Perspective on quantum clocks

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Defining a clock

A clock is:

- a device that measures the passage of time by producing countable "ticks"—an observable sequence of events—that can operate indefinitely through sustainable operation.

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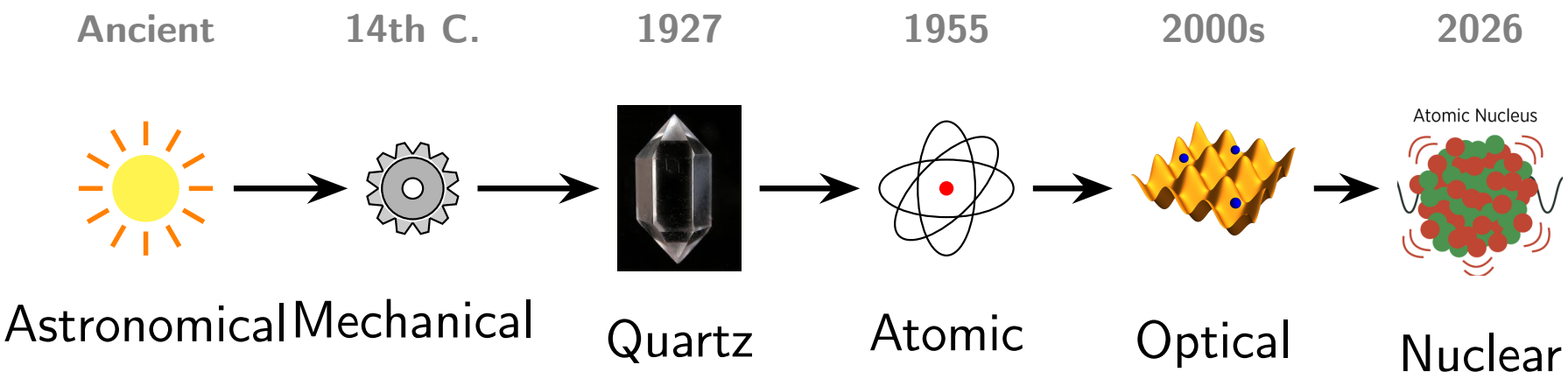
Periodic clock

- The oscillator $\rightarrow$ a mechanism that sustains oscillation with a steady beat.
- The counter $\rightarrow$ is a device that counts those beats and displays the time.

Historical realization



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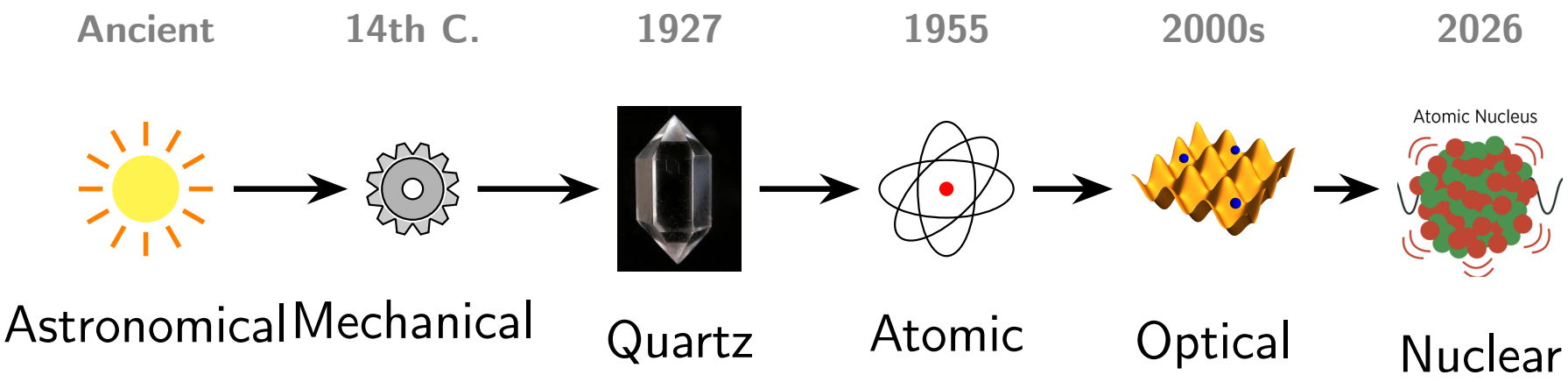
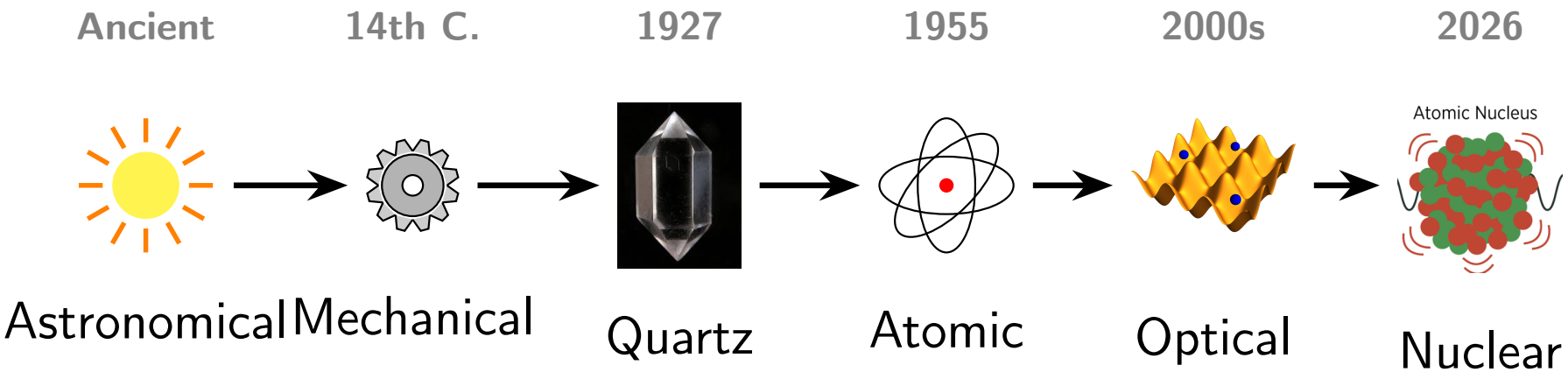


