On 25 July to 1 August 2026 I attended an Oxford University Summer School for Adults on the topic of "**Smaller Than the Atom: A Primer on All Things Quantum**", by Timothy Charlton.

This is my pre-course assignment (c.1500 words) on the topic...

"In this essay we want to start our exploration of small in the classical sense. Taking inspiration from the book powers of 10 where each picture zooms in 10X, choose a length scale (example the size of an ant or a spec of dust) describe the world from this point of view then zoom in 10X. How would your observations of the world change?".

I admit I have, like most people today, used AI to add some meat to my basic idea. But I'm not going to move by simple units of 10, I'm going to try to step from 10^{10} down to 10^{-15} in a few uneven jumps.

My starting point is "Powers of Ten: A Book About the Relative Size of Things in the Universe and the Effect of Adding another Zero"[1], a 1982 book by physicists Philip Morrison[2] and Phylis Morrison, based on two short American documentary films[3] produced in 1977 by Charles and Ray Eames[4] (which was based upon "Cosmic View: The Universe in 40 Jumps"[5], a 1957 book by Dutch educator Kees Boeke[6]).

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[1] https://archive.org/details/powersoften00phil/mode/2up

[2] https://en.wikipedia.org/wiki/Philip_Morrison

[3] https://en.wikipedia.org/wiki/Powers_of_Ten_(film_series)

[4] https://en.wikipedia.org/wiki/Charles_and_Ray_Eames

[5] https://en.wikipedia.org/wiki/Cosmic_View

[6] https://en.wikipedia.org/wiki/Kees_Boeke

I'm at a loss to think of a way to zoom that is more informative than the "A Tour of The Universe" with Lawrence M. Krauss[7]. He does a great job describing the mathematical tool of “powers of ten” to "map the true playing field of physics". Even if it mirrors an earlier 1959 film "How Vast Is Space?"[8], which was also based on the book by Kees Boeke.

So here goes...

GPS as an example of the "Power of Ten"

At a scale of approximately **10^{10} metres**, the orbit of Mercury[9] provided one of the first precise tests of general relativity[10]. Astronomers measured that the perihelion[11] of Mercury’s elliptical orbit advances by an additional 43 arcseconds[12] per century beyond the value predicted by Newtonian mechanics and perturbations from the other planets[13]. Einstein’s field equations[14] accounted for the discrepancy by describing gravity as the curvature of spacetime[15] produced by the Sun’s mass. In this description, Mercury does not follow a closed Newtonian ellipse[16]. Instead, the curvature of

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[7] https://www.youtube.com/watch?v=WOJaAM2ky_I

[8] https://archive.org/details/how-vast-is-space

[9] https://en.wikipedia.org/wiki/Mercury_(planet)#Orbit,_rotation,_and_longitude

[10] https://en.wikipedia.org/wiki/Tests_of_general_relativity

[11] https://en.wikipedia.org/wiki/Apsis#Perihelion_and_aphelion

[12] https://en.wikipedia.org/wiki/Minute_and_second_of_arc

[13] https://en.wikipedia.org/wiki/Mercury_(planet)#Advance_of_perihelion

[14] https://en.wikipedia.org/wiki/Einstein_field_equations

[15] https://en.wikipedia.org/wiki/Curved_spacetime

[16] https://en.wikipedia.org/wiki/Tests_of_general_relativity#Perihelion_precession_of_Mercury

spacetime causes the orbital ellipse itself to rotate gradually over time, producing the observed perihelion precession[17].

At a scale of approximately **10^7 metres**, GPS satellites orbit in spacetime curved primarily by Earth's mass. The operation of the GPS system depends fundamentally on satellite geodesy[18] (the discipline concerned with determining Earth's shape[19]), gravitational reference surface[20], rotational orientation[21], and terrestrial coordinate systems[22] from orbital measurements. GPS receivers[23] calculate position by comparing the arrival times of synchronised satellite signals against precise geodetic reference frames and continuously updated satellite ephemerides[24]. General relativity predicts that clocks at the GPS orbital altitude of approximately 20,200 kilometres above Earth's surface run faster than clocks on Earth by approximately 45 microseconds per day. Special relativity predicts a velocity-induced slowing of approximately 7 microseconds per day due to the satellites' orbital speed of approximately 3.9 kilometres per second. The resulting net relativistic offset of approximately 38 microseconds per day must be incorporated directly into GPS timing models, because uncorrected timing errors would accumulate into positioning errors of about 10 kilometres per day.

