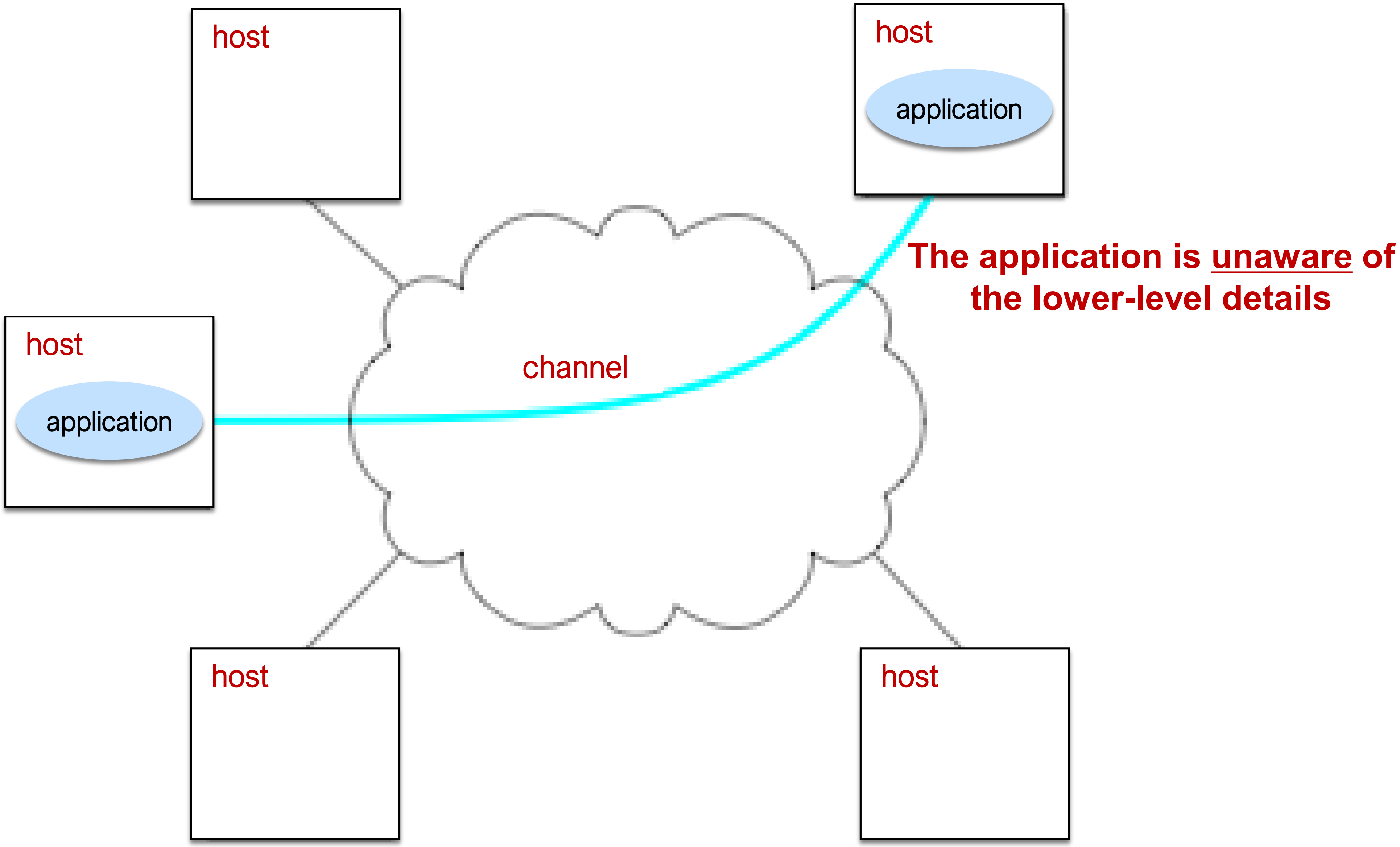
Statistical Time Division Multiplexing





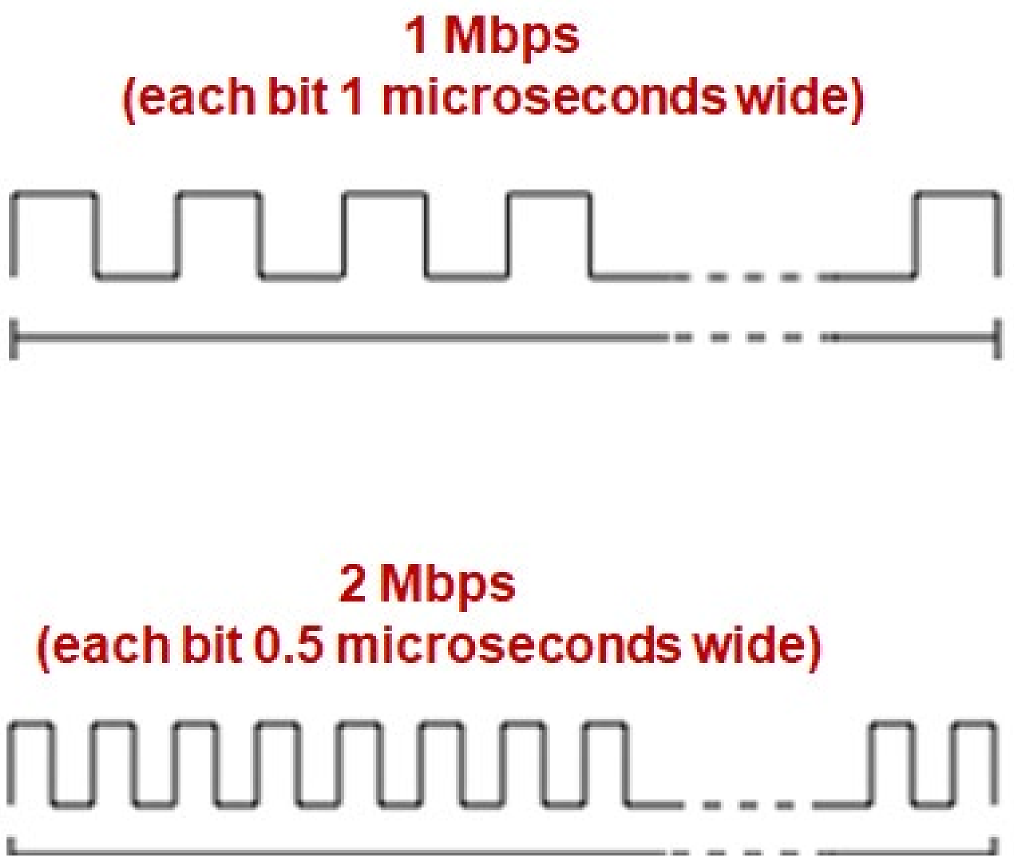
- Translates **streams** to **packets** (sent over shared a link)
- Packet switching, typically “first come first served"
- Optimizes network utilization, but may cause **delay**
- In IP networks: no guarantees on the QoS: “**best-effort delivery**”

