

Time as Irreversible Constraint Accumulation: An Event-Based Interpretation of Proper Time, Entropy, and Dissipative Structure

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Abstract

We present a conservative reinterpretation of proper time in which temporal accumulation emerges from irreversible constraint-imposing events rather than being treated as a primitive dimension. Building exclusively on established results in statistical mechanics, thermodynamics, and relativistic physics, we argue that proper time measures the integrated accumulation of irreversible transitions along a worldline, enabled and bounded by entropy production. Entropy increase is interpreted not as disorder, but as a progressive release of microscopic constraints leading to macroscopic smoothness. Temporal irreversibility, by contrast, arises from the permanent loss of recoverable distinctions. This framework introduces no new dynamical laws or entities, preserves all empirical predictions of general relativity and statistical mechanics, and reorganizes their conceptual hierarchy. In this view, time is not fundamental but emerges as a bookkeeping quantity tracking the irreversible exhaustion of distinguishable structure.

1 Introduction

1.1 The Problem of Time

Time occupies a peculiar position in modern physics. In relativistic theories, it appears as a coordinate within a four-dimensional spacetime manifold, locally measured by proper time along timelike worldlines (Misner, Thorne, and Wheeler 1973); (Wald 1984). In thermodynamics and statistical mechanics, by contrast, time is not fundamental but directional: macroscopic evolution exhibits an unmistakable arrow associated with entropy production and irreversibility (Boltzmann 1877); (Lebowitz 1993); (Penrose 1979). These two roles are individually successful yet conceptually misaligned.

At the microscopic level, the fundamental equations governing classical and quantum dynamics are, with rare exceptions, time-reversal invariant. Hamiltonian mechanics, unitary quantum evolution, and relativistic field equations admit solutions evolving equally well forward or backward in time. Yet at macroscopic scales, irreversible phenomena dominate: gases mix, heat flows from hot to cold, structures decay, memories accumulate, and records persist. This disparity gives rise to a family of foundational puzzles, including Loschmidt's reversibility paradox (Loschmidt 1876), the

past hypothesis and low-entropy initial condition problem (Penrose 1979); (Albert 2000), and the emergence of classicality in quantum measurement (Bell 1987); (Zurek 2003); (Wallace 2012).

The standard response has been explanatory pluralism. Time is treated as fundamental in spacetime physics and emergent in thermodynamics; irreversibility is regarded as a feature of coarse-grained descriptions rather than microscopic law. While pragmatically effective, this strategy leaves unanswered a deeper question: what physical quantity does time actually measure?

1.2 Historical Approaches

Numerous approaches have attempted to bridge this gap. Prigogine and collaborators emphasized dissipative structures and nonequilibrium thermodynamics, arguing that irreversibility is physically fundamental rather than merely epistemic (Prigogine 1977); (Prigogine 1980). Rovelli's thermal time hypothesis proposes that time emerges from the statistical state of a system via modular flow (Rovelli 1993); (Connes and Rovelli 1994). Page and Wootters introduced a relational notion of time arising from correlations between subsystems (Page and Wootters 1983). In quantum gravity, several programs suggest that spacetime itself may be emergent, with time arising from entanglement structure or causal order (Oriti 2009); (Van Raamsdonk 2010).

Despite their diversity, these approaches share a common feature: time is not treated as a primitive entity but as something derived from physical processes. However, they often introduce additional formal machinery or speculative structures. The present work takes a more conservative route.

1.3 The Present Proposal

This paper advances a minimal reinterpretation of proper time that requires no new laws, fields, or dynamics. The proposal is simple:

Proper time measures the accumulation of irreversible constraint-imposing events along a worldline, enabled and bounded by entropy production.

The reinterpretation is ontological rather than dynamical. All standard equations of general relativity, statistical mechanics, and quantum theory remain untouched. What changes is the ordering of explanatory priority. Irreversibility is taken as physically prior to temporal measurement, while time parameters are understood as summaries of irreversible event structure.

Crucially, this view does not oppose entropy increase. Instead, it draws a principled distinction between two complementary and mutually reinforcing processes. On the one hand, entropy increase corresponds to the progressive release of microscopic constraints. As entropy grows, a larger number of microstates become compatible with a given macroscopic description, and the system becomes increasingly smooth in the sense that many distinct microscopic realizations yield indistinguishable macroscopic outcomes. Entropy, in this precise sense, measures the expansion of equivalence classes over microhistories.

On the other hand, time accumulation corresponds to the irreversible loss of recoverable distinctions along a concrete history. Each irreversible transition permanently excludes alternative

pasts that could have led to the same present state. Time, therefore, does not measure the size of equivalence classes, but rather the fact that equivalence classes have been irreversibly enlarged. It records the history of constraint release, not the degree of constraint release itself.

These two processes are not in tension. Entropy increase smooths the space of possibilities by collapsing distinctions, while time accumulation counts the irreversible act of smoothing. Entropy describes how much has been forgotten; time measures that forgetting has occurred.

1.4 Entropy, Constraints, and Smoothness

In statistical mechanics, entropy is proportional to the logarithm of the volume of phase space compatible with macroscopic constraints (Boltzmann 1877); (Gibbs 1902). An increase in entropy therefore corresponds to a *reduction in constraints*: more microscopic configurations yield the same macroscopic outcome. From this perspective, high-entropy states are smooth, not disordered. They are insensitive to microscopic detail.

Irreversible time, however, is not measured by smoothness itself but by the irreversible path taken toward it. Each constraint-releasing transition permanently removes distinctions that could, in principle, have mattered. Once these distinctions are lost, they cannot be reintroduced without external intervention or exponentially rare fluctuations.

The central claim of this paper is that proper time measures this irreversible forgetting. It is a scalar bookkeeping quantity that tracks the accumulation of unrecoverable constraint loss along a worldline. Heat death, on this view, is not stasis but completion: the point at which no further distinctions can be lost and no further time can accumulate.

1.5 Methodological Commitments

The approach adopted in this work is intentionally conservative in both its physical and ontological assumptions. At no point are the established dynamical laws of physics modified, nor are any additional fundamental entities or primitives introduced. The analysis relies exclusively on conceptual and mathematical structures already employed throughout contemporary physics, in particular coarse-graining procedures, entropy production, and the distinction between reversible microscopic dynamics and irreversible macroscopic behavior. A central methodological commitment is the explicit separation between microscopic permissiveness—where dynamical laws admit time-reversed trajectories in principle—and macroscopic irrecoverability, where the overwhelming loss of accessible microhistories renders reversal physically unattainable.

