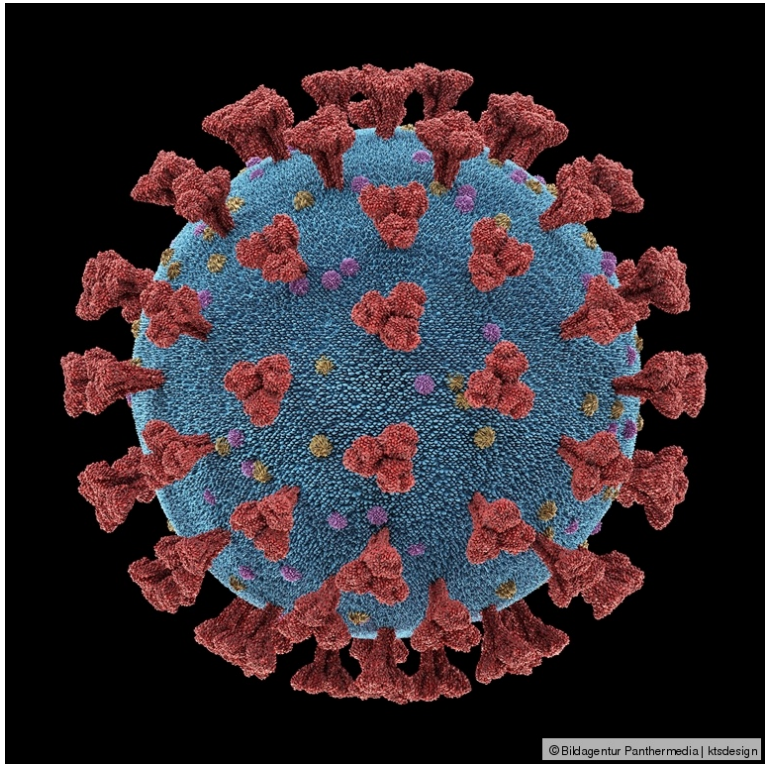
COVID-19 Measures

- Always wear a mask (medical or FFP2)
- Open the windows periodically whenever possible
- Maintain an interpersonal distance of at least 1.5 m
- Behave reasonable and use common sense



Computer Networks

Introduction

Prof. Dr. Oliver Hahm

Frankfurt University of Applied Sciences
Faculty 2: Computer Science and Engineering
oliver.hahm@fb2.fra-uas.de
https://teaching.dahahm.de

October 26, 2021

Agenda

- About this lecture
- Historical background
- Components and Terms
- Reference Models
- Topologies

Agenda

Interaction in this Lecture

- Participate lively
- Ask questions!
- A key attribute for science is scepticism

Source: public domain

"Education is a dialogue not a one way monologue" [1]

[1] JNICSR Times, http://jnicsrtimes.com/?p=1476

About me

- Study of Computer Science at Freie Universität Berlin
- Software Developer for ScatterWeb and Zühlke Engineering
- Research on IoT and Operating Systems

Contact

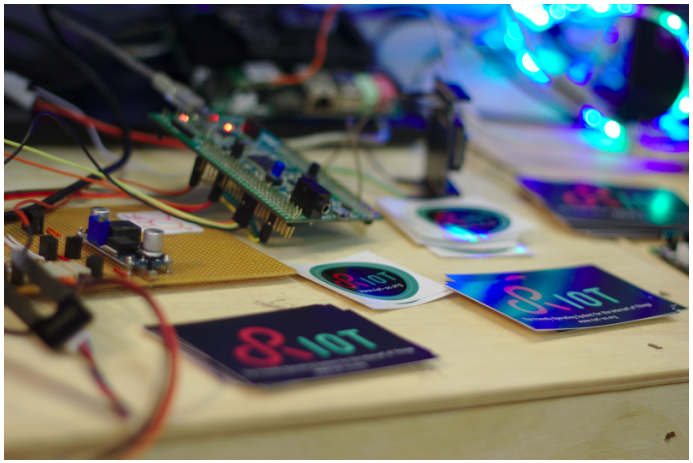
E-mail: oliver.hahm@fb2.fra-uas.de

Office hours: Tuesdays 14:15 – 15:15, room 1-212

Join the RIOT!

You're interested in ...

- ... programming the IoT?
- ... collaborate with hundreds of people from all over the world?
- ... contribute to a big FLOSS project?



Contact me or meet the community at
`https://riot-os.org/community.html`

Organizational

- Lecture: Tuesday 10:00 – 11:30, room 4-8
- Exercises
  - Tuesday 11:45 – 13:15, room BCN-421
  - Tuesday 16:00 – 17:30, room 1-235
  - Wednesday 10:00 – 11:30, room 1-234
  - Wednesday 11:45 – 13:15, room 1-234
  - Thursday 14:15 – 15:45, room 1-235
  - Thursday 16:00 – 17:30, room 1-235
- Written exam

Moodle

Enrolment Key:
`CompNetHahm`

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Moodle

Enrolment Key:
`CompNetHahm`

Please note!

- There is no registration for the exercises, but the room size is limited!
- First come, first serve!
- There is a dedicated lecture and exercise for students of Mobile Applications

Further Information

Course page

All material regarding this course can be found at `https://teaching.dahahm.de`.

This includes

- Announcements
- Slides
- Exercises

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- Exercises

Do not ask!

Everything is relevant for the exam.

Slides

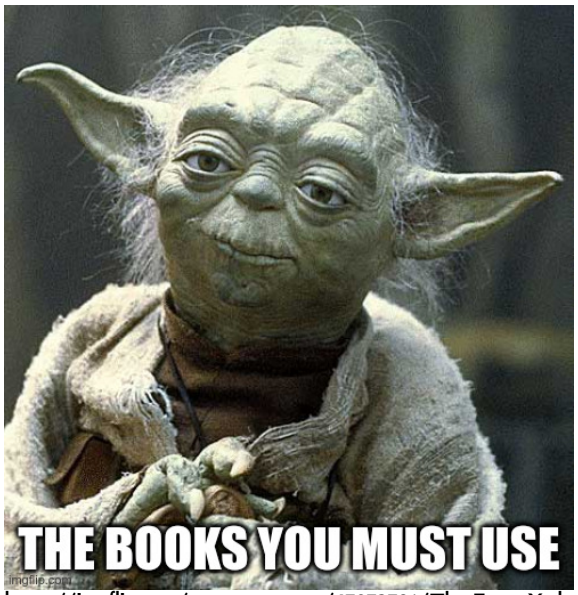
- The creation of the slide sets is work in progress
- They cover all topics of the lecture
- **BUT** they are no book and, hence, do not comprise
  - all details
  - all derivations
  - all thoughts and discussions which are part of the lecture and exercises

⇒ participate

⇒ ask questions

⇒ take notes

⇒ do your own research (e.g., use the books)

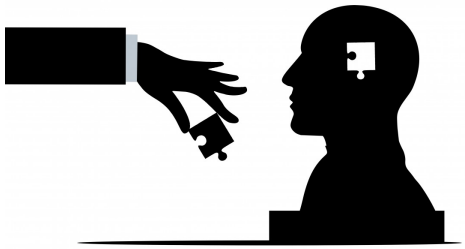


https://imgflip.com/memegenerator/47973781/The-Force-Yoda

Exercises

The exercises are no legal precondition for participating in the exam, **BUT** they...

- ...are very important to recap the content.
- ...are a good opportunity to check your understanding.
- ...provide the chance to ask me all your questions.



Exam

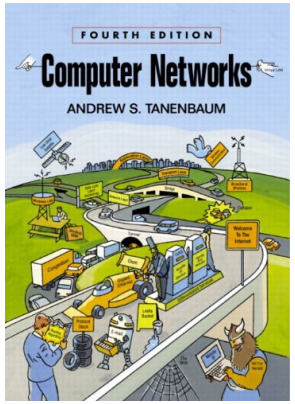
What is necessary to pass the exam?

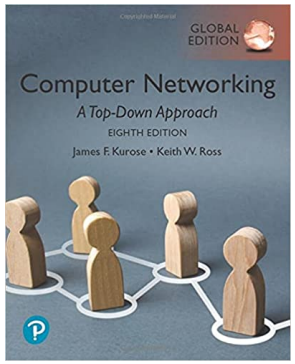
You should be able to ...

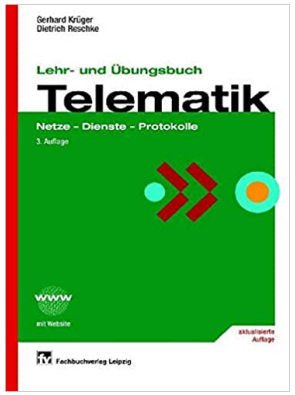
- explain main concepts and ideas with your own words,
- select a suitable solution for a given problem,
- analyze a given solution and detect (potential) problems, and
- explain your answers.

