Computer Networks

Basics

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Agenda

Historical background

Success Factors

Which concept had the biggest impact on the success of the Internet?

The concept of **Freedom** and **Openness**

- **Free** and **Open Systems**
- **Free** and **Open Standards**
- **Free** and **Open Source**

Why Freedom and Openness are important?

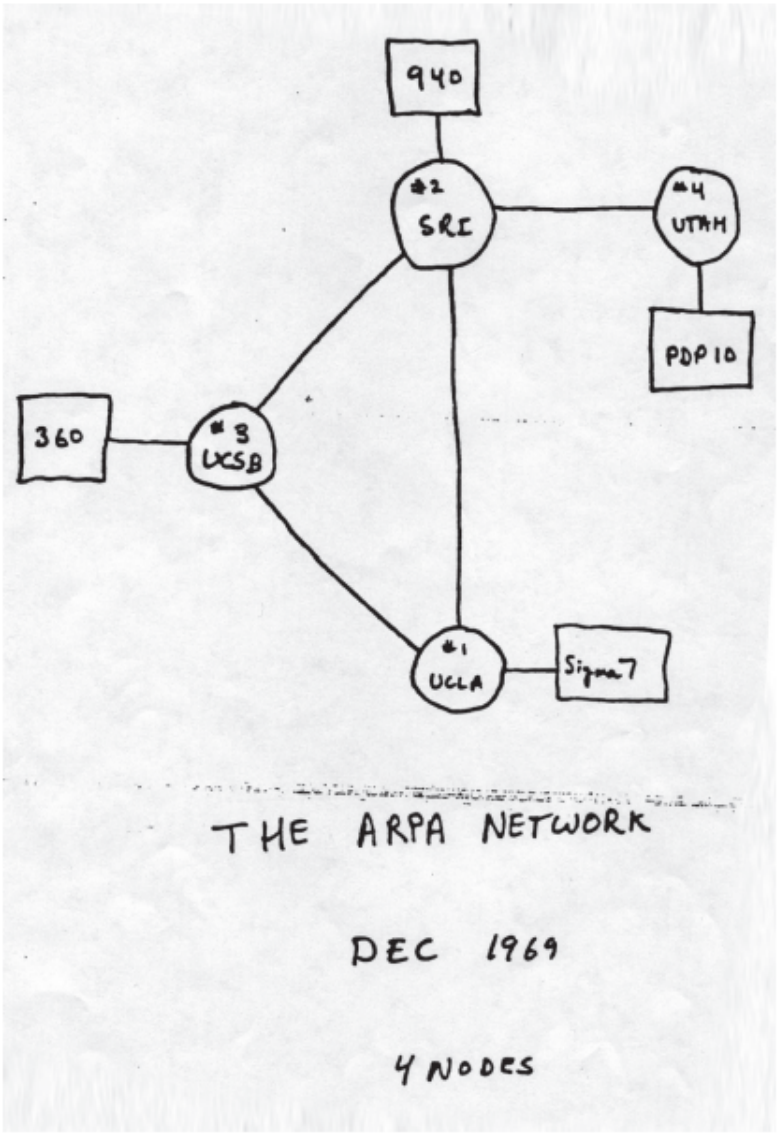
- Diversity
- Security
- Sustainability
- (Digital) Sovereignty

- Privacy
- Freedom

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)