Frequency Standard

- Frequency reference $\rightarrow$ controls and stabilizes the oscillator frequency
- Early clocks used external references (e.g., Earth's rotation).
- Modern clocks use internal frequency standards.

Historical realization



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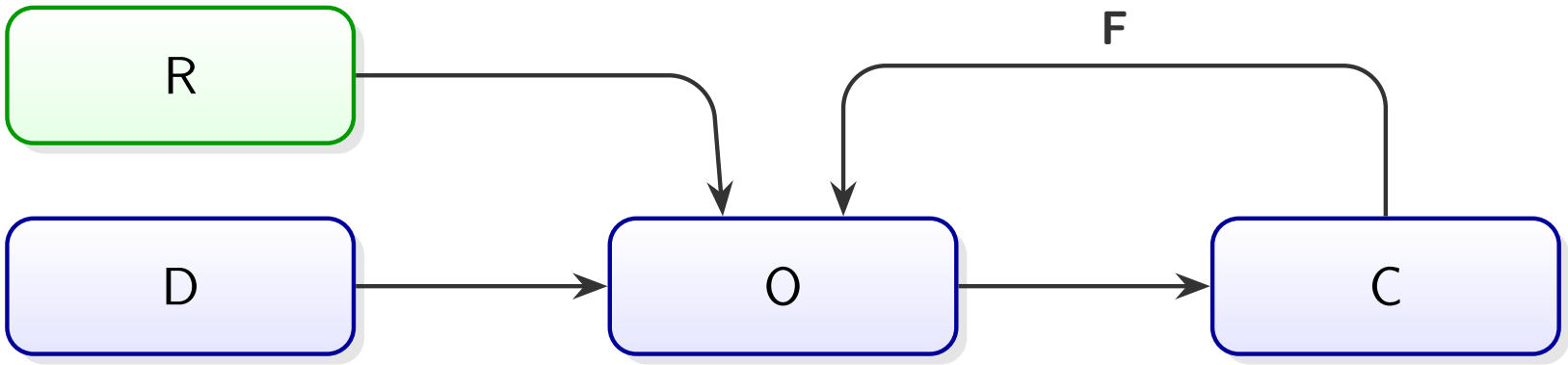
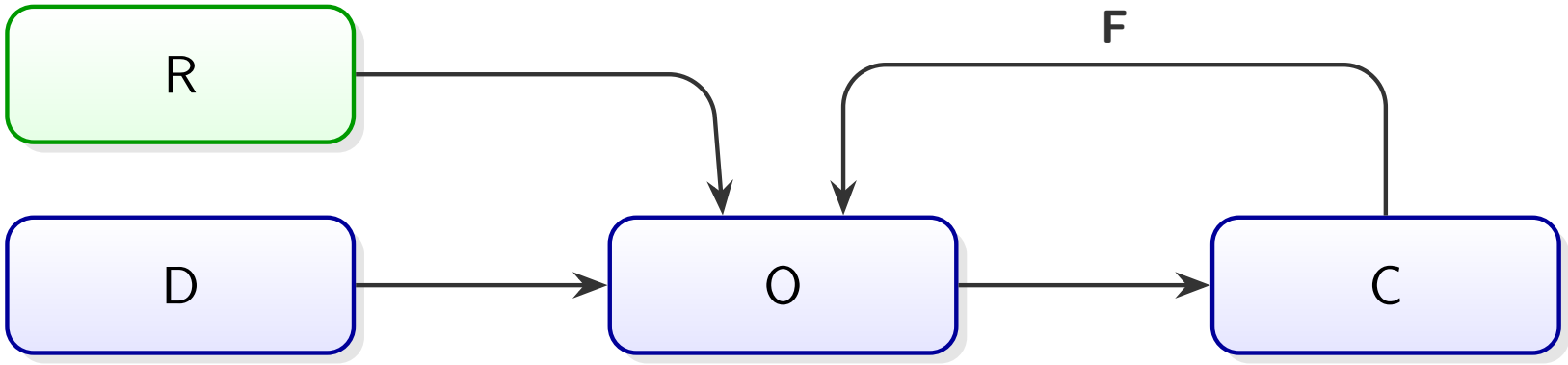
Clock Type	Frequency Standard
Pendulum clock	Pendulum length: $5 \times 10^{-1}\,\mathrm{Hz}$
Quartz clock	Crystal resonance: $3.3 \times 10^{4}\,\mathrm{Hz}$
Atomic clock	$^{133}\mathrm{Cs}$ transition: $9.2 \times 10^{9}\,\mathrm{Hz}$
Optical clock	$^{87}\mathrm{Sr}$ transition: $4.3 \times 10^{14}\,\mathrm{Hz}$
Nuclear clock	$^{229}\mathrm{Th}$ transition: $2.03 \times 10^{15}\,\mathrm{Hz}$

Operational framework



Schematic of a clock including the oscillator O, the driver D, feedback F and counter C.