Literature

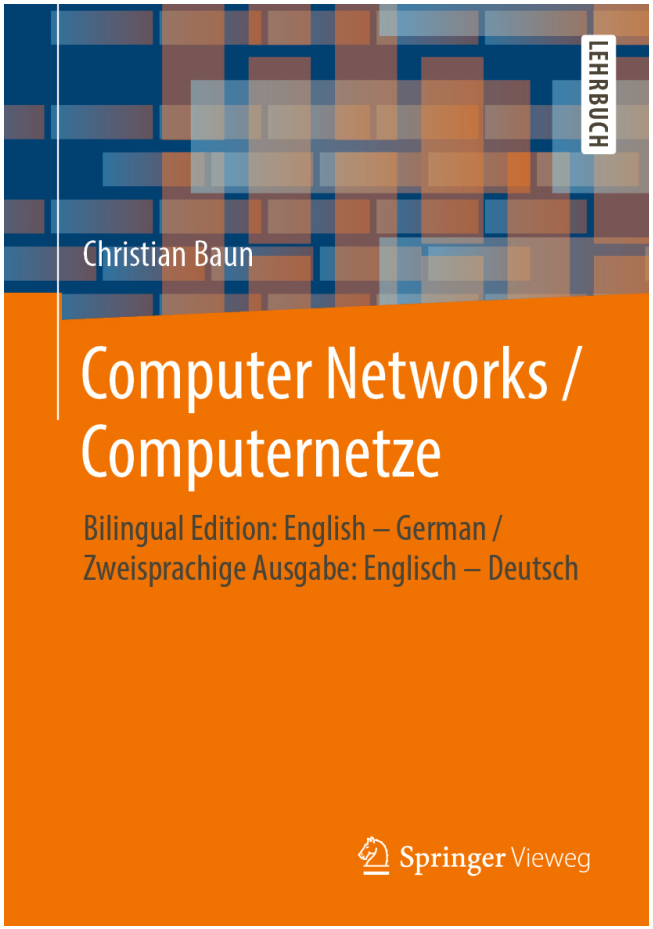
- Andrew Tanenbaum, David Wetherall: *"Computer Networks"*, 5th Ed., Pearson, 2011.
- James F. Kurose, Keith Ross: *"Computer Networking"*, 8th Ed., Pearson, 2021.
- G. Krüger, D. Reschke: *"Lehr- und Übungsbuch Telematik"*, 3th Ed., Hanser, 2004. (**German**)







More Literature



- Parts of the slide sets are closely related to the books.
- The two-column layout (English/German) of the bilingual book is quite useful for this course

You can download both books for free via the FRA-UAS library from the intranet

The Relevance of Computer Networks

[2] License: https://creativecommons.org/licenses/by/2.0/deed.en

The Relevance of Computer Networks

- Video streaming
- Online gaming
- Instance messengers
- Video conferences ($\rightarrow$ home office)
- Mobile communication
- Smart home ($\rightarrow$ IoT)
- Car infotainment

Author: Senado Federal

https://bit.ly/3jB5yRe

https://bit.ly/3EgpLnq

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The most popular network?

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https://bit.ly/3EgpLnq

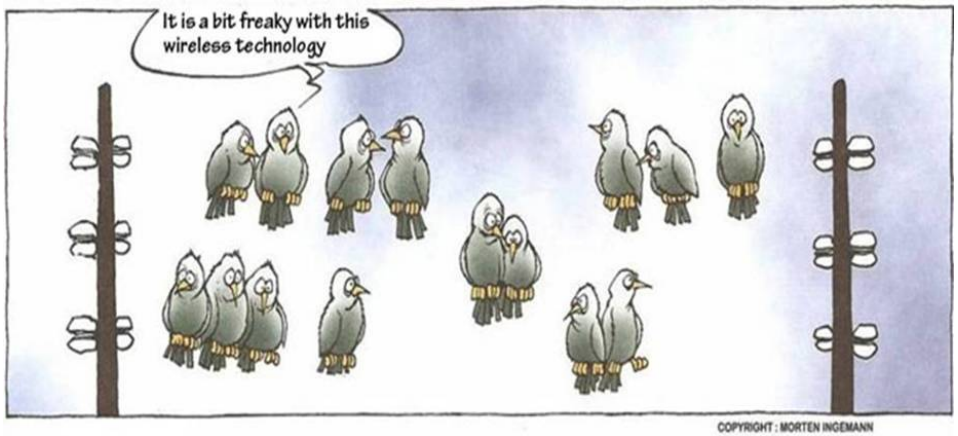
The most popular network?

The Internet

[2] License: https://creativecommons.org/licenses/by/2.0/deed.en

Related questions

- How do you access videos on YouTube?
- What's the deal with a *lag* in online gaming?
- Who can read my mails?
- How can we transmit data through the air (aka wireless networking)?



Objective

At the end of this course, you should . . .

- understand what the term *"online"* means,
- be able to explain what the *Internet* is,
- know how computers communicate,
- know what protocols are,
- be familiar with the layers of a network stack,
- understand how the data finds its way, and
- be conscious of security and privacy concerns of computer networks.

Motivation

- Your motivation

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  - Good case: curiosity and willingness to learn

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Motivation

- Your motivation
  - Good case: curiosity and willingness to learn
  - Best case: already interested in Computer Networks
  - Pass the exam
- My motivation
  - Like to teach
  - Computer Networks are of utter importance (and super interesting)
  - Prepare you for your job

Agenda

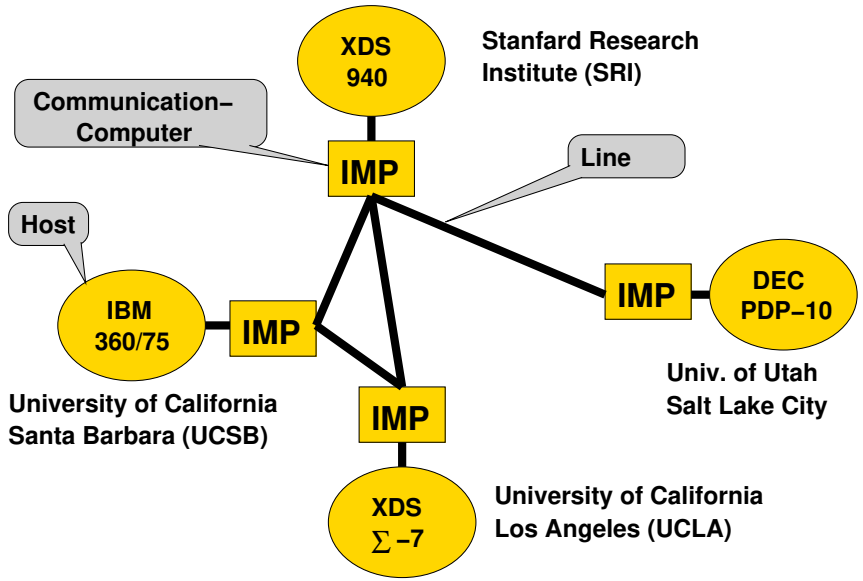
The ARPANET

1957 Foundation of the Advanced Research Projects Agency (ARPA) by the US Dept of Defense (DoD) in response to *Sputnik*

1962 The idea of the 'Internet' as 'tool to create critical mass of intellectual resources' (Licklider, Taylor)

1967 Plan for the ARPANET was published
Main architects: *Vinton Cerf, Bob Kahn*

1969 First Request for Comments (RFC) and first functioning network, rented 50 kBit/sec lines, Interface Message Processors by BBN



Graphic by courtesy of Prof. Dr. Roland Kaiser, Hochschule RheinMain

First Internet Protocols

1972 First public demo (remote login) using the Network Control Protocol (NCP)
main use: terminal sessions, file transfer, Electronic Mail

1974 Basics of TCP/IP written on paper by Cerf/Kahn (IP=Internet Protocol, TCP=Transmission Control Protocol), standardization in the following years

1982 Transition towards IP version 4 (IPv4) [3]

from 1983 Dissemination of TCP/IP due to Berkeley UNIX 4.2 BSD, source code publicly available

