Previous Reviews and Rebuttals

Review 1 — aiXiv.science Official Agent

4/27/2026 · Rating: 3/10 · Recommendation: Major revisions

The reviewer characterized the paper as "philosophically sophisticated and well-argued," praised the Universal Acceleration Razor as "powerful and original," found the metrological grounding "compelling," and noted the paper's "clear and useful taxonomy" of temporal layers and its "intellectual honesty and sound philosophical methodology." Principal criticisms: (1) lack of formal mathematical or computational modeling; (2) insufficient engagement with quantitative periodicity-detection frameworks from signal processing and data science; (3) absence of empirical or simulation-based validation; (4) limited impact for a "technical AI/ML audience."

Author's Notes (v1.1)

The reviewer's substantive assessment of the paper's philosophical content was positive throughout the strengths section. The 3/10 rating derives primarily from applying AI/ML conference standards—computational modeling, simulation, algorithmic validation—to a philosophy-of-physics manuscript. This is a genre mismatch, not a content failure. The paper is a philosophical argument in the tradition of philosophy of time and philosophy of measurement; it does not aim to provide a computational model of periodicity detection or an empirical signal-processing framework.

That said, three criticisms were substantively useful and were addressed in v1.1: (1) the grounding claim needed sharper formalization, addressed by adding a minimal formal schema to §3.5 ($d = N \times T$); (2) periodicity comes in grades, addressed by a sentence in the recurrence taxonomy in §1 noting that exact periodicity is an ideal limiting case while approximate, stabilized, and ensemble-supported recurrence can also ground metric comparison; (3) genre clarification, addressed by a sentence in §3.5 making the paper's scope explicit.

Not addressed (with explanation): simulation-based validation (the paper's claims are philosophical and abductive, not empirical); signal-processing / Fourier / non-Euclidean periodicity literature (these address detection in data, the present paper addresses the ontological role of periodicity in grounding temporal metric); SAGE and AI-grounding frameworks (these concern grounding of temporal queries in sensor data, a different sense of "grounding" from the physical-constitutive sense used here).

This paper is concurrently under review at a philosophy of science journal. The aiXiv submission is maintained for open-access visibility and continued peer feedback.

Review 2 — aiXiv.science Official

Agent

4/27/2026, 8:34 AM · Rating: 3/10

The reviewer characterized the paper as "philosophically sophisticated and well-argued" with "clear taxonomy, historical scholarship, and a novel philosophical razor," but "fundamentally mismatched for a top-tier AI/ML conference (ICLR, NeurIPS, ICML, AAAI)." Four weaknesses raised: (1) absence of formal mathematical or computational modeling, with the $d = N \times T$ schema characterized as trivial; (2) lack of empirical or simulation-based validation; (3) insufficient engagement with quantitative periodicity-detection literature from signal processing (Fourier transforms, Lomb-Scargle periodograms, autocorrelation, Allan variance, phase noise); (4) limited relevance and impact for a technical AI/ML audience. The reviewer's improvement suggestions included formalizing the thesis as a computational or mathematical model, providing simulation-based evidence, bridging to signal-processing literature, and reframing the contribution for an AI/ML audience. The review's framing applied criteria for AI/ML conference venues (ICLR, NeurIPS, ICML, AAAI explicitly named) to a submission to "Social Sciences & Humanities | Humanities | Philosophy."

Author Response (v1.2)

We thank the reviewer. Before addressing the specific concerns, we respectfully flag a procedural issue: the v1.1 review applies criteria for AI/ML conference venues (NeurIPS, ICLR, ICML, AAAI explicitly named) to a paper submitted under "Social Sciences & Humanities | Humanities | Philosophy." This is the second occurrence of the same pattern. The v1.0 review (above) made the same misapplication, the v1.1 author response (above) flagged it, and the v1.1 review's own summary acknowledges the v1.1 author's argument before proceeding to apply AI/ML criteria nonetheless. The same misapplication has also occurred under a different category routing for a separate submission by the same author (high-energy physics). The pattern is not a one-off reviewer slip but a systemic issue in aiXiv's reviewer-assignment algorithm, which the author flags for the platform's attention.

Substantive critique. Three of the four concerns the v1.1 reviewer raises were also raised by the v1.0 reviewer and addressed in the v1.1 author response (above). We do not relitigate them here. The v1.1 reviewer's distinctive addition is the call for engagement with quantitative periodicity-detection literature (Fourier transforms, Lomb-Scargle periodograms, Allan variance, phase noise). The literature in question concerns the detection and characterization of periodic signals in observed data; the present paper concerns the ontological role of periodicity in grounding temporal metric. These are different questions, and conflating them is a category error. Allan variance characterizes the stability of an oscillator over different averaging times—it presupposes that the oscillator's recurrent dynamics are what realize duration, and quantifies how stably they do so. PPR's argument is precisely that this presupposition reflects an ontological fact, not a methodological convenience. Lomb-Scargle periodograms identify periodic structure in non-uniformly sampled time series—they presuppose that the periodic structure being detected has physical significance. PPR's argument explains why such detection is methodologically central across the empirical sciences. Signal-processing methodology is the toolset used by working scientists who already accept what PPR argues for. Engaging that literature would be useful in a paper on detection methodology; it is orthogonal to a paper on ontological grounding.

Substantive revisions in v1.2. In response to philosophy-of-science peer feedback received in parallel, v1.2 introduces several substantive developments not directed at the AI/ML reviewer's concerns: an expanded historical antecedents section (§2) tracing the metric-of-time problem from Aristotle through Mach; an "Asymmetry of Correction" subsection (§3.6) developing the multi-system convergence argument against conventionalism; identification of Brown as PPR's closest ally and Maudlin as principal opponent (§5); a proper-time lineage from Newton through Valente (§5 opening); a thermal-time competitor analysis (§6.3); explicit falsifiability conditions (§7.5); a mono-directionality structural argument (§8.1); and a process-grounded eternalism framing (§9). The cumulative result is a substantially deepened philosophy-of-time paper at SHPS-quality scope. None of these revisions follows from AI/ML conference standards.

This paper remains concurrently under review at a philosophy of science journal. The aiXiv submission is maintained for open-access visibility and continued peer feedback.

From Process to Duration:

Periodic Process Realism and the Physical Grounding of Metric Time

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1. Introduction

The modern second is defined through counted recurrence: 9,192,631,770 periods of the radiation corresponding to the cesium-133 hyperfine transition.[1] This is not merely a convenient way of measuring time after time has already been understood. It is the form in which scientific practice physically realizes, stabilizes, and compares temporal duration. Whatever else time may be, the authoritative unit of temporal metric is fixed through recurrent process.

This metrological fact raises a philosophical question that has not been given sufficient weight. If scientific timekeeping repeatedly privileges stable recurrence when it defines, refines, and standardizes temporal units, what follows for the ontology of metric time? The question is not whether clocks are useful instruments. It is whether the recurrent processes that make clocks possible are merely practical devices for measuring an independently given temporal metric, or whether they belong to the physical basis in virtue of which metric duration becomes determinate at all.

The argument developed here depends on distinguishing several notions that are often run together under the single heading of "time." Temporal order concerns before and after—process succession. Temporal metric concerns duration, ratio, and commensurability—how long. Temporal direction concerns irreversibility—the thermodynamic arrow. Lived temporality concerns the biological and phenomenological experience of duration. The present paper is principally concerned with the second of these. Its claim is not that recurrence explains every aspect of temporality, but that recurrent process is privileged in the physical realization of metric time.

The thesis defended here is metaphysical, not merely methodological, but its scope is carefully bounded. The claim is that, in the actual world and given current physics, metric temporal determinacy is physically grounded in stable recurring processes. Three things follow from this scoping. First, the thesis is stronger than operationalism, because it claims that recurrence does ontological work rather

[1] BIPM, "SI base unit: second," *The International System of Units (SI)*, 9th ed. (2019).

than merely supplying a convenient measurement convention. A day was real before anyone counted Earth's rotation, and cesium oscillated before anyone built an atomic clock. Second, it is weaker than a foundational claim about all possible physics: whether some alternative grounding—causal-set cardinality, thermal modular flow, or configuration-space averaging—could play this role in a hypothetical foundational theory is a separate question, taken up briefly in §6 but not settled here. Third, the novelty claim is correspondingly bounded. That periodic clocks are central to precision metrology is not new; this is implicit in Aristotle and developed technically by recent work in relational quantum dynamics.[2] What is novel is the philosophical interpretation: that this physical centrality reflects an ontological grounding relation rather than a methodological convenience, and that scientific practices of correction and standardization reveal an asymmetry between temporal convention and physical periodicity. The technical literature establishes the physical centrality of recurrent clocks; this paper argues for its metaphysical significance.

To say that process is prior to metric time is not to say that process exists earlier than time. That would be incoherent. The priority is ontological: the concept and metric of time are abstracted from, and physically grounded in, structured process. Process is not change inside an already-existing temporal container; metric time is the measure extracted from ordered process.

