INF3190 - Data Communication

Introduction

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many slides from: Ralf Steinmetz, TU Darmstadt

Problem area and focus

How do we build efficient communication networks?

Focus of the course

- provide a functional understanding of building blocks for data communication
- show how such building blocks can be combined into operational networks
- focus on principles, concepts, and generality
- and learning by doing
- understand principles and concepts by building examples

Course outline

Pensum

- All lectures
- All lecture slides
- All group lessons
- All mandatory assignments and home exams

Not pensum

- The recommended books

What does that mean?

- The books are recommended to improve understanding of the material that is pensum.
- The books contain more topics. These are ***not*** part of the course's pensum.
- In a few cases, the lecture is more up-to-date than the books.

Course outline

1 two-hour lecture per week

1 two-hour common group exercise (not this week)

Theoretical knowledge

- 60% of the grade
- examined in a written 4-hour exam

Practical knowledge

- 1 mandatory assignment (must be passed for admission to written exam)
- 2 home exams (each 20% of the final grade)
- we will interview a sample of people on their solution before grading

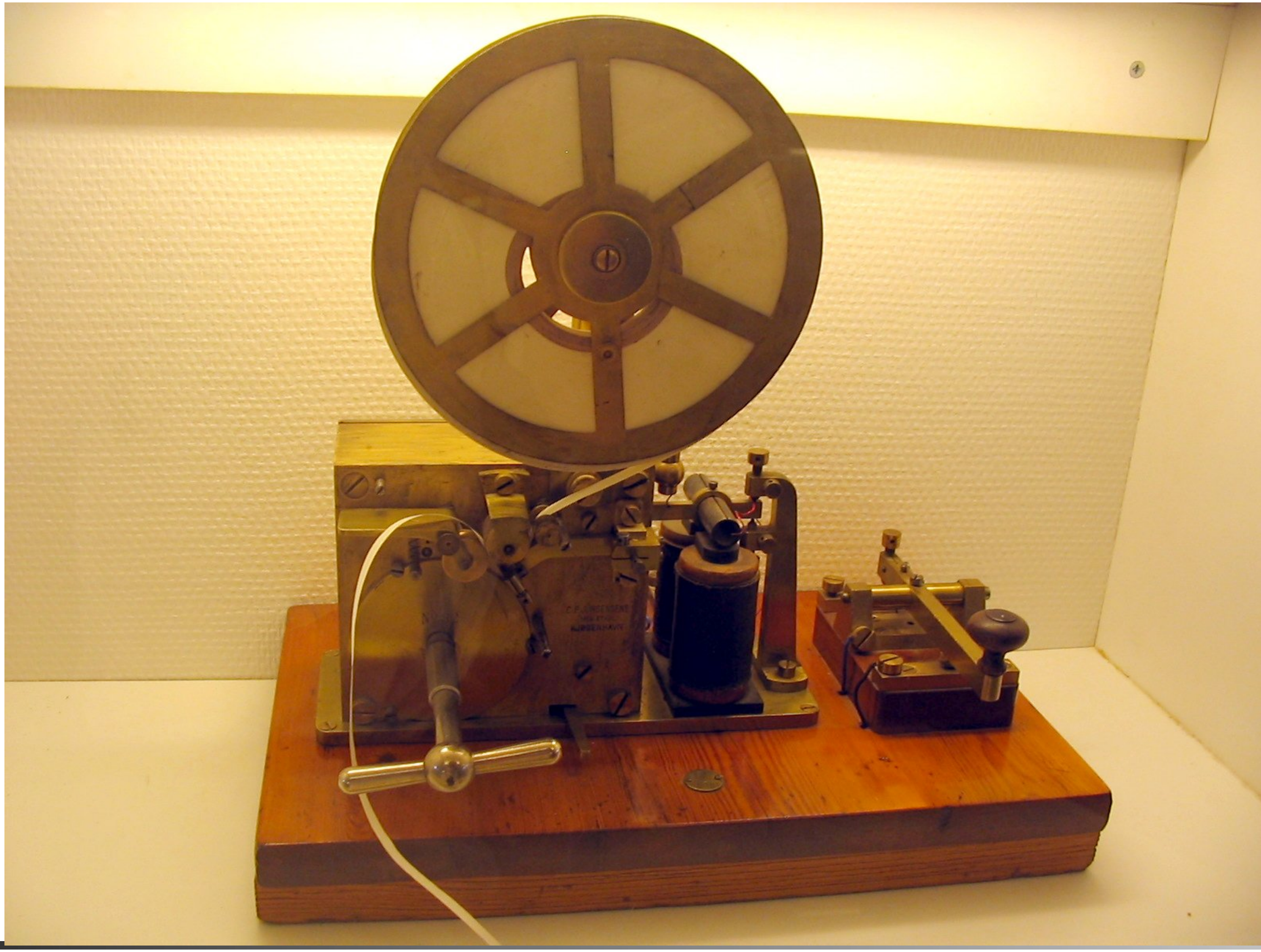
History

- Telegraphy

- Telephony
- Telegraphy vs. Telephony

- The Internet
  - Forefather of the ARPANET
  - The ARPANET
  - Standardization
  - Internetworking

Telegraphy



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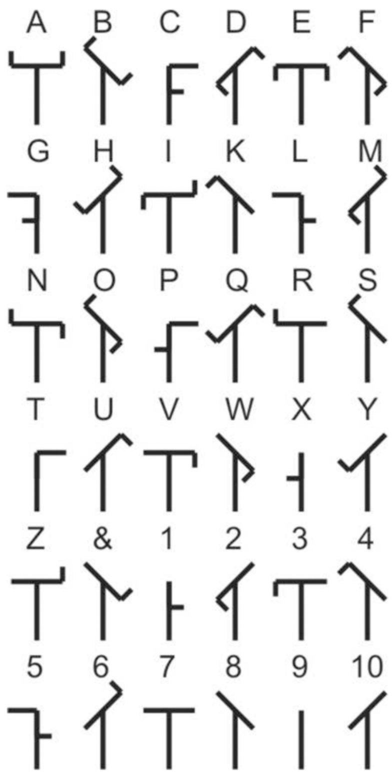
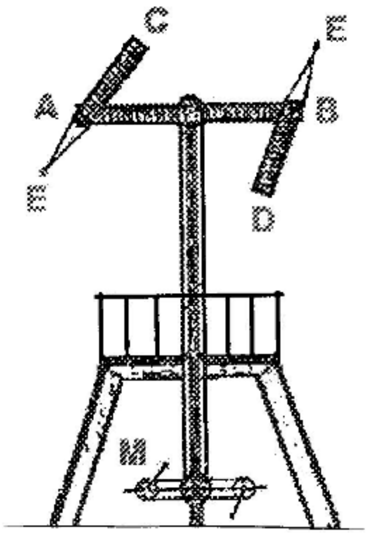
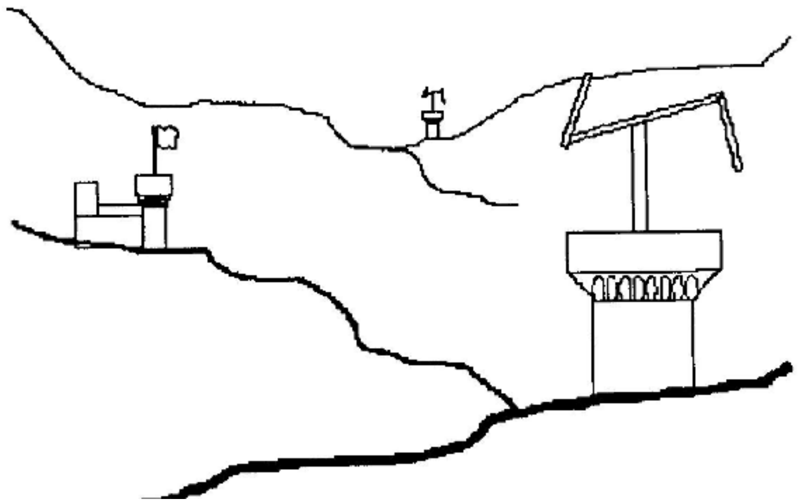
and before

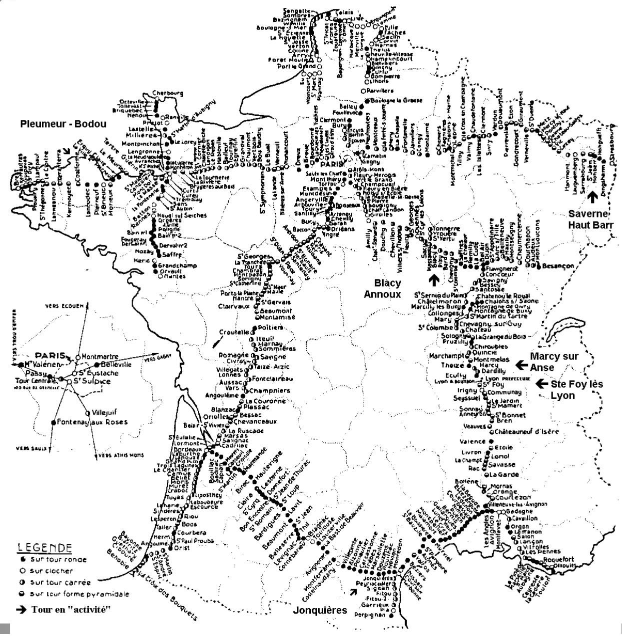


Chappe-Code



Source: www.mathematik.uni-muenchen.de





e.g. 18th century

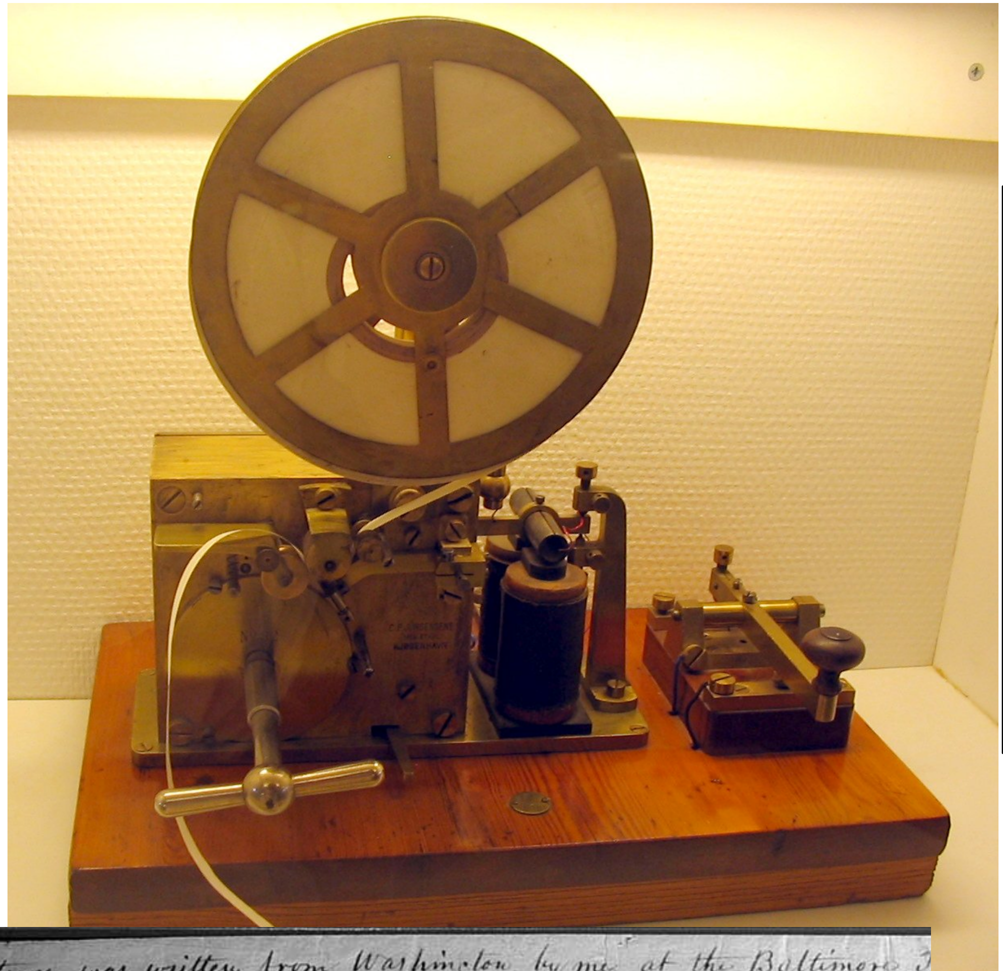
1791: Semaphoric Telegraph (Chappe)

Morse Telegraph

Image source: Wikimedia Commons

Morse transceiver

- One switch to send long and short impulses at sender
  - dahs and dits or
  - dashes and dots
- Dashes and dots
  - punched into paper strip at receiver
- See beginning of first telegraph 'What hath God wrought' (Num 23,23) sent in 1844 from Washington to Baltimore
- Communication network?



