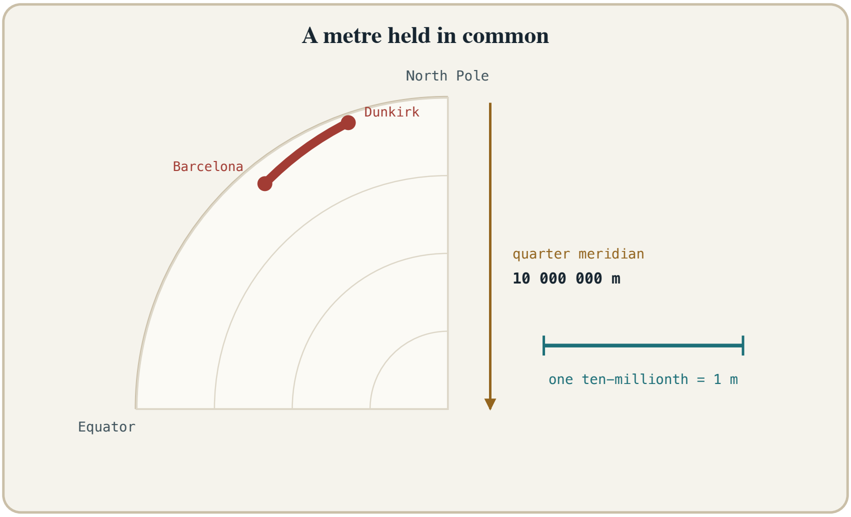
013
Measurement & Units

How long is a metre, really? The answer has changed four times — and the last change was the strangest.

BLOCK I · FOUNDATIONS OF KNOWLEDGE & REASONING

Measurement & Units

How long is a metre, *really*? The answer has changed four times — and the last change was the strangest.



The first metre aimed to be one ten-millionth of Earth's quarter meridian. Delambre and Méchain measured only a short arc and inferred the rest; the result was imperfect, but a unit succeeds by being shared.

In the winter of 1794, in a rented room in Barcelona, the French astronomer Pierre Méchain discovered that two of his latitude readings disagreed, and it broke him. The Revolution had sent him south on one of history's most romantic bureaucratic errands: measure the size of Earth so humanity could own a unit of length that belonged to nobody — *à tous les temps, à tous les peuples*, for all times, for all peoples. No king's forearm. No guild's yardstick. A metre drawn from the planet itself: one ten-millionth of the distance from the North Pole to the Equator.

Méchain had the southern half of the surveyed arc; Jean-Baptiste Delambre had the north. Readings taken from two spots in Barcelona differed by about three seconds of arc, corresponding to roughly a hundred metres on the ground. Without a developed account of random observational error, Méchain treated the discrepancy as personal failure. He concealed and adjusted data, returned to the problem for years, and died of yellow fever in 1804 while trying to measure the arc again. Delambre later found the concealed discrepancy among his papers.

The error did not mean Méchain's instruments were useless. Earth is irregular, and the surveyed arc could not make the intended quarter-meridian exactly 10,000,000 metres. Modern geodesy puts the pole-to-equator meridian distance near 10,002,290 metres, making the historical metre about 0.2 millimetres shorter than the original ideal. We kept it anyway. A unit's job is not to reveal a uniquely true length. Its job is to be **shared**.

WHERE WE ARE

Twelve days built an epistemic toolkit; today it has to touch the world. A measurement is the handshake between a number and a thing. **Day 1** returns in the form of a standard defined to be right, **Day 10** returns through the difference between a convention on the map and a property of the territory, and **Day 12** returns through a calibration network that once terminated at one cylinder in a French vault. **Day 7** taught that information is physical; a unit is the mirror image, where an abstraction must become hardware.

THE MODEL

Three ways to pin down a metre

Strip away the romance and every unit answers one problem: **how do you make two strangers agree?** Modern measurement inherited three broad strategies.

Strategy one: point at a thing. An *artefact definition* makes a particular object the standard. The meridian survey was embodied in the platinum *Mètre des Archives* in 1799; that end standard was replaced in 1889 by the International Prototype Metre, a line standard made from 90% platinum and 10% iridium with an X-shaped cross-section for rigidity, specified at 0 °C. The distance between its two fine lines did not merely measure the metre. That marked interval *was* the metre. The lineage resolves the count: after the original meridian definition came four formal successors – the 1799 archive metre, the 1889 prototype, the 1960 krypton wavelength, and the 1983 light-speed definition.

Strategy two: point at a phenomenon. Artefacts are vulnerable to fire, theft, thermal expansion, contamination, and damage. In 1960 the metre was redefined as 1,650,763.73 wavelengths of the orange-red radiation from a specified transition in krypton-86. Atoms of the same isotope are reproducible: a suitably equipped laboratory no longer had to compare its ruler with a unique bar in Paris.

Strategy three: point at a number. In 1983 the 17th General Conference on Weights and Measures fixed the speed of light in vacuum exactly:

> **c** = *299,792,458 metres per second.*

That value is no longer an experimental estimate with an uncertainty. The metre is instead derived from it: the distance light travels in vacuum during 1/299,792,458 of a second.

This is the day's hinge. A laboratory cannot improve the numerical value of *c* in metres per second; it can improve its realization of the metre and second. The constant acts as an exact conversion factor between them. This *great inversion* – fix a constant, then derive the unit – is the central idea of modern metrology, the science of measurement.

Bridgman's ghost

Percy Bridgman named the broader philosophical idea an **operational definition** in *The Logic of Modern Physics* (1927): a concept is tied to the operations used to measure it. Bridgman won the 1946 Nobel Prize for high-pressure physics, and operationalism spread through 1930s psychology. As a general theory of meaning it was too strict; measuring length with a laser rather than a ruler should not create a different concept of length. In metrology, however, a more modest version survives as the *mise en pratique*: the practical instructions for realizing an SI definition. The decree sits on one shelf; the workshop manual sits on the bench.

THE SCANDAL

Le Grand K, the stopped clock of Sèvres

While the metre moved from object to radiation to fixed constant, one base unit remained in the vault. For 130 years, until 2019, the kilogram was a physical object.

The International Prototype of the Kilogram was a platinum-iridium cylinder 39 millimetres high and 39 millimetres across, made in 1889 and stored beneath three nested bell jars in a climate-controlled vault at the Bureau International des Poids et Mesures in Sèvres, outside Paris. Three independently held keys controlled access. It was formally compared with its official copies in 1889, 1946, and during a campaign around 1989–91. Its nickname was **Le Grand K**.

Le Grand K had a mass of exactly one kilogram with zero definitional uncertainty, because the kilogram *was defined as its mass*. That is where Day 1's stopped-clock warning returns.

Comparisons with its six official copies, the *témoins* or witnesses, and national prototypes showed that the family had diverged by tens of micrograms over a century. The United States prototype K4, for example, was 75 micrograms below the IPK in 1889 and 106 micrograms below it in 1984 – a 31-microgram change in its offset. In 1999 it was 116 micrograms below the IPK, a 41-microgram change from 1889.

Which object changed? The system could not tell us. By construction Le Grand K remained one kilogram; every divergence was assigned to the other objects. A standard defined to be right could never be caught changing. That circularity made it a poor instrument for detecting drift.

The familiar drift story is only half right

Popular accounts often say that Le Grand K mysteriously lost 50 micrograms. The figure actually describes divergence across the prototype family. A 2015 BIPM comparison found that the IPK and its six official copies had behaved as a consistent set since 1991, with an average change of roughly one microgram. No experiment demonstrated that Le Grand K itself was drifting. The deeper problem was that the definition made such a test impossible. The scandal was circularity, not a proven loss of mass.

The network problem was equally severe. Pharmacy scales, semiconductor mass standards, and drug-dose calibrations traced through national standards and official copies toward one cylinder in one vault. The world's mass system had a single root that was vulnerable to contamination, scratching, theft, fire, or damage.

On **16 November 2018**, at Versailles, the 26th CGPM voted to remove that root.

THE REFORM

20 May 2019: the world stopped weighing itself against a lump

The revised SI took effect on World Metrology Day in 2019. It applied the 1983 inversion across all seven base units by fixing seven constants exactly:

- **ΔνCs = 9,192,631,770 Hz** – the caesium-133 hyperfine transition, which defines the **second**.
- **c = 299,792,458 m/s** – the speed of light in vacuum, which defines the **metre**.
- **h = 6.626 070 15 × 10^{-34} J · s** – the Planck constant, which defines the **kilogram**.
- **e = 1.602 176 634 × 10^{-19} C** – the elementary charge, which defines the **ampere**.
- **k = 1.380 649 × 10^{-23} J/ K** – the Boltzmann constant, which defines the **kelvin**.
- **NA = 6.022 140 76 × 10^{23} mol^{-1}** – the Avogadro constant, which defines the **mole**.

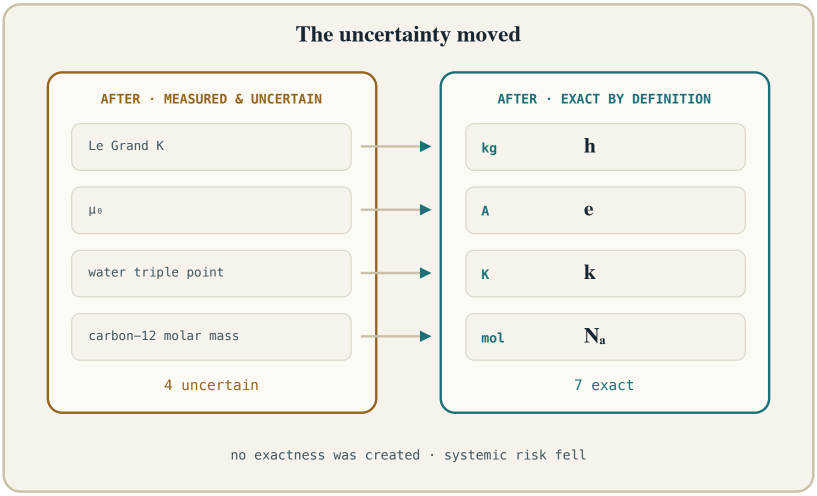
- **Kcd = 683 lm/W** for monochromatic radiation of frequency 540 × 10^{12} Hz — luminous efficacy, which helps define the **candela**.

All SI units now follow from those exact values and the physical procedures that realize them. In principle, a sufficiently equipped laboratory on Mars could realize a kilogram without comparing it with an object on Earth.

The reform did not make nature more certain. It **relocated uncertainty**. Before 2019, Le Grand K's mass was exact while the Planck constant was measured with uncertainty. After 2019, h is exact while Le Grand K's mass is measured with an uncertainty of roughly 10 micrograms and is finally free to change. Four redefined units made the same kind of trade.

Figure · The ledger of uncertainty

Before and after 20 May 2019, seven quantities were exact by definition and four carried measurement uncertainty. Four natural constants crossed into the exact column while four former anchors crossed out. Exactness was exchanged, not created. Pre-reform measured values below use the CODATA 2014 adjustment; post-reform measured values use CODATA 2022.



In 2019, h, e, k, and N_a became exact by definition, while Le Grand K, μ_0, water's triple point, and carbon-12 molar mass became measured and uncertain. The ledger remains seven exact and four uncertain.

QUANTITY	BEFORE 20 MAY 2019	AFTER 20 MAY 2019
Speed of light, c	299,792,458 m/s; exact since 1983	299,792,458 m/s; exact
Caesium frequency, ΔνCs	9,192,631,770 Hz; exact since 1967	9,192,631,770 Hz; exact
Luminous efficacy, Kcd	683 lm/W; exact since 1979	683 lm/W; exact
Planck constant, h	6.626 070 040(81) × 10^{-34} J · s; relative uncertainty 1.2 × 10^{-8}	6.626 070 15 × 10^{-34} J · s; exact
Mass of Le Grand K	1 kg; exact by definition	Approximately 1 kg ± 10 µg; relative uncertainty about 1 × 10^{-8}
Elementary charge, e	1.602 176 6208(98) × 10^{-19} C; relative uncertainty 6.1 × 10^{-9}	1.602 176 634 × 10^{-19} C; exact
Vacuum permeability, μ_0	4pi × 10^{-7} N/A^2; exact under the former ampere	1.256 637 061 27(20) × 10^{-6} N/A^2; relative uncertainty 1.6 × 10^{-10}
Boltzmann constant, k	1.380 648 52(79) × 10^{-23} J/K; relative uncertainty 5.7 × 10^{-7}	1.380 649 × 10^{-23} J/K; exact
Triple point of water	273.16 K; exact under the former kelvin	Approximately 273.1600 K ± 0.0001 K
Avogadro constant, NA	6.022 140 857(74) × 10^{23} mol^{-1}; relative uncertainty 1.2 × 10^{-8}	6.022 140 76 × 10^{23} mol^{-1}; exact
Molar mass of carbon-12	12 g/mol; exact under the former mole	12.000 000 0126(37) g/mol; relative uncertainty 3.1 × 10^{-10}

The four direct trades were kilogram: Le Grand K $\to h$; ampere: fixed $\mu_0 \to e$; kelvin: water's triple point $\to k$; and mole: 12 grams of carbon-12 $\to NA$. The 7-and-4 count is a feature of this reform, not a law of nature. Four units each exchanged one exact anchor for another.

THE MACHINE

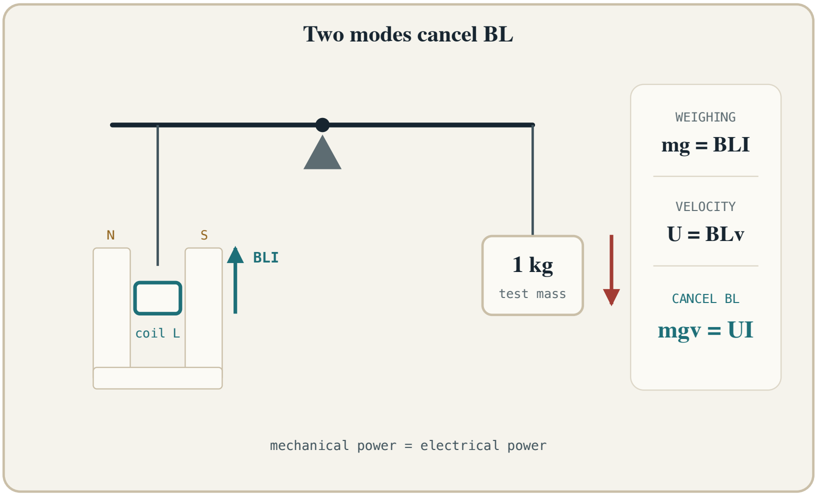
How to weigh a kilogram with Planck's constant

The Planck constant belongs to quantum mechanics. How can it weigh a bag of sugar?

Bryan Kibble answered at Britain's National Physical Laboratory in 1975. A **Kibble balance** compares a mass with an electromagnetic force, then ties the electrical measurements to quantum standards. It operates in two modes, and the same hard-to-measure geometry appears in both.

Figure · Two modes of a Kibble balance

Weighing mode balances the mass against an electromagnetic force. Velocity mode moves the same coil through the same magnetic field. Combining the equations cancels both the magnetic field strength and the effective wire length.



Weighing mode gives mg = BLI and velocity mode gives U = BLv. Combining them cancels the hard-to-measure magnetic field B and wire length L, leaving mgv = UI.

MODE	RELATION	WHAT IS OBSERVED
Weighing	m g = B L I	Current I produces an upward force BLI that balances weight mg.
Velocity	U = B L v	Moving the coil at velocity v through the field produces voltage U.
Combined	m g v = U I, so m = U I / (g v)	The difficult quantities B and L cancel.

Voltage is realized with Josephson junctions, whose quantized steps relate voltage to frequency through h and e. Resistance is realized through quantum Hall plateaux proportional to h/e^2. Current can then be obtained from voltage and resistance. In the product $U \times I$, the elementary charge cancels while h remains. Gravimetry supplies g; laser interferometry supplies v. The traceability chain ends at exact h, c, and $\Delta\nu$Cs rather than a metal cylinder.