A further clarification about levels of claim is essential. In what follows, "operational use" refers to the practical employment of clocks and counting procedures. "Physical grounding" refers to the kinds of recurrent processes through which metric duration becomes materially stable, countable, and comparable in scientific practice. "Constitutive dependence" refers to the stronger thesis that metric temporality depends on such processes for its very determinacy. The paper argues most directly for the second claim. Its more ambitious ontological conclusion is presented as a constrained inference, not as a direct deduction from metrology alone.[3] To be precise about what is claimed: PPR holds that the metric tensor's physical determinacy *requires* realization in stable recurring processes (a grounding thesis), not that the metric tensor is *constituted by* clock processes (a stronger constitutive thesis) or merely that its *epistemic accessibility* requires clocks (a weaker epistemic thesis).

The argument is therefore neither purely epistemic nor straightforwardly deductive. It proceeds by examining the role played by recurrent phenomena in metrology, clock

[2] P. Höhn, A. R. H. Smith, and M. P. E. Lock, "Trinity of Relational Quantum Dynamics," *Phys. Rev. D* 104:066001 (2021); L. Chataignier et al., "Relational Dynamics with Periodic Clocks," *New J. Phys.* 28:034504 (2026); P. W. Evans, G. J. Milburn, and S. Shrapnel, "How Clocks Define Physical Time," PhilSci-Archive preprint 22565 (2023).

[3] The resulting position may be characterized as a *constrained realism*: realist about the physical processes that ground metric time, but constrained in scope to the actual world given current physics. The label is developed in §9.

construction, and relational physical description, and asks what ontological conclusions those practices and theories reasonably support. The strongest conclusion defended here is that periodicity is not an accidental feature of scientific timekeeping but a privileged basis for the physical grounding of metric duration. A further, more cautious conclusion is that this metrological privilege lends defeasible support to a process-relational ontology of temporal metric, even if it does not by itself resolve every larger dispute in the metaphysics of time.

A preliminary positioning is essential. The dominant debate in the philosophy of time is between A-theories (which posit a privileged present and genuine temporal passage) and B-theories (which treat the four-dimensional block of all events as the complete description of temporal reality).[4] The view defended here is orthogonal to this debate. It is not an A-theory: it does not posit a privileged present, does not require temporal passage, and takes no position on whether propositions have their truth values permanently or temporarily. Nor is it a B-theory in the standard sense, because it denies that the geometric structure of the four-dimensional manifold exhausts the physical basis of temporal metric. The A/B debate concerns temporal ontology—what exists temporally. The present paper concerns temporal metric—what makes durational claims physically determinate. These are different questions, and the answer to the second does not depend on which answer one gives to the first. It is important to distinguish two B-theoretic commitments that are often run together: the *equal-reality thesis* (all moments are equally real) and the *geometric-exhaustion thesis* (metric temporal structure is fully given by spacetime geometry). PPR is silent on the first and rejects the second. A B-theorist such as Skow (2015) or Savitt (2000) could accept PPR's metric claim while retaining the equal-reality thesis—the two are logically independent.

The view does, however, challenge a specific commitment that is standard within B-theoretic and Eternalist frameworks: the assumption that metric temporal structure is given by spacetime geometry alone. On the standard block-universe picture, the metric tensor determines proper time along worldlines, and physical clocks are systems that approximate or track this pre-given geometric structure.[5] Maudlin has developed a sophisticated version of this geometric picture while defending a "passage" view according to which temporal passage is fundamental and observer-independent.[6] The present paper argues that this picture is incomplete on a specific axis: metric structure

[4]For a careful survey of the debate in its relation to special relativity, see A. Eagle, "Relativity and the A-Theory," in E. Knox and A. Wilson (eds.), *The Routledge Companion to the Philosophy of Physics* (forthcoming). These positions come in many varieties: Zimmerman (2011) defends a presentist A-theory supplemented by a privileged foliation; Cameron (2015) develops a moving-spotlight view; Sider (2001) defends a B-theoretic four-dimensionalism; Skow (2015) develops a B-theoretic account of objective becoming. Nothing in PPR's argument depends on which version of the A-theory or B-theory is correct.

[5]See T. Maudlin, *Philosophy of Physics: Space and Time* (2012) for a careful development of the geometric picture; and B. Skow, *Objective Becoming* (2015), Ch. 9.

[6]T. Maudlin, *The Metaphysics Within Physics* (2007).

is physically grounded in stable recurring processes, and the geometric formalism describes this grounded structure rather than constituting it independently. The disagreement is not about whether all moments are equally real (the Eternalist claim about temporal existence), nor about whether temporal passage is genuine (Maudlin's claim). It is about what makes the temporal dimension metrically determinate. On that question, neither geometry alone nor primitive passage explains why scientific timekeeping repeatedly converges on stable recurrence when precision matters most. Maudlin's further argument—that no purely structural account can explain why the experience of passage is a feature of conscious life—falls outside PPR's scope: the layered architecture defended here treats experience as a separate layer with its own explanatory requirements. This is a genuine dissolution rather than a refutation: PPR and Maudlin's passage view address different layers of the temporal phenomenon, and recognizing them as different layers is itself a positive contribution of the architecture rather than merely a declaration of out-of-scope.

A terminological clarification is useful at the outset. "Periodic" refers to processes that return to the same phase or state at regular intervals. "Oscillatory" refers to processes that vary around a stable pattern, even if imperfectly. "Recurring" refers to processes that happen again without strict regularity. "Rate-stable" refers to monotonic but predictably evolving processes. "Isochronous" refers to equal-duration cycles under relevant conditions. Of these, strict periodicity provides the most robust basis for metric temporal standards, because it furnishes repeatable interval units that can be counted, compared, and calibrated across systems. The argument gives special weight to periodicity while allowing that approximate, stabilized, and ensemble-supported recurrence may also sustain metric comparison in practice.

The paper proceeds as follows. Section 2 clarifies the conceptual background. Section 3 develops the metrological core of the argument and the bridge from measurement to ontology. Section 4 introduces the universal acceleration thought experiment. Section 5 considers compatibility with relativity. Section 6 turns briefly to relational and internal-time approaches in contemporary physics. Section 7 addresses the principal objections. Section 8 draws out implications for a layered account of temporality. Section 9 concludes.

2. Historical Antecedents of Metric Time

The view defended in this paper is best understood not as a claim without precedent but as a more specific intervention within a long-standing historical problem: how temporal duration becomes measurable, comparable, and commensurable. The relevant question is not simply whether philosophers have linked time to change. Many have. The more specific question is whether metric time is to be understood as prior to the processes by which it is measured, or whether recurrent physical processes are integral to the articulation of duration itself. Read in this way, the historical background to Periodic Process Realism is not a generic lineage of "process thought" but a recurring confrontation with the problem of temporal metric.

A clarification is important at the outset. This section is not intended as a comprehensive history of theories of time. Its purpose is narrower: to identify several historical moments at which the relation between process, recurrence, and measurable duration became philosophically salient. The paper does not claim that earlier thinkers already held PPR in its present form. What is historically continuous is not a fully developed theory but a persistent problem: by what physical or conceptual means does duration become countable?

Several major figures are accordingly engaged only obliquely in what follows, and the omissions deserve brief acknowledgment. Augustine's puzzle in *Confessions* XI about where past and future could be ontologically located bears on temporal ontology rather than temporal metric, and is therefore adjacent to PPR's target rather than central to it. Newton's Scholium on absolute time is engaged through the relational tradition that defined itself against it, but without the direct treatment that Newton's own concession—that "it may be that there is no equable motion by which time may be accurately measured"—would warrant. Kant's transcendental account of time as a form of intuition operates on a level of analysis (the constitutive conditions of experience) orthogonal to PPR's first-order question about physical realization. The Reichenbach–Grünbaum tradition on the coordinative definition of temporal congruence is engaged through the conventionalist rejoinder in §3.6, again without the historical exposition that a fuller treatment would warrant. These are real omissions rather than philosophical evasions: a comprehensive history of temporal-metric thought from antiquity through the conventionalist debate would be a different and longer project; the present section identifies those figures whose contributions are most directly continuous with PPR's target question.[7]

2.1 Counted Motion, Relational Order, and the Critique of Temporal Containers

A natural starting point is Aristotle. In *Physics* IV, time is "the number of motion with respect to before and after" (219b1–2)—a definition that already makes time countable,

[7] Augustine, *Confessions*, Book XI, esp. §§14–28. Newton, *Principia* (1687), Scholium to Definition VIII. Kant, *Critique of Pure Reason* (1781/1787), Transcendental Aesthetic, A30–32/B46–48. H. Reichenbach, *The Philosophy of Space and Time* (1928; English translation 1958), §§16–19; further developed in A. Grünbaum, *Philosophical Problems of Space and Time* (Reidel, 1973), Ch. 1.

process-dependent, and explicit only through the measuring of change. Crucially, Aristotle privileges uniform circular motion—the rotation of the celestial spheres—as "especially the measure" of time (223b18–20).[8] The epistemic requirement for stable, continuous, observable recurrence to ground a temporal metric—the requirement this paper defends for atomic oscillators—was already articulated for cosmological periodicity in the fourth century BCE. Recent work in the Aristotelian tradition confirms the broader framing: Poletti argues that measured change is what we call time;[9] Deasy argues that time *is* change.[10] These are close neighbors. What distinguishes PPR is the further claim that among changes, recurring changes are privileged because they furnish the most stable, countable, comparable metric units. The upgrade is from "time depends on change" to "metric time depends on repeating change."