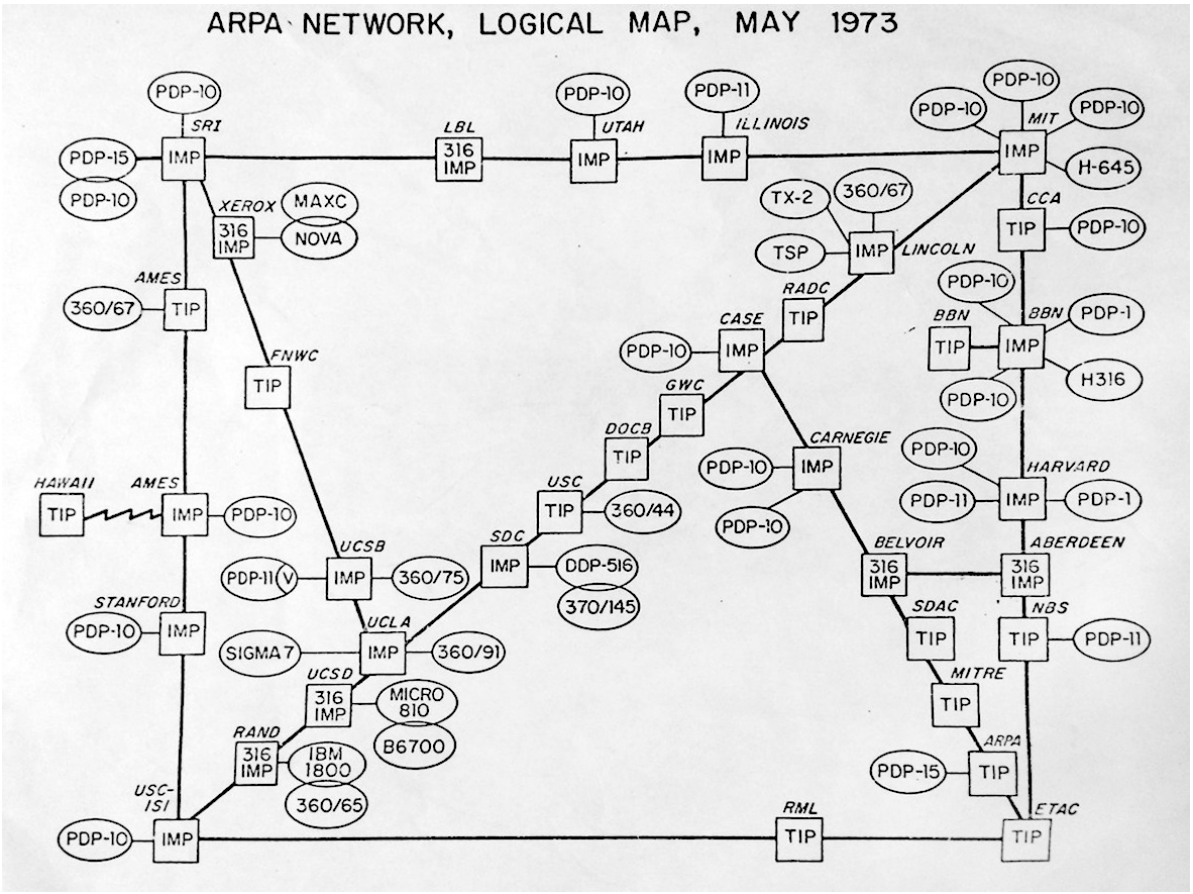
- **1967**: Plan for the ARPANET was published
  Main architects: *Vinton Cerf, Bob Kahn*
- **1969**: First Request for Comments (RFC) and first functioning network, rented 50 kBit/sec lines, Interface Message Processors by BBN



THE ARPA NETWORK

DEC 1969

4 NODES



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

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[1]
- **1995**: The specification of IPv6 (as a successor of IPv4) is published by the IETF

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)

Internet growth

- Amount of AS
  (Autonomous Systems, admin. routing domain)

[1] https://line-mode.cern.ch/www/hypertext/WWW/TheProject.html

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

Components and Terms

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

What do we need for a computer network?

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

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*

2. Transmission medium to send and receive data

- Some sort of a *wire* (e.g., copper or fiber-optic cables)
- For *wireless* data transmission no physical medium is required

3. Network protocols

- Rules that specify, how computers can communicate

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
- Almost any computer that acts as a server will also run client applications

Transmission Media

Different transmission media exists to setup a computer network.

