Distributed Systems

The second half of *Concurrent and Distributed Systems*

https://www.cl.cam.ac.uk/teaching/current/ConcDisSys

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Computer Science Tripos, Part IB

Lecture 3

Time, clocks, and ordering of events

A detective story

In the night from 30 June to 1 July 2012 (UK time), many online services and systems around the world crashed simultaneously.

Servers locked up and stopped responding.

Some airlines could not process any reservations or check-ins for several hours.

What happened?

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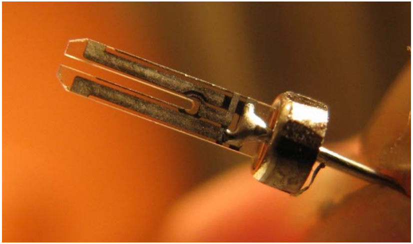
NB. Clock in digital electronics (oscillator)
$\neq$ clock in distributed systems (source of **timestamps**)

Quartz clocks

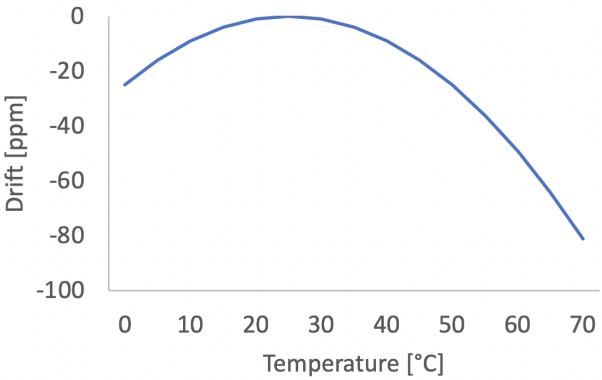
- Quartz crystal laser-trimmed to mechanically resonate at a specific frequency
- Piezoelectric effect: mechanical force $\Leftrightarrow$ electric field
- Oscillator circuit produces signal at resonant frequency
- Count number of cycles to measure elapsed time



Quartz clock error: drift

- One clock runs slightly fast, another slightly slow
- Drift measured in **parts per million** (ppm)
- 1 ppm = 1 microsecond/second = 86 ms/day = 32 s/year
- Most computer clocks correct within ≈ 50 ppm

Temperature significantly affects drift



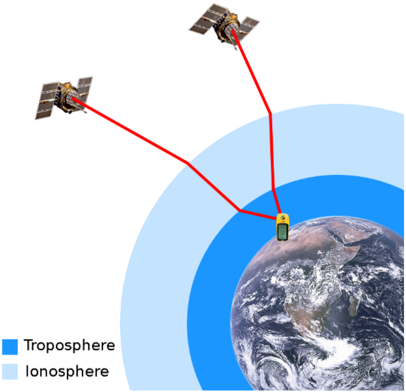
Atomic clocks

- Caesium-133 has a resonance ("hyperfine transition") at ≈ 9 GHz
- Tune an electronic oscillator to that resonant frequency
- 1 second $=$ 9,192,631,770 periods of that signal
- Accuracy ≈ 1 in 10^{-14} (1 second in 3 million years)
- Price $\approx$ £20,000 (?) (can get cheaper rubidium clocks for $\approx$ £1,000)

https://www.microsemi.com/product-directory/cesium-frequency-references/4115-5071a-cesium-primary-frequency-standard

GPS as time source

- 31 satellites, each carrying an atomic clock
- satellite broadcasts current time and location
- calculate position from speed-of-light delay between satellite and receiver
- corrections for atmospheric effects, relativity, etc.
- in datacenters, need antenna on the roof



https://commons.wikimedia.org/wiki/File:Gps-atmospheric-efects.png

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Greenwich Mean Time (GMT, solar time): it's noon when the sun is in the south, as seen from the Greenwich meridian

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Time zones and **daylight savings time** are offsets to UTC

Leap seconds

Every year, on 30 June and 31 December at 23:59:59 UTC, one of three things happens:

- The clock immediately jumps forward to 00:00:00, skipping one second (**negative leap second**)
- The clock moves to 00:00:00 after one second, as usual
- The clock moves to 23:59:60 after one second, and then moves to 00:00:00 after one further second (**positive leap second**)

This is announced several months beforehand.

http://leapsecond.com/notes/leap-watch.htm

How computers represent timestamps

Two most common representations:

- **Unix time**: number of seconds since 1 January 1970 00:00:00 UTC (the "epoch"), *not counting leap seconds*
- **ISO 8601**: year, month, day, hour, minute, second, and timezone offset relative to UTC
  example: `2020-11-09T09:50:17+00:00`

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Conversion between the two requires:

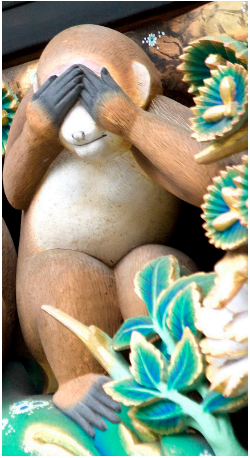
- Gregorian calendar: 365 days in a year, except leap years

  ```
  (year % 4 == 0 && (year % 100 != 0 ||
                     year % 400 == 0))
  ```

- Knowledge of past and future leap seconds...?!

How most software deals with leap seconds

By ignoring them!



https://www.flickr.com/photos/ru_boff/37915499055/

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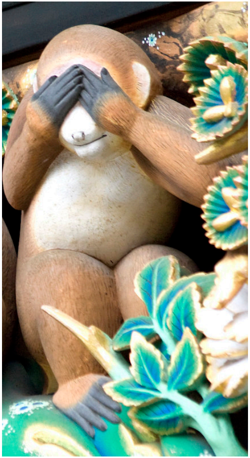

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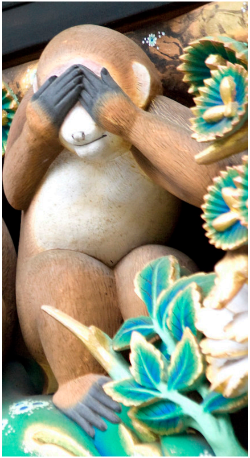

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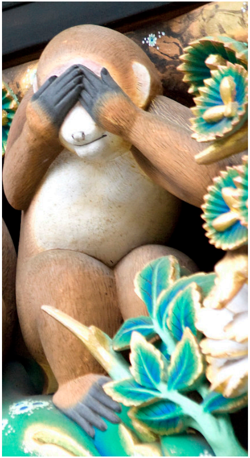
Pragmatic solution: “**smear**” (spread out) the leap second over the course of a day



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Clock synchronisation

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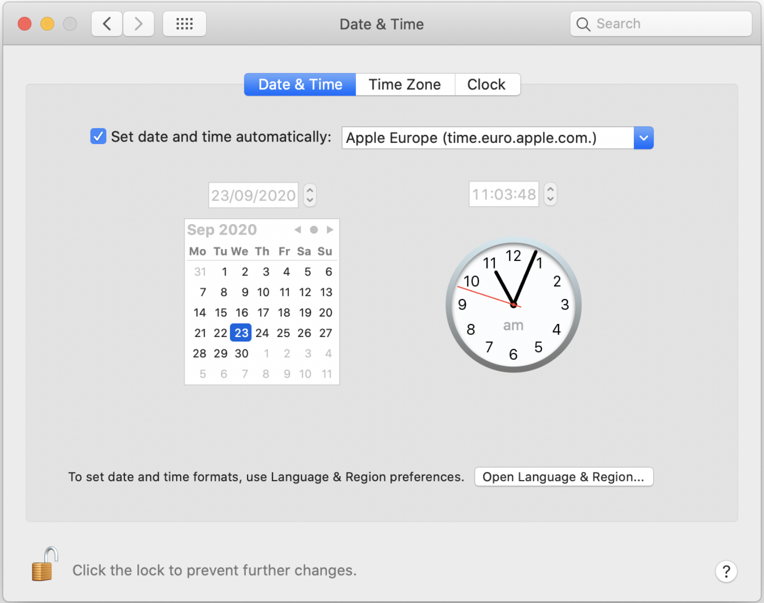
Solution: Periodically get the current time from a server that has a more accurate time source (atomic clock or GPS receiver)

Protocols: Network Time Protocol (**NTP**),
Precision Time Protocol (**PTP**)


Date & Time
Search
Date & Time
Time Zone
Clock
Set date and time automatically:
Apple Europe (time.euro.apple.com.)
23/09/2020
11:03:48
Sep 2020
Mo Tu We Th Fr Sa Su
31 1 2 3 4 5 6
7 8 9 10 11 12 13
14 15 16 17 18 19 20
21 22 23 24 25 26 27
28 29 30 1 2 3 4
5 6 7 8 9 10 11
12 1 2 3 4 5 6 7 8 9 10 11
am
To set date and time formats, use Language & Region preferences.
Open Language & Region...
Click the lock to prevent further changes.
?

