The Missing Layer of Time: A Closure Criterion for When Quantum Possibilities Become — and Remain — Public Facts

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Dec 2025

Abstract

Time enters physical theory in several distinct roles — metrological standard, relativistic invariant, dynamical parameter, operational observable, relational construct — yet none of these specifies when an outcome becomes an established, shareable fact. We argue that this omission is structural: existing notions of time are optimized to describe change, not factuality. We introduce a minimal distinction between evolution time, which parametrizes dynamical processes, and event time, which indexes when physical facts become established. An event is defined operationally by the formation of a physical record that is sufficiently durable to persist and, when facts are shared, sufficiently redundant and accessible to support stable intersubjective agreement; the earliest point at which these conditions are satisfied is the publicization time of the event. This yields a closure criterion — a record-based condition under which an evolving quantum possibility may be treated as a public fact, and remain one while the relevant record conditions continue to hold, without modifying the underlying dynamics, introducing collapse mechanisms, or privileging any interpretation. The principle that certainty cannot be promoted without publicization constrains inference across observers and blocks a class of multi-observer, Wigner's-friend-type paradoxes while leaving unitary evolution untouched. We situate event time within a measurement-based taxonomy of temporal notions and show that it remains well-defined in regimes where global clocks fail, including relativistic settings, relational quantum frameworks, and gravitational collapse, where evolution time becomes regime-limited or breaks down entirely.

Keywords: event time; publicization; quantum factuality; quantum Darwinism; Wigner's friend; relational time; gravitational collapse

1. Introduction

Time plays multiple, distinct roles across physics and cognitive science. In metrology, time is defined operationally through standardized periodic processes and synchronized clocks. In relativity, elapsed time is measured locally as proper time along worldlines, while global temporal ordering becomes frame-dependent. In classical and quantum dynamics, time appears as a parameter governing evolution, not as an observable on equal footing with position or momentum. In psychology and neuroscience, time is inferred indirectly through behavioral tasks and subjective reports, with no single internal "clock" shared across contexts. Each of these notions is well-defined within its own domain, yet they are often conflated under the single label "time," leading to persistent conceptual confusion across domains. This confusion becomes particularly problematic when temporal descriptions are expected to serve roles they were never designed to fill. Clocks measure durations along specific paths, but they do not, by themselves, determine when physical facts occur. Evolution parameters organize equations of motion, but they do not specify when outcomes become definite or shared. Relational and operational approaches to time in quantum theory successfully describe correlations and measurement protocols, yet they remain silent on the conditions under which information becomes stable and intersubjectively accessible. As a result, debates about the "nature of time" frequently mix distinct measurement roles, obscuring the question of how temporal structure relates to physical factuality. A growing body of work across relativity, quantum theory, and gravitational physics further undermines the assumption that a single, global time coordinate can index all physical processes. Special relativity eliminates absolute simultaneity; general relativity admits no preferred global time function in generic spacetimes; relational formulations of quantum mechanics allow different subsystems to define incompatible temporal orderings; and gravitational collapse generically leads to spacetime regions where classical evolution time ceases to be globally well-defined. These results do not merely complicate synchronization—they challenge the idea that facts can be unambiguously indexed by any single notion of time tied to clocks or dynamical parameters. In this paper, we argue that this impasse arises because existing notions of time are optimized to describe change, not factuality. To address this gap, we introduce a minimal distinction between evolution time, which parametrizes dynamical processes, and event time, which indexes when physical facts become established.

An event, in this sense, is not defined by a particular value of a time parameter, but by the formation of a physical record that is sufficiently durable to persist and—when facts are shared—sufficiently redundant and accessible to support stable intersubjective agreement. We refer to the earliest point at which these conditions are satisfied as the publicization time of an event. This distinction does not modify underlying dynamics, introduce new collapse mechanisms, or privilege any particular interpretation of quantum theory. Instead, it constrains inference: certainty about outcomes cannot be promoted across observers until the conditions for public record formation are met. We formalize this constraint as the axiom that certainty cannot be promoted without publicization, which blocks a class of multi-observer paradoxes without altering unitary evolution. Event time is thus an operational construct tied to records and accessibility, not a new dynamical variable. To situate this proposal, we develop a measurement-based taxonomy of time that separates metrological, relativistic, dynamical, operational, relational, subjective, and representational notions by what they measure and what role they play. Within this taxonomy, event time occupies a distinct role: it indexes factual stability rather than duration, ordering, or internal experience. We show that this notion remains well-defined even in regimes where global clocks fail, including relativistic settings, relational quantum frameworks, and the approach to gravitational singularities, where evolution time becomes regime-limited or breaks down entirely. The paper proceeds as follows. Section 2 reviews metrological and relativistic time, emphasizing synchronization and invariance. Section 3 examines evolution time in classical and quantum dynamics. Section 4 surveys operational and relational approaches to quantum time. Section 5 defines the event layer, event time, and publicization time. Section 6 analyzes time without a global clock. Section 7 distinguishes subjective and representational notions of time. Section 8 turns to gravitational collapse and the breakdown of global evolution time. Sections 9 and 10 discuss implications and conclude.

