Time

CSE 486/586: Distributed Systems

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Time

Time is very important to distributed systems.

As we saw, it can be critical for identifying failures.

It can also be used to determine ordering of events.

For most purposes, there must be agreement on timings.

What *is* time, anyway?

Physical Time

We will leave defining spacetime to the physicists!

Instead, we will agree that:

- Time proceeds forward monotonically
- The passage of time is measurable
- The relative passage of time is computable at different locations
- There is an ideal true time

Ideal Time

The ideal, true physical time is standardized.

We call it International Atomic Time (TAI) [1].

We use the related Coordinated Universal Time (UTC) [7].

UTC is a standardized, global reference for “real time.”

Several government services distribute UTC via radio:

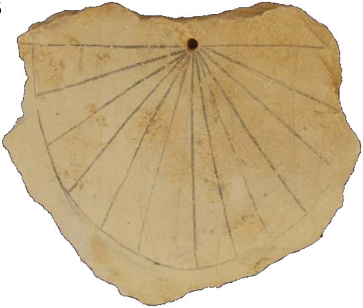
- NIST (WWV, WWVB), CHU, and DCF77
- GPS, GLONASS, Galileo, and BeiDou satellites

Celestial Time

Early humans measured time by celestial motions:

- The diurnal cycle
- The seasons caused by the Earth's orbit
- Relationships of the sun/planets/stars

The sundial is an early celestial timekeeping device.



Mechanical Oscillators

Later, mechanical oscillators based on physical moment were developed:

- Tuning forks
- Pendulums
- Spring escapements

These allowed timekeeping to within seconds per week.

Electromechanical Oscillators

In the early 20th century, crystal oscillators appeared.

Quartz crystals exhibit mechanical resonance when excited by electrical fields.

The first precision computer oscillators[1] were crystals.

Modern watches and computers use crystals and related technologies.

Crystal oscillators keep time to within seconds per year.

[1] "Line clocks," driven from the electrical power line, have also been used.

Atomic Clocks and The Second

The second, symbol s, is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency, $\Delta\nu_{Cs}$, the unperturbed ground-state hyperfine transition frequency of the caesium 133 atom, to be 9,192,631,770 when expressed in the unit Hz, which is equal to s^{-1} [4]

Atomic clocks [3] measure sub-nuclear particle spin to achieve considerable accuracy.

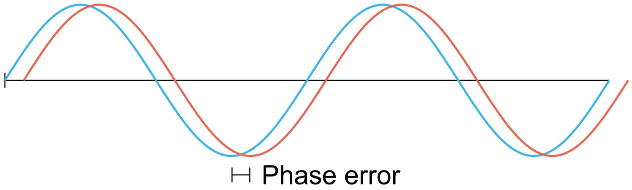
Cesium and Rubidium standards are reasonably available.

Atomic oscillators keep time to within seconds per millenia.

Phase and Frequency

Two clocks may disagree on:

- What time it is: phase error
- How fast time is proceeding: frequency error



Phase and Frequency

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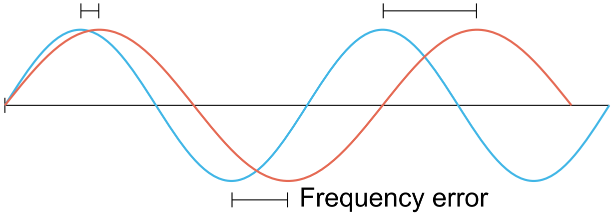


Jitter and Discontinuities

Clocks may change speed slightly over time.

If this change is short-term and about a point, we call it jitter.

Clocks may jump forward or backward abruptly.

We call these jumps discontinuities.

Neither one is desirable!

Clock Discipline

A clock may be corrected by a process called disciplining.

Disciplining is tweaking the clock using external information.

For example:

- A rubidium standard has excellent short-term stability.
- GPS satellite signals have excellent long-term stability.
- The opposites are less true.
- The short-term stability of a GPS signal can be improved by combining the two into a GPS-disciplined oscillator.

Thought Experiment

I give you an extremely stable oscillator.

It pulses exactly once per second, with zero error.

What time is it?

Synchronization

Agreeing on the phase and frequency of time is hard.

It is much easier now than it was just a few years ago!

Computer clocks can be readily synchronized to about ± 10 ms.

External time sources can reduce this to about ± 10 μs.

Higher precision is attainable with more effort.

Network Time Services

It is impractical to attach a GPS to every computer.

(If nothing else they require a view o the sky!)

We use network time protocols to synchronize clocks.

They can be very precise over fast local networks.

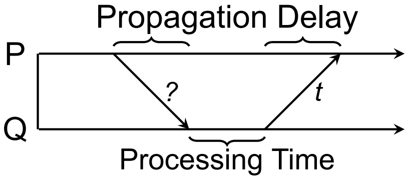
They can be accurate to tens of ms over the global Internet [6].

A Trivial Approach

A trivial approach to synchronization:

- *P* sends "What time is it?" to *Q*
- *Q* replies with "It is time *t*"

The problem is delay:



P's clock is behind *Q*.

Delay

Communication delay leads to phase error.

Communication delay cannot be eliminated.

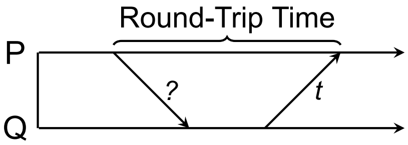
(Why not? The speed of light.)

It is also hard to measure.

Think about it:
If clocks aren't already synchronized, how do you measure it?

Cristian's Algorithm

Cristian's Algorithm [2] tries to estimate and remove delay.



It does this by removing 1/2 round-trip time from *Q*'s response.