Redundancy makes the result credible. The kilogram has a second, largely independent realization: the **silicon sphere**. A near-perfect crystal of isotopically enriched silicon-28 is ground into an extraordinarily round sphere. Measuring its volume, lattice spacing by X-ray interferometry, and isotopic composition determines the number of atoms and connects the result to the Avogadro constant and *h*. Before the redefinition, CODATA's 2017 special adjustment required the silicon-sphere and Kibble-balance experiment families to agree at the 10^{-8} level. They did.

Two routes, using substantially different experimental physics, converged on one value. That is the kind of risky agreement **Day 2** taught us to value.

The most expensive unit conversion in history

On **23 September 1999**, NASA's Mars Climate Orbiter was lost during orbital insertion. Lockheed Martin ground software reported thruster impulse in pound-force seconds while JPL navigation software expected newton seconds, a factor of about 4.45. The mismatch persisted for months. The spacecraft was intended to approach Mars safely but passed at an estimated altitude near 57 kilometres, where it was destroyed or escaped after atmospheric passage. The reported mission cost was **$327.6 million**. The investigation board emphasized a systems failure, not one person's arithmetic: checks that should have exposed the incompatible interface did not do so. Units are a treaty, and a treaty works only when interfaces enforce it.

THE DEBATE

"Is the speed of light changing?" is an incomplete question

The SI is anchored to constants, so are the constants really constant? Since Dirac's Large Numbers Hypothesis in 1937, physicists have explored whether *c*, *G*, or the electron's charge could drift over cosmic time. Varying-speed-of-light cosmologies make the question sound straightforward. It is not.

Michael Duff made the sharpest version of the objection in a three-way exchange with Lev Okun and Gabriele Veneziano, published as *Trialogue on the Number of Fundamental Constants* in 2002. Okun counted three fundamental dimensional constants, *c*, *ħ*, and *G*. Veneziano counted two. Duff counted zero.

A **dimensional constant** such as *c* carries units and therefore partly records our choice of coordinates and conversion conventions. Saying only that the numerical value of *c* changed does not yet specify a unit-invariant physical observation. Since 1983, its SI value is fixed by definition. A physical varying-constant theory must say which observable, dimensionless ratio changes and how.

Dimensionless numbers cannot be altered by changing metres into feet or seconds into years. Two central examples are:

- the **fine-structure constant, alpha approximately 1/137.035 999**, which characterizes electromagnetic coupling and helps set atomic spectra and chemistry;
- the **proton-to-electron mass ratio,** μ = **mp/me approximately 1836.15**.

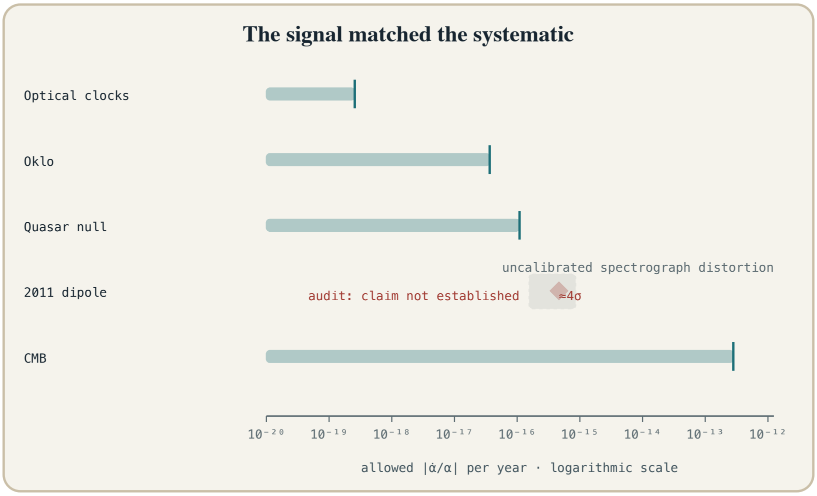
> ***If a claimed variation can be made to vanish by changing units, it is not yet a claim about the world.***

This is Day 10's map and territory in physical form. Dimensional constants encode part of the grid; dimensionless ratios express relations that every unit system must preserve. It is also Day 2's testability rule: "the speed of light varies," without a unit-invariant prediction, forbids no observation. Specify a changing ratio and the claim becomes testable.

So: has alpha moved?

Figure · Limits on drift of the fine-structure constant

Laboratory clocks, geological evidence, quasar spectra, and the cosmic microwave background probe different epochs. Each calibrated result is compatible with no variation. The 2011 quasar dipole is shown separately because a later instrument audit found distortions comparable to the claimed signal.



The roughly four-sigma quasar dipole reported in 2011 was comparable in size to long-range spectrograph distortions found later. Better-calibrated instruments return results consistent with zero drift.

PROBE	TIME BASELINE	REPORTED CONSTRAINT OR RESULT	INTERPRETATION
Yb^+ optical clocks at PTB	26 months	(1/alpha)(dalpha/dt) = 1.8 ± 2.5 × 10^{-19} per year	Compatible with zero; the tightest direct laboratory drift limit in this lesson.
Oklo natural reactors	1.8 billion years	|Δalpha/alpha| below roughly 10^{-7} under nuclear-model assumptions	Strong but model-dependent; simultaneous quark-mass variation would change the inference.
Modern calibrated quasar spectra	Lookback of roughly 10 billion years	Example: Δalpha/alpha = 0.30 ± 1.44 ppm	Compatible with zero.
2011 Keck and VLT dipole claim	Roughly 300 quasar absorption systems; lookback of roughly 10 billion years	Amplitude about 0.97 × 10^{-5}, approximately 4σ	A 2015 audit found wavelength distortions around 0.2 m/s per Å, comparable to the signal and absent from its error budget.
Planck cosmic microwave background	13.8 billion years	Δalpha/alpha = (3.6 ± 3.7) × 10^{-3} at recombination	Much looser, but compatible with zero at the earliest epoch shown.

The astronomical entries constrain Δalpha/alpha, not a constant drift rate. Dividing by lookback time to put them on one rate axis assumes linear drift, so the visual comparison is an order-of-magnitude guide rather than a model-free ranking. The Oklo inference is also conditional on assumptions about other nuclear parameters.

THE FRONTIER · JULY 2026

Where the evidence reaches

EDGE 01 · OPTICAL-CLOCK PERFORMANCE ESTABLISHED · SECOND REDEFINITION PROPOSED FOR 2030, NOT COMPLETED

The second may be redefined in 2030 — the clocks already outran it

Since 1967 the second has been the duration of 9,192,631,770 periods of the caesium-133 hyperfine transition. NIST-F2, a leading caesium fountain, reported systematic uncertainty of **1.1 × 10^{-16}** in 2014, corresponding to roughly one second in 300 million years. Optical clocks tick at much higher frequencies and now report uncertainties more than 100 times smaller.

NIST’s aluminium-ion quantum-logic clock reported **5.5 × 10^{-19} systematic uncertainty** in *Physical Review Letters* on 14 July 2025. It interrogates a single $^{27}Al^+$ ion sympathetically cooled by a co-trapped $^{25}Mg^+$ ion and uses a cryogenic silicon reference cavity linked over 3.6 kilometres of fibre. JILA's strontium lattice clock reported **8.1 × 10^{-19}** in 2024. Press descriptions called the aluminium device the "world's most accurate clock" and spoke of 19 decimal places; the peer-reviewed result is the stated uncertainty and a threefold stability improvement.

The definition has become a bottleneck. The CGPM roadmap asks the metrology community to be ready to propose a redefinition at the 29th CGPM in **2030**, contingent on reliable optical standards, ultra-stable links, reproducibility across laboratories, and agreement among clocks based on different transitions. A BIPM draft resolution dated 30 June 2026 says there is still no consensus on a single species versus an ensemble. The performance milestone is established; the choice and redefinition are not.

EDGE 02 RATIO MEASURED SENSITIVITY PROJECTED NO DETECTION

A clock transition inside a nucleus

Precision atomic clocks normally use electronic transitions. Thorium-229 has an unusually low nuclear excited state, near 8.4 eV, accessible to lasers. In 2024 a rapid sequence of results reached it: Tiedau and colleagues reported laser excitation of the isomer at PTB; Elwell and colleagues reported solid-state excitation; and Zhang, Ooi, Higgins and collaborators used a vacuum-ultraviolet frequency comb to compare the nuclear transition directly with JILA's strontium atomic clock. The 4 September 2024 *Nature* result improved precision on the nuclear frequency by roughly a million-fold.

A nucleus is about 10,000 times smaller than an atom and is shielded from many external fields by its electron cloud, allowing dense solid-state samples. The transition energy also arises from a near-cancellation of large nuclear contributions, which may amplify sensitivity to changes in alpha. Claims of exactly 10,000-fold sensitivity are too sharp: Beeks and colleagues estimated an enhancement factor **K = 5900 ± 2300** in 2025, with roughly 40% uncertainty and dependence on a semi-classical nuclear model. The transition is a genuine new measurement platform. Detection of dark matter or varying alpha remains a research goal.

EDGE 03 NULL FINE-STRUCTURE DRIFT RESULT ESTABLISHED

The tightest direct answer is consistent with zero

Two transitions in the same ytterbium ion respond differently to alpha. PTB compared the E3 octupole and E2 quadrupole transitions for 26 months:

> ***(1/alpha)(dalpha/dt) = 1.8 ± 2.5 × 10^{-19} per year***
>
> *Filzinger et al.*, Physical Review Letters *130:253001, 22 June 2023.*

The estimate is centered near zero. It improved on a 2021 comparison that reported 1.0(1.1) × 10^{-18} per year for alpha and −8(36) × 10^{-18} per year for μ. If the quoted 2.5 × 10^{-19}-per-year one-sigma sensitivity scale persisted linearly over 13.8 billion years, it would accumulate to about 3.5 parts per billion — a deliberately model-dependent extrapolation, not a cosmological bound. Oklo's 1.8-billion-year-old natural reactors constrain |Δalpha/alpha| to roughly 10^{-7} under nuclear-model assumptions. Planck's cosmic-microwave-background analysis gave Δalpha/alpha = (3.6 ± 3.7) × 10^{-3} at recombination, 13.8 billion years ago. Across these different assumptions and epochs, every result shown here is compatible with zero.

EDGE 04 ● QUASAR ALPHA DIPOLE CONTESTED BY INSTRUMENT SYSTEMATICS

A beautiful claim undermined by its instrument

Using the many-multiplet method on roughly 300 quasar absorption systems, Webb, King, Murphy, Flambaum and colleagues reported in 2011 that alpha appeared smaller in one direction of the sky and larger in the other: a spatial dipole at about 4σ. The result combined observations from Keck's HIRES spectrograph in Hawaii and the VLT's UVES spectrograph in Chile.

Whitmore and Murphy — Murphy was also an author of the original report — audited the instruments in 2015 by supercalibrating them against asteroid and solar-twin spectra. They found long-range wavelength distortions around **0.2 m/s per Å** in both instruments. Those distortions were absent from the original error budget and large enough to imitate a signal of the reported size. Better-calibrated instruments such as HARPS and ESPRESSO have returned null results in high-precision single systems, including Δalpha/alpha = 0.30 ± 1.44 ppm. The dipole is therefore not established evidence for spatial variation; instrument systematics provide a sufficient competing explanation.

EDGE 05 ● FINE-STRUCTURE MEASUREMENT DISCREPANCY UNRESOLVED

alpha is stable, yet our best measurements disagree

The irony is sharp: alpha shows no detected drift, yet its two most precise atom-recoil determinations do not agree. Berkeley's caesium measurement gave alpha^{-1} = 137.035 999 **046**(27) in 2018. The Paris rubidium result gave alpha^{-1} = 137.035 999 **206**(11) on 2 December 2020, with an uncertainty of 81 parts per trillion. The values differ by about **5.4**σ.

CODATA 2022 expanded the input uncertainties by a factor of 2.5 to accommodate the inconsistency and recommended alpha^{-1} = 137.035 999 177(21). A 2023 Harvard electron-*g*-factor determination gives 137.035 999 166(15), nearer the Paris value but not enough to settle the recoil discrepancy. The leading expectation is an unidentified systematic in at least one measurement, not new physics, but no accepted cause has been found. The value of alpha returns on **Day 46**, where it enters the Standard Model prediction for the muon's magnetic moment.

EDGE 06 ● GRAVITATIONAL-CONSTANT MEASUREMENT PROBLEM ESTABLISHED

G remains extraordinarily difficult to measure

The recommended value of alpha has relative uncertainty around 1.5 parts in 10 billion. Newton's gravitational constant **G** has relative uncertainty about **2.2 parts in 100,000** in CODATA 2018: 6.674 30(15) × 10^{-11}. The best experiments disagree by more than their stated errors. Li, Xue, Luo and collaborators measured *G* by two independent methods in one laboratory in 2018, each with uncertainty near 11.6 ppm, yet the two results still differed.

Why not fix *G* by decree, as the SI fixed *h*? A useful defining constant must support a practical realization of the unit. No apparatus can disseminate a kilogram through the attraction between laboratory masses at the 10^{-8} level. Quantum electrical effects are controllable enough for a Kibble balance; laboratory gravity is not. *G* therefore remains measured and uncertain.

EDGE 07 ● MILLIMETRE-SCALE GRAVITATIONAL REDSHIFT ESTABLISHED ● CLOCK-NETWORK DARK-MATTER SEARCHES PROMISING

A clock can detect a one-millimetre height difference

General relativity predicts that a clock deeper in a gravitational field runs more slowly. In 2022, Bothwell, Kennedy, Aeppli, Ye and collaborators resolved the gravitational redshift across **one millimetre** of a strontium cloud. They measured a frequency gradient of [−12.4 ± 0.7(stat) ± 2.5(sys)] × 10^{-19} per centimetre, consistent with the predicted −10.9 × 10^{-19}/cm.

At this sensitivity a clock becomes an altimeter. **Chronometric levelling** measures differences in Earth's gravitational potential by comparing clocks at different heights. ESA's **ACES** package launched on 21 April 2025, was installed on the International Space Station, and began activation on 28 April. Commissioning remained ongoing in 2026 rather than having completed a science campaign. Its PHARAO caesium clock was reported within specification while work continued on the space hydrogen maser. ACES is intended to test gravitational redshift and constant variation from orbit.

Networks of separated clocks also search for ultralight scalar dark matter. Such a field could modulate dimensionless constants and create correlated or differential frequency signals as Earth moves through it. No detection has been made; the established result is the increasingly sensitive measurement method and the limits it sets.

A shadow over measurement — for Day 134

Lengths, masses, and frequencies have well-tested quantitative structure. We also assign numbers to intelligence, pain, happiness, and job satisfaction. In 1940 the British Association's **Ferguson Committee** concluded that sensation intensity had not been shown to be measurable in the required sense. S. S. Stevens replied in 1946 by defining measurement as "the assignment of numerals to objects according to rules" and popularizing nominal, ordinal, interval, and ratio scales. That framework has dominated statistics teaching. Joel Michell argues that psychometrics too often assumes that an attribute has quantitative structure instead of demonstrating it. Hold the dispute for **Day 134**. Whenever a number appears, ask whether the attribute has been shown to possess magnitude or has merely been assigned a score.

OPEN QUESTIONS

What's genuinely unsettled

- **Which optical transition should define the second?** Strontium, ytterbium, aluminium, or a weighted ensemble? The infrastructure consequences are long-lived, and no choice has consensus.
- **Why do the Berkeley and Paris measurements of alpha differ by 5.4σ?** At least one unrecognized systematic is likely; none has been accepted.
- **Why is G still so hard to measure?** After two centuries, leading error bars remain mutually inconsistent. The unresolved issue may be technique, underestimated systematics, or physics absent from the models.
- **Do dimensionless constants drift below today's limits?** Many theories beyond the Standard Model permit tiny variations. Null results near 10^{-19} per year constrain couplings; they do not prove exact constancy.
- **Is any natural unit system privileged?** Planck units combine c, $\hbar$, and G. If dimensional constants partly encode conventions, do Planck units reveal deep structure or simply provide an especially useful grid?
- **What information can fixed definitions hide?** Exact SI values cannot register drift, but comparisons of dimensionless ratios remain sensitive. That is why experiments watch alpha, μ, and other invariant combinations.