1. Guided transmission media
2. Wireless transmission

- **Copper cable**: Data is transferred as electrical impulses
- **Fiber-optic cable**: Data is transferred as light impulses

- Wireless transmission can be realized **directed** and **undirected**
- Directed transmission can base on the following technologies:
  - **Radio technology**: Electromagnetic waves in the radio frequency spectrum (radio waves) (e.g., directed WLAN and satellite Internet access)
  - **Infrared**: Electromagnetic waves in the spectral range (e.g., IrDA)
  - **Laser**: Data is transferred as light impulses via Laser Bridge
- Undirected wireless transmission is mostly based on radio technology (e.g., WLAN, cellular networks, terrestrial broadcasting and satellite broadcasting) or sonar

Protocols

A protocol is the set of all previously made agreements between communication partners, e.g.,

- 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)

Different Types of Networks

Can you think of different examples for computer networks?

Computer Networks distinguished by their Dimension (1/2)

- 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
  - Dimension: Few meters
  - Technologies: USB, FireWire, WLAN, Bluetooth, IrDA
- **Local Area Network (LAN)**
  - Local network
  - Range covers an apartment, building, company site or university campus
  - Dimension: 500-1000 m
  - Technologies: Ethernet, Wireless LAN (WLAN)

Computer Networks distinguished by their Dimension (2/2)

- **Metropolitan Area Network (MAN)**
  - Connects LANs
  - Range covers a city or agglomeration area
  - 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
  - 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

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

Group Communication: Multicast and Anycast

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

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

- What are the use cases?
- What are the pros and cons?

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

- 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

Latency = Propagation delay + Transmission delay + Waiting time

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

- Distance: Length of the network connection
- Speed of light: $299,792,458$ 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
  - 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

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

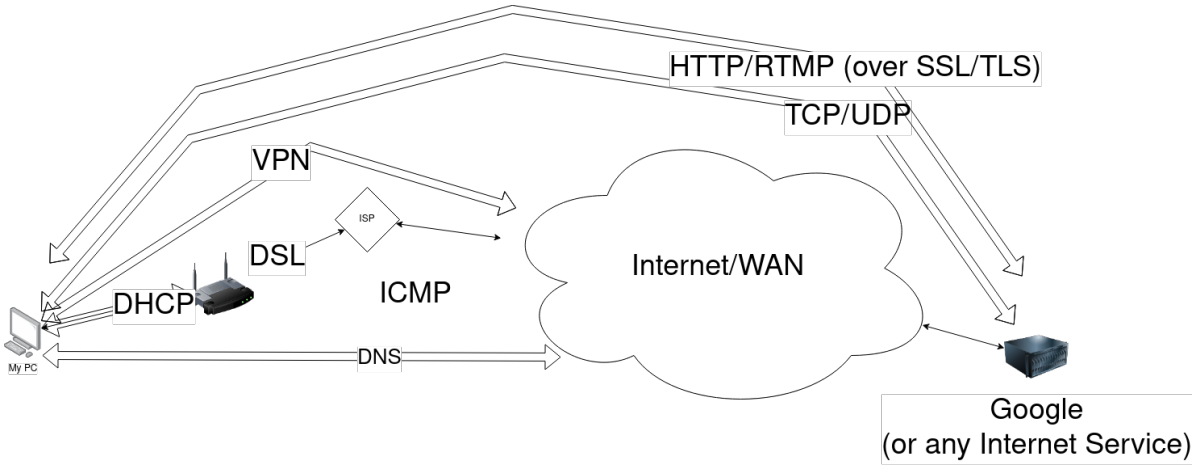
- There are a maximum number of $1,000,000$ Bits inside the network line
  - This is equivalent to $125,000$ Bytes ($= 125$ kB)

How does a Computer Network work?

You need information about someone/something:

- What do you do?
- Which problems are to solve?