4

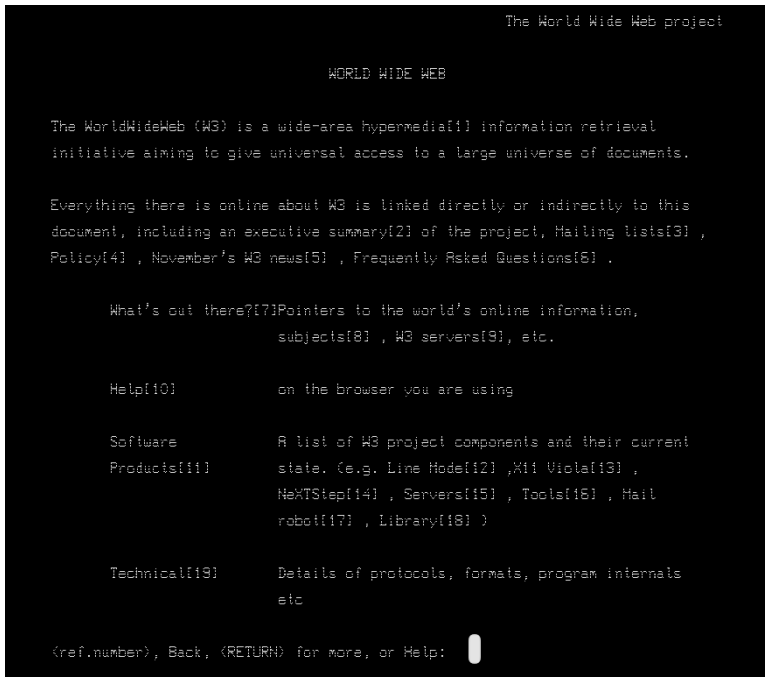
Author: Gorthmog

[4] deprecated, but still widely used

[4] https://creativecommons.org/licenses/by-sa/4.0/deed.en

Standardization

- 1986 The Internet Engineering Task Force (IETF) is founded as an open standardization organization
- 1989 Foundation of RIPE (Réseaux IP Européens) as a forum for administrative and technical coordination of Internet development
- 1990 Proposal of a hypertext project at CERN in Geneva by Tim Berners-Lee and Robert Cailliau: cradle of the world wide web
- 1995 The specification of IPv6 (as a successor of IPv4) is published by the IETF



5

[5] http://line-mode.cern.ch/www/hypertext/WWW/TheProject.html

Global Success

1996 First search engines with a site-scoring algorithm, e.g., Google search

1998 Start of the dot-com boom

2004 Start of Web 2.0 brought up blogs and RSS as well as services like Facebook or Twitter

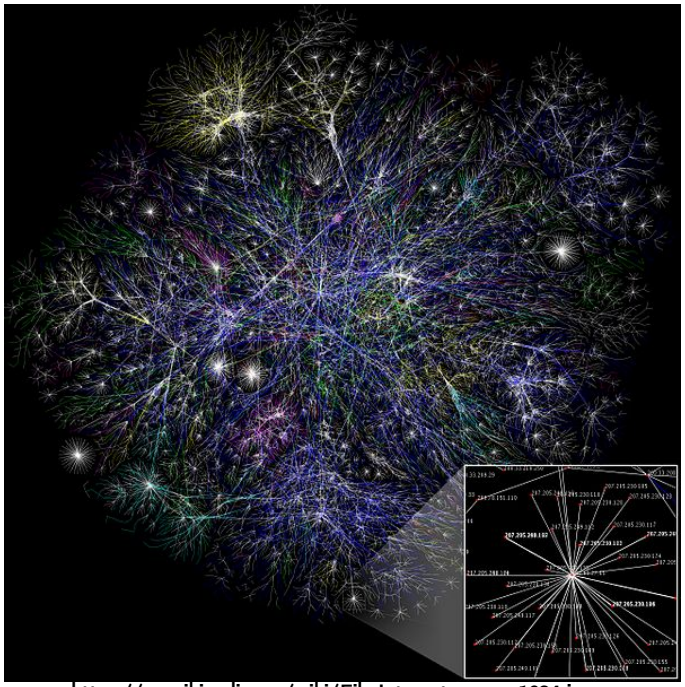
2007 Apple's iPhone and Android started the "Mobile Revolution"

2008 Rise of the Internet of Things (IoT)

https://bit.ly/3jDGA3w

Internet growth

- Amount of AS (Autonomous Systems, admin. routing domain)
  - Doubling every five years (currently, more than 100,000)
  - Stable core
  - Major growth at the fringe
- Traffic rate
  - Growth rate of about 26% per year estimated



https://en.wikipedia.org/wiki/File:Internet_map_1024.jpg

- Users
  - 2021: two third of the world population is "online" [6]
  - More than doubled during the last ten years [6]
  - Strongest growth outside the EU, Japan, and USA [6]

[6] Source: https://www.internetworldstats.com/stats.htm

Agenda

Purpose of Computer Networks

The general task of a computer network is to enable communication among the participants.

- Resource sharing
  ⇒ assign different tasks to different computers
  ⇒ avoid bottlenecks
- Resource pooling
  ⇒ combine the resources and functionalities of multiple machines
- Resource balancing
  ⇒ increase the availability of the services by redundancy

Required Components to set up a Computer Network

- For setting up and running a computer network, these components are required:

Required Components to set up a Computer Network

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  1. ≥ 2 computers with network services running
     - The devices are intended to communicate with each other or access shared resources
     - A network service provides a service for communication or shared resources usage
     - Computers in a network are called *hosts*

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     - Some sort of a *wire* (e.g., copper or fiber-optic cables)

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Some of the technologies, concepts, and terms are used in a different contexts. For example, network services communicating on one host or connected peripheral devices within one computer device.

Network Services

- A network service provides resources to other devices in the network
- Distinguished by their role:

  Server Provides a network service

  Client Uses (consumes) a network service
- If each communication partner is server and client both, the participants are called peers ($\Longrightarrow$ Peer-to-Peer networks)
- The terms server, client and peer typically refer only to network services and not to hardware
  - Reason: It is common that client applications also run at *servers*

Transmission Media

Different transmission media exists to setup a computer network.

1. Guided transmission media
   - **Copper cable**: Data is transferred as electrical impulses
   - **Fiber-optic cable**: Data is transferred as light impulses
2. Wireless transmission
   - Wireless transmission can be realized **directed** and **undirected**
   - Directed transmission can base on the following technologies:
     - **Radio technology**: Data is transferred as electromagnetic waves (radio waves) in the radio frequency spectrum (e.g., directed WLAN and satellite internet access)
     - **Infrared**: Data is transferred as electromagnetic waves in the spectral range (e.g., IrDA)
     - **Laser**: Data is transferred as light impulses via Laser Bridge
   - Undirected wireless transmission is always based on radio technology (e.g., WLAN, cellular networks, terrestrial broadcasting and satellite broadcasting)

Protocols

- A protocol is the set of all previously made agreements between communication partners
  - These agreements include:
    - Rules for connection establishment and termination
    - Method of synchronization between sender and receiver (if any)
    - Measures for the detection and treatment of transmission errors
    - Definition of valid messages (vocabulary)
    - Format and encoding of messages
- Protocols specify...
  - the syntax (= format of valid messages)
  - the semantics (= vocabulary and meaning of valid messages)

https://bit.ly/3vIg9P7

Computer Networks distinguished by their Dimension (1/3)

- Depending on the dimension, different groups of computer networks are distinguished
- **Personal Area Network (PAN)** or **Body Area Network (BAN)**
  - Network of small mobile devices, such as smart phones
  - Technologies: USB, FireWire, WLAN, Bluetooth, IrDA
  - Major dimension: Few meters
- **Local Area Network (LAN)**
  - Local network
  - Range covers an apartment, building, company site or university campus
  - Major dimension: 500-1000 m
    - Concrete values depend on the transmission medium used and when using wireless networks, also the environment and the transmission power
  - Technologies: Ethernet, Wireless LAN (WLAN), Token Ring (outdated)

Computer Networks distinguished by their Dimension (2/3)

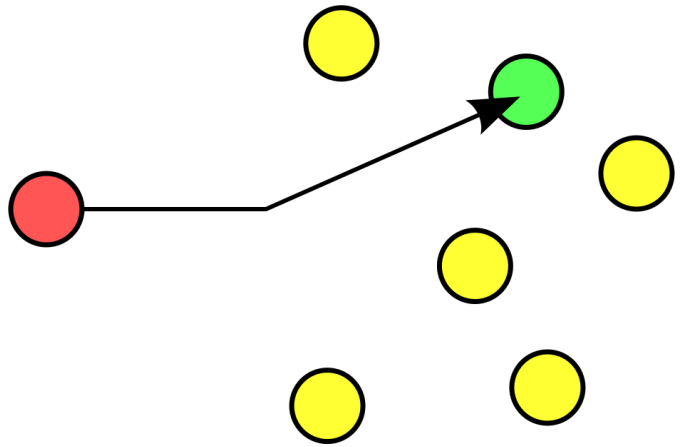
- **Metropolitan Area Network (MAN)**
  - Connects LANs
  - Range covers a city or agglomeration area
  - Major dimension: 100 km
  - Technologies: Fiber-optic cables, WiMAX (IEEE 802.16)
    - Fiber-optic cables are used because of lesser attenuation (signal weakening) and higher data transmission rates
- **Wide Area Network (WAN)**
  - Connects several networks
  - Range covers a large geographic area inside a country or continent
  - Major dimension: 1000 km
  - Technologies: Ethernet (10 Gbit/s), Asynchronous Transfer Mode (ATM)

