Clock Synchronisation

Physical Clocks

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Outline

1. Introduction
2. Computer clocks
   - Clock drift and clock skew
3. Synchronisation
   - Cristian's algorithm
   - Berkeley algorithm
   - Network Time Protocol
   - Precision Time Protocol

Why do we need clocks?

The only reason for time is so that everything doesn't happen at once.

Albert Einstein

Why do we need clocks?

- temporal ordering of events produced by concurrent processes
- synchronisation between senders and receivers of messages
- serialisation of concurrent access to shared objects
- *to know the time an event occurred at a computer*
- *no global clock in a distributed system*

Logical vs. physical clocks

- Logical clock ➲ keeps track of ordering of events
- Physical clocks ➲ keep and coordinate time of day

Physical clocks

1927 Quartz clocks

- crystal oscillator
- accuracy:
  - standard oscillator - 6 parts per million at 31℃($<$ 0.29 sec/day)
  - good oscillator - about one second in 10 years

1955 Atomic clocks

- the most accurate time and frequency standards
- a *second* = duration of 9 192 631 770 cycles of radiation = transition between two energy levels of the caesium-133 atom
- accuracy:
  - 1 part in 10^{14}, i.e., $<$ 1 second in 6 million years
- use:
  - primary standards for international time distribution services
  - control the wave frequency of television broadcasts
  - global navigation satellite systems
- International Atomic Time (TAI)

Time standard

1961 Coordinated Universal Time (UTC)

- derived from TAI, but adjusted to UT1 by adding a *leap second*
  - ♦ including 2012, a total of 25 leap seconds added (30 June 2012)

☺ Check *The One-second War (What Time Will You Die?)*

- broadcast
  - ♦ land-based signals are accurate to about 0.1-10 milliseconds
  - ♦ satellite-based signals are accurate to about one microsecond

- **UT0** - obtained from astronomical observations
- **UT1** - UT0 corrected for polar motion, i.e., the actual Earth's rotation with respect to the solar time
- **UT2** - UT1 corrected for seasonal variations in Earth's rotation

Physical & software clocks

- Physical clock
  ♦ CMOS clock circuit that counts oscillations of a quartz
  ♦ after a specified number of oscillations, the clock increments a register, thereby adding one *clock-tick* to a counter that represents the passing of time: $H_i(t)$
  ♦ battery backup to continue measuring when computer power is off

- Software clock - to timestamp events

$$C_i(t) = \alpha H_i(t) + \beta$$

  - $C_i(t)$ approximates the real physical time t at process p_i
  - e.g., a 64-bit number giving nanoseconds since some base time

Clock resolution

- Period between the updates of the clock value.
- Successive events can be distinguished if the clock resolution is smaller than the time interval between the two events.

Physical clocks in distributed systems

- local processes obtain the value of the current time
- processes on different computers can timestamp their events
- but clocks on different computers may give different times
- difficult to synchronise: even if clocks on all computers in a distributed system are set to the same time, their clocks will eventually vary quite significantly unless corrections are applied

Problem

Computer clocks hardly ever agree on time!

Clock drift

- Clocks tick at different rates
- **Clock drift rate** is the relative amount that a computer clock differs from a perfect clock
- Recall:
  ✌ Typical quartz clocks *drift rate* is about 10^{-6} secs/sec
  ✌ High-precision quartz clocks *drift rate* is about 10^{-8} or 10^{-9} secs/sec

What happens to clocks when their batteries become very low?

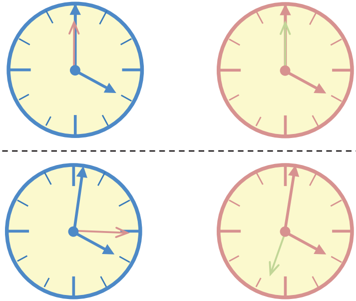
Clock skew

- **Clock skew** defines the difference between the times on two clocks: $|Ci(t) - Cj(t)|$
- Reasons:
  - clock drift
  - the clocks may have been set differently on different machines