The Big Picture

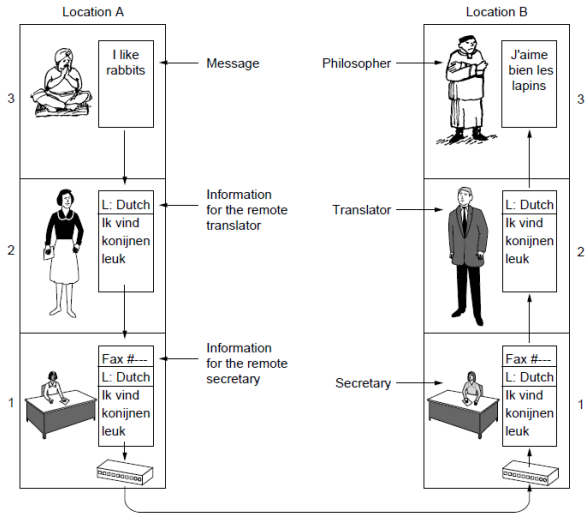


Reference Models

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



Source: Tanenbaum & Wetherall, © Pearson Education-Prentice Hall and D. Wetherall, 2011

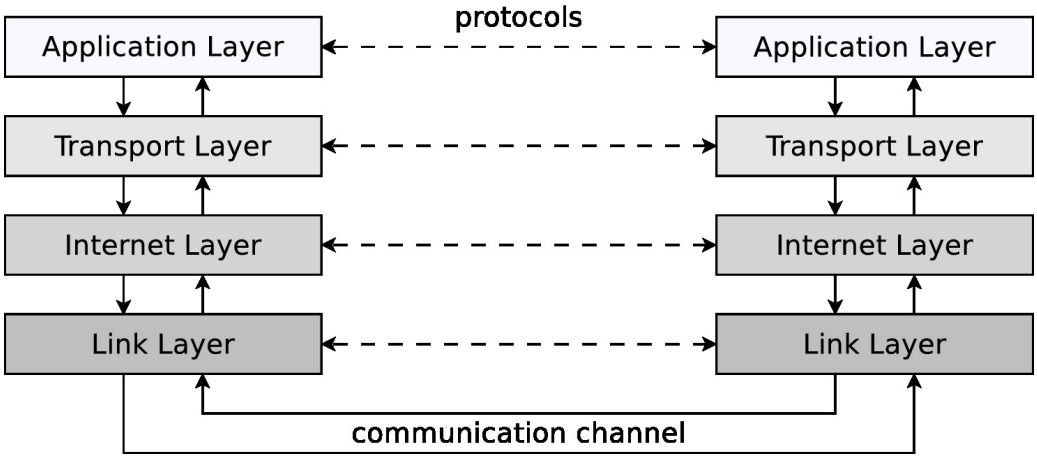
TCP/IP Reference Model or DoD Model

- 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

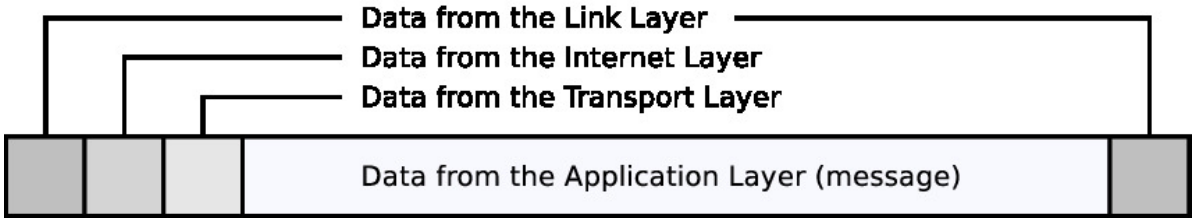
Number	Layer	Protocols (Examples)
4	Application Layer	HTTP, FTP, SMTP, POP3, DNS, SSH, Telnet
3	Transport Layer	TCP, UDP
2	Internet Layer	IPv4, IPv6, IPX
1	Link Layer	Ethernet, WLAN, ATM, FDDI, PPP, Token Ring