In this respect, the present framework aligns with forms of structural and ontic minimalism in the philosophy of physics, according to which explanatory progress is achieved not by proliferating theoretical entities but by clarifying the structural commitments implicit in successful theories (Ladyman and Ross 2007). The aim is therefore not to propose new physics, but to make explicit what existing physical theories already entail regarding the nature, measurement, and apparent directionality of time.

1.6 Outline of the Paper

Section 2 develops an event-based framework for irreversibility grounded in coarse-graining and typicality. Section 3 analyzes entropy as an enabling bound on irreversible events and clarifies its role as constraint release. Section 4 reinterprets proper time in terms of irreversible event accumulation and shows compatibility with relativistic time dilation. Section 5 examines limiting cases, including equilibrium, recurrence, and heat death. Section 6 relates the framework to established theories and models, including general relativity, Ising systems, and renormalization group flow. Section 7 discusses implications for quantum gravity, cosmology, and biology. Appendices provide formal clarifications and connections to information-theoretic bounds.

2 States, Events, and Irreversibility

2.1 The Representational Status of States

Modern physics is overwhelmingly formulated in terms of *states*. Classical systems are represented as points in phase space, quantum systems as vectors or density operators in Hilbert space, and fields as configurations over spacetime. These representations are indispensable for calculation, prediction, and control. However, their ontological status is more subtle.

A physical state rarely corresponds to a unique microhistory. Instead, it summarizes an equivalence class of histories compatible with a given level of description. In classical statistical mechanics, a macrostate corresponds to an enormous region of phase space rather than a single point (Boltzmann 1877); (Lebowitz 1993). In quantum mechanics, reduced density matrices encode partial information after environmental tracing, suppressing access to full microstate detail (Zurek 2003); (Schlosshauer 2007). In both cases, a state functions as a *compression* of historical information rather than a generator of it.

This motivates a shift in explanatory emphasis. If states encode histories rather than determine them, then treating states as ontologically primitive risks conflating representational convenience with physical necessity. A complementary description takes *events*—irreversible transitions that alter what histories remain possible—as the fundamental building blocks.

2.2 Events as Constraint-Imposing Transitions

Definition 2.1 (Event). An *event* is a physical transition that irreversibly imposes constraints on future evolution by permanently excluding a set of previously possible microhistories.

This definition is intentionally coarse-grained. An event need not be instantaneous or discontinuous; it may be extended in time and spatially distributed. What distinguishes an event from reversible evolution is not its temporal profile but its *irrecoverability*.

Example 2.1. Canonical examples of irreversible constraint-imposing events arise across classical, quantum, and statistical physics. Inelastic collisions provide a familiar case: relative kinetic energy is irreversibly dispersed into microscopic degrees of freedom, constraining future motion by eliminating the possibility of reconstructing the pre-collision state without extraordinary fine-tuning.

Spontaneous symmetry breaking offers a second illustration, in which a system selects one vacuum from a set of degenerate possibilities, thereby excluding alternative macroscopic configurations and permanently reducing the space of accessible futures (Anderson 1972). In quantum systems, decoherence interactions between a system and its environment suppress phase coherence between superposed states, enforcing an effectively classical set of alternatives and rendering interference effects operationally inaccessible (Zurek 2003). Finally, the formation of bound structures—such as atoms, molecules, or gravitationally bound systems—constitutes an irreversible imposition of constraints, as binding energies and environmental dissipation eliminate vast classes of microhistories that would otherwise remain dynamically available.

In each case, the system transitions from a state compatible with many possible continuations to one compatible with fewer. The excluded alternatives are not merely unlikely; they are dynamically inaccessible without external intervention or exponentially rare fluctuations.

2.3 Coarse-Graining and Macroregion Reduction

To formalize irreversibility, consider a microscopic state space Γ evolving under reversible dynamics Φ_t . Let

$$C : \Gamma \rightarrow \bar{\Gamma}$$

be a coarse-graining map that assigns each microstate to a macrostate. For $\bar{\gamma} \in \bar{\Gamma}$, define the associated macroregion

$$\Gamma_{\bar{\gamma}} = C^{-1}(\bar{\gamma}).$$

Lemma 2.1 (Irreversibility via Macroregion Reduction). *A transition $\gamma_1 \rightarrow \gamma_2$ is irreversible relative to coarse-graining C if*

$$\Gamma_{C(\gamma_2)} \subsetneq \Gamma_{C(\gamma_1)}.$$

Proof. The strict inclusion indicates that the set of microstates compatible with the post-transition macrodescription is strictly smaller than that compatible with the pre-transition macrodescription. Microhistories in the difference

$$\Gamma_{C(\gamma_1)} \setminus \Gamma_{C(\gamma_2)}$$

are permanently excluded from future evolution starting at γ_2 . Because the microscopic dynamics are reversible, this exclusion cannot arise from the equations of motion alone; it arises from coarse-graining and environmental entanglement. The exclusion is therefore irreversible at the macroscopic level. \square

Remark 2.1. This definition does not contradict microscopic reversibility. Rather, irreversibility emerges from the interaction between reversible microdynamics and information-losing descriptions, consistent with Boltzmannian and modern typicality-based accounts (Albert 2000); (Goldstein et al. 2012).

2.4 Typicality and the Direction of Constraint Loss

Irreversibility depends not on logical necessity but on overwhelming typicality. Given a low-entropy initial condition, almost all microscopic trajectories compatible with that condition evolve toward macrostates occupying vastly larger regions of phase space (Lebowitz 1993); (Goldstein 2001).

Proposition 2.1 (Thermodynamic Typicality). *Let μ be the Liouville measure on Γ . For a macrostate $\bar{\gamma}$, the fraction of trajectories originating in $\Gamma_{\bar{\gamma}}$ that evolve toward macrostates with larger macroregions approaches unity as system size increases.*

Sketch. Liouville measure is preserved under Φ_t . For macroscopic systems, macroregions corresponding to higher entropy occupy exponentially larger volumes of phase space. Consequently, almost all trajectories originating in a low-entropy macroregion enter higher-entropy macroregions and remain there for overwhelmingly long times. Detailed arguments appear in (Lebowitz 1993); (Albert 2000). \square

This establishes a crucial asymmetry: while microscopic dynamics permit constraint restoration in principle, such restorations are atypical to the point of physical irrelevance.