Example

1 Sep 04:00:00

3 Oct 04:00:00



04:01:16
skew = +76 secs
+76 secs/32 days
drift = 2,38 sec/day

04:01:34
skew = +94 secs
+94 secs/32 days
drift = 2,94 sec/day

Clock corectness

- H_i is said to be correct if its drift rate is within a bound $\rho > 0$ (e.g., 10^{-6} secs/sec)
- The error in measuring the interval between real times t and t' is bounded:
  - $(1-\rho)(t'-t) \leq H_i(t') - H_i(t) \leq (1+\rho)(t'-t)$ (where $t' > t$)
  - forbids jumps in time readings of physical clocks
- Weaker condition of *monotonicity*
  - $t' > t \Rightarrow C(t') > C(t)$
  - e.g., required by UNIX *make* operation
  - can achieve monotonicity with a physical clock that runs fast by adjusting the values of α and β in $C_i(t) = \alpha H_i(t) + \beta$
- A faulty clock is one that does not obey its correctness condition
  - *crash* failure - a clock stops ticking
  - *arbitrary* failure - any other failure e.g., jumps in time

Consider the 'Y2K bug' - what sort of clock failure would that be?

Get accurate time

- Put a GPS receiver to each computer
  ➠ $\approx$ 1 microsecond of UTC
-

Cost, power, convenience, environment.

Get accurate time

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Get accurate time

- ~~Put a GPS receiver to each computer~~
  ~~➠ ≈ 1 microsecond of UTC~~
- Put a radio receiver
  ➠ ≈ 0.1-10 milliseconds of UTC

Cost, power, convenience, environment.

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Cost, power, convenience, environment.

Get accurate time

Synchronise with another machine, one with more accurate clock!

Synchronising computer clocks

External synchronisation

Process's clock is synchronised with an external authoritative time source S

- $|S(t) - C_i(t)| < \delta$, $\delta > 0$, $i = 1, 2, ..., N$, $t \in I$, I is an interval of real times
- The clock C_i is accurate to within the bound δ

Internal synchronisation

Processes' clocks are synchronised with one another

- $|Ci(t) - Cj(t)| < \delta$, $\delta > 0$, $i = 1, 2, ..., N$, $t \in I$, I is an interval of real times, and C_i and C_j are clocks at processes p_i and p_j
- The clocks C_i and C_j agree within the bound δ

- Are internally synchronised clocks also externally synchronised?
- If a set of processes P is synchronised externally within a bound δ, is then P also internally synchronised? If yes, what is the bound?

Synchronous distributed system

A distributed system is *synchronous*, if:

1. the time to execute each step of a process has known lower and upper bounds
2. each process has a local clock whose drift rate from the real time has a known bound (ρ)
3. each message transmitted over a channel is received within a known bounded time (min, max)

Synchronisation

- Server S sends its local time T_{server} to a client C in a message m
- C could set its clock to $T_{server} + T_{trans}$, where T_{trans} is the time to transmit m
- T_{trans} is unknown, but $min \leq T_{trans} \leq max$
- Let u be the uncertainty in the message transmission time, so that $u = max - min$. Then, client sets the clock to $T_{server} + (max + min)/2$, so that $skew \leq u/2$

Asynchronous system

Internet

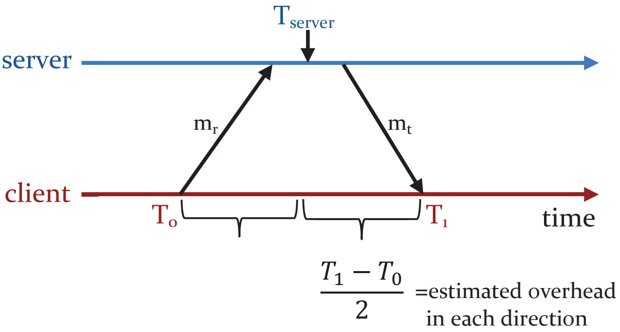
We can only say $T_{trans} = min + x$, where $x \geq 0$.

- Cristian's algorithm
- Berkeley algorithm
- Network Time Protocol
- Precision Time Protocol

Cristian's algorithm (1989)

Steps

1. A time server receives signals from a UTC source
2. Client requests time in m_r and receives T_{server} in m_t from the server
3. The client sets its clock to $T_{new} = T_{server} + \frac{T_{round}}{2}$

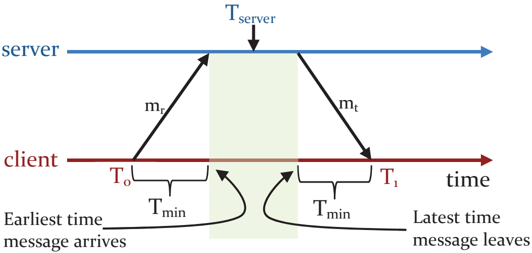


T_{round} is the round-trip time recorded by the client, i.e., $T_{round} = T_1 - T_0$

Accuracy

Let T_{min} be the minimum message delay (transition time). Then,

- T_{min} is the earliest time the server puts T_{server} in message m_t after the client sent m_r, and
- T_{min} is the latest time before m_t arrived at the client, and
- $[T_{server} + T_{min}, T_{server} + Tround - T_{min}]$ is the range of the time by the server's clock when m_t arrives.