To anchor this taxonomy, the canonical reference table is hosted as shared vocabulary in Supplement I, Part 7:

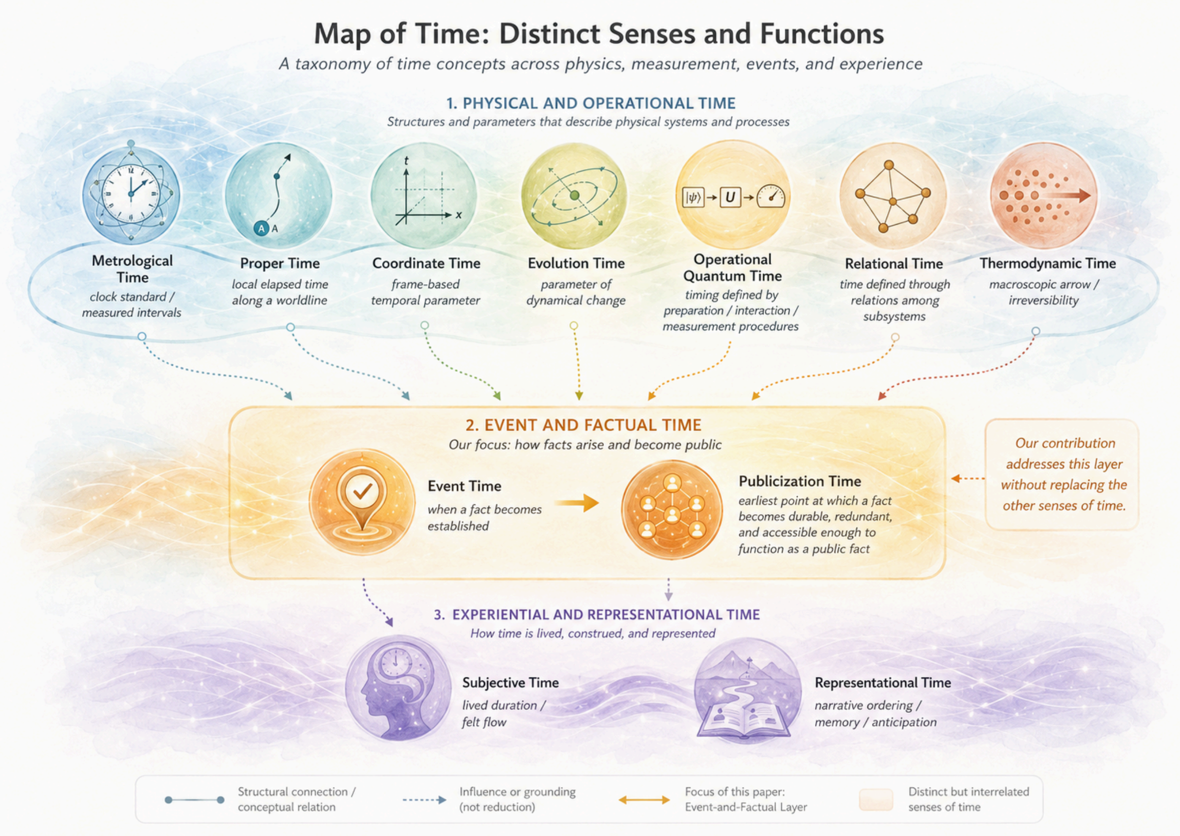

Figure 1. Map of Time: distinct senses and functions. A taxonomy of time concepts across physics, measurement, events, and experience. The event-and-factual layer (event time, publicization time) is the focus of this paper; the contribution addresses this layer without replacing the other senses of time. Canonical reference table: Supplement I, Part 7.

2. What Does It Mean to Measure Time? (Metrology and Relativity)

To clarify the role that time plays in physical description, it is essential to begin with how time is actually measured. In practice, time measurement is not the direct observation of an abstract parameter, but the comparison of physical processes—most commonly, the counting of cycles of a stable oscillator. This operational foundation underlies both modern metrology and relativistic physics, and it sharply constrains what measured time can and cannot represent.

2.1 Metrological Time: Standards and Synchronization

In contemporary physics, the unit of time is defined by convention and realized through specific physical systems. The SI second is defined via a fixed number of periods of radiation associated with a hyperfine transition of the cesium-133 atom. This definition provides a reproducible standard that can be instantiated by atomic clocks with extremely high stability. Global time scales such as International Atomic Time (TAI) are constructed by combining readings from ensembles of such clocks distributed across laboratories, while civil time scales introduce additional conventions to remain aligned with Earth's rotation. Crucially, these time scales are coordination schemes, not fundamental temporal structures. They rely on procedures for synchronization, averaging, and dissemination, all of which presuppose communication protocols and agreed-upon reference frames. The success of modern technologies such as satellite navigation systems demonstrates the extraordinary precision of these schemes, but their meaning remains operational: metrological time is the outcome of comparing clock readings under specified conventions. What metrological time provides, therefore, is not a universal temporal flow, but a standardized way of relating durations measured along different physical systems. It answers the question "how long did this process take according to these clocks?"

2.2 Proper Time and Local Measurement in Relativity

Relativity sharpens this operational perspective by identifying the quantity that clocks actually measure. In both special and general relativity, an ideal clock records proper time along its worldline. Proper time is invariant: different observers may disagree on coordinate descriptions, but they agree on the elapsed time registered by a given clock following a specific path through spacetime. This invariance comes at a price. Proper time is inherently local. Two clocks following different trajectories between the same events may accumulate different amounts of proper time, as illustrated by velocity-dependent time dilation in special relativity and gravitational time dilation in general relativity. There is no observer-independent notion of simultaneity across extended regions of spacetime, and no global "now" that all observers share.

From an operational standpoint, relativity therefore replaces the idea of a single global time with a network of local clock readings related by spacetime geometry. Time measurement becomes path-dependent: what is measured depends on where a clock goes and how it moves. Synchronization procedures exist, but they are frame-dependent and convention-laden, rather than absolute.

2.3 Coordinate Time and the Limits of Global Description

In many physical calculations, it is convenient to introduce a coordinate time that labels slices of spacetime or parametrizes solutions of equations of motion. Such coordinates play an indispensable role in modeling and prediction, but they should not be conflated with directly measured quantities. Coordinate time is a bookkeeping device whose physical interpretation depends on the chosen frame and metric structure. General relativity makes this distinction unavoidable. In generic curved spacetimes, there may be no preferred global time coordinate at all, and different choices of foliation can lead to inequivalent temporal descriptions. Even when a global coordinate time can be defined, it need not correspond to any physically realizable clock. As a result, coordinate time lacks the operational immediacy of proper time and the standardization of metrological time.