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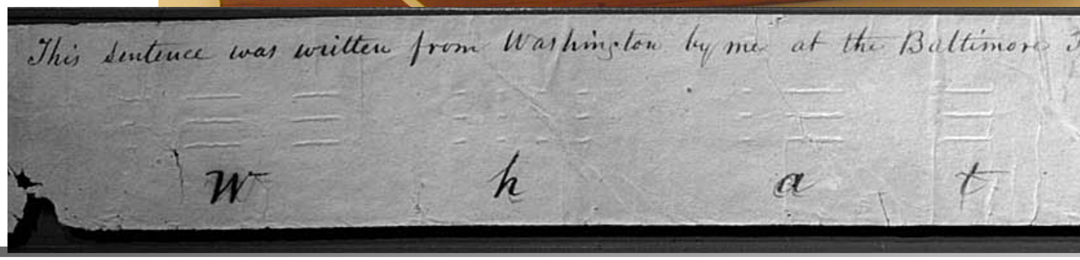


Morse Telegraph

Image source: Wikimedia Commons

Telegraph Network in United States 1916

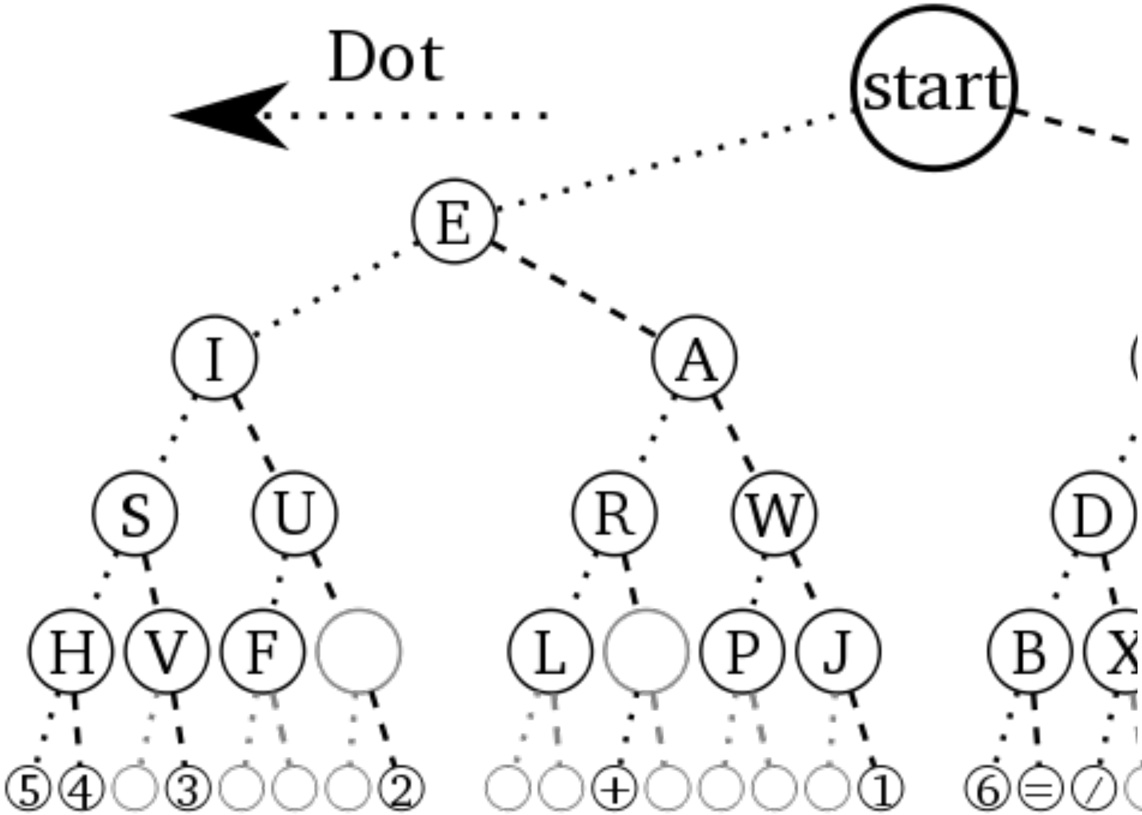
- Similarities to today's Internet?
- Signal coding?
- Type of switching?
  - Packet?
  - Message?
  - Circuit?
- Type of service?
  - Connection oriented?
  - Connectionless?
- Repeaters?
- Routers?

Morse Telegraph

Image source: Wikimedia Commons

Morse Code

- Variable length
- Short code for frequently used letter



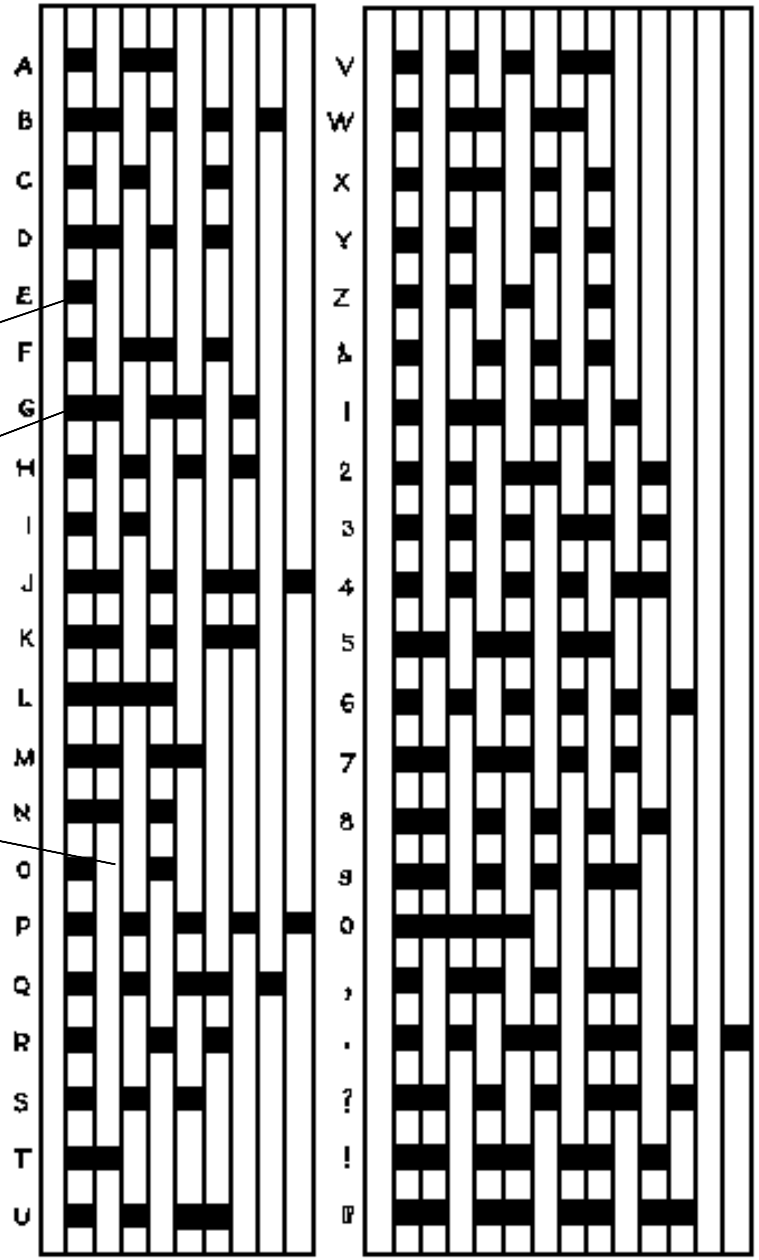
Letter	Relative frequency in the English language
e	12.702%
t	9.056%
a	8.167%
o	7.507%
i	6.966%
n	6.749%
s	6.327%
h	6.094%
r	5.987%
d	4.253%
l	4.025%
c	2.782%
u	2.758%
m	2.406%
w	2.361%
f	2.228%
g	2.015%
y	1.974%
p	1.929%
b	1.492%
v	0.978%
k	0.772%
j	0.153%
x	0.150%
q	0.095%

Morse Telegraph

Image source: Wikimedia Commons

Morse Code

- Original was more complex
- but O was shorter



- intra-character gap (3 slots)
- intra-word gap (4)
- intra-sentence (59

Baudot Telegraph

Image source: Wikimedia Commons

Baudot time multiplex system

Forefather of teletypewriters (TTYs)

Baud rate (symbol rate) of transmission named after Baudot

Challenge

- to increase number of telegraph messages

Solution

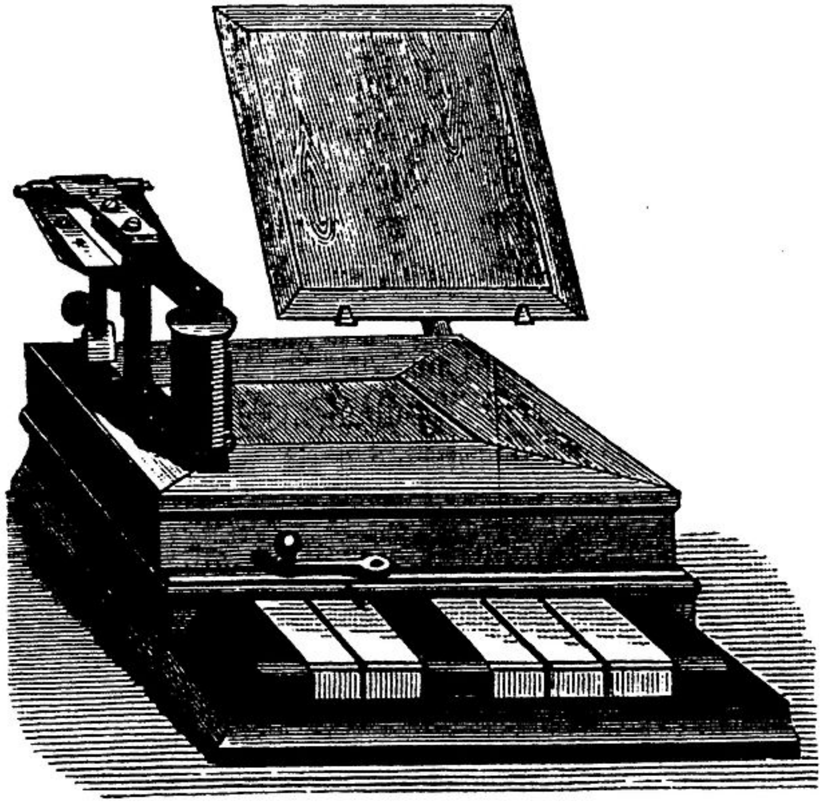
- time multiplexing
- connect multiple telegraphs over same line

First attempts failed

- problems with synchronization of sender and receiver
- reason: variable length morse code

Baudot solved problem

- fixed length (5 bit) code
- synchronized time multiplexing



Baudot Telegraph

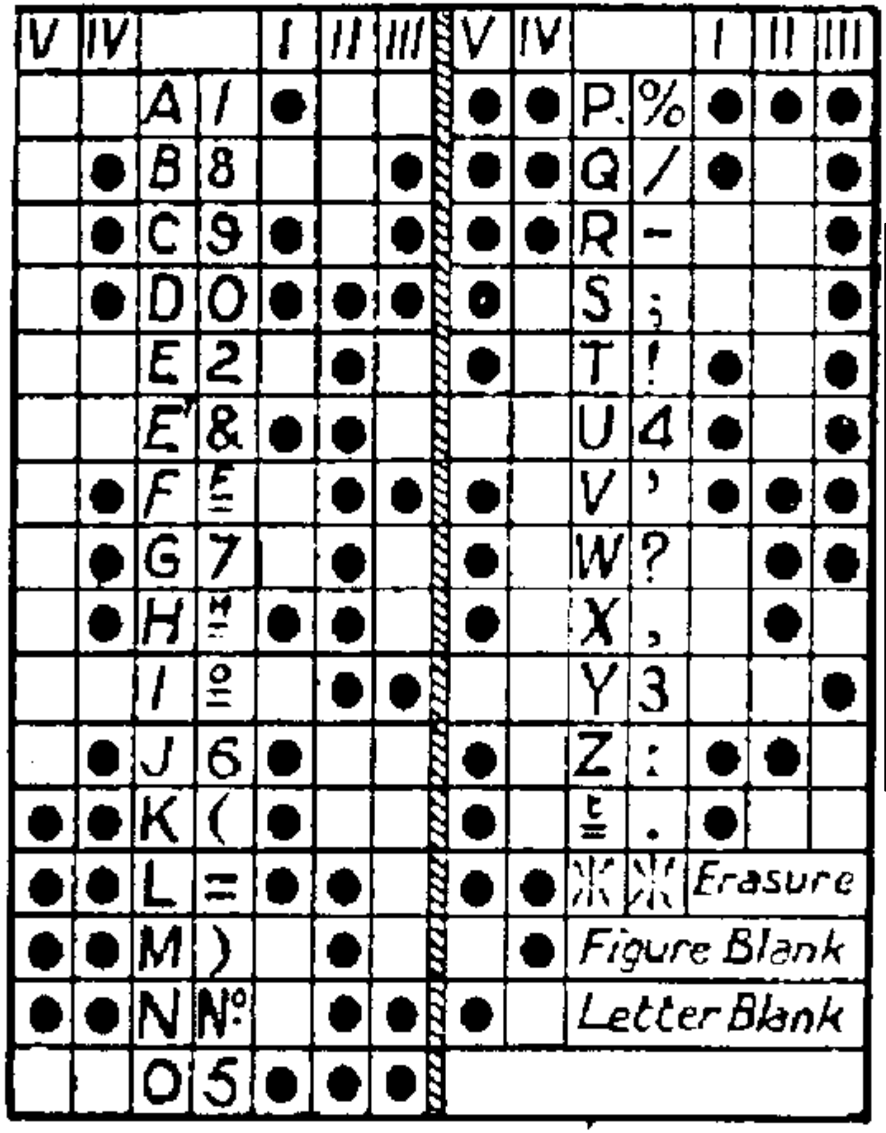
Baudot code

Fixed length 5 bit code

- Allows for $2^5=32$ symbols
- Restricted to five bits
  due to hardware constraints
  - Workaround by shifting alphabet
    to represent more characters

Later standardized by CCITT (ITU-T)