Operational framework



Schematic of a clock including the oscillator O, the driver D, feedback F and counter C.

- Oscillator: Generates a periodic signal
- Driver: Supplies energy
- Reference: Defines stable frequency
- Readout Produces ticks
- Feedback: Corrects drift

Performance Metrics

Clock performance can be characterized using three main quantities.

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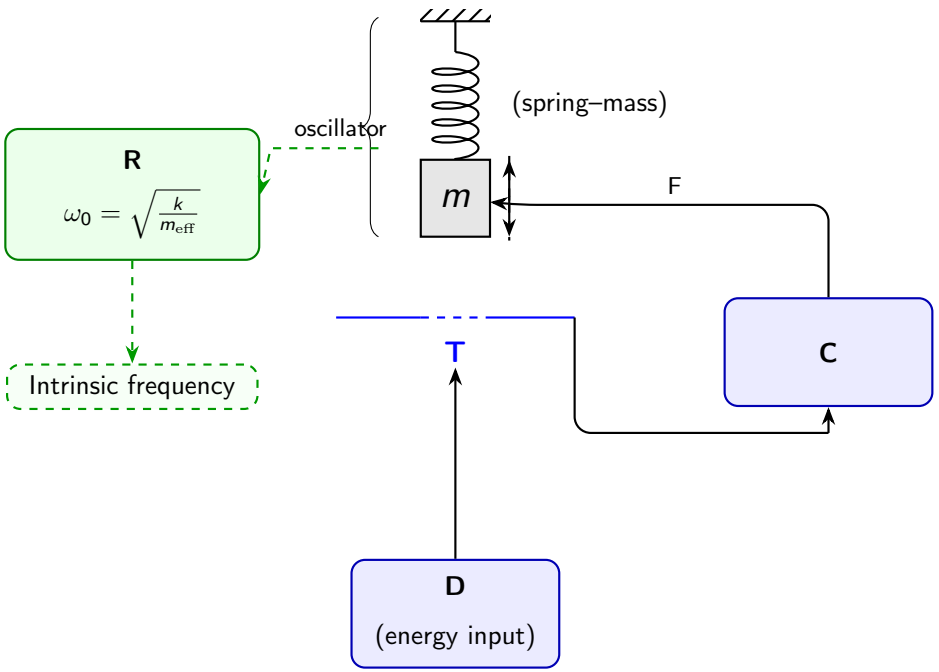
- Accuracy: closeness to the reference value
- Precision: linewidth or frequency uncertainty
- Stability: long-term frequency fluctuations

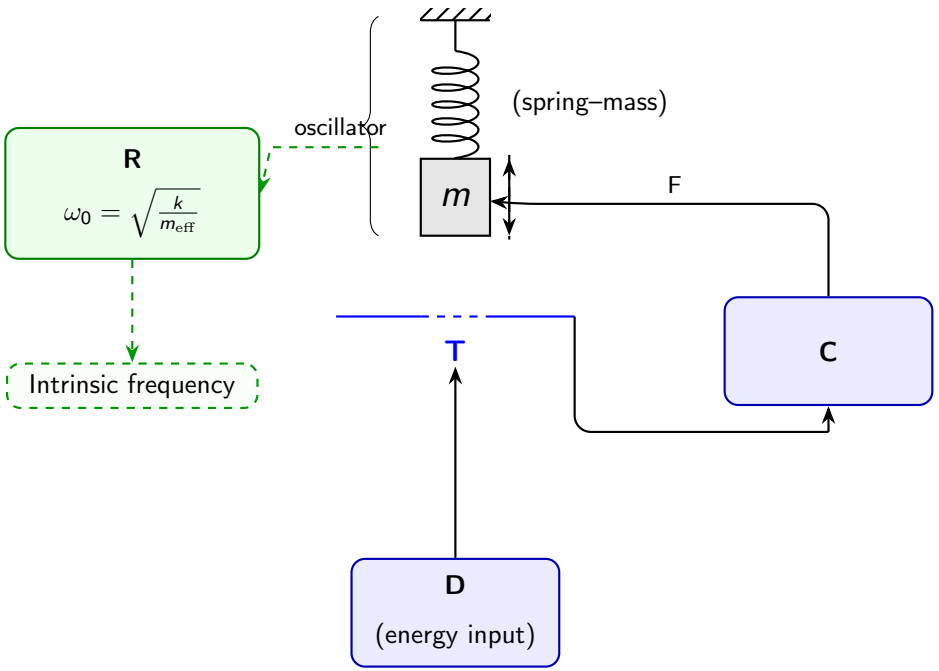
Realization: Mechanical clock



Schematic of mechanical clock showing the oscillator O, driver D, transducer T, counter C, feedback S, and frequency reference R.