2.5 Quantum Irreversibility and Decoherence

In quantum mechanics, irreversibility arises through decoherence. Consider a system S interacting with an environment E , with joint Hilbert space $\mathcal{H}_S \otimes \mathcal{H}_E$. Unitary evolution entangles S with E , yielding a reduced density matrix

$$\rho_S = \text{Tr}_E \rho_{SE}.$$

Definition 2.2 (Decoherence). Decoherence is the dynamical suppression of off-diagonal terms in ρ_S relative to a preferred pointer basis due to environmental entanglement (Zurek 1981); (Joos et al. 2003).

Proposition 2.2 (Decoherence as Constraint Accumulation). *Decoherence irreversibly constrains the system to classical alternatives by excluding coherent superpositions from future effective evolution.*

Proof. Environmental entanglement distributes phase information across an enormous number of degrees of freedom. Reconstructing the original superposition would require precise control of the environment, which is physically infeasible. Thus, decoherence imposes a one-way reduction of accessible effective states, satisfying the macroregion reduction criterion. \square

Remark 2.2. From the present perspective, decoherence is not primarily about randomness or collapse, but about the irreversible loss of recoverable distinctions. It is therefore a paradigmatic example of time-generating constraint accumulation.

2.6 States as Quotients of Event Histories

The foregoing analysis suggests a reversal of explanatory priority.

Proposition 2.3 (States as Historical Quotients). *Macroscopic states are equivalence classes of event histories under coarse-graining, not primitive ontological entities.*

States arise by identifying histories that differ only in details rendered irrelevant by accumulated constraint loss. As entropy increases, more distinctions are erased, enlarging equivalence classes. In this sense, entropy corresponds to *smoothness*: many microhistories collapse onto the same macroscopic description.

Time, however, is not the smoothness itself. It is the irreversible process by which distinctions are erased.

Remark 2.3. This distinction resolves a common confusion: entropy increase releases constraints, while time accumulation records the irreversible act of releasing them. Smoothness grows; time counts the smoothing.

3 Entropy as an Enabling Bound

3.1 Entropy Beyond Disorder

Entropy is often described informally as a measure of disorder. While pedagogically convenient, this characterization obscures the operational role entropy plays in physics. In statistical mechanics, entropy quantifies the logarithmic size of an equivalence class of microstates compatible with a macroscopic description.

For a macrostate $\bar{\gamma}$ with associated macroregion $\Gamma_{\bar{\gamma}} \subset \Gamma$, the Boltzmann entropy is

$$S_B(\bar{\gamma}) = k_B \ln |\Gamma_{\bar{\gamma}}|,$$

where $|\Gamma_{\bar{\gamma}}|$ denotes the Liouville volume of the macroregion (Boltzmann 1877); (Lebowitz 1993).

Entropy therefore measures not disorder, but *degeneracy*: the number of distinct microhistories that are rendered macroscopically indistinguishable. High entropy corresponds to a loss of fine-grained distinctions, not to chaos in any naive sense.

Remark 3.1. Entropy increase corresponds to an increase in the number of ways a system can be partitioned, coarse-grained, or “sliced” while yielding the same macroscopic outcome. In this sense, entropy is a measure of representational smoothness.

3.2 Entropy as Constraint Release

The macroregion formalism makes explicit that entropy increase corresponds to a *reduction in constraints*. Each constraint restricts the accessible region of phase space. Releasing constraints enlarges the macroregion.

Definition 3.1 (Constraint). A *constraint* is a restriction on the set of accessible microstates compatible with a system’s macroscopic description.

Lemma 3.1 (Entropy Increase as Constraint Release). *An increase in entropy corresponds to a strict weakening of macroscopic constraints, enlarging the equivalence class of microstates compatible with a given description.*

Proof. Let $\bar{\gamma}_1$ and $\bar{\gamma}_2$ be macrostates such that

$$\Gamma_{\bar{\gamma}_1} \subsetneq \Gamma_{\bar{\gamma}_2}.$$

Then

$$S_B(\bar{\gamma}_2) - S_B(\bar{\gamma}_1) = k_B \ln \frac{|\Gamma_{\bar{\gamma}_2}|}{|\Gamma_{\bar{\gamma}_1}|} > 0.$$

Thus, entropy increase corresponds exactly to the relaxation of constraints defining $\bar{\gamma}_1$. The macrodescription $\bar{\gamma}_2$ enforces fewer restrictions on compatible microstates. \square

This framing dissolves the apparent paradox that entropy both “destroys order” and “enables dynamics.” Entropy does not destroy structure directly; it relaxes constraints, allowing many microhistories to be treated as equivalent.

3.3 Entropy Production and Irreversible Events

While entropy itself is a state function, *entropy production* characterizes irreversible transitions between states. Let $\sigma = dS/d\tau$ denote the entropy production rate with respect to proper time.

Lemma 3.2 (Entropy Production as a Necessary Condition for Events). *Irreversible constraint-imposing events require strictly positive total entropy production.*

Proof. From Section 2, an irreversible event corresponds to the permanent exclusion of microhistories from future accessibility. Such exclusion cannot occur in a closed, entropy-conserving system without violating Liouville’s theorem or unitarity.

However, when a system interacts with an environment, entropy may be exported. Let $S_{\text{tot}} = S_{\text{sys}} + S_{\text{env}}$. The second law requires

$$\frac{dS_{\text{tot}}}{d\tau} \geq 0.$$

An event may locally reduce the system’s effective macroregion by transferring information to the environment, but this transfer necessarily increases environmental entropy. Hence, irreversible events require $\sigma_{\text{tot}} > 0$. \square

Remark 3.2. Entropy production is not a side effect of irreversibility; it is its enabling condition. Without entropy export, no constraint can be permanently imposed or released.

3.4 Dissipative Structures and the Role of Entropy Flux

Dissipative structures provide the clearest illustration of entropy as an enabling bound rather than a destructive force. Systems such as convection cells, reaction-diffusion patterns, and living organisms maintain local organization by exporting entropy to their surroundings (Prigogine 1977); (Nicolis and Prigogine 1977); (Kondepudi and Prigogine 1998).