- International telegraph alphabet 1
- Forefather of ASCII code

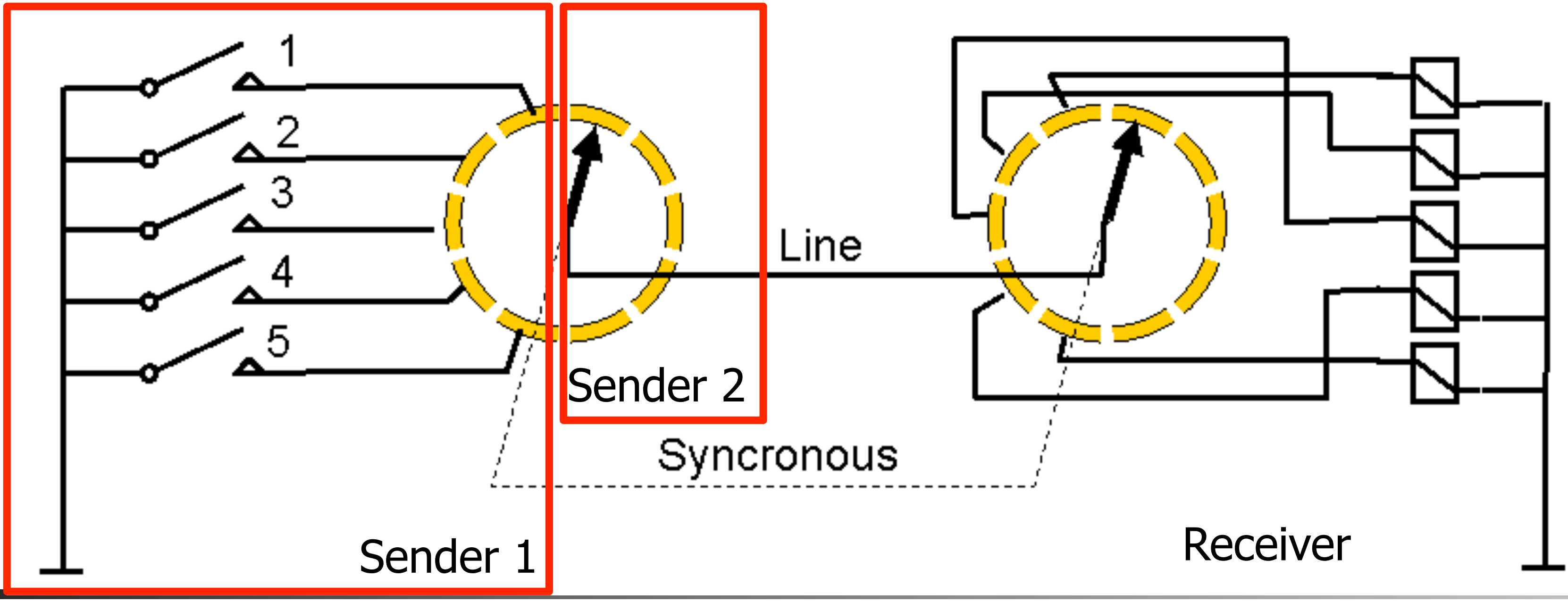


Baudot Telegraph

Image source: Wikimedia Commons

Baudot time multiplex system

- Multiple senders/receivers connected to distributor
  - Copper segments with rotating brushes
- Distributors
  - at sender and
  - receiver side synchronized
- Serialization of characters typed on Baudot keyboard
- Time multiplexing of input from multiple keyboards



Telephony

Image source: Wikimedia Commons

Telephony

Image source: Wikimedia Commons

First telephones in 1870s sold pairwise

- With dedicated, direct line

Assuming a full mesh

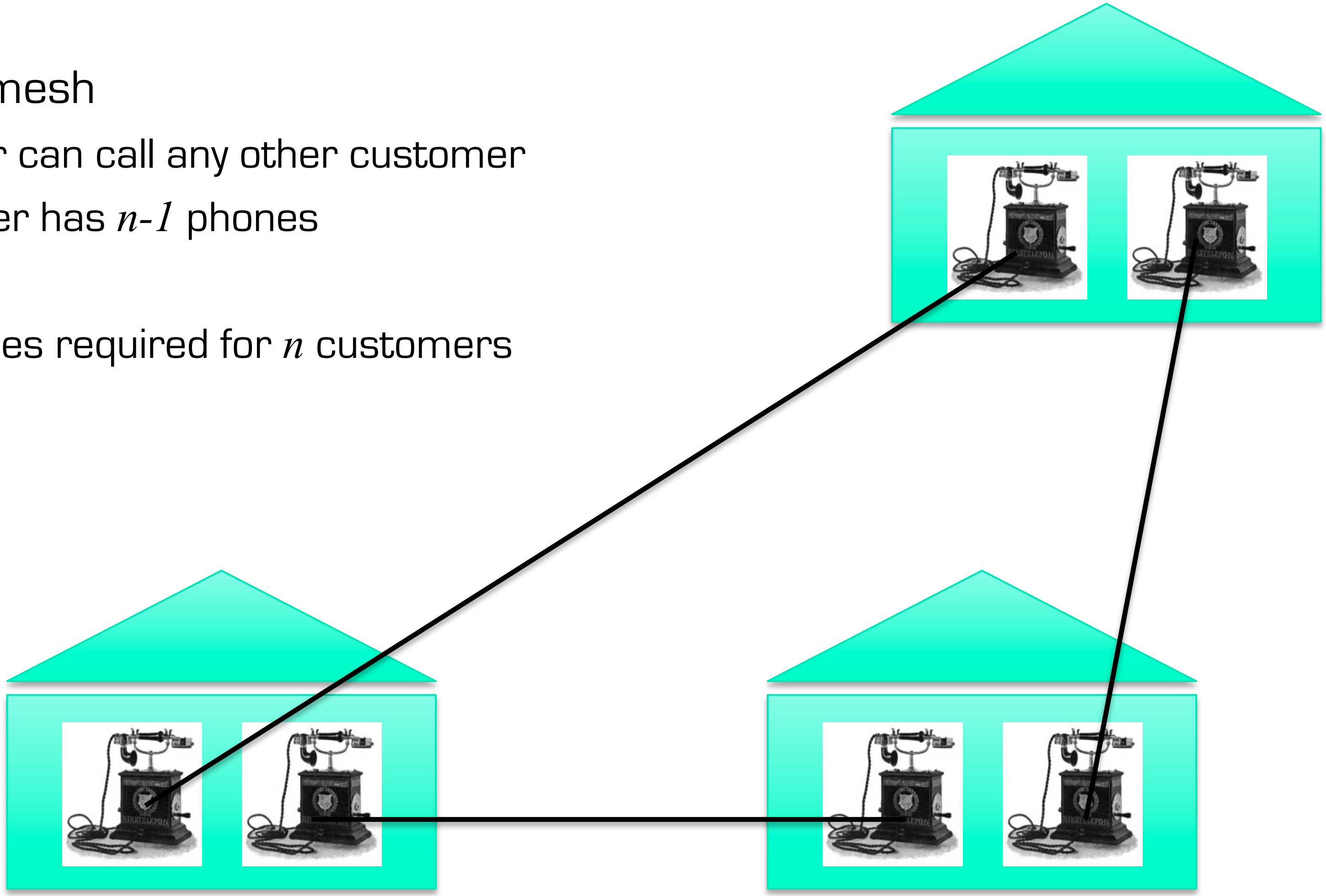
- Each customer can call any other customer

→ Each customer has n-1 phones

→ $\frac{n \cdot (n-1)}{2}$ lines required for n customers

Scalability?

- O(?) phones required?
- O(?) lines required?



Telephony

Telephone switches reduced complexity of phone network

- Line from each phone to central switchboard
- Long distance lines between switchboards
- First switches manually operated
- Complexity?
  - O(?) phones required?
  - O(?) lines required?
- Basic principle in use till today

Image source: Wikimedia Commons

Telephony

Strowger switches automated phone exchange

- Stepping switch with two degrees of freedom
- Hierarchical use with national & area code

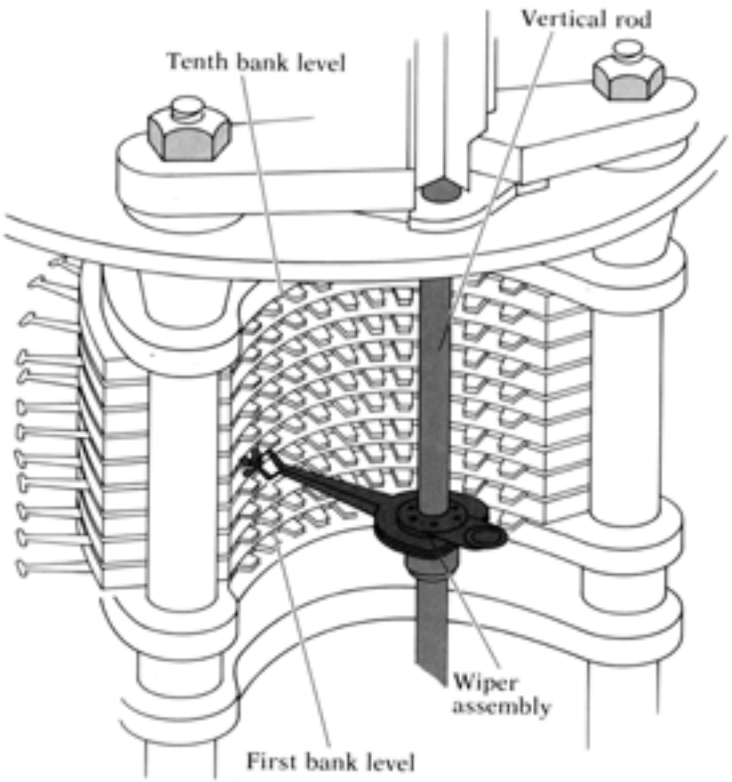
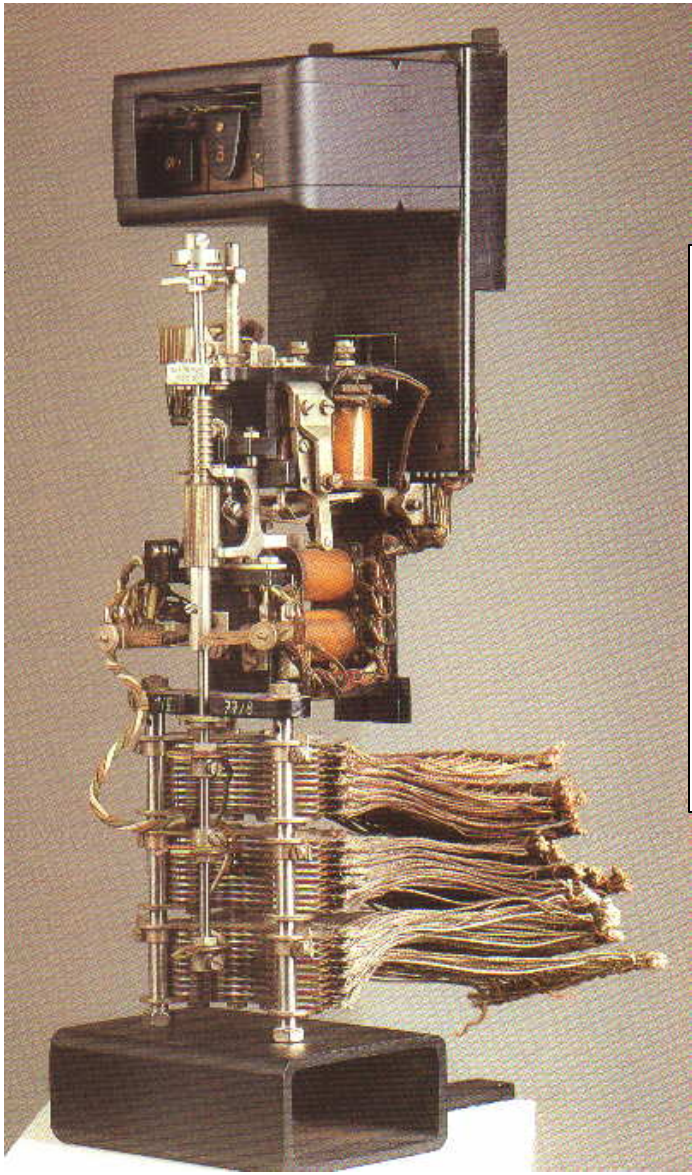


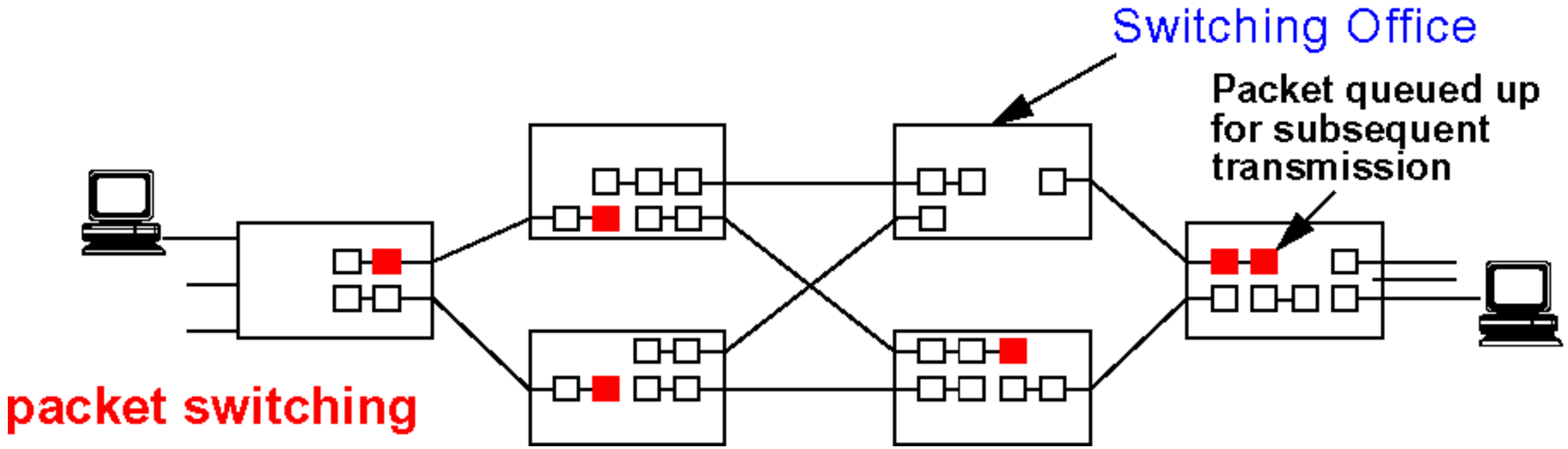
Image source: harvard.edu



Telegraphy vs. Telephony

Telegraph networks

- Message switching
  - Telegram as discrete unit forwarded from sender to receiver via relay stations
  - No dedicated line between Sender S and Receiver R
- Connectionless service
  - Subsequent telegrams from S to R may use different lines
  - E.g. in case of line failures
- Compare: packet switching in today's internet
  - Messages (packets) limited in size