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May contact multiple servers, discard outliers, average rest

Makes multiple requests to the same server, use statistics to reduce random error due to variations in network latency

Reduces clock skew to a few milliseconds in good network conditions, but can be much worse!

Estimating time over a network

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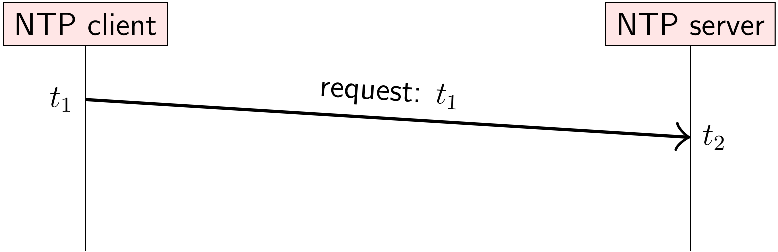

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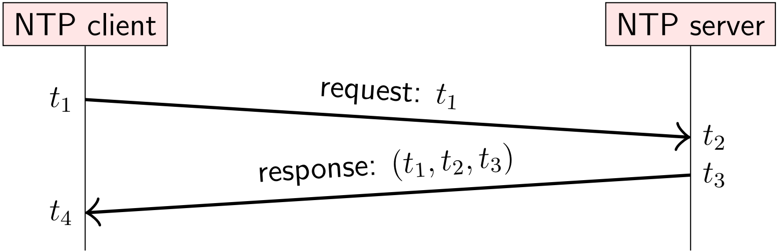

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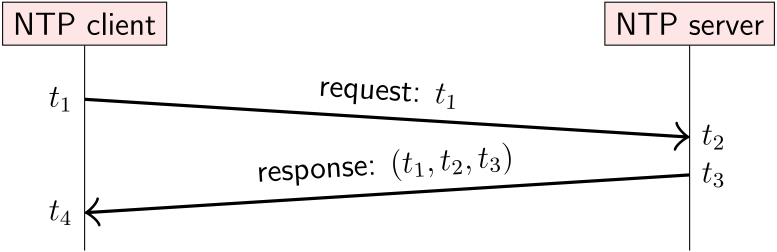

Round-trip network delay: $\delta = (t_4 - t_1) - (t_3 - t_2)$

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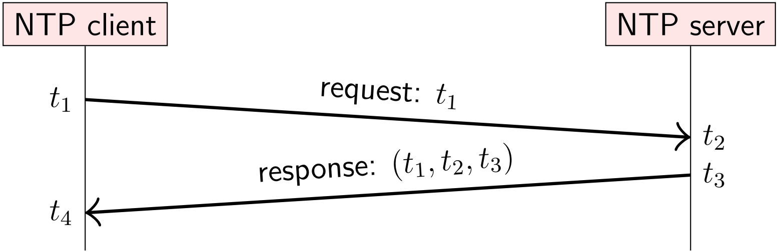

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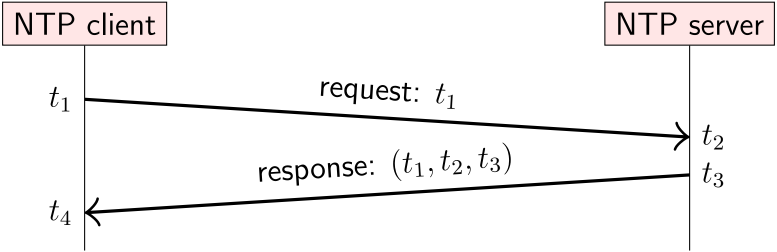

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Estimated clock skew: $\theta = t_3 + \frac{\delta}{2} - t_4 = \frac{t_2 - t_1 + t_3 - t_4}{2}$

Correcting clock skew

Once the client has estimated the clock skew θ, it needs to apply that correction to its clock.