Big idea

A unit is a treaty. Modern metrology fixes a constant and derives the unit from it: the metre followed this inversion in 1983, and four more base units changed anchors on 20 May 2019.

Best analogy

Le Grand K was Day 1's stopped clock cast in platinum. Because it was defined as exactly one kilogram, the system could never detect whether it had changed; the 2019 uncertainty ledger moved exactness to constants that laboratories can realize independently.

Live controversy

Every dimensionless probe shown here is compatible with no drift in alpha, and instrument distortions undermine the famous quasar dipole. Yet the two leading atom-recoil measurements of alpha disagree by 5.4σ, while G remains far less precisely known.

information (a unit as shared code; uncertainty as a budget that can be moved) · energy (h, k, Josephson junctions, and the quantum Hall effect) · computation (traceability as a rooted network, with 2019 removing the unique root) · light emergence — with Day 7's "information is physical" meeting its mirror: a unit is where abstraction becomes hardware.

TOMORROW → DAY 14

Synthesis: How We Know

Block I closes. Thirteen days supplied tools: Gettier's luck, Popper's swans, Bayes's dial, Pearl's scissors, Shannon's bit, Anderson's "more is different," Meadows's loops, Box's useful lies, Simon's scissors, Barabási's hubs, and today's uncertainty ledger. Tomorrow we turn them on ourselves and build a personal confidence-calibration framework for the remaining 166 days. The epistemology block ends with another measurement problem: how do you put a calibrated number on how sure you are?

SOURCES

Sources & further reading

1. BIPM. *The International System of Units (SI Brochure), 9th edition* (2019, updated 2024). bipm.org/en/publications/si-brochure Seven defining constants and their exact values; adopted by the 26th CGPM on 16 November 2018 and effective 20 May 2019.
2. Alder, K. (2002). *The Measure of All Things: The Seven-Year Odyssey and Hidden Error That Transformed the World.* Free Press. Delambre and Méchain, 1792–1799; the Barcelona latitude discrepancy and its concealment.
3. Newell, D. B. et al. (2018). “The CODATA 2017 values of h, e, k, and NA for the revision of the SI.” *Metrologia* 55(1): L13–L16. Special adjustment fixing h = 6.626 070 15 × 10^{-34} J · s; doi:10.1088/1681-7575/aa950a.
4. Mohr, P. J., Newell, D. B., Taylor, B. N. & Tiesinga, E. (2024). “CODATA Recommended Values of the Fundamental Physical Constants: 2022.” arXiv:2409.03787. alpha^{-1} = 137.035 999 177(21), with a 2.5 expansion factor for the recoil-measurement inconsistency; CODATA 2018 G = 6.674 30(15) × 10^{-11}.
5. Marshall, M. et al. (2025). “High-Stability Single-Ion Clock with 5.5 × 10^{-19} Systematic Uncertainty.” *Physical Review Letters* 135:033201. Published 14 July 2025; NIST $^{27}Al^{+}$ quantum-logic clock.
6. Aeppli, A., Kim, K., Warfield, W., Safronova, M. S. & Ye, J. (2024). “Clock with 8 × 10^{-19} Systematic Uncertainty.” *Physical Review Letters* 133:023401. JILA strontium optical-lattice clock; reported 8.1 × 10^{-19}.
7. Bothwell, T., Kennedy, C. J., Aeppli, A. et al. (2022). “Resolving the gravitational redshift across a millimetre-scale atomic sample.” *Nature* 602:420–424. Published 17 February 2022; doi:10.1038/s41586-021-04349-7.
8. Zhang, C., Ooi, T., Higgins, J. S. et al. (2024). “Frequency ratio of the ^{229m}Th nuclear isomeric transition and the ^{87}Sr atomic clock.” *Nature* 633:63–70. Published 4 September 2024; first nuclear-to-atomic frequency comparison.
9. Tiedau, J. et al. (2024). “Laser Excitation of the Th-229 Nucleus.” *Physical Review Letters* 132:182501. PTB laser excitation; see also Elwell et al., *Physical Review Letters* 133:013201 (2024), on solid-state excitation.
10. Beeks, K. et al. (2025). “Fine-structure constant sensitivity of the Th-229 nuclear clock transition.” *Nature Communications* 16:9147. Enhancement factor K = 5900(2300), with substantial uncertainty and model dependence.
11. Filzinger, M. et al. (2023). “Improved limits on the coupling of ultralight bosonic dark matter to photons from optical atomic clock comparisons.” *Physical Review Letters* 130:253001. Published 22 June 2023; (1/alpha)(dalpha/dt) = 1.8(2.5) × 10^{-19} yr^{-1} from $^{171}Yb^{+}$ E3/E2 comparisons over 26 months.
12. Lange, R. et al. (2021). “Improved Limits for Violations of Local Position Invariance from Atomic Clock Comparisons.” *Physical Review Letters* 126:011102. Published 8 January 2021; alpha and μ drift constraints.
13. Duff, M. J., Okun, L. B. & Veneziano, G. (2002). “Trialogue on the number of fundamental constants.” *JHEP* 03:023. Published 8 April 2002; dimensional constants as unit conventions and the observable role of dimensionless ratios.
14. Damour, T. & Dyson, F. (1996). “The Oklo bound on the time variation of the fine-structure constant revisited.” *Nuclear Physics B* 480:37–54. |Δalpha/alpha| of order 10^{-7} over 1.8 billion years under model assumptions; see Flambaum and Wiringa (2009) for quark-mass sensitivity.
15. Webb, J. K., King, J. A., Murphy, M. T. et al. (2011). “Indications of a spatial variation of the fine structure constant.” *Physical Review Letters* 107:191101. Approximately 4σ Australian-dipole claim, amplitude near 0.97 × 10^{-5}.
16. Whitmore, J. B. & Murphy, M. T. (2015). “Impact of instrumental systematic errors on fine-structure constant measurements with quasar spectra.” *MNRAS* 447:446–462. Long-range wavelength distortions around 0.2 m/s per Å in HIRES and UVES, comparable to the claimed dipole.

17. Parker, R. H., Yu, C., Zhong, W., Estey, B. & Müller, H. (2018). “Measurement of the fine-structure constant as a test of the Standard Model.” *Science* 360:191–195. Berkeley caesium recoil, $alpha^{-1}$ = 137.035 999 046(27).

18. Morel, L., Yao, Z., Cladé, P. & Guellati-Khélifa, S. (2020). “Determination of the fine-structure constant with an accuracy of 81 parts per trillion.” *Nature* 588:61–65. Published 2 December 2020; Paris rubidium recoil, $alpha^{-1}$ = 137.035 999 206(11).

19. Li, Q., Xue, C., Luo, J. et al. (2018). “Measurements of the gravitational constant using two independent methods.” *Nature* 560:582–588. Two HUST methods at roughly 11.6 ppm, with mutually different results.

20. Dimarcq, N. et al. (2024). “Roadmap towards the redefinition of the second.” *Metrologia* 61:012001. CCTF/CGPM plan aiming for a possible proposal at the 29th CGPM in 2030; endorsed by CGPM Resolution 5 in November 2022.

21. Heavner, T. P. et al. (2014). “First accuracy evaluation of NIST-F2.” *Metrologia* 51:174. Caesium fountain systematic uncertainty of 1.1×10^{-16}.

22. Boulder Atomic Clock Optical Network Collaboration (2021). “Frequency ratio measurements at 18-digit accuracy using an optical clock network.” *Nature* 591:564–569.

23. Planck Collaboration (2015). “Planck intermediate results. XXIV. Constraints on variation of fundamental constants.” *Astronomy & Astrophysics* 580:A22. Δalpha/alpha = $(3.6 \pm 3.7) \times 10^{-3}$ at recombination; arXiv:1406.7482.

24. Bridgman, P. W. (1927). *The Logic of Modern Physics.* Macmillan. Operational definitions; see the Stanford Encyclopedia of Philosophy, “Operationalism”.

25. Stevens, S. S. (1946). “On the theory of scales of measurement.” *Science* 103:677–680. Nominal, ordinal, interval, and ratio scales; written after the Ferguson Committee report. For the dissent, see Michell, J., *Measurement in Psychology* (Cambridge University Press, 1999).

26. NASA/JPL (1999). *Mars Climate Orbiter Mishap Investigation Board – Phase I Report.* Published 10 November 1999; pound-force seconds versus newton seconds and the loss of the mission.

27. BIPM. “The Metre Convention.” bipm.org/en/metre-convention Signed on 20 May 1875 by 17 states; 150th anniversary in 2025. See also CGPM Resolution 3 (November 2022), adopting the prefixes ronna, quetta, ronto, and quecto.

28. BIPM (30 June 2026). *Draft Resolutions – 28th meeting of the CGPM*, version 4. CGPM/2026-Draft Resolutions Draft Resolution B records that no consensus has been reached on a single species versus an ensemble for a new definition of the second, and asks for a proposal at the 29th CGPM in 2030.

29. ESA (25 April 2025). “ACES finds its home in orbit.” esa.int Launch on 21 April 2025, installation on the International Space Station on 25 April, and the commissioning plan.

30. CNES (Winter 2026). “PHARAO putting clocks right.” *CNESMAG* 99. English edition (PDF) PHARAO was delivering its expected in-space performance while the space hydrogen maser remained non-operational and a workaround was under study.

31. NIST (1985, 2001). Measurements of United States prototype kilogram K4. 1985 comparison; 1999 recalibration report. K4 was 75 µg below the IPK in 1889, 106 µg below in 1984, and 116 µg below in 1999.

OPTIONAL APPENDIX · DAY 013 · 1/2

The Fossils in the Machine

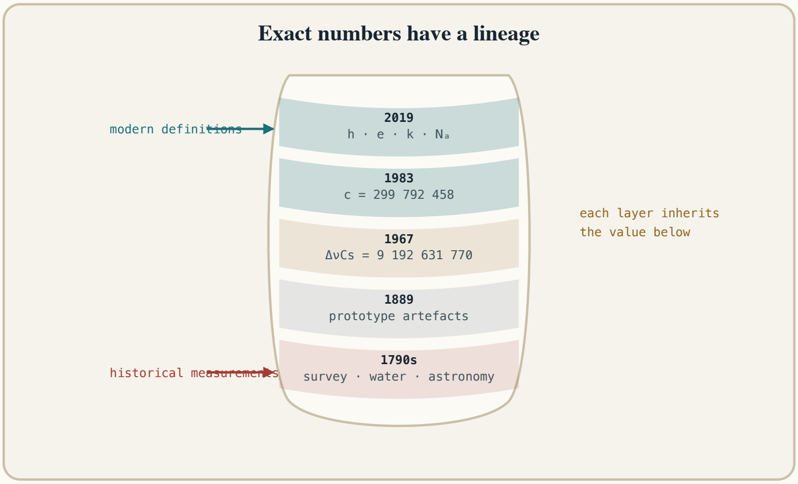
BEYOND THE MAIN TEXT · OPTIONAL READING

Here is a question that ought to nag at you after the main descent. The 2019 SI is built on seven defining constants, assigned exact numerical values by international agreement. Fine. But look at the numbers: c = 299 792 458 m/s; h = 6.626 070 15 × 10^{-34} J · s; and $\Delta\nu_{Cs}$ = 9 192 631 770 Hz. If the CGPM had the power to write the numbers, why not round c to 300 000 000 and shave the metre by about 0.07%? Almost nobody outside a laboratory would notice.

The answer is not a technicality. **Every one of those numbers was reverse-engineered to preserve continuity with the thing it replaced.** Continuity outranks elegance and convenience because a unit that quietly changes size has broken its one promise. The digits were inherited, not chosen. Follow them down, layer by layer, and the most modern definitions in science turn out to be carrying fossils.

Figure · A core sample through the SI

The seven defining constants sit above standards inherited from 1983, 1967, 1889, and 1799. At bedrock lie a French meridian survey, Revolutionary water, and observations of the Moon.



The exact digits of the modern SI were not chosen from scratch. Each layer preserves continuity of unit size and therefore inherits traces of earlier definitions, artefacts, and measurements.

CONTINUED FROM THE MAIN DESCENT

We left off with **Duff's razor**—if a claimed variation vanishes when you change units, it was never a claim about the world—and with a ledger showing that the 2019 reform *moved* uncertainty rather than abolishing it. Now we open the machine and inspect six things: the fossils buried in the exact numbers; the unit laboratories worked around; the reason a dirty semiconductor can supply a reproducible standard to ten digits; the models and judgments inside an uncertainty budget; the human eye hiding among cosmic invariants; and the collision between the definition of the second, the shape of Earth, and the melting of Greenland.

PART I THE LINEAGE

Follow the digits down

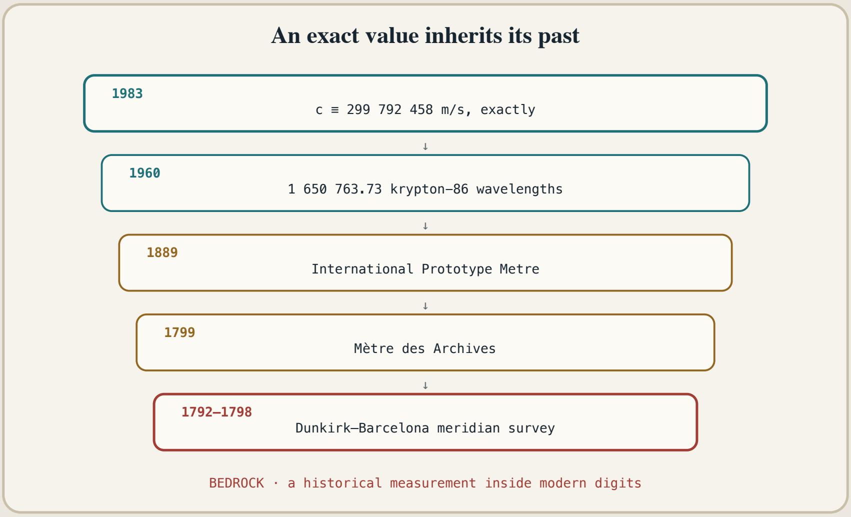
Take *c* first. In 1983 the CGPM fixed the speed of light at 299 792 458 m/s. That was the best measured value at the time—measured, of course, *in metres*. The metre of 1983 was the krypton metre of 1960, built to match the platinum-iridium bar of 1889, made as faithfully as possible from the *Mètre des Archives* of 1799, cut from the survey that Delambre and Méchain dragged across France between 1792 and 1798—the survey with a concealed discrepancy in it.

The numerical value 299 792 458 is therefore not a unit-free fingerprint of light. It preserves the best measured value of *c* in the inherited metre and second, whose lineages reach through the krypton bar and astronomical time to a French survey and observations of the Moon. The physics is light; the digits also record Méchain and the clocks that followed him.

The kilogram's ancestry is wetter. The second's is stranger: its last digits encode the motion of the Moon, photographed between 1954 and 1958. Pick a unit and drill.

Figure · The lineage of an exact number

Each layer inherits its value from the layer beneath it. The decisive move is where a measured number with an uncertainty becomes an exact definition.



The number fixed for c came from the best measurement in the previous metre, which inherited earlier standards in turn. A modern exact value therefore preserves a historical measurement lineage.