Telegraphy vs. Telephony

Telephone networks

Circuit switching

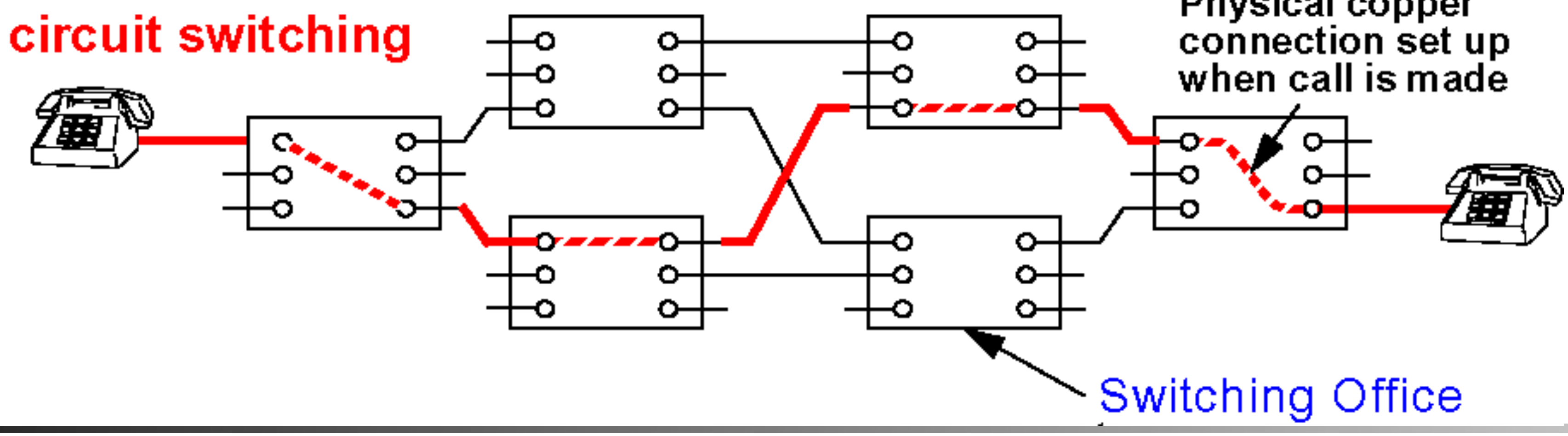
- Dedicated line between Sender S (caller) and Receiver R (callee)
- Reserved exclusively for entire call duration

Connection oriented service

- Communication always follows same path
- Three phases: connect (dial), talk (data exchange), disconnect (hang up)

Concepts still in use in today

- No dedicated lines but reserved resources
- E.g., connecting an ISDN call reserves 64kbit/s between caller and callee



The Internet

Image source: Wikimedia Commons

Forefather of the ARPANET (1965)

First wide-area network built by Marill and Roberts in 1965

- 'Toward a Cooperative Network of Time-shared Computers'
  - American Federation of Information Processing Systems conference 1966
- Connecting a TX-2 at MIT to a PDP-1 at Santa Monica
  - TX-2 built at MIT, spin-off: Digital Equipment Corporation (DEC)
  - PDP-1 built by DEC
- Connection via telephone line at 1200 bits per second

Motivation: connecting heterogeneous systems

- Early software highly specialized for machine it ran on
  - Software written in assembler code
  - Platform independent languages yet to come
- Using software written for machine A on machine B required high effort
  - Porting code or rewriting from scratch equally complex tasks

The ARPANET (~1967 - 1972)

Goals

- Load sharing
  - Send program and data for processing to remote machine
  - Required identical computers at that time
- Message service

Had been tried before

- Data sharing
  - Send program for processing to remote data
- Program sharing
  - Send data for processing to remote program
- Remote service
  - Send query to remote program and data
  - Harness specialized hardware and software

Extended goals of ARPANET for heterogeneous environments

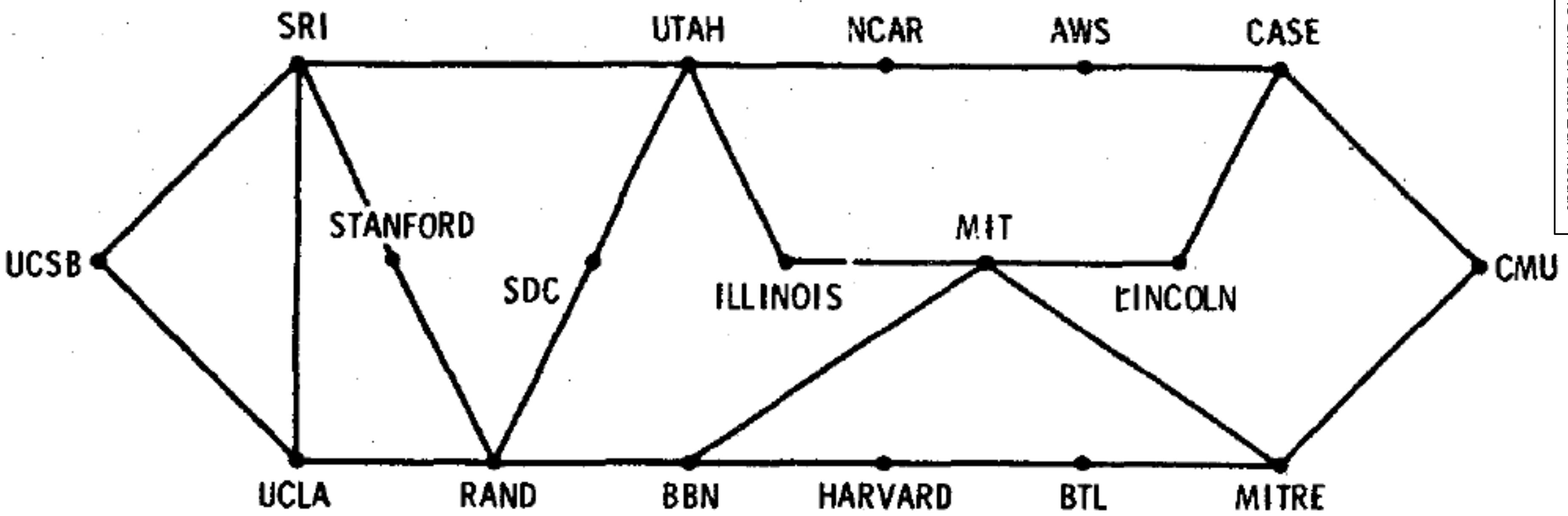
The ARPANET

Image source: Computer network development to achieve resource sharing, AFIPS 1970

Core component: network connections

- 50 kbit/s full-duplex leased telephone lines (AT&T)
- Minimum two paths between any two IMPs

Topology as planned in 1970



The ARPANET

Norway was the first country connected outside the US

Kjeller
same building as UNIK

first satellite link of the ARPANET

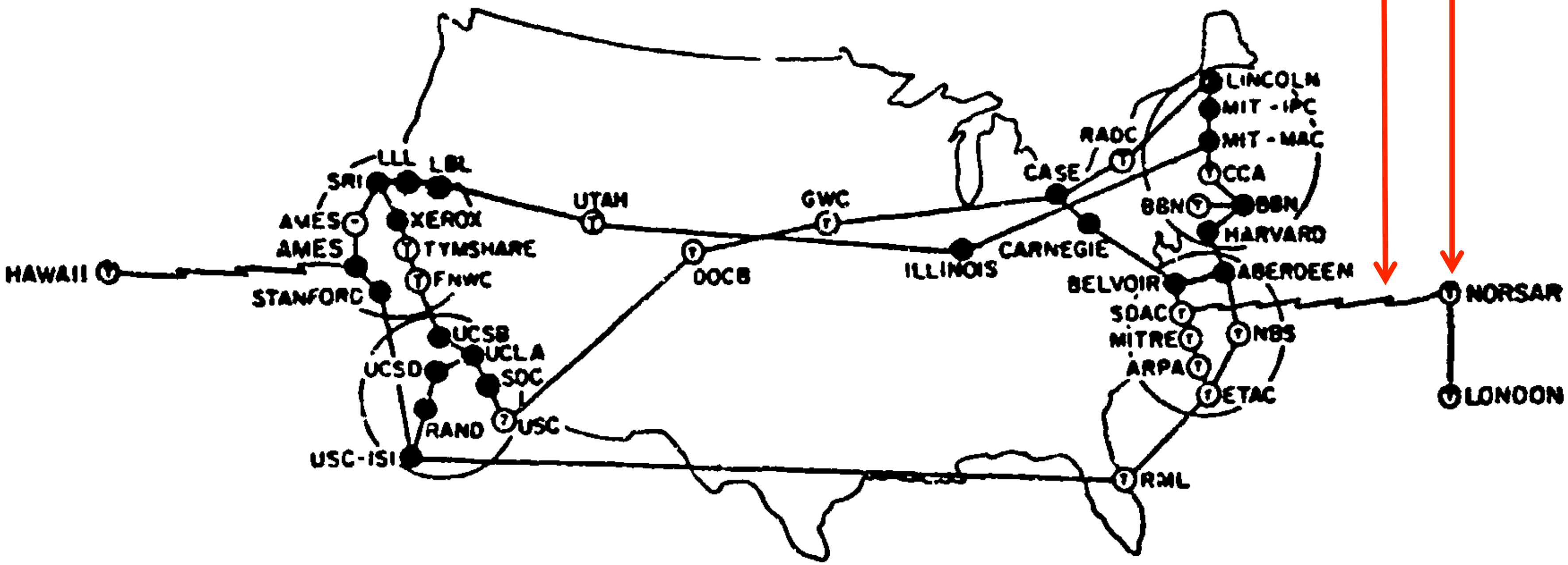


Figure 11: September 1973

Image source: DARPA: A History of the Internet, BBN Report 4799, 1991 (scan downloaded from at darpa.mil)

Standardization (1969 onwards)

Problem: developing communication protocols requires consensus

- different locations, institutions, manufacturers, operators ... involved
  → Standards required
- scientific publication process **too slow**
- industrial standardization process **too slow** and too expensive

Solution: request for comments (RFCs)

- at first: memos, minutes of meetings circulated by snail mail
- tater: published electronically
  - FTP, HTTP

Other documents

- there are also (less famous) Internet Engineering Notes (**IEN**)
- and **Internet standards** ("upgraded" RFCs)

Standardization (1969 onwards)

Request for Comments (RFCs)

- Provide fast and open access
- updated list found at **`http://www.rfc-editor.org/rfc-index.html`**

RFC Index

Num	Information
0001	**Host Software** S. Crocker [April 1969] (TXT = 21088) (Status: UNKNOWN) (Stream: Legacy)
0002	**Host software** B. Duvall [April 1969] (TXT = 17145) (Status: UNKNOWN) (Stream: Legacy)
0003	**Documentation conventions** S.D. Crocker [April 1969] (TXT = 2323) (Obsoleted-By RFC0010) (Status: UNKNOWN) (Stream: Legacy)
0004	**Network timetable** E.B. Shapiro [March 1969] (TXT = 5933) (Status: UNKNOWN) (Stream: Legacy)
0005	**Decode Encode Language (DEL)** J. Rulifson [June 1969] (TXT = 26408) (Status: UNKNOWN) (Stream: Legacy)
0006	**Conversation with Bob Kahn** S.D. Crocker [April 1969] (TXT = 1568) (Status: UNKNOWN) (Stream: Legacy)
0007	**Host-IMP interface** G. Deloche [May 1969] (TXT = 13408) (Status: UNKNOWN) (Stream: Legacy)
0008	**ARPA Network Functional Specifications** G. Deloche [May 1969] (PDF = 750612) (Status: UNKNOWN) (Stream: Legacy)
0009	**Host Software** G. Deloche [May 1969] (PDF = 722638) (Status: UNKNOWN) (Stream: Legacy)
0010	**Documentation conventions** S.D. Crocker [July 1969] (TXT = 3348) (Obsoletes RFC0003) (Obsoleted-By RFC0016) (Updated-By RFC0024, RFC0027, RFC0030) (Status: UNKNOWN) (Stream: Legacy)
0011	**Implementation of the Host - Host Software Procedures in GORDO** G. Deloche [August 1969] (TXT = 46971, PDF = 2186431) (Obsoleted-By RFC0033) (Status: UNKNOWN) (Stream: Legacy)
0012	**IMP-Host interface flow diagrams** M. Wingfield [August 1969] (TXT = 177, PS = 1489750, PDF = 1163721) (Status: UNKNOWN) (Stream: Legacy)
0013	**Zero Text Length EOF Message** V. Cerf [August 1969] (TXT = 1070) (Status: UNKNOWN) (Stream: Legacy)

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7424	**Mechanisms for Optimizing Link Aggregation Group (LAG) and Equal-Cost Multipath (ECMP) Component Link Utilization in Networks** R. Krishnan, L. Yong, A. Ghanwani, N. So, B. Khasnabish [January 2015] (TXT = 60733) (Status: INFORMATIONAL) (Stream: IETF, Area: ops, WG: opsawg)
7425	**Adobe's RTMFP Profile for Flash Communication** M. Thornburgh [December 2014] (TXT = 103979) (Status: INFORMATIONAL) (Stream: INDEPENDENT)
7426	**Software-Defined Networking (SDN): Layers and Architecture Terminology** E. Haleplidis, K. Pentikousis, S. Denazis, J. Hadi Salim, D. Meyer, O. Koufopavlou [January 2015] (TXT = 85111) (Status: INFORMATIONAL) (Stream: IRTF)
7427	**Signature Authentication in the Internet Key Exchange Version 2 (IKEv2)** T. Kivinen, J. Snyder [January 2015] (TXT = 39041) (Updates RFC7296) (Status: PROPOSED STANDARD) (Stream: IETF, Area: sec, WG: ipsecme)
7435	**Opportunistic Security: Some Protection Most of the Time** V. Dukhovni [December 2014] (TXT = 27451) (Status: INFORMATIONAL) (Stream: IETF, WG: NON WORKING GROUP)
7436	**IP-Only LAN Service (IPLS)** H. Shah, E. Rosen, F. Le Faucheur, G. Heron [January 2015] (TXT = 74340) (Status: HISTORIC) (Stream: IETF, Area: rtg, WG: l2vpn)
7437	**IAB, IESG, and IAOC Selection, Confirmation, and Recall Process: Operation of the Nominating and Recall Committees** M. Kucherawy [January 2015] (TXT = 77786) (Obsoletes RFC3777, RFC5078, RFC5633, RFC5680, RFC6859) (Also BCP0010) (Status: BEST CURRENT PRACTICE) (Stream: IETF, WG: NON WORKING GROUP)
7438	**Multipoint LDP (mLDP) In-Band Signaling with Wildcards** IJ. Wijnands, E. Rosen, A. Gulko, U. Joorde, J. Tantsura [January 2015] (TXT = 36744) (Updates RFC6826, RFC7246) (Status: PROPOSED STANDARD) (Stream: IETF, Area: rtg, WG: mpls)
7439	**Gap Analysis for Operating IPv6-Only MPLS Networks** W. George, C. Pignataro [January 2015] (TXT = 64087) (Status: INFORMATIONAL) (Stream: IETF, Area: rtg, WG: mpls)

Internetworking (~1972 onwards)

Internetworking concepts proposed by Kahn in 1973

- Goal: to connect different networks

Ground rules valid until today

- No internal changes required to connect a network to the Internet
- Best effort communication
- Stateless gateways/routers used for connection of networks
- No global control
- Also
  - dealing with packet loss, pipelining, fragmentation, global addressing, flow control, ...