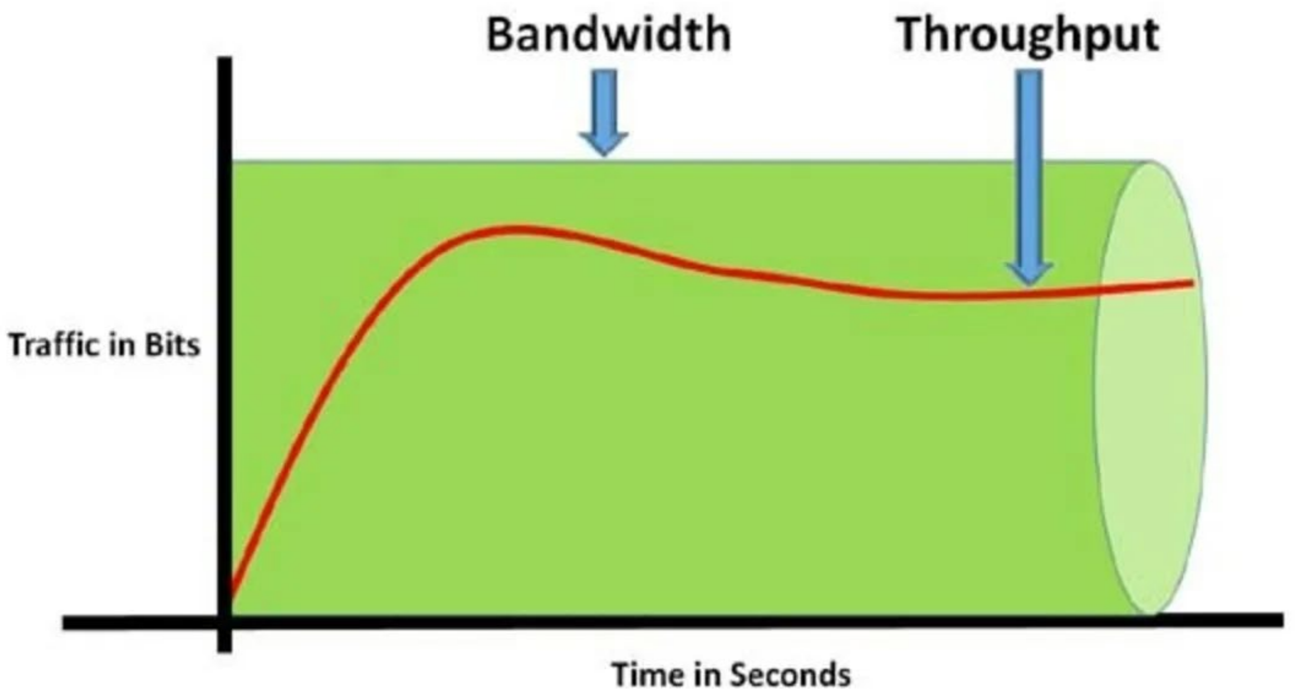
Application View of the Network



- Pairs of processes communicate via streams/channels
  - for example: mail client and mail server
- This is the model provided by the so-called **TCP protocol**

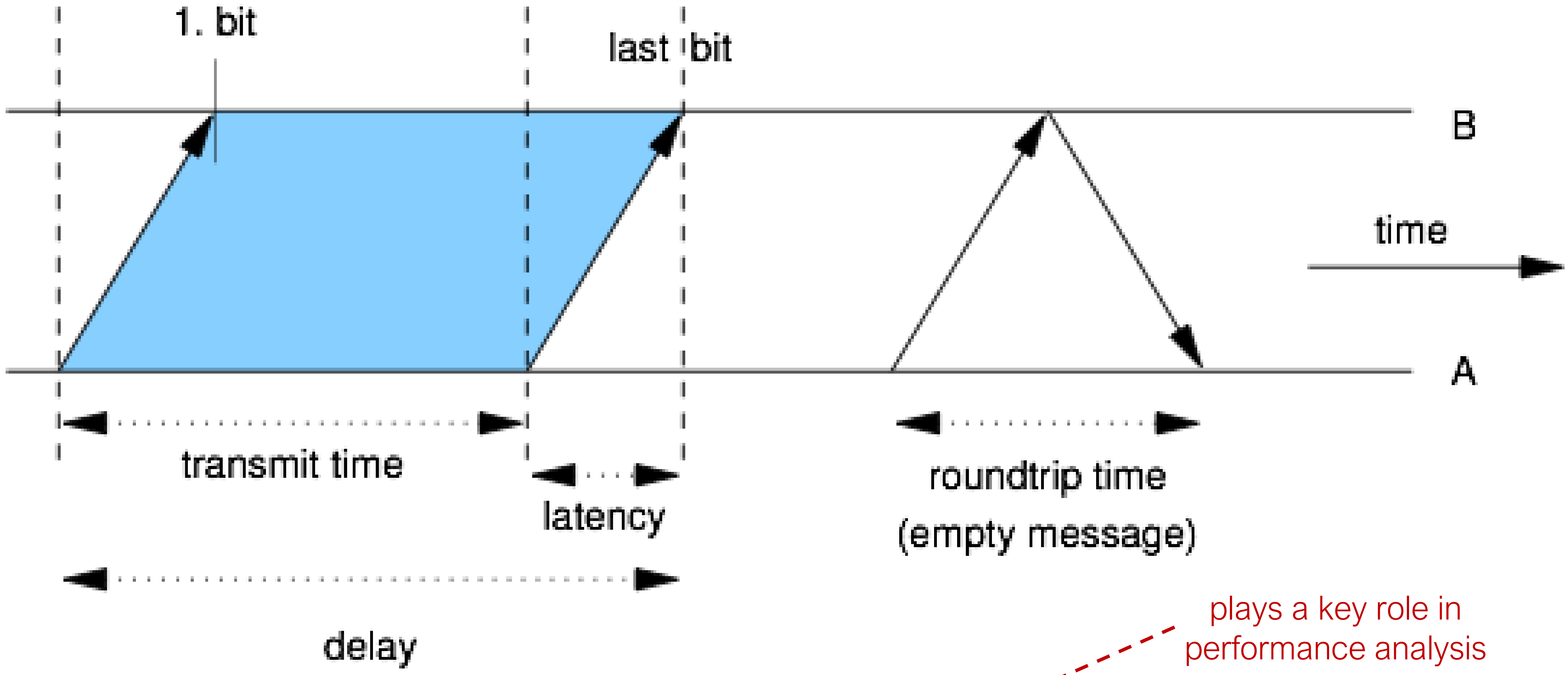
Bandwidth and Throughput





- **Bandwidth:** data transmission rate ("theoretical")
- **Throughput** (or "goodput"): actually **achieved** bandwidth