Described in **RFC 1122 (TCP/IP)**

TCP/IP Reference Model – Message Structure

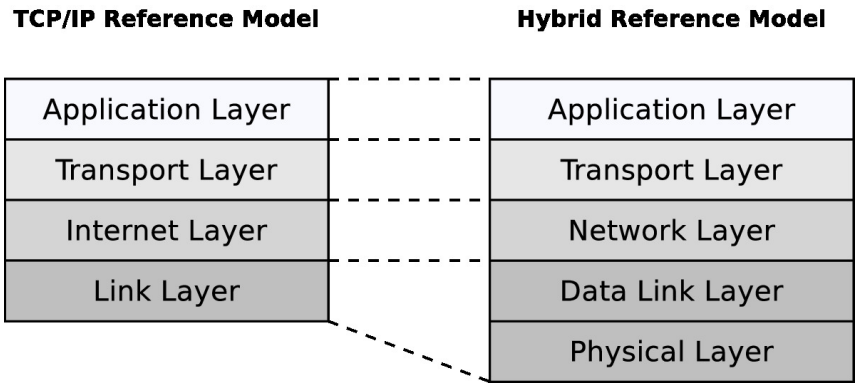


- Each layer adds additional information as header to the message
  - Some protocols (e.g., Ethernet) add in the link layer not only a header but also a trailer at the end of the message
  - The receiver analyzes the header (and trailer) on the same layer



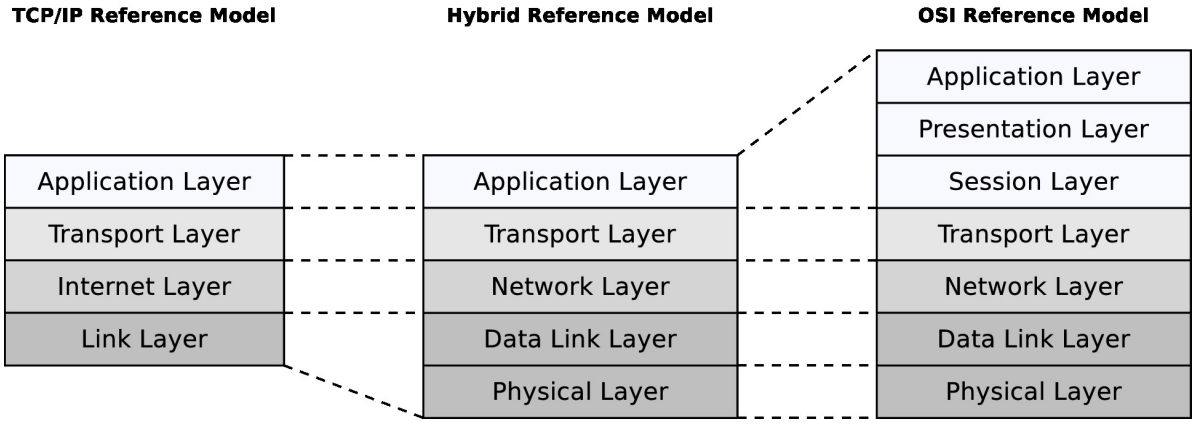
Hybrid Reference Model

- 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



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

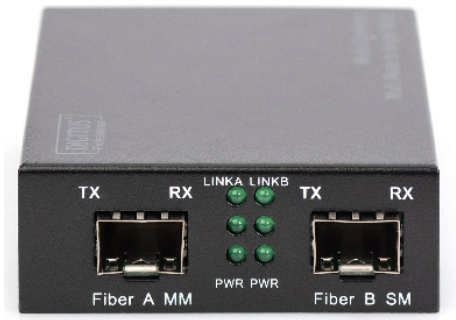
Protocols Describe how the layer is implemented

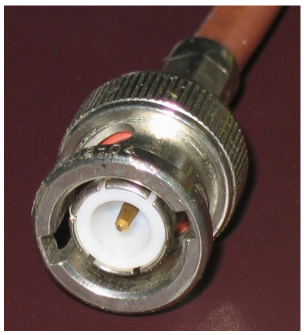
Physical Layer I

- **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?