Organizational changes

Who is behind RFCs?

Started in 1969 by ARPANET working group (WG)

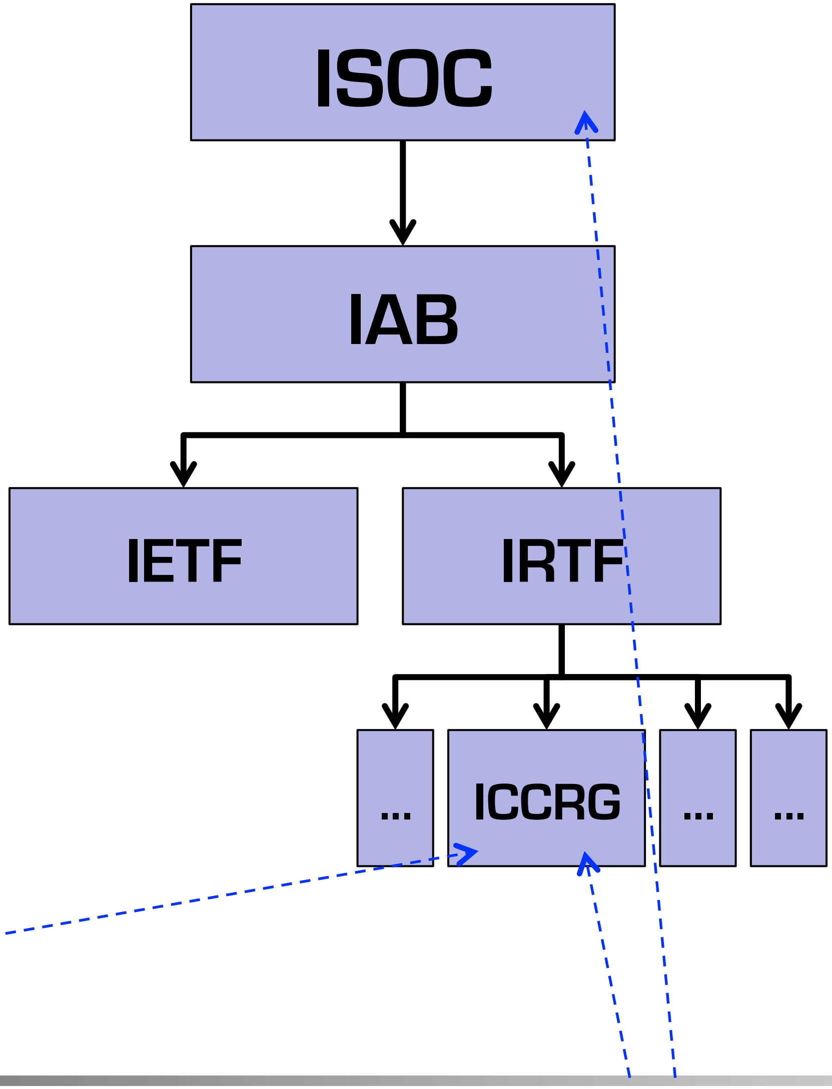
Eventually, this became the **Internet WG**

ICCB (Internet Configuration Control Board), 1981
➔ **IAB** (Internet Advisory Board), 1984
➔ **IAB** (Internet Activities Board), 1986
➔ **IAB** (Internet Architecture Board), 1992

IETF (Internet Engineering Task Force), 1986
IRTF (Internet Research Task Force), 1989

ISOC (Internet Society), 1992

Structure today



Since 1980

Mobile telephony

SMS

Web

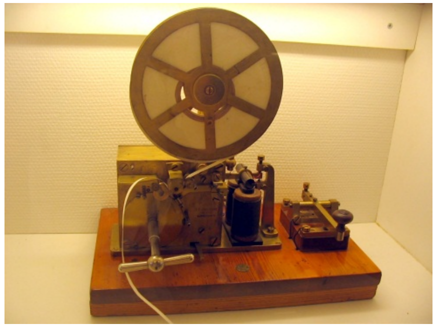
Peer-to-Peer

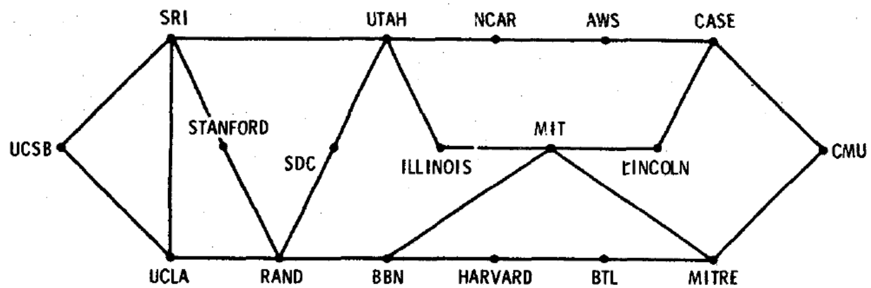
and applications

- Web services
- Streaming services
- …
- Social networks
- Twitter
- Snapchat
- …

Part I → Part II

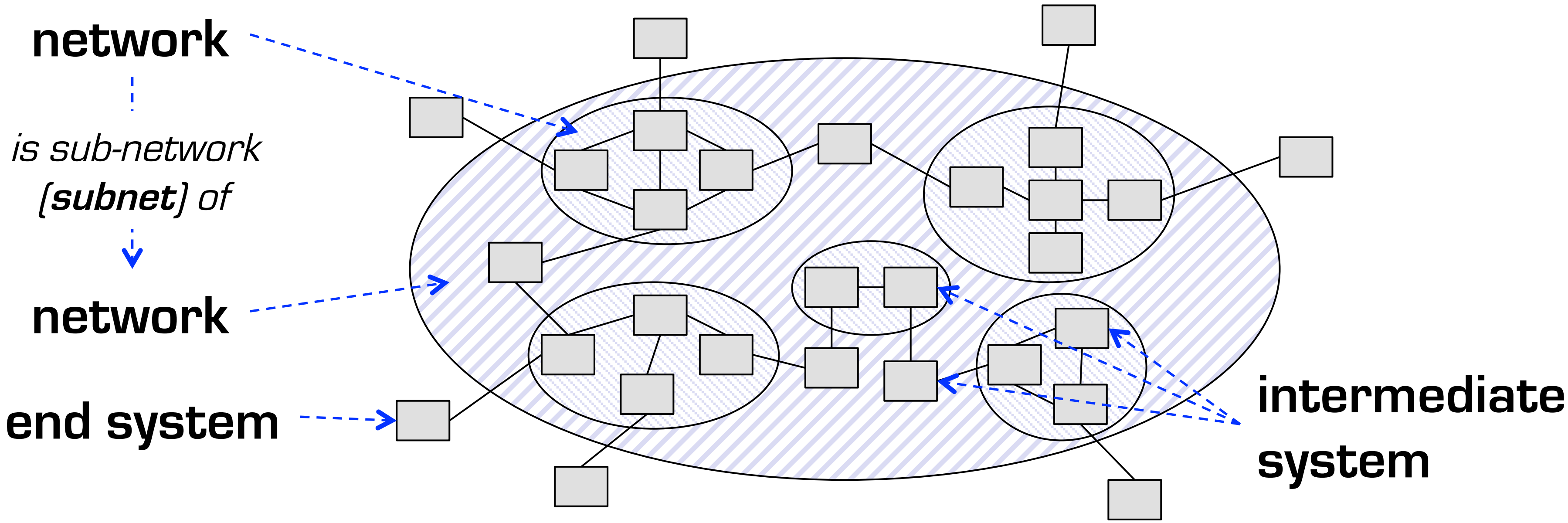
- Part I – History





- Part II – Basics
  - Network Structures
  - Layers
  - Layer functions and services
  - Terminology

Network Components



End system

- end systems are "at the edge" of a network
- examples: computer, mobile phone, terminal, printers
- ISO name: Data Terminal Equipment (DTE)

Intermediate system

- examples:
  - router, switch
  - gateway
  - repeater, bridge
- ISO name: Data Switching Exchange (DSE)

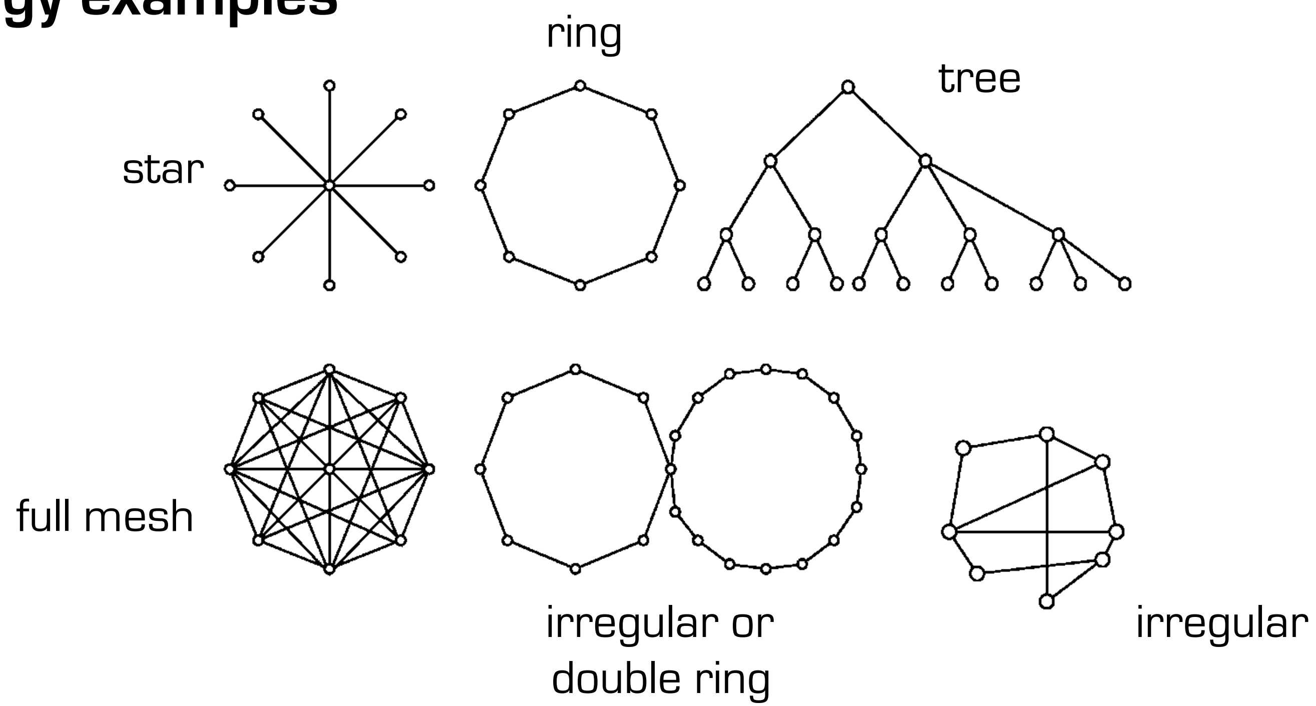
node

Network Structures

Point-to-point channels

- net = multitude of cable and radio connections often also called a network
- whereby a cable always connects two nodes
- more prevalent in wide area domains (e. g. telephone)

Topology examples



Network Structures

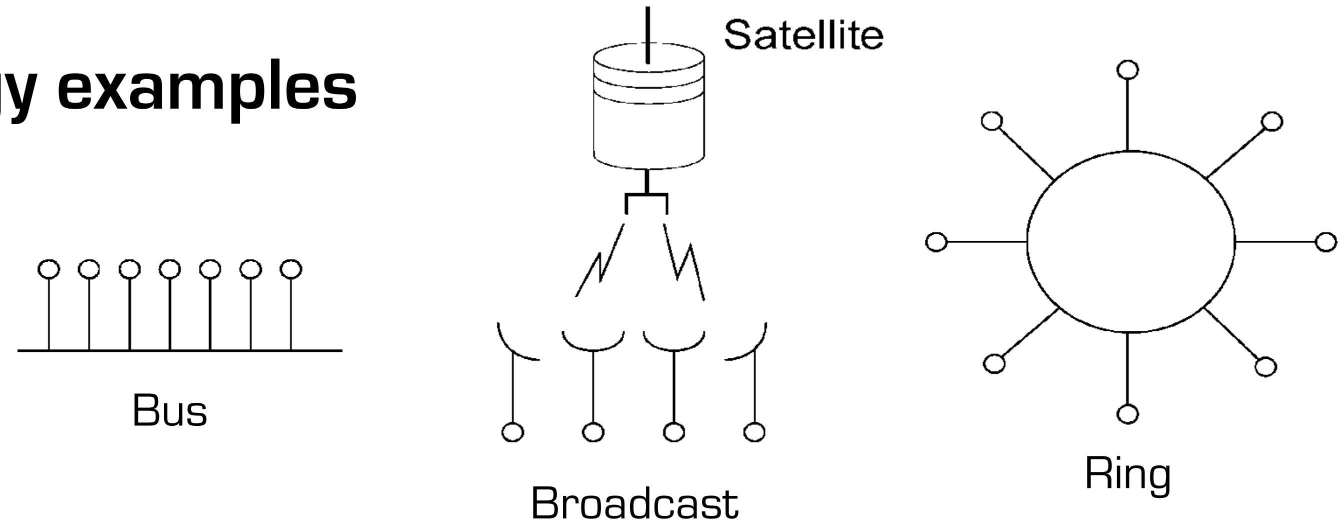
Broadcasting channels

- systems share one communication channel
- one sends, all others listen

Used for

- wireless: only option (mobile phone, satellite, radio, sensors, NFC tags, ...)
- wired: older local networks

