CS 925

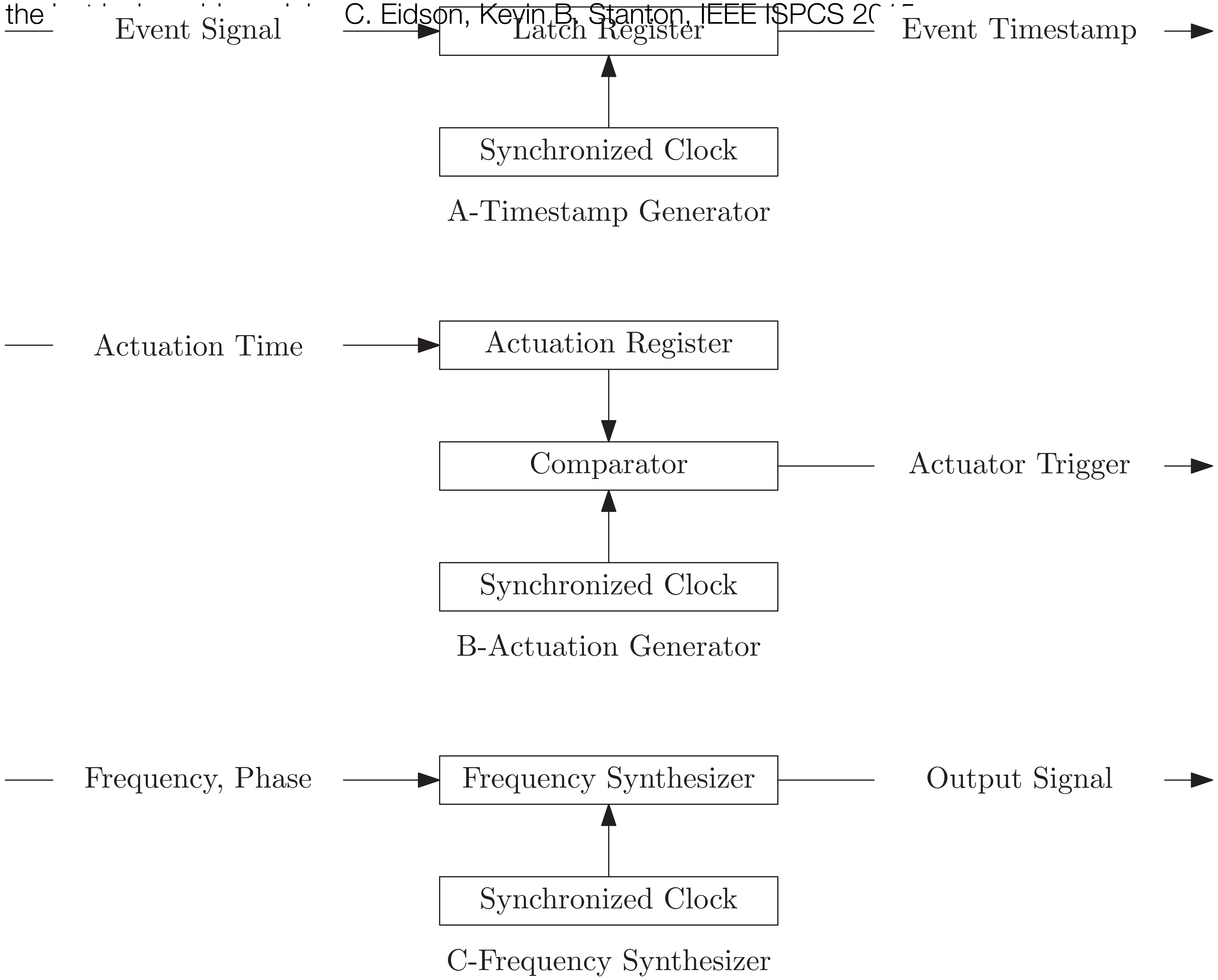
Lecture 21

Network-based Time Synchronization

Tuesday, April 16, 2024

Motivation

Timing in cyber-physical systems: the [illegible] C. Eidson, Kevin B. Stanton, IEEE ISPCS 20[illegible]



Current Applications

- Navigation
  - Satellite positioning
  - Indoor navigation
- Telecom networks
- IoT networking
  - e.g., LoRa
- Power grid
  - Synchrophasor networks

Applications

- Industrial automation
  - Industry 4.0
- High-speed algorithmic securities trading
  - trade scheduling
  - globally-timestamped logs of trades (for audit)
- Professional audio-video
- High-energy particle physics

Applications

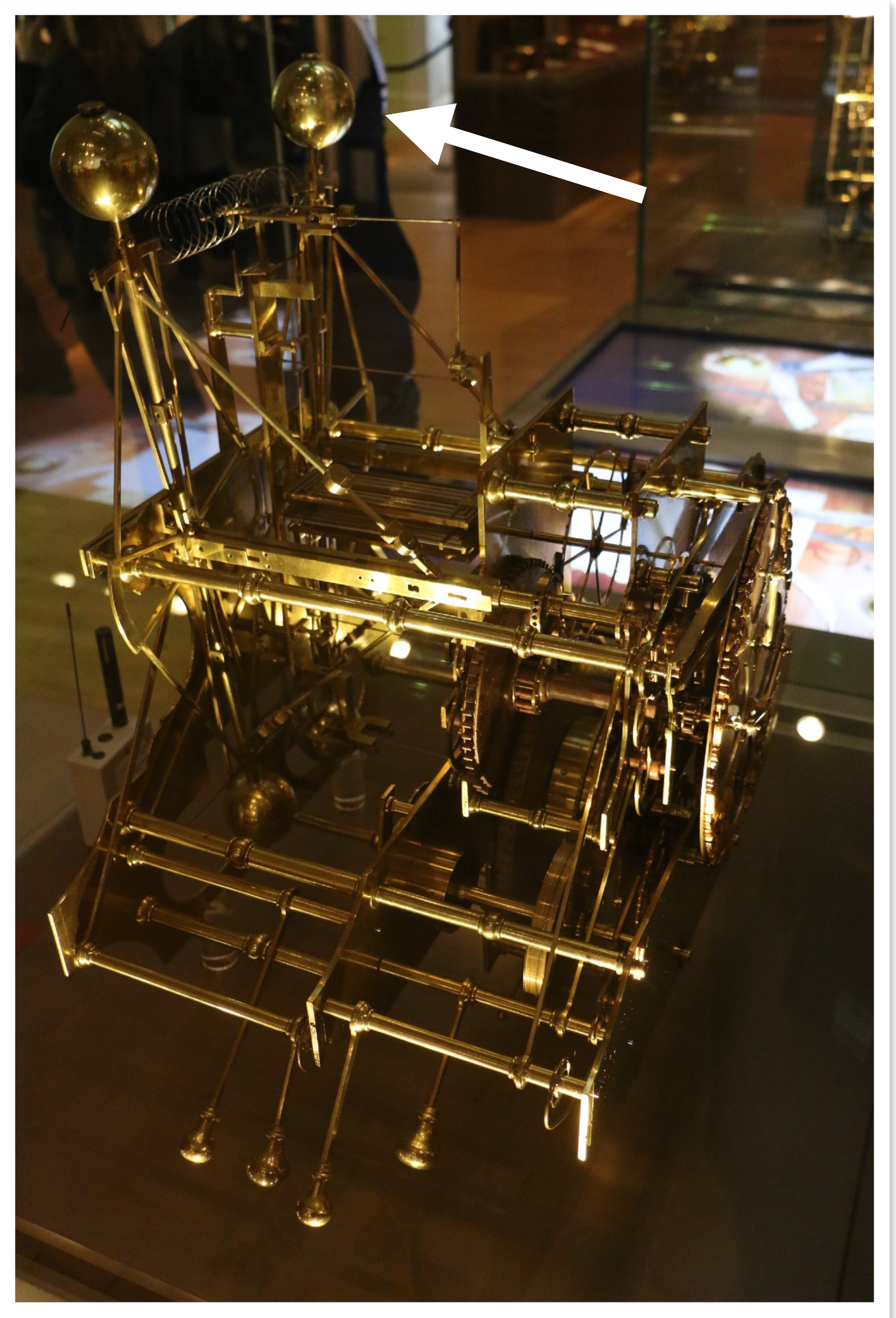
- Distributed consensus in blockchain algorithms (Algorand)
- Consistency in geographically-distributed data centers (Google)
- Power conservation in IoT (LoRa)
- Stereo audio (Apple HomePod)
- Delayed message authentication (IEEE 1588)