2.4 What Time Measurement Does—and Does Not—Provide

Taken together, metrology and relativity establish a clear but limited role for measured time. Clocks measure durations along specific worldlines, and standardized procedures allow these measurements to be compared across systems. Relativity ensures that such measurements are internally consistent while denying any universal temporal ordering independent of observers and geometry. What time measurement does not provide is a criterion for when physical facts become established or shared. A clock reading can tell us how much proper time has elapsed for a given system, but it does not by itself specify when information becomes durable, accessible, or intersubjectively agreed upon. These distinctions are invisible to metrological standards and invariant under relativistic transformations. This gap is not a failure of clocks or of relativity; it reflects the fact that time measurement is optimized to quantify duration and synchronization, not factuality. In the sections that follow, we will show that this limitation persists when time is treated as a dynamical parameter in classical and quantum theories, motivating the introduction of a distinct notion of time tied to record formation and public accessibility.

3. Evolution Time in Classical and Quantum Dynamics

Having clarified how time is measured through clocks and coordinated across reference frames, we now turn to a different role that time plays in physical theory: its function as a parameter governing dynamical evolution. In both classical and quantum physics, time is indispensable for describing change, yet it enters these theories in a manner fundamentally distinct from measured or observed quantities.

3.1 Time as a Parameter of Classical Dynamics

In classical mechanics, time appears as an external parameter with respect to which physical quantities evolve. The equations of motion specify how positions, momenta, and fields change as functions of time, but time itself is not a dynamical variable within the system. It is neither generated by the system nor altered by it; instead, it serves as an independent ordering parameter that structures trajectories in phase space. This role of time is conceptually simple but operationally indirect. Classical theory does not explain how time is measured; it assumes that a suitable clock exists and that its readings can be identified with the parameter appearing in the equations of motion. The connection between the abstract parameter and physical clocks is made externally, typically by synchronizing the equations with empirical time standards. As a result, classical evolution time organizes descriptions of change but does not itself carry physical content beyond that role. Statements about the evolution of quantum states—even when decohered—do not by themselves determine which outcomes may be treated as physical facts. Factual claims require additional physical conditions tied to record formation and accessibility.

3.2 Evolution Time in Quantum Theory

Quantum mechanics inherits and sharpens this distinction. In standard formulations, the state of a quantum system evolves according to a time-dependent Schrödinger equation, with time again appearing as an external parameter. Observables such as position, momentum, or spin are represented by operators acting on the system's state, but time is not represented by a universal operator on the same footing. This asymmetry is not accidental. Attempts to treat time as an observable analogous to position encounter well-known obstacles, particularly when the Hamiltonian is bounded below. As a result, quantum theory typically treats time as a parameter that labels evolution rather than as a quantity that is directly measured within the system. The temporal structure of the theory is therefore inherited from the external coordination of clocks, not generated internally by the system's dynamics. Despite this, quantum mechanics is extraordinarily successful at predicting time-dependent phenomena. Decay rates, oscillations, and interference patterns are all described in terms of evolution with respect to a time parameter. What is crucial for the present discussion is that these predictions concern how states change, not when outcomes become facts.

3.3 Operational Time in Quantum Experiments

In practice, experimentalists do measure quantities that appear to be temporal, such as arrival times, lifetimes, or delays. However, these quantities are defined operationally through specific measurement protocols that involve coupling the system to detectors, clocks, or external degrees of freedom. They do not correspond to a single, universal "time observable," but rather to families of measurement outcomes associated with particular experimental setups. These operational notions of time are therefore context-dependent. Different experimental arrangements can yield different temporal distributions for the same underlying system, and the interpretation of these distributions depends on how the measurement is implemented. Such quantities are best understood as derived observables that encode information about interactions and detection events, not as fundamental time variables. This distinction reinforces the point that evolution time in quantum theory remains a parameter that organizes predictions, while measured temporal quantities arise from interactions with external systems that themselves rely on clocks and records.

3.4 The Limits of Evolution Time

Across classical and quantum physics, evolution time plays a unifying and indispensable role: it provides a consistent parameter with respect to which laws of motion are expressed. Yet this role is limited. Evolution time does not, by itself, specify when information becomes stable, accessible, or shared among observers. It orders change, but it does not determine factuality. This limitation becomes especially clear in situations where different observers or subsystems employ different temporal coordinations. Relativistic effects, relational descriptions, and quantum measurement protocols can all lead to multiple, equally valid evolution parameters. In such contexts, the assumption that a single time parameter can index physical facts becomes untenable. The failure here is not dynamical but conceptual. Evolution time was never designed to serve as a criterion for the emergence of facts; it is a tool for modeling change. Recognizing this distinction opens the door to a complementary notion of time—one that does not parametrize evolution, but instead indexes when events become physically established. The next section examines existing approaches to time in quantum theory that attempt to bridge this gap, and clarifies why an additional layer is required.

4. Quantum Time: Operational and Relational Approaches

The special role of time in quantum theory has long been recognized as a source of conceptual tension. While quantum mechanics relies on time to describe evolution, it does not treat time as an observable in the same sense as other physical quantities. In response, a substantial literature has developed operational and relational approaches to temporal description, each seeking to clarify how temporal information arises in quantum systems. These approaches illuminate important aspects of measurement and correlation, but they do not resolve the question of when physical facts become established.