Topology examples



Network Types

Distance between Processors	CPUs jointly located on/in..	Example
<= 0,1 m	Boards	usually tightly coupled multi-processor system
1 m	Systems	NFC, BAN, PAN
10 m	Rooms	LAN, SAN
100 m	Buildings	
1 km	Campuses	
10 km	Cities	MAN
100 km	Countries (national)	WAN
1.000 km	Continents (intern.)	
>= 10.000 km	Planets	

- NFC: near field communication, BAN: body area network, PAN: personal area network
- LAN: Local Area Network: IEEE 802.3 (Ethernet), IEEE 802.11 ("WiFi", "WLAN"), ...
- SAN: storage area network (iSCSI)
- MAN: Metropolitan Area Network: DSL, EPON, ...
- WAN: Wide Area Network: Frame Relay, SDH, ATM, all optical networks (WDM)
- Inter-Planetary Internet: http://www.ipnsig.org/
  - belongs to the class of delay-tolerant networks

Protocols and layers

Problem: engineering communication means

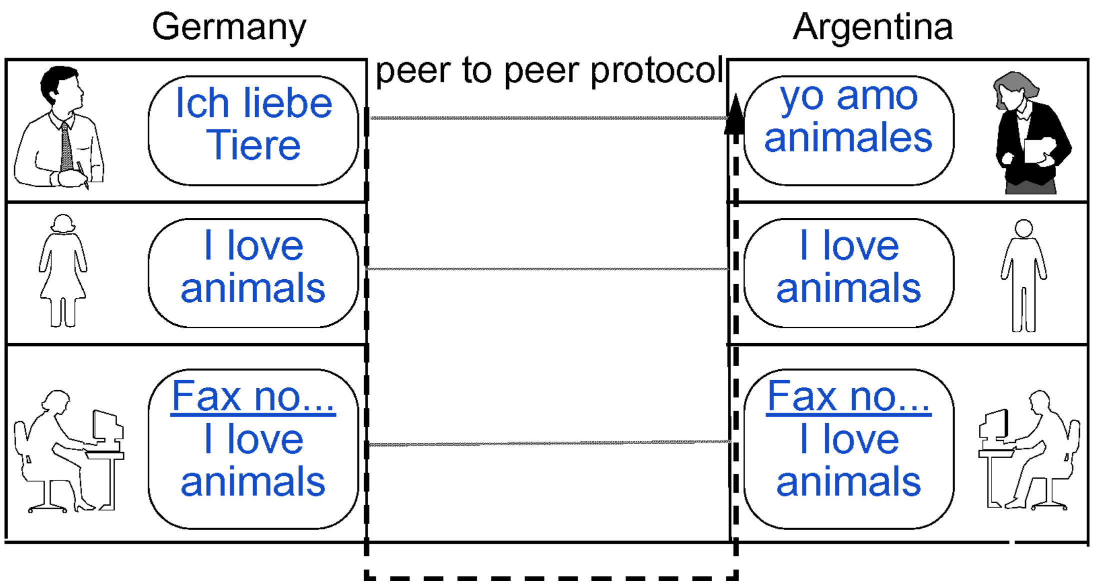
- multitude of partially very complex tasks
- interaction of differing systems and components

Simplification

- to introduce abstraction levels of varying functionalities
- general: “module”, preferable: “layer”, “level”

Example

- biologists with translator and e.g. secured encrypted FAX-office



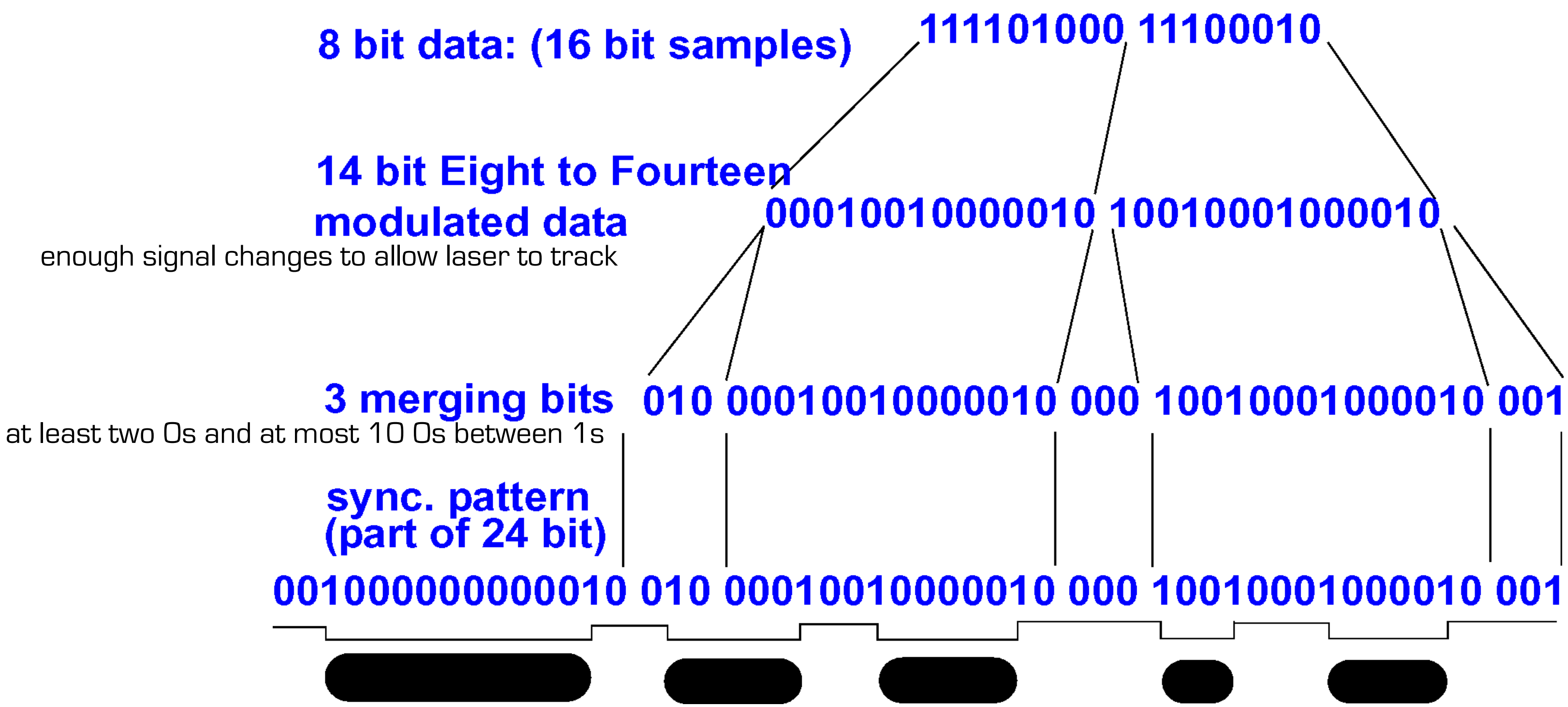
Layer Concept

Layers exist in various areas

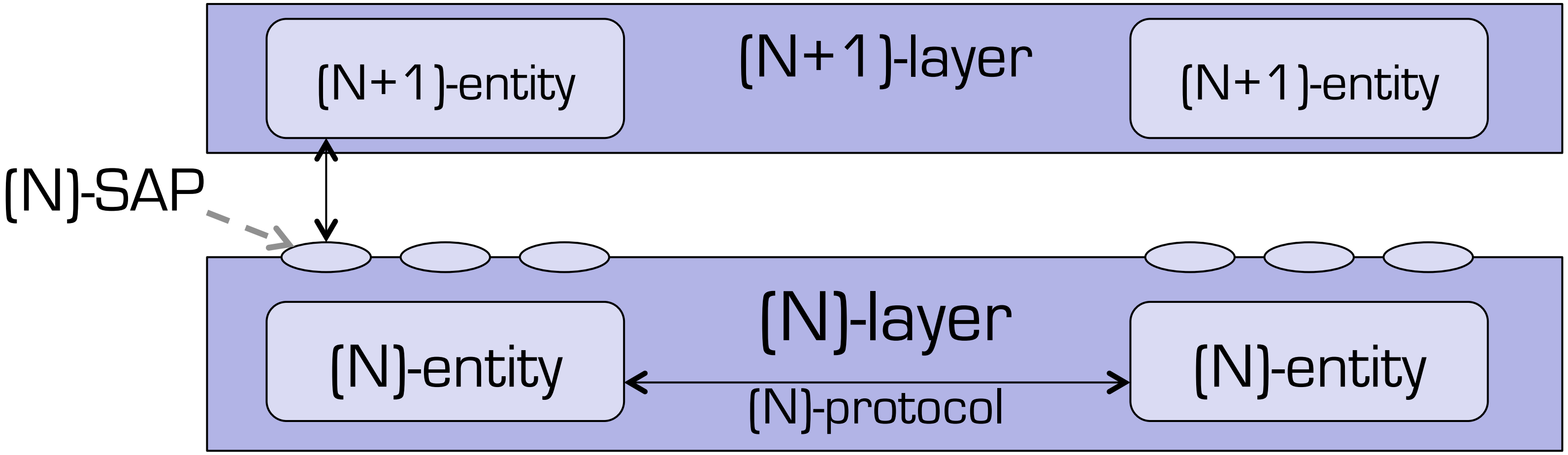
- e. g.
  - compression: MPEG
  - CD technology

Example: CD Digital Audio

- here also levels, here also data units



Layers in General (OSI)



(N)-Layer

- abstraction level with defined tasks

(N)-Entity

- active elements within a layer
- process or intelligent I/O module
- **peer entities**: corresponding entities on different systems

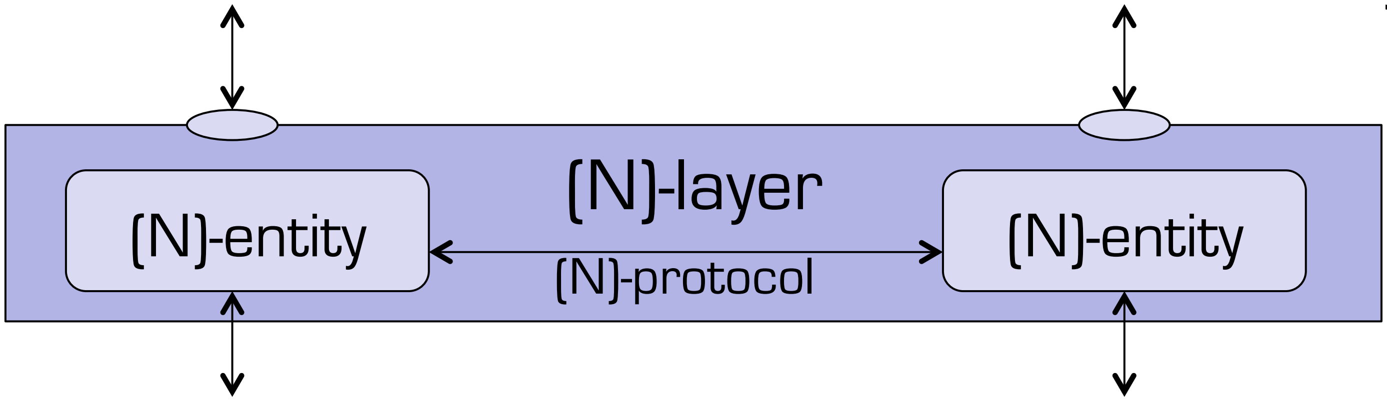
(N)-Service Access Point, (N)-SAP

- service identification
- describes how layer N provides a service for layer N+1
- an Entity can offer several services

(N)-Protocol

- a multitude of rules for transferring data between same-level entities

Protocol: Communication between same Layers



Definition of protocol

- A protocol defines
  - the format
  - the order of messages
  - exchanged between two or more communicating entities
  - as well as the actions taken on transmission and/or reception of a message or other event
- It does not define
  - the services offered to layer N+1
  - the services used (N-1-SAP)

Protocol

- Protocol syntax: rules for formatting
- Protocol semantics: rules for actions in case of a message or event
- Note: semantics must be defined as behaviour of all communicating peers

Messages have lots of names

- protocol data unit (PDU)
- frame, packet, message, datagram
- symbol

Reference Model for Open Systems Interconnection

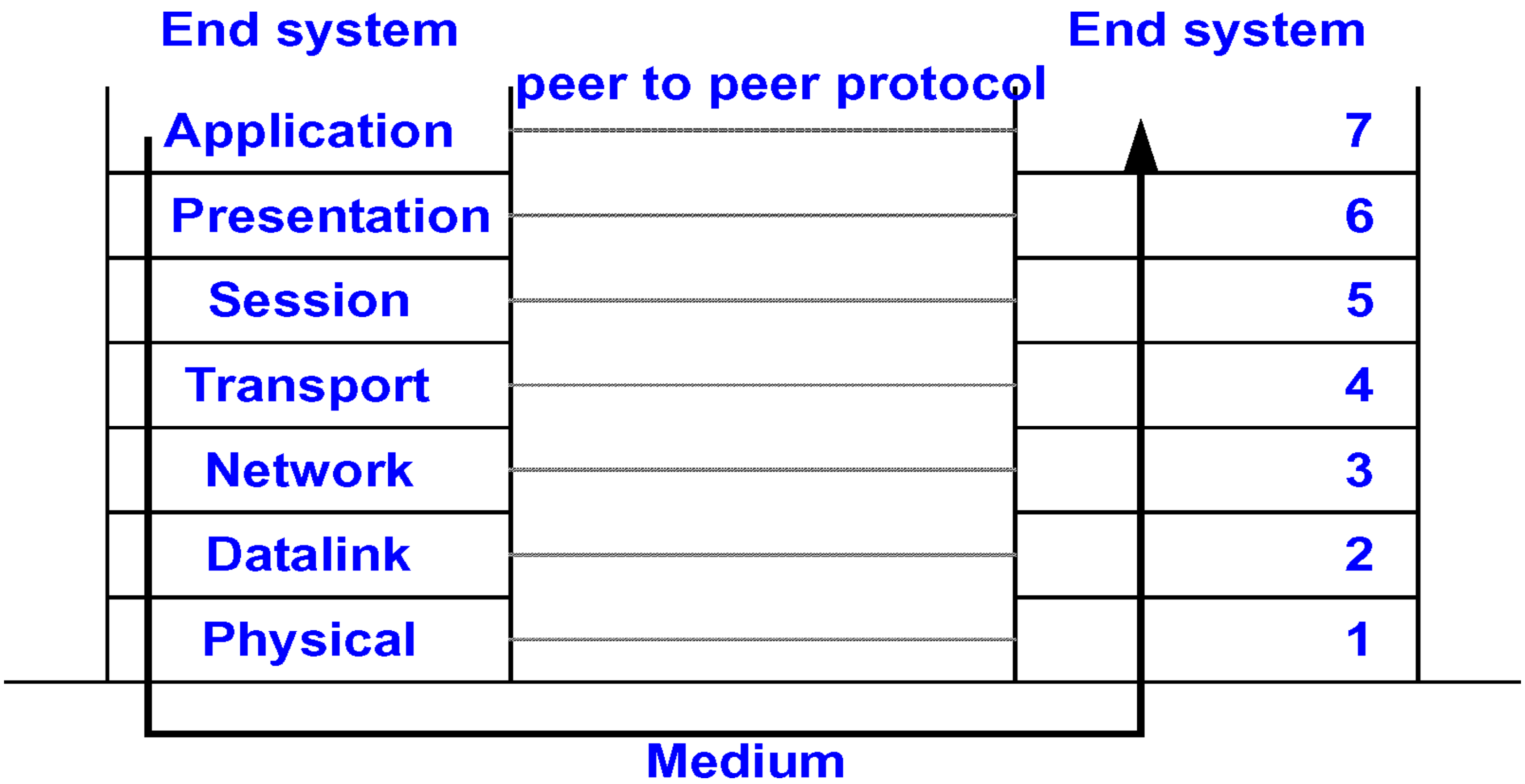
ISO OSI (Open Systems Interconnection) Reference Model