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)

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 (→ connectionless)

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

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

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*)

Many network applications do not require a dedicated **session layer** protocol.

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

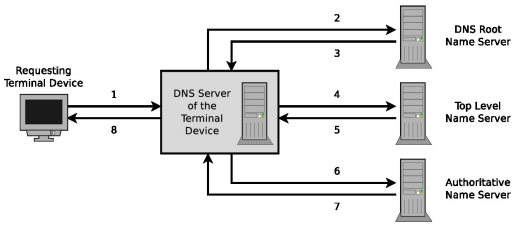
The functionality of the **presentation layer** is often implemented as part of the **application layer**.

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

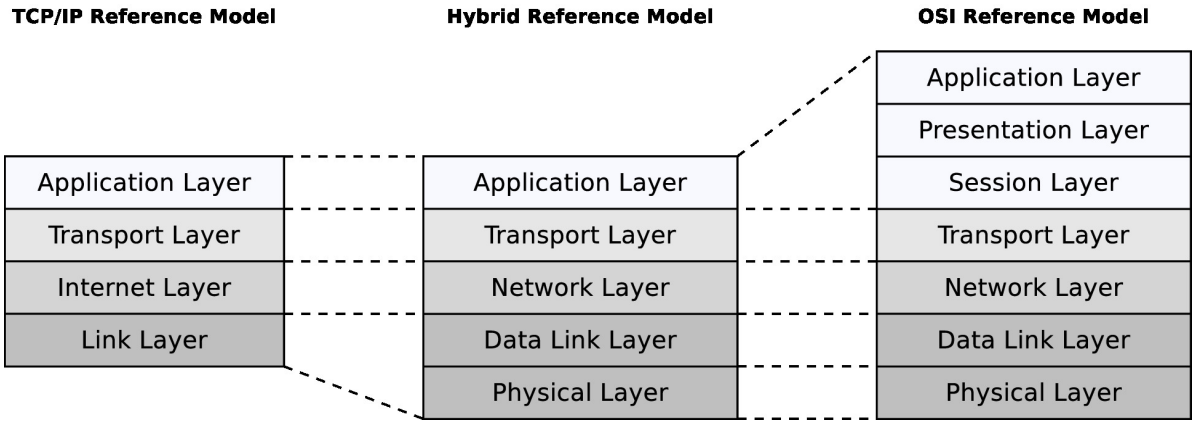
`wikipedia.org` (CC0)

pixabay.com (CC0)



Reference Models – Summary

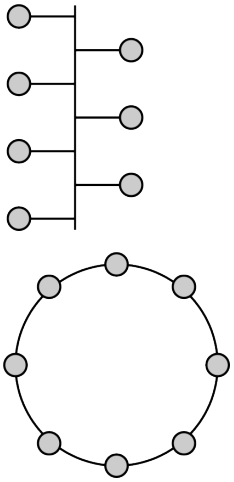
- The OSI reference model is the most fine granular and is most widely used
- Protocols of the **physical** and the **data link layer** are often highly entangled in practice
- Many network applications do not require dedicated protocols on the **session** and **presentation layer**
  - Their functionality is often implemented as part of the **transport** or **application layer**

