Distributed Systems

Distributed Time

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Motivation

Problems of unsynchronized computer clocks

- Timestamps of files (make)
- Time-triggered execution of tasks ($\rightarrow$ cron)
- TDMA based medium access control

Goal

- Establishing a systemwide **time** in distributed systems
- **Synchronicity** with real (external) time
- Synchronization of computer **clocks**

Applications

- Correct functioning of **timebased** local and distributed **applications**
- Correct **ordering of events** in distributed systems
- **Performance measurement** in distributed systems
- Distributed **real-time systems** including the synchronicity with the real global time

Agenda

- Definition of Time
- Computer Clocks
- Synchronization Protocols
- Logical Clocks

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What is Time?

Could you define what time is?

Time in the Course of History

Astronomical Time

- Based on the **uniform movement of celestial bodies** and their observation

Time in the Course of History

Astronomical Time

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- **Apparent time**
  - Average duration of the rotation of the earth
  - Mean solar day: Zenith to Zenith (until 1956)
  - 1 second $= \frac{1}{24 \cdot 60 \cdot 60}$ solar day
  - Little stability (Deceleration of the rotation of the earth, fluctuation because of mass displacement)

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  - Little stability (Deceleration of the rotation of the earth, fluctuation because of mass displacement)
- **Sidereal time** ($\rightarrow$ *stardate* in *Star Trek*)
  - Average duration of the period of the earth around the sun
  - 1 second $= \frac{1}{31.556.925{,}9747}$ part of the tropical year 1900 (since 1957)

Physical Time

Based on (periodical) physical processes

Typical examples:

- Candle clock (burning of wax)
- Pendulum clock (accuracy at best: 10^{-7})
- Quartz clock (accuracy at best: 10^{-9}, typical: $10^{-5} \ldots 10^{-6}$)

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Atomic Clock

- Definition in the International System of Units (SI) (since 1967): *"1 second is the duration of 9192631770 periods of radiation produced by transition of an electron between two hyperfine levels of a Cesium-133 atom."*
- Cesium-133 clock, accuracy at best: 10^{-14}, typical: 10^{-13}
  $\rightarrow < 1\mu s$ per year
- Cesium fountain, accuracy: $< 10^{-15}$

Physikalisch-Technische Bundesanstalt (PTB)

- In Braunschweig
- Operation of multiple atomic clocks (CS1-CS4, CSF1)
- Responsibility for the **legal time** in Germany (since 1978)
- Operation of distribution services

https://www.meinberg.de/images/xatomuhr.jpg.pagespeed.ic.3l8wJGqj54.jpg

Which time is it?

Now we have an accurate definition for the period called second, but...

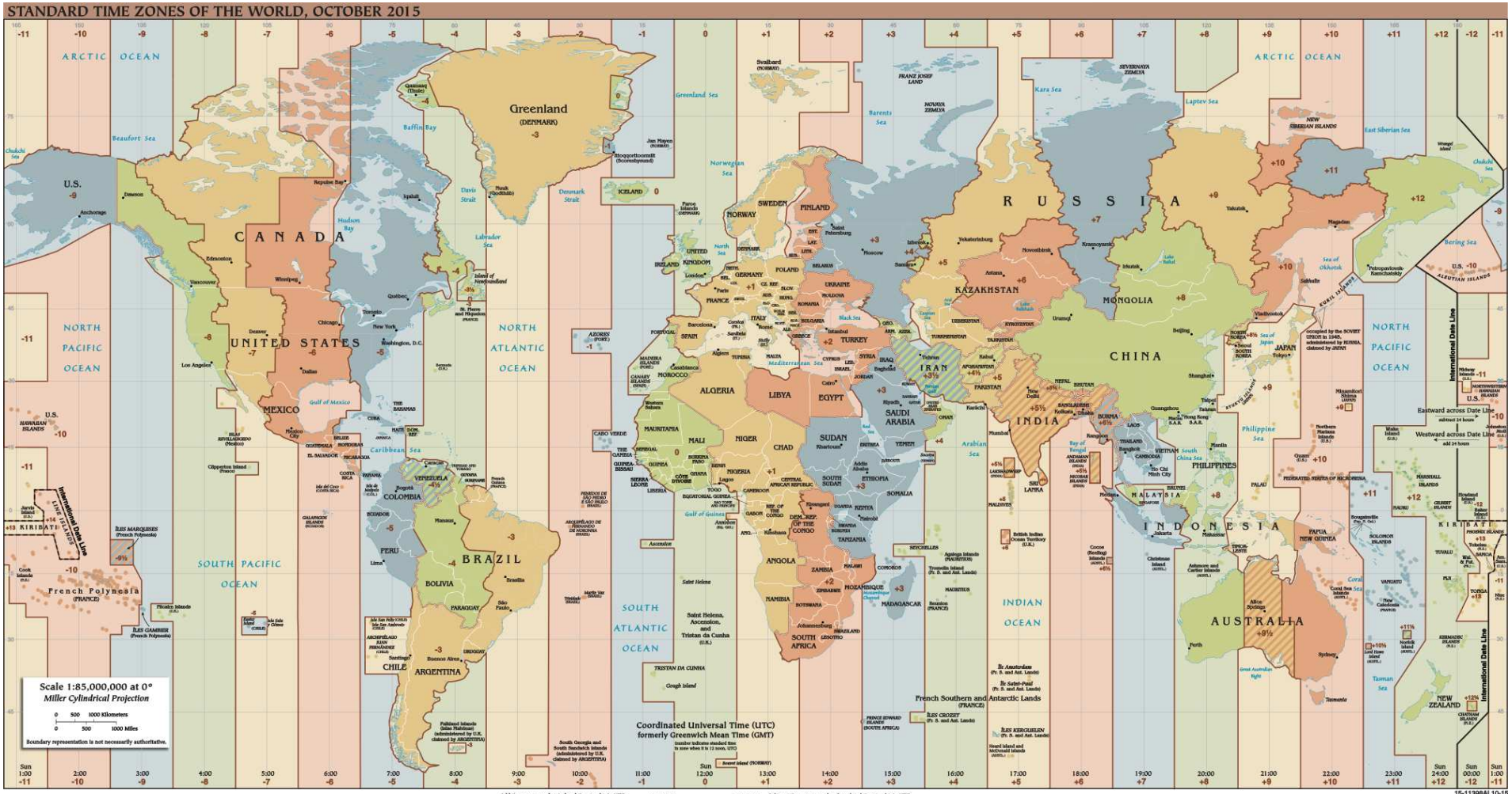
How do we know which time it is?

Time Systems

GMT: Greenwich Mean Time

- Local time (real and average), common until ca. 1880
- Problem for the railway schedules
- Greenwich Mean Time legal standard time in England since 1880
- Since 01.06.1891: German and Austro-Hungarian railway administration introduce the time at the 15th longitude as mitteleuropäische Eisenbahn-Zeit (M. E. Z.).
- *Deutsches Reich*: legal time since 01.04.1893 is defined as *"the average apparent time at the 15th longitude eastern of Greenwich"*
- Meridian Conference at Washington 1884 defines Greenwich as prime meridian and introduces time zones → apparent time
- Since 01.01.1925: Begin of the day at midnight (for astronoms until then at midday)

Time Zones



https://commons.wikimedia.org/wiki/File:Standard_Time_Zones_of_the_World_(October_2015).svg

UT, TAI, and UTC

UT: Universal Time

- World time is derived from sidereal time (since 1957) at prime meridian
- UT1: Correction of polar motion

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TAI: Temps Atomique International

- Mean atomic time since 01.01.1958
- Operation of ca. 250 atomic clocks worldwide
- Coordinated on a global scale by the Bureau International de l'Heure (BIH)

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UTC: Coordinated Universal Time

- Current standard for time (since 1972)
- Based on TAI, but adjusted to UT1 by leap seconds on a difference of more than 900 ms
- **Deviation**: 1 second in $300,000$ years

Historical Time Distribution Services

- *One O'Clock Gun*

https://upload.wikimedia.org/wikipedia/commons/d/d9/One_OClock_Gun.JPG

  - **Problem:**
    Transmit time of sound

- Time ball

https://www.flickr.com/photos/flissphil/2530153597/

  - **Problem:**
    Line of sight required

Modern Time Distribution Services

Long-wave radio transmitter

- e.g., in Germany: DCF77 (77.5 kHz, Frankfurt/Mainflingen)
- Based on atomic clock CS-2 at PTB
- Second intervals
- Modulated full BCD time code (58 bit) every minute
- Accuracy
  - $2 \cdot 10^{-13}$ averaged over 100 days
  - 1-10 ms per second (atmospheric noise)

GOES Satellite System

- Geostationary Operational Environment Satellite
- Accuracy ca. 0.5 ms
- Service of the NOAA from 1974 to 2004

GPS-based Time Distribution

- Global Positioning System, original primary military
- 24 satellites, orbital period 12 h, at least 4 are always apparent
- Cesium clocks on board
- Synchronization against clocks of other satellites via ground station with an accuracy of ± 5 ns
- Position determination through different **signal runtimes**
- Artificial inaccuracies in times of crisis
- Differential GPS makes additionally use of ground stations with a known location (geodesy)

GPS based clock

- GPS signal as reference of a PLL circuit
- High-precision second pulse (pps = pulse per second)
- Typical accuracy: ca. $1\mu s$

Other Satellite-based Time Distribution Services

Galileo satellite system (operated by EU/ESA)

- European system, compatible with GPS (GPS III)
- Up to 30 satellites
  - Each of it with two atomic clocks
  - Sending timestamps and location data
  - Global coverage
- Services
  - Free service for locating, navigation, and clock synchronization (accuracy ca. 4 m horizontal, 8 m vertical)
  - Commercial service (accuracy 1 m, movement 0.2 m/sec) (surveying, network synchronization, fleet management)
  - Safety-of-Life service, (safety critical applications aviation, shipping, and railways)
  - Service "'of public interest"', (Signal with very high accuracy, quality, reliability, and integrity for sovereign applications)

Other Systems: GLONASS (Russia) and Beidou (China)

Terms

Reference time

- Approximation of the real physical time

Deviation and accuracy

- Absolute or relative difference to a reference time

Precision and resolution

- Smallest period between two successive displayable points in time

Stability

- Frequency variation of a clock (Often given as ppm)