Definition 3.2 (Dissipative Structure). A *dissipative structure* is a system maintained far from equilibrium through continuous entropy production and exchange with an environment.

Proposition 3.1 (Entropy as an Enabling Bound). *Entropy production both enables and limits the persistence of organized structures by bounding the rate at which constraints may be imposed or released.*

Conceptual Argument. If entropy production is too low, gradients decay and the system relaxes toward equilibrium, eliminating structure. If entropy production is too high, fluctuations overwhelm constraint stabilization mechanisms. Stable dissipative structures exist only in intermediate regimes where entropy production sustains gradients while remaining bounded (Prigogine 1980); (Seifert 2012). \square

This clarifies the apparent tension: entropy does not compete with structure. Structure exists because entropy production allows irreversible constraint cycling.

3.5 Fluctuation Theorems and the Cost of Reversal

Modern fluctuation theorems quantify the improbability of entropy-decreasing processes. The Crooks fluctuation theorem states

$$\frac{P_F(\sigma = A)}{P_R(\sigma = -A)} = \exp\left(\frac{A}{k_B}\right),$$

where P_F and P_R are probabilities of forward and reverse processes (Crooks 1999); (Jarzynski 1997).

Corollary 3.1 (Exponential Suppression of Constraint Restoration). *The probability of reversing an irreversible constraint-imposing event decreases exponentially with the entropy produced.*

Remark 3.3. This explains why constraint release is effectively one-way at macroscopic scales. Reversing entropy production is not forbidden, but it is so improbable that it does not contribute to operational time.

3.6 Heat Death as Maximal Smoothness

The traditional description of heat death emphasizes stasis or “nothing happening.” This is misleading. At heat death, microscopic dynamics continue, but macroscopic distinctions vanish.

Definition 3.3 (Macroscopic Smoothness). A system is *macroscopically smooth* if a large class of coarse-grainings yield indistinguishable macroscopic descriptions.

Proposition 3.2 (Heat Death as Constraint Exhaustion). *Thermodynamic equilibrium corresponds to maximal smoothness: all remaining macroscopic constraints have been released.*

Proof. At equilibrium, entropy is maximized subject to conserved quantities. No further macroregion enlargement is possible. All accessible microstates belong to a single dominant equivalence class. Thus, all macroscopic distinctions have been erased. \square

Remark 3.4. Heat death is not stasis but completion. It is the saturation of constraint release, not the cessation of microscopic activity.

3.7 Entropy, Smoothness, and Time

At this stage it is useful to distinguish three closely related, but conceptually non-identical, notions that are often conflated in both physical and philosophical discussions: entropy, entropy production, and time.

Entropy characterizes the degree of smoothness of a system. Formally, it measures the size of equivalence classes of microstates that are indistinguishable under a given coarse-graining. High entropy corresponds to large equivalence classes, in which many microscopic configurations yield the same macroscopic description. In this sense, entropy quantifies how many distinctions have already been erased: it is a static measure of degeneracy or smoothness.

Entropy production, by contrast, is a dynamical notion. It refers to the irreversible process by which these equivalence classes are enlarged. When entropy is produced, constraints are released: distinctions that once mattered for future evolution are permanently discarded, typically through dissipation into an environment. Entropy production is therefore not merely a change in a numerical quantity, but a structural transformation in the space of possibilities available to the system.

Time, in the present framework, is distinct from both of these. Time does not measure smoothness itself, nor does it directly measure the rate of smoothing. Rather, it measures the accumulated record that such irreversible smoothing has occurred. Proper time tracks the history of constraint release along a worldline: it is a bookkeeping variable that counts the irreversible losses of distinction that have been stabilized by entropy production.

From this perspective, entropy measures how much has been forgotten, while time measures the fact that forgetting has taken place. The two are inseparable, but not identical. A system may possess high entropy without producing additional entropy, in which case smoothness is maximal but time ceases to accumulate. Conversely, entropy production marks the ongoing erasure of distinctions, and it is this irreversible process that underwrites temporal passage. This distinction will be essential in the reinterpretation of proper time that follows.

4 Proper Time Reinterpreted

4.1 The Operational Meaning of Proper Time

In relativistic physics, proper time τ is defined geometrically as the invariant length of a timelike worldline γ :

$$\tau = \int_{\gamma} \sqrt{-g_{\mu\nu} dx^{\mu} dx^{\nu}}.$$

This definition is formally precise and empirically successful (Misner, Thorne, and Wheeler 1973); (Wald 1984). However, it is silent on the physical nature of the quantity being accumulated.

Operationally, proper time is measured by clocks. Every physical clock functions by undergoing transitions between distinguishable states and leaving stable records of those transitions. These

transitions are necessarily irreversible. Atomic clocks rely on spontaneous emission; mechanical clocks dissipate energy; digital clocks erase information.

Remark 4.1. The metric definition specifies *how much* time accumulates along a worldline, but not *what physical process* performs the accumulation.

This motivates a reinterpretation: proper time is not an abstract parameter but a physical tally of irreversible transitions.

4.2 No Reversible Clock Lemma

We formalize this intuition.

Lemma 4.1 (No Reversible Clock Lemma). *A system undergoing only perfectly reversible dynamics cannot function as a physical clock.*

Proof. A clock must produce a sequence of distinguishable states that persist and can be compared. Persistence requires the elimination of alternative microhistories leading to the same macroscopic record. This elimination constitutes logical irreversibility.

By Landauer's principle, any logically irreversible operation requires a minimum entropy increase of $k_B \ln 2$ per bit erased (Landauer 1961); (Bennett 2003). If a system undergoes only reversible dynamics, no entropy is produced, no information is erased, and no stable records can form.

Therefore, no perfectly reversible system can serve as a clock. \square

Remark 4.2. This lemma holds classically and quantum mechanically. Unitary evolution alone cannot produce records; decoherence and environmental coupling are required (Zurek 2003); (Schlosshauer 2007).

4.3 Event Density and Temporal Accumulation

We now formalize the central proposal.

Definition 4.1 (Irreversible Event Density). Let $\mathcal{E}(x)$ denote the density of irreversible constraint-imposing events along a worldline at spacetime point x , measured per unit parameter λ .

Theorem 4.1 (Proper Time as Constraint Accumulation). *Proper time along a worldline is proportional to the cumulative density of irreversible events along that worldline:*

$$\tau = \alpha \int_{\gamma} \mathcal{E}(x) d\lambda,$$

where α is a calibration constant fixed by operational clock standards.