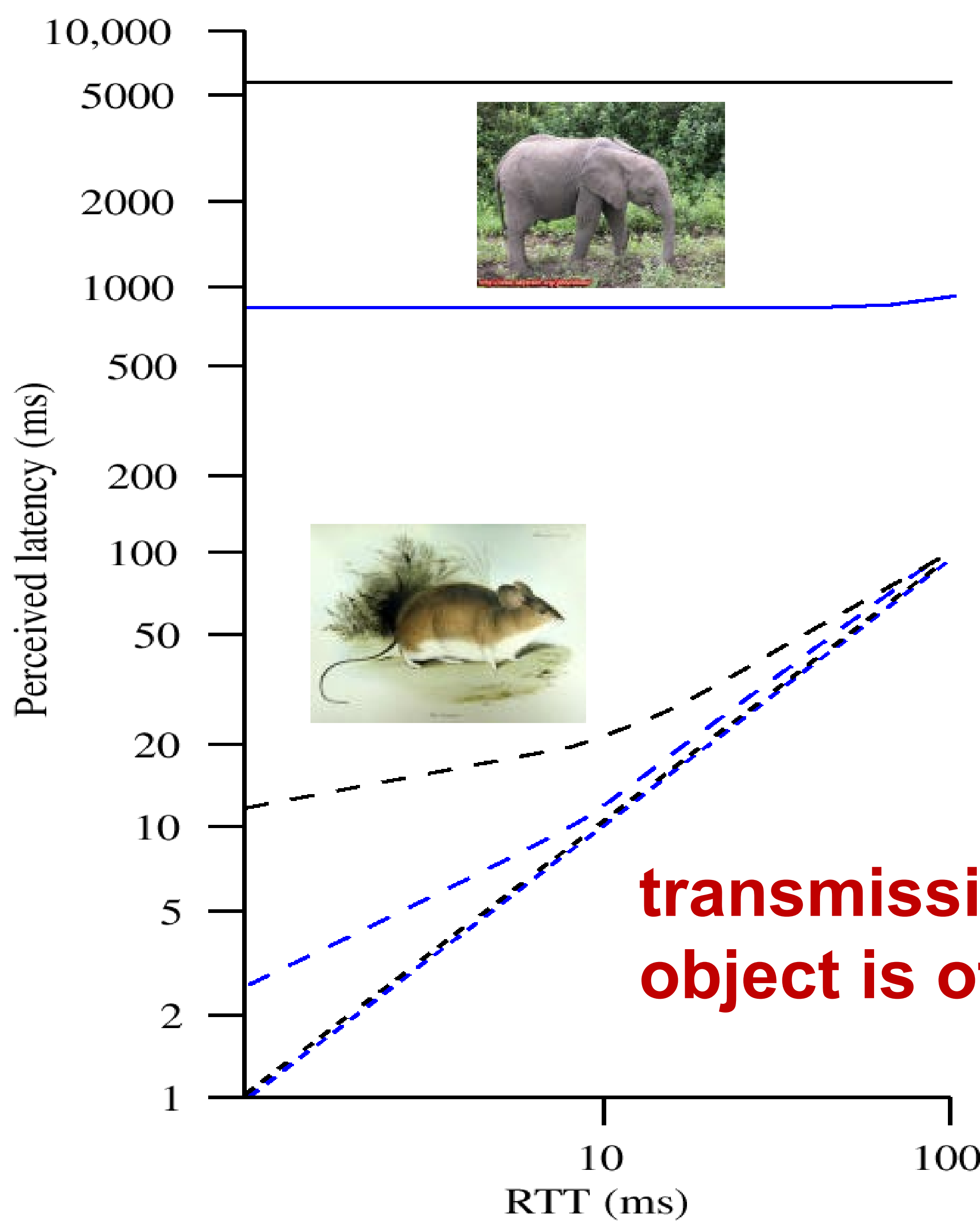
Latency, Delay and Round-Trip Times (RTT)



plays a key role in performance analysis

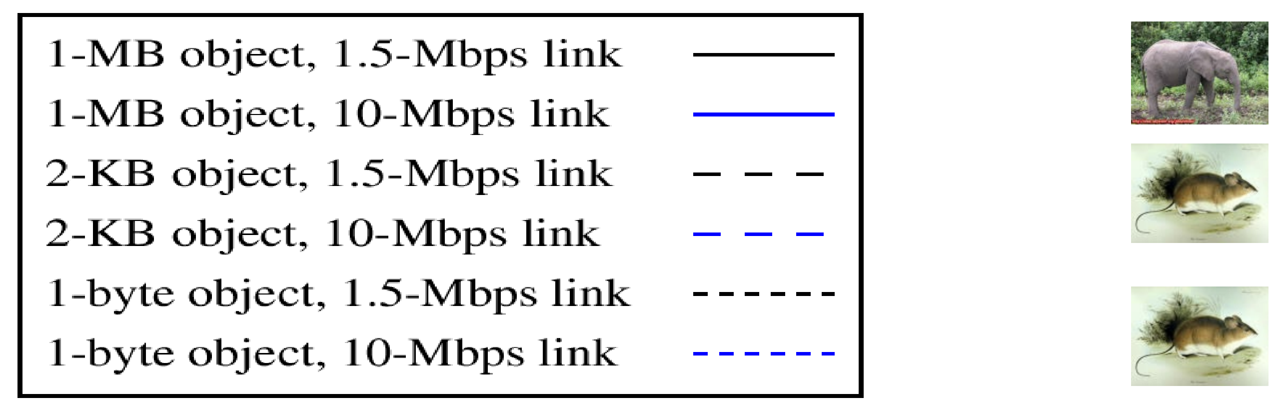
- **latency** = signal propagation + **queueing**
- **signal propagation** = distance / speed of light
- **transmit time** = message size / bandwidth

Bandwidth-bound versus Delay-bound



transmission of <u>large</u> object is often <u>bandwidth-bound</u>

throughput is a key performance metric



transmission of small object is often delay-bound

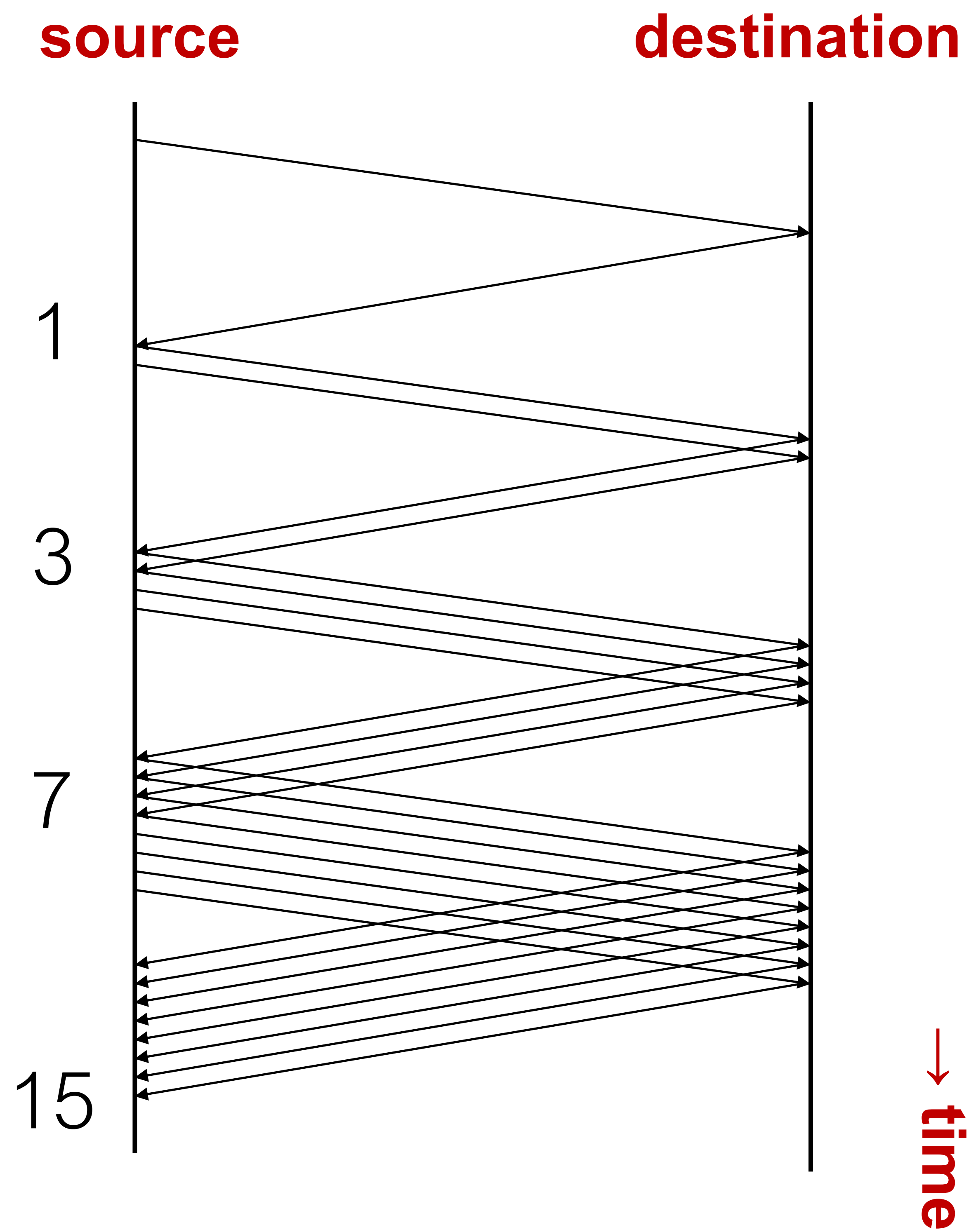
Mice and Elephants

- **Objects downloaded over the Internet are typically either very small, or very large**