UNIT AND LAYER	DEFINITION OR REALIZATION	WHAT THE VALUE INHERITS
Metre · 2019–today	The metre through the seven defining constants	Unchanged in substance since 1983.
Metre · 1983	c = 299 792 458 m/s exactly; one metre is the distance light travels in 1/299 792 458 s	The best measured value was frozen so the light-defined metre matched the krypton metre.
Metre · 1960	1 650 763.73 wavelengths of krypton-86's orange-red $2p_{10}$–$5d_5$ line	The irregular count was chosen to match the 1889 bar.
Metre · 1889	International Prototype Metre, 90% Pt / 10% Ir, X-shaped cross-section, read between two scratches at 0 °C	Made to copy the Mètre des Archives.
Metre · 1799	The platinum end-bar Mètre des Archives, deposited in Paris	Cut from the Delambre–Méchain survey.
Metre · 1792–1798	Dunkirk–Barcelona meridian survey	Méchain's concealed three-arcsecond discrepancy and an overestimated flattening of Earth left the metre about 0.2 mm short of its intended definition; the quadrant is about 10 002 290 m.
Kilogram · 2019	$h = 6.626\ 070\ 15 \times 10^{-34}$ J · s exactly; realized with a Kibble balance or silicon sphere	CODATA's 2017 special adjustment kept the new kilogram continuous with Le Grand K.
Kilogram · 1889	Le Grand K, a 90% Pt / 10% Ir cylinder, 39 mm × 39 mm, kept under three keys at Sèvres	Made to match the Kilogramme des Archives.
Kilogram · 1799	The platinum Kilogramme des Archives, accepted by the Commission des Poids et Mesures	Intended to equal one cubic decimetre of water at maximum density.
Kilogram · 1793–1799	Lefèvre-Gineau and Fabbroni weigh pure water near 4 °C, because the freezing point was difficult to reproduce	The bucket of water made Le Grand K about 28 ppm heavier than a true litre of water.
Second · 2019–today	The second through $\Delta\nu$Cs	Unchanged in substance since 1967.
Second · 1967	$\Delta\nu$Cs = 9 192 631 770 Hz exactly for the caesium-133 ground-state hyperfine transition	The 1958 measured frequency was adopted and its ±20 Hz uncertainty on the Ephemeris Time scale was discarded.
Second · 1958	9 192 631 770 ± 20 cycles per ephemeris second, Physical Review Letters 1:105	Caesium comparisons against Ephemeris Time over 1954.0–1958.5, read from Moon-camera photographs.
Second · 1960	1/31 556 925.9747 of the tropical year 1900	The year was computed from Newcomb's solar tables rather than observed.

UNIT AND LAYER	DEFINITION OR REALIZATION	WHAT THE VALUE INHERITS
Second · bedrock	Lunar-occultation photography of the Moon in 1954–1958 and Newcomb's nineteenth-century solar ephemeris	Beneath them, the second had been 1/86 400 of an irregular rotating day.

The sixty-three years when a litre was not a litre

The kilogram was *supposed* to be the mass of one cubic decimetre of water. It was not quite. When the physicists of 1889 cast Le Grand K to match the *Kilogramme des Archives*, they inherited a small error: the cylinder came out roughly **28 parts per million heavier** than a true litre of water. In 1901 the 3rd CGPM then defined the litre as the volume of one kilogram of water at maximum density, hanging a unit of volume from a standard of mass. From 1901 to 1964, **one litre was officially 1.000 028 cubic decimetres**. The 12th CGPM abrogated that definition in 1964 and returned the litre to the metre. The artefact had contaminated everything it touched.

The second's lineage contains the appendix's most important move. In 1958, Markowitz, Hall, Essen, and Parry reported the caesium frequency against Ephemeris Time as **9 192 631 770 ± 20 cycles per ephemeris second**. It was a frequency measurement with an uncertainty.

In 1967, the 13th CGPM took the measured number, discarded the ±20, and declared the remainder exact. That was the 2019 reform fifty-two years early. The uncertainty did not evaporate; it was absorbed into the definition, just as the uncertainty in h was absorbed in 2019 and the uncertainty in c in 1983. Every time we make a constant exact, we repeat the same rite: freeze the final measured value and move its uncertainty elsewhere.

> *A defining constant freezes a measured numerical value so the unit remains continuous. The physics—and every dimensionless comparison—remains open to test.*

PART II THE UNIT LABORATORIES WORKED AROUND

The ampere's twenty-nine-year secret

Here is the pre-2019 definition of the ampere:

> *The ampere is that constant current which, if maintained in two straight parallel conductors of* **infinite length**, *of negligible circular cross-section, and placed 1 metre apart in vacuum,*

> ***would produce between these conductors a force equal to 2 × 10⁻⁷ newton per metre of length.***

Infinite length. Negligible cross-section. Vacuum. No apparatus could instantiate those idealizations literally. Finite current balances could approximate them with calculated corrections, but the definition was extraordinarily difficult to realize accurately. It remained in international measurement law for **seventy-one years**, from 1948 until 2019.

Electrical metrologists therefore seceded. On **1 January 1990**, following a CIPM recommendation, they adopted *conventional values*[1]—deliberately and explicitly *not the SI*—for the two quantum constants they actually used:

- $K_{J-90} = 483\,597.9$ GHz/V, the Josephson constant;
- $R_{K-90} = 25\,812.807\ \Omega$, the von Klitzing constant.

Both were assigned zero uncertainty, creating a parallel system of the conventional volt V_{90}, conventional ohm Ω_{90}, and conventional ampere A_{90}. For twenty-nine years, every precision voltmeter was calibrated in a currency close to SI legal tender but not technically legal tender. Precision electrical measurements had lost formal traceability to the fundamental physical constants.

The 2019 reform ended the secession. The **26th CGPM** abrogated the conventional values, defined the ampere through *e*, and legalized what electrical laboratories had been doing all along.

The reform was designed so that units would not visibly change. That promise held everywhere except the domain that had gone outside the old system. On 20 May 2019, **voltage-related quantities became 1.067 × 10^{-7} larger** and **resistance-related quantities 1.779 × 10^{-8} larger**. The step was invisible in ordinary life and seismic to anyone calibrating voltage references. The reform's one visible disruption fell precisely where the old definition had been least usable.

PART III WHY ANY OF THIS WORKS

The metrologist's best friend is an integer

In the Kibble-balance route, the kilogram is realized through electrical standards based on the **Josephson effect** and the **quantum Hall effect**. The independent silicon-sphere route uses different experimental physics. Why can a superconducting junction or a semiconductor sample—imperfect objects made from different materials in different laboratories—nevertheless reproduce $h/2e$ and h/e^2 to ten significant figures?

Their outputs are counted, not measured.

[1] Conventional electrical values were exact agreed values used outside the SI so laboratories could realize volts and ohms reproducibly with quantum effects.

Brian Josephson predicted the first effect in **1962**, as a 22-year-old graduate student, and received the 1973 Nobel Prize. Shine microwaves of frequency f at a superconducting junction and its voltage locks onto steps,

$$U = nf\frac{h}{2e},$$

where n is an integer. Within a valid Josephson operating step, its nominal voltage depends on the microwave frequency and two defining constants rather than on material or geometry. A real realization still carries uncertainty from frequency, wiring, step identification, and whether the junction remains in the required operating regime.

Klaus von Klitzing found the same pattern in **1980** and received the 1985 Nobel Prize. Put a two-dimensional electron gas in a strong magnetic field and the Hall resistance climbs a staircase,

$$R = \frac{R_K}{i} = \frac{h}{ie^2},$$

with i an integer. Silicon, gallium arsenide, and graphene give the same plateaux and the same heights to parts in 10^{10}.

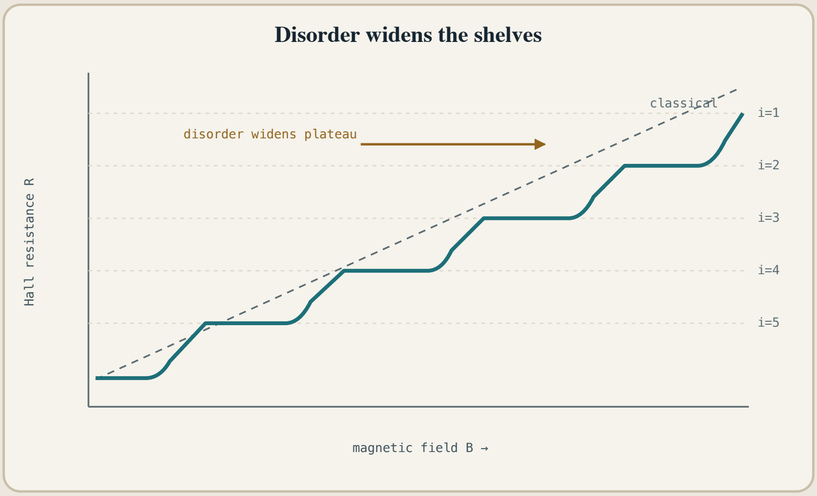
The quantization is *topological*[2]. Within the appropriate low-temperature, high-field, non-dissipative regime, the integer invariant cannot drift by 0.1%; it can only change by leaving that regime or moving to another plateau. Real standards therefore verify plateau selection, contact resistance, current limits, and the absence of breakdown.

The useful twist is that a cleaner sample does not give better plateaux. **Without disorder, there would be no broad plateaux at all.** Disorder localizes electronic states between Landau levels and gives each plateau a finite width—a flat shelf on which a measurement can sit. A perfectly pure crystal would supply exact quantization only at isolated field values: correct and useless. The imperfection is load-bearing.

[2]Topological protection ties the Hall plateau to an integer invariant that cannot change continuously under small deformations or imperfections.

Figure · The quantum Hall staircase

Schematic model: disorder widens the field range over which Hall resistance remains pinned to an integer plateau without moving its ideal height. The slider illustrates the qualitative mechanism, not a literal material-response calculation.



Sample disorder broadens exact quantization into flat plateaux a measurement can occupy without moving their heights. The imperfection is a working condition of the quantum Hall resistance standard.

DISORDER REGIME	SHAPE OF THE CURVE	METROLOGICAL CONSEQUENCE
Almost none · schematic	The illustrative response approaches a classical ramp; quantized values occupy vanishingly narrow ranges.	No stable shelf on which to park a measurement.
Modest · schematic	Plateaux appear in the model, but remain narrow and fragile against field drift.	Quantized in principle, practically difficult to use.
Substantial · schematic	Plateaux become wide and flat while their ideal heights remain RK/i.	Within its validated operating regime, i = 2 realizes the exact defining relation RK/2 = 12 906.403 729 652···Ω with a finite realization uncertainty.

The result supplies the hidden spine of the 2019 reform: **build standards whose ideal outputs are discrete and protected.** An artefact can shed a fingerprint's worth of platinum; a lamp can run slightly warm. A quantum standard can still be misidentified, miscounted, or driven outside its operating regime, but those failure modes can be tested rather than silently redefining the unit.

The SI has run relentlessly toward counting. The 1960 metre counted wavelengths. The 2019 mole counts entities. The silicon-sphere kilogram counts atoms. The Josephson volt identifies steps; the quantum Hall ohm identifies plateaux; the second counts oscillations. Every escape from the artefact has leaned harder on discrete structure plus checks that the apparatus is realizing the intended state.

This is Day 7 returning from an unexpected direction. Shannon taught that information is discrete and physical. Metrology adds the corollary: *discreteness can make a standard robust*, because a validated integer step is less vulnerable to small material drift than an artefact's continuously changing surface.

PART IV THE CALIBRATED ARITHMETIC OF ERROR

Precise, true, or accurate? They are three different things

The familiar archery-target picture is often taught backwards. The distinction matters:

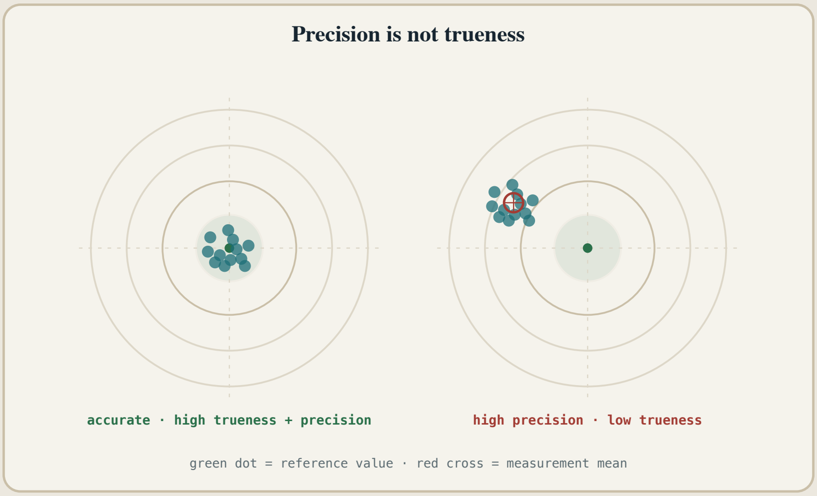
- **Precision** is the tightness of the grouping: how much repeated answers scatter.
- **Trueness** asks whether the centre of the grouping sits on the bullseye: it concerns bias.
- **Accuracy** requires both.

The asymmetry is uncomfortable: **precision is visible from inside your laboratory; trueness is not.** Repeat a measurement a thousand times and you learn how well the apparatus agrees with itself. Those repetitions alone say nothing about whether it agrees with the world. The most dangerous quadrant is therefore not a messy cloud but a tight cluster confidently displaced from the bullseye. It looks publishable.

The main descent's alpha dipole illustrates the danger without supplying a clean textbook verdict. Its published error budget omitted long-range wavelength distortions comparable to the claimed signal. The 2015 audit did not prove that every possible dipole is false; it removed the basis for treating this one as established. More observations with the same uncorrected instruments could have narrowed an interval around an artefact, while an external calibration audit exposed the missing systematic.

Figure · Precision, trueness, and accuracy

Bias moves the mean away from a reference quantity value; scatter spreads repeated measurements around their mean. The four combinations require different remedies.



Precision describes repeatability; trueness describes proximity of the mean to a reference value. A tight biased cluster is dangerous because more repetitions only make the biased answer look more certain.

BIAS	SCATTER	DIAGNOSIS	WHAT HELPS
Low	Low	Accurate: high trueness and high precision.	Maintain calibration and independent checks.
Low	High	High trueness on average, but low precision.	More independent measurements reduce scatter as $1/\sqrt{N}$.
High	Low	Precise but wrong—the dangerous quadrant.	More repeats make the wrong answer look more certain; only calibration or an external audit can expose the bias.
High	High	Low trueness and low precision; the visible mess can be safer than a tight biased cluster because it does not masquerade as certainty.	Reduce both the systematic bias and the random scatter.

The judgment inside every uncertainty budget

The *GUM*[3]—the *Guide to the Expression of Uncertainty in Measurement*—governs how calibration certificates are written. It did not abolish **error**. It distinguishes the unknowable error of a particular result from the uncertainty used to characterize the values reasonably attributable to the measurand.

"Error" is the difference between a measured value and a reference quantity value, but the actual error normally remains unknown. *Uncertainty*[4] instead characterizes the dispersion of values that could reasonably be attributed to the measurand. A report may give a standard uncertainty or an expanded interval with stated coverage assumptions. Neither is direct access to truth, and not every reported uncertainty is a frequentist confidence interval.

It then divides evaluation into two kinds:

- **Type A** uncertainty is evaluated statistically from repeated observations. It describes countable variation and precision.
- **Type B** uncertainty is evaluated by other information: a calibration certificate, manufacturer's data sheet, handbook value, physical model, prior experience, and ultimately the considered judgment of an expert.

Type B is a route of **evaluation**, not a declaration that every input is a subjective Bayesian prior. Its probability distributions can come from calibration data, physical models, published specifications, or expert judgment, depending on the case. Once expressed as standard uncertainties, Type A and Type B contributions are propagated through the same uncertainty budget. The important epistemic point is narrower and more durable: even a reported **5.4-sigma** discrepancy can fail when the uncertainty model omits an instrumental bias, and a reported "±" can depend on judgments about models, calibrations, and possible systematics as well as on repeatability statistics. That is why the Berkeley–Paris alpha tension remains unresolved and why an unidentified systematic can hide inside a beautiful error bar for years.

And before precision, definition

Before either Type A or Type B evaluation, the GUM recognizes *definitional uncertainty*[a] as a component caused by finite detail in the measurand's definition. What is "the temperature of this room"—at the ceiling or floor, averaged in what way, over which interval? No thermometer can rescue a vague question because the vagueness belongs to the measurand. Sharpen the

[3] The Guide to the Expression of Uncertainty in Measurement sets the international framework used to report and combine measurement uncertainty.