Justification. By Lemma 4.1, time measurement requires irreversible events. Each such event corresponds to a reduction in future-accessible microhistories and therefore to entropy production.

The integral $\int \mathcal{E}(x) d\lambda$ counts the total number of irreversible constraint-imposing transitions experienced along γ . Empirical consistency requires that this accumulation match the metric proper

time defined by $g_{\mu\nu}$. Therefore, \mathcal{E} must be constrained such that its integral reproduces relativistic predictions.

No modification to spacetime geometry is required; only the physical interpretation of τ is altered. \square

Remark 4.3. This does not define $\mathcal{E}(x)$ uniquely. Different clock constructions realize different microscopic mechanisms, but all share irreversible event accumulation.

4.4 Entropy, Event Density, and Smoothness

It is essential to distinguish between entropy and time.

Entropy measures the size of equivalence classes — macroscopic smoothness. Event density measures the irreversible *process* by which those classes are enlarged.

Proposition 4.1 (Entropy Does Not Measure Time). *High entropy does not imply large elapsed time. Only entropy production contributes to time accumulation.*

Proof. At equilibrium, entropy is maximal but entropy production vanishes. From Lemma 3.2, irreversible events cease. Therefore, time accumulation halts despite maximal entropy. \square

Remark 4.4. Entropy is a static measure of smoothness; time is a cumulative measure of irreversible forgetting.

4.5 Gravitational Time Dilation as Event Suppression

Gravitational time dilation is experimentally well confirmed (Pound and Rebka 1960); (Hafele and Keating 1972). In a static gravitational field, clocks deeper in the potential well accumulate less proper time relative to distant observers.

Proposition 4.2 (Gravitational Event Suppression). *In strong gravitational fields, irreversible event density per unit coordinate time is reduced, resulting in slower proper time accumulation.*

Heuristic Argument. In a Schwarzschild spacetime, the redshift factor $\sqrt{|g_{00}|}$ reduces locally measured frequencies relative to distant observers (Tolman 1930). Atomic transition rates, chemical reaction rates, and thermal fluctuation rates scale accordingly.

Each clock tick corresponds to an irreversible transition (e.g., photon emission). Reduced transition rates imply fewer irreversible events per coordinate time. By Theorem 4.1, proper time accumulates more slowly. \square

Remark 4.5. This interpretation preserves the equivalence principle: locally, clocks function normally; globally, event rates differ due to spacetime geometry.

4.6 Kinematic Time Dilation

Lorentz time dilation arises for clocks in relative motion.

Corollary 4.1 (Kinematic Event Dilution). *For observers in relative motion, moving clocks undergo fewer irreversible events per unit coordinate time in the rest frame, producing Lorentz time dilation.*

Conceptual Argument. A moving clock's internal processes are constrained by relativistic kinematics. Proper acceleration phases alter constraint accumulation asymmetrically, resolving the twin paradox (Misner, Thorne, and Wheeler 1973). Event density along the accelerated worldline is reduced relative to the inertial frame. \square

4.7 Why Smoothness Does Not Stop Time

At first glance, the identification of heat death with maximal smoothness appears to imply infinite time. This is incorrect.

Proposition 4.3 (Smoothness Without Time). *A system may possess maximal entropy (smoothness) while exhibiting zero proper time accumulation.*

Proof. At equilibrium, entropy is maximal and $\sigma = 0$. By Lemma 3.2, irreversible events cease. Therefore, $\mathcal{E}(x) = 0$ and $d\tau/d\lambda = 0$. Microscopic motion continues, but no time is recorded. \square

Remark 4.6. This resolves the apparent paradox: heat death is not eternal time but the exhaustion of time-generating processes.

4.8 Time as Irreversible Forgetting

The reinterpretation developed in this work may be distilled into a single unifying perspective. Constraints encode distinctions: they differentiate one future from another by excluding alternatives. To impose a constraint is to declare that certain microhistories are no longer admissible, and it is precisely this act of exclusion that gives physical events their irreversibility.

Entropy, in this light, is not merely a measure of disorder but a measure of constraint release. As entropy increases, the number of distinct macroscopic constraints decreases, and the system admits a larger degeneracy of microstates that are operationally indistinguishable. Entropy production thus corresponds to the irreversible shedding of fine-grained distinctions, whether through dissipation, decoherence, thermalization, or environmental entanglement.

Crucially, this irreversible release of constraints produces records. A record is not a preserved state, but the absence of alternatives: a trace left behind because certain possibilities have been permanently erased. All clocks, memories, and histories consist of such records, stabilized by entropy production and protected against reversal by exponential suppression.

Time, on this view, is not a background parameter through which processes unfold. It is the accumulated record of irreversible forgetting. Proper time measures how much of the universe's space of possibilities has been permanently collapsed along a worldline. Temporal passage does not occur because the universe is active, dynamic, or restless; it occurs because the universe forgets, and because that forgetting cannot be undone.

5 Near-Equilibrium and the Cessation of Time

5.1 Equilibrium as Constraint Saturation

Thermodynamic equilibrium is commonly described as a state of maximal entropy subject to conserved quantities. In the present framework, equilibrium admits a sharper interpretation: it is the saturation of constraint release.

Definition 5.1 (Equilibrium). A system is in thermodynamic equilibrium if all macroscopic observables compatible with conserved quantities are dynamically stable and entropy production vanishes:

$$\sigma = \frac{dS}{d\tau} = 0.$$

At equilibrium, no further coarse-grained distinctions can be erased without external intervention. All remaining constraints are either conserved or dynamically irrelevant.

5.2 Event Density Near Equilibrium

Entropy production governs irreversible event density.

Lemma 5.1 (Vanishing Event Density at Equilibrium). *If a system is at thermodynamic equilibrium, then the irreversible event density $\mathcal{E}(x)$ along any worldline internal to the system vanishes.*

Proof. By Lemma 3.2, irreversible events require $\sigma > 0$. At equilibrium, $\sigma = 0$ everywhere. Therefore, no irreversible constraint-imposing transitions occur. Hence $\mathcal{E}(x) = 0$. \square

Remark 5.1. Microscopic motion persists at equilibrium. However, such motion is fully reversible and does not impose new macroscopic constraints.

5.3 Temporal Exhaustion Theorem

We may now state a central result.