- **Small ("mice"): few kBytes**
  - mail, messages, simple Web pages,…

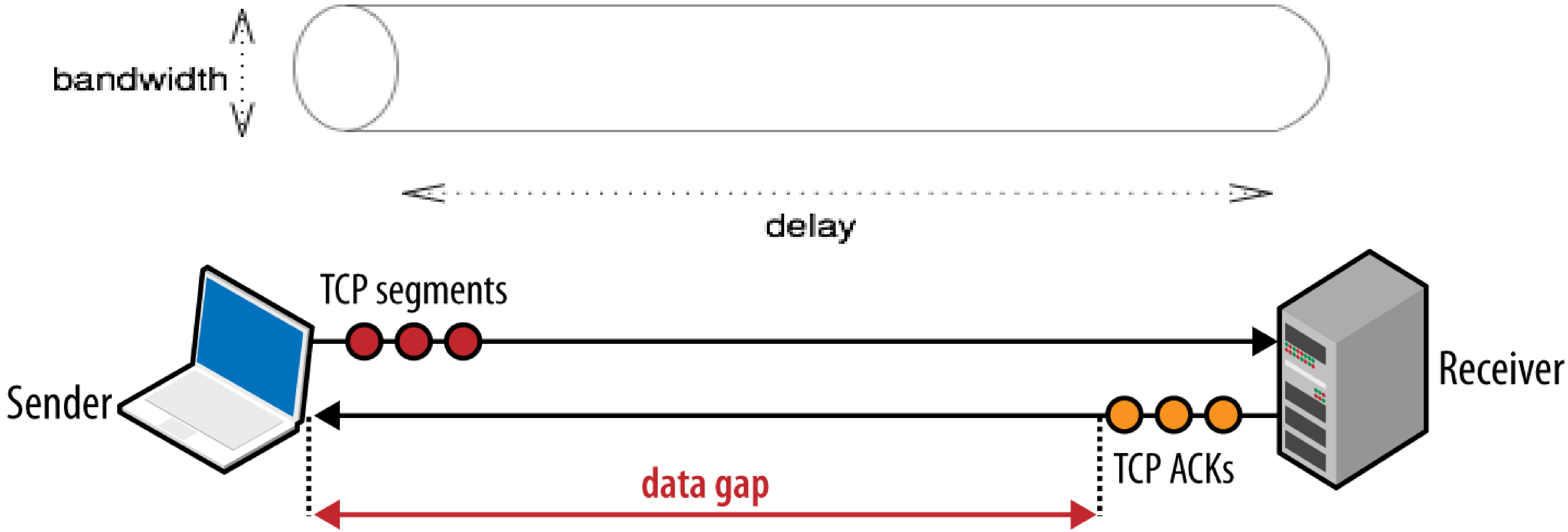
- **Large ("elephants"): many Mega/Giga/Tera-bytes**
  - videos, large documents, scientific measurement data…

Mice Transmission Times



- Small objects consist of small number of packets
- TCP download is typically performed in **Slow Start phase** (see course on TCP/IP)

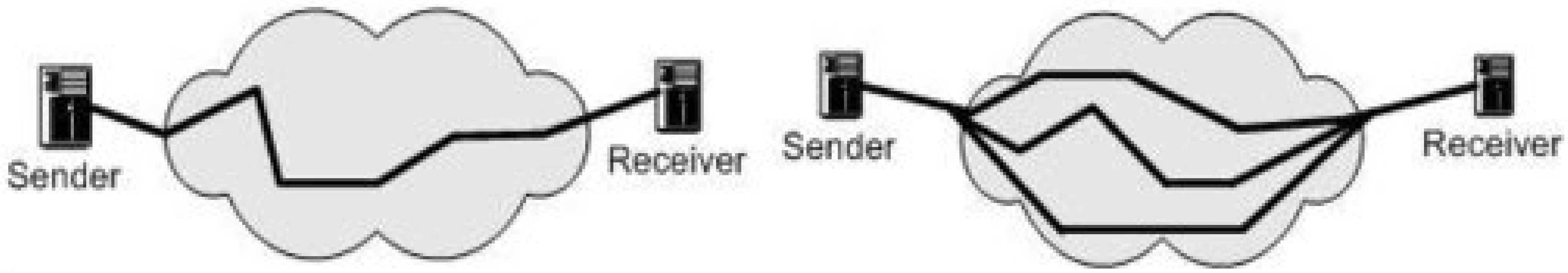
Bandwidth-Delay Product (BDP)



- **Flow control** in place to avoid overloading the receiver
- **Window size** = number of not yet acknowledged packets
- **BDP = bandwidth x RTT = maximum congestion window size**

$$\text{maximum throughput of a TCP connection} = \frac{\text{maximum window size}}{\text{RTT}}$$

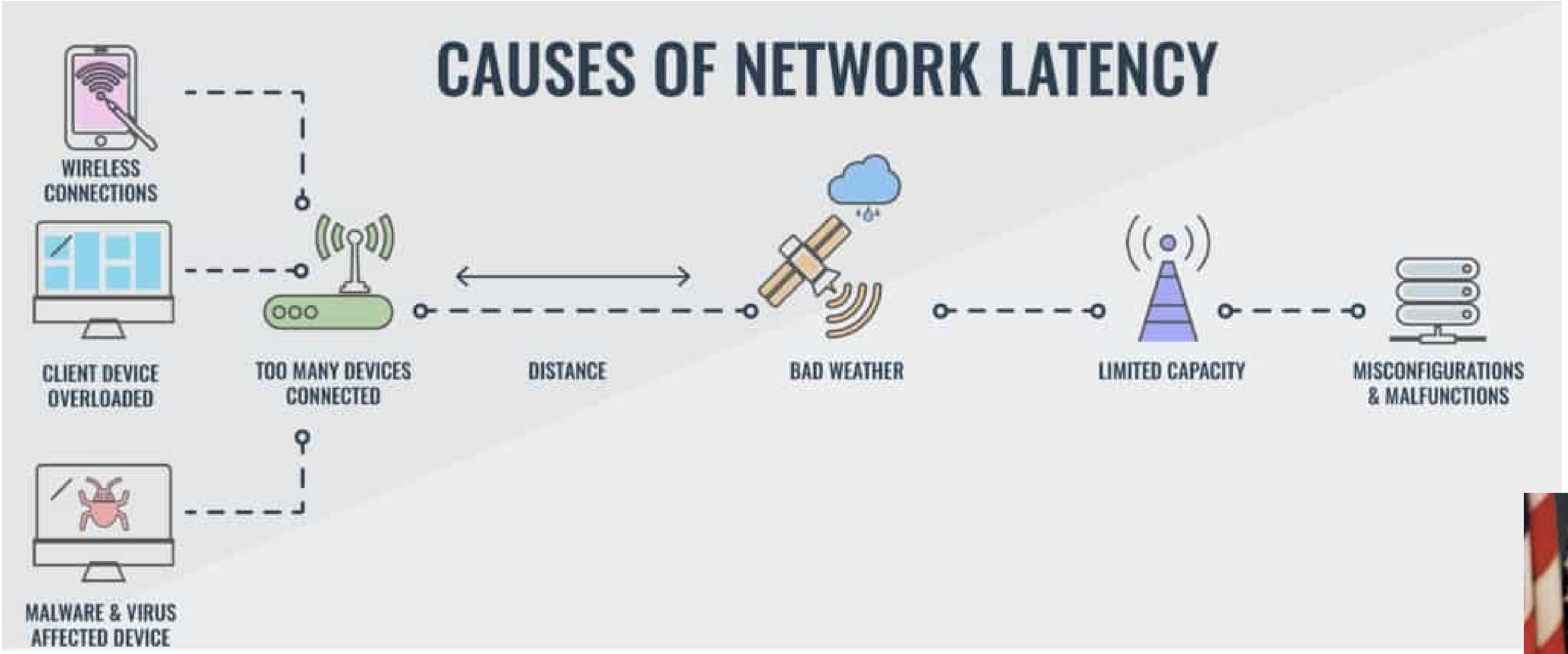
Bandwidth is Overrated



Single path connection vs. multipath connections

- It is relatively simple to increase bandwidth
  - e.g., use **more than one link in parallel**
  - optical fiber is improving, and so are wireless technologies
- In the Internet core, a single optical fiber can handle 400 wavelengths with 171 Gbit/s per channel, in total >70 Tbit/s

It's the Latency, Stupid!