- Oscillator: mass–spring system

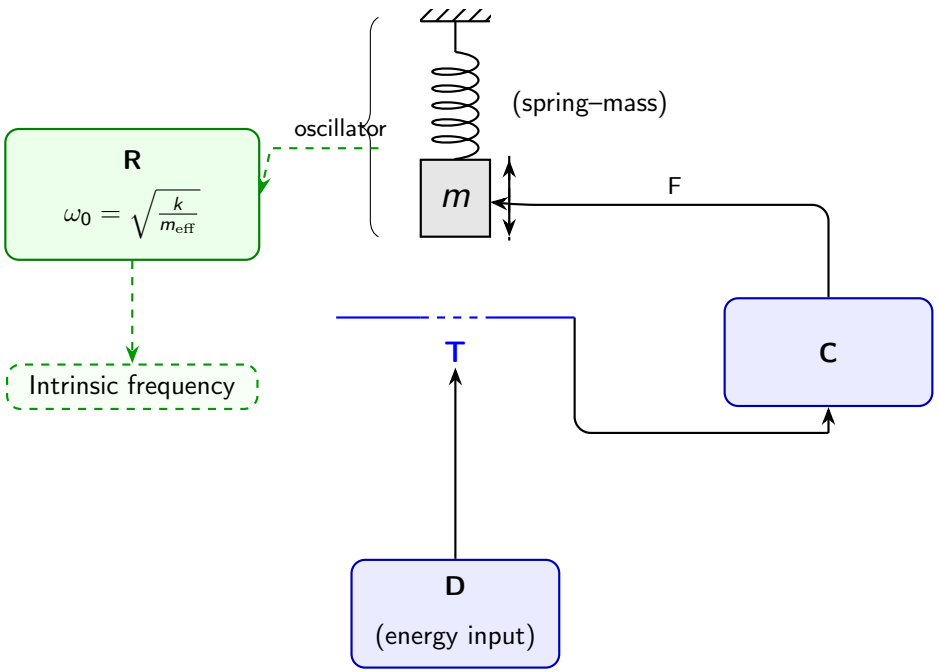
Realization: Mechanical clock



Schematic of mechanical clock showing the oscillator O, driver D, transducer T, counter C, feedback S, and frequency reference R.

- Oscillator: mass–spring system
- Frequency reference: natural resonance

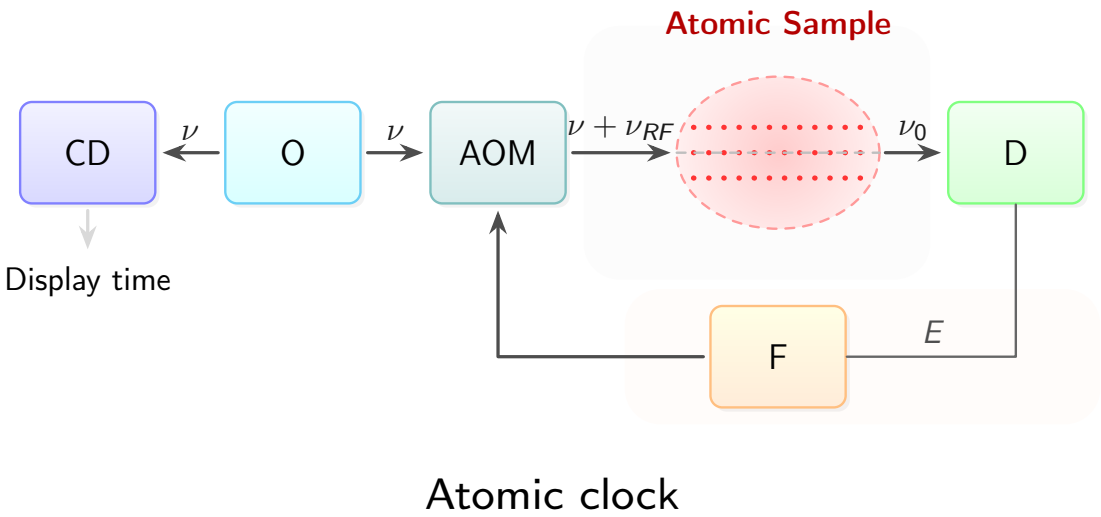
Realization: Mechanical clock



Schematic of mechanical clock showing the oscillator O, driver D, transducer T, counter C, feedback S, and frequency reference R.