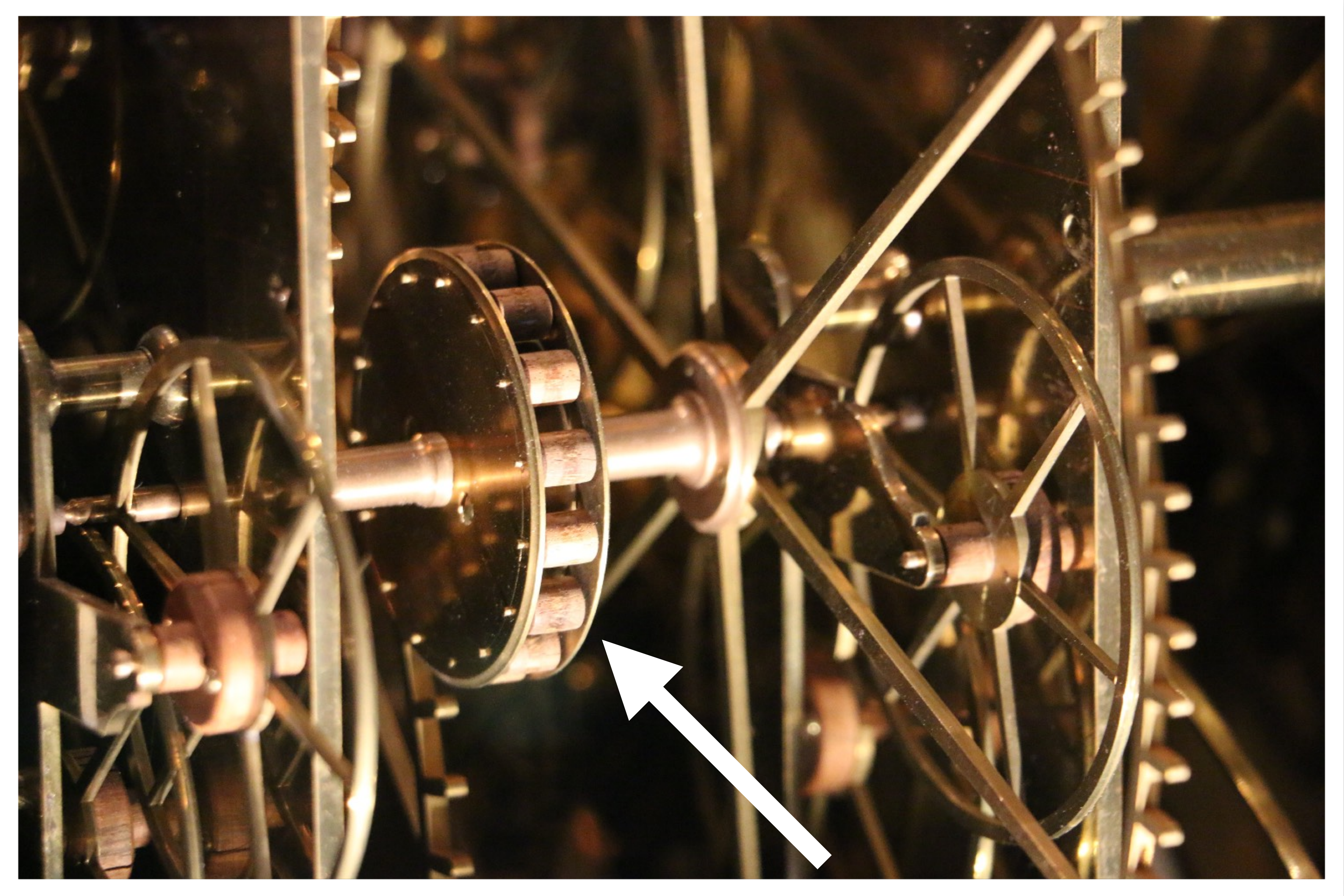
Three challenges

- What is the "correct" time?
  - "Clock in the sky" - time derived from astronomical observations
  - Atomic time (which one? TAI, UTC)
  - Says who? Consortium of national bureaus of standards
  - Mostly futile question when you bring in the theory of relativity
- Design a clock that keeps the correct time (syntonized with the reference)
- Design a mechanism for time transfer

Johan Stradanus inv., Philip Galle ex., c.1595

Precise clocks





John Harrison marine clocks
to be used to determine
ship's longitude

National time reference

- NIST 7 Cesium Frequency Standard (1993)