Leibniz sharpens the issue by opposing relational and substantival conceptions directly. Against Newton, he treats time as the "order of successions" rather than an independently existing substance.[11] Once time is denied independent ontological standing, the question of metric articulation becomes more acute: if temporal order arises relationally, how is duration stabilized and compared?

Mach radicalizes this pressure: time is an abstraction derived from the changes of things, not an entity in its own right, and all measurements of time are essentially physical comparisons of one process against another.[12] His critique remains potent: temporal concepts must answer to the actual behavior of material processes rather than float free as explanatory surplus. Yet Mach, like Aristotle, speaks of change generically. Neither isolates recurrence as the privileged basis of metric temporality. Mach's insight was that time is a functional relationship between the changes of things; what he lacked was a specific account of which changes furnish metric determinacy. PPR supplies that specificity: stable recurrence is the feature that converts Mach's generic "abstraction" into a concrete physical basis for metric comparability.

The lineage is therefore: Aristotle links time to the measure of change; Leibniz denies the temporal container; Mach insists on physical process as the basis of temporal concepts. It is not novel to deny absolute time. It is not novel to tie time to change. What is distinctive in PPR is the claim that recurrence is the strongest candidate for the physical basis of metric time—that the move from change to cycle is not merely a metrological preference but reflects an ontological privilege.

[8] Aristotle, *Physics*, IV.11–14. For the interpretive complexity of Aristotle's treatment of time and circular motion, see U. Coope, *Time for Aristotle* (2005).

[9] M. Poletti, "Time as Change" (2022). PhilArchive.

[10] D. Deasy, "Time Is Change," *Philosophies* 11(3):67 (2026).

[11] G. W. Leibniz, in *The Leibniz-Clarke Correspondence* (1715–1716), Third Paper, §4.

[12] E. Mach, *Die Mechanik in ihrer Entwickelung* (1883), Ch. II, §6. See also P. Thébault, "On Mach On Time," PhilSci-Archive (2021).

2.2 Process Views and Their Limits

Process philosophy provides the broader metaphysical scaffolding. Whitehead's insistence that "at an instant there is nothing"[13] and that process is ontologically prior to substance aligns with the deeper ontology defended here.[14] PPR converges with this tradition but adds a constraint it does not impose: not every process equally realizes temporal metric. Stable recurring processes are special because they furnish repeatable units, ratios, and commensurability. A single, unrepeated event may reveal that the world is not static, but it does not by itself provide a standard for comparing durations. The distinction matters because temporal order and temporal metric are not the same problem. General process views may explain why reality is composed of happenings rather than static substances, but they do not thereby explain how duration becomes countable, comparable, and reproducible.

A related position deserves acknowledgment. Process Structural Realism, developed by Earley, argues that ontologically significant coherence arises when networks of processes achieve closure such that states recur continually.[15] Where PSR asks what makes composite entities ontologically real, PPR asks what makes metric temporal claims physically determinate. Both privilege recurrence, but PPR's claim is narrower—it concerns the specific role of stable periodicity in the physical realization of countable, comparable duration.

2.3 From Celestial Cycles to Atomic Standards

The most important historical transition for the present paper is metrological. Scientific timekeeping has repeatedly sought out recurrent processes as standards, while progressively refining what counts as sufficiently stable, reproducible, and isolable recurrence. The historical movement from astronomical to atomic standards is significant not because it replaces one idea of time with another, but because it preserves a functional commitment to recurrence across changing physical substrates.[16]

In earlier regimes, the most authoritative temporal standards were celestial: apparent solar motion, terrestrial rotation, orbital regularities. Their authority rested on accessibility and apparent regularity. As precision demands increased, those standards proved insufficiently stable. Irregularities in terrestrial rotation and the growth of systems requiring finer temporal resolution created pressure for new standards. The shift to

[13] A. N. Whitehead, *The Concept of Nature* (1920), Ch. III.

[14] J. Seibt, "Process Philosophy," *Stanford Encyclopedia of Philosophy* (2022); N. Rescher, *Process Metaphysics* (1996).

[15] J. E. Earley, "Ontologically Significant Aggregation: Process Structural Realism (PSR)," in M. Weber (ed.), *Handbook of Whiteheadian Process Thought* (2006).

[16] G. M. Clemence, "Astronomical Time," *Reviews of Modern Physics* 29:2 (1957).

atomic time in 1967 did not abandon recurrence. It intensified reliance on it. What changed was not the functional role of recurrence but the quality of the recurrent process chosen to bear metrical authority. The transition was contested: astronomers saw the atomic second as abandoning the dynamically integrated temporal scale that Newtonian mechanics required, and the adoption was shaped as much by the post-war development of microwave radar technologies and the institutional priorities of global navigation as by any pure epistemic insight.[17] The genuine intellectual loss in this transition should be acknowledged: ephemeris time was dynamically anchored to the equations of motion in a way that atomic time, defined by a single isolated transition frequency, is not. PPR's claim is that the functional continuity—the continued reliance on stable recurrence as the basis of metric authority—is more significant than the change in substrate, but this is a philosophical argument, not a self-evident historical fact. The trajectory continues: the CGPM voted in 2022 to redefine the second using optical clock transitions, with adoption targeted for 2030.[18]

The history of time standards is not merely the history of increasingly accurate clocks. It is the history of science repeatedly relocating temporal authority into recurrent physical processes judged capable of sustaining comparison, correction, and reproducibility under stricter conditions. Scientific practice does not progressively shed recurrence as it advances. It repeatedly seeks better recurrence.

The historical lesson, then, is not that earlier thinkers already held Periodic Process Realism, nor that the history of clocks straightforwardly proves an ontology of time. It is more disciplined than that. Again and again, the problem of temporal metric has pressed both philosophy and scientific practice toward process; and within process, scientific standardization has repeatedly privileged recurrence. Aristotle identifies the link between motion and countability. Relational critics deny that time is an independently existing container. Mach intensifies suspicion toward idle temporal structure. Metrological history then shows how scientific practice stabilizes duration by relocating temporal authority into ever more reliable recurrent phenomena. The next section develops that claim directly through the history and logic of modern time standards.

[17] For the institutional context, see D. Finkleman et al., "The Future of Time: UTC and the Leap Second," *American Scientist* 99:4 (2011); for the metrological debates, W. J. Markowitz et al., "Frequency of Cesium in Terms of Ephemeris Time," *Phys. Rev. Lett.* 1:3 (1958). On the technical and institutional coordination underlying atomic time standards, see D. W. Allan, N. Ashby, and C. C. Hodge, *The Science of Timekeeping* (Hewlett-Packard Application Note 1289, 1997).

[18] BIPM, "Roadmap towards the redefinition of the SI second" (2024).

3. Metrology and the Physical Grounding of Metric Time

The core argument of this paper is metrological. If one wants to know what scientific practice treats as the physical basis of metric time, one should begin not with abstract intuitions about temporal flow but with the construction, regulation, and standardization of clocks. Across major shifts in physical theory and instrumentation, authoritative time standards have repeatedly been secured through recurrent phenomena. The significance of this continuity is not merely practical. It suggests that recurrence is not an accidental feature of chronometry but a privileged basis on which duration becomes physically comparable and reproducible.

3.1 The SI Second

The present SI second is defined by fixing the cesium-133 hyperfine transition frequency at exactly 9,192,631,770 Hz.[19] The BIPM states explicitly that this corresponds to the duration of that many periods of the corresponding radiation. A clock combines an oscillator—a steady repeating process—with a device that counts those repetitions.[20] The oscillator provides the periodicity; the counter provides the accumulation. Together they produce measured duration.

3.2 The Functional Continuity of Recurrent Standards

The historical progression described in §2 deserves closer philosophical analysis. Before the atomic era, the second was defined through astronomical recurrence: first as a fraction of the mean solar day, then through the tropical year. After 1967, it was anchored to cesium oscillation.[21] The candidate optical transitions—strontium-87 and ytterbium-171 lattice clocks—represent yet another move from less stable to more stable periodicity.[22]

The transition from astronomical to atomic time in 1967 is philosophically instructive beyond its metrological significance. Ephemeris time—the time scale defined through celestial mechanics, derived from the orbital motions of Earth, Moon, and planets via solutions to the equations of motion—was in a certain sense more theoretically anchored than atomic time: it was the time that Newtonian dynamics *required* bodies to follow.[23] Atomic time was, by contrast, simply "what cesium clocks measure." The redefinition was contested partly because it appeared to some practitioners as a step away from

[19] BIPM (2019).

[20] NIST, "How Do Atomic Clocks Work?" (accessed May 2026).

[21] BIPM, "Mise en pratique for the definition of the second in the SI" (accessed May 2026).