4.1 Time as an Observable: Operational Constructions

In standard quantum mechanics, time appears as an external parameter rather than as a self-adjoint operator. This asymmetry is not merely conventional. Attempts to define a universal time operator canonically conjugate to the Hamiltonian encounter structural obstructions when the Hamiltonian is bounded below. As a result, quantum theory does not admit a single, global time observable applicable to all systems. Nevertheless, quantum experiments routinely involve quantities that appear temporal in nature, such as arrival times, dwell times, and decay times. These are defined operationally through specific measurement protocols, often using generalized measurements. Rather than corresponding to a fundamental time observable, such quantities emerge from the interaction between the system, detectors, and auxiliary degrees of freedom that function as clocks. Operational time observables are therefore inherently context-dependent. Their definitions depend on how the measurement is implemented, what is being detected, and how outcomes are recorded. Different experimental arrangements can yield different temporal distributions for the same system, reflecting differences in coupling and detection rather than properties of an underlying time variable. These constructions are valuable for describing experimental outcomes, but they do not supply a universal temporal index.

4.2 Relational Time and Clock–System Correlations

A distinct line of work treats time as a relational quantity that emerges from correlations between subsystems. In these approaches, one subsystem is designated as a clock, and the evolution of other subsystems is described conditionally on the state of this clock. This construction originates with Page and Wootters, who showed that a stationary global state can encode the apparent evolution of one subsystem relative to another acting as a clock [1], and it has since been given an explicit experimental illustration using entangled photon polarizations [2]. From this perspective, time is not an external parameter but an internal degree of freedom relative to which change is described. Relational formulations clarify how temporal ordering and effective dynamics can arise without introducing a preferred background time. They are particularly relevant in closed or cosmological settings, where no external clock is available.

However, relational time is intrinsically clock-dependent: different choices of clock can lead to different effective temporal descriptions. In general, there is no guarantee that distinct clocks yield consistent orderings or durations. This multiplicity is not a flaw of relational approaches; it reflects the absence of a privileged temporal structure in quantum theory. At the same time, it underscores a limitation. If different relational clocks define incompatible temporal orderings, then temporal description alone cannot determine when outcomes are mutually agreed upon or when information becomes shared across observers.

4.3 The Persistence of the Factuality Gap

Operational and relational approaches address important questions about how temporal information is extracted from quantum systems and how dynamics can be described without a background clock. What they do not address is the emergence of factuality—the transition from evolving quantum states and correlations to outcomes that can be treated as definite and shared. Operational time observables describe distributions of measurement outcomes, but they presuppose the existence of records in which those outcomes are registered. Relational time describes conditional evolution, but it does not specify when conditional statements become physically meaningful beyond a given subsystem. In both cases, temporal description remains tied to change and correlation, not to the stability or accessibility of information. This gap becomes especially salient in multi-observer scenarios, where different observers may have access to different subsystems or records. In such settings, temporal parameters—whether operational or relational—do not suffice to determine when it is legitimate to promote a local outcome to a shared fact. The difficulty is not dynamical; it lies in the absence of criteria linking temporal description to record formation and accessibility. Operational and relational time are treated as regime-limits of the event layer in Supplement I, Part 8 (Quantum Operational Time; Collapse and Time Breakdown; Time as Path Length).

4.4 Summary and Transition

Quantum theory thus provides a rich set of tools for describing time-dependent behavior, but these tools are optimized for organizing evolution and correlations rather than for indexing physical facts. Time appears as a parameter, as a derived observable, or as a relational construct, depending on context. None of these roles, however, specifies when information becomes stable, public, or intersubjectively valid. In the next section, we introduce a complementary notion of time that addresses this omission. By defining events in terms of record formation and accessibility, we distinguish the time at which change occurs from the time at which facts become established. This distinction preserves the successes of operational and relational approaches while supplying a missing criterion for factuality that is independent of any particular choice of clock or temporal parameter.

5. Event Time and Publicization: When Facts Occur

The preceding sections show that time, as measured by clocks or represented in physical theories, consistently serves to organize change, not to establish factuality. Metrological time measures durations, relativistic time orders local experiences, and evolution time parametrizes dynamical laws. Operational and relational approaches in quantum theory refine these roles but do not bridge the gap between evolving descriptions and stable outcomes. To address this gap, we introduce a distinct notion of time tied not to evolution, but to the emergence of physical facts.

5.1 Events as Record Formation

We define an event as the formation of a physical record that is sufficiently stable to persist beyond transient fluctuations. A record, in this sense, is any physical imprint—macroscopic or microscopic—that correlates with an outcome and is dynamically robust under the relevant environmental conditions. The defining feature of a record is not its size or classical appearance, but its durability: once formed, it must remain accessible for a non-negligible interval without requiring fine-tuned control. This definition is intentionally operational. It does not presuppose a particular interpretation of quantum mechanics, nor does it invoke collapse as a dynamical process. Instead, it identifies events with the establishment of correlations that resist erasure and can, in principle, be consulted by an observer or another system at a later time. Events are therefore distinguished from mere interactions or correlations that arise and dissipate without leaving a lasting trace. These objects — event variable, sector separation, record observable, durability window, redundancy, and publicization time — are stated formally in Supplement I, Part 1 (Definitions); this paper uses them without re-deriving them.