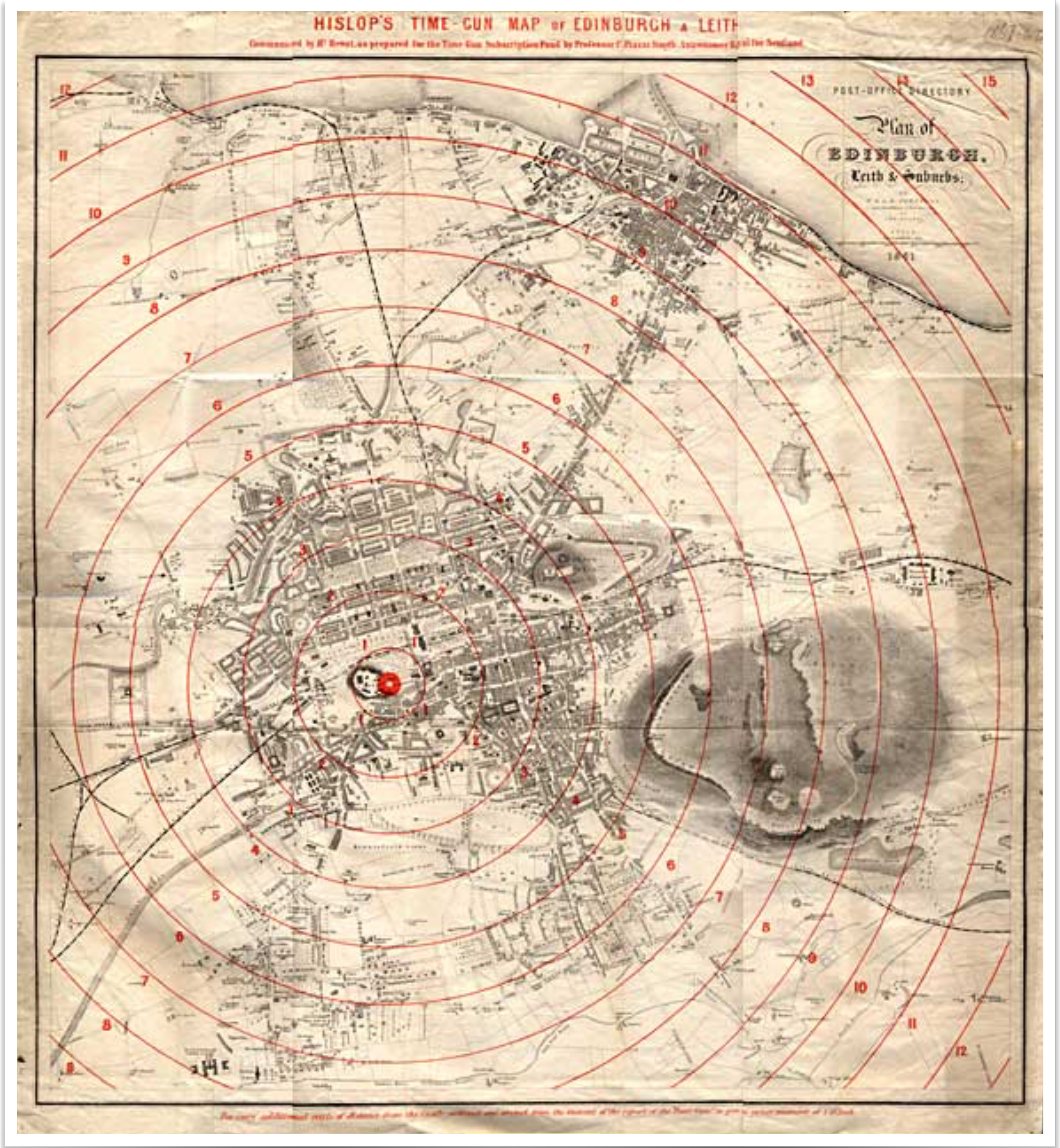
Time transfer

- Dropping balls…

Telegraph Time Ball at the Strand, London, 1852.

Time transfer

- One O'clock Gun Edinburgh Castle



Centralized time reference

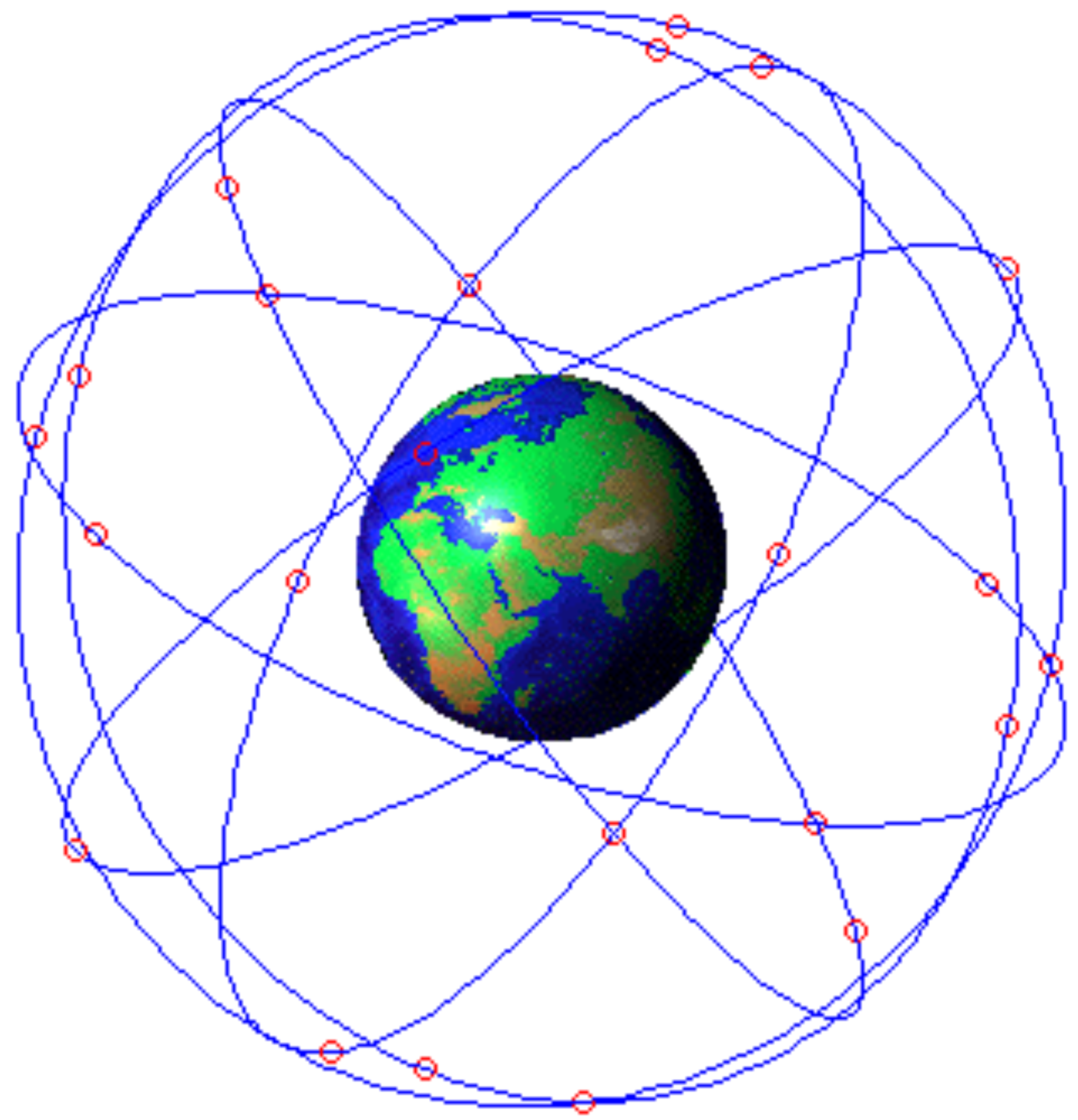
- Radio broadcast
  - WWV broadcasting from Fort Collins, CO