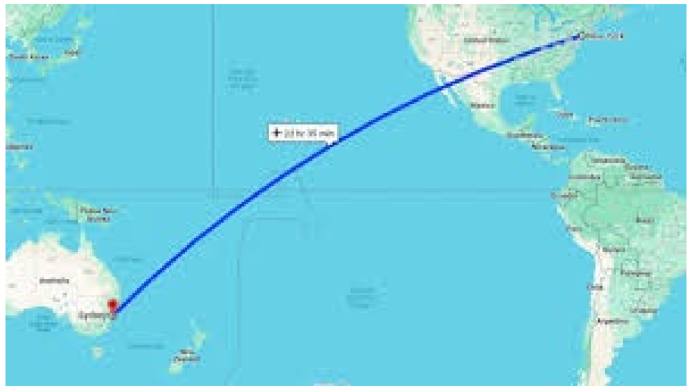
Components of delay (also known as "latency")

- **propagation** delay (signal propagation, depending on physical distance)
- **transmission delay** (packet length / bandwidth)
- **processing delay** (time required to process a packet like framing, forwarding)
- **queueing delay** (time a packet waits in queues)

Signal Latencies

Route	Distance	Time, light in vacuum	Time, light in fiber	RTT in fiber
New York to San Francisco	4,148 km	14 ms	21 ms	42 ms
New York to London	5,585 km	19 ms	28 ms	56 ms
New York to Sydney	15,993 km	53 ms	80 ms	160 ms
Equatorial circumference	40,475 km	133.7 ms	200 ms	400 ms

- Signal latency is determined by the **laws of physics**
- We can not do anything about that
- Speed of light in vacuum: 3×10^8 m/s
- Speed of light in fiber/copper: 2×10^8 m/s

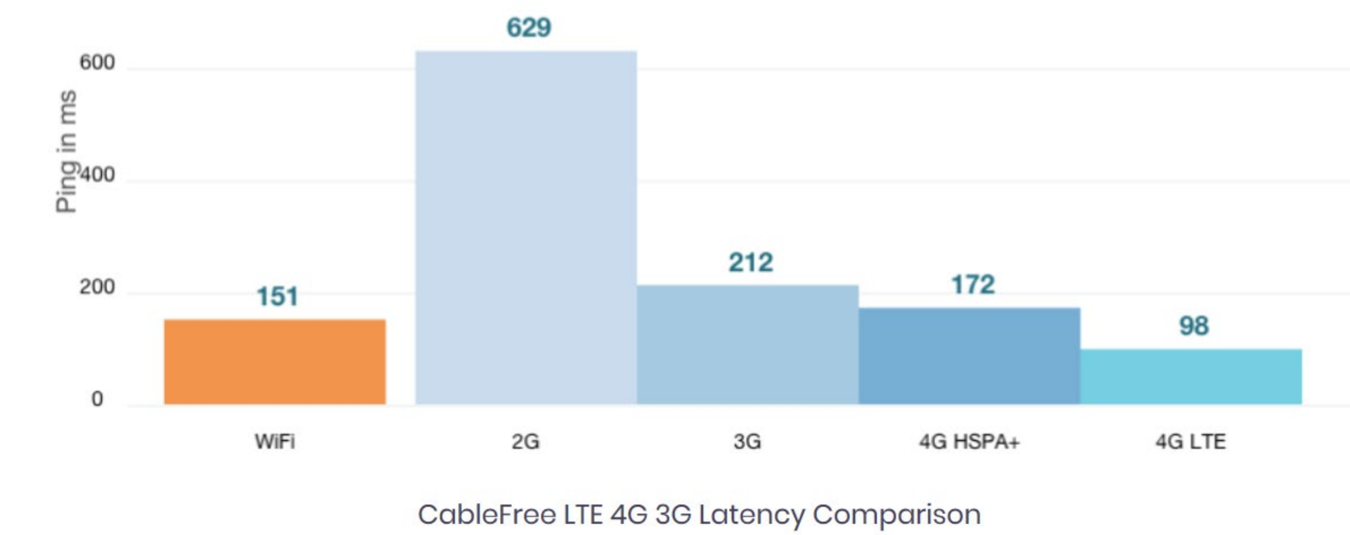


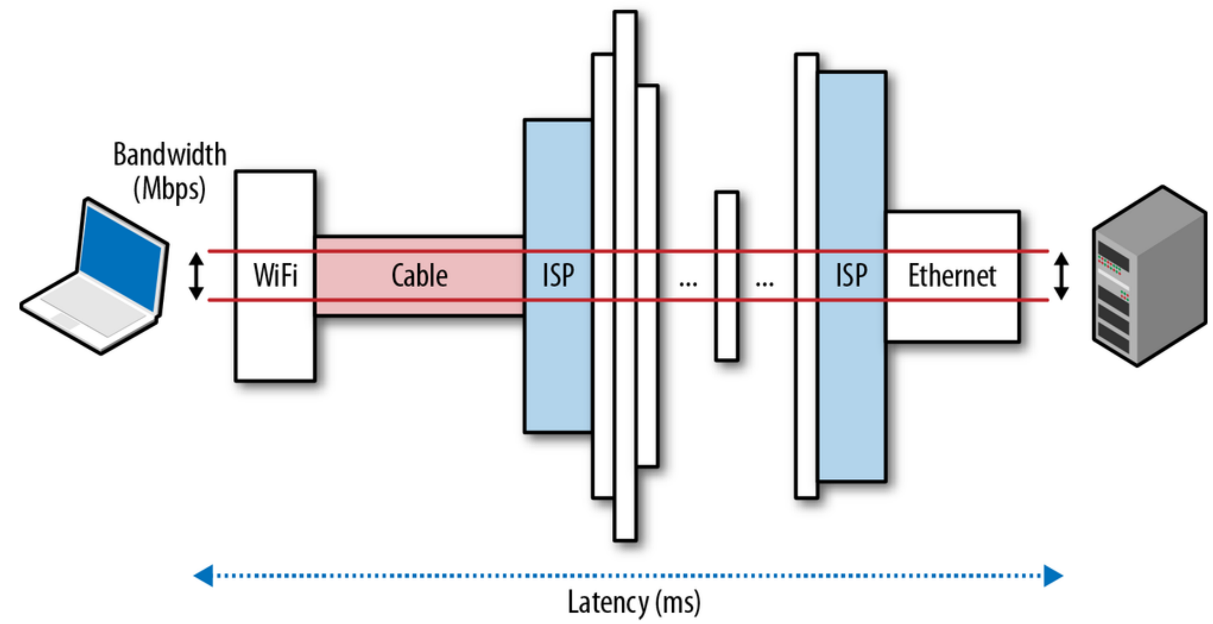
Packet Latencies in Practice

Route	Distance	Time, light in vacuum	Time, light in fiber	RTT in fiber
New York to San Francisco	4,148 km	14 ms	21 ms	42 ms
New York to London	5,585 km	19 ms	28 ms	56 ms
New York to Sydney	15,993 km	53 ms	80 ms	160 ms
Equatorial circumference	40,475 km	133.7 ms	200 ms	400 ms