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[17] https://en.wikipedia.org/wiki/Apsidal_precession

[18] https://en.wikipedia.org/wiki/Satellite_geodesy

[19] https://en.wikipedia.org/wiki/Figure_of_the_Earth

[20] https://en.wikipedia.org/wiki/Geoid

[21] https://en.wikipedia.org/wiki/Earth's_rotation

[22] https://en.wikipedia.org/wiki/Spatial_reference_system

[23] https://en.wikipedia.org/wiki/Satellite_navigation_device

[24] https://en.wikipedia.org/wiki/Ephemeris

Satellite gravimetry[25] plays a secondary but essential role by refining the gravitational field models upon which high-precision geodesy depends. Earth's gravitational field[26] deviates significantly from spherical symmetry[27] due to rotational flattening[28], topographic mass distributions, mantle density variations[29], ocean circulation[30], and temporal redistribution of water and ice masses. Satellite gravimetry missions such as GRACE[31] and GOCE[32] measure these variations by detecting small perturbations in satellite motion and inter-satellite separation[33] (I think that operational GPS does not yet depend on these refinements). The resulting geopotential[34] and geoid[35] models improve precise orbit determination, terrestrial reference systems[36], and altitude calibration within GPS. In this hierarchy, satellite geodesy provides the primary spatial and relativistic framework required for navigation, while satellite gravimetry refines the gravitational models that increase the accuracy and stability of that framework.

At a scale of approximately **10^5 metres**, the dominant structure is the satellite-receiver geometry from multiple GPS satellites onto a regional area of Earth's surface. A GPS receiver does not measure its position from a single satellite, but estimates distance from several satellites by comparing the arrival times of their radio signals. Each timing measurement defines a

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[25] https://en.wikipedia.org/wiki/Satellite_gravimetry

[26] https://en.wikipedia.org/wiki/Gravity_of_Earth

[27] https://en.wikipedia.org/wiki/Gravity_anomaly

[28] https://en.wikipedia.org/wiki/Earth_ellipsoid

[29] https://en.wikipedia.org/wiki/Geodynamics

[30] https://en.wikipedia.org/wiki/Ocean_current

[31] https://en.wikipedia.org/wiki/GRACE_and_GRACE-FO

[32] https://en.wikipedia.org/wiki/GOCE

[33] https://en.wikipedia.org/wiki/Satellite_constellation

[34] https://en.wikipedia.org/wiki/Geopotential

[35] https://en.wikipedia.org/wiki/Geoid

[36] https://en.wikipedia.org/wiki/International_Terrestrial_Reference_System_and_Frame

pseudorange[37] from one satellite (i.e. not a true geometric range), and because the receive clock bias is unknown, the spheres generally do not intersect perfectly. The receiver solves a nonlinear least-squares[38] estimate problem using at least four satellites. So the position emerges from multilateration[39], i.e. the conversion of precisely timed satellite signals into a spatial fix on Earth's surface.

At a scale of approximately **10^3 metres**, the dominant structure is the urban transportation network, represented in the onboard mapping software as a connected graph of roads, intersections, and permitted routes. The GPS receiver continuously estimates its geographic coordinates from satellite timing signals, while the navigation software matches those coordinates to the most probable position on the mapped road network using map-matching algorithms[40], motion history, and routing constraints. Successive position updates are then combined with stored map geometry to calculate direction, speed, estimated arrival time, and turn-by-turn navigation through the city-scale street system.

An additional communications layer operating at approximately 10^3 metres is the cellular communication network[41] linking the smartphone to nearby overlapping radio cells distributed throughout the urban environment. While GPS provides the primary global positioning signal, the device simultaneously maintains continuous synchronisation with LTE[42] or 5G[43] infrastructure

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[37] https://en.wikipedia.org/wiki/Pseudorange

[38] https://en.wikipedia.org/wiki/Non-linear_least_squares

[39] https://en.wikipedia.org/wiki/Trilateration

[40] https://en.wikipedia.org/wiki/Map_matching

[41] https://en.wikipedia.org/wiki/Cellular_network

[42] https://en.wikipedia.org/wiki/LTE_(telecommunication)

[43] https://en.wikipedia.org/wiki/5G

through the exchange of radio control, scheduling, and mobility-management signals on millisecond timescales during active operation. These terrestrial communication links provide assisted-GPS timing data, map updates, traffic information, and supplementary positioning estimates derived from cellular and Wi-Fi signal measurements. As the device moves through overlapping radio cells, the network continuously adjusts timing, signal allocation, and handover state in order to preserve low-latency connectivity across the city-scale communication system.