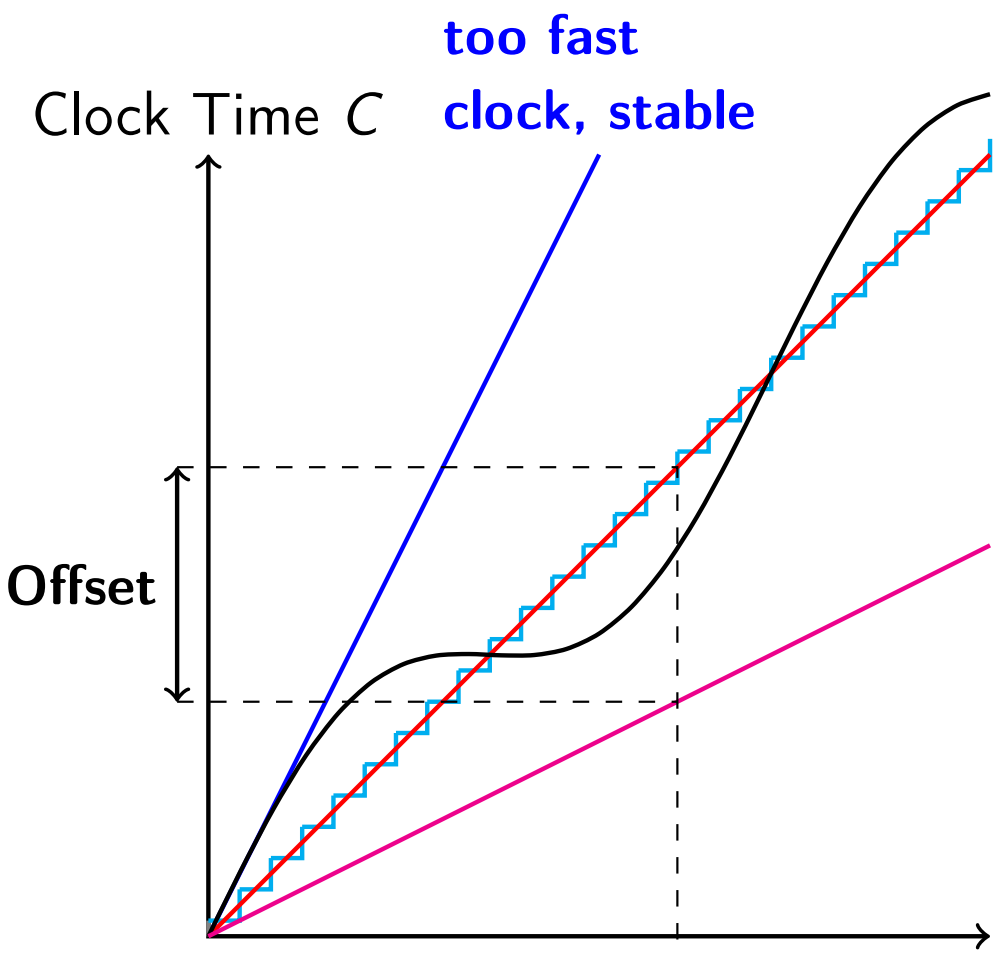
Offset

- Time difference between two clocks

Drift

- Frequency difference between two clocks

Illustration



Clock with high accuracy, but low stability

ideal clock: $\frac{dC}{dt} = 1$

Clock with high accuracy and stability, but low precision

too slow clock, stable

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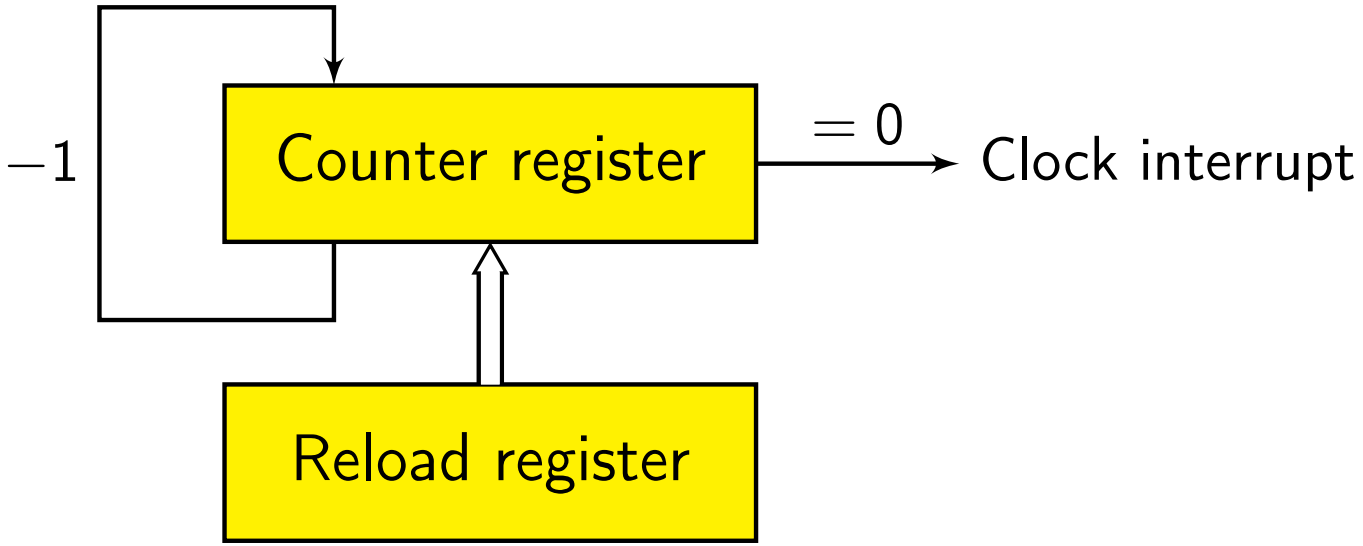
Hardware of a Computer Clock



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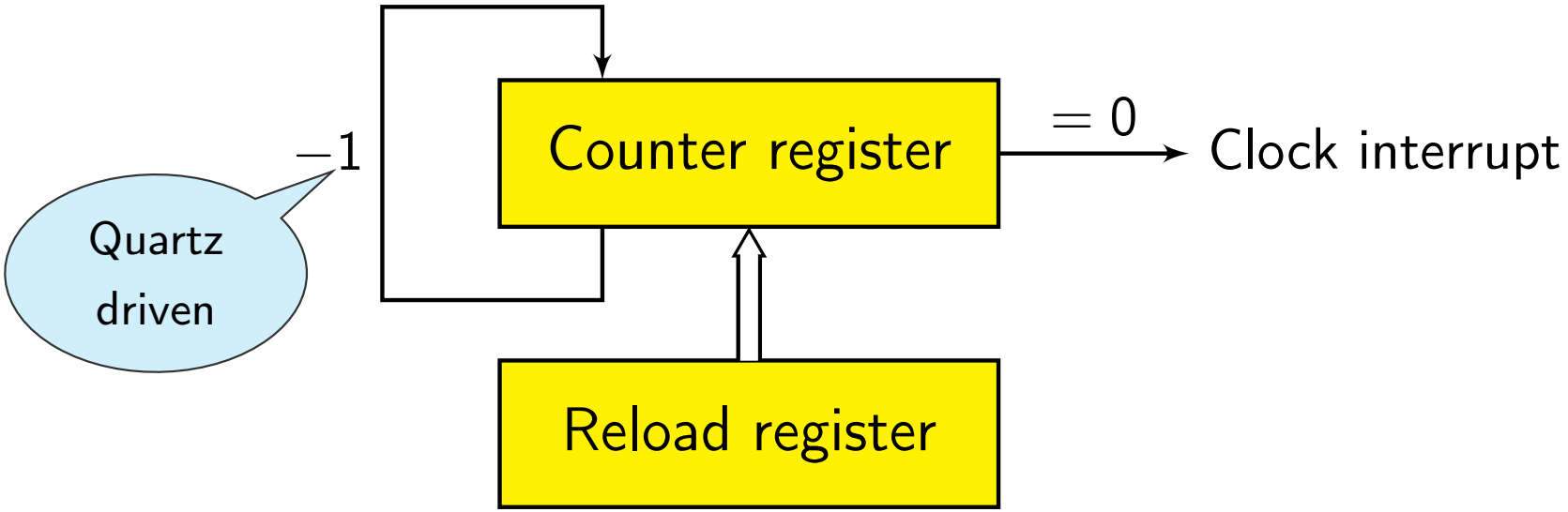