- Oscillator: mass–spring system
- Frequency reference: natural resonance
- Performance: limited by friction and environmental noise

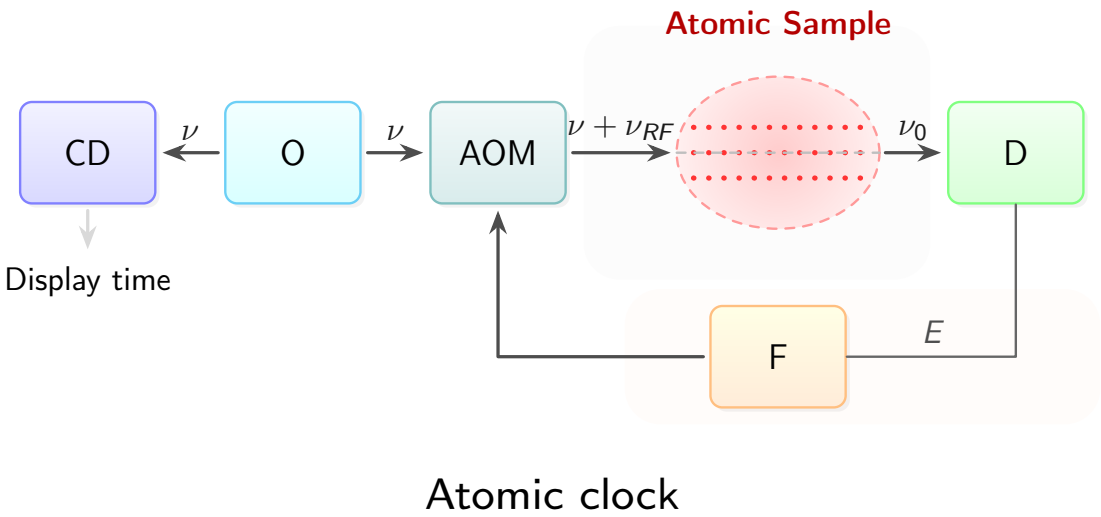
Realization: atomic clock



Atomic clock

- AOM: acousto-optic modulator

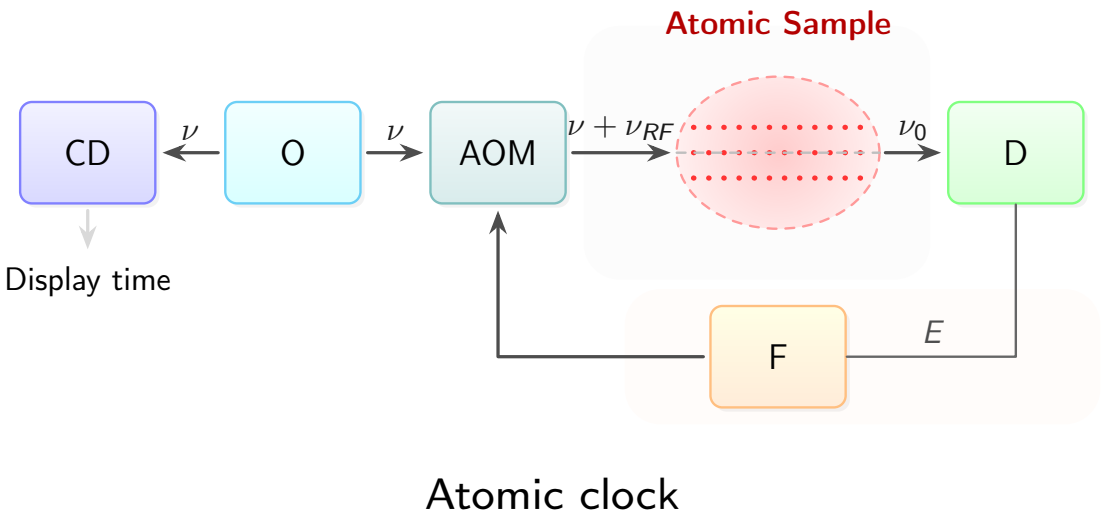
Realization: atomic clock



Atomic clock

- AOM: acousto-optic modulator
- Frequency reference: atomic transition ν_0

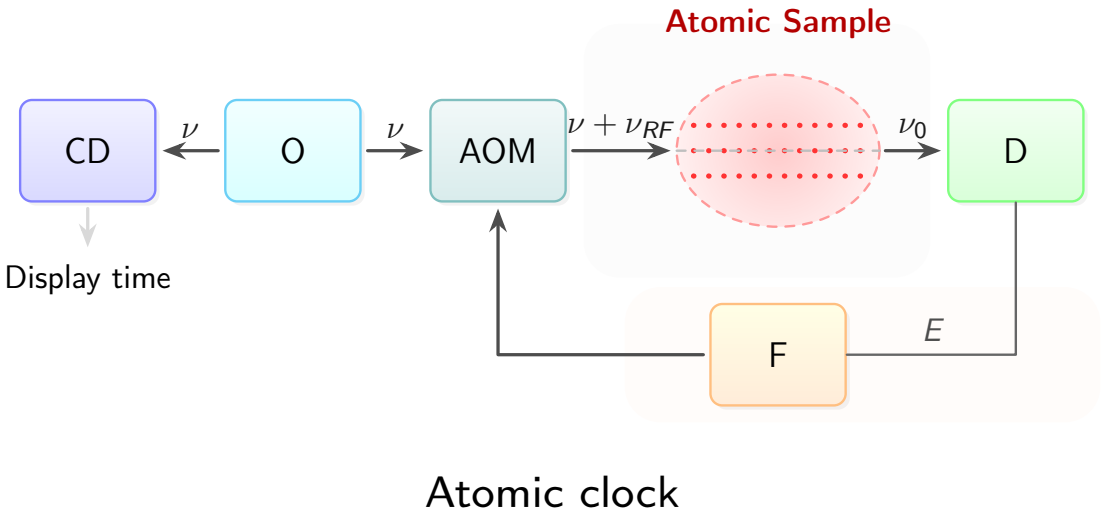
Realization: atomic clock



Atomic clock

- AOM: acousto-optic modulator
- Frequency reference: atomic transition ν_0
- Oscillator: microwave field