Theorem 5.1 (Temporal Exhaustion at Equilibrium). *In the limit of thermodynamic equilibrium, proper time accumulation asymptotically halts, despite ongoing microscopic dynamics.*

Proof. From Theorem 4.1,

$$\frac{d\tau}{d\lambda} \propto \mathcal{E}(x).$$

By Lemma 5.1, $\mathcal{E}(x) = 0$ at equilibrium. Therefore, $d\tau/d\lambda = 0$, and proper time ceases to accumulate.

Microscopic trajectories continue to evolve reversibly, but no irreversible records form. Hence, no operational time passes. \square

Remark 5.2. This result does not contradict relativity or thermodynamics. It concerns the physical instantiation of clocks, not the mathematical structure of spacetime.

5.4 Poincaré Recurrence Without Temporal Reversal

The Poincaré recurrence theorem states that a finite Hamiltonian system will return arbitrarily close to its initial microstate after sufficiently long time (Poincaré 1890); (Zermelo 1896). This has sometimes been interpreted as challenging the irreversibility of thermodynamics.

In the present framework, recurrence is benign.

Proposition 5.1 (Recurrence Does Not Reverse Time). *Poincaré recurrence does not undo accumulated proper time or reverse irreversible constraints.*

Proof. Recurrence concerns microscopic states under reversible dynamics. It does not entail the simultaneous recurrence of environmental degrees of freedom or the undoing of macroscopic records.

Moreover, recurrence times scale exponentially with system size. During the overwhelmingly long near-equilibrium interval preceding recurrence, $\sigma \approx 0$ and $\mathcal{E}(x) \approx 0$. Therefore, essentially no proper time accumulates during this interval.

Recurrence thus occurs in a regime where time has effectively stopped, rather than reversing time. \square

Remark 5.3. Recurrence is compatible with thermodynamics because it does not constitute macroscopic constraint reversal (Albert 2000); (Lebowitz 1993).

5.5 Heat Death as Maximal Smoothness

The classical notion of heat death describes a universe that has reached maximum entropy, with no free energy gradients remaining (Adams and Laughlin 1997).

In the present framework, heat death is not eternal stasis but completion.

Definition 5.2 (Macroscopic Smoothness). A system is macroscopically smooth if all coarse-grainings compatible with conserved quantities yield indistinguishable macrostates.

Lemma 5.2 (Entropy as Smoothness). *Increasing entropy corresponds to increasing smoothness: an increase in the number of distinct microscopic realizations yielding the same macroscopic description.*

Proof. Entropy is defined as

$$S = k_B \ln |\Gamma_{\bar{\gamma}}|.$$

As $|\Gamma_{\bar{\gamma}}|$ increases, more microstates correspond to the same macrostate. This increases invariance under coarse-graining and hence smoothness. \square

Proposition 5.2 (Heat Death as Constraint Exhaustion). *Heat death corresponds to the exhaustion of available irreversible constraint releases, not to the persistence of infinite temporal duration.*

Proof. At heat death, entropy is maximal and entropy production vanishes. By Lemma 5.1, irreversible event density is zero. Therefore, no further proper time accumulates.

The universe remains dynamically active at the microscopic level but temporally inert at the macroscopic level. \square

5.6 Why Heat Death Is Not Stasis

It is crucial to avoid a common misconception.

Remark 5.4. Heat death is not static. It is dynamically smooth.

Microscopic motion continues indefinitely. Quantum fluctuations persist. However, these fluctuations do not generate records, constraints, or distinguishable macrostates. Without irreversible forgetting, there is no time.

5.7 Time Is Not Infinite

We may summarize the section with a strong but conservative claim.

Theorem 5.2 (Finiteness of Time Accumulation). *The total amount of proper time that can accumulate in a closed system is finite and bounded by the system's capacity for irreversible constraint release.*

Argument. Each irreversible event consumes free energy and increases entropy. The second law bounds total entropy increase. Therefore, the total number of irreversible events — and hence total proper time — is finite. \square

Remark 5.5. This does not imply the universe has a final moment. It implies that temporal accumulation has a limit, beyond which change no longer counts as time.

5.8 Interim Summary

Near thermodynamic equilibrium, the structure of the system reaches a limiting regime in which the distinctions that once supported irreversible evolution are exhausted. Entropy attains its maximal value, not merely in the sense of disorder, but in the deeper sense that the space of admissible macroscopic descriptions becomes maximally degenerate. Many microscopic configurations correspond to the same macroscopic outcome, and no further informative distinctions can be drawn by coarse-graining.

In this regime, smoothness is complete. The system admits no persistent gradients, no stable asymmetries, and no remaining mechanisms by which novel constraints could be imposed. Microscopic motion continues, but it no longer produces macroscopic differentiation. As a consequence, irreversible events—understood as transitions that permanently restrict future evolution—cease to occur.

Since proper time, in the present framework, is proportional to the cumulative density of such irreversible events, its accumulation correspondingly halts. Temporal passage does not end through catastrophe or dynamical breakdown, but through saturation. The arrow of time terminates not in collapse or explosion, but in silence: a state in which nothing further can be irreversibly decided.

6 Relation to Existing Frameworks

The event-based interpretation of proper time proposed in this work does not compete with existing physical theories. Instead, it reorganizes their conceptual dependencies while preserving all formal

structure and empirical predictions. In this section we demonstrate explicit compatibility with general relativity, nonequilibrium statistical mechanics, lattice models, and renormalization group theory.

6.1 General Relativity

6.1.1 Metric Structure and Geodesic Motion

General relativity defines spacetime as a pseudo-Riemannian manifold $(\mathcal{M}, g_{\mu\nu})$ whose metric determines causal structure and proper time along timelike curves (Misner, Thorne, and Wheeler 1973); (Wald 1984). The present framework leaves this structure untouched.

Proposition 6.1 (Metric Compatibility). *The event-based interpretation preserves all predictions of general relativity concerning geodesic motion, gravitational redshift, and clock comparison experiments.*

Proof. Proper time remains defined by

$$\tau = \int_{\gamma} \sqrt{-g_{\mu\nu} dx^{\mu} dx^{\nu}}.$$

The reinterpretation concerns the physical realization of clocks, not the mathematical definition of τ . Since $\mathcal{E}(x)$ is constrained such that its integral reproduces the metric interval, all relativistic predictions remain unchanged. \square

6.1.2 Black Hole Thermodynamics

Black holes provide a crucial testbed for any interpretation linking time and entropy. Black hole entropy is proportional to horizon area,

$$S_{\text{BH}} = \frac{k_B A}{4\ell_P^2},$$

and Hawking radiation represents an irreversible process (Bekenstein 1973); (Hawking 1975).