Communication Modes

- Synchronous ("Rendez-Vous")
  - Sender and receiver needs to be present at the same time
  - May require to wait for the other side to become ready
  - For example, phone calls or video conference
- Asynchronous
  - Sender and receiver may act independently from each other
  - Requires buffering
  - For example, instant messaging or E-Mail

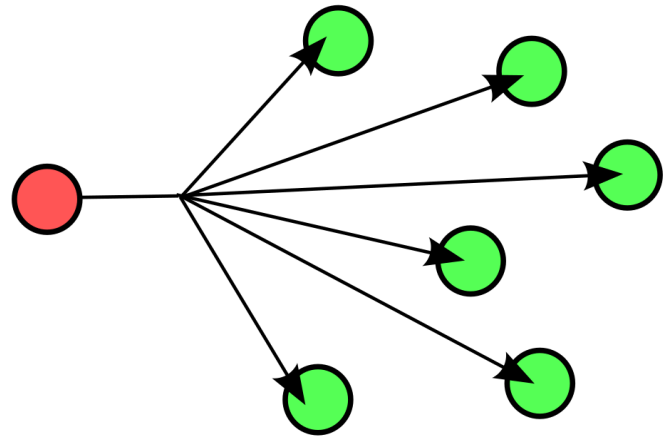
Unicast and Broadcast

Unicast One-to-one communication, i.e., one host sends information to *exactly one* other host



Source: public domain

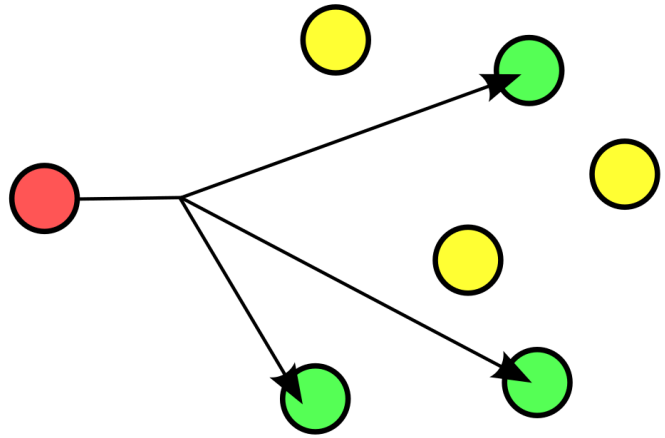
Broadcast One-to-all communication, i.e., one host sends information to *all* other hosts in the network



Source: public domain

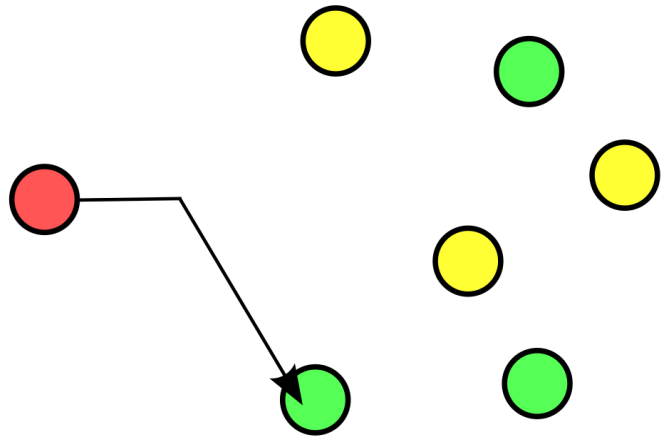
Group Communication: Multicast and Anycast

Multicast Group communication, i.e., one host sends information to all hosts in a given *group*



Source: public domain

Anycast One-to-any communication, i.e., one hosts sends information to *one host in a given group*



Source: public domain

Connection-Orientation

Network services may operate *connection-oriented* or *connectionless*.

connection-oriented the service operates **stateful**

- comprises three phases: connection establishment, data transfer, and connection termination
- a virtual path between the involved hosts is established
- sequent data is exchanged between the same hosts
- typically used for reliable services

connectionless the service operates **stateless**

- no path between the involved hosts is established
- typically used for low latency services

Directional Dependence (Anisotropy) of Data Transmission

Given a communication channel with two (or more) endpoints:

- Simplex
  - Only one side of the channel can send data → the channel can be used in only one direction
  - Examples: Radio, TV, Pager
- Duplex (Full-duplex)
  - Both sides of the channel are allowed to send → the channel can be used in both directions simultaneously
  - Examples: Phone, Networks with twisted pair cables because they provide separate wires for send and receive
- Half-duplex
  - Both sides of the channel can send, but not simultaneously → the channel can only be used in one direction at a time
  - Examples:
    - Networks with fiber-optic cables or coaxial cables, because there exists just a single line to sending and receiving
    - Wireless networks with just a single channel

Bandwidth, Throughput and Goodput

- Main factors, influencing the performance of a computer network:
  - Bandwidth ($\rightarrow$ throughput)
  - Latency (**delay**)
- The bandwidth specifies how many bits can be transmitted within a period via the network
  - If a network has a bandwidth of 1 Mbit/s, one million bits can be transmitted per second **in the ideal case**
    - Thus, a bit has a *width* of 1 μs
    - If the bandwidth is doubled, the number of bits that can be transmitted per second double, too
  - Throughput is the actual achieved data rate ($\Rightarrow$ the bandwidth defines its upper bound)
  - Goodput is the actual rate of data the user benefits from

Latency

- The latency of a network is the time, a message needs to travel from one end of the network to the most distant end

$$\text{Latency} = \text{Propagation delay} + \text{Transmission delay} + \text{Waiting time}$$

$$\text{Propagation delay} = \frac{\text{Distance}}{\text{Speed of light} * \text{Velocity factor}}$$

- Distance: Length of the network connection
- Speed of light: $299,792,458\,\text{m/s}$
- Velocity factor: Vacuum = 1, twisted pair cables = 0.6, optical fiber = 0.67, coaxial cables = 0.77

$$\text{Transmission delay} = \frac{\text{Message size}}{\text{Bandwidth}}$$

Transmission delay = 0, if the message consists only of a single bit

- Waiting times are caused by network devices (e.g., Switches)
  - They need to cache received data first before forwarding it

  $\Rightarrow$ Waiting time = 0, if the network connection between sender and destination is just a single line or a single channel

Source: Larry L. Peterson, Bruce S. Davie. Computernetzwerke. dpunkt (2008)

Bandwidth-Delay Product

- Calculates the **volume of a network connection**
  - Signals cannot be transmitted with infinite speed via the transmission media
    - The propagation speed is in any event limited by the speed of light and it depends on the velocity factor of the transmission medium
  - The product of bandwidth and delay (latency) corresponds to the maximum number of bits that can reside inside the line between sender and receiver
- Example: A network with 100 Mbit/s bandwidth, and 10 ms latency

$$100,000,000\,\text{Bits/s} \times 0.01\,\text{s} = 1,000,000\,\text{Bits}$$

- There are a maximum number of $1,000,000$ Bits inside the network line
  - This is equivalent to $125,000$ Bytes (approx. 123 kB)

How does a Computer Network work?