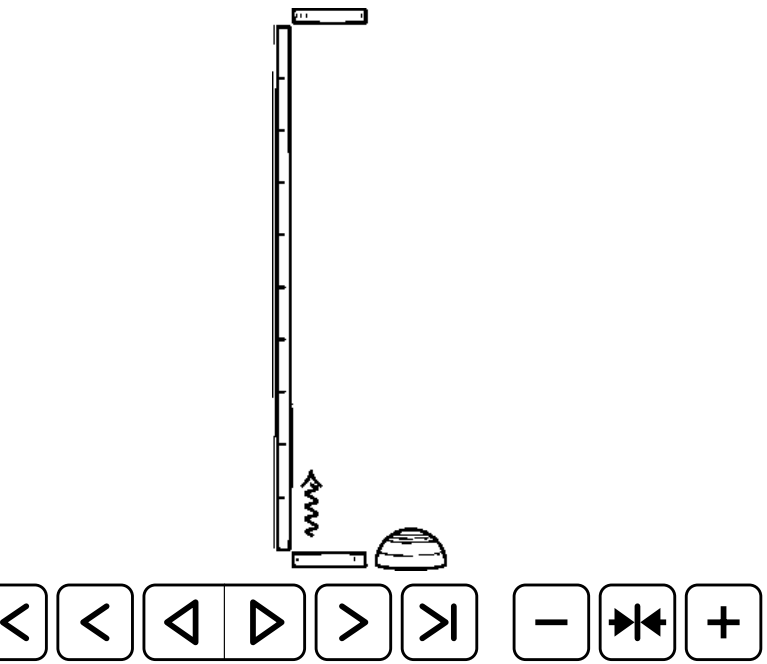
Realization: atomic clock



Atomic clock

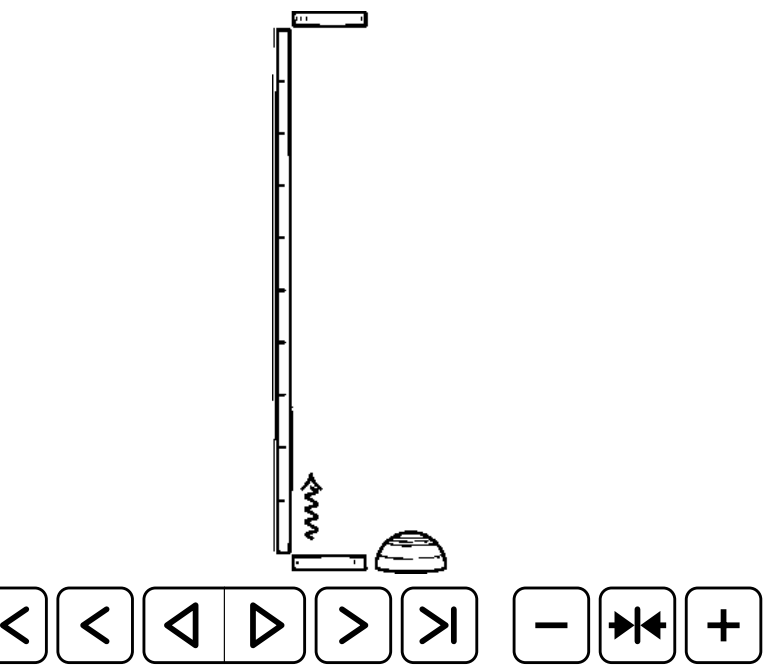
- AOM: acousto-optic modulator
- Frequency reference: atomic transition ν_0
- Oscillator: microwave field
- Performance: high accuracy, precision, and stability

Geometrodynamic clock



Einstein's light clock: simplified model

Geometrodynamic clock



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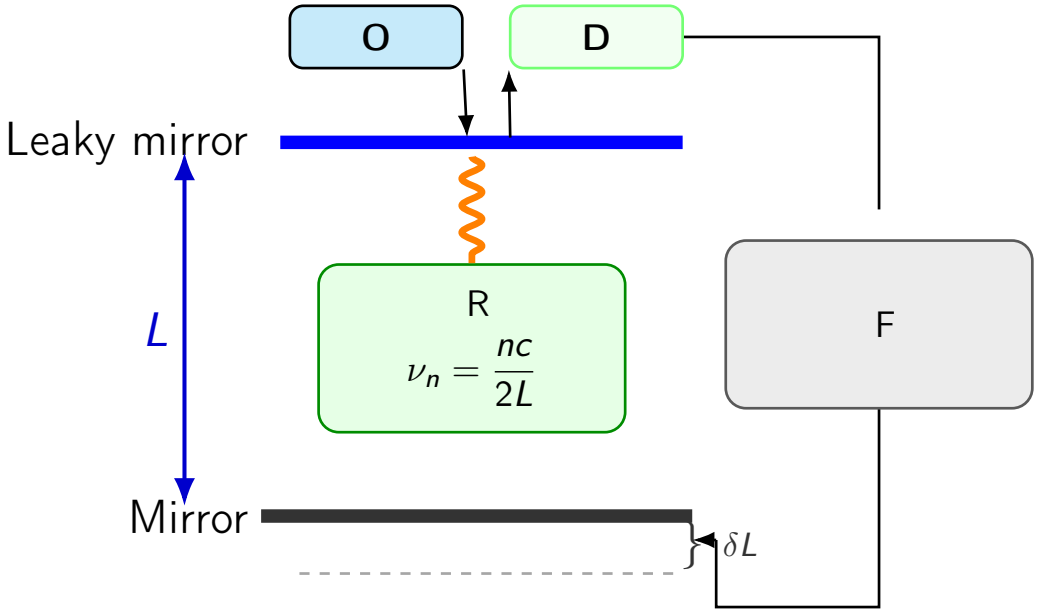