Proposition 6.2 (Event Density Near Horizons). *Near black hole horizons, irreversible event density as measured by distant observers is suppressed, leading to asymptotic freezing of proper time.*

Physical Argument. Processes near the horizon appear infinitely time-dilated to distant observers. Hawking radiation carries entropy outward, while infalling degrees of freedom are effectively thermalized at the stretched horizon (Susskind, Thorlacius, and Uglum 1995). From the exterior viewpoint, irreversible event rates vanish asymptotically, and thus proper time accumulation halts. \square

This interpretation aligns naturally with the membrane paradigm and horizon complementarity without modifying spacetime geometry.

6.2 Statistical Mechanics and Nonequilibrium Physics

6.2.1 Entropy Production as Primary

Modern statistical mechanics assigns central importance to entropy production rather than entropy itself (Lebowitz 1993); (Seifert 2012). In the present framework, entropy production determines event density and thus time accumulation.

Proposition 6.3 (Primacy of Entropy Production). *Entropy production rate, not entropy value, governs the accumulation of proper time.*

Proof. Entropy is a state function and may remain constant over extended periods. Entropy production measures irreversible transitions between states. Since irreversible events define $\mathcal{E}(x)$, only entropy production contributes to time accumulation. \square

6.2.2 Fluctuation Theorems

Fluctuation theorems quantify the probability of entropy-decreasing trajectories (Jarzynski 1997); (Crooks 1999). These results place precise bounds on constraint reversal.

Corollary 6.1 (Bounded Reversibility). *The probability of reversing accumulated proper time decreases exponentially with the magnitude of entropy production.*

Proof. From Crooks' theorem,

$$\frac{P(\sigma)}{P(-\sigma)} = e^{\sigma/k_B}.$$

Thus, reversing a macroscopic sequence of irreversible events is exponentially suppressed, ensuring effective irreversibility of time accumulation. \square

6.3 Ising Models and Phase Transitions

Lattice models provide concrete realizations of constraint formation and release.

6.3.1 Domain Formation as Constraint Imposition

The Ising model exhibits spontaneous symmetry breaking below critical temperature (Onsager 1944); (Goldenfeld 1992).

Example 6.1 (Domain Wall Formation). During a quench, local spin alignment imposes long-range constraints. Each stabilized domain wall excludes vast regions of phase space and constitutes an irreversible event.

Proposition 6.4 (Criticality and Event Throughput). *Irreversible event density is maximized near critical points and suppressed deep in ordered or disordered phases.*

Proof. Near criticality, correlation lengths diverge and fluctuations span multiple scales, enabling maximal constraint formation. Away from criticality, degrees of freedom are either frozen (ordered phase) or unconstrained (disordered phase), reducing irreversible event rates (Hohenberg and Halperin 1977). \square

This explains why critical phenomena are associated with maximal dynamical richness and temporal structure.

6.4 Renormalization Group as Constraint Selection

Renormalization group (RG) flow describes how effective theories change with scale (Wilson and Kogut 1974); (Cardy 1996).

Definition 6.1 (Effective Constraint). A constraint is effective at scale ℓ if it restricts macroscopic behavior after coarse-graining to that scale.

Proposition 6.5 (RG Flow as Constraint Filtering). *Renormalization group flow systematically removes irrelevant constraints while preserving those that dominate macroscopic dynamics.*

Proof. Coarse-graining integrates out short-scale degrees of freedom. Operators with negative scaling dimension decay, while relevant operators grow. This mirrors the macroregion reduction of Lemma ??: the effective constraint set shrinks as scale increases. \square

Remark 6.1. RG flow can be interpreted as tracking which irreversible constraints survive at each scale, linking microscopic reversibility to macroscopic time.

6.5 Unification via Constraint Geometry

We may now state a unifying result.

Theorem 6.1 (Time as Cumulative Quotienting). *Proper time measures the cumulative quotienting of microscopic degrees of freedom into macroscopic equivalence classes under irreversible coarse-graining.*

Proof. Each irreversible event identifies previously distinct microhistories as equivalent. Entropy quantifies the size of these equivalence classes. Proper time integrates the rate at which this quotienting occurs along a worldline. \square

This geometric interpretation clarifies how entropy simultaneously represents loss of constraint and gain of smoothness.

6.6 Interim Summary

Taken together, the preceding analyses show that the proposed event-based interpretation of time coheres naturally with several major theoretical frameworks in contemporary physics, each of which constrains a different aspect of irreversible constraint accumulation.

Within general relativity, the spacetime metric fixes the geometric structure along which event accumulation occurs. The metric does not generate time directly, but it constrains the admissible rates at which physical processes—and therefore irreversible events—can occur along a worldline. In this sense, relativistic geometry acts as a regulator of constraint accumulation, ensuring covariance and consistency with observed time dilation effects.

Statistical mechanics supplies the dynamical substrate for irreversibility. Through entropy production, it governs when and how constraints can be imposed, stabilized, or released into the environment. The second law does not merely describe the evolution of macrostates; it bounds the very possibility of irreversible events, and thus bounds the accumulation of time itself.

Lattice models, such as Ising-type systems, provide explicit and tractable illustrations of constraint formation. In these models, symmetry breaking, domain formation, and defect stabilization correspond to concrete instances of irreversible constraint imposition. Their dynamics make visible, in a controlled setting, how local constraint accumulation can coexist with global entropy increase.

Finally, the renormalization group formalizes how constraints survive or are eliminated across scales. By identifying which microscopic features remain relevant at macroscopic levels, renormalization theory can be understood as tracking the persistence of constraints under coarse-graining. This offers a natural bridge between reversible microdynamics and irreversible macrodynamics, aligning directly with the event-based account of time.

Across these domains, time appears not as a fundamental substance or external parameter, but as an accounting variable for irreversible forgetting: a cumulative measure of how many alternative futures have been permanently excluded by the physical history of a system.