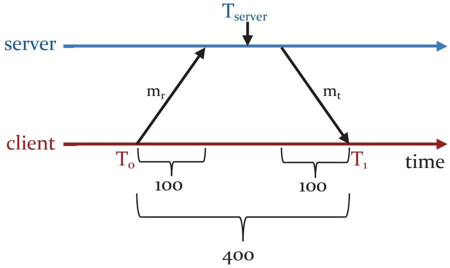
Accuracy $= \pm(T_{round}/2 - T_{min})$

What is the potential problem in using a single time server?

Example

1. request sent at (T_0): 04:01:16.200
2. response received at (T_1): 04:01:16.600
   ➠ response contains time (T_{server}): 04:02:30.200

- round time: $T_1 - T_0$
  ➠ 04:01:16.600-04:01:16.200 = 400 msecs
- best guess: the timestamp was generated 200 msecs ago
- set time (T_{new}): 04:02:30.200+200 = 04:02:30.400



$$accuracy = \pm\frac{600-200}{2} - 100 = \pm 200 - 100 = \pm 100$$

Berkeley algorithm (1989)

About

- Internal synchronisation of a group of computers
- Assumes no machine has an accurate time source
- Each machine runs time dæmon
- One machine represents a server (master), others are slaves

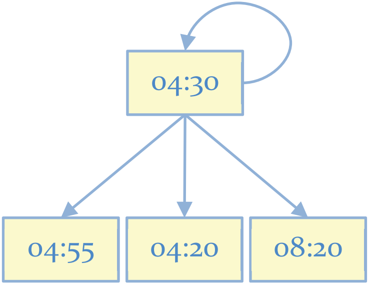
Steps

1. A master polls to collect clock values from slaves
2. Machines response with their clock values
3. Once responses are gathered, the master computes **an average**
   - the average includes master's own time
   - the average is fault-tolerant – it ignores faulty clocks
   - an average eliminates the tendencies of machine's clocks to run slow or fast
4. Master sends the required adjustment (offset) to the slaves
   ➠ better than sending the time. Why?

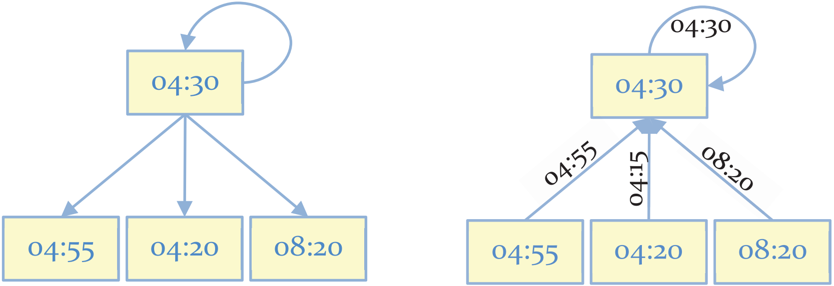
Observation:

- 15 computers, clock synchronisation 20-25 milliseconds, drift rate $< 2\text{x}10^{-5}$

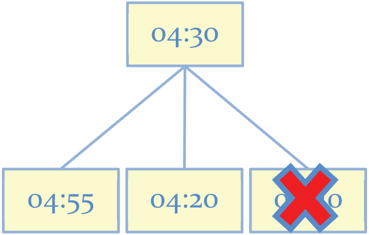
Example



Example

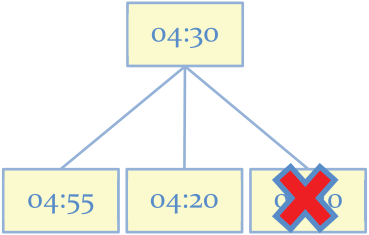


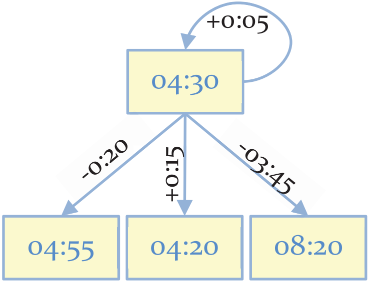
Example



$$\textit{fault-tolerant average} = \frac{04{:}30 + 04{:}55 + 04{:}20}{3} = 04:35$$

Example





$$\textit{fault-tolerant average} = \frac{04{:}30+04{:}55+04{:}20}{3} = 04:35$$

Network Time Protocol

About

A time service that played a large role in time synchronisation by keeping networked computer clocks synchronised to within *milliseconds* of each other.