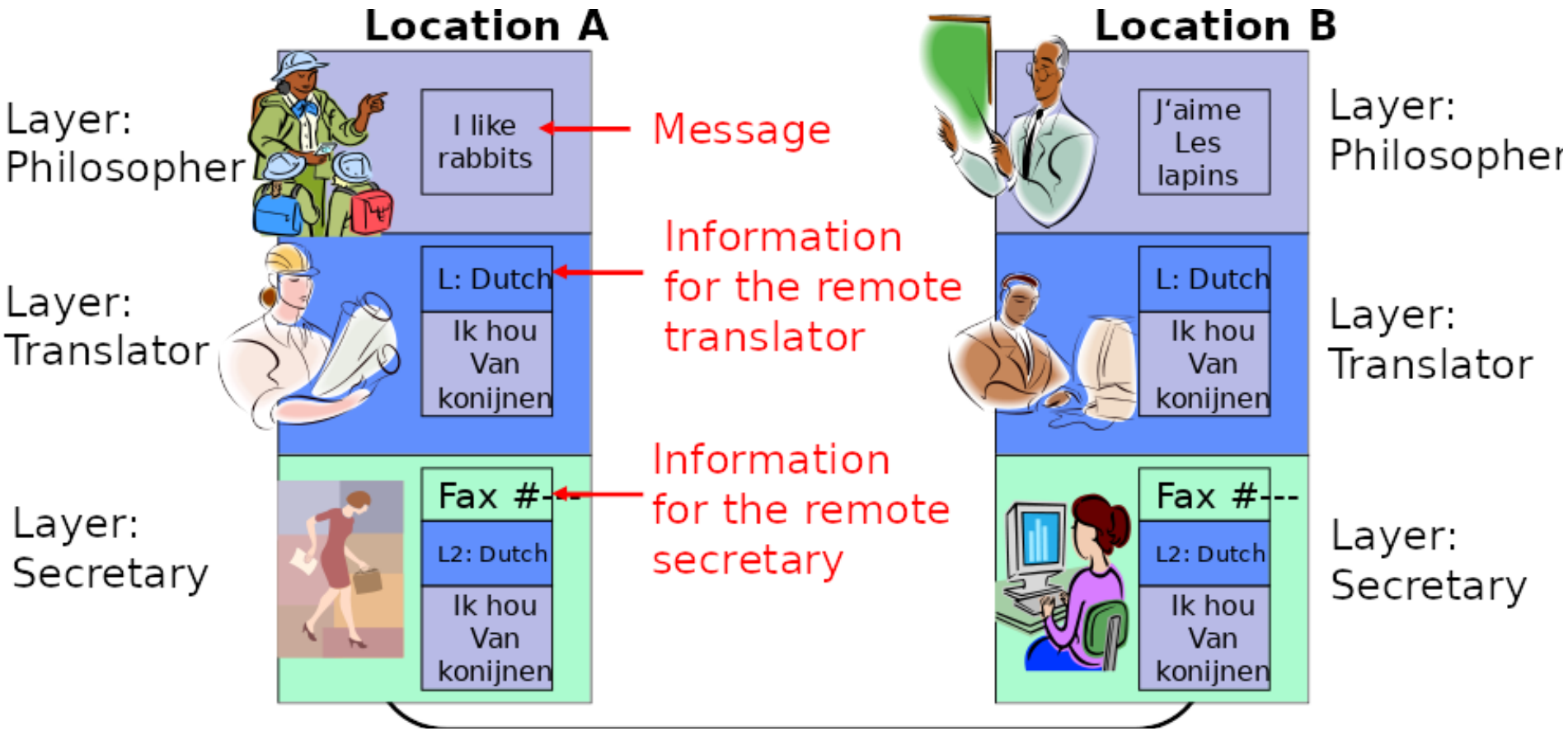
You need information about
someone/something?
What do you do?

Agenda

Reference Models

- Reference models are used to describe computer networks independently of concrete technologies
- Such a reference model consists of several layers
- Each layer addresses a particular aspect of communication and offers interfaces to the neighboring layer
- Each layer defines their own protocols that define syntax and semantics of parts of a transmitted message (e.g., header and trailer)
- These message parts are encapsulated
- Because each layer is complete in itself, single protocols can be modified or replaced without affecting all aspects of communication
- The most popular reference models are...
  - the **TCP/IP reference model**,
  - the **ISO/OSI reference model**, and
  - the **hybrid reference model**

"Philosopher-Translator-Secretary"-Architecture



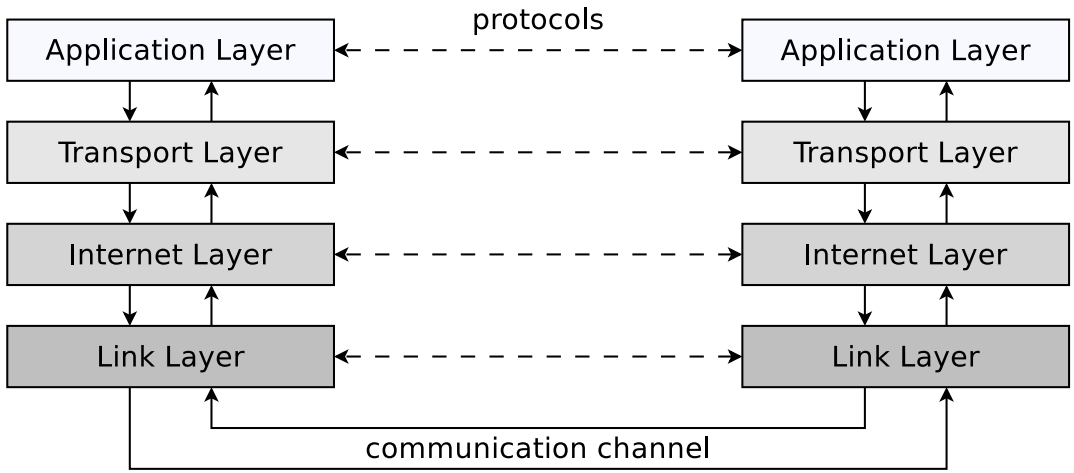
Graphic by courtesy of Prof. Dr. Thomas C. Schmidt, HAW Hamburg

TCP/IP Reference Model or DoD Model

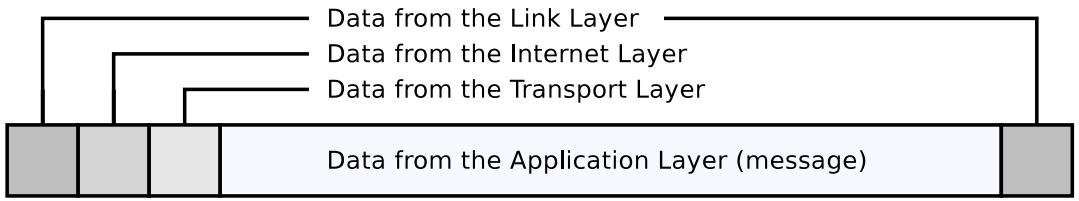
- Developed from 1970 onwards by the Department of Defense (DoD) in the Arpanet project
- Divides the required functionality to realize communication into 4 layers
- For each layer, it is specified, what functionality it provides
  - These requirements are implemented by communication protocols
    - Concrete implementation is not specified and can be implemented in different ways
    - Therefore, for each of the 4 layers, multiple protocols exist

Number	Layer TCP/IP (RFC 1122)	Layer DoD (RFC 871)	Protocols (Examples)
4	Application Layer	Process Layer	HTTP, FTP, SMTP, POP3, DNS, SSH, Telnet
3	Transport Layer	Host-to-Host Layer	TCP, UDP
2	Internet Layer		IPv4, IPv6, IPX
1	Link Layer	Network Interface Layer	Ethernet, WLAN, ATM, FDDI, PPP, Token Ring

TCP/IP Reference Model – Message Structure

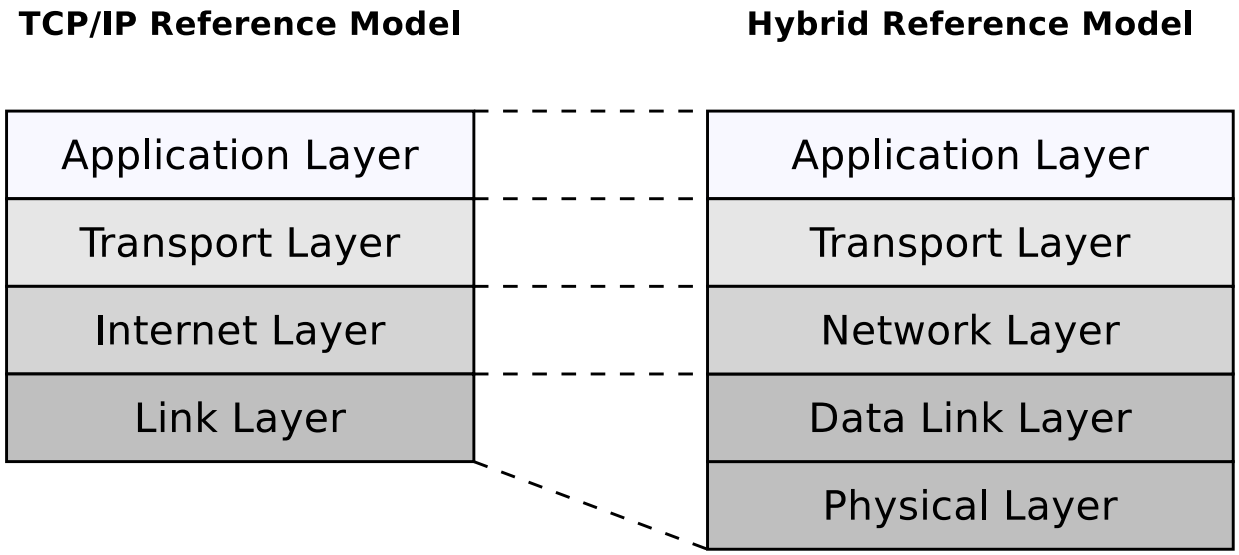


- Each layer adds additional information as header to the message
  - Some protocols (e.g., Ethernet) add in the link layer not only a header but also a trailer at the end of the message
  - The receiver analyzes the header (and trailer) on the same layer