- If $|\theta| < 125$ ms, **slew** the clock:
  slightly speed it up or slow it down by up to 500 ppm
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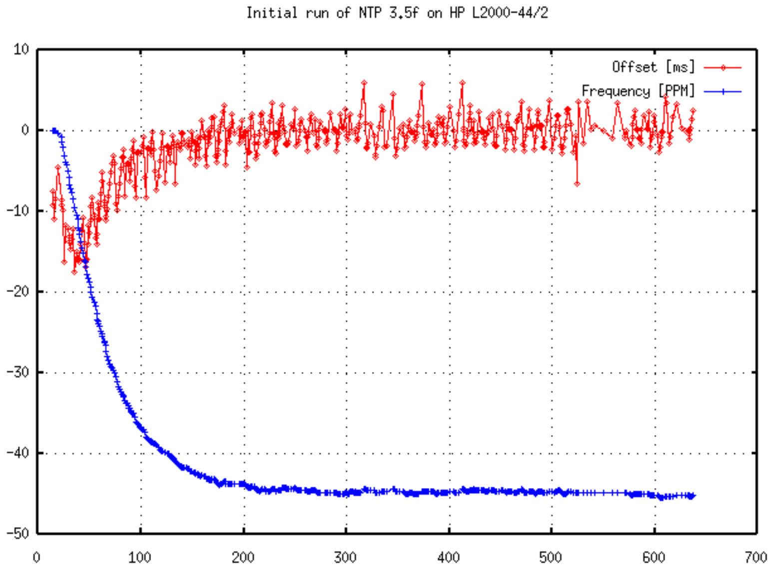
- If $|\theta| \geq$ 1,000 s, **panic** and do nothing
  (leave the problem for a human operator to resolve)

Systems that rely on clock sync need to monitor clock skew!



http://www.ntp.org/ntpfaq/NTP-s-algo.htm

Monotonic and time-of-day clocks

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// GOOD:
long startTime = System.nanoTime();
doSomething();
long endTime = System.nanoTime();
long elapsedNanos = endTime - startTime;
// elapsedNanos is always >= 0
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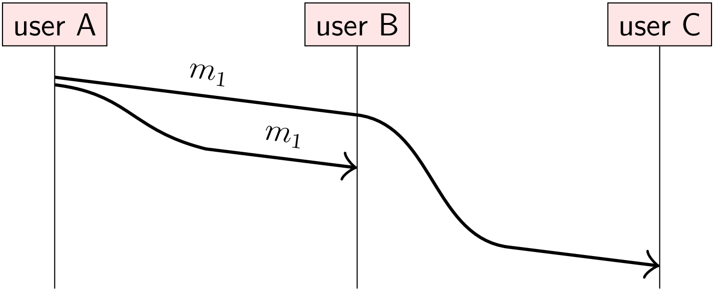
Ordering of messages



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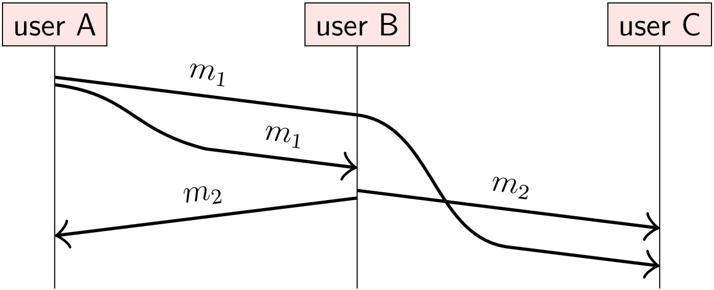

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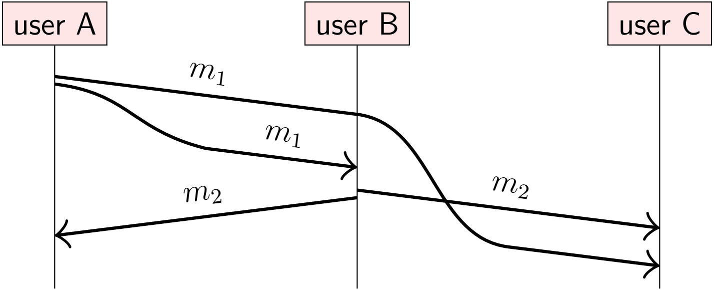