[4] Measurement uncertainty characterizes the dispersion of values that could reasonably be attributed to the quantity being measured; it is not a known distance from truth.

measurand and much of the uncertainty budget may disappear; leave it vague and precision cannot save it. Hold that for Day 134, when someone tries to measure "intelligence."

[a] Definitional uncertainty is the component left because the quantity being measured cannot be specified with unlimited detail.

PART V THE OTHER FOUR

Listening to a gas, counting a dozen, and the human eye hiding in the SI

The kelvin: determine Boltzmann's constant by listening

The leading route to *k* was *acoustic gas thermometry*[5]. Fill a precisely machined resonant cavity with argon, ring it, and measure the speed of sound *u*. Because an ideal gas obeys $u^2 = \gamma kT/m$, the pitch of the gas reveals Boltzmann's constant. Independent checks came from dielectric-constant gas thermometry, which reached about 1.9 × 10^{-6}, and Johnson-noise thermometry, which extracts *k* from the thermal hiss across a resistor. Three unrelated physical routes converged on one number.

The new kelvin's real payoff appears at the extremes. The old definition anchored thermodynamic temperature to the triple point of water, 273.16 K; primary thermometry and practical scales then disseminated temperature through multiple methods and fixed points, with the traceability chain becoming less direct far from the anchor. The new kelvin permits primary realization at the temperature of interest. **The reform changed nothing in a kitchen and opened better routes at the extremes.**

The official practical temperature scale

Most laboratories do not use thermodynamic temperature directly. They use **ITS-90**, the International Temperature Scale of 1990, a practical scale built from fixed points and interpolation formulae. ITS-90 is known to differ from thermodynamic temperature; the differences $T - T_{90}$ are measured, tabulated, and published. The working scale is a documented approximation to thermodynamic temperature. It is Day 10's "all models are wrong, some are useful" with the discrepancy domesticated into a lookup table.

[5] Acoustic gas thermometry infers thermodynamic temperature or the Boltzmann constant from resonant sound frequencies in a gas whose properties and cavity geometry are known.

The mole: a dozen, writ large—and chemists objected

Since 2019, a mole is exactly **6.022 140 76 × 10^{23} entities**. It is a count, decoupled from the kilogram. Some chemists raised a sharp objection: if the mole is only a number, is "amount of substance" really a base quantity, or a dimensionless count wearing a costume? A dozen is not a base unit. Why is a mole? The dispute reaches beyond pedantry to whether the seven-base-unit SI reflects nature or the history of its committees.

The candela: an alien could never derive it

The candela fixes $K_{\text{cd}} = 683$ lm/W for monochromatic radiation at **540 × 10^{12} Hz**, green light near 555 nm. The frequency is the peak of **V(λ)**, the photopic luminosity function: the standard human eye-response curve adopted by the CIE in **1924** from a modest set of observers. Photometry weights every other wavelength by V(λ).

Among the speed of light, quantum of action, and elementary charge, the seventh defining slot therefore canonizes **the average sensitivity of a human retina**. Even 683 was reverse-engineered for continuity with candle-based standards. An alien civilization given our seven defining numbers could reproduce all seven SI units, but it could derive none of their historical scale choices from physics alone. The candela is distinctive because its definition adds a human visual-response function, not because the other six numerical scales are inevitable.

So why seven? The careful answer might be zero

History supplied the count. Maxwell proposed length, mass, and time; Giorgi argued in 1901 that electromagnetism needed a fourth unit; the mole and candela accreted for chemistry and lighting. The base/ derived split is a bookkeeping convention rather than a discovery.

Planck units push in the other direction by setting *c*, ħ, *G*, and often *k* to one: a length near 1.62 × 10^{-35} m, time near 5.39 × 10^{-44} s, and temperature near 1.42 × 10^{32} K. Yet the **Planck mass is about 22 micrograms**, roughly a flea's egg —strangely human-scale beside an unimaginably small length and enormous temperature. That juxtaposition is not itself the hierarchy problem; the physics problem concerns the enormous gap between the electroweak and Planck scales, which Day 45 will revisit. Duff's question remains: are Planck units nature's units or simply a cleaner arbitrary grid?

PART VI TIME'S MESSY EDGES

The second collides with the shape of Earth

Earth is a poor clock. Lunar tides slow rotation by roughly 1.7 milliseconds per century. Core and mantle exchange angular momentum; the crust still rebounds from ice ages that ended about ten thousand years ago; the atmosphere moves with El Niño; earthquakes alter the moment of inertia. The wobble is irregular.

Timekeepers therefore maintain three times. **TAI** counts caesium ticks without consulting the sky. **UT1** measures Earth's actual rotation angle, which determines astronomical noon. **UTC** runs on atomic seconds but inserts a *leap second*[6] whenever needed to stay within 0.9 seconds of UT1. Twenty-seven leap seconds have been inserted since 1972; the latest was on 31 December 2016.

Leap seconds cannot be scheduled far ahead—notice arrives only about six months in advance because Earth does not rotate predictably—and they have disrupted computer systems. In November 2022 the CGPM resolved to increase the permitted difference between UT1 and UTC by or before 2035, with the intended consequence that leap seconds cease for an extended period. "Abolish leap seconds" is useful shorthand, not the resolution's literal wording.

Then Earth sped up. The years 2020 – 2024 included exceptionally short days, raising an unprecedented possibility: a **negative leap second**, a minute containing 59 seconds. Most leap-second software assumes the adjustment will be positive; the opposite direction has never been deployed.

EDGE A1 ● ESTABLISHED ● EXTRAPOLATION

Global warming is postponing the first negative leap second

Duncan Agnew published the analysis in *Nature* **628**: 333 – 336 on **27 March 2024**. Two changes in Earth's spin are opposing one another.

First, since 1972 the liquid core has steadily slowed. Conservation of angular momentum makes the rest of the planet speed up; a day is now about **0.0025 seconds shorter** than fifty years ago.

Second, melting in Greenland and Antarctica redistributes mass from the poles toward the equator, a change measured by satellite gravimetry. Earth becomes slightly more oblate and slows, like a spinning skater extending her arms.

The ice is opposing the core. Agnew's extrapolation indicates that without polar ice loss UTC would have needed its first negative leap second around **2026**. With the ice-melt effect, the date moves to roughly **2029**.

[6] A leap second is an occasional one-second adjustment to UTC that keeps civil atomic time close to Earth's irregular rotation time, UT1.

The evidence labels matter. Polar ice loss has measurably slowed Earth's rotation: that measurement is established and rests on satellite gravimetry. **Agnew's paper** extrapolated a date near 2029 from the trends then available; it is not a settled current forecast. Nor is the effect a climate "silver lining": warming is only delaying a software problem.

The epistemic payoff is striking. Clocks have become precise enough to detect another planetary process. **The melting ice sheets are audible in the timing of a caesium atom.** Day 9's coupled systems, Day 177's climate, and Day 13's metrology meet in a second that may or may not exist in 2029.

EDGE A2 ● ESTABLISHED

Sea level is where the clocks agree

At the 10^{-18} level, a clock's rate depends on where it is. Raise a clock by one centimetre and general relativity shifts its tick rate by about 1.1×10^{-18}, now a measurable amount. Comparing two frontier clocks therefore requires their heights above the geoid to roughly a centimetre—and the global geoid is not known that well.

The definition of the second has run into geodesy. Arne Bjerhammar proposed in 1985 that the relativistic geoid be defined as *the surface closest to mean sea level on which clocks run at the same rate*. Sea level is where the clocks agree.

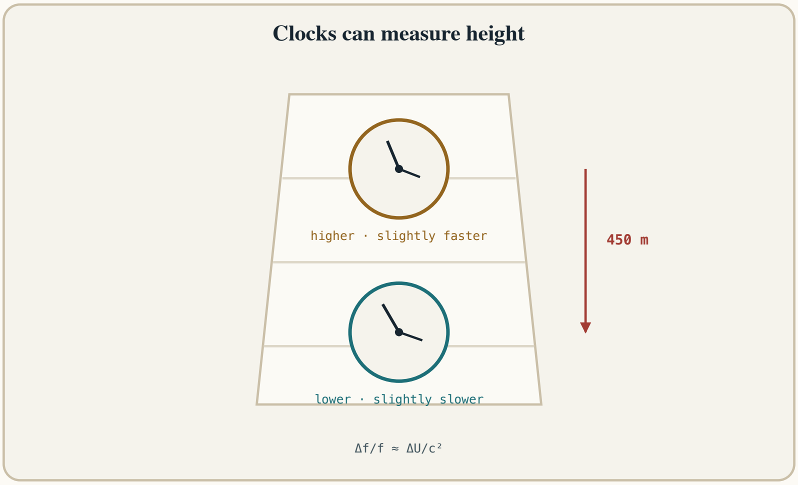
Run the idea backwards and *chronometric levelling*[7] uses a clock as an altimeter. Hidetoshi Katori's group carried two transportable strontium lattice clocks into the **Tokyo Skytree**, placed one at the base and one **450 m** higher on the observation deck, and connected them with 700 m of fibre. The upper clock ran faster by about **21.18 Hz** out of roughly 429 trillion, testing gravitational redshift to $(1.4 \pm 9.1) \times 10^{-5}$ (Takamoto et al., *Nature Photonics* **14**: 411–415, 6 April 2020).

Clock networks could monitor volcanic inflation, crustal deformation, and thinning ice by their gravitational effect on time. We set out to measure time and built an altimeter for the planet.

[7] Chronometric levelling compares clock rates to infer differences in gravitational potential and therefore height.

Figure · A clock as an altimeter

Two strontium clocks separated vertically by 450 metres in Tokyo Skytree measured the relativistic difference in their tick rates.



General relativity makes the higher clock tick slightly faster. Modern optical-clock comparisons can convert a frequency difference into gravitational potential and therefore measure centimetre-scale, and potentially smaller, height changes.

PART VII SPENDING ENTANGLEMENT

The floor beneath the floor—and why squeezing is not free

Quantum mechanics now changes from the thing being measured into the thing being spent.

Interrogate N independent atoms and each readout collapses to "excited" or "not excited." Independent quantum outcomes make frequency uncertainty fall only as $1/\sqrt{N}$. This *quantum projection noise*[8] establishes the *standard quantum limit*[9]. It is a limit on uncorrelated particles, not on lasers, vacuum systems, or budgets.

The escape is to correlate the atoms. A *spin-squeezed state*[10] makes one collective

[8] Quantum projection noise is the statistical fluctuation produced when independent quantum two-level systems are measured.

[9] The standard quantum limit gives the $1/\sqrt{N}$ precision scaling for N independent, uncorrelated probes.

[10] Spin squeezing entangles an ensemble so quantum uncertainty is reduced in the measurement direction at the cost of greater uncertainty in a conjugate direction.

component quieter by making another noisier. In principle, the limiting scaling improves from $1/\sqrt{N}$ toward $1/N$, the Heisenberg limit. Entanglement becomes a resource.

It works. Eckner and colleagues used Rydberg interactions to squeeze a programmable strontium clock array, obtaining about four decibels of metrological gain, stability **$1.087(1) \times 10^{-15}$ at 1 s**, and performance **1.94(1) dB below the SQL** (*Nature* **621**: 734 – 739, 30 August 2023). In 2025, two spin-squeezed ensembles of about **30 000 strontium atoms** in a two-dimensional lattice, read through cavity-QED quantum non-demolition measurements, reached fractional frequency precision of **1.1×10^{-18}** with a **2.0(2) dB** gain over the SQL (*Physical Review Letters* **135**: 193202, 7 November 2025), the most precise entanglement-enhanced clock reported in the source material.

EDGE A3 ● ESTABLISHED ● OVERSOLD

The caveat the headlines leave out

Squeezing helps only when quantum projection noise is the limiting noise. In a large optical lattice clock, it usually is not. Interrogation-laser noise, aliased by dead time between measurement cycles through the Dick effect, can dominate once the ensemble contains more than a modest number of atoms.

Schulte, Lisdat, Schmidt, Sterr, and Hammerer quantified the restriction (*Nature Communications* **11**: 5955, 2020). For conventional cyclic Ramsey interrogation of one ensemble with then-leading clock lasers, squeezing improves a strontium lattice clock only below a **critical atom number of about one thousand**. Even a tenfold laser improvement leaves the critical number below roughly 100 000. Small multi-ion traps and tweezer arrays can benefit in regimes different from large lattice ensembles; a single ion, by itself, offers no ensemble to squeeze.

The demonstrations and gains are real. Their payoff is conditional on a noise regime that many flagship clocks do not occupy. “Entanglement will make clocks arbitrarily good” is true only in a limit and misleading in a working laboratory.

OPEN QUESTIONS

Still unsettled

- Is “amount of substance” a genuine base quantity, or is the mole a dozen with a Nobel Prize?
- Should the candela remain a base unit when its weighting rests on a 1924 average retina?
- Can the global geoid ever be known to a centimetre? If not, maps rather than clocks may limit the redefined second.

- Should the new second rest on one optical transition—simple but brittle—or a weighted ensemble—robust, inelegant, and more future-proof? A BIPM draft resolution dated 30 June 2026 records that no consensus has been reached and asks the community to submit a redefinition proposal to the 29th CGPM in 2030.
- Does fixing a constant stop us from discovering variation? No: only dimensionless ratios carry unit-independent claims, and those remain measurable. The important task is understanding why.
- If exact numerical values are fossils of our history, an alien civilization would use different digits for the same physics. Which parts of science describe the world, and which record that *we* were the measurers?

CLOSING

The ghost in the machine

The 2019 SI is a cathedral of invariants. Nothing in it can rust, be stolen, gather fingerprints, or be dropped by a nervous technician. It is among the most durable things bureaucracy has built.

Yet at the bottom of its core sample lie:

- a **mis-surveyed meridian** through Revolutionary France, including a discrepancy that Méchain concealed and that consumed him;
- a **cubic decimetre of water**, weighed in 1799 and off by 28 parts per million;
- four years of **photographs of the Moon**, taken between 1954 and 1958 and checked against a table of the Sun computed before the electron was known.

We did not escape history. We encoded it. The constants are exact now, but they are exactly *our* numbers: values chosen to preserve continuity with prior standards and measurements within the transition uncertainties. That is not a defect. It is the system.

A unit is therefore a treaty across space and time. The refusal to round *c* promises everyone who measured before us that the meaning of their numbers will not silently change. Méchain hid a discrepancy and it broke him. Two centuries later, metrology understood it and, rather than changing the size of the metre, preserved the continuity of everything built above it.

Big idea

The SI's exact numbers are fossils reverse-engineered to preserve continuity with what they replaced. A unit is a treaty not only across space but across time, and modern metrology repeatedly converts a measured value into an exact definition while moving its uncertainty elsewhere.

Best analogy

Drill through the definitions and find a French meridian, Revolutionary water, and Moon photographs at bedrock. The quantum Hall staircase adds a second image: disorder makes an exact integer standard usable without changing its value.

Live controversy

Entanglement beats the standard quantum limit, but laser noise can erase the practical gain; the negative-leap-second date is extrapolated even though polar ice loss measurably slows Earth; and geodesy may limit the next definition of the second.

information (discreteness as the root of trust) · computation (traceability chains and leap-second software) · energy (Josephson junctions, quantum Hall standards, and acoustic thermometry) · emergence (topological protection surviving disorder). A callback to **Day 4** remains useful but bounded: some Type B evaluations include expert judgment about models and systematics, while the category itself is not synonymous with a Bayesian prior.

BACK TO THE MAIN LINE · DAY 14

Synthesis: What the Fossils Preserve

Carry two ideas onward. First, precision can be measured from inside a system while trueness requires an external reference. Second, an uncertainty budget can combine repeated-observation statistics with calibration data, models, specifications, and considered expert judgment. The calibrated response is to identify those inputs and state their scope.