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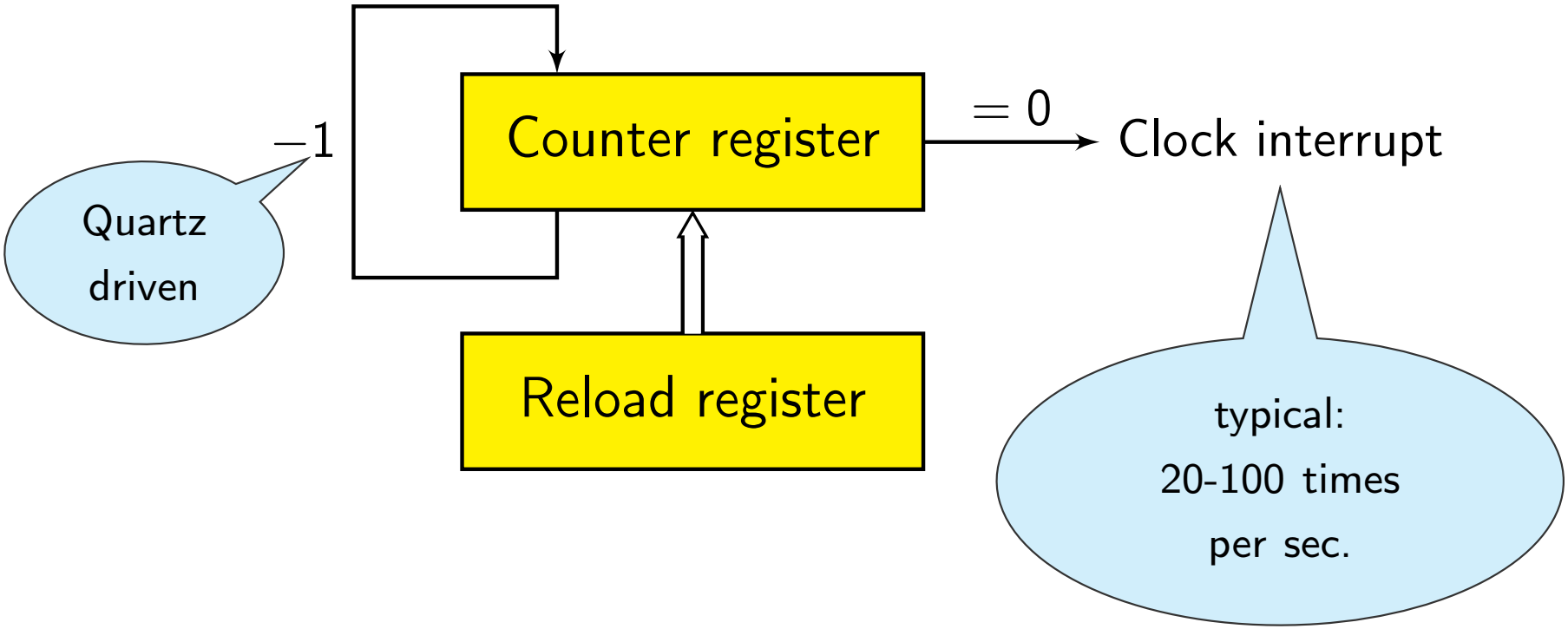
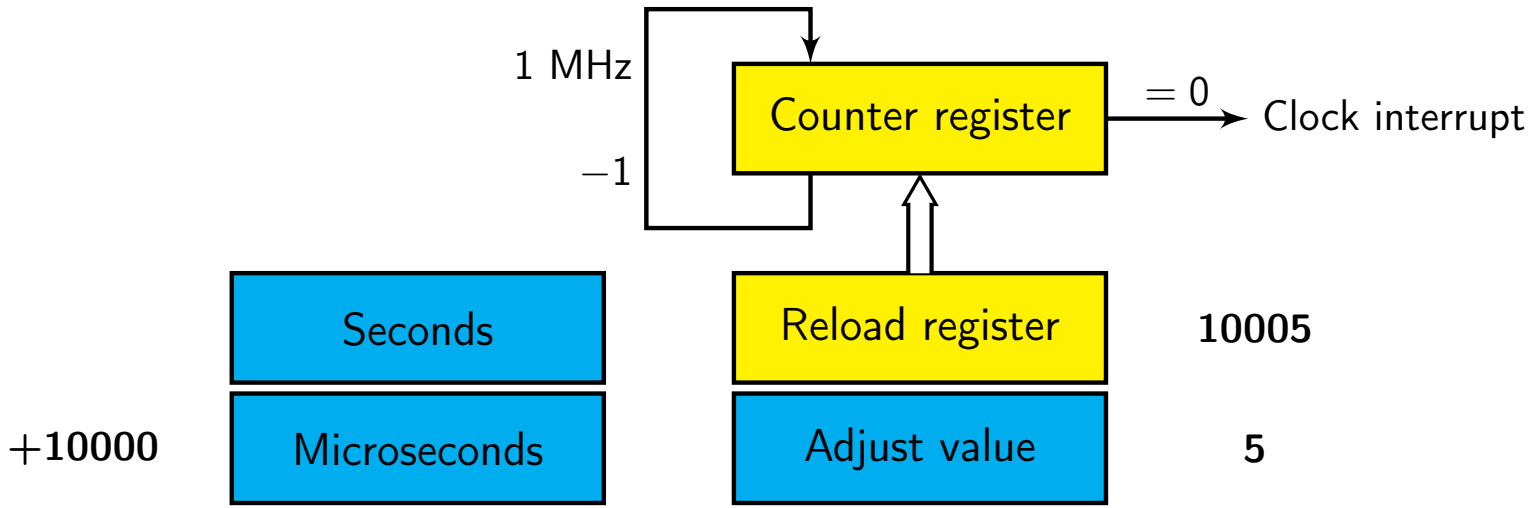


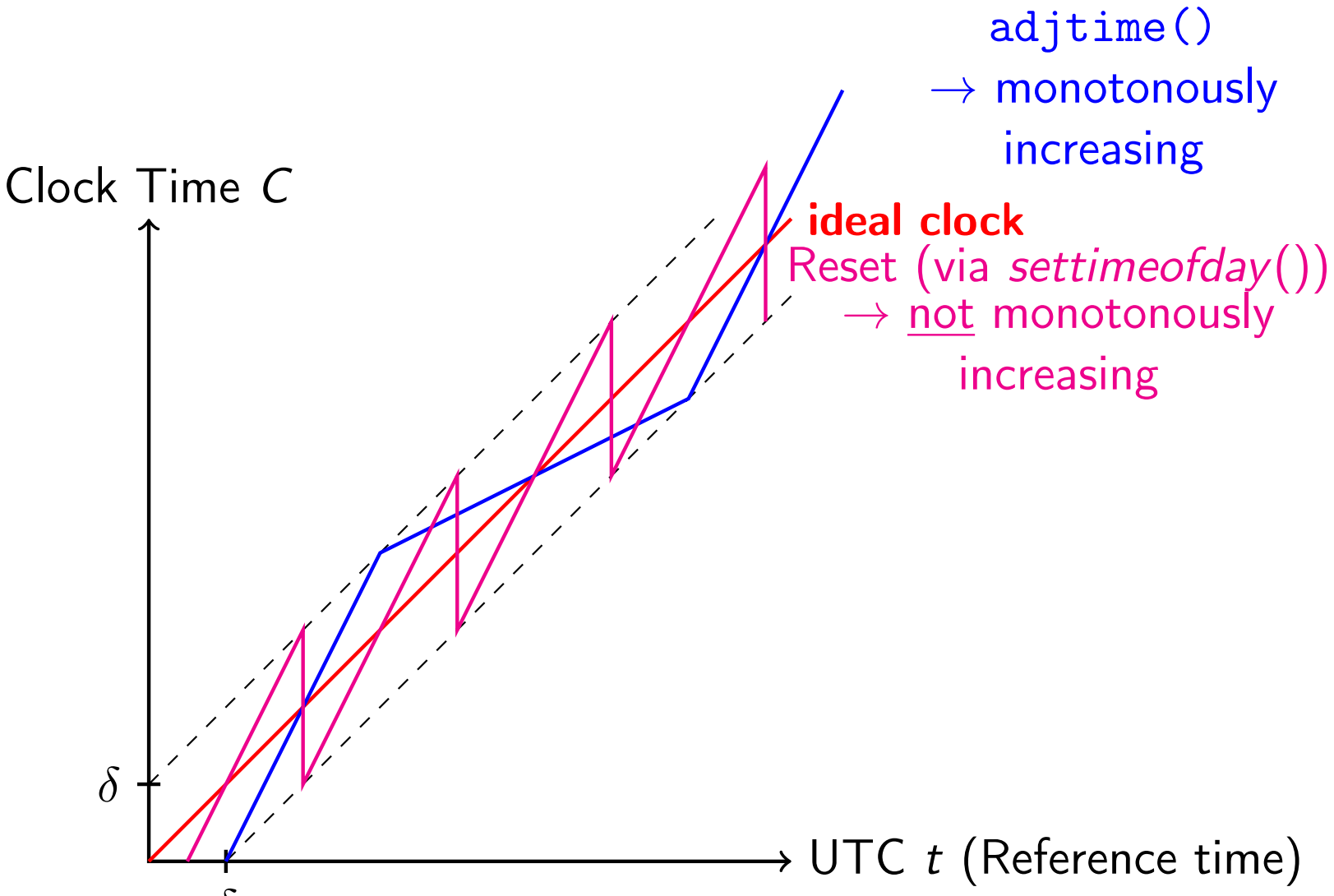
Operating System Clocks

Example: UNIX

- two 32 bit (or 64 bit) integer variables
  - Number of seconds since 1.1.1970 ($\rightarrow$ *Year 2038 problem*)
  - Number of μs (or ns) in the current second
- Typical 100 interrupts/s
- On interrupt the variables are increased by the nominal number of μs
- Adjust value for compensation of the drift of the quartz
- System services: `settimeofday`, `adjtime`



Correction Principle



Reference Time Sources

DCF77 clock for relaxed system time requirements

- Accuracy typical: $\pm$ 2 ms

GPS clock for high system time requirements

- Accuracy typical: $\pm$ 250 ns

Atomic clock

- Rubidium/Cesium sources
- Special approval necessary
- Rack mounting
- In part only for military usage

Computer interface

- Generation of pulse-per-second (pps) signals as interrupts
- Encoded timecode signals,
  e.g., IRIG standard (Inter Range Instrumentation Group)

Accurate Local OS Clocks

Use of a external reference time source
Linux kernel with Nano-Kernel-Patch

- Increase of the system clock resolution to $1ns$ (instead of μs)
- Default in newer Linux kernels
- Use of pps signals as reference time source via interrupts
- Correction of system clock according to reference time of the hardware clock
- Variance of interrupt latency effects the accuracy
- Multiple external time sources for a single computer are possible to further increase the accuracy
- Accuracy: typical < 1 μs

Example: David L. Mills' Uhren (Uni Delaware)

http://doc.ntp.org/4.1.2/refclock.htm

- Spectracom 8170 WWVB Receiver
- Spectracom 8183 GPS Receiver
- Hewlett Packard 105A Quartz Frequency Standard
- Hewlett Packard 5061A Cesium Beam Frequency Standard
- NTP primary time server **rackety** and **pogo** (elsewhere)

Commercial Time Server

Time Server

- Dedicated LAN network node for time synchronization
- Internal or external reference time source
- Support for standard protocols (NTP, SNTP, PTP/IEEE 1588)

Producs of many variants

- Meinberg (D)
- IPCAS (D)
- Galleon (UK)
- ELPROMA (NL)
- Time Tools (UK)