- **Signal latencies** cover physical distance only
- Actual wires follow **longer paths** due to geographic, political, or even commercial reasons
    - each hop (router) on the path adds processing overhead
- In practice, the RTT between New York and Sydney is more like 200-300 ms, rather than 160 ms (still pretty good)

Last Mile Latency





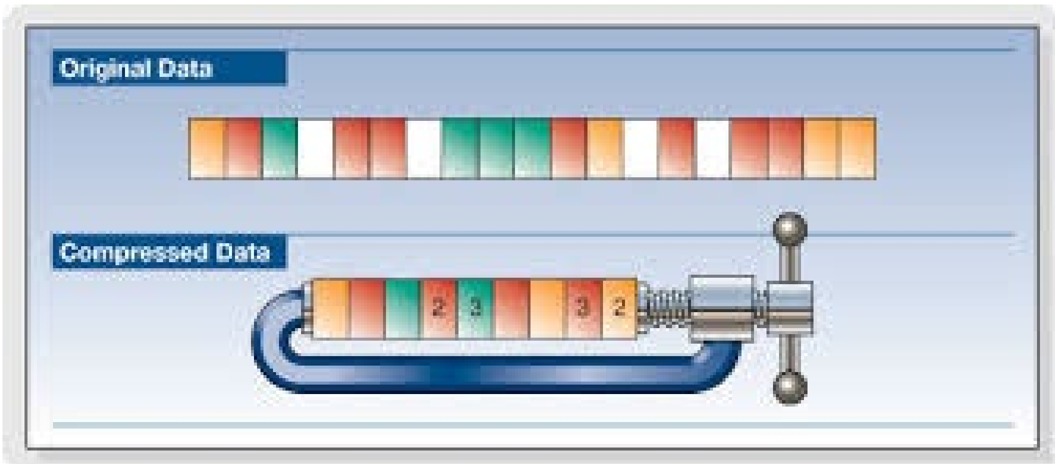
- While global links (e.g. undersea cables) show latency close to physical signal propagation, the connection from customers to their ISP add significant latency

- “Last mile” problem

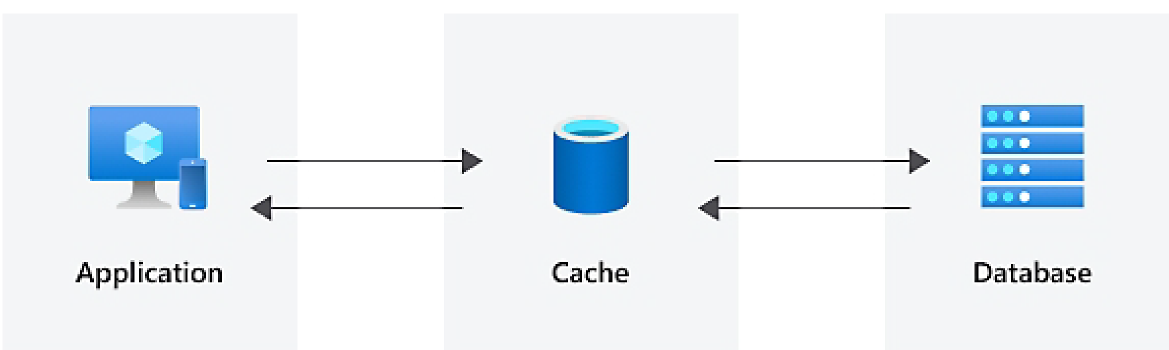
- Other measured latencies over **wired** technologies:
  - fiber-to-the-home: 18 ms
  - TV cable: 26 ms
  - DSL: 44 ms

Low Bandwidth at the Network Edge

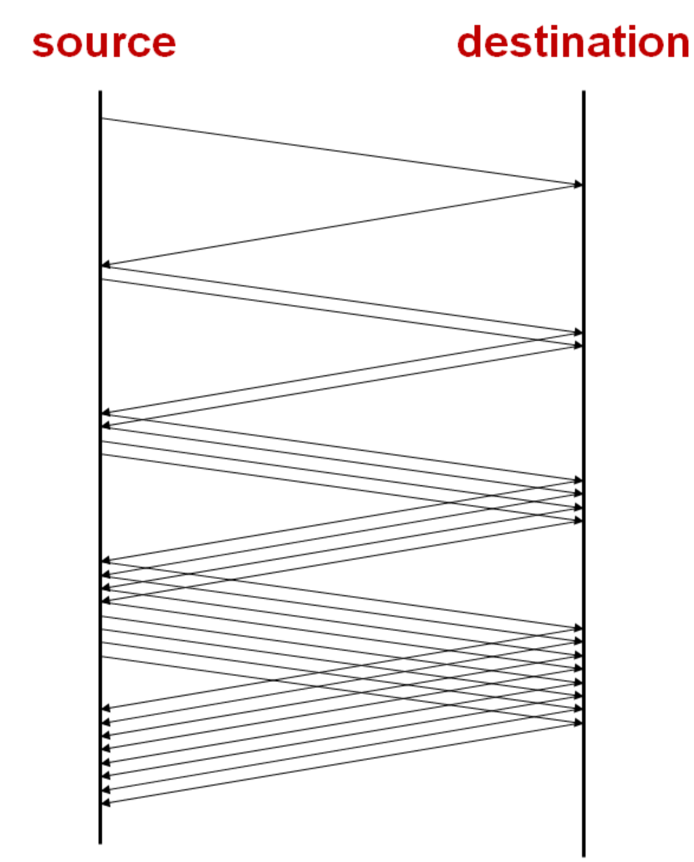
Compression



Caching



Overhead



How to deal with low bandwidth (“work arounds”)?

- use data compression → send less data
- reduce networking overhead → example: selective acknowledgments
- use caching: store “local” copies to avoid

Human Perception of Delay

MOS	R-values	Quality	Impairment
4.5	90-100	excellent	Imperceptible
4	80-90	good	Perceptible, not annoying
3	70-80	fair	Slightly annoying
2	60-70	poor	Annoying
1	0-60	bad	Very annoyoing

Example E-model classification of standardized Mean Opinion Scores for Voice-over-IP