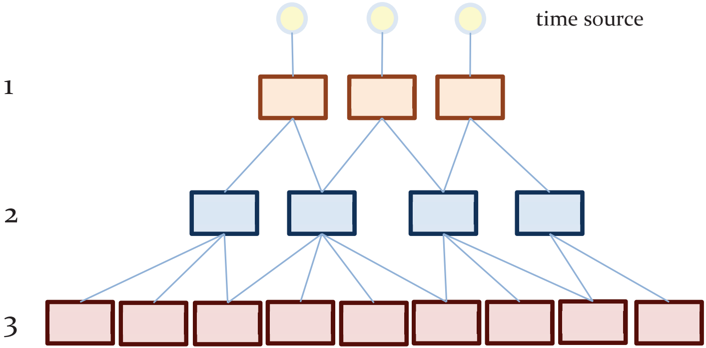
- 1988 (v1): RFC 1059, clock filter, selection and discipline algorithms, client/server and symmetric modes
- 1989 (v2): RFC 1119, formal model, pseudo-code, Control Message Protocol, cryptographic authentication,
- 1992 (v3): RFC 1305, formal error analysis, timekeeping quality, broadcast mode, reference clock drivers
- 2010 (v4): RFC 5905-5908,IPv4, IPv6 and OSI support, improved accuracy to tens of *microseconds*, dynamic server discovery, manycast mode

Design goals

- Enable clients across the Internet to be synchronised accurately to UTC
- Provide a reliable service that can handle extensive losses of connectivity
- Enable clients to resynchronise frequently enough
- Protect against interference with the time service

Synchronisation subnet

- Stratum 1: primary servers connected directly to UTC
- Stratum 2: secondary servers synchronised to primary servers
- ...



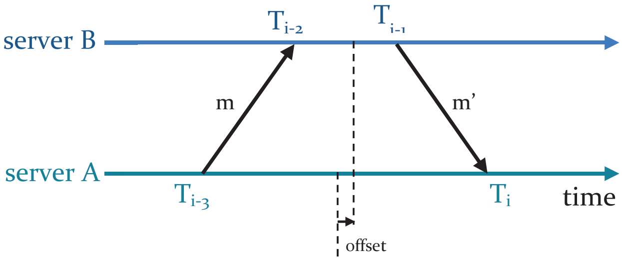
Synchronisation modes

- **Multicast** mode
  - ➠ a server within a high-speed LAN multicasts time
  - ➠ not very accurate, but efficient
- **Procedure-call** mode
  - ➠ similar to Cristiain's algorithm
  - ➠ higher accuracy, useful if no hardware multicast
- **Symmetric** mode
  - ➠ pairs of servers exchange messages containing time information
  - ➠ very high accuracy

In all modes, *UDP* is used!

Synchronisation strategy (message exchange)

- Each message bears timestamps of recent events:
  - T_{i-3}: local time when the previous message was sent
  - T_{i-2}: local time when the previous message was received
  - T_{i-1}: local time when the current message was sent
- Recipient notes the time of receiving the message, T_i
- In the symmetric mode, there can be a non-negligible delay between messages



Accuracy

- For each pair of messages between two servers, NTP calculates an *estimated offset* Θ_i and a *delay* δ_i.

Let two servers exchange a pair of messages, and let Θ be the *actual offset* between the servers' clocks and t, t' the transmission times of the messages. Then,

$$T_{i-2} = T_{i-3} + t + \Theta \text{ and } T_i = T_{i-1} + t' - \Theta.$$

The *delay* equals the total transmission time

$$\delta_i = t + t' = T_{i-2} - T_{i-3} + T_i - T_{i-1}.$$

The *estimated offset* is

$$\Theta_i = \frac{(T_{i-2} - T_{i-3}) + (T_{i-1} - T_i)}{2}.$$

The *actual offset* is $\Theta = \Theta_i + \frac{(t' - t)}{2}$.
Since $t > 0$ and $t' > 0$, the value of $t' - t$ must be between δ_i and $-\delta_i$. Therefore,

$$\Theta_i - \frac{\delta_i}{2} \leq \Theta \leq \Theta_i + \frac{\delta_i}{2},$$

So, Θ_i is an estimate of the offset and δ_i is a measure of the accuracy.