- model for layered communication systems
- defines fundamental concepts and terminology
- defines 7 layers and their functionalities

7	Application Layer
6	Presentation Layer
5	Session Layer
4	Transport Layer
3	Network Layer
2	Data Link Layer
1	Physical Layer

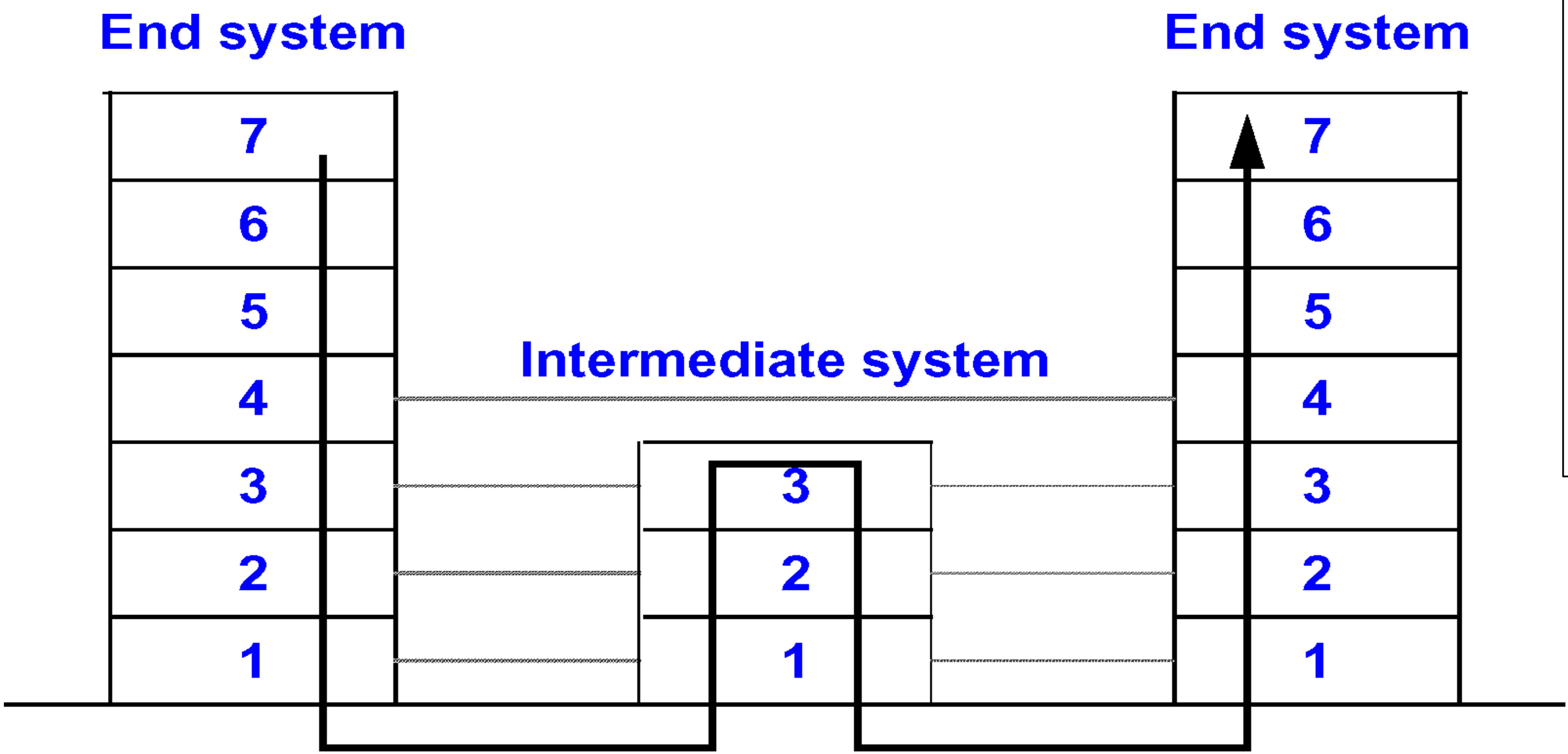
Architecture

Actual data flow between two systems



OSI Architecture

Real data flow with intermediate systems



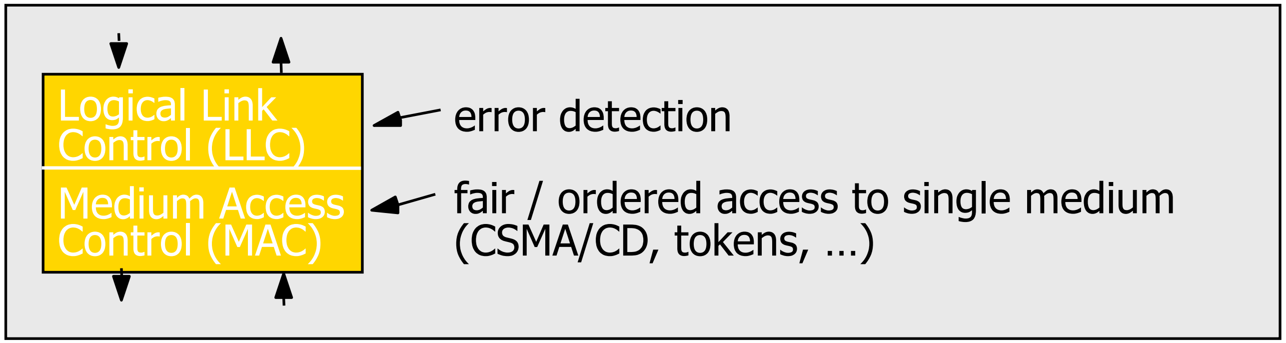
Layers and theirs Functions

<table>
<tr><th>Layer</th><th>Function</th></tr>
<tr><td>1
Physical</td><td>Signal representation of bits: sending bit 1 is also received as bit 1 (and not as bit 0):
▪ mechanics: connector type, cable/medium,..
▪ electronics: voltage, bit length,..
▪ procedural:
  ▪ unidirectional or simultaneously bidirectional
  ▪ initiating and terminating connections

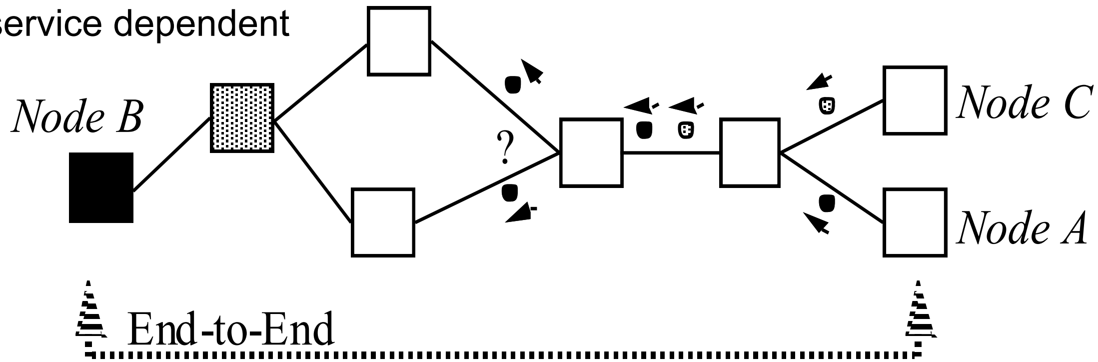
Protocol example: RS232-C = ITU-T V.24; other: ITU-T X.21</td></tr>
<tr><td>2
Data Link</td><td>Reliable data transfer between adjacent stations with frames
▪ introducing data frames and acknowledgement frames
▪ error recognition and correction within the frame:
  ▪ manipulation, loss, duplication
  ▪ Residual & "severe" errors deferred to higher layers
▪ fast sender, slow receiver:
  ▪ flow control
▪ distribution network requires access control:
  ▪ Medium Access Control (MAC)</td></tr>
</table>

ISO-OSI Layers: Functions

Layer	Function
2 **Data Link**	Layer 2 may already include some flow control Goal: protect slow receiver Flow control can be sophisticated (sliding window protocol), For example, avoid slow stop-and-go for satellite connections Broadcast networks (LAN) often with two sublayers Logical Link Control (LLC) Medium Access Control (MAC)



ISO-OSI Layers: Functions

<table>
<tr><th>Layer</th><th>Function</th></tr>
<tr><td>3
Network</td><td>connects (as relationship between entities)
end system to end system
▪ (subnets) with packets
▪ routing, for example
  ▪ fixed, defined during connect, dynamic
  ▪ congestion control (too many packets on one path)
  ▪ quality of service dependent


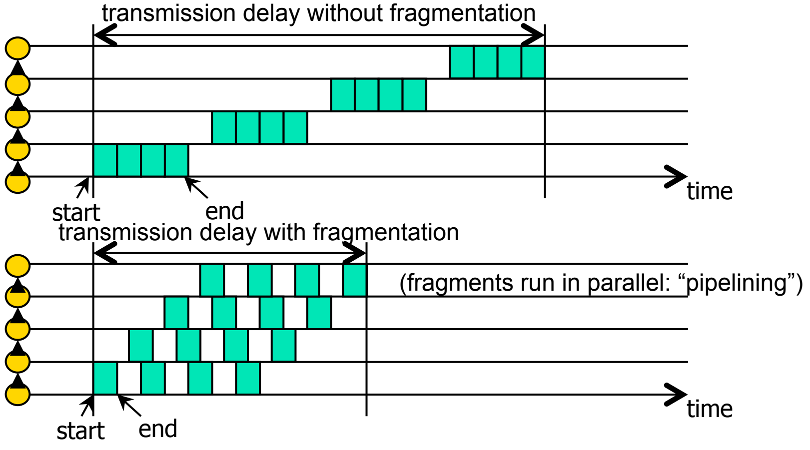
▪ varying subnets, Internetworking
  ▪ translating addresses, limit packet size
▪ comment: in broadcast networks:
  ▪ routing often simplified or non-existent,
  i.e. this layer does often not exist here
▪ example: IP (connectionless), X.25 (connection-oriented)</td></tr>
</table>

Continue here 2nd lecture

ISO-OSI Layers: Functions

Layer	Function

4 Transport	**Connection (as relationship between entities)**
	From source (application/process) to destination (application/process)
	▪ optimize required quality of service and costs
	  ▪ 1 L4 connection corresponds to 1 L3 connection
	▪ increase throughput:
	  ▪ 1 L4 connection uses several L3 connections (splitting)
	▪ minimize costs:
	  ▪ several L4 connections multiplexed onto 1 L3 connection
	▪ process addressing, connection management, error correction
	▪ fast sender, slow receiver:
	  ▪ flow control
	▪ protocol example: TCP



ISO-OSI Layers: Functions

<table>
<tr><th>Layer</th><th>Function</th></tr>
<tr><td>5
Session</td><td>support a “session” over a longer period
▪ synchronization
(during interrupted connection)
▪ token management
(coordinate the simultaneous processing of different applications)
e.g. Google OT (operation transformation) allows Docs to continue seamlessly between home and university networks</td></tr>
<tr><td>6
Presentation</td><td>data presentation independent from the end system
▪ negotiating the data structure,
▪ conversion into a global data structure
▪ examples:
  ▪ data types: date, integer, currency,
  ▪ ASCII, Unicode, …</td></tr>
<tr><td>7
Application</td><td>application related services
▪ examples:
  ▪ electronic mail, directory service
  ▪ file transfer, WWW, P2P, …</td></tr>
</table>

OSI 7-Layer Architecture Summary

7. Application Layer A: cooperating entities
6. Presentation Layer P: exchange of data (semantics!)
5. Session Layer S: structured dialogue
4. Transport Layer T: end2end msg. stream between individual processes
3. Network Layer N: packet stream between end systems
2. Data Link Layer D: error-recovering frame stream, adjacent sys.
   - LAN comprises
     - L.2b: Logical Link Control
     - L.2a: Media Access Control
1. Physical Layer PH: unsecure bitstream between adjacent systems

- Note:
  - – Many service functions carried out in several layers / services !
  - → Overhead, even reversal in part due to net homogeneity

Data Units

- Application level "messages" are processed as data units.