Sources & further reading

1. Markowitz, W., Hall, R. G., Essen, L. & Parry, J. V. L. (1958). “Frequency of Cesium in Terms of Ephemeris Time.” *Physical Review Letters* **1**(3): 105–107. doi:10.1103/PhysRevLett.1.105—the origin of 9 192 631 770, measured with an uncertainty of ±20 cycles per ephemeris second from Moon-camera observations over 1954.0–1958.5. The 13th CGPM adopted the value in 1967 and discarded the uncertainty.

2. 11th CGPM (1960), Resolution 9: the second as 1/31 556 925.9747 of the tropical year for 1900 January 0 at 12 h Ephemeris Time. The year was computed from Newcomb's tables of the Sun rather than observed. See Dimarcq et al., *Metrologia* 61:012001 (2024), §2, for the official history.

3. 3rd CGPM (1901), Declaration 1—the litre as the volume of 1 kg of water at maximum density; abrogated by the 12th CGPM (1964), Resolution 6. BIPM resolution. During those 63 years, 1 litre = 1.000 028 dm^3.

4. "The Millilitre." *Nature* **124**: 622 (1929). nature.com/articles/124622a0. Lavoisier and Haüy's provisional standard; Lefèvre-Gineau and Fabbroni's 1799 determination of the mass of a cubic decimetre of water—the ancestor of Le Grand K and therefore of *h*.

5. Stock, M., Davis, R., de Mirandés, E. & Milton, M. J. T. (2019). "The revision of the SI—the result of three decades of progress in metrology." *Metrologia* **56**: 022001. doi:10.1088/1681-7575/ab0013—the electrical step change on 20 May 2019: voltage-related quantities 1.067×10^{-7} larger and resistance-related quantities 1.779×10^{-8} larger.

6. BIPM, *SI Brochure, 9th ed., Appendix 2: Practical realization of the ampere* (20 May 2019). BIPM PDF. KJ = 483 597.848 416 984 GHz/V and RK = 25 812.807 459 3045 Ω exactly; RK exceeds RK-90 by 17.793×10^{-9}.

7. Taylor, B. N. & Witt, T. J. (1989); CIPM recommendation adopting **KJ-90** = **483 597.9 GHz/V** and **RK-90** = **25 812.807** Ω, effective 1 January 1990. See Kaneko, N. (2017), "Review of quantum electrical standards…," *IEEJ Transactions on Electrical and Electronic Engineering* **12**: 1–13, on the loss of formal SI traceability.

8. Josephson, B. D. (1962). "Possible new effects in superconductive tunnelling." *Physics Letters* **1**: 251–253. Nobel Prize in Physics, 1973.

9. von Klitzing, K., Dorda, G. & Pepper, M. (1980). "New Method for High-Accuracy Determination of the Fine-Structure Constant Based on Quantized Hall Resistance." *Physical Review Letters* **45**: 494. Nobel Prize in Physics, 1985. For the topological origin, see Thouless, Kohmoto, Nightingale & den Nijs, *Physical Review Letters* **49**: 405 (1982).

10. JCGM 100:2008, *Evaluation of measurement data—Guide to the expression of uncertainty in measurement (GUM)*. BIPM JCGM publications. The distinction between error and uncertainty, Type A and Type B evaluation, and definitional uncertainty.

11. Agnew, D. C. (2024). "A global timekeeping problem postponed by global warming." *Nature* **628**: 333–336. Published 27 March 2024; doi:10.1038/s41586-024-07170-0—polar ice loss slowed Earth's rotation; the paper's extrapolation moved a possible first negative leap second from about 2026 to about 2029. That date is not presented here as a settled current forecast.

12. 27th CGPM (November 2022), Resolution 4, *On the use and future development of UTC*—the permitted maximum value of |UT1 − UTC| is to increase by or before 2035 so that leap-second adjustments cease for an extended period. The same meeting's Resolution 3 adopted the prefixes ronna, quetta, ronto, and quecto.

13. Takamoto, M., Ushijima, I., Ohmae, N., Yahagi, T., Kokado, K., Shinkai, H. & Katori, H. (2020). "Test of general relativity by a pair of transportable optical lattice clocks." *Nature Photonics* **14**: 411–415. 6 April 2020; doi:10.1038/s41566-020-0619-8—Tokyo Skytree, 450 m height difference, redshift tested to $(1.4 \pm 9.1) \times 10^{-5}$.

14. Mehlstäubler, T. E., Grosche, G., Lisdat, C., Schmidt, P. O. & Denker, H. (2018). "Atomic clocks for geodesy." *Reports on Progress in Physics* **81**: 064401. Chronometric levelling and the correspondence between 10^{-18} clock performance and 1 cm height. See Denker et al., *Journal of Geodesy* **92**: 487–516 (2018); Bjerhammar (1985) on the relativistic geoid; and Vermeer (1983) on "chronometric levelling."

15. Eckner, W. J., Darkwah Oppong, N., Cao, A., Young, A. W., Milner, W. R., Robinson, J. M., Ye, J. & Kaufman, A. M. (2023). "Realizing spin squeezing with Rydberg interactions in an optical clock." *Nature* **621**: 734–739. 30 August 2023—about 4 dB metrological gain, stability 1.087(1) × 10^{-15} at 1 s, and performance 1.94(1) dB below the standard quantum limit.

16. "Clock Precision beyond the Standard Quantum Limit at the 10^{-18} Level." *Physical Review Letters* **135**: 193202 (7 November 2025). arXiv:2505.04538—two spin-squeezed ensembles of about 30 000 ^{87}Sr atoms; 1.1 × 10^{-18} fractional precision and 2.0(2) dB gain over the SQL after SPAM correction.

17. Schulte, M., Lisdat, C., Schmidt, P. O., Sterr, U. & Hammerer, K. (2020). "Prospects and challenges for squeezing-enhanced optical atomic clocks." *Nature Communications* **11**: 5955. With then-leading clock lasers, squeezing helps a Sr lattice clock only below a critical atom number near 1000, and below about 10^5 even with a tenfold better laser.

18. Itano, W. M. et al. (1993). "Quantum projection noise: Population fluctuations in two-level systems." *Physical Review A* **47**: 3554. See Wineland et al. (1992), *Physical Review A* **46**: R6797, and Kitagawa & Ueda (1993), *Physical Review A* **47**: 5138, the founding spin-squeezing papers.

19. Dimarcq, N. et al. (2024). "Roadmap towards the redefinition of the second." *Metrologia* **61**: 012001. The mandatory criteria and published fulfilment levels; the ^{87}Sr 698 nm transition became a secondary representation in October 2006. See NIST's public summary of the single-transition-versus-ensemble choice and the BIPM's 30 June 2026 draft resolutions, which record no consensus and request a proposal for 2030.

20. 16th CGPM (1979), Resolution 3: the candela, defined through 540 × 10^{12} Hz and 1/683 W/sr. The frequency is the peak of the CIE 1924 photopic luminosity function V(λ); 683 preserved continuity with candle standards.

21. Fischer, J. et al. (2018). "The Boltzmann project." *Metrologia* **55**: R1–R20. Acoustic gas thermometry, dielectric-constant gas thermometry, and Johnson-noise thermometry as independent routes to *k*. For the practical scale, see BIPM's *Supplementary Information for the ITS-90* and published T − T90 differences.

OPTIONAL APPENDIX · DAY 013 · 2/2

The Bleeding Edge

BEYOND THE MAIN TEXT · OPTIONAL READING

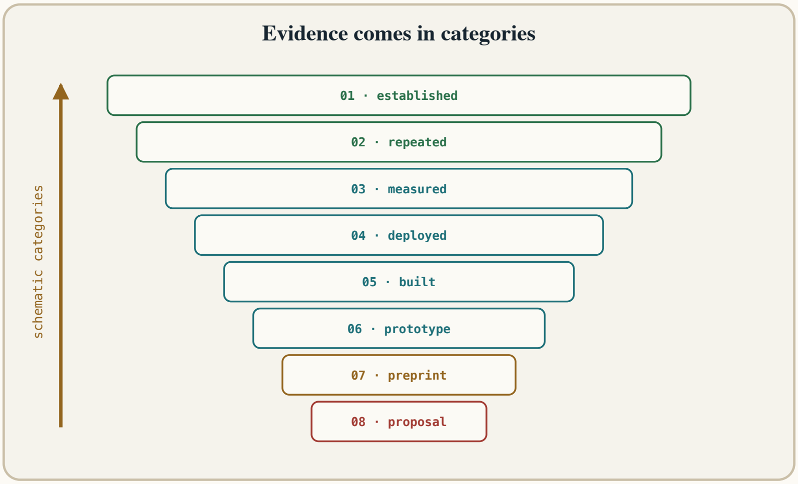
On **22 October 2025**, *Nature* published a paper by Joseph Aziz and Richard Howl with a title that, if correct, would overturn the logic of a flagship proposed quantum-gravity experiment: “Classical theories of gravity produce entanglement.” The experiment would place two masses in superposition, let them interact only through gravity, and ask whether they emerge entangled. A local classical channel should not create entanglement, so a positive result had been treated as evidence that gravity itself must be quantum.

Aziz and Howl argued that the inference changes in full quantum field theory: a classical gravitational field can entangle the masses too. Within three weeks, Marletto, Oppenheim, Vedral, Wilson, Diósi, and Di Biagio circulated the first technical replies. Xue and collaborators and Gundhi and collaborators followed in April 2026. Several argued that discarded transition amplitudes cancel the effect when restored. The dispute remains active and contested; key rebuttals are preprints rather than settled peer-reviewed conclusions.

This is the frontier from the inside. Most items below are peer-reviewed post-2020 results. One central item—the thorium-229 feedback-loop clock and its dark-matter constraints—is a **3 June 2026 preprint**, and it is labeled as such throughout. Publication establishes that a claim is ready for scrutiny, not that its conclusion is final.

Figure · The frontier is bottom-heavy

Established measurements, field deployments, laboratory demonstrations, preprints, proposals, and active disputes represent different kinds of evidence. The frontier is bottom-heavy, but these categories answer different questions rather than forming a universal total order.



Frontier work cannot be ranked by headline excitement alone. Feasibility proposals, laboratory demonstrations, peer-reviewed measurements, and field deployments answer different questions and cannot be reduced to one universal axis.

HOW TO READ THIS APPENDIX

The main descent supplied settled metrology; Appendix I exposed the inherited history inside it. This appendix is deliberately provisional. It separates what an experiment or calculation has demonstrated from the stronger conclusion projected from it. Keep Day 2's question in hand: *what result would show this claim false?* A claim that cannot answer is not ready, however prestigious the venue.

PART I THE CLOCK SPECIES EXPLOSION

Everyone is building a different clock now

For two decades, optical clocks were largely a two-horse race: neutral atoms in a lattice, especially strontium or ytterbium, versus one trapped ion, especially aluminium or ytterbium. Since 2020 the field has diversified because the aim is no longer only timekeeping. Different clocks respond to different possible new physics, so a varying constant or dark-matter field may reveal itself when a menagerie of clocks disagrees.

Clocks made of stripped atoms

Remove thirteen of argon's eighteen electrons and $\mathbf{Ar^{13+}}$ remains: a highly charged ion whose electrons sit deep in the nuclear field. It is comparatively insensitive to stray fields that trouble other clocks, while some transitions in *highly charged ions* are exceptionally sensitive to alpha.

The obstacle was cooling and reading an ion with no accessible cooling transition. In 2022, Steven King, Lukas Spieß, Piet Schmidt, and colleagues at PTB co-trapped Ar^{13+} with a beryllium ion, sympathetically cooled it, and read it through quantum logic. The first HCI optical clock achieved systematic uncertainty of $\mathbf{2.2 \times 10^{-17}}$ on its first demonstration (King et al., *Nature* **611**: 43 – 47, 2 November 2022). Comparing $^{36}Ar^{13+}$ and $^{40}Ar^{13+}$ also resolved the QED contribution to nuclear recoil in a many-electron system for the first time.

ESTABLISHED DEMONSTRATION PROJECTED The clock demonstration is established. Its present uncertainty is roughly two dozen times worse than the best Al^{+} clock result, and no HCI clock has yet set a competitive new-physics bound. The attraction is a higher possible ceiling and stronger sensitivity, not a result already delivered.

Clocks made of molecules

Atomic clocks are highly sensitive to alpha. The proton-to-electron mass ratio $\mu = m_p/m_e \approx 1836$ is less visible because an atom responds only weakly to nuclear mass. Molecules vibrate, and their vibrational frequencies depend directly on nuclear masses.

The simplest molecule, $\mathbf{HD^{+}}$, contains one proton, one deuteron, and one electron. Two groups advanced its precision spectroscopy in 2020: Alighanbari, Giri, Constantin, Korobov, and Schiller (*Nature* **581**: 152 – 158), and Patra, Germann, Karr, Koelemeij, and colleagues (*Science* **369**: 1238). They determined μ at the **part-per-trillion** level while testing three-body QED. Kortunov and colleagues reached a resolving power of about 3×10^{11}, corresponding to a fractional transition-frequency uncertainty near 3.3×10^{-12} (*Nature Physics* **17**: 569, 2021).

Molecular hydrogen ions are therefore becoming an independent source of fundamental constants rather than only a test object. When two leading measurements of alpha already disagree at 5.4σ, independent routes matter.

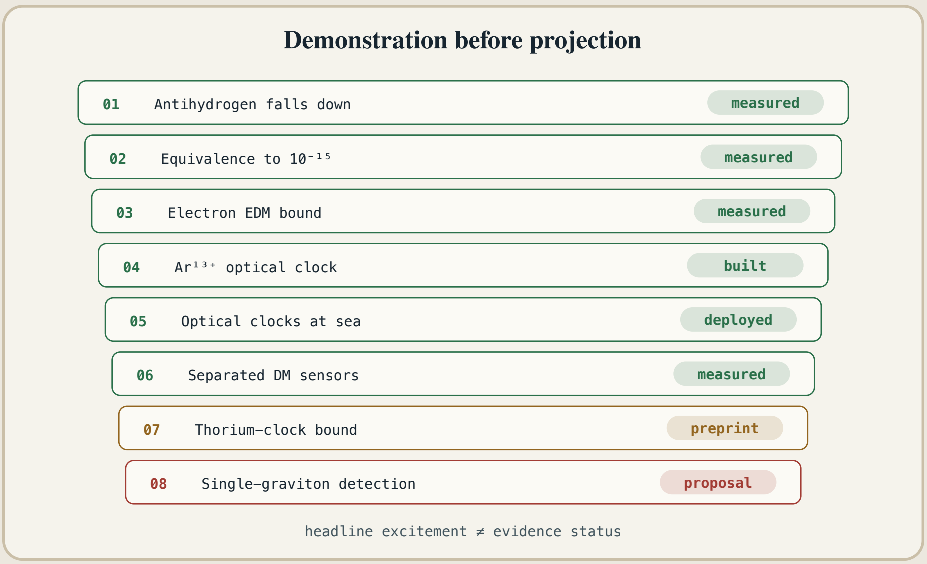
Clocks that go to sea

In 2022, three optical clocks made by Vector Atomic sailed around the Hawaiian islands aboard a naval ship for **twenty days**. Each 35-litre package contained an iodine spectrometer, fibre-frequency comb, and controls. The clocks ran continuously and accumulated timing errors below **300 picoseconds per day** (Roslund et al., *Nature* **628**: 736–740, 24 April 2024).

This was not a precision record. The paper contrasts the sea clocks with laboratory optical clocks below 10^{-18} fractional inaccuracy, but the at-sea figure is a timing-error and instability result rather than a like-for-like accuracy comparison. The result mattered because leading laboratory clocks are not readily deployable: clock geodesy, dark-matter networks, and GPS-independent navigation are constrained by ruggedness as well as precision. ESTABLISHED

Figure · The readiness ladder

Eight post-2020 claims are compared by what was demonstrated rather than by headline excitement. A firm measurement, a field deployment, a method demonstration, a preprint result, and a theoretical proposal are distinct evidential categories, not a universal ranking.



Antihydrogen fall, orbital equivalence tests, the electron-EDM bound, unusual optical clocks, and separated dark-matter sensors have measurements behind them. Thorium constraints remain a preprint and single-graviton detection remains a proposal.