At a scale of approximately **10^{-1} metres**, the dominant physical object is the smartphone[44] (or separate navigator) through which satellite-derived positioning data is presented to a user in real time. The device integrates a GPS receiver, processor, inertial sensors[45], wireless communication systems, and graphical mapping software within a handheld device. Position estimates calculated from satellite signal timing are combined with locally stored or network-delivered map data and rendered as an interactive visual interface, allowing the user to interpret geographic position, movement, and routing information directly at human scale.

At a scale of approximately **10^{-2} metres**, the dominant physical structure is the GPS antenna inside a mobile device that receives microwave signals transmitted from orbiting satellites. GPS satellites broadcast electromagnetic signals near 1.57542 GHz on the L1 band[46], corresponding to a wavelength of approximately 19 centimetres. Although physically smaller than the free-space wavelength, through the use of compact folded geometries, dielectric loading, and integration with the handset chassis, the antenna is engineered to efficiently couple incoming microwave radiation into the receiver electronics. At this scale, navigation depends on the controlled reception of

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[44] https://en.wikipedia.org/wiki/Smartphone

[45] https://en.wikipedia.org/wiki/Inertial_measurement_unit

[46] https://en.wikipedia.org/wiki/L_band

extremely weak radio-frequency signals whose propagation times encode the satellite-to-receiver distance measurements used for positioning.

A GPS satellite transmits roughly 20–50 Watts RF power, but by the time the signal reaches a smartphone antenna, the received power is comparable to or below the thermal electronic noise[47] *inside the receiver. The received GNSS*[48] *signals are extraordinarily weak by conventional radio standards. For civilian GPS L1 signals at the Earth's surface, the received power is typically on the order of* 10^{-16} *Watts, or approximately -130 dBm*[49] *to -120 dBm, depending on satellite elevation, antenna gain, atmospheric conditions, and receiver environment. What is remarkable is that the receiver is still able to extract the signal using spread-spectrum correlation*[50]*, long integration times, precise pseudorandom codes*[51]*, and carrier tracking loops. The signal is therefore recoverable statistically even when buried beneath the receiver noise floor*[52]*.*

At present, the dominant GNSS antenna architectures used in smartphones are compact PIFA-derived and printed multi-band antenna structures[53] *integrated directly into the handset chassis and flexible RF substrate layers. These antennas are engineered to operate simultaneously across multiple frequency bands supporting GPS, Galileo*[54]*, GLONASS*[55]*, BeiDou*[56]*, LTE, Wi-Fi, and Bluetooth within highly constrained enclosure geometries. Unlike dedicated external GNSS*

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[47] https://en.wikipedia.org/wiki/Noise_(electronics)

[48] https://en.wikipedia.org/wiki/Satellite_navigation

[49] Is decibel-milliwatts, see https://en.wikipedia.org/wiki/DBm

[50] https://en.wikipedia.org/wiki/Direct-sequence_spread_spectrum

[51] https://en.wikipedia.org/wiki/Pseudorandom_noise

[52] https://en.wikipedia.org/wiki/Noise_floor

[53] https://en.wikipedia.org/wiki/Inverted-F_antenna

[54] https://en.wikipedia.org/wiki/Galileo_(satellite_navigation_system)

[55] https://en.wikipedia.org/wiki/GLONASS

[56] https://en.wikipedia.org/wiki/BeiDou

antennas, smartphone antenna systems are strongly coupled to the conductive frame, battery geometry, and surrounding dielectric materials of the device itself, requiring extensive impedance tuning, adaptive matching networks, and electromagnetic co-design with the radio-frequency front end. Their compact dimensions impose efficiency limitations relative to larger resonant structures, but their low profile, manufacturability, and multi-service integration make them the dominant architecture for mass-market mobile devices.