m_1 = "A says: The moon is made of cheese!"
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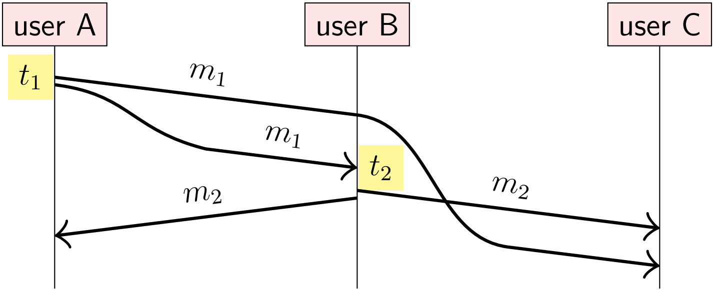
C sees m_2 first, m_1 second,
even though logically m_1 **happened before** m_2.

Ordering of messages using timestamps?



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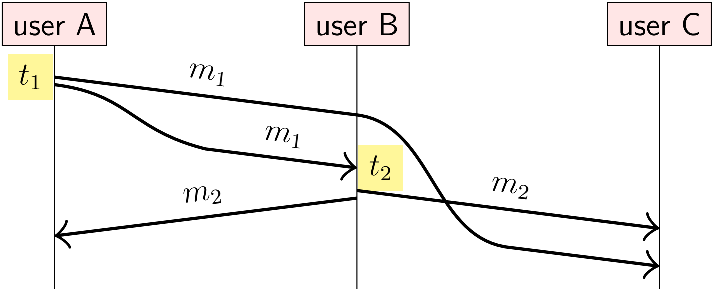

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Problem: even with synced clocks, $t_2 < t_1$ is possible.
Timestamp order is inconsistent with expected order!

The happens-before relation

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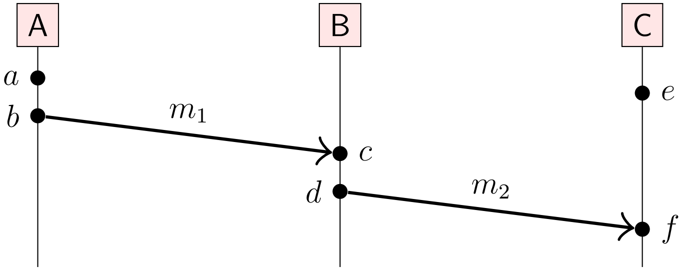
The happens-before relation is a partial order: it is possible that neither $a \rightarrow b$ nor $b \rightarrow a$. In that case, a and b are **concurrent** (written $a \parallel b$).

Happens-before relation example



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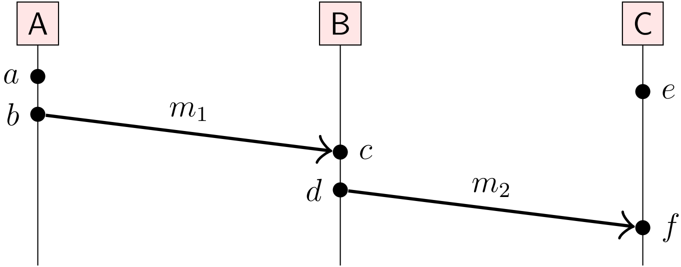

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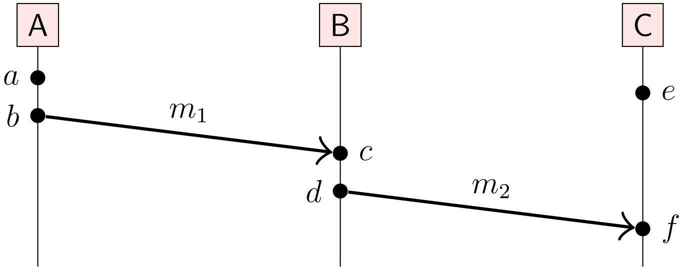

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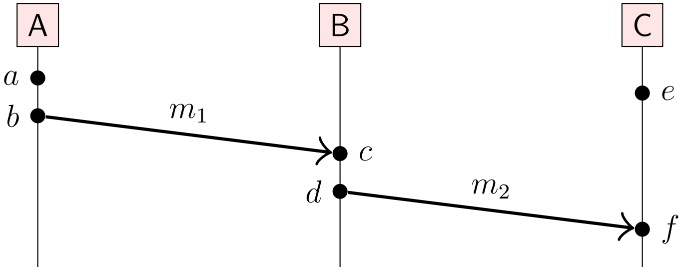