CLAIM	DEMONSTRATED	NOT DEMONSTRATED OR REMAINING CAVEAT	STATUS
Antihydrogen falls down	ALPHA-g measured $g_{\bar{H}}$ = 0.75 ± 0.13(stat+sys) ± 0.16(sim) in units of g.	Equality with ordinary-matter gravity; the test is only about 25% precise.	Established, coarse test
Weak equivalence principle at 10^{-15}	MICROSCOPE found the Eötvös ratio consistent with zero after 2.5 years in orbit and included a same-composition control pair.	No equivalence-principle violation was detected.	Established null
Electron EDM below 4.1×10^{-30} e · cm	The HfF^{+} experiment set the 90% confidence bound with roughly three-second coherence.	The claim that this directly excludes all physics above 10 TeV depends on couplings and cancellations.	Established, model-bound reach
A clock made from Ar^{13+}	The first HCI optical clock reached 2.2×10^{-17} systematic uncertainty and resolved QED nuclear recoil.	No HCI clock has yet produced a competitive alpha-variation bound.	Established demonstration
Optical clocks at sea	Three 35-litre iodine clocks ran for 20 days with less than 300 ps/day timing error.	Laboratory optical clocks are more accurate, but the timing-error figure is not a like-for-like accuracy metric; this result addresses rugged deployment.	Established deployment
A 2,220 km cavity link helps hunt dark matter	A frequency comparison of cavity-stabilized lasers over 2,220 km, together with GPS atomic clocks, opened the first constraints on scalar dark matter coupling to electrons alone.	No dark matter was detected; the result is a null using an established method.	Established method
A nuclear clock constrains the strong force	A 3 June 2026 preprint reports a closed feedback loop and dark-matter constraints over 20 s to one day.	Peer review and independent confirmation remain; the alpha-sensitivity factor K = 5900 ± 2300 leaves large theory uncertainty.	Promising preprint

CLAIM	DEMONSTRATED	NOT DEMONSTRATED OR REMAINING CAVEAT	STATUS
Detect a single graviton	A 2024 paper presents a theoretical feasibility argument for phonon-resolved absorption in a massive resonator.	No detector has been built and no graviton detected; even quantized absorption may not prove a quantized field.	Proposal

PART II THE NUCLEAR CLOCK GROWS UP

From "we excited it" to "we constrained dark matter with it"

The main descent treated the thorium-229 nuclear clock as a striking demonstration: laser excitation of the nucleus at PTB in April 2024, then a direct comparison with a strontium clock in September 2024. The dark-matter application was a well-motivated hope, not yet a result.

A TU Wien-led collaboration now reports closing the **feedback loop**, the step that distinguishes spectroscopy from an operating clock. Continuous absorption spectroscopy supplied rapid feedback that stabilized a continuous-wave laser to the 148 nm transition of ^{229}Th nuclei embedded in a millimetre-scale calcium fluoride crystal at room temperature. The group then searched the transition for periodic changes and slow drift over timescales from **20 seconds to one day**.

The reported photon-coupling constraints are competitive with atomic-clock bounds. The reported sensitivity to the **strong force** and **quark masses** reaches parameter space electronic clocks cannot access because the thorium isomer energy is a near-cancellation of electromagnetic and strong-interaction contributions.

PREPRINT; NOT PEER REVIEWED The result is arXiv:2606.04997, submitted **3 June 2026**, and was not peer reviewed at the time represented here. If the result survives scrutiny, it establishes a new method. Its inferred reach also depends on an alpha-sensitivity factor known only to about 40%, $K = 5900 \pm 2300$ (Beeks et al., *Nature Communications* **16**: 9147, 2025). Separately, precise nuclear sensitivity factors for the strong-force and quark couplings cannot yet be calculated, so the preprint shows illustrative benchmark bands at 10^4 and 10^5. That factor-of-ten span is a benchmark range, not a statistically quantified uncertainty distribution. This is precisely the Day 6 pattern: a tight experiment multiplied by a loose coefficient.

Why this item may matter

The nuclear clock has crossed a consequential threshold in the preprint's report: it is no longer only an object whose transition can be excited, but an instrument used to constrain another phenomenon. The Kibble balance and optical frequency comb became scientifically transformative at the same object-to-instrument transition. The supplied appendix predicts that this clock will be in textbooks by **2040**; that is an editorial forecast, while peer review and independent use will determine whether the nuclear clock has fully crossed the threshold.

PART III THE CLOCK AS DARK-MATTER DETECTOR

Sensors far apart, seeing different parts of the same wave

Suppose dark matter is an *ultralight scalar field*[11] rather than particles striking a detector. If such a field couples to ordinary matter, constants could oscillate: electron mass would change slightly and clock frequencies would wobble.

For the lightest candidates, the wavelength can exceed a laboratory or even the solar system. Every local instrument then samples almost the same field at the same instant. Some couplings shift co-located references with the same response together and cancel from their comparison. For those reference pairs, the coupling is structurally invisible, not merely weakly constrained.

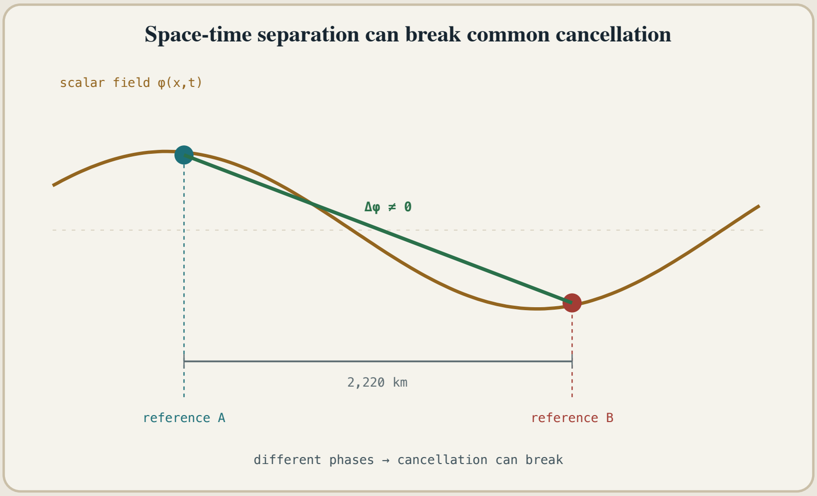
The 2025 solution was to stop making only local comparisons. Filzinger, Caddell, Jani, Steinel, Giani, Huntemann, and Roberts compared sensors separated in space and time so they sampled different field phases. Existing data supplied a frequency comparison between two optical cavities linked over **2,220 km**, plus atomic clocks aboard **GPS satellites**. The analysis set the **first constraints on scalar dark matter coupling to electrons alone**, for masses from 10^{-19} to 2×10^{-15} eV/ c^2 (*Physical Review Letters* **134**: 031001, 23 January 2025).

● ESTABLISHED; NULL RESULT No dark matter was detected. The advance was a new window opened without a new detector: the geographical baseline became the apparatus.

[11] An ultralight scalar dark-matter model treats dark matter as a coherently oscillating field whose enormous wavelength can make it behave like a wave across astronomical distances.

Figure · Separation breaks the blind spot

Two references with the same response produce no differential signal when they sample an exactly common field shift. Separation in space and time can let sensors sample different phases or arrival times, turning the baseline into part of the detector.



The schematic shows how separation can prevent a common response from cancelling. The real study compared cavity-stabilized lasers and separately analyzed GPS clocks; in its accessible mass range, sample timing rather than the spatial phase drawn here dominated.

SENSOR GEOMETRY	DIFFERENTIAL SIGNAL	INTERPRETATION
Same place, phase, and response	Zero for an exactly common shift, even if the field effect is large.	A structural blind spot for equally sensitive references: common-mode motion cancels from the comparison.
Separated by a long baseline	Different sampled phases or arrival times can produce a nonzero difference.	The cancellation can break; the separation becomes part of the apparatus.
Shorter field wavelength	A smaller separation can reach a large phase difference.	Heavier candidate fields can vary over a shorter baseline.
Filzinger et al. analysis	2,220 km cavity link plus GPS clocks.	For the relevant masses, time delay between sensor samples is the dominant real effect; the wave geometry expresses the same cancellation-breaking principle.

PART IV GRAVITY WEIGHED BY QUANTUM THINGS

Down to a flea's egg—and then the interesting part starts

Gravity measurements usually use large source masses—Cavendish used lead balls, and modern measurements of *G* use kilograms of tungsten—because shrinking a same-density sphere rapidly weakens its signal. At comparable geometry the source mass scales as R^3, so halving its radius costs a factor of eight in the available gravitational effect.

In 2021, Tobias Westphal, Hans Hepach, Jeremias Pfaff, and Markus Aspelmeyer measured gravitational coupling between two gold spheres of **1 mm radius and 90 mg mass**, roughly four houseflies. A miniature torsion balance and 350 hours of integration reached systematic accuracy of 4×10^{-11} m/s^2 (*Nature* **591**: 225–228, 11 March 2021). It was the smallest source mass whose gravitational field had then been directly measured.

The **Planck mass, about 22 micrograms**, is a target scale in some quantum-gravity proposals rather than a hard experimental threshold. Reaching source masses around or below that scale could make quantum superposition of the source a plausible ambition, opening the question of whether its gravitational field must also be quantum.

From another direction, Holger Müller's group replaced the couple of seconds available to free-falling atoms by holding them in an optical lattice. With an interferometer open for up to a minute, they measured a miniature source mass's attraction as **33.3 ± 5.6(stat) ± 2.7(syst) nm/s^2**, overall accuracy 6.2 nm/s^2—more than four times better than the source's free-fall comparison. The result agreed with Newtonian gravity and excluded screened-fifth-force chameleon and symmetron models over the natural parameter region analyzed (Panda et al., *Nature* **631**: 515–520, 18 July 2024).

EDGE B1 ● ESTABLISHED ● COARSE PRECISION

Antimatter falls down; its exact rate remains open

For decades, a fringe but testable possibility persisted: antimatter might fall upward. General relativity predicts otherwise, but the prediction had not been tested directly.

In 2023, CERN's ALPHA collaboration trapped antihydrogen in the vertical ALPHA-g magnetic bottle, lowered barriers at the top and bottom, and recorded where about 2,000 anti-atoms annihilated over a month (*Nature*, 28 September 2023).

Antihydrogen falls **down**. The acceleration was $g_{\bar{H}} = 0.75 \pm 0.13\,(\text{stat} + \text{sys}) \pm 0.16\,(\text{sim})$ in units of *g*, consistent with attractive gravity at roughly **25% precision**.

The direction is established; equality with ordinary matter is not. Ordinary matter's equivalence principle is tested to about one part in 10^{15}, leaving fourteen orders of magnitude between the tests. Reaching even **1%** requires order-of-magnitude reductions in magnetic-gradient and initial-condition systematics; AEgIS and GBAR pursue different methods and therefore different failure modes.

EDGE B2 • ESTABLISHED

Galileo's experiment in orbit, to fifteen decimal places

The weak equivalence principle says composition does not change free-fall acceleration. The MICROSCOPE satellite tested it with nested titanium-alloy and platinum masses in orbit, measuring the electrostatic forces needed to keep them aligned. Its 2.5-year mission included five months of clean science data and a same-composition control pair for one third of the data (Touboul et al., *Physical Review Letters* **129**: 121102, 14 September 2022).

The Eötvös ratio η was consistent with zero at $\mathbf{10^{-15}}$. No violation appeared. Ordinary matter is therefore tested to fifteen decimal places while antimatter is directly tested only to roughly one part in four.

EDGE B3 • ESTABLISHED • MODEL-DEPENDENT

The electron's dipole moment—and why a tabletop can reach beyond a collider

The electron's electric dipole moment is not a literal measure of geometric roundness. It is a spin-aligned electric dipole whose nonzero value would violate parity and time-reversal symmetries. The Standard Model prediction is far below present experimental reach, while many extensions predict values in the 10^{-27} to 10^{-30} e · cm range. A nonzero electron EDM would therefore be evidence of new physics.

JILA traps $\mathbf{HfF^+}$ molecular ions, where electrons experience enormous internal electric fields, and lets them precess coherently for up to **three seconds**. Roussy and colleagues reported (*Science* **381**: 46–50, July 2023):

> $|d_e| < 4.1 \times 10^{-30}\ e \cdot \mathrm{cm}$ *at 90% confidence.*

The result is consistent with zero and improves the prior bound by about 2.4. The supplied source compares the allowed asymmetry to a bump smaller than a few atoms if an electron were enlarged to Earth's size; that is a scale analogy, not a literal picture of electron shape.

The frequent claim that this "probes above 10 TeV" is true only under assumptions about coupling strength and the absence of cancellations. It is a model-dependent reach, not a direct energy-frontier exclusion. The tabletop experiment and the **27 km** LHC measure different things; the bound is established while the headline comparison is conditional.

PART V TWO ROUTES TO THE AMPERE

Two ampere realizations—and an open triangle

The 2019 ampere is defined through elementary charge *e*: current is charge counted per second. The most literal realization is a *single-electron pump*[12], a nanoscale gate moving one electron at a time at known frequency *f*, so $I = ef$. At one gigahertz the current is about 160 picoamps—precisely defined but difficult to measure.

The target relative uncertainty for a practical **direct electron-counting** standard is roughly **one part in 10^8**. Slow pumps produce currents too small to compare accurately; fast pumps miss or add electrons. The fixed-*e* definition therefore preceded a sufficiently accurate direct-counting realization, although the ampere could still be realized through other electrical standards.

The chronology matters. In 2017, a silicon single-trap pump exceeded **1 nanoampere** at 7.4 GHz, but its current deviated from the ideal value by about 20 parts per million and was measured with about one-part-per-million uncertainty—well short of the 10^{-8} target. In 2025, a scalable silicon demonstration parallelized four pumps at 200 MHz and produced a plateau above **2 nanoamperes** with three pumps at 2.1 GHz. That established a route to higher current, not 10^{-8} accuracy.

A separate route combines the Josephson voltage and quantum Hall resistance standards through Ohm's law, using a superconducting cryogenic current comparator for scaling. A 2025 *Nature Communications* experiment generated microampere currents with relative uncertainties below **10^{-8}**. That is an established ampere realization, but it derives current from the Josephson and quantum Hall effects rather than independently counting electrons.

The **quantum metrology triangle** is the independent comparison: does current from a single-electron pump agree with current derived from Josephson volts and quantum Hall ohms through $V = IR$? A Josephson-plus-quantum-Hall generator alone reuses two sides and therefore cannot close the three-sided test.

> *If repeated independent triangle tests failed after their systematics were excluded, the consistency of the three quantum electrical effects—or of their realizations—would need revision.*

The independent electron-pump comparison needed to close the triangle at 10^{-8} remains unfinished. ● ESTABLISHED BELOW 10^{-8} ● PROMISING; UNFINISHED

[12] A single-electron pump transfers a controlled integer number of electrons per cycle, ideally producing current I = ef at drive frequency f.

A quieter revolution: the ohm leaves the basement

Traditional quantum Hall resistance standards required temperatures below **1 K** and roughly ten-tesla magnets, restricting them to national laboratories. **Epitaxial graphene** standards now reach better than **2 nΩ/Ω** accuracy at 4.2 K, 4.5 T, and high current. A 2025 *Physical Review Applied* report found the accuracy remained after **800 km of road transport** between institutes. Cryocooler systems can avoid liquid helium. ESTABLISHED The performance and road test are established. PROJECTED Wider migration from national laboratories toward calibration laboratories and industrial benches remains a projection; if realized, it would flatten the Day 12 traceability network.

PART VI THE WILDEST PROPOSAL

Can you detect a single graviton?

Freeman Dyson argued that detecting one graviton was effectively hopeless: gravity couples too weakly, and a detector large enough to compensate might collapse under its own gravity or need to be the size of Jupiter.