Accuracy

- NTP servers filter pairs $<\Theta_i, \delta_i>$ by estimating reliability from variation, which allows them to select peers. The eight most recent pairs are saved. It selects the Θ_i with the smallest δ_i (the smaller delay, the better accuracy).
- Accuracy of tens of milliseconds over Internet paths and 1 millisecond on LANs (v3)

Precision Time Protocol

About

A packet-based synchronisation mechanism able to synchronise LAN-networked computer clocks within tens of *nanoseconds* of each other.

- 2002 (v1): local networks
- 2008 (v2): improved accuracy, precision and performance

Design goals

- Provide sub-microsecond synchronisation of real-time clocks in distributed (measurement and control) systems
- Applicable to LANs supporting multicast communication
- Provide a simple, administration-free installation
- Support heterogeneous systems of clocks
- Impose minimal resource requirements on networks and hosts

Approach

- Master-slave hierarchy
- Master
  - time reference for one or more slaves
  - selected by Best Master Clock (BMC) algorithm
- Devices: ordinary clock, boundary clock, transparent clocks, *etc.*

Devices

- Ordinary clock
  - a device with a single network connection
  - either a source or destination for a synchronisation reference
- Boundary clock
  - a device with multiple network connections
  - accurately bridges synchronisation from one network segment to another – distributes a master clock to different parts of the network
  - contains a timekeeper and multiple ports
- Transparent clock
  - a device that connects a group of devices without segmenting the PTP network
  - exposes its slave devices to the PTP master
  - improves distribution accuracy

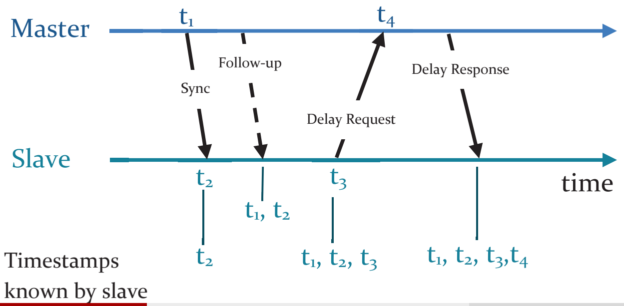
Configurations and synchronisation modes

- *Software-only* configuration – ordinary clocks
- *Hardware timestamping* configuration – ordinary clocks, boundary clocks, transparent clocks

- **End-to-end** mode – a slave issues a *Delay Request* message and a master responds with a *Delay Response*
- **Peer-to-peer** mode – a device issues a *Peer Delay Request* message to an immediate neighbour (not necessarily master) which responds with *Peer Delay Response*
  - ➡ better performance when network traffic
  - ➡ better accuracy

Software-only configuration in end-to-end mode

- Master: periodically transmits a *Sync* message by UDP multicast
  - $t1$: time when the *Sync* message is sent by the master
  - $t2$: time when the *Sync* message is received by the slave
  - $t1$: actual time when the *Sync* left the master contained in the *Follow-up* message
  - $t3$: time when the *Delay Request* message is sent by the slave
  - $t4$: time when the *Delay Request* message is received by the master
- Master: sends a *Delay Response* to the slave containing $t4$



NTP vs. PTP

Property	**NTP**	**PTP**
Network	WAN (LAN)	LAN (WAN)
Network topology	Well-defined	Not necessarily well-defined
Security	Good	Low
Special hardware	No	Boundary clocks, transparent switches
Server discovery	Multicast (LAN)	Unicast (WAN)
Network reorganisation	Semi-autonomous	Autonomous
Synchronisation methodology	clock offset, message delays, servo algorithm to adjust a device's timekeeper	clock offset, message delays, no servo algorithm
Timescale	UTC	TAI and UTC offset
Performance (accuracy)	Milliseconds (WAN)	Nanoseconds (LAN, hardware), sub-milliseconds (LAN, software-only), milliseconds (WAN)

Summary

- Clocks on different systems will always tick differently
- Accurate timekeeping is important for distributed systems
- Algorithms synchronise clocks in spite of their drift and the variability of message delays
- Timestamped messages, estimated delay of message transmission, estimated offset between different clocks, synchronised to UTC or to a local source
- For ordering of an arbitrary pair of events at different computers, clock synchronisation is not always practical

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