5.2 Publicization and Event Time

Not all records are immediately accessible to multiple observers. Some records remain localized or private, while others become redundantly encoded in the environment. This redundant proliferation of pointer information across many environmental fragments is the mechanism by which records become objective in the quantum-Darwinism sense [4-6], with the accessible information per fragment bounded by the Holevo quantity (Supplement

I, Part 6). The event layer treats such redundancy as necessary but not sufficient — durability is an independent requirement (Supplement I, Parts 3–4). We refer to the process by which a record becomes sufficiently accessible to support shared inference as publicization. Publicization may involve amplification, environmental coupling, or replication across multiple degrees of freedom, but it need not be instantaneous or global. We define the event time of an outcome as the earliest point at which the corresponding record satisfies the conditions required for publicization. This time is not defined by a particular clock reading or evolution parameter. Rather, it is indexed by the physical availability of the record itself. Event time, therefore, depends on properties such as durability, redundancy, and accessibility, rather than on synchronization conventions or coordinate choices. This notion of time is orthogonal to evolution time. Two systems may evolve continuously according to the same dynamical laws while differing in when, or whether, an event occurs. Event-time order and record persistence are formalized in Supplement I, Part 3 (Event Closure Theorem; Record Persistence Theorem; Event-Time-Order Corollary).

Conversely, an event may occur without any distinctive signature in the evolution parameter, reflecting the fact that event time is tied to record formation rather than to dynamical change.

5.3 No Certainty Without Publicization

The introduction of event time leads to a natural constraint on inference. We formalize this constraint as the principle that certainty cannot be promoted without publicization (the Axiom of No Certainty Promotion; Supplement I, Part 2). That is, an outcome may be treated as a physical fact for a given observer only once the corresponding record is available to that observer, and it may be treated as a shared fact only once the record is accessible in a manner that supports intersubjective agreement. This principle does not alter the underlying dynamics of quantum or classical systems. Instead, it restricts the circumstances under which observers are licensed to make definitive claims about outcomes. By separating the evolution of states from the establishment of facts, it blocks a class of multi-observer paradoxes that arise when certainty is implicitly assumed to propagate faster than records can be formed or accessed. Importantly, this constraint is not observer-dependent in an arbitrary sense. It is grounded in physical conditions on records, not in epistemic attitudes. Different observers may legitimately assign different degrees of certainty depending on their access to records, but these differences reflect physical asymmetries in information availability rather than inconsistencies in the underlying theory. Multi-observer contradictions arise when certainty is promoted globally based on local or private records. Enforcing record-relative publicization blocks these contradictions without modifying unitary dynamics. The formal statement — that restricting factual assertions to closure-satisfying events blocks Frauchiger–Renner / Wigner's-friend derivations [7][8] — is the Consistency of Event Assertions result (Supplement I, Part 3). This paper invokes it; it does not reproduce the demonstration.

5.4 Compatibility with Existing Frameworks

Event time is not intended to replace metrological, relativistic, or dynamical notions of time. Instead, it complements them by addressing a role they do not fill. Clocks remain essential for measuring durations; evolution parameters remain essential for predicting change; relational and operational times remain essential for describing correlations. Event time addresses a separate question: when does a result count as a fact? Because event time is defined operationally through record formation, it remains well-defined even in regimes where global clocks fail or evolution time becomes ambiguous. Relativistic frame dependence, relational clock choices, and even the breakdown of smooth spacetime near gravitational singularities do not undermine the concept of event time, provided that records and their accessibility can still be meaningfully discussed. This separation allows temporal description to remain flexible without sacrificing factual consistency. Evolution may be continuous and reversible, while event formation is discrete and constrained. By respecting this distinction, one can preserve the successes of existing temporal frameworks while clarifying their limits.

5.5 Summary

In this section, we have distinguished evolution time, which parametrizes change, from event time, which indexes the establishment of physical facts. Events are defined by the formation of durable records, and event time is determined by the earliest point at which such records become accessible. The principle that certainty cannot be promoted without publicization constrains inference without modifying dynamics, providing a minimal and operational account of factuality that is compatible with relativity, quantum theory, and their known limitations. The following sections build on this distinction to show how event time remains meaningful in the absence of a global clock, how it relates to subjective and representational notions of time, and how it clarifies the breakdown of evolution time in gravitational collapse.

6. Time Without a Global Clock

The preceding sections have shown that time, across its many uses, does not provide a single, universal structure capable of indexing physical facts. Clocks measure durations along worldlines; evolution parameters organize change; operational and relational approaches describe correlations. What none of these guarantees is the existence of a global temporal reference against which all events can be unambiguously ordered. In this section, we show that the absence of a global clock is not a technical inconvenience but a structural feature of modern physics, and that event time remains meaningful precisely because it does not rely on such a clock.

6.1 The Loss of Global Simultaneity

Special relativity eliminates absolute simultaneity: observers in relative motion disagree on whether spatially separated events occur at the same time. This is not a limitation of synchronization technology but a fundamental feature of spacetime structure. Any attempt to define a global “now” requires choosing a reference frame, and different choices yield incompatible temporal orderings for spacelike-separated events. General relativity deepens this result. In generic curved spacetimes, there is no preferred foliation into spacelike hypersurfaces labeled by a global time parameter. While special classes of spacetimes admit convenient time coordinates, these are neither unique nor physically privileged. Temporal ordering beyond local neighborhoods becomes a matter of convention rather than invariant structure. As a consequence, no globally defined clock or time coordinate can be taken as the authoritative index of when facts occur. Any temporal description that depends on such a structure inherits its frame dependence and arbitrariness.

6.2 Relational and Context-Dependent Temporal Orderings

Quantum theory reinforces this conclusion. Relational formulations allow different subsystems to serve as clocks for one another, yielding effective time parameters defined by correlations. These constructions are internally consistent, but they are not unique: different choices of clock lead to different temporal descriptions. In general, there is no guarantee that these descriptions agree on ordering or duration outside restricted contexts. This multiplicity is not a defect of relational approaches; it reflects the absence of a fundamental temporal background. However, it implies that temporal orderings derived from relational clocks cannot, by themselves, determine when outcomes should be treated as shared facts. Temporal description remains context-dependent, while factual consistency demands criteria that transcend particular clock choices.