Increasingly common in modern high-end devices are multi-frequency and multi-band GNSS antenna systems designed to support simultaneous reception on L1/E1 and L5/E5 bands[57] *(e.g. Apple's recent Pro iPhones). Dual-frequency reception improves ionospheric delay correction*[58]*, carrier-phase stability, multipath rejection, and urban positioning accuracy by allowing the receiver to compare signal propagation characteristics across multiple frequencies. These systems are typically implemented using advanced printed antenna geometries, phased feed structures, and integrated low-noise amplifier chains fabricated directly into multilayer antenna carrier assemblies. The transition toward multi-band GNSS architectures is driven by the increasing availability of modernised satellite constellations and the growing demand for sub-meter positioning performance within dense urban environments.*

Patch antennas[59] *remain widely used in precision GNSS applications because of their favourable circular polarisation characteristics, hemispherical reception pattern, and comparatively strong rejection of low-angle multipath reflections. In recent years, compact ceramic patch antennas and active antenna modules have also become increasingly common in indoor and near-indoor positioning systems, where direct line-of-sight satellite visibility is partially degraded. Under these conditions, receivers often combine weak GNSS signals with assisted-GPS data, inertial navigation*

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[57] https://gssc.esa.int/navipedia/index.php/GNSS_signal

[58] https://gssc.esa.int/navipedia/index.php/Ionospheric_Delay

[59] https://en.wikipedia.org/wiki/Patch_antenna

systems, Wi-Fi positioning, and terrestrial radio measurements to maintain navigation continuity. Indoor reception remains challenging because the GNSS spread-spectrum signal power spectral density lies below thermal noise prior to despreading/correlation processing, making them highly susceptible to attenuation, multipath propagation, and signal obstruction by reinforced concrete, metallic structures, and coated architectural glass.

The increasing dependence of navigation systems on weak spread-spectrum[60] *GNSS signals has also produced growing concern regarding spoofing*[61] *and jamming*[62] *attacks. Civilian GNSS signals are openly specified and comparatively low power, allowing adversarial transmitters to generate counterfeit navigation signals*[63] *capable of displacing or destabilising receiver position estimates. Modern spoofing attacks may manipulate pseudorange timing*[64]*, carrier phase, Doppler characteristics, and navigation message content while maintaining apparent signal coherence with legitimate satellite transmissions. These vulnerabilities have accelerated development of more advanced antenna systems including adaptive beamforming*[65] *arrays, null-steering receivers, controlled reception pattern antennas (CRPA)*[66]*, angle-of-arrival discrimination systems, and tightly coupled multi-sensor fusion architectures integrating inertial navigation*[67] *and terrestrial radio positioning. Future GNSS antenna development is increasingly focused on spatial filtering*[68]*, interference suppression, authenticated navigation signals, and resilient multi-frequency reception capable of operating within contested electromagnetic environments.*

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[60] https://en.wikipedia.org/wiki/Spread_spectrum

[61] https://en.wikipedia.org/wiki/Spoofing_attack

[62] https://en.wikipedia.org/wiki/Mobile_phone_jammer

[63] https://en.wikipedia.org/wiki/GNSS_spoofing

[64] https://en.wikipedia.org/wiki/Pseudorange

[65] https://en.wikipedia.org/wiki/Beamforming

[66] https://en.wikipedia.org/wiki/Controlled_reception_pattern_antenna

[67] https://en.wikipedia.org/wiki/Inertial_navigation_system

[68] https://en.wikipedia.org/wiki/Spatial_filter

Also at a scale of approximately **10^{-2} metres**, another dominant physical structure is the microwave radiation[69] used to interrogate and stabilise the frequency of the atomic clocks[70] carried aboard GPS satellites. In Cesium atomic clocks[71], microwave signals near 9.192631770 GHz are tuned to the hyperfine transition frequency of Cesium-133 atoms[72], corresponding to a free-space wavelength of approximately 3.26 centimetres. The microwave field is confined within resonant structures engineered so that electromagnetic standing-wave modes remain phase-stable and precisely matched to the atomic transition. At this scale, the stability of the GPS timing system depends on resonance between electromagnetic waves and quantised atomic energy states.