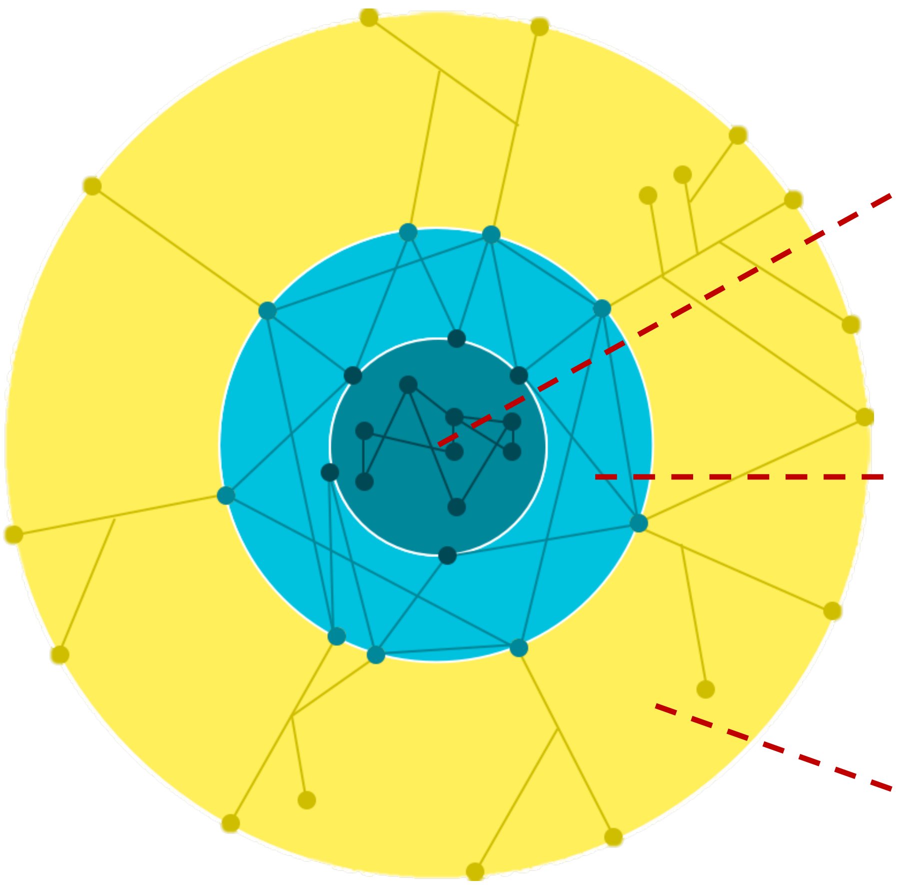
Aad de Mos

1. Humans **notice delay** of 100-200 ms
2. > 300 ms is reported as "sluggish"
3. > 1000 ms make users think about other things

Content Delivery Networks (CDN's) bring content closer to the user by a **global network of local replicas**

Google’s CDN

Hierarchical structure

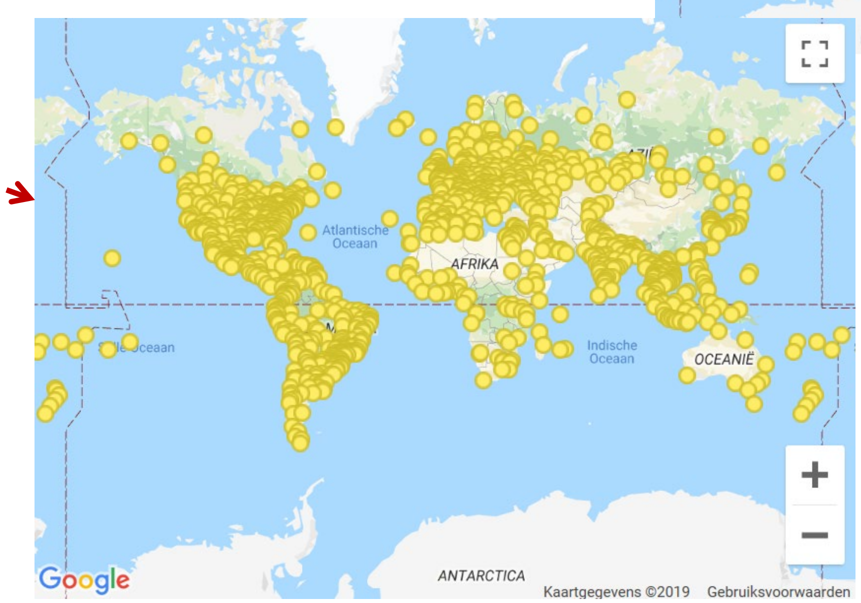


- Core data centers
- Edge Points of Presence (PoPs)
- Edge caching and services nodes (Google Global Cache, or GGC)

Data centers

Edge Points of Presence (PoPs)

Edge global cache



https://peering.google.com/#/infrastructure

Latency, not Bandwidth, is the Bottleneck for Websites

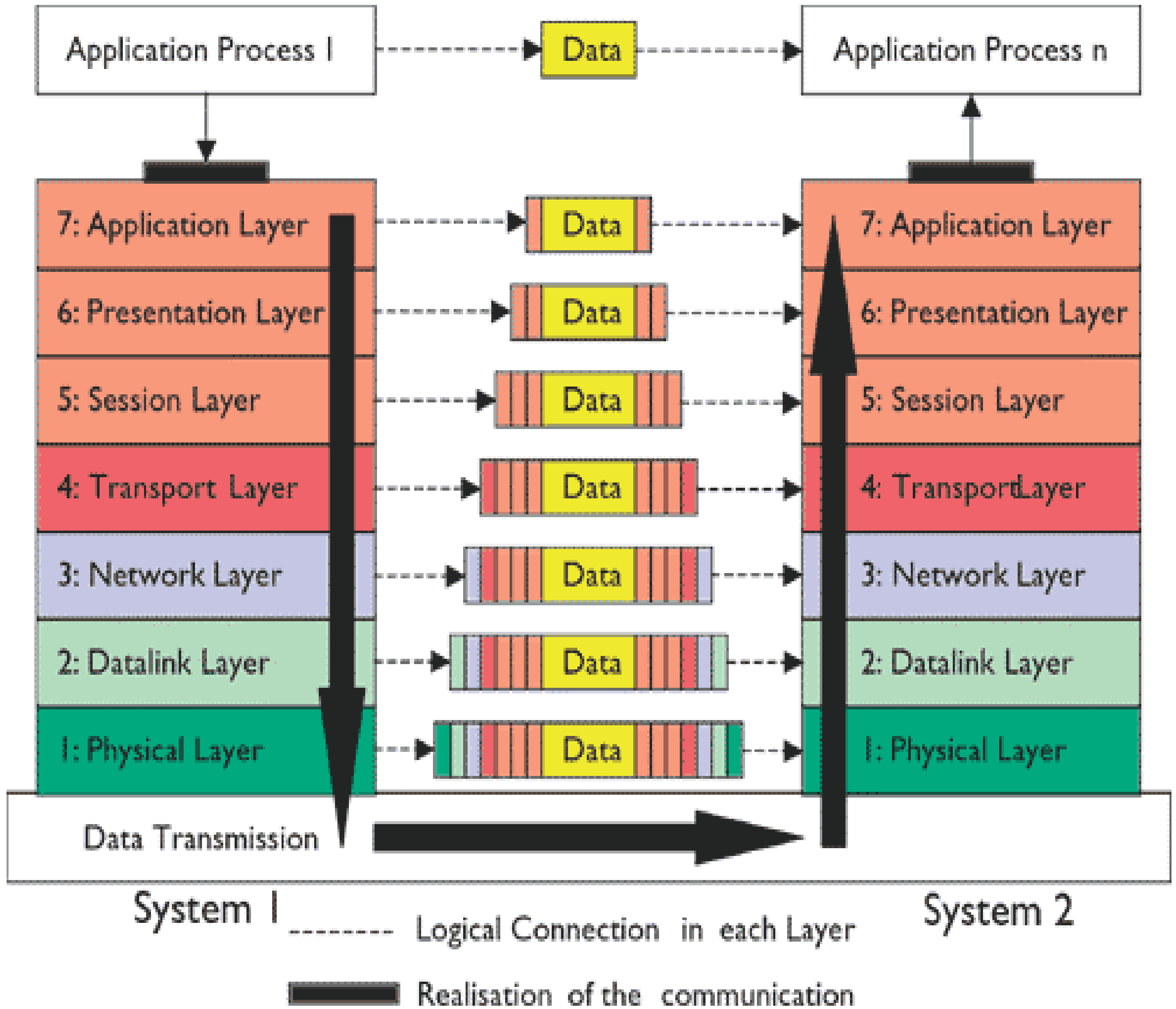
- For understanding **why**, we need to study the mechanics of the TCP and HTTP protocols

- The **problem** is that **we can not lower network latency** (much), so our applications need to work around it in a smart way

- We also need **some basic understanding** of how packets are handled in client and server, and the processing delay caused by it