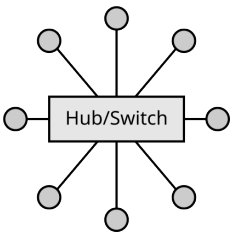


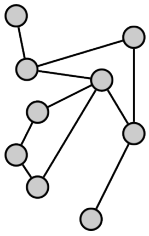
Topologies

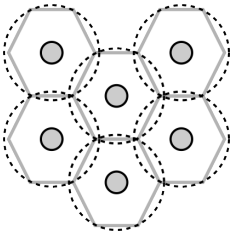
Topologies of Computer Networks

- 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



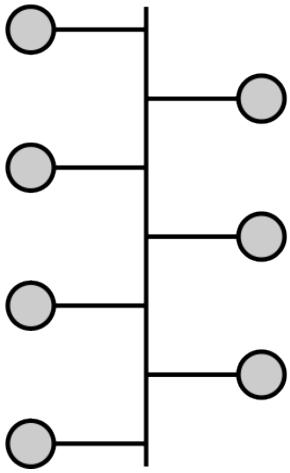






Bus Network

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

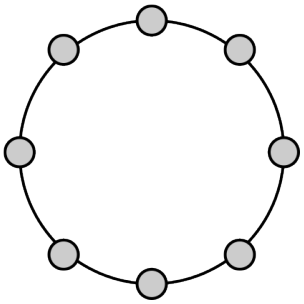


- No active components between the terminal devices and the shared communication cable
  - If a node fails, it does not affect the network itself
- **Advantage**: Cheap to implement
  - In the past, Hubs and Switches have been expensive

- **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, SPI

Ring Network

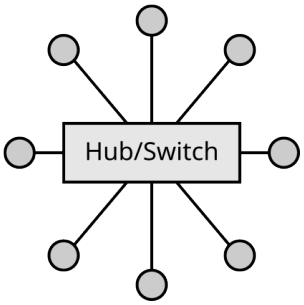


- Connects node to node
- All data is transferred from nodes to nodes until the destination is reached
- Disruption of a single link $\Longrightarrow$ network failure
- Each node is also a repeater, which amplifies the signal
  - For that reason, large-sized rings (transmission medium dependent) are possible
  - Maximum ring length for Token Ring: 800 m

Examples:

- Token Ring (**logical**): 4-16 Mbps
- Fiber Distributed Data Interface (FDDI): 100-1000 Mbps

Star Network



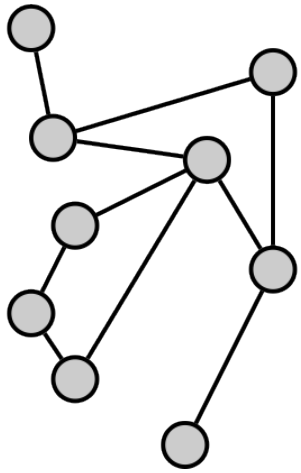
- All nodes are connected directly with a central component (Hub or Switch)
- Failure of the central component leads to a failure of the network itself
  - The central component can be implemented in a redundant way
- Failure of a node do not cause a failure of the network itself

- **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

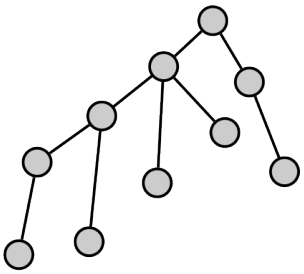


- Each node is connected with one or more other nodes
  - In a **fully connected mesh network**, the nodes are all connected to each other
- If nodes or connections fail, communication inside the network is typically still possible because the frames are redirected
- **Advantages**: Failure safe (depends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

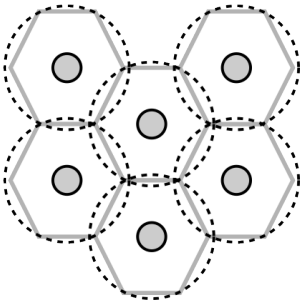


- A dedicated root node exist with one or more edges
  - Every edge leads to a leaf node or to the root of another tree
- Several star topology networks are hierarchically connected
- **Advantages**:
  - Failure of a terminal device (leaf node) has no consequences
  - Good expandability and long distances 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

Examples:

- 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 its complete Token Ring product lineup

Summary

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?