- Phone: Talking Clock

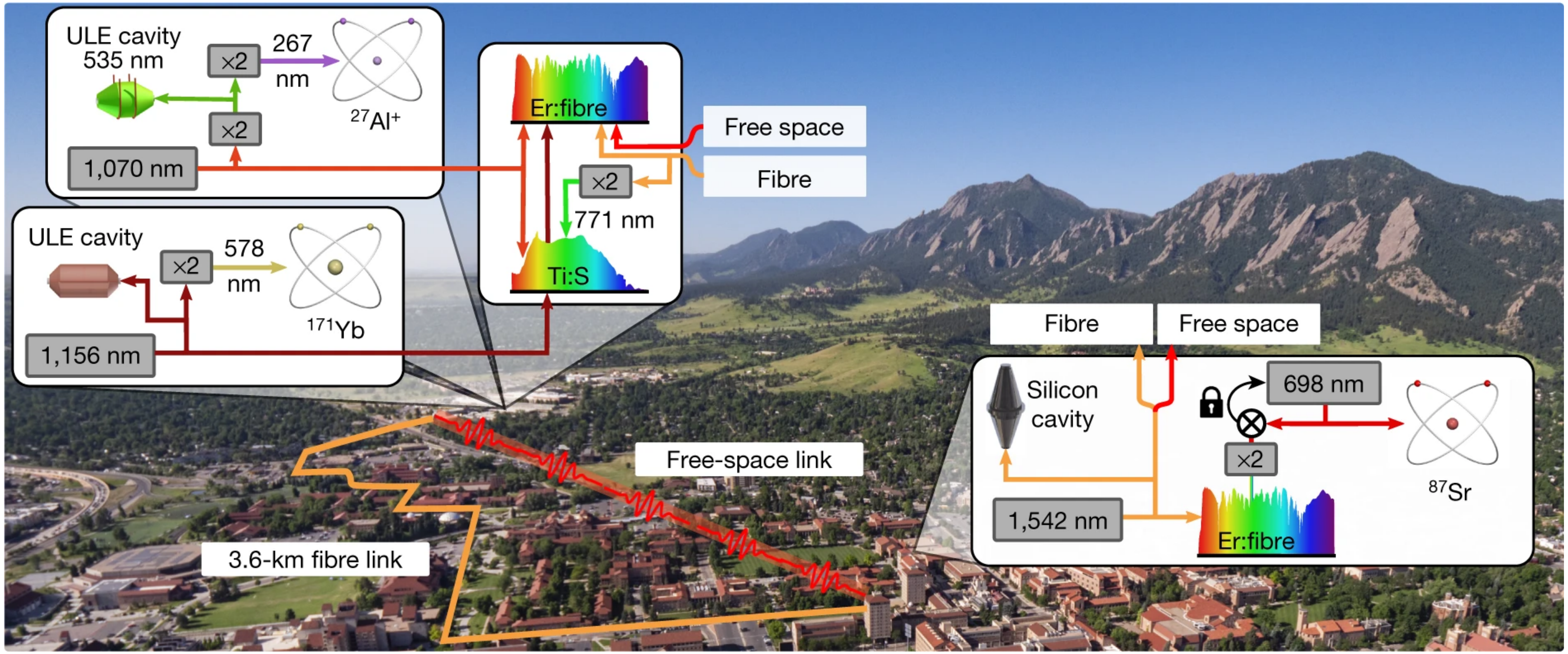
- Minute or second time signal from a reference time source

GNSS-based systems

- Multiple satellites with high-precession clocks on board at known precise locations send the timing information to terrestrial clients:
  - location
  - precise time (!)
- Operational systems:
  - GPS (USA)
  - Glonass (Russia)
  - BeiDou (China)
  - Galileo (European Union)
  - QZSS (Japan)



10^{-18} uncertainty…



Source: Frequency ratio measurements at 18-digit accuracy using an optical clock network, Nature, March 2021, https://doi.org/10.1038/s41586-021-03253-4

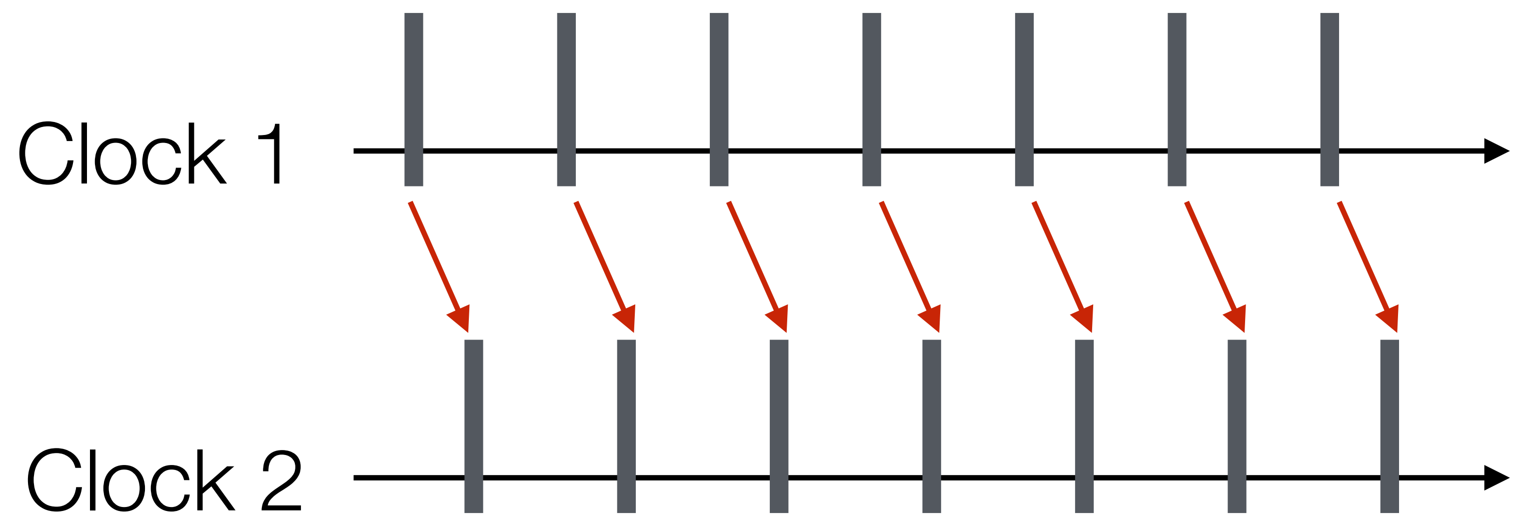
Synchrony vs syntony

- Clocks are said to be synchronized (at a specific point in time) when they "show the same time"
  - synchrony = same time
- Clocks are said to be syntonized (over a period of time) when they "tick" at the same rate
  - syntony = same tone (frequency)