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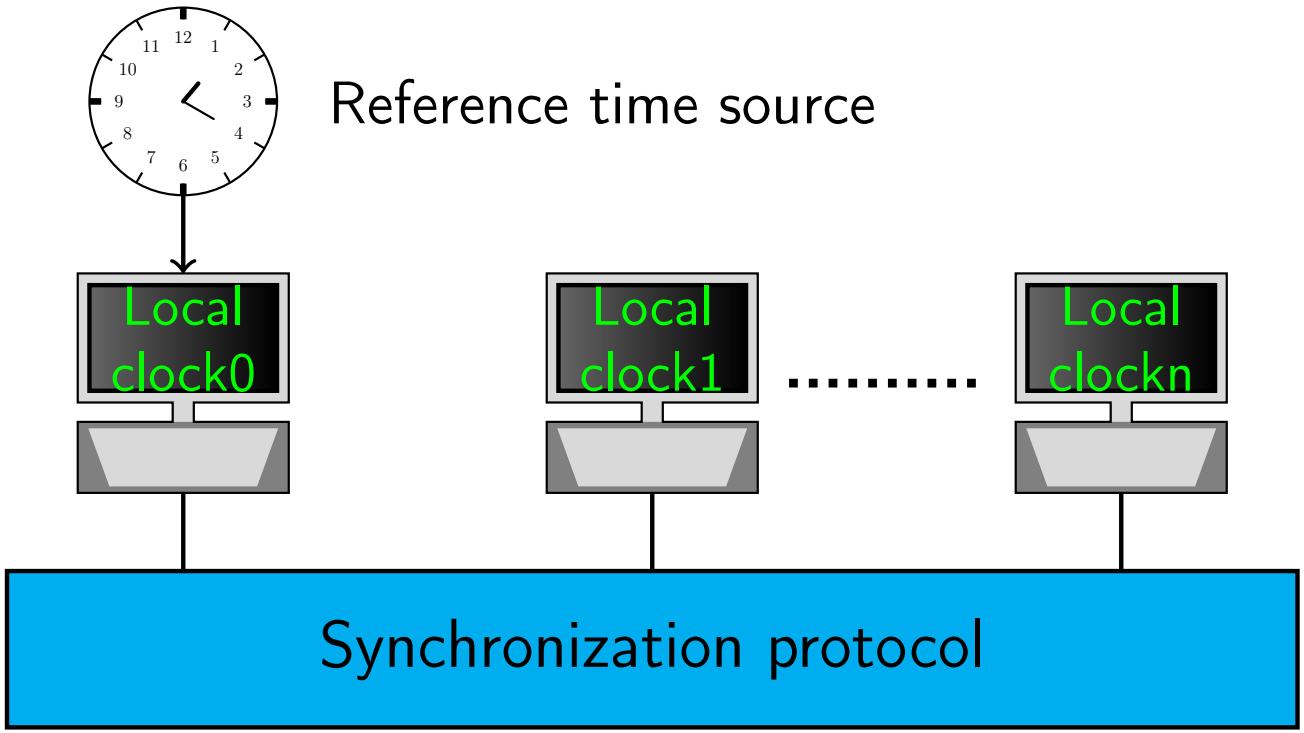
Synchronization Protocols

Construction of a distributed time basis for computer systems

- UTC-based external reference time source
- Local clocks in computer systems
- **Synchronization protocol**



Problems

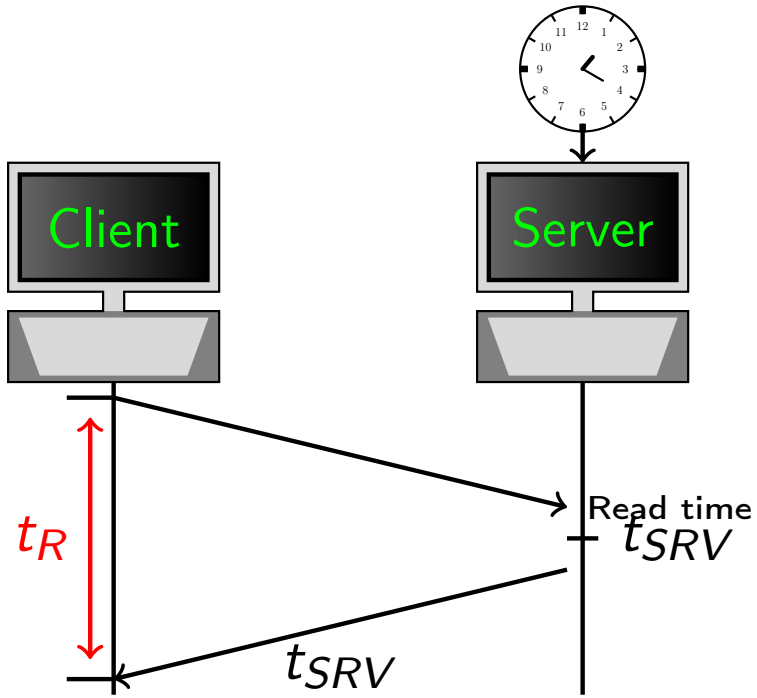
- Message delay in a network is not deterministic
- Processing time for protocol messages is not deterministic

$\Rightarrow$ **No exact synchronization possible**

Cristian's Algorithm (1989)

- Passive time server (as reference time source)
- Periodical polling of time by clients
- Measure average round trip time (including processing time on server)
- **Drawbacks:**
  - "Going backward" of a clock is possible
  - Jitter in message runtimes

Set: $t_{local} = t_{SRV} + \frac{t_R}{2}$



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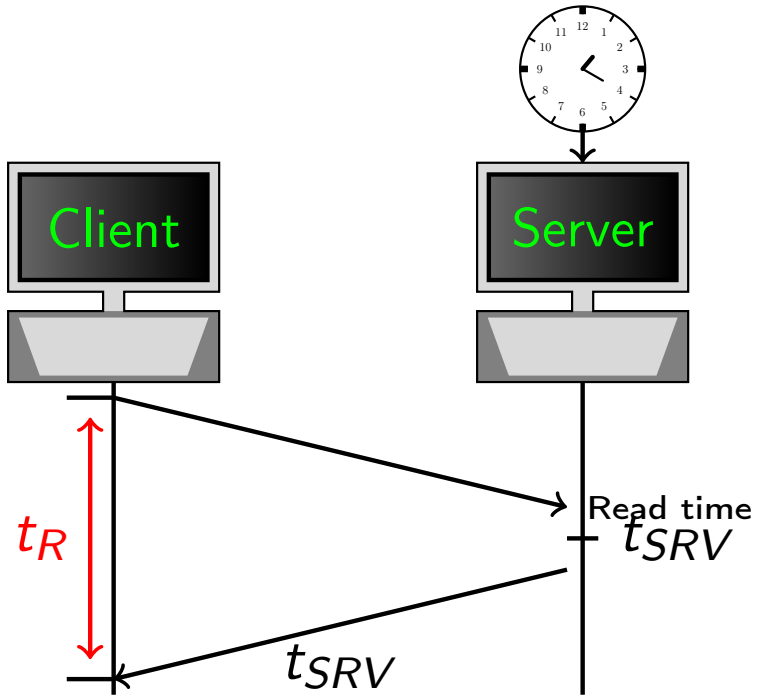


Round trip time (RTT) – measured with local clock of the client

Time Synchronization Protocol (TSP)

- Berkeley UNIX `timed`
- Based on ICMP/IP
- Establishes average network time on all sites
- Client/server algorithm
  - Active server: Polls current time from all nodes and calculates average
  - Distributes offset to each client
- Uses `settimeofday()` and `adjtime()` on the nodes
- **Severe drawbacks**
  - "Going backward" of a clock is possible
  - No compensation of variation of message runtimes
  - No error estimation
  - Bad scalability
- Variant: Server with external reference time source distributes current time instead of calculated average

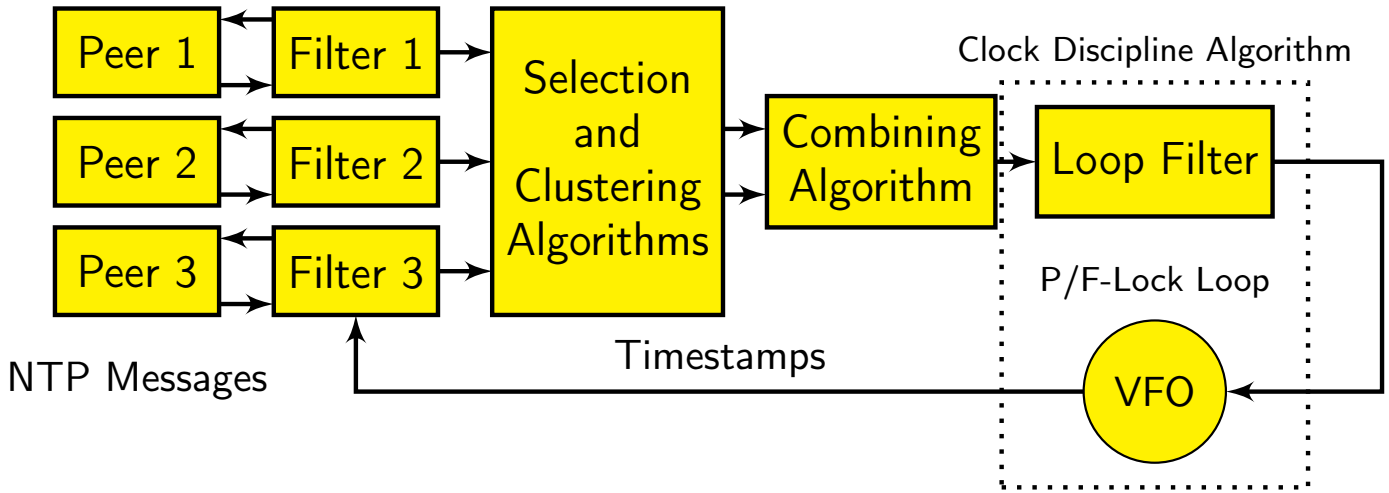
Network Time Protocol (NTP)

- Development primarily driven by D. Mills (Univ. of Delaware)
- **Reference implementation:** `http://www.ntp.org`
- **Goals**:
  - High accuracy
  - Handle varying message runtimes
  - Handle computer failures by using multiple time servers (peers)
  - Sorting out of obviously useless time sources ($\rightarrow$ false ticker)
  - Limited authentication and encryption
  - High scalability
- Accuracy:
  - In LAN < 1 ms, Internet $<$ *ca.*10 ms