Geometrodynamic clock: our model

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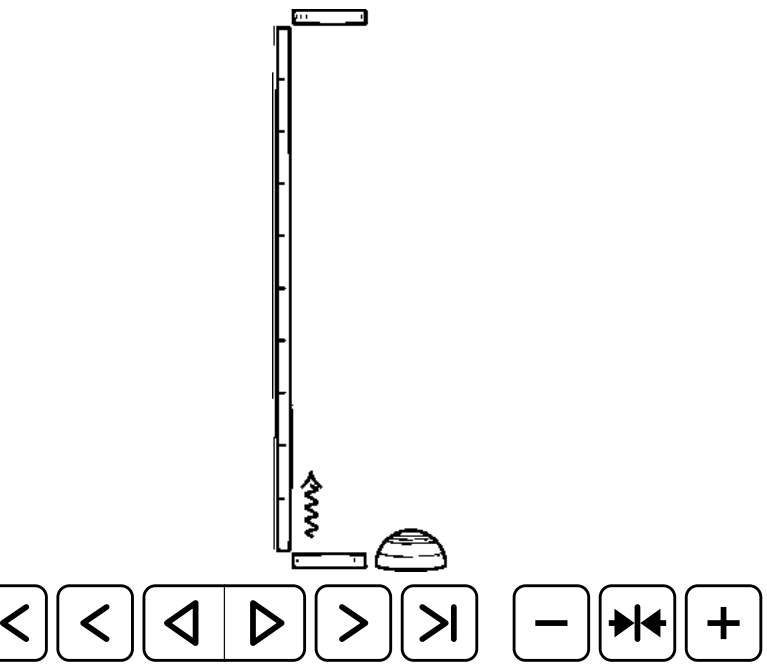

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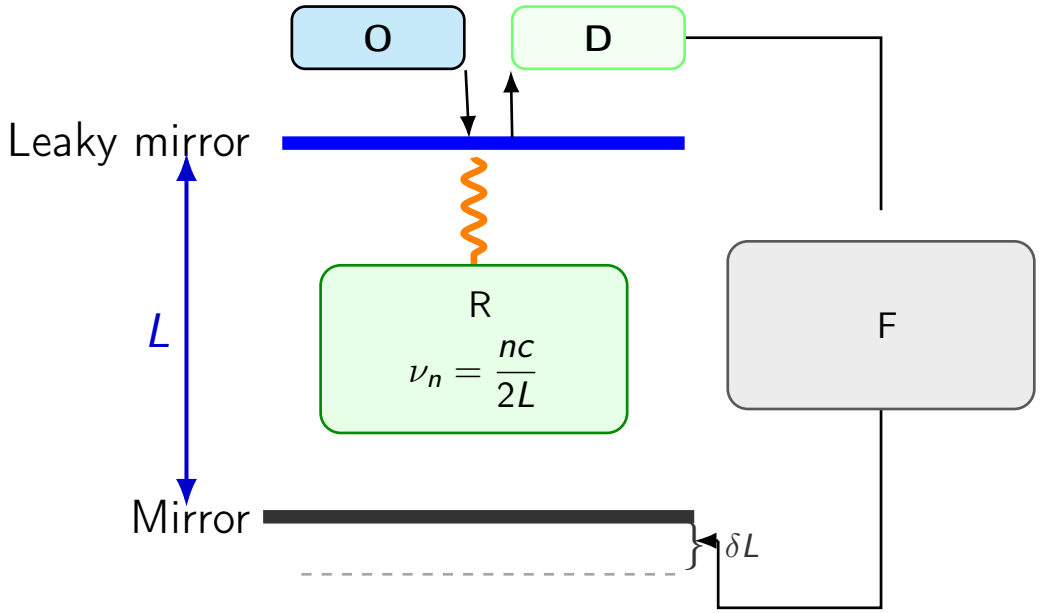

Geometrodynamic clock: our model

- Frequency reference: cavity geometry
- Oscillator: optical field
- Performance: sensitive to cavity-length and spacetime perturbations

Quantum clock

In current usage, the term "quantum clock" often refers to a frequency standard that uses nonclassical quantum resources to improve clock performance [1]

[1] ("Entanglement-enhanced optical atomic clocks". In: *Applied Physics Letters* 121.21 [2022], "Clock Precision beyond the Standard Quantum Limit at 10^{-18} Level". In: *Phys. Rev. Lett.* 135 [19 Nov. 2025], p. 193202)