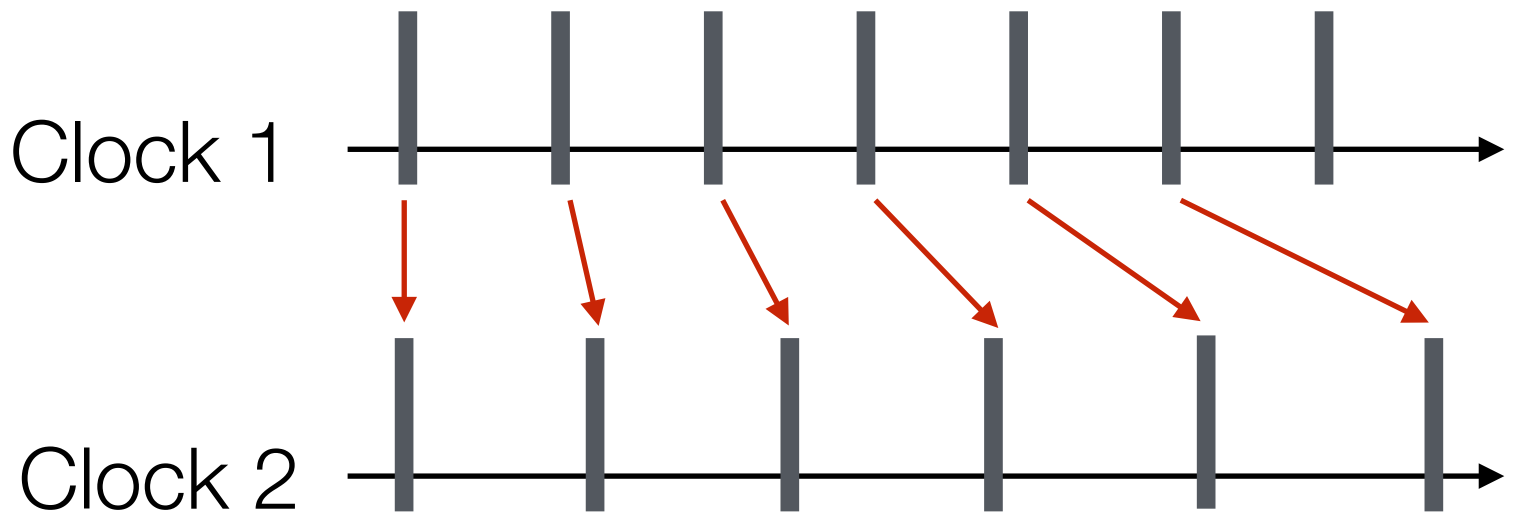
- We need solutions for synchronization and syntonization

Offset and Skew

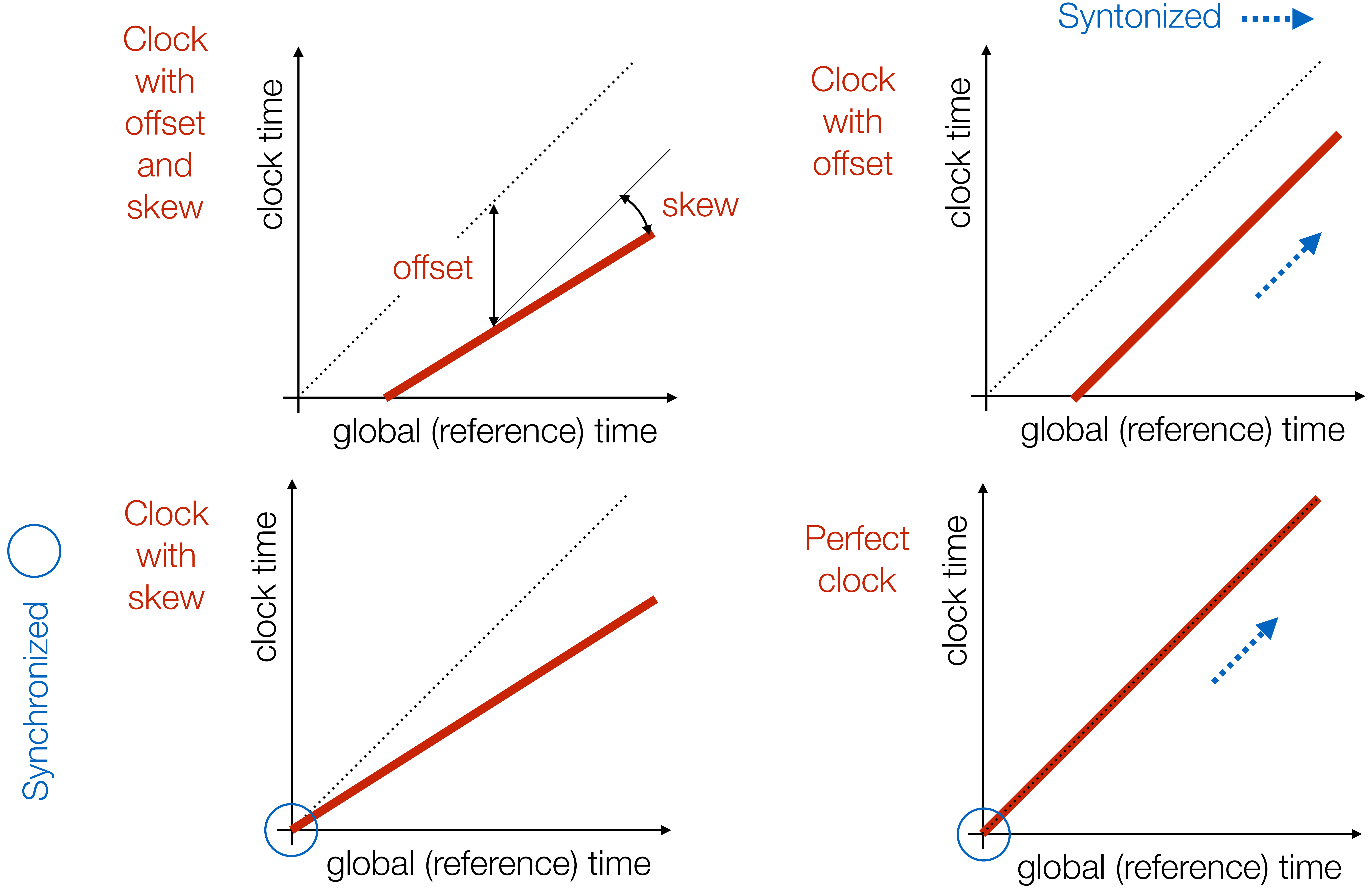
- Offset - difference between the clock time and global (reference) time (a.k.a. phase difference)



- Skew - the rate with which the clock drifts with respect to the global (reference) time (a.k.a. frequency difference)