Today's Internet standard

- RFC 1305, 1992, early Versions RFC 1129, RFC 958 (1985)
- $> 1,000,000$ hosts, router ...
- Uses UDP, port 123
- UNIX `ntpd`, `xntpd` (Clients available for most other systems)

NTP Functioning



(Figure by Mills)

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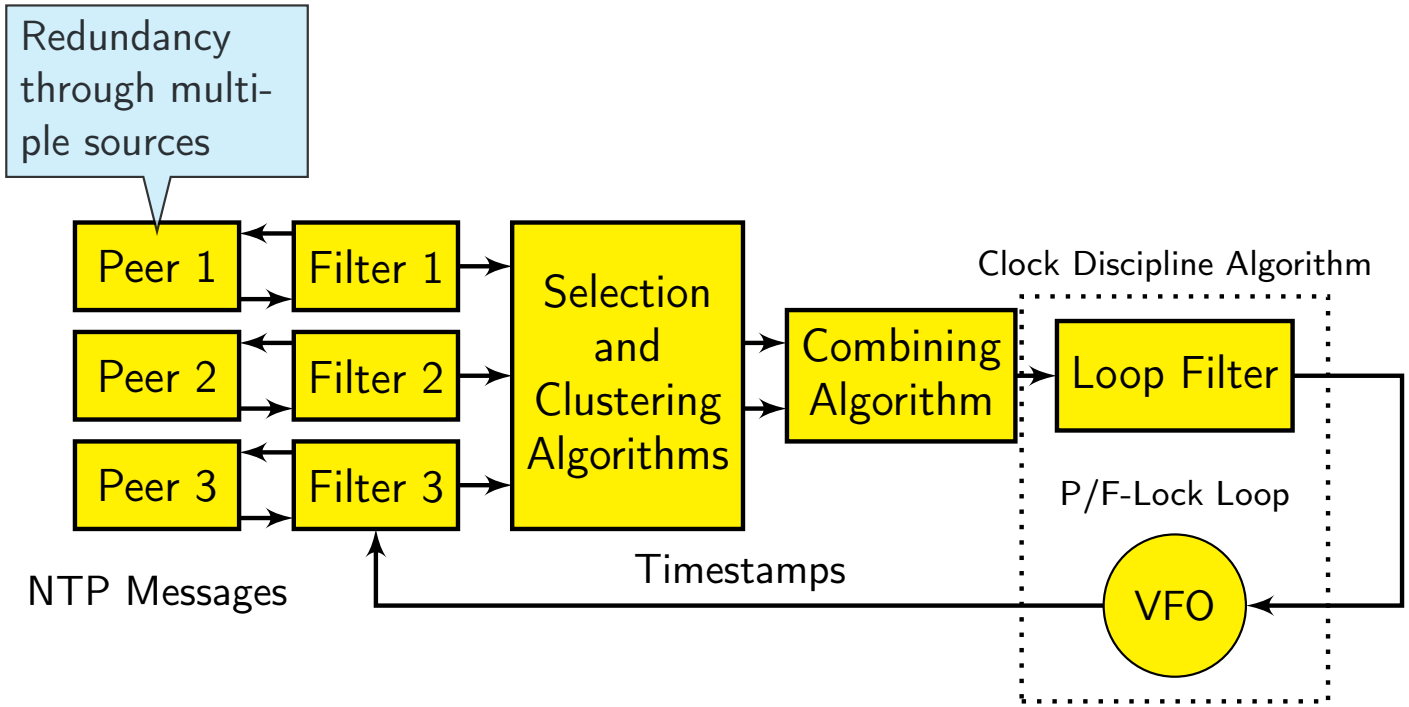

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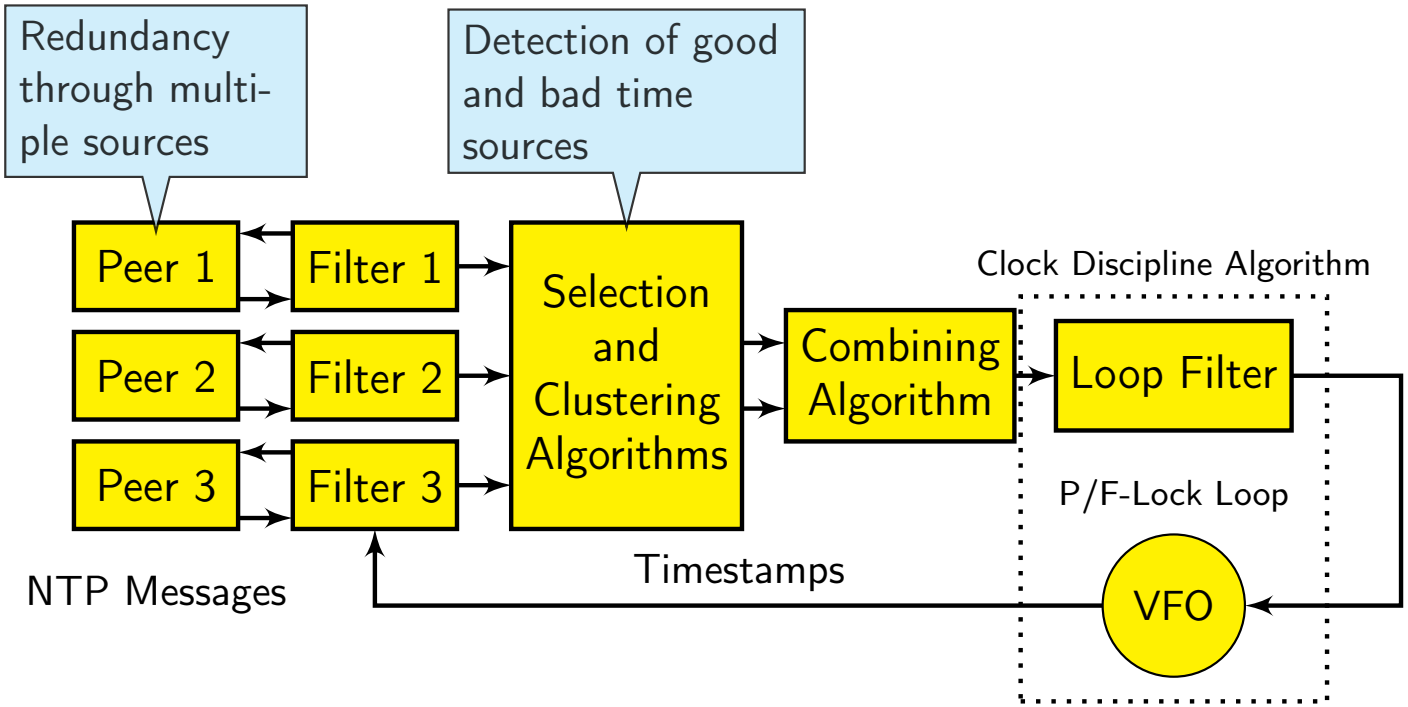

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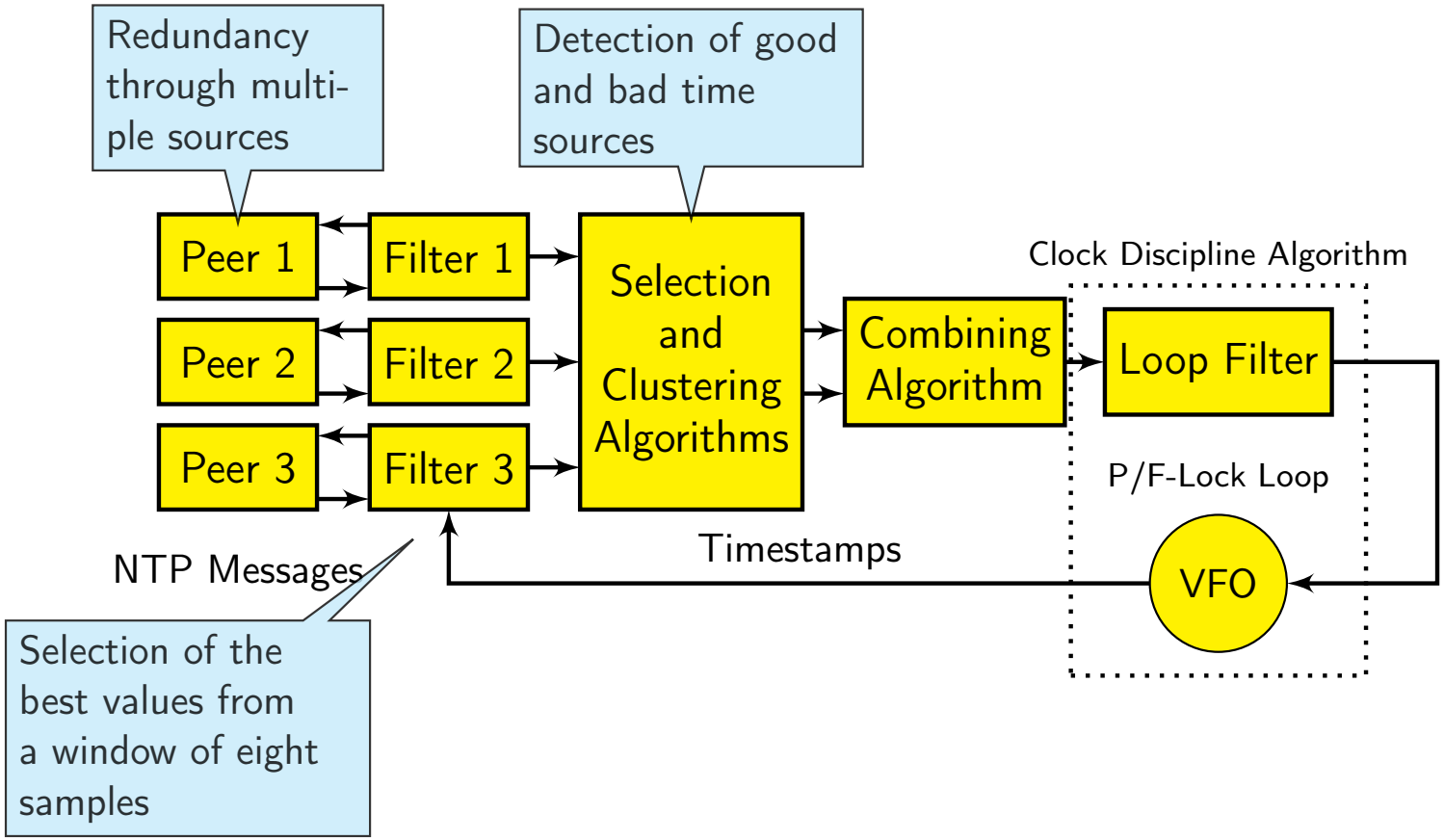