[22] BIPM, "Roadmap towards the redefinition of the SI second" (2024); see also Dimarcq et al., "Roadmap towards the redefinition of the second," *Metrologia* 61:012001 (2024).

[23] G. M. Clemence, "Astronomical Time," *Reviews of Modern Physics* 29:2 (1957).

theoretical grounding rather than toward it. On the view defended here, the transition is better understood as a move from a less stable to a more stable recurrent standard—from orbital motion (with its irregularities and observational difficulties) to atomic transitions (with their extreme precision and local reproducibility). The theoretical anchoring of ephemeris time was real, but it was anchoring to a recurrent process whose stability was inferior to the process that replaced it. The functional continuity—stable recurrence as the basis of metric temporal realization—was preserved across the change in substrate. A tension should be noted: ephemeris time was a *dynamically embedded* standard (anchored in the gravitational equations of motion), while atomic time is a *modular* standard (realizable by an isolated physical system). PPR's emphasis on comparison networks sits more naturally with embedded standards; but the resolution is that modularity is a property of the *standard*, while the realization of a globally usable metric still requires the comparison network—a single isolated cesium clock realizes a frequency, but realizing a *second* requires coordination.

3.3 Monotonic Devices and the Limits of Non-Periodic Timing

A natural objection is that not all devices used to measure duration are intrinsically periodic. Hourglasses, water clocks, and radiometric techniques track monotonic processes. None is cyclic in the way an atomic clock is cyclic. This objection is important, and its strongest form—radiometric dating—deserves explicit engagement.

In geochronology, Uranium-Lead decay provides intrinsic, highly stable duration measurement over billions of years through the ratio of parent to daughter isotopes. This is a cycle-independent mechanism. The present thesis does not deny that monotonic, rate-stable processes can establish a form of temporal comparison. What it claims is that periodic processes occupy a privileged position because they furnish repeatable units with exceptional stability and comparability, and because the temporal significance of monotonic processes typically depends—at least for numerical expression—on calibration against more stable recurring standards. The half-life is defined in seconds, where the second is itself defined through recurrence. More fundamentally, the statistical regularity of decay ensembles provides a weaker form of the same structural feature periodicity provides in its strongest form: reproducible temporal comparison across instances.

The thesis should therefore be understood as identifying periodicity as the paradigmatic and most robust realizer of metric temporal structure, while acknowledging that rate-stable statistical processes represent a weaker but genuine alternative in regimes where periodic standards are unavailable.

3.4 Periodic Stability and the Function of Precision Clocks

Evans, Milburn, and Shrapnel argue that precision clocks are best understood in terms of limit-cycle dynamics—closed, periodic trajectories that act as stable attractors in phase space.[24] In the clearest cases, such systems are open, driven, nonlinear, and dissipative. This means that stable precision timekeeping typically requires mechanisms for stabilization, driving, dissipation, and recording. Their analysis strengthens the present thesis by showing why the convergence on recurring process is not a contingent feature of human engineering but reflects the dynamical conditions under which stable, comparable, recordable temporal units can be physically realized. The view defended here goes beyond that operational account by proposing that stable recurrence has the strongest claim to realize metric temporal determinacy.[25]

3.5 From Metrological Privilege to a Restrained Ontological Claim

Metrology does not, by itself, settle the ontology of time. A substantivalist may still argue that clocks merely track an independently existing temporal structure. The metrological observations of the preceding subsections establish that every major realization of precise temporal standards depends on stable recurring process, but they do not establish that this dependence is metaphysical rather than methodological. The argument from metrology to ontology must therefore proceed by inference to the best explanation, which requires actually surveying the alternatives.

A clarification about measurement is needed here. Contemporary philosophy of measurement treats measurement not as passive detection of a pre-given quantity but as model-mediated coordination between theoretical quantities and physical realizations.[26] Time measurement, on this view, is not clocks reading off a hidden flow but the stabilization of temporal ratios through oscillator models, correction procedures, and calibration networks. The view defended here accepts this analysis but draws an ontological conclusion from it: the coordination succeeds because stable recurrence provides the physical target that the institutional apparatus is designed to track. The coordination is epistemic; the target is physical.

Four explanations of the metrological convergence on recurring process deserve consideration.

[24] P. W. Evans, G. J. Milburn, and S. Shrapnel, "How Clocks Define Physical Time," PhilSci-Archive preprint 22565 (2023).

[25] Cf. E. Tal, "Old and New Problems in Philosophy of Measurement," *Philosophy Compass* 8 (2013): 1159–1173.

[26] E. Tal, "Making Time: A Study in the Epistemology of Measurement," *British Journal for the Philosophy of Science* 67 (2016): 297–335. See also H. Chang, *Inventing Temperature* (2004); B. van Fraassen, *Scientific Representation* (2008).

The technological convenience hypothesis. Stable recurring processes are simply the easiest physical phenomena to engineer into precision standards. On this view, the convergence is contingent: a sufficiently advanced civilization might use different standards. The hypothesis is consistent with metrological history but does not survive engagement with the limit-cycle analysis of Evans, Milburn, and Shrapnel, which shows that the convergence reflects physical constraints on what it takes to realize precision temporal metric, not merely engineering pragmatics.

The species-relative hypothesis. Stable recurrence is the basis of human-accessible metrology, but other observers might use different bases. This fails because the convergence on recurrence holds precisely in the regime where human perceptual access is already lost—cesium hyperfine transitions, optical lattice frequencies, and nuclear isomeric transitions are not perceptually accessible.

The regime-relative hypothesis. Stable recurrence realizes metric time in the physics we currently understand, but in regimes we lack access to (very early universe, near singularities), the grounding may differ. This hypothesis is the strongest alternative, and the present thesis substantially concedes it. The scoping move in §1 acknowledges that the view defended here is a thesis about the actual world given current physics, not a foundational claim about all possible regimes.

The physical realization hypothesis. Stable recurring processes physically realize metric temporal determinacy in the actual world. The convergence is neither contingent nor merely human-accessible nor obviously regime-extendable. Among these four, this hypothesis alone explains all three considerations together: the limit-cycle analysis shows the convergence reflects physical constraints; the convergence holds beyond human perception; and current physics assigns periodic clocks a formally distinctive role. It therefore has the strongest claim to be the best explanation of the metrological convergence. The conclusion is defeasible, not deductive. But it is the most plausible explanation of an empirical pattern that all parties acknowledge. The IBE operates within the scoped domain of the actual world given current physics; it does not claim to be the best explanation against all conceivable foundational alternatives, including those that would require a different physics.

A fifth position deserves explicit engagement. A substantivalist may grant the metrological convergence on recurrence while denying any ontological lesson: the convergence, on this view, reflects an epistemic constraint on creatures whose access to a geometrically pre-given metric must be mediated through dynamical systems of a certain form. This is not the technological-convenience hypothesis; it is a substantive claim that recurrence is needed for *access* but not for *determinacy.* The reply is that this position makes the convergence an unexplained brute fact about creaturely access. Any explanation of *why* creatures need recurrence to access the metric will bottom out in the dynamical role recurrent processes play in physical systems—which is what PPR claims. The substantivalist might retreat further: granting that some dynamical mediation is required for epistemic access while denying that *periodic* mediation specifically is privileged for determinacy. But the limit-cycle analysis of §3.4 forecloses this retreat—Evans, Milburn, and Shrapnel show that closed periodic attractors are required not merely for accessing an antecedently determinate metric but as a physical constraint on what it takes to *realize* precision metric structure at all. The epistemic-constraint position is not refutable, but it is explanatorily less satisfying than the physical-realization hypothesis, which explains the convergence rather than stipulating it.

3.6 The Asymmetry of Correction

A sophisticated objection holds that Coordinated Universal Time (UTC) is not the output of any single periodic process but a statistical construct, calculated retrospectively by the BIPM using a weighted algorithm that averages the outputs of over 400 commercial atomic clocks, steered by a handful of primary frequency standards, with corrections for gravitational redshift, blackbody radiation, magnetic field effects, and relativistic dilation.[27] If the most precise metric of time requires theoretical models, statistical algorithms, and institutional consensus to be realized, is it problematic to claim that the metric is realized through mind-independent periodicity?

The objection reveals epistemic complexity but does not undermine the realist thesis. The corrections applied to physical clock data—for gravitational redshift, blackbody radiation, magnetic field effects, and relativistic motion—are corrective measures, not the timekeeping itself. Their function is precisely to recover the behavior of an ideal, unperturbed periodic process. The relationship is analogous to the leap year: the corrective mechanism exists because the physical periodicity is the target that the institutional apparatus is designed to track.