Offset and Skew



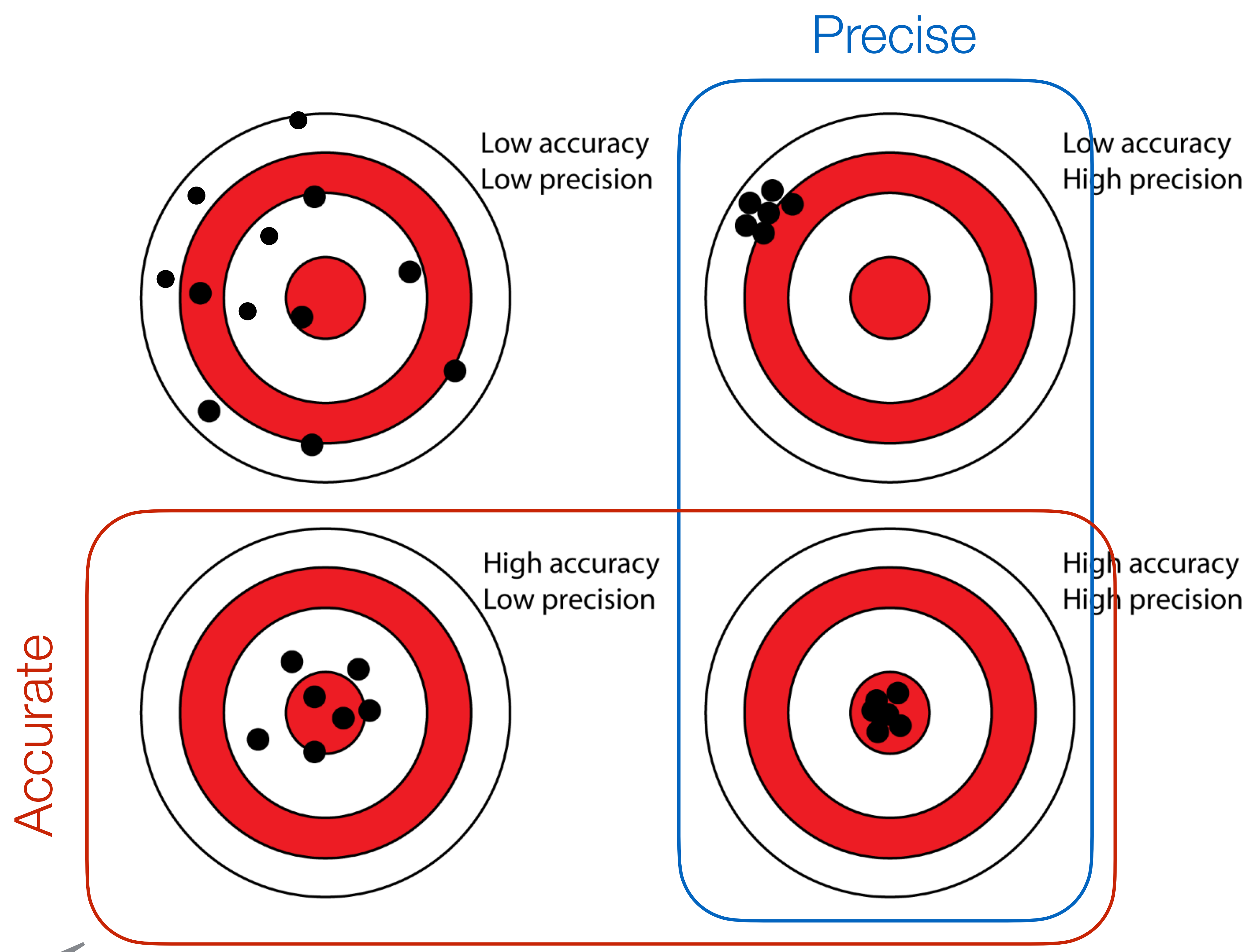
Offset and Skew

- Ideally, knowing the the values for skew s and offset o (*and assuming the they are constant*), the clock time t_c can be converted to global (reference) time t_g:

$$t_g = t_c + (\Delta t \cdot s + o)$$

Precision and Accuracy

- **Precision**
  - how well the clock tracks passing of time (over a period of time)
- **Accuracy**
  - how well the clock reflect the global time (at an instant)



ALERT: Frequently used but highly misleading analogy

Maintaining local time

- Synchronize with a reference clock to find offset
  - adjust the clock time (how?)
- Do it periodically to find skew
  - adjust the clock

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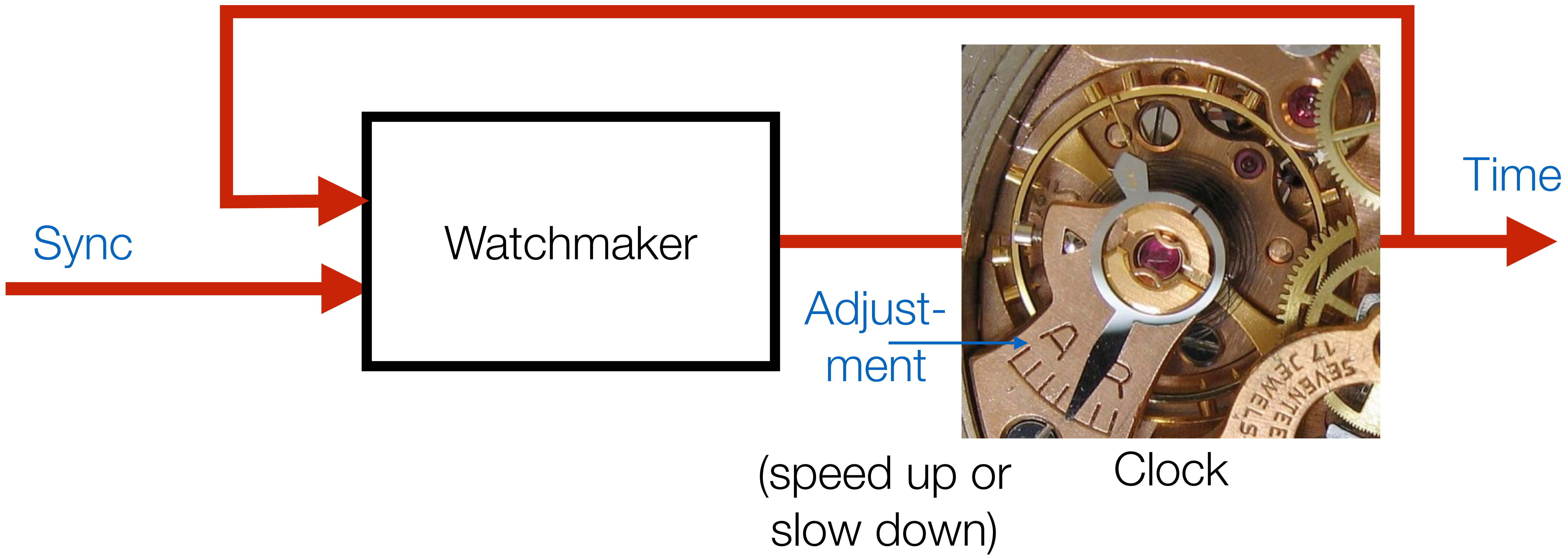