In 2024, Germain Tobar, Sreenath Manikandan, Thomas Beitel, and Igor Pikovski proposed a different route (*Nature Communications* **15**: 7229). The analogy is the photoelectric effect. Light's quantization was inferred from discrete energy absorption rather than from visually catching a photon.

The proposal does not specify one universal multi-tonne niobium detector. The required mass and material depend on the target source: the paper estimates about **15 kg** for a beryllium resonator tuned to GW170817 and also analyzes tonne-scale bars. The resonator would be cooled to its motional ground state at millikelvin temperature. When an astrophysical gravitational wave passes, a quantized interaction could drive **one-phonon jumps** corresponding to absorbed energy $E = \hbar\nu$. Continuous quantum-state monitoring would resolve the jumps and correlate them with LIGO's observation of the same event: a gravito-phononic photoelectric effect.

PROPOSAL; NO DETECTION Nothing has been detected. The paper establishes a theoretical feasibility argument, not an experiment. No device combines the required resonator mass, quality factor, millikelvin temperature, and nondestructive single-phonon readout. An interpretive caveat remains even if discrete absorption were observed: a quantized absorber can receive energy in lumps from a coherent classical wave, so quantized transfer is not automatically identical to proving that the gravitational field itself is quantized. The proposal is conceptually striking and far from realization.

PART VII WHEN PEER REVIEW IS NOT ENOUGH

The Aziz–Howl dispute, and what it teaches

The setup was the proposed quantum-gravity witness: entangle two masses through gravity alone, and infer that gravity must be quantum because a local classical channel cannot create entanglement.

Aziz and Howl's peer-reviewed *Nature* paper (**646**: 813 – 817, 22 October 2025) argued that in quantum field theory classical gravity can transmit quantum information and generate entanglement. If correct, the witness would no longer distinguish classical from quantum gravity.

Technical replies followed rapidly. Marletto, Oppenheim, Vedral, and Wilson argued that the model does not produce the claimed entanglement and that any remaining effect would be mediated by quantized matter. Diósi's response was titled "No, classical gravity does not entangle quantized matter fields." Di Biagio defended a route by which it might. Gundhi and colleagues argued in April 2026 that discarded transition amplitudes generate the apparent effect and that restoring them preserves an initially factorized state. Xue and colleagues also posted a preprint response. The rebuttals cited here remain preprints, and the dispute is **active and contested**, not resolved by counting papers.

EDGE B4 ● ACTIVELY CONTESTED

Publication begins the test

The lesson is not that peer review is useless or that *Nature* cannot be trusted. Peer review filters for work that specialists judge competent, novel, and worth scrutiny; it is not a truth oracle. Here a serious claim was published and specialists immediately attacked precise terms in a decidable calculation. The speed and specificity of the response are evidence of scientific correction in progress, not evidence that a verdict already exists.

> *Publication is the beginning of a claim's life, not the end of it. Treat "peer-reviewed" as a starting gun, not a finish line.*

The most useful status is neither "true" nor "false" but **not yet settled**.

OPEN QUESTIONS

What would settle these

- **Does classical gravity entangle?** The dispute is over specific terms in a calculation. A peer-reviewed synthesis, convergent calculations, or agreement about the discarded amplitudes could resolve it.
- **Can an HCI clock beat 10^{-18}?** Success would provide a much stronger alpha-sensitive instrument; irreducible motional systematics could stall the programme at the demonstration stage.
- **Will an independent electron-pump leg close the quantum metrology triangle at 10^{-8}?** Failure after independent checks would be major evidence that a realization—or, only after systematics were excluded, the underlying physics—is incomplete.
- **Can the thorium sensitivity factors be narrowed?** The measured alpha-sensitivity factor K carries about 40% uncertainty, while strong-force and quark sensitivities are currently represented by illustrative benchmarks; nuclear-clock bounds inherit that theory dependence.
- **Does antimatter fall at exactly g?** The direction is known; fourteen orders of magnitude separate its present precision from ordinary-matter equivalence tests.
- **Could a clock network ever detect an oscillating constant?** A reproducible alpha oscillation matched across clocks and an inferred dark-matter frequency would overturn today's null picture. No such signal exists.

Big idea

Precision measurement has become a frontier tool: clocks search for dark matter, molecules determine mass ratios, tabletop experiments constrain new physics, and milligram spheres approach quantum-gravity regimes. The essential skill is separating demonstration, inference, and projection.

Best analogy

The gravito-phononic photoelectric effect seeks quantization in discrete absorbed energy, while the space-time-separated dark-matter search turns a 2,220 km cavity link into part of the detector and adds GPS clocks as a second dataset. One is an unbuilt proposal; the other is an established null method.

Live controversy

Aziz and Howl's peer-reviewed claim that classical gravity can produce entanglement has drawn multiple technical preprint rebuttals and remains active. Venue and review status identify the stage of scrutiny, not the final answer.

information (entanglement as a channel) · computation (electron pumps count current and the metrology triangle checks nature's arithmetic) · energy (gravitons as quanta and the eEDM as a vacuum probe) · emergence (topological protection in transportable graphene standards). Callbacks: **Day 2** on falsifiability and peer correction, **Day 6** on tight measurements multiplied by loose coefficients, **Day 12** on flattening traceability networks, and **Day 43** on entanglement as a possible witness.

BACK TO THE MAIN LINE · DAY 14

Synthesis: Reading the Frontier

Day 13 now has three layers: the settled SI and null results, the fossilized numbers inherited from earlier standards, and the provisional frontier. For calibration practice, choose three claims from this appendix and estimate the probability that each will still be accepted in 2035. The exercise forces demonstration, projection, and evidence status into the same judgment.

Sources & further reading

1. Aziz, J. & Howl, R. (2025). "Classical theories of gravity produce entanglement." *Nature* **646**: 813–817. Published 22 October 2025; doi:10.1038/s41586-025-09595-7. Status: actively contested. Preprint responses include Marletto, Oppenheim, Vedral & Wilson, "Classical gravity cannot mediate entanglement"(arXiv:2511.07348); Diósi, "No, classical gravity does not entangle quantized matter fields"(arXiv:2511.00852); Di Biagio, "The simple reason why classical gravity can entangle"(arXiv:2511.02683); Xue et al. (arXiv:2604.16276); and Gundhi et al., "Can classical theories of gravity produce entanglement?"(arXiv:2604.19696). Diósi, Di Biagio, and Marletto et al. submitted their replies in November 2025; Xue et al. and Gundhi et al. followed in April 2026. The replies are preprints and do not themselves settle the dispute.
2. King, S. A., Spieß, L. J., Micke, P., Wilzewski, A., Leopold, T., Benkler, E., Lange, R., Huntemann, N., Surzhykov, A., Yerokhin, V. A. et al. (2022). "An optical atomic clock based on a highly charged ion." *Nature* **611**: 43–47. 2 November 2022; doi:10.1038/s41586-022-05245-4—Ar^{13+} systematic uncertainty 2.2×10^{-17} and first resolution of QED nuclear recoil in a many-electron system. The comparison is to Brewer et al., "$^{27}Al^{+}$ Quantum-Logic Clock with a Systematic Uncertainty below 10^{-18}," *Physical Review Letters* **123**: 033201 (2019), doi:10.1103/PhysRevLett.123.033201, which reported 9.4×10^{-19} systematic uncertainty. See also Kozlov et al., "Highly charged ions: optical clocks and applications in fundamental physics," *Reviews of Modern Physics* **90**: 045005 (2018).
3. Alighanbari, S., Giri, G. S., Constantin, F. L., Korobov, V. I. & Schiller, S. (2020). "Precise test of quantum electrodynamics and determination of fundamental constants with HD^{+} ions." *Nature* **581**: 152–158. See Patra et al., "Proton–electron mass ratio from laser spectroscopy of HD^{+} at the part-per-trillion level," *Science* **369**: 1238–1241 (2020), and Kortunov et al., *Nature Physics* **17**: 569–573 (2021). The Kortunov paper's 2024 author correction updates derived mass-ratio values without changing its conclusions: *Nature Physics* **20**: 1034; doi:10.1038/s41567-024-02557-2.

4. Roslund, J. D., Cingöz, A., Lunden, W. D., Partridge, G. B., Kowligy, A. S., Roller, F., Sheredy, D. B., Skulason, G. E., Song, J. P., Abo-Shaeer, J. R. & Boyd, M. M. (2024). "Optical clocks at sea." *Nature* **628**: 736–740. 24 April 2024; doi:10.1038/s41586-024-07225-2—three 35-litre iodine clocks, 20 days aboard a Pacific naval vessel, timing errors below 300 ps/day. The paper separately notes laboratory optical clocks below 10^{-18} fractional inaccuracy; that accuracy figure and the sea clocks' timing-error or instability figures do not support one like-for-like multiplier. See Hilton et al., "Demonstration of a mobile optical clock ensemble at sea," *Nature Communications* **16**: 6063 (2025).

5. Toscani De Col, L. et al. (2026). "A thorium-229 optical nuclear clock with feedback loop." arXiv:2606.04997, submitted 3 June 2026; **preprint, not peer reviewed at the time represented here**. Reports a closed feedback loop on the 148 nm transition in a room-temperature CaF_2 crystal and dark-matter constraints over 20 s to one day. The inferred reach depends on Beeks et al., *Nature Communications* **16**: 9147 (2025), K = 5900(2300). The preprint says precise nuclear sensitivity factors cannot currently be calculated and presents 10^4 and 10^5 as illustrative benchmark bands rather than a quantified uncertainty distribution. See Higgins et al., *Physical Review Letters* **134**: 113801 (2025); Caputo et al., *Physical Review C* **112**: L031302 (2025); and Fuchs et al., *Physical Review X* **15**: 021055 (2025).

6. Filzinger, M., Caddell, A. R., Jani, D., Steinel, M., Giani, L., Huntemann, N. & Roberts, B. M. (2025). "Ultralight Dark Matter Search with Space-Time Separated Atomic Clocks and Cavities." *Physical Review Letters* **134**: 031001. 23 January 2025—first constraints on scalar-dark-matter coupling to electrons alone for masses 10^{-19} to 2×10^{-15} eV/c^2, using a 2,220 km fibre-linked cavity comparison and GPS satellite clocks. See Schioppo et al., *Nature Communications* **13**: 212 (2022), and Kennedy et al., *Physical Review Letters* **125**: 201302 (2020).

7. Westphal, T., Hepach, H., Pfaff, J. & Aspelmeyer, M. (2021). "Measurement of gravitational coupling between millimetre-sized masses." *Nature* **591**: 225–228. 11 March 2021; doi:10.1038/s41586-021-03250-7—two approximately 90 mg gold spheres, source modulated at 12.7 mHz, 350 h integration, systematic accuracy 4×10^{-11} m/s^2 and statistical precision 4×10^{-12} m/s^2.

8. Panda, C. D., Tao, M. J., Ceja, M., Khoury, J., Tino, G. M. & Müller, H. (2024). "Measuring gravitational attraction with a lattice atom interferometer." *Nature* **631**: 515–520. 18 July 2024; doi:10.1038/s41586-024-07561-3—33.3 ± 5.6(stat) ± 2.7(syst) nm s^{-2} and overall accuracy 6.2 nm s^{-2}; constraints on chameleon and symmetron screened-fifth-force models. See Panda et al., "Coherence limits in lattice atom interferometry at the one-minute scale," *Nature Physics* **20**: 1234 (2024).

9. ALPHA Collaboration (Anderson, E. K. et al.) (2023). "Observation of the effect of gravity on the motion of antimatter." *Nature* **621**: 716–722. 28 September 2023—about 2,000 ALPHA-g events; best fit $g_{\bar{H}}$ = 0.75 ± 0.13(stat+sys) ± 0.16(sim) in units of g. Attractive direction is established; equality with ordinary-matter acceleration is not.

10. Touboul, P., Métris, G., Rodrigues, M., Bergé, J., Robert, A. et al. (MICROSCOPE Collaboration) (2022). "MICROSCOPE Mission: Final Results of the Test of the Equivalence Principle." *Physical Review Letters* **129**: 121102. 14 September 2022—Eötvös ratio consistent with zero at 10^{-15} using titanium and platinum test masses and a same-composition control pair. See *Classical and Quantum Gravity* **39**: 204009 (2022).

11. Roussy, T. S., Caldwell, L., Wright, T., Cairncross, W. B., Shagam, Y., Ng, K. B., Schlossberger, N., Park, S. Y., Wang, A., Ye, J. & Cornell, E. A. (2023). "An improved bound on the electron's electric dipole moment." *Science* **381**: 46–50. July 2023—$|d_e| < 4.1 \times 10^{-30}$ e · cm at 90% confidence from trapped $^{180}Hf^{19}F^+$ with about three-second coherence. The "above 10 TeV" interpretation is model-dependent. See Caldwell et al., *Physical Review A* **108**: 012804 (2023).

12. Tobar, G., Manikandan, S. K., Beitel, T. & Pikovski, I. (2024). "Detecting single gravitons with quantum sensing." *Nature Communications* **15**: 7229. doi:10.1038/s41467-024-51420-8—a proposal, not a detection. It considers source-dependent acoustic-resonator designs, including an approximately 15 kg beryllium resonator for GW170817 and illustrative tonne-scale bars, cooled to the quantum ground state with stimulated absorption resolved as quantum jumps. On the field-quantization caveat, see Manikandan & Wilczek, *Physical Review A* **112**: 043716 (2025).

13. Djordjevic, S., Behr, R. & Poirier, W. (2025). "A primary quantum current standard based on the Josephson and the quantum Hall effects." *Nature Communications* **16**: 1447. 10 February 2025; doi:10.1038/s41467-025-56413-9—Josephson-plus-quantum-Hall programmable current generation in the microampere range at relative uncertainties below 10^{-8}; an ampere realization, not an independent three-leg triangle closure. For direct electron counting, see Yamahata, G., Giblin, S. P., Kataoka, M., Karasawa, T. & Fujiwara, A., "High-accuracy current generation in the nanoampere regime from a silicon single-trap electron pump," *Scientific Reports* **7**: 45137 (2017), doi:10.1038/srep45137—more than 1 nA at 7.4 GHz, about 20 ppm deviation and about 1 ppm measurement uncertainty. For parallel scaling, see Yamahata, G., Shimizu, T., Nishiguchi, K. & Fujiwara, A., "Scalable Parallel Single-Electron Pumps in Silicon with Split-Source Control in the Nanoampere Regime," *Nano Letters* **25**: 10202–10208 (2025), doi:10.1021/acs.nanolett.5c02327—four pumps in parallel and a plateau above 2 nA, but not a 10^{-8} accuracy result. See Scherer & Camarota, "Quantum metrology triangle experiments: a status review," *Measurement Science and Technology* **23**: 124010 (2012).

14. "Graphene quantum Hall resistance standard for realizing the unit of electrical resistance under relaxed experimental conditions." *Physical Review Applied* **23**: 014025 (2025). Accuracy better than 2 nΩ/Ω at B = 4.5 T, I = 232.5 μA, and T = 4.2 K; stability maintained over 2.5 years and after 800 km road transport. The transport test is established; wider industrial deployment is projected.

15. Long-baseline atom interferometry: **MAGIS-100** (Abe et al., *Quantum Science and Technology* **6**: 044003, 2021) and **AION** (Badurina et al., *JCAP* **05**: 011, 2020). Both facilities target ultralight dark matter and mid-band gravitational waves around 0.1–10 Hz. An AION prototype paper, *Nature* **654**: 622–628 (17 June 2026), doi:10.1038/s41586-026-10617-1, experimentally validates common-mode noise rejection between two long-baseline interferometers. It is an enabling demonstration, not a dark-matter or gravitational-wave detection.

16. Schulte, M., Lisdat, C., Schmidt, P. O., Sterr, U. & Hammerer, K. (2020). "Prospects and challenges for squeezing-enhanced optical atomic clocks." *Nature Communications* **11**: 5955. The standing caveat on when entanglement-enhanced metrology improves a real clock.

The thorium feedback-loop result is a June 2026 preprint and is identified as such. The technical replies in the Aziz – Howl dispute are also preprints; they establish an active disagreement, not a final verdict.