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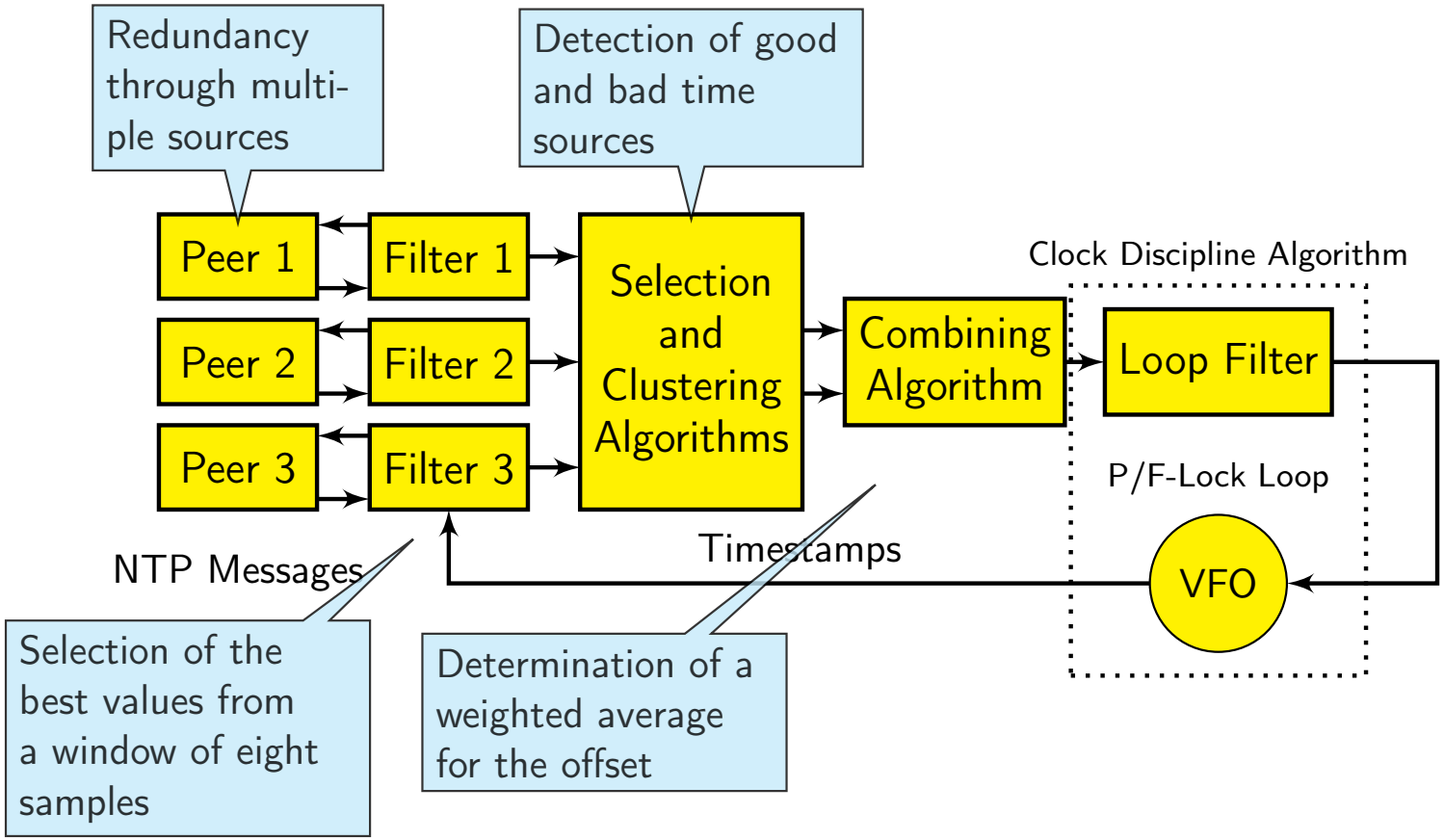

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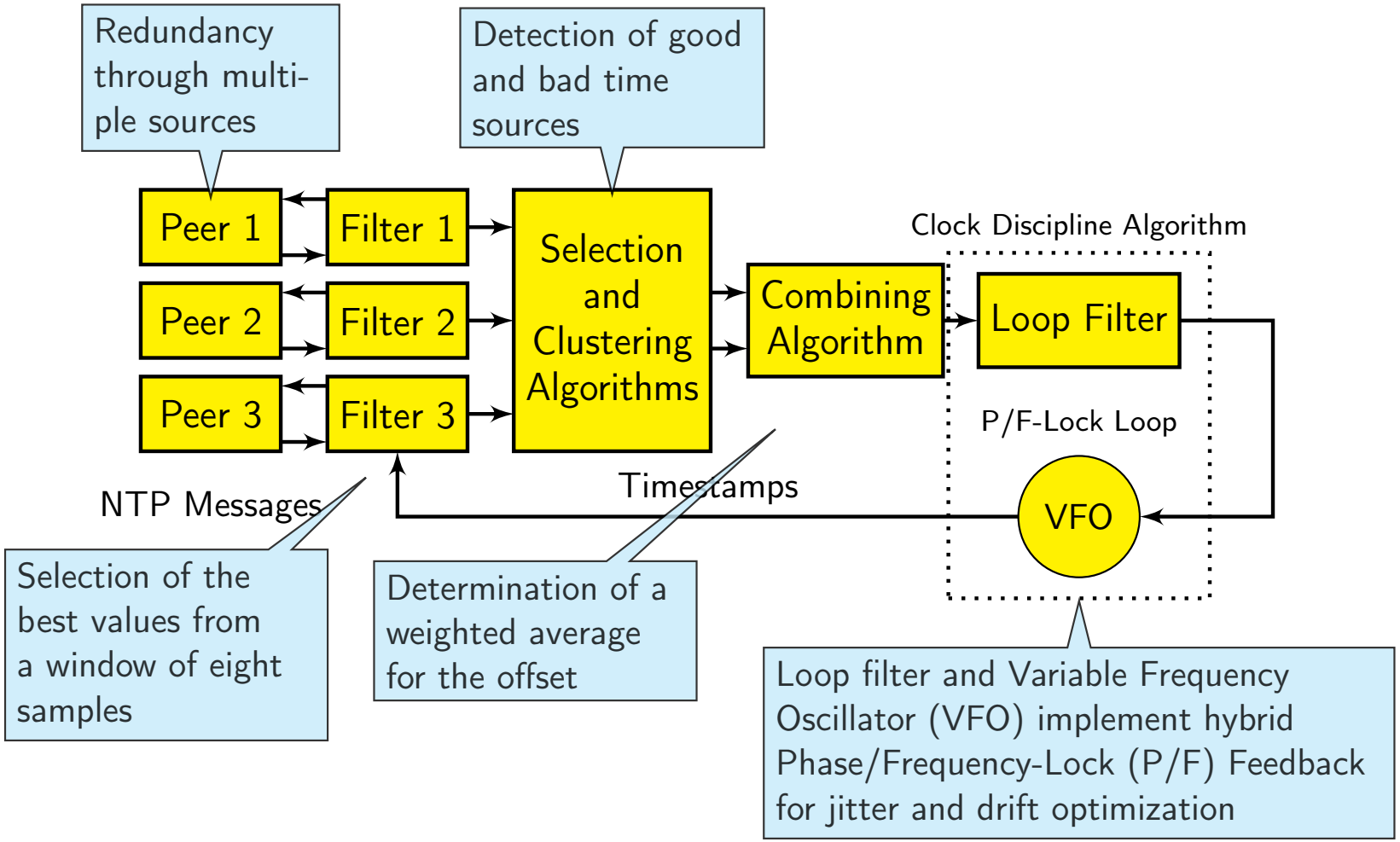


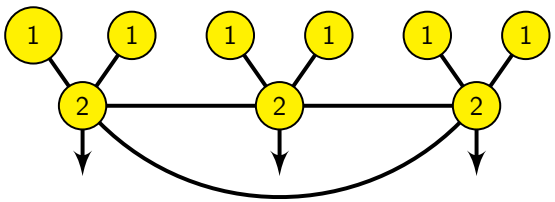
(Figure by Mills)

NTP Hierarchies

Server set and provide time, clients request time

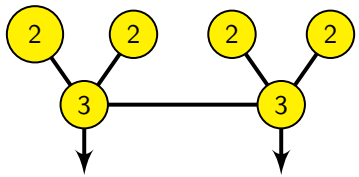
Hierarchy formation of the servers by **stratum** level

- Nodes with external reference time sources form stratum 1 server (Accuracy: < 1 μs possible)
- Stratum n - server synchronize with stratum $n - 1$ server etc.
- Internet usage (2022)
  - Respectively ca. 300 active stratum 1 and stratum 2 servers
    `http://support.ntp.org/bin/view/Servers/StratumOneTimeServers`
  - Practical: 4 layer hierarchy, load balancing through regional NTP pool server
- Typical structures:

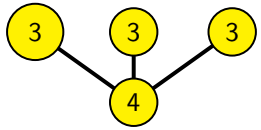


time server
(fault-tolerant)

Company



Department time server
(fault-tolerant)



Workstation

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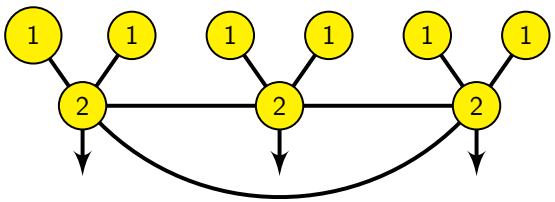