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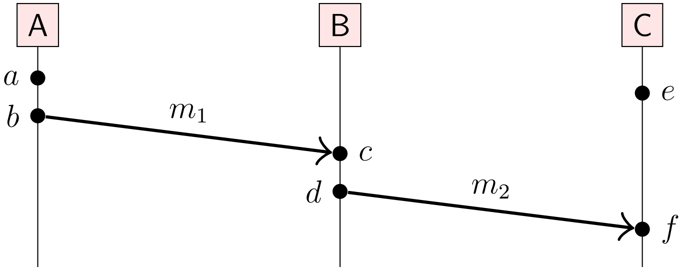

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- $a \parallel e$, $b \parallel e$, $c \parallel e$, and $d \parallel e$

Causality

Taken from physics (relativity).

- When $a \rightarrow b$, then a **might have caused** b.
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Happens-before relation encodes **potential causality**.

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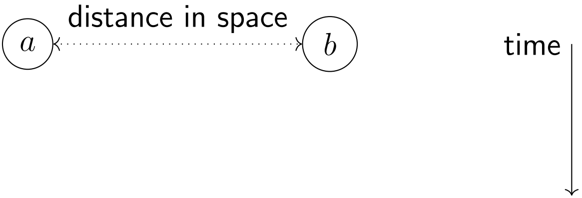
Happens-before relation encodes **potential causality**.

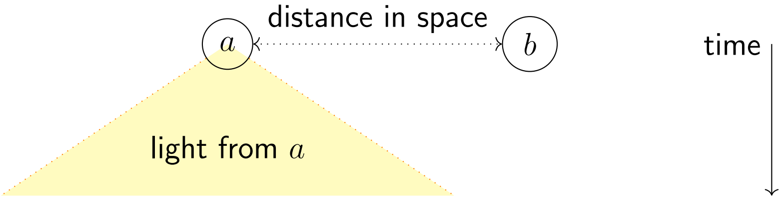


Causality

Taken from physics (relativity).

- When $a \to b$, then a **might have caused** b.
- When $a \parallel b$, we know that a **cannot have caused** b.

Happens-before relation encodes **potential causality**.



Causality

Taken from physics (relativity).

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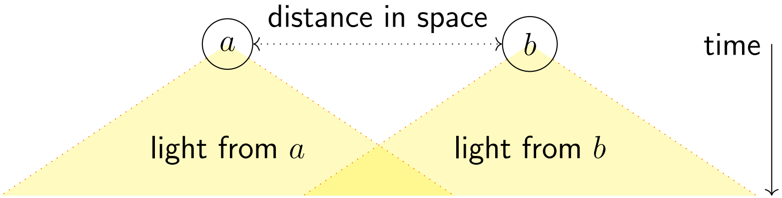

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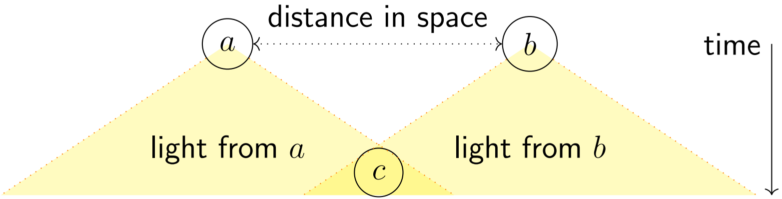

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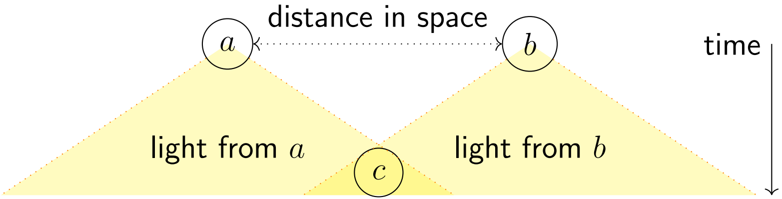

Let $\prec$ be a strict total order on events.
If $(a \to b) \implies (a \prec b)$ then $\prec$ is a **causal order**
(or: $\prec$ is "consistent with causality").
NB. "causal" $\neq$ "casual"!