At a scale of approximately **10^{-5} metres**, the dominant physical structures are the micrometre-scale features within the integrated clock-control circuitry, including the lithographic interconnects, passive components and transistor-scale circuit that continuously compares the measured atomic resonance against the generated microwave frequency. The complete feedback electronics are much larger (10^{-3}), but their performance depends on phase stability, noise control, and drift management across these micro-fabricated structures.

At a scale of approximately **10^{-6} metres** (the micrometre scale), the dominant physical structure is the transistor[73], the fundamental switching and amplification device used throughout the GPS receiver and atomic clock control electronics. Modern integrated circuits can contain billions of field-effect transistors[74] fabricated onto silicon wafers[75], each regulating the movement of charge

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[69] https://en.wikipedia.org/wiki/Microwave (between 300 MHz and 300 GHz)

[70] https://en.wikipedia.org/wiki/Atomic_clock

[71] https://en.wikipedia.org/wiki/Caesium_standard

[72] https://en.wikipedia.org/wiki/Unit_of_time

[73] https://en.wikipedia.org/wiki/Transistor

[74] https://en.wikipedia.org/wiki/Field-effect_transistor

[75] https://en.wikipedia.org/wiki/Wafer_(electronics)

carriers[76] conductive channels created by applied electric fields. Advanced processors such as the Apple A17 Pro contain around 19 billion transistors, while modern dual-frequency, multi-band GNSS chips may contain up to 100 million transistors. By varying the applied voltage, these transistors control the conductivity of their channels, enabling electronic logic operations, signal amplification, and very precise timing functions through large-scale semiconductor integration[77].

At a scale of approximately **10^{-8} metres**, the dominant physical structure is the transistor gate oxide[78] and conductive channel region, whose dimensions approach the characteristic quantum-mechanical length scales of electrons in solid materials. In modern semiconductor devices, insulating layers (can be a few nanometers thick) separate conducting regions while controlling electron transport through electrostatic fields. At these dimensions, quantum tunnelling[79] can contribute significantly to leakage currents[80], because electrons can penetrate potential barriers that would be impermeable under classical physics, and thus limit further transistor miniaturisation.

Stat*e-of-the-art integrated circuits*[81] *are presently fabricated using semiconductor process nodes nominally marketed at 3 nanometers and approaching 2 nanometers, although these labels no longer correspond directly to a single physical transistor dimension. In advanced FinFET*[82] *and gate-all-around (GAAFET)*[83] *transistor architectures, effective gate lengths can be of the order of* 10^{-8} *metres (very vendor specific), while gate oxide thicknesses may approach only a few atomic layers (again often vendor rhetoric). At these dimensions, device behaviour is increasingly*

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[76] https://en.wikipedia.org/wiki/Charge_carrier

[77] https://en.wikipedia.org/wiki/Integrated_circuit

[78] https://en.wikipedia.org/wiki/MOSFET

[79] https://en.wikipedia.org/wiki/Quantum_tunnelling

[80] https://en.wikipedia.org/wiki/Leakage_(electronics)

[81] https://en.wikipedia.org/wiki/Integrated_circuit

[82] https://en.wikipedia.org/wiki/Fin_field-effect_transistor

[83] https://en.wikipedia.org/wiki/Multigate_device#GAAFET

constrained by quantum tunnelling, statistical dopant fluctuations[84]*, parasitic capacitance*[85]*, heat dissipation, and variability arising from atomic-scale imperfections in material structure. Further miniaturisation beyond the current silicon CMOS*[86] *regime is expected to depend on new transistor geometries, high-mobility channel materials, three-dimensional integration, and alternative computational architectures including carbon nanotube devices*[87]*, two-dimensional semiconductors*[88]*, spintronic*[89] *systems, and quantum computing*[90] *elements. Although experimental devices have demonstrated functional structures approaching atomic-scale dimensions, practical large-scale semiconductor manufacturing is increasingly limited not by lithographic resolution*[91] *alone, but by the fundamental electronic, thermodynamic, and quantum-mechanical constraints governing charge transport in condensed matter systems.*