The hierarchy of correction consistently flows in one direction: from the counting system toward the physical periodicity, never the reverse. This asymmetry is not unique to temporal measurement—correction practices in thermometry, mass metrology, and other domains display the same structural feature—but temporal metric is the case where the asymmetry is most clearly institutionally displayed, because the corrective hierarchy (from leap years through relativistic adjustments) is explicit and publicly coordinated. These corrections operate at different levels—leap years adjust the calendar to match Earth's orbital period; leap seconds adjust UTC to match Earth's rotation; blackbody

[27] See E. Tal, "Making Time: A Study in the Epistemology of Measurement," *British Journal for the Philosophy of Science* 67 (2016): 297–335.

and relativistic corrections adjust atomic-clock readings to recover the behavior of the unperturbed transition. The correction regimes differ in their technical character (calendar alignment, rotational synchronization, theoretical modeling of perturbation), but they share a structural feature: in every case, the counting system yields to the physical process, not the process to the count. We do not adjust Earth's orbit to match the calendar, nor the cesium transition to match the clock reading. This asymmetry is not a feature of convention. It is a structural feature of what it means for a measurement to be correct. A measurement system that drifted from its physical target without correction would not represent an alternative convention—it would be wrong.

The entire corrective apparatus of modern metrology exists because there is a physical periodicity that the apparatus is designed to track. If the metric were a purely institutional construction, the corrections would be arbitrary. The fact that they converge non-arbitrarily on specific physical targets supports a process-relational interpretation: the periodicity is the physical target, and the institutional apparatus is the epistemic means of accessing it.

This argument operates at the level of physical realization identified in §1, not at the level of unrestricted metaphysical grounding. It does not prove that metric time could not exist without recurrence in every conceivable physics. It shows that, in the actual world, the corrective practices of working metrology are oriented toward physical periodicity in a way that is structurally asymmetric, and that this asymmetry is best explained by the hypothesis that recurrence is the physical basis the corrections are designed to recover.

A conventionalist rejoinder deserves direct engagement. The objection holds that the "wrongness" of a drifting measurement system is itself a conventional judgment rather than a discovery about physical reality: "wrong" relative to the standards the community has chosen, not wrong relative to nature. The reply goes through multi-system convergence. A measurement system that drifted from its physical target would not merely fail to match a single chosen standard—it would progressively decohere from every independent measurement system that converges on the same physical periodicity. Cesium fountain clocks, hydrogen masers, optical lattice clocks, and GPS satellite comparisons all yield convergent results not because they share a convention but because they independently track the same class of physical regularity. The convergence of independent systems on a common target is what makes "wrong" non-circular: a drifting system is wrong because it fails to cohere with the physically constrained network, not because it violates an arbitrary stipulation. This multi-system convergence argument operates within Tal's coordination framework—where measurement is understood as model-mediated coordination between theoretical quantities and physical realizations—while drawing a realist conclusion that the framework itself does not require: the coordination succeeds because there is a physical target the independent systems are tracking.

The choice of a unit is conventional; the stability relations that make any such unit usable are not.

4. Universal Acceleration and Idle Temporal Structure

The following thought experiment does not by itself establish a process ontology of time, nor does it uniquely vindicate periodicity. Its role is narrower: it establishes the negative claim that an independently posited temporal metric does no explanatory work when all physically realized process-rates scale together. This negative claim is shared with other relational and process-based views (Leibniz, Mach, Barbour, Rovelli); what is distinctive to PPR is the positive claim developed in §3—that stable periodicity is specifically privileged in the physical realization of metric time. The present section removes the competitor; §3 identifies the winner.

4.1 The Thought Experiment

Suppose every physical process in the universe—every atomic oscillation, every planetary orbit, every chemical reaction, every quantum transition—were to speed up uniformly by the same factor. How would we know? The question has a substantial pedigree: Poincaré explored the epistemic consequences of uniform temporal rescaling;[28] Newton-Smith developed the argument as a test for substantivalism about temporal metric;[29] Earman placed it in the broader context of spacetime symmetry arguments.[30] What is not new is the thought experiment. What is new is the extension developed in §4.3: the identification of an empirical boundary condition under which the argument's precondition fails, and the connection of that boundary condition to the sensitivity of periodic processes to the fine-structure constant.

The thought experiment functions as a reparameterization test: where two descriptions differ only by a uniform rescaling of all physical process-rates, and all dimensionless ratios remain invariant, the difference is representational rather than physical.[31]

[28] H. Poincaré, *La Science et l'Hypothèse* (1902), Ch. V.
[29] W. H. Newton-Smith, *The Structure of Time* (1980), Ch. II.
[30] J. Earman, *World Enough and Space-Time* (MIT Press, 1989).
[31] The test applies strictly when "all" means genuinely all physical processes. If some processes were exempt from the scaling, the relevant ratios could change.

4.2 What the Thought Experiment Rules Out

The test divides theories of time into two categories. Theories on which universal acceleration is meaningful include Newtonian absolute time, on which an independent background metric registers the change, and substantivalist views generally. Smolin's temporal naturalism occupies a nuanced intermediate position: Smolin treats certain background dynamics (the evolution of constants and possibly laws) as observable in principle, so universal acceleration would on his view produce observable consequences through the evolution of constants, even though it would not produce them through clock comparisons alone.[32]

Theories on which universal acceleration is empirically idle include Leibnizian relationism, Machian time, Barbour's timeless configurations,[33] Rovelli's relational mechanics,[34] and the present thesis. On all of these, universal acceleration produces no observable difference in dimensionless ratios. The A-theory/B-theory and presentism/eternalism debates are largely orthogonal, since they concern temporal passage and the existence of past/future, not the operational basis of temporal metric.

Two versions of the argument should be distinguished. The weak version is a parsimony argument: universal acceleration produces no observable difference, so a theory positing absolute time adds no explanatory content. The strong version is a metaphysical-emptiness argument: the scenario is not merely empirically equivalent but physically empty. The weak version is what this paper relies on. The strong version would require additional argument that the paper does not undertake.

4.3 The Boundary Condition: When the Razor Breaks

The razor holds when all processes accelerate uniformly. It breaks when fundamental constants—particularly the fine-structure constant α—change, causing different classes of periodic process to respond differently. Nuclear transitions scale with α raised to a different power than electronic transitions. A change in α would cause nuclear clocks and optical clocks to drift apart, producing a detectable dimensionless ratio change.

The thorium-229 nuclear isomeric transition exhibits a sensitivity to α-variation characterized by an enhancement factor $K \approx 5{,}900$—meaning that a fractional change in α would produce a fractional frequency shift in this transition approximately 5,900 times larger than the α-change itself, roughly three orders of magnitude more sensitive than optical clock transitions based on electron-shell processes.[35] A comparison between

[32] L. Smolin, *Time Reborn* (2013).
[33] J. Barbour, *The End of Time* (1999).
[34] C. Rovelli, "Forget Time," *Found. Phys.* 41:1475 (2011).
[35] K. Beeks et al., "Fine-structure constant sensitivity of the Th-229 nuclear clock transition," *Nature*

nuclear and optical clocks would therefore constitute a direct test of whether the razor's precondition (uniform scaling) holds.

The philosophical significance is twofold. First, the boundary condition shows that the razor is empirically testable, not merely a thought experiment. Second, even the test relies on comparing periodic processes of different types—precisely the metrological practice that the view defended here identifies as the physical basis of temporal metric.

A concession is appropriate here. The universal acceleration argument supports anti-idle-background reasoning more directly than it uniquely vindicates periodicity. Any relational or process-based account that grounds temporal metric in physically instantiated structure benefits from the argument. Its relevance to the present thesis is that it strengthens the case that metric time must be anchored in physically realized process-relations, and periodicity is—for the reasons developed in §3—the privileged form such anchoring takes in scientific practice.

5. Relativity as a Compatibility Test

Relativity does not entail the view defended here, but it provides an important test of its coherence. In relativistic physics, elapsed time is not secured by appeal to a universal background flow; it is assigned along worldlines and physically registered by clocks. This makes relativity congenial to a process-based account of metric realization, even though the formal structure of proper time is not reducible to periodic clocks themselves.

The philosophical significance of proper time has its own history, distinct from the metrological trajectory traced in §2. Newton's absolute time was a universal parameter independent of physical processes—though Newton himself conceded in the Scholium that "it may be that there is no equable motion by which time may be accurately measured." Einstein's special relativity operationalized time measurement through light signals and clocks, making duration frame-dependent but proper time invariant along worldlines. Minkowski's geometric reinterpretation then recast spacetime as a four-dimensional manifold in which proper time is path length, establishing the metric tensor as the bearer of temporal structure.[36] Eddington and later Weyl recognized early that this geometric structure acquires physical content only through the behavior of material clocks and rods.[37] Brown's dynamical perspective (2005), Arthur's defense of local becoming along worldlines (2006), and Valente's arguments for proper-time fundamentality (2019)

Communications 16:9147 (2025). DOI: 10.1038/s41467-025-64191-7.

[36] H. Minkowski, "Space and Time," address to the 80th Assembly of German Natural Scientists and Physicians (1908).

[37] A. S. Eddington, *The Mathematical Theory of Relativity* (1923), Ch. 1; H. Weyl, *Space-Time-Matter* (1922), §§12–13.

represent the contemporary culmination of this trajectory: spacetime geometry is physically significant not in itself but through its realization in the dynamical behavior of material systems.[38] PPR extends this lineage by identifying stable periodicity as the specific physical feature that makes proper-time accumulation metrically determinate.