Image credit: https://en.wikibooks.org/wiki/Budget_Watch_Collecting/Regulating

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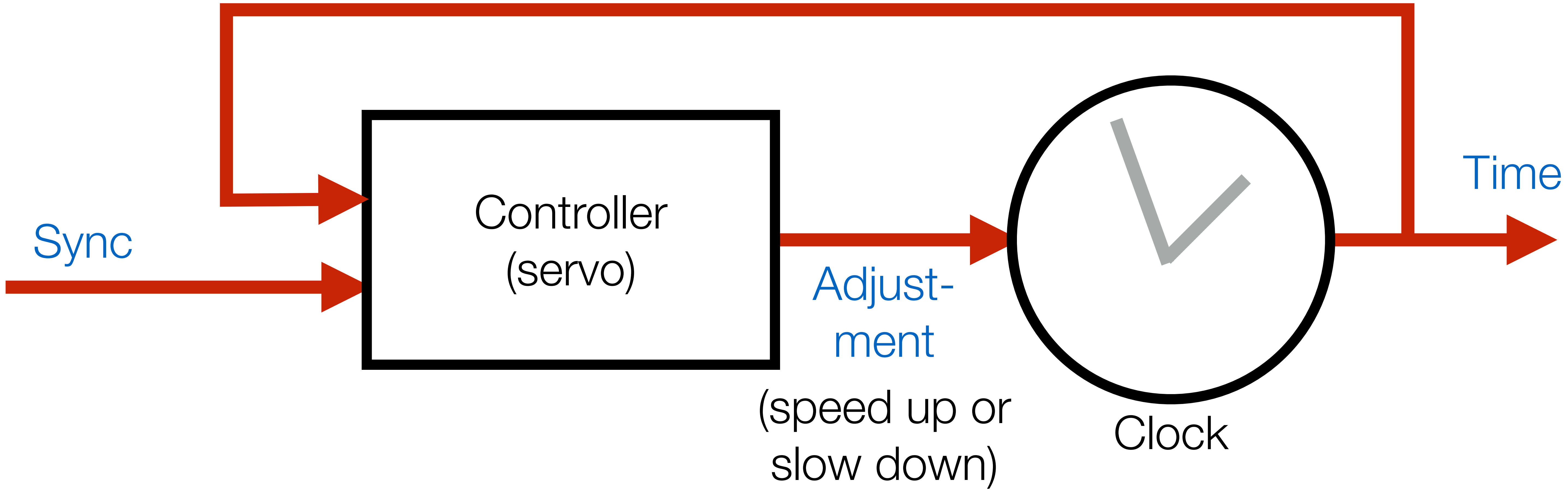

Time transfer

- Let's assume that I have the most precise master clock that money can buy and that the clock is synchronized to some form of universal time
- *You need precise time…*
  … so I write the current time on Post-it note and take it to you …
- The key issue is time transfer and the key challenge is the latency of the communication

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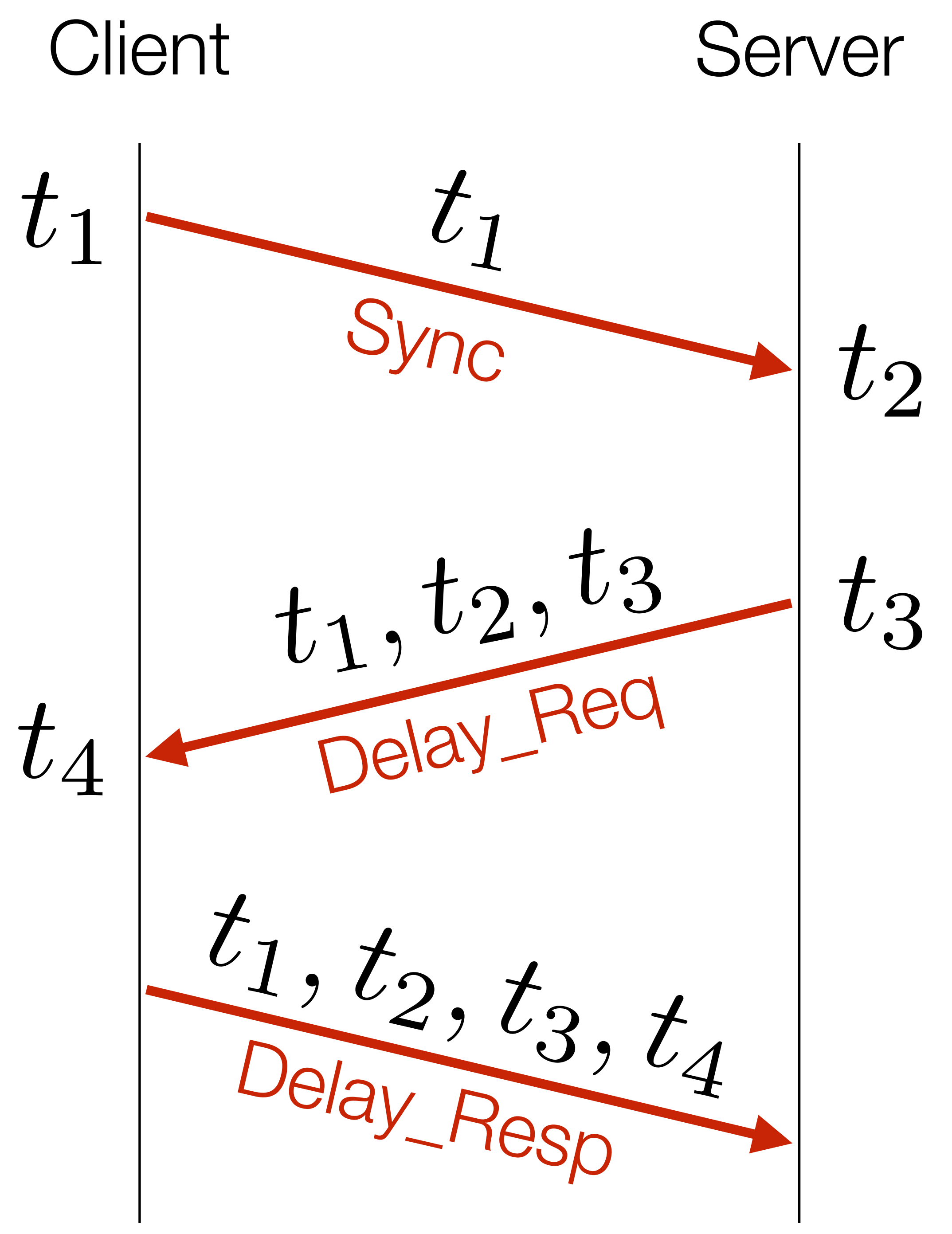