- Following notions for data units have become common:
  - packet: "unit of transportation" (may contain fragments)
  - datagram: instead of packet if sent individually (connectionless)
  - frame: with final envelope, ready to send (next to lowest layer)
  - cell: small packet (or packet fragment) of fixed size

- OSI terminology: „message" is a PDU
  - PDU: Protocol Data Unit
  - SDU: Service Data Unit = payload - optionally carried in PDU for user
    - (N)-PDU: semantics understood by peer entities of (N)-service
    - (N)-PDU = (N)-information plus (N)-SDU
    - (N)-SDU = (N-1)-information plus (N-1)-SDU

Five Layer Reference, Internet Reference Model and a Comparison

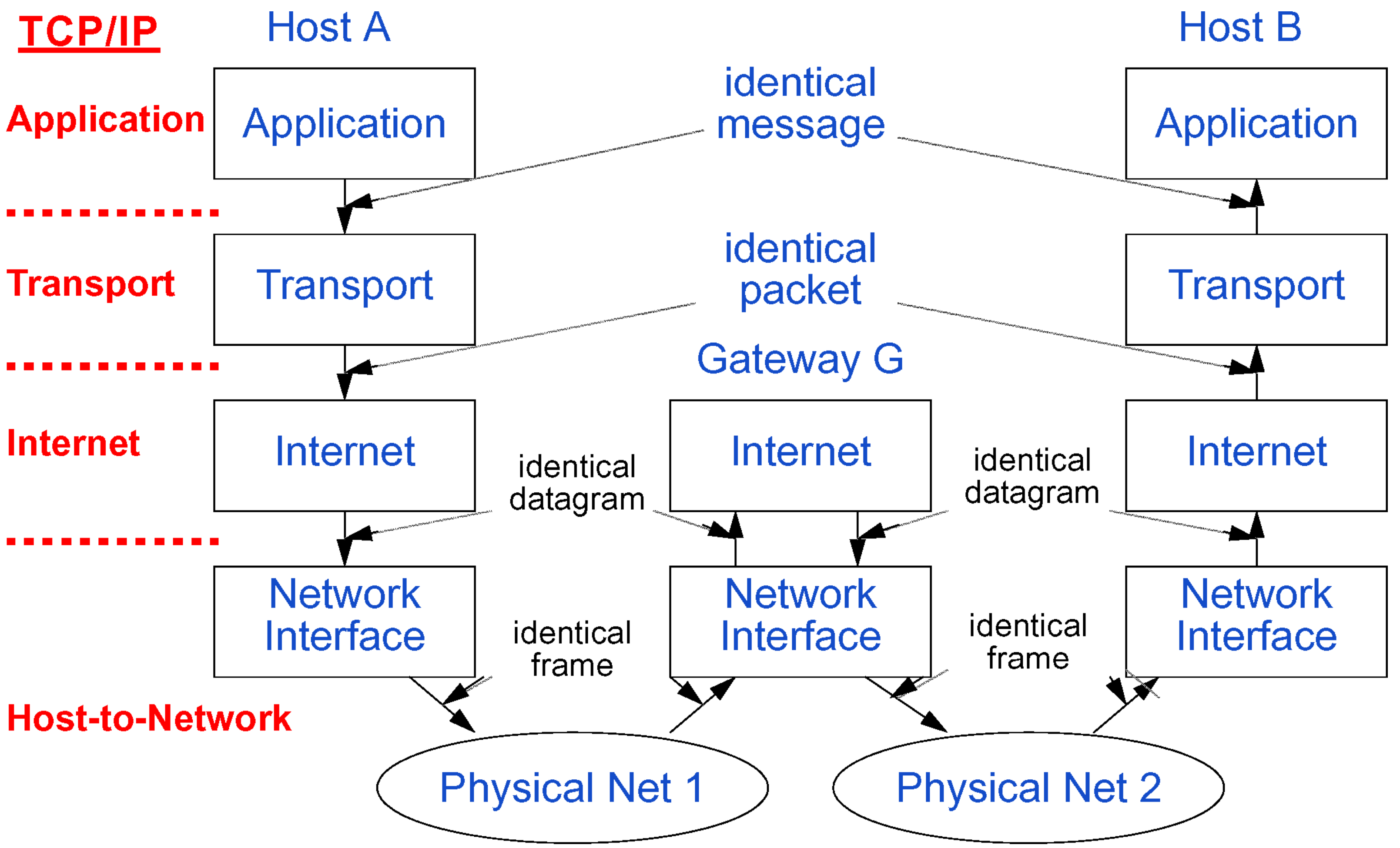
OSI Reference Model

4	5	Application Layer	
3	4	Transport Layer	danger !
2	3	Network Layer	
1	1/2	Network Interface Layer	

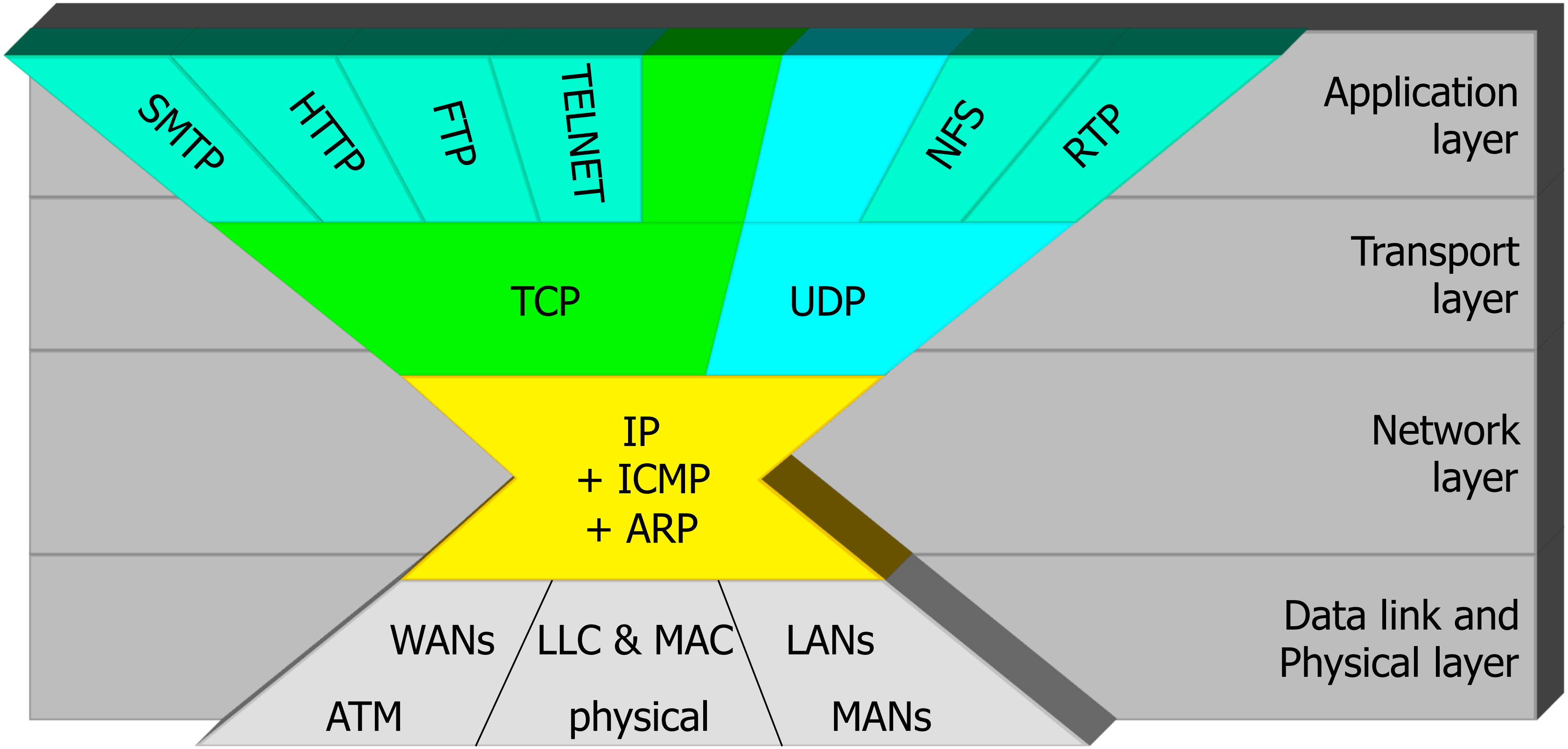
TCP/IP Reference Model Internet Architecture

- ISO-OSI presentation, session and application layer merged
- ISO-OSI data link layer and physical layer merged to form Network Interface

TCP/IP Reference Model: Internet Architecture



Internet Protocol Stack



Nickname: "Hourglass Model"

Comparing the Reference Models

ISO-OSI: standardized too late

- implementations usually worse than those of Internet protocols
- in general, however, mainly good concepts

TCP/IP (Internet)

- TCP/IP already prevalent, SMTP too, now e. g. WWW
- integrated into UNIX

Layer		Function
5	Application	application related services incl. ISO-OSI L5 and L6 (as far as necessary)
4	Transport	connection end/source (application/process) to end/ destination (application/process)
3	Network	connection end-system to end-system
2	Data Link	reliable data transfer between adjacent stations
1	Physical	sending bit 1 is also received as bit 1

Example: Layers in Action

What happens in different layers when you use your browser to access a website?

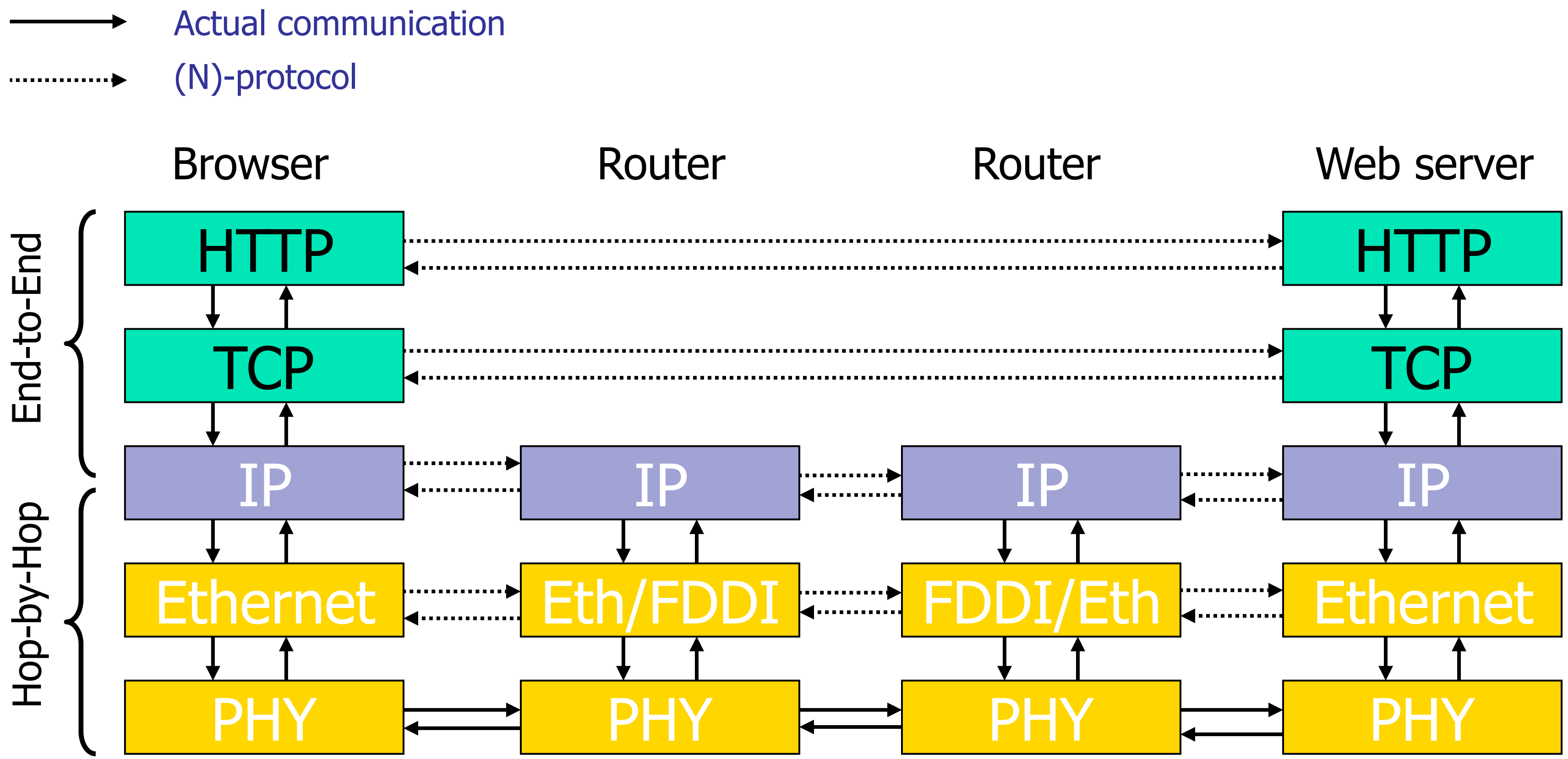
Remember: Internet has only 5 layers (or 4)

- Layers 5, 6, and 7 implemented in a single application layer

In Internet, layers 3 and 4 are somewhat confused

- Transport protocol TCP (or UDP) and network protocol IP
- Sometimes hard to draw a clear line where TCP ends and IP begins
- Example:
  - Early Congestion Notification (ECN) capability is indicated on layer 3 and congestion is indicated on layer 3
  - Sender is told about receiver's reception of congestion signal on layer 4
- **But**: Basic functionality is clearly separated

Layers in Action



- Request goes down on layers at browser
- Physical layer handles actual sending of message to next (neighbor) node
- Network protocol (IP) takes care of routing message to destination
  - Possibly several hops from one router to another
  - At each router, message goes up to IP-layer for processing
- Transport and application layers converse end-to-end

Functionality Recap

Layer 5,6,7

- Create HTTP request
- Invoke layer 4 (= TCP)
- Process reply (= web page)

Layer 4

- Open reliable connection to web server
- Make sure data arrives in the order it was sent
- Do not saturate network
  - Congestion control

Layer 3

- Route messages from client to web server
- Messages passed from router to router
- Layer 3 provides end-to-end service through hop-by-hop actions

Layer 2

- Put data from layer 3 in frames
- Send frames to immediate neighbor

Layer 1

- Actual transmission of a frame as a bitstream

Each layer performs some critical function

Layering not always "clean"

- Who handles congestion control or reliability?

Networking Protocol Map ... (Source www.javvin.com)