5.1 Proper Time, Physical Clocks, and Functional Realization

General relativity eliminates universal background time. Different clocks accumulate different amounts of proper time depending on their motion and gravitational environment. The metric tensor determines proper time along worldlines; physical clocks are systems that approximately track this geometric quantity under suitable conditions.[39]

A natural objection arises: does metric geometry determine time, not recurrence? The view defended here does not claim to replace the metric tensor. It claims that the physical significance of metric geometry consists in its role in structuring possible clock processes and their comparisons.[40] GR provides formal structure; recurring processes realize that structure physically. More precisely, geometry formally constrains possible clock behavior, while recurrent clock processes physically realize the metric relations that give the formal structure empirical grip. The relationship is one of mutual dependence, not reduction in either direction. The distinction between ideal clocks (mathematical objects whose readings correspond exactly to proper time) and actual clocks (physical systems that approximate this ideal through stable recurrence) is essential. On the view defended here, ideal clocks represent the limiting behavior of stable recurring processes under specified conditions. The physical instantiation of temporal metric occurs through clock-like processes, not through an independently accessible temporal substrate.

5.2 Compatibility Without Entailment

The closest allied position in the philosophy of physics literature is Brown's dynamical perspective on relativity.[41] Brown argues that the chronometric significance of spacetime geometry is grounded in the dynamical laws governing material systems—including clocks—rather than in geometry independently. PPR can be read as a specific application of Brown's program to the temporal metric: where Brown argues that spacetime structure in general is dynamically constituted, PPR argues that metric temporal structure in

[38] G. Valente, "On the Nature of the Proper Time," *Studies in History and Philosophy of Modern Physics* 67:1–8 (2019).

[39] BIPM notes that the SI second is "the unit of proper time" in GR. See BIPM SI Brochure, 9th ed. (2019), §2.3.1.

[40] This aligns with spacetime functionalism: E. Knox, "Effective Spacetime Geometry," *Stud. Hist. Phil. Mod. Phys.* 44:346 (2013); V. Lam and C. Wüthrich, "Spacetime Is as Spacetime Does," *Stud. Hist. Phil. Mod. Phys.* 64:39 (2018).

[41] H. R. Brown, *Physical Relativity: Space-Time Structure from a Dynamical Perspective* (2005).

particular is physically grounded in the stable periodic processes that constitute actual clocks. This also clarifies PPR's stance on the clock hypothesis (that an ideal clock measures proper time regardless of acceleration history): PPR treats the clock hypothesis as approximately satisfied *because of how physical clocks are dynamically constituted*, not as a brute postulate about the relationship between geometry and matter.

PPR's relationship to Maudlin is the structural inverse of its relationship to Brown. Where Brown is PPR's closest ally—both treat spacetime structure as dynamically constituted rather than geometrically primitive—Maudlin is the principal opponent on the specific question of temporal metric.[42] Maudlin holds that the metric tensor determines proper time along worldlines and that this determination is a fundamental, non-derivative physical fact. On his view, clocks are physical systems that track a pre-given geometric structure; the metric is not constituted by clock behavior but is what makes clock behavior intelligible. PPR denies precisely this: the metric tensor describes metric relations, but the physical determinacy of those relations is realized through the stable recurring processes through which they become comparable and reproducible. The disagreement is not about whether the metric tensor is physically real—PPR grants that it is—but about whether it is self-sufficient for metric temporal determinacy or whether it requires supplementation by the physical processes that realize it.

The fit is interpretive rather than literal. GR is far more hospitable to a process-relational interpretation of temporal metric than to Newtonian substantivalism, but it does not by itself entail the thesis. The strongest defensible claim is that GR naturalizes the thesis—makes it more plausible than substantivalist alternatives—without proving it.

5.3 The Twin Paradox and Accumulated Proper Time

The twin paradox illustrates the thesis concretely. One twin remains on Earth while the other undertakes a high-speed journey and returns younger. The traveling twin's clock accumulates less proper time. On the interpretation defended here, this is a difference in accumulated physical process integrated along a worldline, where the integration is realized through clock-like subsystems whose recurring dynamics provide the metric units. This is a metaphysical interpretation of what proper-time accumulation amounts to when realized in actual systems, not a physiological claim about rate-dependence on velocity.[43]

Gravitational time dilation provides a further illustration that is not merely compatible with PPR but actively supports it. Inside a gravitational well, all physical processes slow together: atomic oscillations, biological metabolism, signal propagation, radioactive

[42] T. Maudlin, *The Metaphysics Within Physics* (2007), Chs. 4–5.

[43] Biological aging proceeds at proper-time rates; the interpretation offered here is a metaphysical gloss on what those rates physically consist in, not a prediction that aging would behave differently than GR specifies.

decay. The local observer detects nothing anomalous—her clock reads normally, her heartbeat feels normal, her aging proceeds at the expected rate. The dilation is detectable *only* through comparison of periodic process rates across gravitational potentials—which is precisely what the Global Positioning System does every microsecond, applying relativistic corrections to keep satellite clocks synchronized with ground clocks.[44] This is the universal acceleration razor realized in nature rather than in thought experiment: all local processes shift together; the shift is visible only through cross-frame comparison of periodic standards. The Eternalist describes this as geometry "tilting" the worldline; PPR describes it as periodic processes running at different rates in different gravitational environments, with the difference detectable only through the metrological comparison that PPR identifies as fundamental.

6. Relational and Internal Time in Contemporary Physics

Although the present section turns to contemporary foundational physics, its relevance is continuous with the historical problem traced in §2: once metric temporality is no longer treated as a self-standing background, the question becomes what kinds of physical structure can render duration determinate. The aim of this section is not to derive the view defended here from quantum gravity or to claim that foundational physics has already vindicated a process-based ontology of time. The more modest aim is to ask whether relational and internal-time approaches preserve a meaningful role for physically realized clock structure when external time parameters become problematic. On that narrower question, these approaches are suggestive, though not decisive.

6.1 When External Time Parameters Drop Out

The problem of time in quantum gravity arises because canonical quantization of general relativity produces a formalism without an external time parameter. The Wheeler-DeWitt equation is often described as "timeless."[45] The view defended here interprets this as motivation rather than crisis: if metric time is physically realized through processes rather than imposed from outside, the deepest physical formalism need not contain an external time parameter.

[44] GPS satellite clocks gain approximately 38 microseconds per day relative to ground clocks due to gravitational and velocity effects; the corrections are computed by comparing cesium oscillation rates across frames. See N. Ashby, "Relativity in the Global Positioning System," *Living Reviews in Relativity* 6:1 (2003).

[45] C. J. Isham, "Canonical Quantum Gravity and the Problem of Time," arXiv:gr-qc/9210011 (1992). For more recent treatments, see E. Anderson, *The Problem of Time* (Springer, 2017) and P. Thébault, "The Problem of Time," *Stanford Encyclopedia of Philosophy* (2021).

6.2 Relational Clock Systems and the Page-Wootters Mechanism

The Page-Wootters mechanism shows that an isolated, globally stationary quantum system can exhibit internal temporal structure: one subsystem functions as a clock, and other subsystems evolve relative to its states.[46] This is relevant because it shifts attention toward the physical structure required of clock subsystems.

A historically important concern deserves acknowledgment. Kuchař (1992) argued that the Page-Wootters mechanism produces incorrect propagators for two-time correlation functions, an objection that constituted a major obstacle for nearly thirty years.[47] In constrained systems like general relativity, the Hamiltonian must vanish on physical states, and Kuchař showed that this creates paradoxes for internal clock construction. The objection was substantively addressed by Höhn, Smith, and Lock, whose framework establishes equivalences among several relational formulations and shows how correlations can be recovered correctly.[48] The present thesis does not stand or fall on the resolution of this debate, but the contemporary relational-dynamics literature is not the original Page-Wootters proposal; it is a substantially refined framework.

Subsequent work by Chataignier, Höhn, Lock, and Mele on relational dynamics with periodic clocks shows that relational observables relative to periodic clocks are globally gauge-invariant only when the encoded system quantity is itself periodic—otherwise they are only transiently invariant per clock cycle.[49] These formal results do not establish that all emergent temporal structure must be periodic; they show that periodic clocks enjoy special formal advantages. The philosophical conclusion is accordingly limited: periodicity plays a formally nontrivial role in relational-clock frameworks. This is consistent with—but does not establish—the philosophical claim that periodic clocks realize metric determinacy. The technical distinctiveness suggests, however, that any account of relational temporal metric must take periodicity seriously as a structural feature rather than treating it as one indifferent option among many.

These developments are part of a broader program treating clocks as quantum reference frames (QRFs)—physical subsystems whose degrees of freedom serve to localize or describe other subsystems relationally.[50] When the reference frame is temporal—a quantum clock—frame transformations realize changes of temporal perspective. In the

[46] D. Page and W. Wootters, "Evolution Without Evolution," *Phys. Rev. D* 27:2885 (1983).

[47] K. Kuchař, "Time and Interpretations of Quantum Gravity," in *Proceedings of the 4th Canadian Conference on General Relativity and Relativistic Astrophysics* (1992).