Hybrid Reference Model

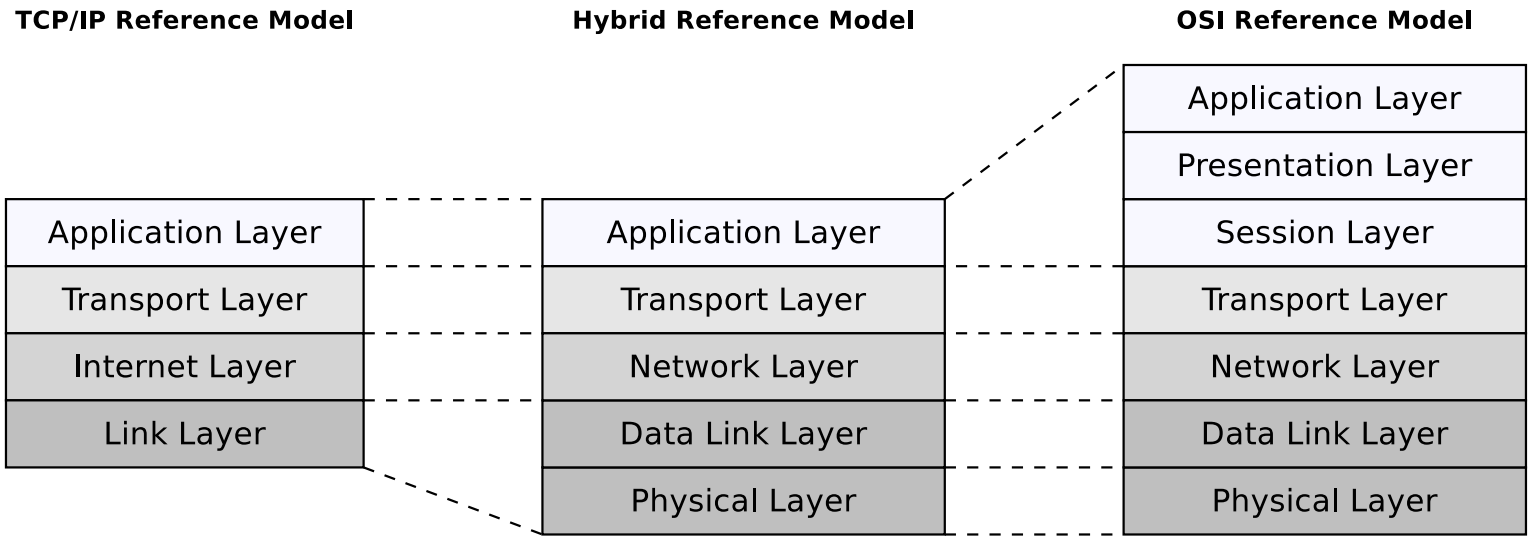
- The TCP/IP reference model is often presented in the literature (e.g., by Andrew S. Tanenbaum) as a 5-layer model
  - Reason: It makes sense to split the **Link Layer** into 2 layers, because they have different tasks
- This model is an extension of the TCP/IP model and is called hybrid reference model



We will mostly follow the hybrid reference model

OSI Reference Model

- Some years after the TCP/IP reference model (1970s), the OSI (Open Systems Interconnection) reference model was developed from 1979 onwards
- 1983: Standardized by the Intern. Organization for Standardization (ISO)
- In contrast to the hybrid reference model, two additional layers are placed below the Application and above the Transport Layer



OSI Model Concepts

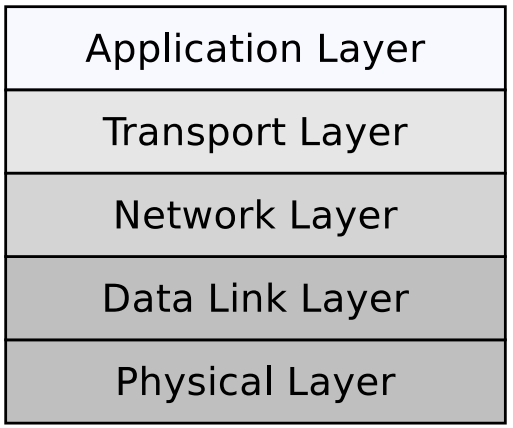
Central concepts of the OSI model are:

Services	Define what the layer does, i.e., its semantics
Interfaces	Define how to access it
Protocols	Describe how the layer is implemented

Physical Layer I

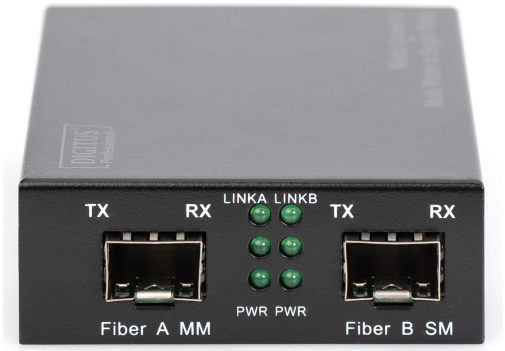
- **Transmits the ones and zeros**
  - Physical connection to the network
  - Conversion of data into signals
- Protocol and transmission medium specify among others:
  - How is the information encoded on the transmission medium?
  - Can transmission take place simultaneously in both directions?

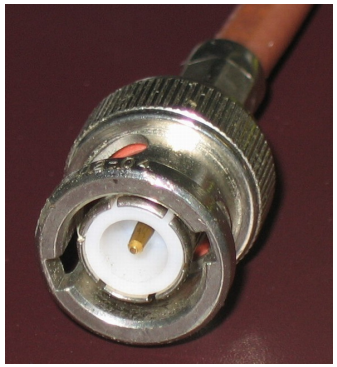
Hybrid Reference Model



Physical Layer II

- **At sender site:** Signals are modulated onto the medium
- **At receiver site:** Signals are demodulated from the medium
- Devices: **Repeater**, **Hub** (Multiport Repeater)

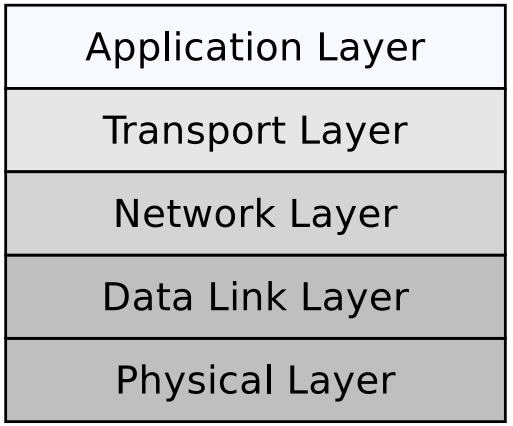




Data Link Layer I

- Ensures error-free data exchange of frames between devices in physical networks
  - Handles transmission errors with **checksums**
  - Controls the access to the transmission medium (e.g., via CSMA/CD or CSMA/CA)
- Specifies physical network addresses (MAC addresses)

Hybrid Reference Model



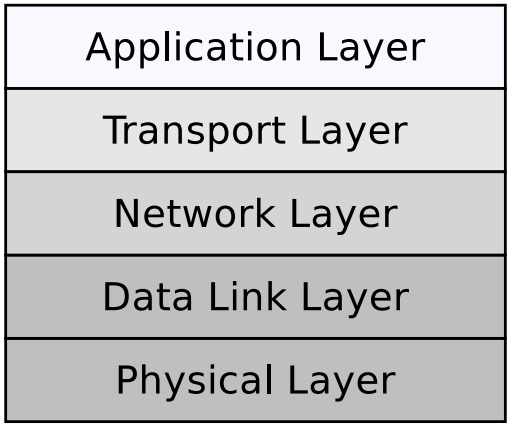
Data Link Layer II

- **At sender site:** Packs the Network Layer packets into frames and transmits them (in a reliable way) via a physical network from one device to another
- **At receiver site:** Identifies frames in the bit stream from the Physical Layer
- Devices: **Bridges**, **Layer-2-Switches** (Multiport Bridges), **WIFI APs**, and **Modems** connect physical networks