Assuming that:

- Propagation delays are equal
- Processing time is small

…this approximates the error in the delay.

NTP

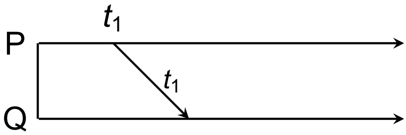
The NTP protocol [5] tries to tighten this bound.

It improves performance over the global Internet.

It does this by:

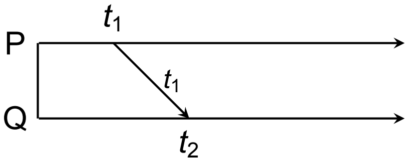
- Including some extra timestamps
- Querying multiple time servers

NTP Exchange



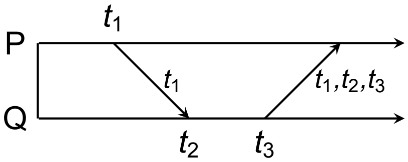
P sends t_1, the local time at which it sends its query.

NTP Exchange



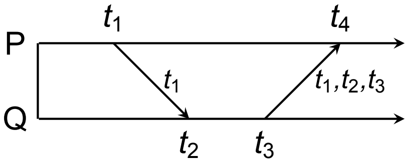
Q records the local time t_2 when it receives the query.

NTP Exchange



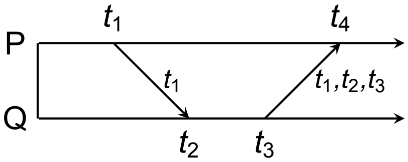
Q eventually sends its reply at time t_3, and includes all three timestamps.

NTP Exchange



P receives the reply at time t_4 and records all four timestamps.

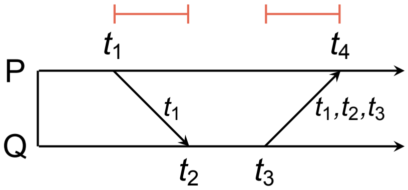
NTP Exchange



P can calculate:

- The phase difference between *P* and *Q*'s clocks:
$$\Theta = \frac{1}{2}\left[(t_2 - t_1) + (t_3 - t_4)\right]$$
- The round-trip delay:
$$\delta = (t_4 - t_1) - (t_3 - t_2)$$

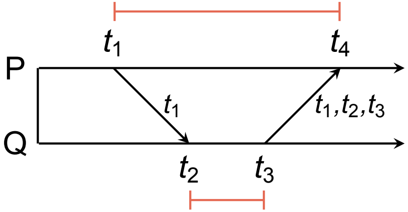
NTP Exchange



$$\Theta = \frac{1}{2}\left[(t_2 - t_1) + (t_3 - t_4)\right]$$

These intervals are differences between the *P* and *Q* clocks.

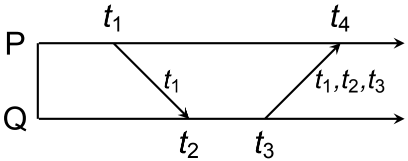
NTP Exchange



$$\delta = (t_4 - t_1) - (t_3 - t_2)$$

These intervals are local measurements at P and Q.

NTP Exchange



Θ is the adjustment for *P*'s clock.

δ bounds the error between the clocks at *P* and *Q*.

δ is calculated into the goodness of *Q* as a time source.

Additional Complexities

NTP tracks multiple servers and tries to build a picture of:

- The absolute accuracy of server clocks.
- Network conditions affecting time signals
- The relative frequency error of system clocks
- The relative phase error of the local clock to UTC

It continuously selects the best estimate of UTC and disciplines the local clock.

By tracking local frequency error it can survive network outages.

Summary

- Time is important to distributed systems
- There are standards for measuring time
- Different clock technologies have strengths and weaknesses
- Clocks experience relative phase and frequency errors
- Synchronization protocols must deal with network delays
- NTP provides robust synchronization over Internet paths

Next Time …

- Logical Clocks

References I

Optional Readings

[1] *BIPM — International Atomic Time*. URL: `https://www.bipm.org/en/bipm/tai/tai`.

[2] Flaviu Cristian. "A Probabilistic Approach to Distributed Clock Synchronization". In: *Proceedings of the International Conference on Distributed Computing Systems*. June 1989, pp. 288–296. URL: `https://search.lib.buffalo.edu/permalink/01SUNY_BUF/12pkqkt/cdi_ieee_primary_37958`.

References II

[3] Arthur O. McCoubrey. "History of Atomic Frequency Standards: A Trip through 20th Century Physics". In: 1996, pp. 1225–1241. URL: `https://ieee-uffc.org/about-us/history/uffc-s-history/history-of-atomic-frequency-standards-a-trip-through-20th-century-physics/`.

[4] Bureau International des Poids et Mesures. *The International System of Units (SI) (Ninth Edition)*. 2019. URL: `https://www.bipm.org/utils/common/pdf/si-brochure/SI-Brochure-9.pdf`.

[5] David L. Mills. *Network Time Protocol Version 4 Reference and Implementation Guide*. Tech. rep. 06-6-1. NTP Working Group, June 2006. URL: `https://www.eecis.udel.edu/~mills/database/reports/ntp4/ntp4.pdf`.

References III

[6] David L. Mills. *NTP Performance Analysis*. Aug. 2004. URL: https://www.eecis.udel.edu/~mills/database/brief/perf/perf.pdf.

[7] *Standard-frequency and time-signal emissions*. Recommendation ITU-R TF.460-6. 2002. URL: https://www.itu.int/dms_pubrec/itu-r/rec/tf/R-REC-TF.460-6-200202-I!!PDF-E.pdf.

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