6.3 Regime Dependence and the Breakdown of Evolution Time

The limitations of global time become most explicit in extreme regimes. In gravitational collapse, classical evolution time ceases to be globally extendable: spacetime may become geodesically incomplete, and smooth foliation by time parameters can fail. Near singularities, as suggested by the BKL scenario, dynamics becomes ultra-local, and the notion of a synchronized global time loses operational meaning. In these regimes, evolution time remains useful locally but cannot serve as a universal index across the system. Any attempt to assign a single temporal ordering to all processes becomes ill-defined. Yet physical processes continue to occur, and records may still form and persist within accessible regions. The breakdown of global evolution time, therefore, does not imply the breakdown of factuality; it reveals the inadequacy of evolution time as a universal index.

6.4 Event Time as a Clock-Independent Index

Event time, as defined by record formation and publicization, does not presuppose a global clock. It is indexed by physical conditions—durability, redundancy, and accessibility of records—rather than by coordinate labels or synchronization schemes. As such, it remains well-defined in contexts where clocks disagree, relational orderings diverge, or evolution time becomes regime-limited. Because event time is tied to records, it is inherently local but not solipsistic. Different observers may access records at different moments according to their own clocks, yet they can agree on the occurrence of an event once the relevant records become mutually accessible. Agreement is grounded in shared physical evidence, not in shared temporal coordinates. This feature allows event time to function as a unifying index of factuality across disparate temporal frameworks. It does not compete with clock time or evolution time; it constrains their interpretive use. Where clocks and evolution parameters suffice, event time coincides with them. Where they fail, event time continues to provide a meaningful criterion for when facts occur.

6.5 Summary

The absence of a global clock is a structural consequence of modern physics, not a technical limitation. Relativity, quantum theory, and gravitational collapse each undermine the assumption that a single temporal parameter can index all physical facts. By separating the time of change from the time of factual establishment, event time provides a minimal, clock-independent notion that remains valid across regimes. This separation allows temporal description to remain flexible while preserving consistency in the assignment of physical facts. In the next section, we examine how this framework relates to subjective and representational notions of time, and how internal temporal structure can be understood as a projection layered on top of the event-based foundation described here.

7. Subjective and Representational Time

The absence of a global clock and the separation between evolution time and event time do not imply that temporal experience is illusory or irrelevant. Rather, they clarify the status of subjective and representational time as distinct layers that organize perception, action, and inference. In this section, we situate these notions within the broader framework developed thus far, emphasizing their descriptive role and their dependence on underlying physical processes without reducing one to the other.

7.1 Subjective Time as Inference, Not Measurement

Human experience of time exhibits well-documented variability. Perceived duration, temporal order judgments, and simultaneity assessments depend on context, attention, emotional state, task demands, and neural dynamics. These variations reflect the fact that subjective time is not measured directly but inferred from internal signals and external cues. Experimental paradigms such as interval estimation, temporal bisection, synchronization tasks, and order judgments reveal that subjective time is constructed from distributed processes rather than generated by a single internal clock. Different tasks engage different neural circuits and yield different temporal distortions. The resulting temporal representations are therefore task-dependent and context-sensitive, even within a single observer. From the perspective of the present framework, subjective time does not compete with metrological or physical notions of time. It serves a different function: organizing temporal experience and guiding behavior under uncertainty. Subjective temporal judgments reflect internal models of change and expectation, not direct access to physical temporal parameters.

7.2 Representational Time and Projection

Beyond subjective experience, many systems—biological and artificial—employ internal representations that encode temporal structure implicitly. These representations may take the form of sequences, gradients, or dynamic trajectories in state space. What they share is that temporal information is encoded relationally, as patterns of change rather than as explicit timestamps. Representational time can be understood as a projection of underlying physical processes into an internal coordinate system optimized for prediction and control. The "time" that appears in these representations is therefore neither metrological nor dynamical in the physical sense; it is experienced as a derived parameter that indexes ordering, anticipation, or coherence within the representational space. Importantly, representational time may diverge from both clock time and event time. A system may internally compress or dilate temporal intervals, reorder events based on salience, or smooth over gaps in information. These transformations do not alter the occurrence of physical events; they reflect how those events are encoded and utilized internally.

7.3 Constraints from Event Time

While subjective and representational times are flexible, they are not unconstrained. Their reliability depends on the existence of stable external records to which internal representations can ultimately be anchored. Event time provides this anchor. Without durable records, subjective temporal inferences cannot be calibrated or corrected, and representational time loses its connection to physical reality. This dependence runs in one direction. Event time does not depend on subjective experience, but subjective and representational times depend on event time for validation. A system may internally represent temporal structure in many ways, but those representations gain physical significance only insofar as they track events that have been established through record formation. This asymmetry clarifies the relationship between internal time and physical facts. Subjective time organizes experience; representational time organizes inference; event time organizes factuality. Confusing these roles leads to category errors, such as treating experiential distortions as failures of physical time or expecting physical theories to account for phenomenological temporal flow. A formal treatment of subjective and representational time as information-geometric projections is developed in separate companion work and is not required for any result in this paper. The parallel asserted is structural only. The same grammar recurs across regimes; no evidential weight transfers between them. A result in one regime is not evidence about another.

7.4 Implications for Multi-Observer Consistency

The distinction between subjective, representational, and event time is particularly important in multi-observer contexts. Different observers may experience time differently, employ different internal representations, or access records at different moments according to their own clocks. These differences need not lead to inconsistency, provided that factual claims are anchored to event time rather than to subjective impressions or representational orderings. Event time thus serves as a coordination layer across agents with heterogeneous temporal representations. Agreement does not require synchronized experiences or identical internal clocks; it requires access to shared records. This perspective aligns with the broader theme of the paper: consistency in physical description arises from shared evidence, not shared temporal intuition.