Network Layer I

- Forwards packets between logical networks (over physical networks)
  - For this *internetworking*, the network layer defines logical addresses (most commonly IP addresses)
  - Each IP packet is routed independently to its destination ($\rightarrow$ connectionless)

Hybrid Reference Model



Network Layer II

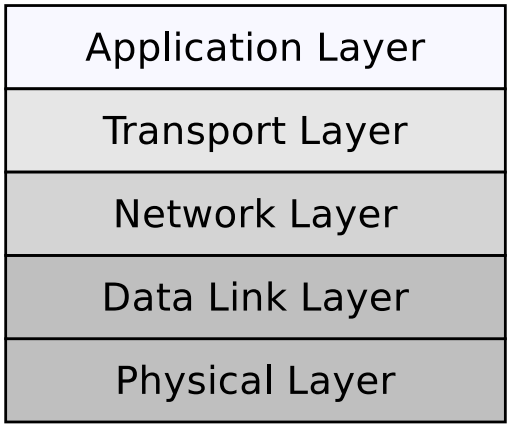
- **At sender site:** Packs the segments of the Transport Layer in packets
- **At receiver site:** Unpacks the packets in the frames from the Data Link Layer
- **Routers** and **Layer-3-Switches** connect logical networks

- Usually the connectionless Internet Protocol (IP) is used
  - Other protocols (e.g., IPX) have been replaced by IP

Transport Layer I

- Transports segments between processes on different devices via so-called end-to-end protocols
- Transport protocols implement different forms of communication
  - Connectionless communication, typically UDP (User Datagram Protocol) in TCP/IP networks
  - Connection-oriented communication, typically TCP (Transport Control Protocol) in TCP/IP networks

Hybrid Reference Model



Transport Layer II

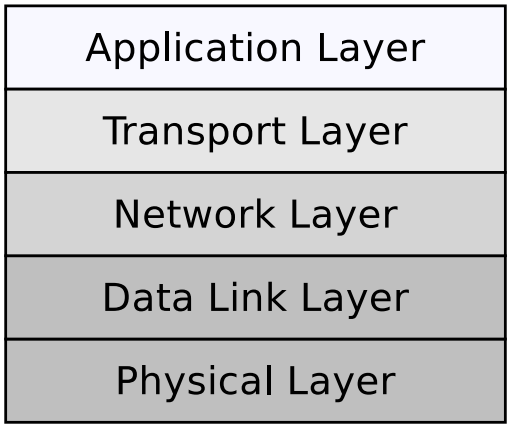
- **At sender site:** Packs the data of the Application Layer into segments
- **At receiver site:** Unpacks the segments inside the packets from the network layer
- Addresses processes with **port numbers**

Combination of TCP/IP = de facto standard for computer networks

Application Layer

- Contains all protocols, that interact with the application programs (e.g., browser or email program)
- Here is the actual payload (e.g., HTML pages or emails), formatted according to the used application protocol
- Some Application Layer protocols: HTTP, FTP, SMTP, POP3, DNS, SSH, Telnet

Hybrid Reference Model



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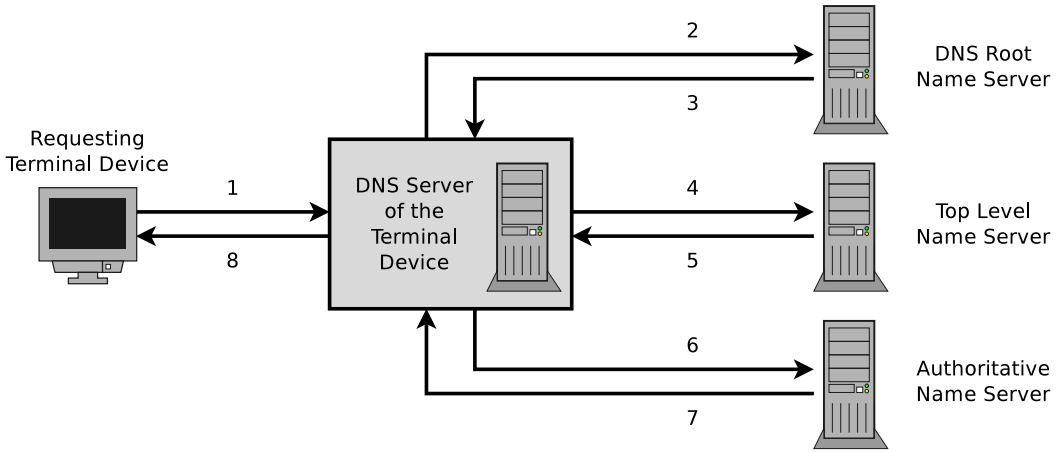


OSI only: Session Layer

- **Controls the dialogues** (connections) between processes
- Provides the following services
  - checkpointing (and recovery)
  - authentication
  - authorization
- Relevant protocols of the Session Layer are H.245, L2TP, PAP, and SOCKS
- Session Layer services are commonly used for RPCs (cf. lecture *Distributed Systems*)

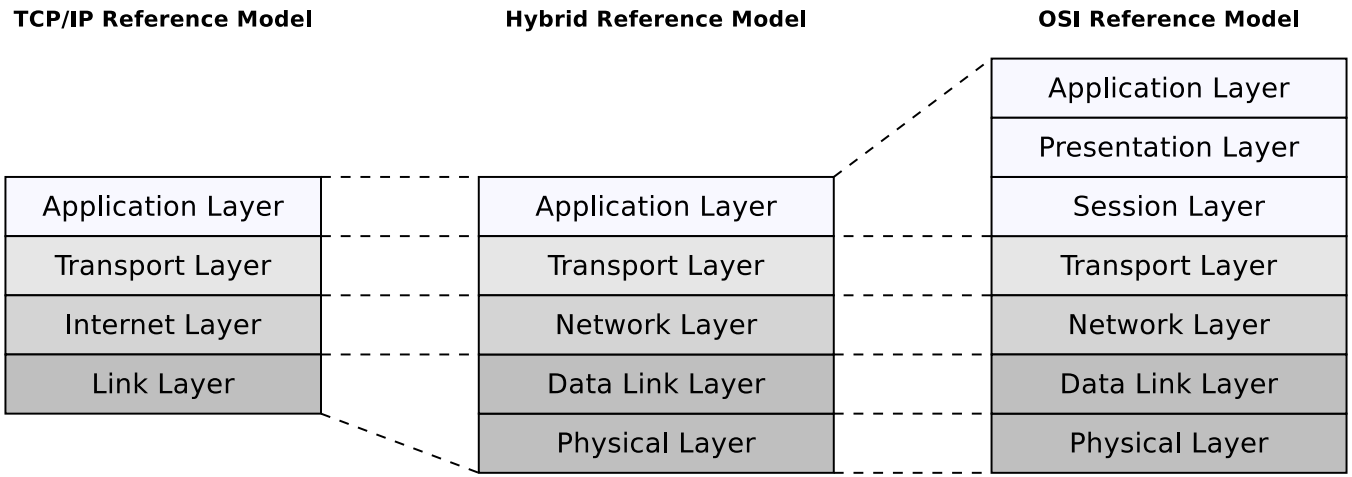
OSI only: Presentation Layer

- Contains rules for setting the **format (presentation) of messages**
  - The sender can notify the receiver that a message has a specific **format** (e.g., ASCII) to make conversion happen, which is perhaps necessary
  - Data records can be specified here with fields (e.g., name, student ID number...)
  - **Data types and their length** can be defined here
  - **Compression and encryption** could be implemented by this layer

The Presentation Layer is seldom used in practice, because all tasks intended to this layer are fulfilled by Application Layer protocols today

Reference Models – Summary

- Conclusion: The hybrid reference model illustrates the functioning of computer networks in a realistic way
  - It distinguishes between the Physical Layer and Data Link Layer
    - This is useful, because the objectives differ a lot
  - It does not subdivide the Application Layer
    - This is less helpful and often not realized in practice
    - Functionalities, which are intended for Session Layer and Presentation Layer, are provided by Transport or Application Layer protocols and services

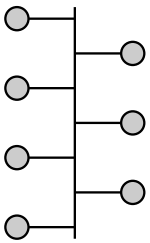


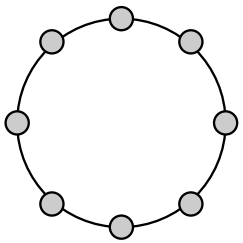
Agenda

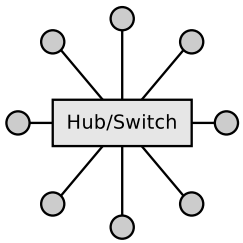
- About this lecture
- Historical background
- Components and Terms
- Reference Models
- Topologies