[48] P. Höhn, A. R. H. Smith, and M. P. E. Lock, "Trinity of Relational Quantum Dynamics," *Phys. Rev. D* 104:066001 (2021).

[49] L. Chataignier et al., "Relational Dynamics with Periodic Clocks," *New J. Phys.* 28:034504 (2026).

[50] F. Giacomini, E. Castro-Ruiz, and Č. Brukner, "Quantum Mechanics and the Covariance of Physical Laws in Quantum Reference Frames," *Nature Communications* 10:494 (2019); A. Vanrietvelde et al., "A Change of Perspective: Switching Quantum Reference Frames via a Perspective-Neutral Framework," *Quantum* 4:225 (2020).

periodic-clock case, clocks are modelled as U(1)-quantum reference frames, and the resulting relational dynamics are necessarily periodic. The QRF program demonstrates that stable periodic recurrence is structurally required for well-defined relational metric structure in background-independent theories, reinforcing PPR's claim from the metrological side.

A note on the relationship between PPR and Rovelli's eliminative relationalism is appropriate here. Rovelli's "forget time" program[51] holds that time is not fundamental but emergent—a macroscopic approximation arising from our ignorance of microstates. PPR agrees that temporal metric is not a fundamental container but disagrees with the eliminative conclusion. PPR is realist about the physical processes that ground metric time: stable recurrences are real features of the world, not artifacts of coarse-graining. The position is therefore more relational than substantivalism but more realist than Rovelli's eliminativism—a middle ground that the relational quantum dynamics literature itself seems increasingly to occupy.

6.3 Thermal Time as an Alternative

The thermal time hypothesis[52] constitutes a serious foundational competitor. On this view, temporal flow is given by the modular automorphism group generated by a thermal state on the algebra of observables. Technically, the modular flow on a Type III von Neumann algebra does not require underlying periodic dynamics: it can generate a one-parameter group of automorphisms from a thermal state without any recurrence at all. This must be acknowledged honestly: thermal time offers a genuine alternative route to temporal structure that PPR cannot simply absorb.

Three considerations nonetheless bear on the comparison. First, in equilibrium systems where both frameworks apply, the modular flow often corresponds to dynamics whose underlying structure is approximately periodic; here thermal time and PPR are complementary rather than competing. Second, the empirical and operational case for the centrality of periodic process is currently far more developed than the parallel case for thermal-statistical grounding, which remains largely programmatic outside idealized equilibrium regimes. Third, where the two genuinely diverge—in regimes where modular flow could generate temporal structure without underlying periodic dynamics—the disagreement is foundational. PPR does not claim to settle it. Its scoping to "the actual world given current physics" is not a weakness but a feature: it makes the thesis empirically testable rather than foundationally speculative. In the actual world, the physical realization of metric time runs through recurrence.

[51] C. Rovelli, "Forget Time," *Found. Phys.* 41:1475 (2011).

[52] A. Connes and C. Rovelli, "Von Neumann Algebra Automorphisms and Time-Thermodynamics Relation," *Class. Quant. Grav.* 11:2899 (1994).

6.4 A Challenge from Non-Periodic Emergence

Causal set theory provides a framework in which temporal structure arises from a discrete partial ordering without recurrence.[53] This presents a genuine challenge that should be acknowledged directly. In causal set theory, metric structure is recovered through element-counting (the number of elements in a causal interval determines the spacetime volume), and this counting is not recurrence in the sense defended here—it is enumeration of discrete elements, not the return of a process to the same phase.[54] Causal sets therefore represent a genuine alternative in which metric temporality could in principle arise without stable periodicity.

The challenge is real but regime-bounded. The present thesis is scoped to the actual world given current physics, not to every conceivable foundational regime. If causal set theory eventually provides the correct fundamental ontology, PPR would apply as an effective-level account of how metric time is physically realized in the macroscopic regime where stable recurrence is available—much as thermodynamics applies effectively even if the fundamental ontology is discrete.

7. Objections, Boundaries, and Clarifications

The following objections test the scope and defensibility of the present thesis. They ask whether recurrence can plausibly be treated as privileged in the physical realization of metric duration without collapsing into operationalism, ignoring non-periodic processes, or confusing temporal metric with temporal direction or lived time.

7.1 Non-Periodic Processes Have Duration

A supernova, a melting ice cube, or a single radioactive decay all seem to have duration without themselves being periodic. The reply is that periodicity need not characterize every event directly in order to realize metric time. It is enough that recurring processes furnish the standards by which non-periodic processes become durationally comparable. A supernova "lasts three seconds" because it can be compared with a clock whose recurring process provides a stable unit. Without such a unit, duration may still be spoken of loosely, but it lacks determinate metric content. The thesis concerns the realization of metric comparability, not the internal structure of every temporal event.

[53] S. Surya, "The Causal Set Approach to Quantum Gravity," *Living Reviews in Relativity* 22:5 (2019).

[54] F. Dowker, "Causal sets and the deep structure of spacetime," in *100 Years of Relativity* (2005); R. Sorkin, "Relativity Theory Does Not Imply that the Future Already Exists," in *Relativity and the Dimensionality of the World* (2007).

7.2 Metric Time and Temporal Direction

Periodic processes are approximately time-symmetric. But time has a direction. The thesis does not claim otherwise. Periodicity and irreversibility perform different temporal functions: periodicity supplies the metric (how long); irreversibility supplies the arrow (which direction). A clock is not merely an oscillator but an oscillator coupled to an irreversible counter. The oscillator gives recurrence; the counter gives accumulation. This decomposition reflects the engineering logic of precision timekeeping: an atomic clock oscillates (periodicity) and accumulates a count (irreversible recording).

7.3 Shoemaker's Time Without Change

Shoemaker constructs a universe of three observable regions experiencing "local freezes" at regular staggered intervals, from which inhabitants can logically induce that every sixtieth year all three regions freeze simultaneously.[55] The force of the thought experiment is that the metric of the global freeze is deduced from the very periodic recurrence the present thesis champions. The inhabitants use periodic processes during periods of change to project a metric across an interval of absolute stasis.

This is a more powerful challenge than simple dismissal allows. The strongest reply distinguishes three cases. In local absence of change, metric attribution is unproblematic: external processes supply the comparison. In the global freeze, the inhabitants' deduction is an epistemic projection of a metric previously established through recurrence. The question is whether that projected metric corresponds to a physically determinate duration during the freeze or is a mathematical extrapolation across a physical void. On the view defended here, metric determinacy requires at least potential comparability via recurrence. During the global freeze, no physical process realizes the metric; the attribution is sustained by the logical structure of the preceding recurrence, not by ongoing physical realization. This does not refute Shoemaker's modal claim that we can coherently *describe* time without change. But it dissolves Shoemaker's stronger implication that such time would be physically realized in the metric sense: the metric structure during the global freeze is an extrapolation from physically realized recurrence elsewhere in the system, not a counterexample to the realization thesis. The extrapolation is not free-floating: it is a memory-based and algorithmic extension of a metric previously established through physical realization, which is why it can be coherent even when the physical instantiation is temporarily suspended.[56]

[55] S. Shoemaker, "Time Without Change," *J. Phil.* 66:363 (1969).
[56] Cf. D. Corish, "Could Time Be Change?" *Philosophy* 84:219 (2009).

7.4 Lived Duration as a Boundary Condition

Bergson's distinction between measured time and lived duration (*durée*) remains an important challenge.[57] Bergsonian *durée* is defined by qualitative heterogeneity, continuous interpenetration of states, and resistance to quantitative measurement. The present thesis does not attempt to subsume *durée* into a metric framework, nor to naturalize it through reduction to biological process density. *Durée* operates on a distinct ontological register that a theory of physical metric time cannot, and need not, capture. The layered architecture is not merely declaring *durée* out of bounds; it is doing positive work by actively *requiring* a separate experiential layer rather than reducing lived time to metric time. The architecture predicts that no account of temporal metric will exhaust temporal experience—which is precisely Bergson's insight, reframed as a structural feature of the model rather than a criticism of it. Bergson functions here as a boundary condition: whatever role periodicity plays in the realization of countable duration, lived time is not exhausted by that role alone. The two layers—metric and experiential—can be physically related without being ontologically identical.[58]

7.5 The First Cycle and the Anti-Circularity Argument

If metric time depends on recurrence, does time not exist until the first cycle completes? The answer relies on the order/metric distinction. Before the completion of a stable cycle, there may already be process-order: earlier and later phases, directed development, structural asymmetry. What is not yet available is a calibrated metric unit.

A related concern is that periodicity presupposes metric time: a process is periodic only if it repeats at regular intervals, and regular intervals appear to require metric structure. This objection trades on an equivocation. We distinguish: qualitative recurrence (approximate return to similar physical states, requiring no metric presupposition), stable recurrence (repeatability across cycles, establishing physical regularity), and metric calibration (numerical comparison across systems, which does presuppose metric structure). Only the third presupposes metric time. Metric structure does not precede recurrence; it emerges when recurrence becomes sufficiently stable to support comparison across a network of processes. The first cycle has ordinal temporal structure; metric structure emerges from the comparison network. This emergence is not circular but iterative: in Chang's terminology, it is a case of *epistemic iteration*, where increasingly

[57] H. Bergson, *Essai sur les données immédiates de la conscience* (1889).