7.5 Summary

Subjective and representational notions of time play indispensable roles in cognition and inference, but they are neither fundamental nor universal. They are constructed, context-dependent, and optimized for internal use. By distinguishing these notions from metrological time, evolution time, and event time, we can acknowledge their importance without conflating their functions. Event time provides the minimal physical anchor that allows subjective and representational temporal structures to connect to established facts, even in the absence of a global clock.

In the final section, we turn to gravitational collapse and extreme regimes to show how the breakdown of global evolution time further reinforces the necessity of separating change from factuality.

8. Gravitational Collapse and the Breakdown of Evolution Time

The limitations of global time identified in earlier sections become unavoidable in regimes governed by strong gravity. In gravitational collapse, the assumptions that support a single, globally valid evolution parameter cease to hold, even at the level of classical general relativity. This breakdown does not signal the disappearance of physical processes or the incoherence of description; rather, it exposes the limits of evolution time as a universal index. In this section, we show how gravitational collapse reinforces the need to distinguish between time as a parameter of change and time as an index of factuality.

8.1 Evolution Time and Geodesic Incompleteness

Classical general relativity predicts that sufficiently compact gravitational collapse generically leads to spacetime regions that are geodesically incomplete. Singularity theorems establish that, under broad conditions, families of timelike or null geodesics cannot be extended arbitrarily far. Importantly, this result does not require perfect symmetry or idealized matter models; it follows from global geometric conditions such as the formation of trapped surfaces and the focusing of geodesics. Geodesic incompleteness signals a failure of global evolution time. If spacetime trajectories cannot be extended, then no single time parameter can be defined that smoothly indexes all physical processes. The breakdown is not merely technical. It reflects the fact that the classical manifold description itself reaches a boundary of applicability, beyond which evolution time loses its role as a global organizing parameter.

8.2 Horizons, Predictability, and the Limits of Global Ordering

Even before singularities are encountered, gravitational collapse challenges global temporal description through the presence of horizons. Event horizons separate regions of spacetime with fundamentally different causal accessibility. Observers outside a horizon cannot assign temporal coordinates to events inside in any operationally meaningful way, while infalling observers may experience finite proper time to reach regions that are indefinitely delayed in external coordinate descriptions. This causal separation undermines any attempt to use a single evolution time to index events across the entire system. Temporal ordering becomes observer-dependent, and coordinate time loses its operational connection to physical clocks. In rotating or charged black-hole solutions, additional structures such as Cauchy horizons further complicate matters by threatening the determinism of classical evolution itself. These features are not artifacts of coordinate choice; they reflect genuine limits on predictability and accessibility imposed by spacetime geometry. As a result, evolution time ceases to provide a reliable guide to when physical processes can be treated as part of a shared physical narrative.

8.3 Ultra-Local Dynamics and the Loss of Synchronization

Near spacelike singularities, classical analyses suggest that dynamics become increasingly ultra-local. In this regime, the behavior of fields at different spatial locations decouples, and evolution is dominated by local terms rather than by spatial interactions. The approach to the singularity is characterized by rapidly varying, anisotropic behavior that resists description by a single, synchronized time parameter. In such settings, even the notion of a common local time becomes fragile. Each spatial region effectively carries its own temporal evolution, and attempts to impose a global ordering become increasingly artificial. Evolution time remains definable in restricted neighborhoods, but its extension across the system no longer reflects any physically meaningful coordination. This regime dependence illustrates a general point: evolution time is not guaranteed to retain global validity across all physical circumstances. Its usefulness is contingent on assumptions—smoothness, extendibility, synchronization—that fail in extreme gravitational contexts.

8.4 Event Time in the Absence of Global Evolution

Despite the breakdown of global evolution time, physical events do not disappear. Records can still form, persist, and become accessible within causally connected regions. Observers may lose the ability to coordinate all processes within a single temporal framework, but they do not lose the capacity to identify when particular outcomes become established relative to accessible records. Event time, defined by record formation and publicization, remains meaningful precisely because it does not depend on extending a time parameter across the entire spacetime. It applies locally and operationally: an event occurs when a record becomes durable and accessible within a given causal domain. Agreement across observers depends on the sharing of records, not on synchronization with a global clock. In this sense, gravitational collapse does not undermine factuality; it reveals the inadequacy of evolution time as a universal index. Event time continues to function wherever records can be formed and consulted, even when evolution time becomes fragmented, observer-dependent, or ill-defined. A complementary regime-limit is the time-reverse of collapse. White-hole solutions are geometrically admissible in general relativity — exact time-reverses of black-hole interiors — yet thermodynamically suppressed: realizing one demands a finely tuned, entropy-decreasing configuration that generic dynamics does not supply. Within the event-layer framing this is a *realization condition*, not a prohibition: a white hole is permitted by the geometry but disfavored by the conditions under which durable records form. The framework therefore predicts the rarity of its own conjectural objects rather than asserting them.

8.5 Summary

Gravitational collapse provides a concrete illustration of the limits of evolution time. Singularity formation, horizons, and ultra-local dynamics each disrupt the assumptions required for a global temporal parameter to organize physical processes. These disruptions do not eliminate events or records; they eliminate the possibility of using evolution time as a universal clock. By separating the time of change from the time of factual establishment, the event-based framework remains applicable in regimes where classical temporal structure breaks down. This reinforces the central claim of the paper: factuality requires an index independent of global evolution time.

9. Discussion

The missing layer of time becomes clearer with the distinction of event time from evolution time, publicization time, and factuality. These measurements have been obscured because the same collective term—time—is used to refer to metrological standards, relativistic invariants, dynamical parameters, operational observables, and subjective experience. By disentangling these roles and introducing a separate notion of event time tied to record formation, we clarify how factuality can remain well-defined even in the absence of a global clock.