$$RTT = (t_4 - t_1) - (t_3 - t_2)$$

$$Offset = (t_2 - t_1) - \frac{RTT}{2}$$

Time transfer - example

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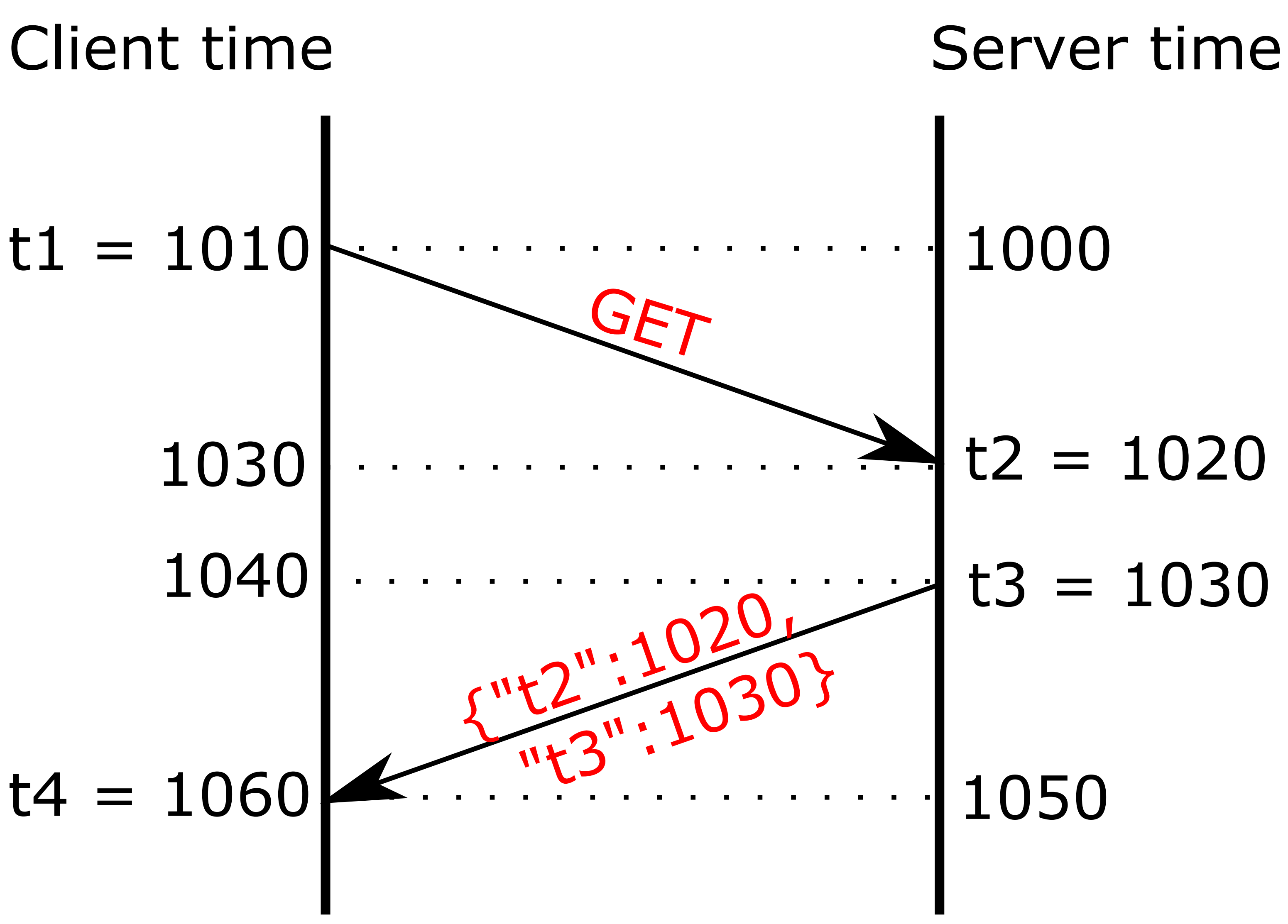

RTT = (1060 - 1010) - (1030 - 1020) = 40 units

Offset = (1010 + 40/2) - 1020 = 10 units

The client clock is 10 units ahead of the server clock

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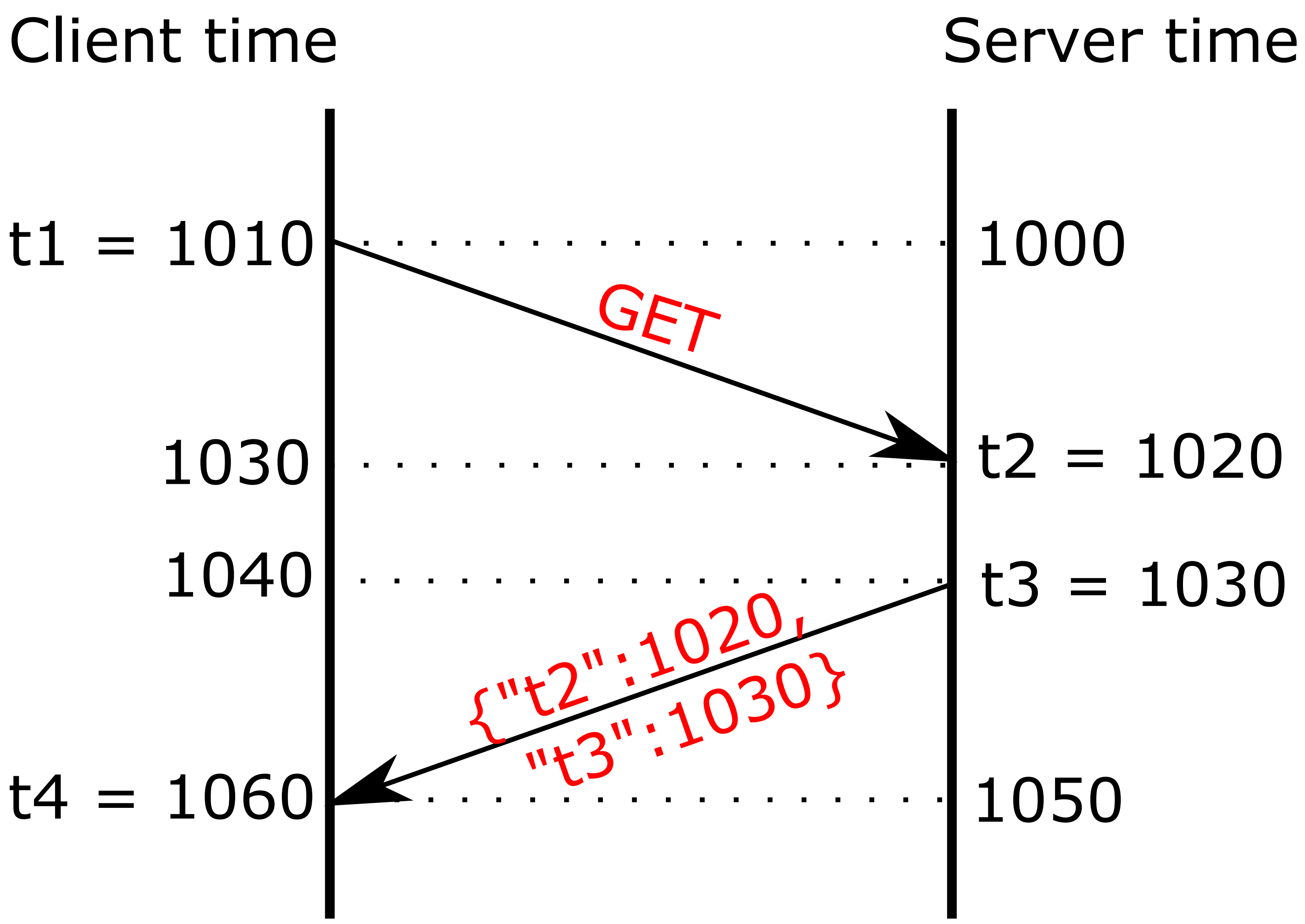
Assumption! Sometimes not true in real systems



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