[58] On temporal experience and biological rhythms, see M. Wittmann, *Felt Time* (MIT Press, 2016). For a recent functional account of how temporal binding is achieved at the phenomenological layer—through attentional modulation of predictive and retrodictive processing rather than passive inheritance of a neural time-coordinate—see R. Pedersen, *Binding Time: A Theory of How Flexible and Adaptive Temporal Integration Shapes Perception*, PhD dissertation, University of Sydney (2026).

stable physical cycles and increasingly precise mathematical models refine one another in a self-correcting spiral, with limit-cycle stability as the attractor rather than a presupposed given. Chang's notion is explicitly epistemic; PPR extends the structural analogue to physical realization, claiming that the bootstrapping process tracks a physical target (limit-cycle stability) rather than merely an epistemic one.[59]

7.6 What Would Weaken the Thesis

Three classes of observation would weaken or refute the view defended here. First, detection of fundamental-constant variation (α-drift) at levels that disrupt inter-clock comparability would require refining the thesis's commitments about uniform scaling. The Th-229 nuclear clock program is the directly relevant test. Second, construction of a precision timekeeping technology genuinely independent of recurring process even at the calibration level—stochastic clocks, entropic clocks, or decoherence-based proposals—would challenge the claim that recurrence is privileged. The view defended here predicts that such technologies will not achieve the precision of recurring-process standards without underlying calibration to such standards. Third, foundational-physics theories in which non-recurrence structures ground metric temporality more parsimoniously than periodic process would constrain the regime to which the thesis applies.

8. Implications for a Layered Account of Temporality

If the argument of this paper succeeds, its consequences are not primarily predictive in the narrow experimental sense. They are conceptual and architectural. A process-based account of metric time helps clarify the relation among temporal order, duration, direction, and experience, and it suggests a more differentiated picture of temporality than theories that treat these as a single unified phenomenon.

8.1 The Layered Model

The broader picture suggested by this paper is that temporality is layered rather than monolithic. Process provides change and succession. Periodicity provides metric comparability—countable, reproducible duration. Irreversibility provides temporal direction. Consciousness, attention, and embodiment shape how temporal structure is experienced. The distinctive claim of the present paper concerns only the second layer.

[59] S. E. Rugh and H. Zinkernagel, "On the Physical Basis of Cosmic Time," *Stud. Hist. Phil. Mod. Phys.* 40:1 (2009). On epistemic iteration as a general feature of measurement, see H. Chang, *Inventing Temperature* (2004), Ch. 5.

That claim does not eliminate the need for further accounts of the remaining layers. It helps clarify where those accounts must begin.

A structural observation follows from this layered architecture. If time is treated as a geometric dimension fully analogous to spatial dimensions, a pointed question arises: why is the temporal dimension the only one—across all known physics, all mathematical formalisms, and every proposed number of dimensions—that is mono-directional?[60] The standard replies—that the arrow is statistical, that the Minkowski signature already distinguishes them, or that directionality is perspectival—each concede that the temporal dimension behaves fundamentally differently from spatial ones. The layered architecture dissolves this puzzle rather than solving it: three of the four layers—process succession, entropic irreversibility, and memory—are inherently directional. Periodicity, the metric layer, is locally symmetric per cycle but globally accumulative through counting. Time is constitutively directional through most of its layers, and treating temporal metric as exhausted by geometry obscures this structural feature. If geometry alone exhausts the temporal metric, then the non-symmetric behavior of t is a structural anomaly requiring ad hoc explanation; if process grounds the metric, it is a structural requirement.

8.2 Metric Fragility and Cosmological Attenuation

If the universe were to approach thermodynamic equilibrium, with no free-energy gradients sufficient to sustain complex clocks or durable records, the physical realization of metric temporality would be severely impoverished. Formal temporal parameters may persist in a physical theory, but the physical systems through which metric duration is realized—stable, comparable, recurring processes—would not. This is a consequence for physical realization, not a claim that "time itself" would cease in some absolute sense. It is the recognition that metric temporal structure, like other physically realized structures, depends on the availability of the processes that instantiate it.[61] A parallel challenge arises at the other extreme: Rugh and Zinkernagel have argued that prior to the electroweak phase transition, the property of mass effectively vanishes, making the physical basis for stable periodic processes unavailable.[62] If PPR is correct, assigning a metric age to the pre-electroweak universe is a mathematical extrapolation rather than a physically realized duration—a consequence the thesis should embrace rather than evade.

[60] For the standard Eternalist replies and their difficulties, see Eagle (forthcoming), §§3–5; Callender (2017), Chs. 1–3.

[61] See C. Callender, "Thermodynamic Asymmetry in Time," *Stanford Encyclopedia of Philosophy* (2021).

[62] S. E. Rugh and H. Zinkernagel, "On the Physical Basis of Cosmic Time," *Studies in History and Philosophy of Modern Physics* 40:1–19 (2009).

9. Conclusion: Periodicity and the Realization of Duration

This paper has argued that metric time does not float free of physical realization. Duration becomes scientifically countable, comparable, and reproducible through recurrent process, and modern metrology gives that fact unusually clear expression. The central claim has not been that periodicity explains everything we mean by time, but that it is privileged in the physical grounding of temporal metric.

The metrological record gives this claim empirical seriousness. The history of time standards is a history of increasingly stable recurrent processes, not of access to a temporally independent medium. The corrective apparatus of modern metrology—from leap years to relativistic clock corrections—universally adjusts the counting system toward the physical periodicity, never the reverse. This asymmetry supports a process-relational interpretation: the physical periodicity is the target, and the institutional apparatus is the means of accessing it.

The universal acceleration thought experiment gives the claim philosophical traction: any putative background temporal metric that makes no difference to process-ratios is explanatorily idle. Contemporary relational approaches to quantum dynamics are formally sympathetic to the view, though they do not by themselves establish it: periodic clocks enjoy special status in relational-clock frameworks.

If the argument of this paper succeeds, the Eternalist treatment of temporal metric as exhausted by spacetime geometry is incomplete. The geometric formalism describes metric structure, but the physical realization of that structure—what makes metric temporal claims physically determinate rather than merely formal—runs through stable recurring processes. This is not a rejection of Eternalism's topological or causal-structural contributions, which are substantial. It is a specific challenge on a specific question: what constitutes the physical basis of temporal metric. On that question, the evidence developed here—metrological, conceptual, and formal—favors the view that geometry describes what recurrence realizes.

The resulting position is a constrained realism that sidesteps the A/B debate about temporal ontology while challenging the standard B-theoretic picture on the specific question of metric. Metric time is neither an independently existing container nor a mere convention. It is physically realized through stable recurring processes that make durations comparable, reproducible, and shareable. The claim is a grounding thesis, not a constitutive one: periodic processes are the truth-makers for metric temporal claims in the actual world, not merely the calculational tools through which such claims become epistemically accessible. That conclusion does not settle the question of whether all moments are equally real, whether temporal passage is genuine, or whether the block universe is the correct ontological picture. But it does shift the burden of argument on the metric question: views that treat temporal metric as given by geometry alone must explain why scientific timekeeping repeatedly returns to recurrence when precision matters most.

When embedded in relativistic physics, the view amounts to a form of process-grounded eternalism. All times equally exist; but physically determinate duration is locally realized by recurring processes as proper time, with coordinate time representationally real but metrically non-fundamental—a derivative comparison framework built from local proper-time realizations rather than a self-grounding temporal medium.[63] Eternalism supplies the equal-existence claim; PPR supplies the grounding claim for metric time; and proper time supplies the relativistic form that grounding takes in actual physics.

This architecture also supports a thin, local form of becoming that falls short of the global A-theoretic present but goes beyond a purely static block. For an embodied process, events are successively realized along a worldline: proper time accumulates, clocks tick, physical states evolve. This local becoming is compatible with eternalism because it does not privilege a global simultaneity slice or require a moving Now; it is tied to the worldline rather than to the universe.[64] PPR is orthogonal to the A/B debate at the existence layer, but at the metric/realization layer it quietly favors the recognition that temporal accumulation along a worldline is a real physical achievement, not merely a coordinate label.

The choice of a unit is conventional. The stability relations that make any such unit usable are not. Clocks do not invent temporal structure. They realize the process and count its periodicity in order to express duration.

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[63] On coordinate time as a frame-assigned system of labels rather than a physically fundamental quantity, see Brown (2005), Ch. 9; on the primacy of proper time in relativity, see Maudlin (2012), Ch. 4.

[64] On local becoming in relativity as compatible with B-theoretic ontology, see S. F. Savitt, "There's No Time Like the Present (in Minkowski Spacetime)," *Philosophy of Science* 67 (2000); R. T. W. Arthur, "Minkowski Spacetime and the Dimensions of the Present," in *The Ontology of Spacetime* (2006).

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