OSI Reference Model

7 Layers



HTTP, FTP, browsers — supports application and end-user processes

JPEG, MPEG — transform data into the form that the application layer can accept

NFS — establishes, manages and terminates connections between application

TCP, UDP — flow control, data transfer between end systems (hosts)

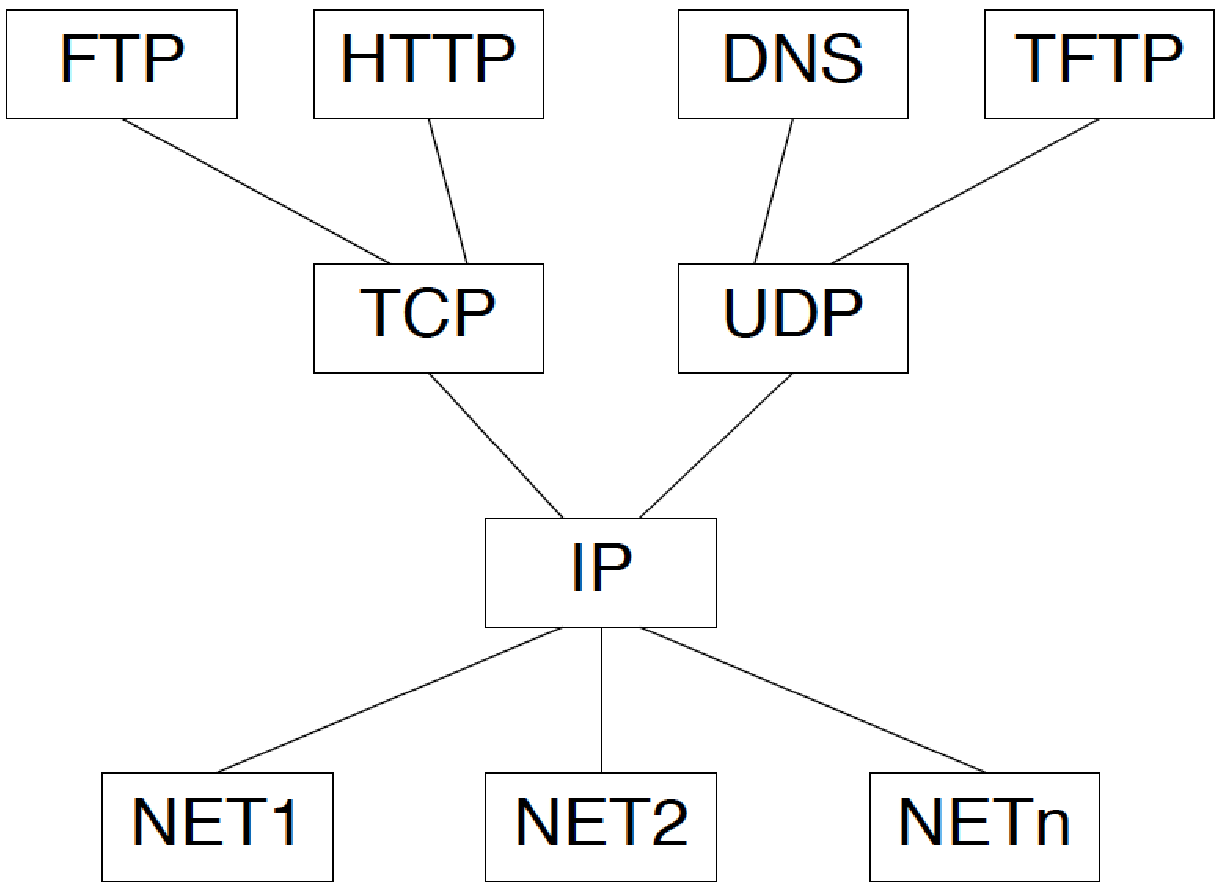
IP — switching, routing between nodes

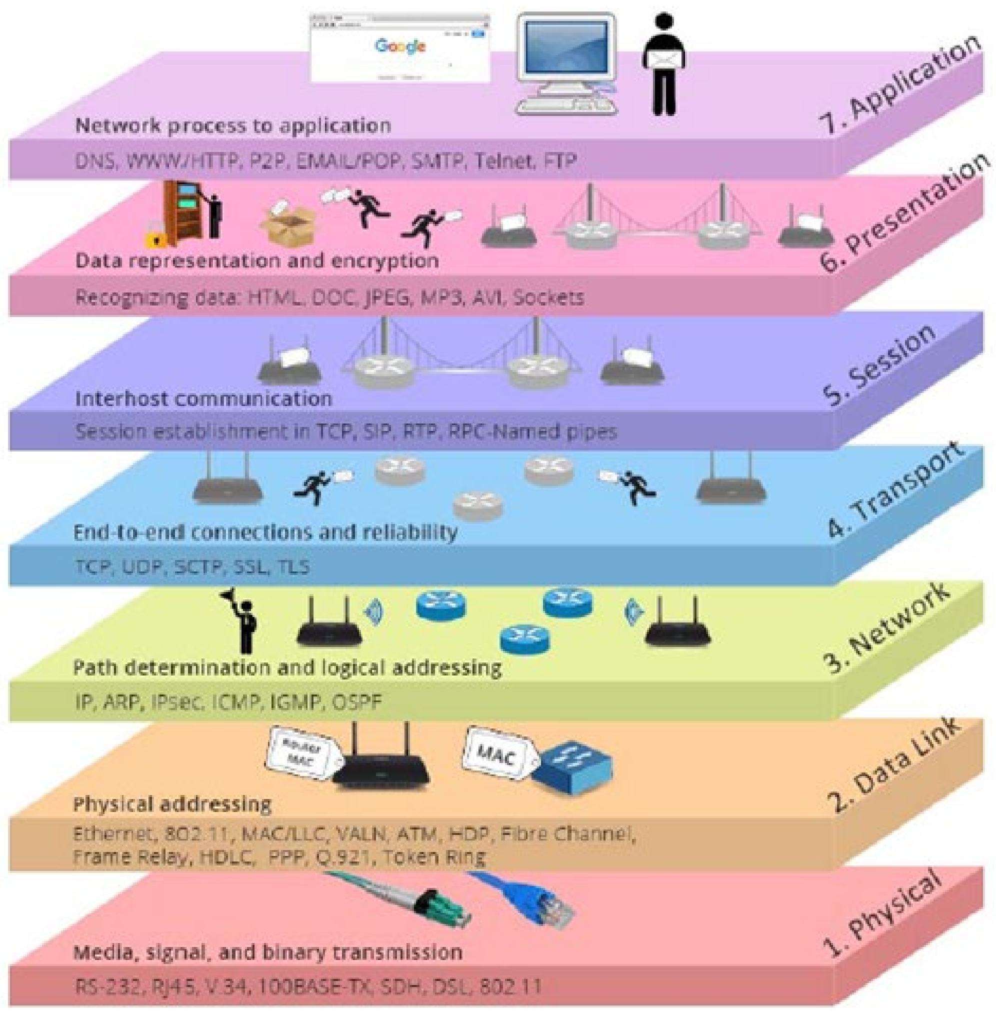
802.11, ATM — medium access control synchronization, error checking

RS232 — hardware, cables

- OSI stack is a standard for how communication networks work
- Different layers of abstraction
- Encapsulation

IP as generic protocol that runs over all networks





“hour-glass model”

OSI reference model

Wrap-Up

Wrap-up of today's lecture

1. Examples of performance degradation
2. Performance-critical systems
3. Course overview
4. Basics and networking principles
5. Bandwidth versus latency
6. OSI reference model

Background reading material for this week:
I. Grygorik, "High Performance Browser Networking", chapter 1

Next lecture:
Introduction to performance modeling