9.1 What This Framework Does—and Does Not—Claim

It is important to emphasize what the present framework does not attempt to do. It does not propose a new physical time parameter, nor does it modify the dynamical laws of classical or quantum theory. No claim is made to resolve the problem of time in quantum gravity, to explain consciousness, or to derive collapse from first principles. Instead, the framework operates at the level of inference: it constrains when certainty about outcomes may be legitimately promoted, given the physical availability of records. Event time is therefore not an alternative to evolution time, but a complementary index. Where clocks and evolution parameters suffice, event time coincides with them. Where they diverge or fail, event time continues to provide a criterion for factual stability without imposing additional structure on the dynamics.

9.2 Relation to Existing Interpretations and Approaches

The event-based framework is compatible with a wide range of interpretive positions. It does not privilege collapse-based or no-collapse interpretations of quantum mechanics, nor does it rely on specific mechanisms of decoherence or environmental redundancy, though it is consistent with them [3-6]. By focusing on records rather than on wavefunction dynamics, it sidesteps debates about ontology while preserving empirical adequacy. Similarly, the framework aligns naturally with relational and operational approaches to time without inheriting their limitations. Relational clocks and operational time observables remain valid tools for describing correlations and measurements. Event time supplements these tools by addressing the conditions under which outcomes become shared facts, a question they do not directly answer.

9.3 Multi-Observer Consistency and the Promotion of Certainty

One of the principal motivations for introducing event time is the need for consistency across observers. In multi-observer scenarios, different observers may employ different clocks, inhabit different frames, or access different subsystems. If factual claims are implicitly indexed to evolution time or to internal clock readings, inconsistencies can arise. By anchoring factuality to record accessibility rather than to temporal parameters, the framework ensures that certainty propagates only as fast as records do. This constraint—formalized as the principle that certainty cannot be promoted without publicization—resolves a class of apparent paradoxes without altering the underlying theory. It reflects a physical asymmetry in information availability rather than a subjective limitation of observers. It helps to make the promotion structure explicit as a ladder. (i) A private record supports observer-relative conditioning — an agent correlated with a local outcome may hold conditioned certainty about it. (ii) A durable record supports stable reference by that agent over time. (iii) A durably redundant, publicized record supports intersubjective factual assertion. Certainty may be promoted only as one climbs: conditioned certainty at rung (i) is not licensed as a public fact until rungs (ii)–(iii) hold. Multi-observer contradictions arise precisely when a claim is advanced across rungs it has not reached — treating private conditioning as global fact. The formal constraint and its paradox-blocking consequence are stated formally in Supplement I, Part 3.

9.4 Implications for Extreme Regimes

The separation between evolution time and event time becomes most compelling in regimes where global temporal structure breaks down. Gravitational collapse, horizons, and ultra-local dynamics each undermine the assumption that a single time parameter can index all processes. Yet in these regimes, records may still form and persist within accessible domains. Event time remains applicable precisely because it does not rely on extending a time coordinate across the entire spacetime. This observation suggests a broader lesson. The breakdown of evolution time does not imply the breakdown of physical description; it indicates the need for descriptive layers that are robust under regime change. Event time provides such a layer by grounding factuality in record formation rather than in global temporal order.

9.5 Open Questions and Future Directions

While the framework developed here is deliberately minimal, it raises several questions for future work. The quantitative characterization of record durability and accessibility, the relationship between publicization and environmental redundancy, and the extension of event-based reasoning to relativistic quantum field theory all merit further investigation. Additionally, the interplay between event time and subjective temporal experience offers a promising avenue for interdisciplinary study, provided that descriptive and normative roles are carefully distinguished. More broadly, the framework invites a reevaluation of how time is used in foundational discussions. By separating the roles of measurement, evolution, and factuality, it becomes possible to address longstanding confusions without introducing unnecessary metaphysical commitments.

9.6 Summary

The central claim of this paper is not that time must be redefined, but that its roles must be distinguished. Clocks measure durations, evolution parameters organize change, and event time indexes when facts become established. Conflating these roles obscures the structure of physical description and generates avoidable paradoxes. By introducing event time as a record-based index of factuality, we provide a framework that remains valid across domains and regimes, including those in which global temporal structure fails.

10. Conclusion

Time enters physical theory in many distinct and indispensable ways. Clocks measure durations along worldlines, relativistic frameworks relate local temporal experiences without privileging global simultaneity, and dynamical laws evolve states with respect to an external parameter. Operational and relational approaches in quantum theory refine these roles by tying temporal description to measurement contexts and subsystem correlations. Yet none of these notions, taken alone, provides a criterion for when physical facts become established. In this paper, we have argued that this omission is structural rather than accidental. Modern physics offers no single, global clock capable of indexing all physical processes, and in extreme regimes such as gravitational collapse, even evolution time becomes regime-limited or breaks down entirely. These results do not undermine physical description; they reveal the need to distinguish between time as a parameter of change and time as an index of factuality. To address this gap, we introduced event time, defined operationally through the formation and publicization of durable physical records. Event time does not replace existing notions of time, nor does it modify underlying dynamics. Instead, it constrains inference by grounding certainty in physical accessibility. The principle that certainty cannot be promoted without publicization ensures consistency across observers without invoking privileged frames, global synchronization, or interpretive commitments about collapse. By separating measurement time, evolution time, and event time, we have provided a framework that remains applicable across domains, from metrology and relativity to quantum measurement, cognition, and gravitational collapse. This separation clarifies long-standing confusions about the role of time in physical theory and explains why factual consistency can be maintained even when temporal descriptions diverge.

The broader lesson is modest but consequential: physical theories need not supply a single, universal notion of time to support a coherent account of reality. What they must supply are conditions under which facts become established and shared. Event time, as defined here, provides a minimal and operational answer to that requirement.

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