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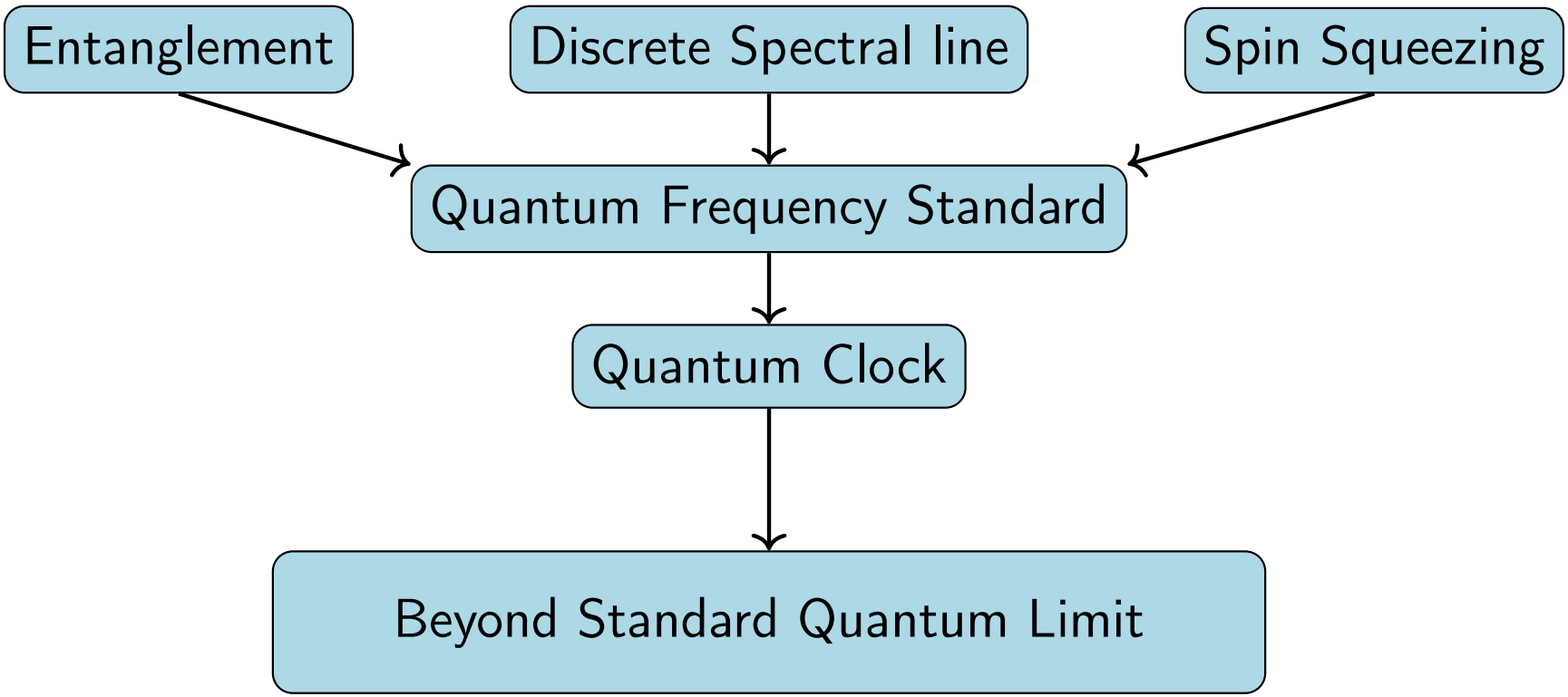

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Quantum network of clocks

A quantum network of clocks links distant clocks through **quantum-correlated frequency references**. **GHZ entanglement** [2] or **distributed spin-squeezed states** [3] across the network.

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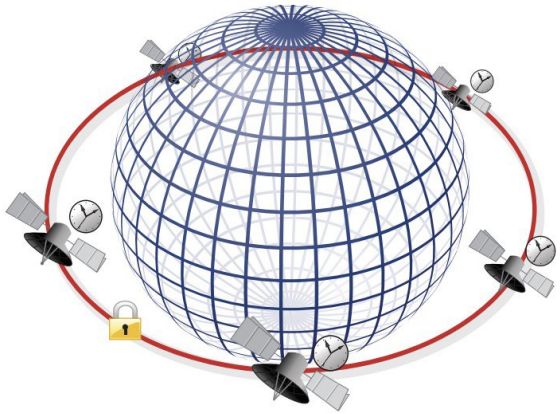
$$|\mathrm{GHZ}\rangle = \frac{1}{\sqrt{2}}\left(|g\rangle^{\otimes N} + |e\rangle^{\otimes N}\right).$$



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Questions are:

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- To have a quantum clock, which elements should be quantized?
- What are the quantum resources for timekeeping?
- Does a quantum network of clocks require entanglement and correlations between all clock components?

Outlook

- A clock is not merely a frequency reference; it is an operational architecture.

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- Different clock realizations share common elements.

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- A clock is not merely a frequency reference; it is an operational architecture.
- Different clock realizations share common elements.
- Quantizing a clock requires identifying which components and resources are genuinely quantum.

Thank You!

Questions?

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