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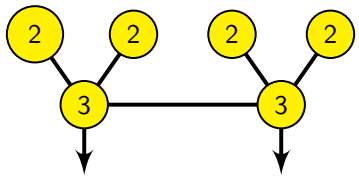

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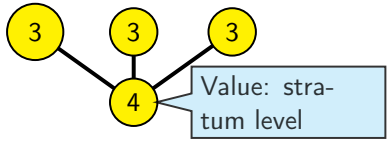
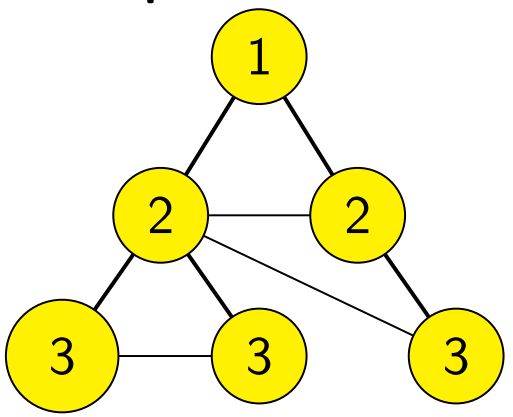


Workstation

NTP Properties

- Dynamically determined logical connection structure with redundant backup connections
  - Spanning trees with minimal weight based on the server level and overall synchronization delay of each server towards primary servers
- Message exchange between servers between 64s and 1024s (17 min) - depending on the connection quality
- 64 bit timestamps
  - 32 bit for seconds since 01.01.1900 00:00:00
  - 32 bit for parts of second
- Use of `settimeofday()` and `adjtime()` to adjust bigger resp. smaller ($< 0.128sec$) corrections
- Avoid jumps

Example connection topology



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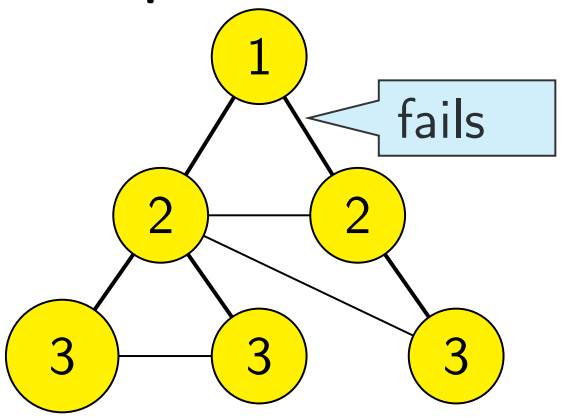

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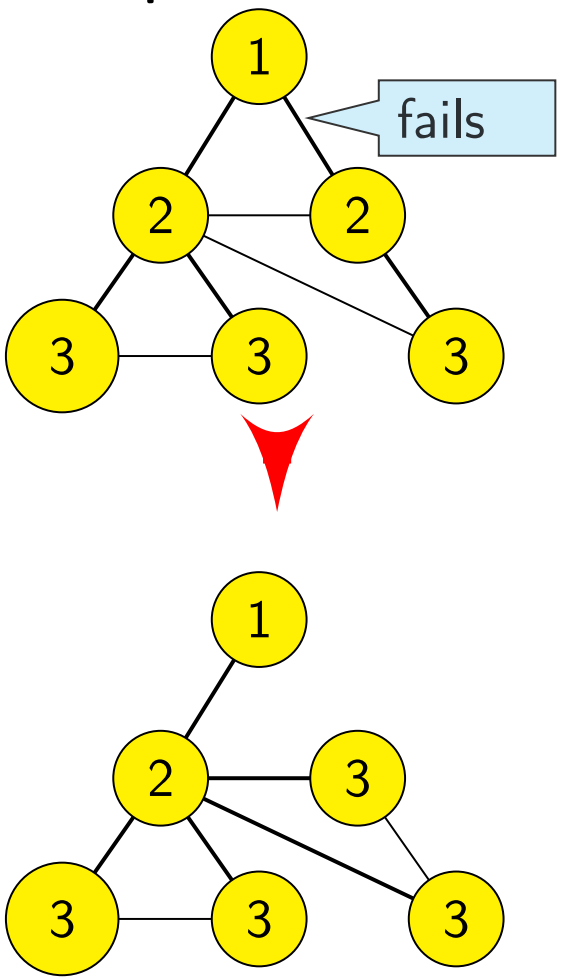
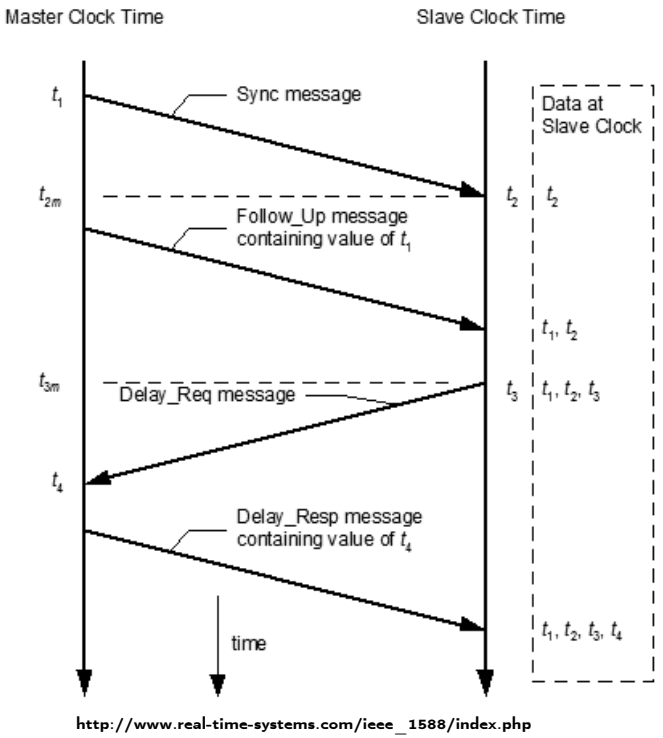


Precision Time Protocol (PTP, IEEE 1588)

- Mostly for measurement and control applications
- Achieves higher precision compared to NTP for networks with limited spatial expansion
- Client/server procedure
- Automatical selection of the best clock as grandmaster clock
- Primarily used for Ethernet networks
- Timestamping unit can be implemented as part of the network controller (in hardware)

$\Rightarrow$ Accuracy in the range of nanoseconds, in software in the range of μs

- Ptpd as open implementation
- Improved version IEEE 1588-2008



$$t_2 - t_1 = offset + d$$
$$t_4 - t_3 = -offset + d$$
$$offset = \frac{(t_2 - t_1 - t_4 + t_3)}{2}$$

Related Standards and Alternatives

- Simple Network Time Protocol (SNTP)
  - Simplified version of NTP
  - Compatible message format
  - No frequency compensation $\Rightarrow$ less accuracy but also less computational resources required
- Secure versions of NTP
  - Network Time Security (NTS)
  - NTPsec
  - tlsdate

Agenda

- Definition of Time
- Computer Clocks
- Synchronization Protocols
- Logical Clocks

Logical Timestamps

Real time is not always required

Examples:

- Order of events (before - after)
- Timestamp-based concurrency control in databases

Happened-before Relation

- **Notation**: $a \rightarrow b$ (a happened-before b)
- Events within the same process are ordered linearly
- Message sending:
  - a be the event of sending a message m
  - b be the reception of a message m at a different process
  - $\Rightarrow a \rightarrow b$
- Relation is transitive:
  - $a \rightarrow b,\ b \rightarrow c \Rightarrow a \rightarrow c$
- Concurrency:
  - If neither $a \rightarrow b$ nor $b \rightarrow a$ is true, a and b are called concurrent

Clock condition

Definition

$a \rightarrow b \Rightarrow C(a) < C(b)$

$C(a)$ refers to the (logical) time when event a is happening

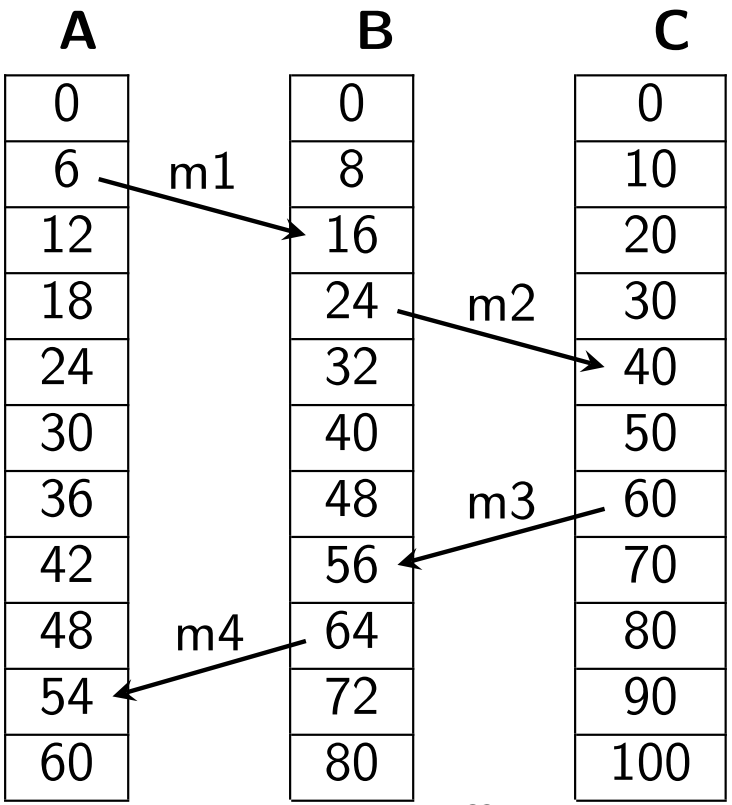
Lamport Clocks

Lamport algorithm for logical clocks (1978)

Assumptions:

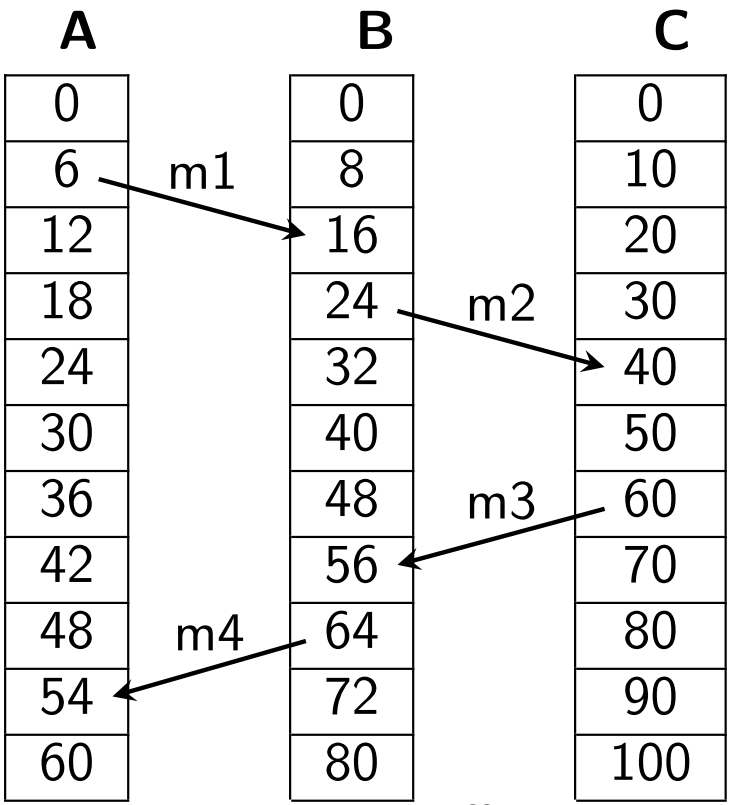
- Processes communicate via messages (and only via messages)
- Each process P has a logical clock C_P
- Each event e of process P receives a logical timestamp ($\rightarrow$ *Lamport Timestamps*): $C_P(e)$
- Two successive events e_i and e_{i+1} of a process have never the same timestamp: $C_P(e_i) < C_P(e_i + 1)$

Example for a Lamport Clock

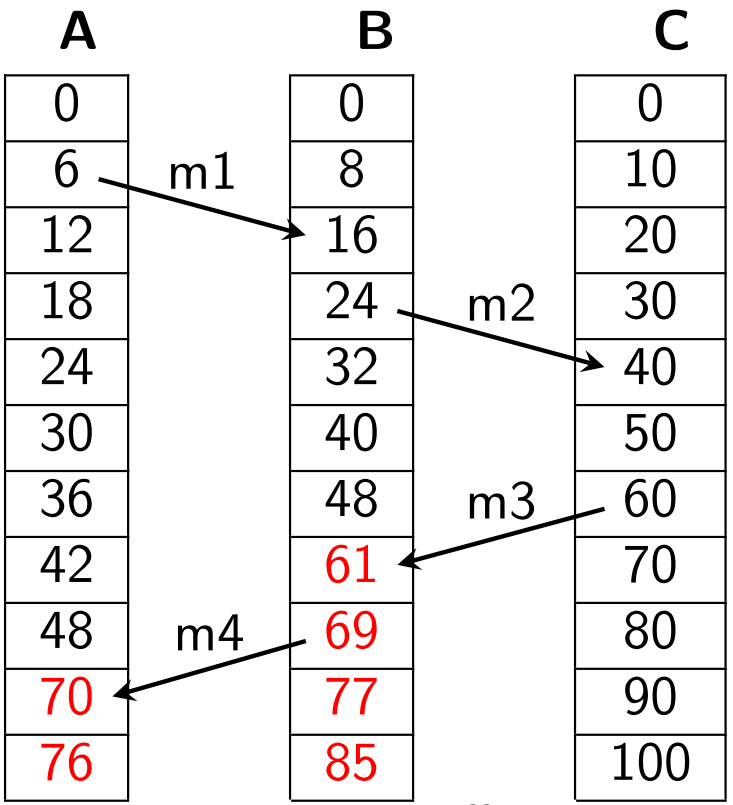


Clocks with differing speed without correction

Example for a Lamport Clock



Clocks with differing speed without correction



Clocks with differing speed with correction

Lamport Clock Algorithm

- Consideration of **causality** in message communication
- Sending event s of a message m in process A:
  - Timestamp $C_A(s)$
  - Send message m together with the current timestamp of the sending process $t = C_A(s)$
- Reception event e for message m at process B:
  - Be $C_B(old)$ the timestamp of the last event in B
  - Set $C_B(e) := max\{C_B(old), t\} + 1$
- If two events in different processes should have the same timestamp, ordering happens wrt to the process order
- Algorithm fulfills the clock condition

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- If two events in different processes should have the same timestamp, ordering happens wrt to the process order
- Algorithm fulfills the clock condition
- Reversal does **not** hold true:
  $C(a) < C(b) \Rightarrow a \rightarrow b$ is wrong!

$\rightarrow$ Lamport clocks do not solve the causality problem

Vector Clocks

by Mattern (Uni Kaiserslautern, 1989)

Vector clocks solve (among others) the causality problem

Algorithm:

- Message based communication
- Each process P_i has a local clock VC_i as vector of timestamps
- Local event in P_i:
  - $VC_i[i] := VC_i[i] + 1$, otherwise unchanged
- Sending event in P_i:
  - $VC_i[i] := VC_i[i] + 1$ (increase own event counter)
  - Send message containing the local vector time $vt = VC_i$
- Reception event in P_k:
  - $VC_k[j] := max\{VC_k[j], vt[j]\}$ for all j
  - $VC_k[k] := VC_k[k] + 1$ (increase own event counter)

Comparison of Timestamps for Vector Clocks

- $S \leq T :\Rightarrow S[i] \leq T[i]$ for all i
- $S < T :\Rightarrow S \leq T$ and $S \neq T$
- $S||T :\Rightarrow \neg(S < T)$ and $\neg(T < S)$

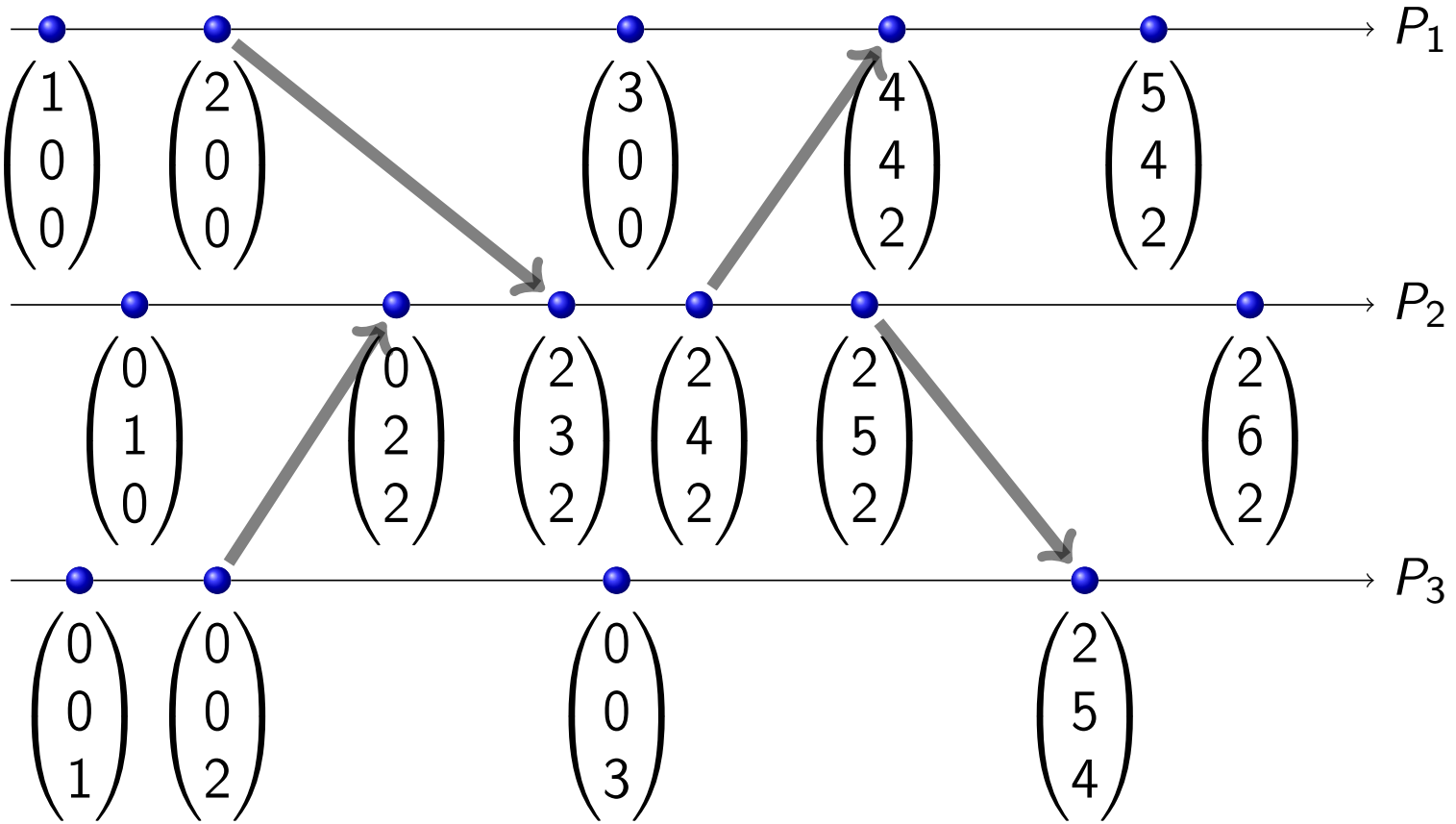
Concurrency

- Events a and b are concurrent $\Leftrightarrow VC(a)||VC(b)$

Causality

- $a \rightarrow b \Leftrightarrow VC(a) < VC(b)$

Vector Clocks Example



- Causal dependent events, e.g., $(0,0,1) \rightarrow (5,4,2)$, $(1,0,0) \rightarrow (2,6,2)$
- Concurrent events, e.g., $(0,0,3) || (5,4,2)$

Important takeaway messages of this chapter

- Times can be compared to a reference time wrt to stability, precision, and resolution. Drift and offset can be measured.
- To synchronize local clocks in a distributed system to a reference time source a clock synchronization protocol is required.
- Lamport and vector clocks can be used for logical timestamps