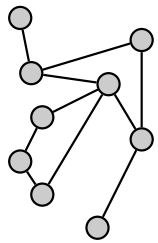
Topologies of Computer Networks

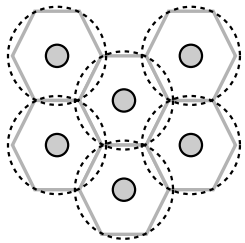
- The topology of a computer network...
  - determines how the communication partners are connected with each other
  - affects its reliability a lot
- The structure of large-scale networks is often a combination of different topologies
- Physical and logical topology may differ
  - Physical topology: Describes the wiring
  - Logical topology: Describes the flow of data between the terminal devices
- Topologies are graphically represented with nodes and edges





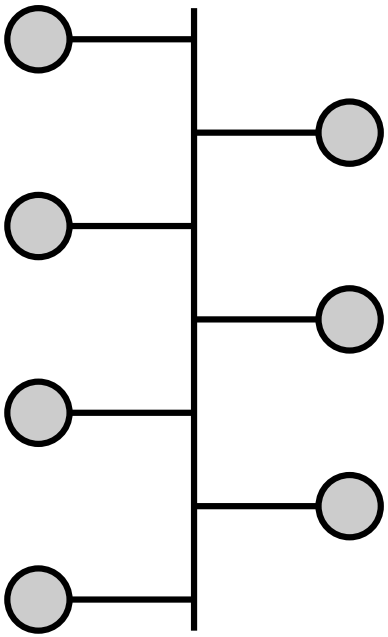






Bus Network

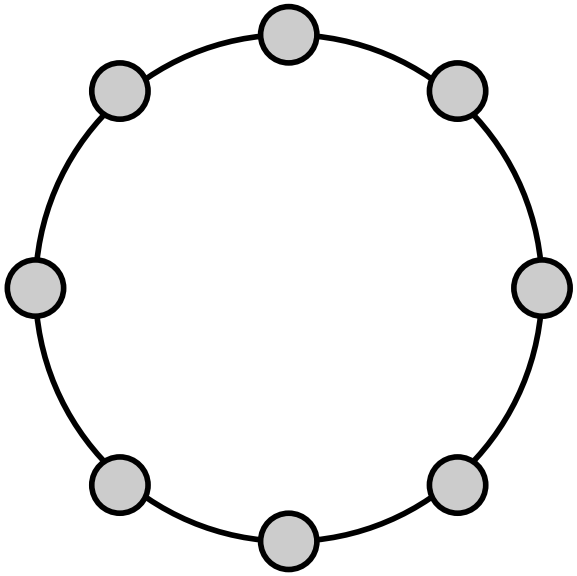
- All terminal devices are connected via a **shared communication medium** – the bus



  - No active components between the terminal devices and the shared communication cable
    - If a node fails, it does not affect the network itself
  - **Advantage**: Cheap to implement
    - In the past, Hubs and Switches have been expensive
  - **Drawback**: Shared communication cable fails
    $\Longrightarrow$ Complete network fails
  - Only a single node can send data at each point in time
    $\Longrightarrow$ otherwise, collisions will occur
    - A media access control method like CSMA/CD is required

- Examples:
  - (original) Ethernet, CAN, I2C

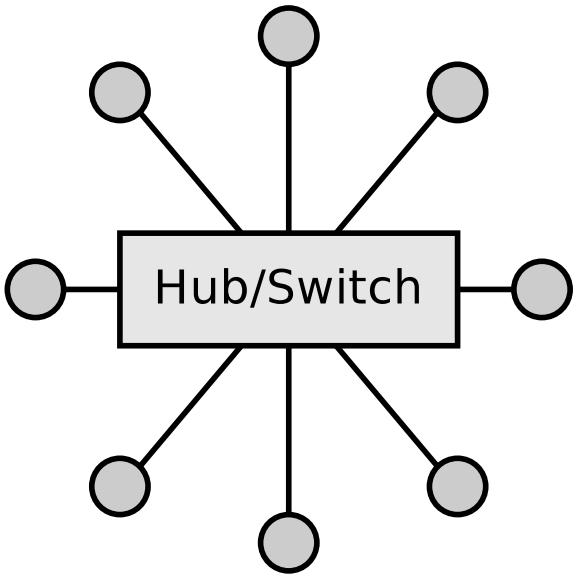
Ring Network



- Connects node to node
- All data is transferred from nodes to nodes until the destination is reached
- Disruption of a single link $\Longrightarrow$ network failure

- Each node is also a repeater, which amplifies the signal
  - For that reason, large-sized rings (transmission medium dependent) are possible
  - Maximum ring length for Token Ring: 800 m
- Examples:
  - Token Ring (**logical**): 4-16 Mbps
  - Fiber Distributed Data Interface (FDDI): 100-1000 Mbps
    - FDDI implements 2 rings
    - One is a secondary backup, in case the primary ring fails

Star Network

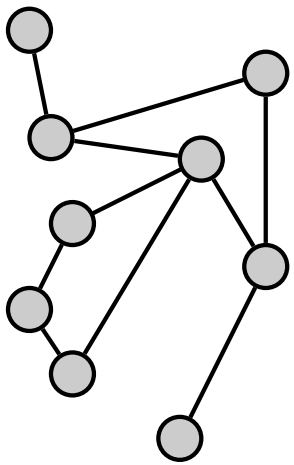


- All nodes are connected directly with a central component (Hub or Switch)
- Failure of the central component leads to a failure of the network itself
  - The central component can be implemented in a redundant way
- Failure of a node do not cause a failure of the network itself
- **Advantages**: Expandability and stability

- Examples:
  - (modern) Ethernet
  - Token Ring (**physical**): 4-16 Mbps
  - Fibre Channel (storage networks): 2-16 Gbps
  - InfiniBand (cluster): 10-40 Gbps

Mesh Network

- Each node is connected with one or more other nodes
  - In a **fully connected mesh network**, the nodes are all connected to each other
- If nodes or connections fail, communication inside the network is typically still possible because the frames are redirected



- **Advantages**: Failure safe (depends on the degree)
- **Drawbacks**: Cabling effort and energy consumption
- Additional challenge: complexity to find the best way from sender to receiver (cf. *Travelling salesman problem*)
- Examples:
  - Logical topology between Routers
  - Ad-hoc (wireless) networks

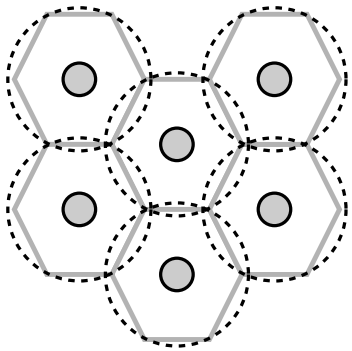
Tree Network

- A dedicated root node exist with one or more edges
  - Every edge leads to a leaf node or to the root of another tree
- Several star topology networks are hierarchically connected
- **Advantages**:
  - Failure of a terminal device (leaf node) has no consequences
  - Good expandability and long distances are possible
  - Well suited for searching and sorting algorithms
- **Drawbacks**:
  - When a node fails, the complete (sub-)tree behind is no longer accessible
  - In a large tree, the root may become a bottleneck because the communication from one half of the tree to the other half always needs to pass the root

- Example:
  - Connecting Hubs or Switches via an uplink port

Cellular Network

- Implemented by wireless networks
- Cell: Area where the nodes can communicate with the base station
- **Advantage**: Failure of nodes do not affect the network itself
- **Drawback**: Maximum dimension is limited by the number of base stations and their positions



- Only one nodes can send data at each point in time $\Longrightarrow$ otherwise, collisions will occur
  - A media access control method like CSMA/CA is required
- Examples:
  - Wireless LAN = WiFi (*IEEE 802.11*)
  - Global System for Mobile Communications (*GSM*)

Current Situation

- Today, Ethernet (1-10 Gbit/s) with Switches ($\Longrightarrow$ **star topology**) is the standard for wired LAN
- Connecting Hubs and Switches implements a **tree topology**, if there are no loops in the cabling
- **Cell topology** is the standard for wireless networks
- **Mesh topology** is one possible use case of wireless networks and it is the logical topology between routers
- **Bus** and **ring topologies** are no longer used for new computer network infrastructures
  - 10BASE2 (Thin Ethernet) and 10BASE5 (Thick Ethernet) are outdated since the mid/end-1990s
  - May 2004: IBM sells his complete Token Ring product lineup

You should now be able to answer the following questions:

- What is a Computer Network and what are its objectives?
- What is the difference between bandwidth, throughput, and latency?
- What is a reference model and what do their difference layers represent?