Over the next decade, the most significant developments in integrated-circuit miniaturisation are expected to occur not through continued reduction of planar transistor dimensions alone, but through increasingly complex three-dimensional integration architectures. Contemporary high-performance processors already employ fabrication stacks containing tens to more than one hundred structural and interconnect layers, while advanced 3D NAND memory devices[92] *exceed several hundred vertically integrated active layers. Current semiconductor roadmaps project near-*

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[84] https://en.wikipedia.org/wiki/Random_dopant_fluctuation

[85] https://en.wikipedia.org/wiki/Parasitic_capacitance

[86] https://en.wikipedia.org/wiki/CMOS

[87] https://en.wikipedia.org/wiki/Carbon_nanotube_field-effect_transistor

[88] https://en.wikipedia.org/wiki/Two-dimensional_semiconductor

[89] https://en.wikipedia.org/wiki/Spintronics

[90] https://en.wikipedia.org/wiki/Quantum_computing

[91] https://en.wikipedia.org/wiki/Electron-beam_lithography#Resolution_capability (target is 15 nm)

[92] https://en.wikipedia.org/wiki/Flash_memory

term transition from FinFET to gate-all-around (GAAFET) and complementary FET (CFET)[93] *architectures during the late 2020s and early 2030s, enabling vertically stacked transistor channels with improved electrostatic control at dimensions approaching only a few nanometers. Beyond this period, further increases in computational density are expected to rely on monolithic three-dimensional integration*[94]*, backside power delivery*[95]*, heterogeneous chiplet*[96] *systems, and advanced interconnect packaging rather than continued geometric shrinking alone. Although experimental devices have demonstrated transistor-scale structures approaching atomic dimensions, long-term semiconductor scaling is increasingly constrained by heat dissipation, interconnect delay, quantum tunnelling, fabrication variability at atomic scales, and the growing energy cost of data movement within densely layered electronic systems.*

At a scale of near **10^{-10} metres**, the dominant physical structure is the Cesium atom itself, whose electronic and nuclear magnetic interactions define the reference transition used in atomic clocks. In Cesium-133, the hyperfine transition arises from the interaction between the magnetic moment of the nucleus[97] and the magnetic field generated by the surrounding electron cloud. Atomic clocks stabilise microwave oscillators by tuning them to the exact frequency required to induce transitions between these hyperfine energy states. The frequency of 9.192631770 GHz defines the SI second[98] and forms the timing reference upon which the GPS system depends.

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[93] https://en.wikipedia.org/wiki/2_nm_process

[94] https://en.wikipedia.org/wiki/Three-dimensional_integrated_circuit

[95] https://en.wikipedia.org/wiki/Backside_power_delivery

[96] https://en.wikipedia.org/wiki/Chiplet

[97] https://en.wikipedia.org/wiki/Nuclear_magnetic_moment

[98] https://en.wikipedia.org/wiki/Second#Future_redefinition

Future atomic time standards are expected to transition from microwave Cesium-133 clocks toward optical atomic clocks[99] *based on laser-driven electronic transitions in atoms such as Strontium-87, Ytterbium, and Aluminum ions. Unlike Cesium clocks, which operate near* 10^{10} *hertz microwave frequencies, optical clocks stabilise lasers against atomic transitions occurring at frequencies approaching* 10^{15} *hertz, providing substantially higher timing resolution and fractional frequency stability. These systems typically use laser cooling*[100]*, optical lattices*[101]*, ion traps*[102]*, and ultra-stable reference cavities to isolate atoms from thermal and environmental perturbations while measuring atomic transitions with extreme precision. Experimental optical clocks have already demonstrated uncertainties approaching* 10^{-18}*, exceeding the performance of existing Cesium standards by more than two orders of magnitude. Current international metrology programs are therefore evaluating future redefinition of the SI second based on optical frequency standards, with potential applications including relativistic geodesy, deep-space navigation, ultra-precise satellite synchronisation, and fundamental tests of gravitation and quantum physics.*

And we should not ignore the long-term potential of nuclear clocks[103]*.*

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[99] https://en.wikipedia.org/wiki/Atomic_clock#Potential_for_redefining_the_second

[100] https://en.wikipedia.org/wiki/Laser_cooling

[101] https://en.wikipedia.org/wiki/Optical_lattice_clock

[102] https://en.wikipedia.org/wiki/Trapped-ion_quantum_computer

[103] https://en.wikipedia.org/wiki/Nuclear_clock