7 Extended Discussion and Open Questions

The preceding sections established that proper time may be reinterpreted as the cumulative density of irreversible constraint-imposing events along a worldline, without altering any formal predictions of existing theories. We now explore broader implications, conceptual clarifications, and open questions raised by this reinterpretation.

7.1 Quantum Gravity and Emergent Spacetime

Many approaches to quantum gravity suggest that spacetime geometry is not fundamental, but emergent from more primitive non-geometric degrees of freedom. Examples include loop quantum gravity (Rovelli 2004), causal set theory (Sorkin 2003), group field theory (Oriti 2009), and tensor network models of spacetime emergence (Van Raamsdonk 2010).

Remark 7.1. If spacetime geometry emerges, then proper time cannot be ontologically prior to the processes that generate geometry. The event-based interpretation is therefore naturally aligned with emergent spacetime programs.

In many such approaches, geometry arises from patterns of entanglement or combinatorial relations. Crucially, entanglement dynamics involve decoherence, coarse-graining, and effectively irreversible transitions.

Proposition 7.1 (Event-Based Time in Emergent Spacetime). *If spacetime geometry emerges from microscopic degrees of freedom, then proper time must likewise emerge from irreversible processes within those degrees of freedom.*

Conceptual Argument. Emergent geometry is defined only after coarse-graining microscopic structures. Coarse-graining is an irreversible operation that discards information. Since proper time is defined relative to geometry, it inherits this irreversibility and cannot precede it ontologically. \square

Thus, the present framework does not merely tolerate emergent spacetime; it predicts that time itself must emerge from irreversible constraint accumulation.

7.2 Entropy, Constraint Release, and Smoothness

A potential source of confusion arises from the dual role of entropy. Entropy is often described as disorder or randomness, but in the present framework entropy is more precisely understood as *constraint release*.

Definition 7.1 (Constraint). A *constraint* is a restriction on the set of microstates compatible with a macroscopic description.

Definition 7.2 (Constraint Release). Entropy increase corresponds to the removal or weakening of constraints, enlarging the set of microstates consistent with macroscopic observables.

This interpretation is standard in statistical mechanics: high-entropy states admit many micro-realizations, whereas low-entropy states require precise coordination.

Lemma 7.1 (Entropy as Equivalence Proliferation). *An increase in entropy corresponds to an increase in the number of distinct microstates that are macroscopically indistinguishable.*

Proof. By definition,

$$S = k_B \ln |\Gamma_{\bar{\gamma}}|.$$

As S increases, the macroregion volume grows. This corresponds to a proliferation of microstates yielding the same macroscopic outcome, i.e. an increase in equivalence classes under coarse-graining. \square

This clarifies an apparent tension: entropy increase corresponds to fewer constraints but more smoothness. The system becomes easier to describe precisely because fewer distinctions matter.

7.3 Heat Death as Maximal Smoothness

The heat death of the universe is often portrayed as a static, featureless end state. In the present framework, it is more accurately described as *maximal smoothness*.

Definition 7.3 (Macroscopic Smoothness). A system is macroscopically smooth if a wide class of coarse-grainings yield indistinguishable macroscopic descriptions.

Proposition 7.2 (Heat Death as Smoothness Maximum). *Thermodynamic equilibrium maximizes macroscopic smoothness by eliminating persistent constraints.*

Proof. At equilibrium, entropy is maximal subject to conserved quantities. All microstates compatible with those quantities are equally probable. Any coarse-graining respecting the conserved quantities yields the same macroscopic description. Thus, the system is maximally smooth. \square

Corollary 7.1 (Temporal Saturation). *In a maximally smooth state, proper time accumulation halts because no further irreversible constraints can be imposed.*

This reframes heat death not as stasis, but as completion: the exhaustion of all constraint-imposing processes.

7.4 Cosmological Arrow of Time

The cosmological arrow of time is traditionally explained via a low-entropy initial condition (Penrose 1979); (Carroll 2010). The present framework refines this explanation.

Proposition 7.3 (Arrow of Time as Constraint Gradient). *The arrow of time points in the direction of increasing cumulative constraint release.*

Proof. Given a low-entropy initial condition, the system contains many constraints that can be irreversibly relaxed. Each relaxation increases entropy and accumulates proper time. The direction in which constraint release is possible defines the arrow of time. \square

This interpretation avoids reifying time asymmetry. Instead, it locates asymmetry in the availability of constraint relaxation pathways.

7.5 Boltzmann Brains and Atypical Fluctuations

Boltzmann brain scenarios posit observers arising from rare entropy-decreasing fluctuations (Albrecht and Sorbo 2004). These scenarios are problematic because they predict observers without extended histories.

Proposition 7.4 (Event Deficit of Boltzmann Brains). *Boltzmann brain configurations lack sufficient irreversible constraint accumulation to support extended proper time.*

Proof. A Boltzmann brain arises via a fluctuation that briefly imposes structure without sustained entropy production. Such a configuration lacks a dense event history and therefore lacks accumulated proper time. It cannot support long-lived observation or memory. \square

This disfavors Boltzmann brains without invoking anthropic arguments.

7.6 Biological Time and Aging

Living organisms are paradigmatic dissipative structures (Schrödinger 1944); (Prigogine 1980). They maintain internal constraints by exporting entropy to their environment.

Definition 7.4 (Biological Time). Biological time is the accumulation of irreversible physiological constraints within an organism.

Proposition 7.5 (Aging as Constraint Saturation). *Aging corresponds to the progressive accumulation of irreversible constraints that reduce physiological flexibility.*

Proof. Damage accumulation, epigenetic locking, and loss of repair capacity impose irreversible constraints on biological function (Hayflick 2000); (López-Otín et al. 2013). These constraints reduce the number of viable physiological trajectories, corresponding to biological aging. \square

This aligns biological time with physical time: both measure irreversible loss of future possibilities.

7.7 Open Questions

Although the preceding analysis establishes the internal consistency and physical plausibility of interpreting proper time as irreversible constraint accumulation, several substantive questions remain unresolved. These questions do not call for the introduction of new physical principles, but rather for a more precise articulation of how existing principles are to be applied within the proposed framework.

First, there remains the problem of specifying the event density $\mathcal{E}(x)$ in a manner that is both physically meaningful and broadly applicable across different classes of systems. While the qualitative role of irreversible events is clear, a systematic characterization of what counts as an event, how event rates are to be computed, and how these rates depend on underlying microdynamics remains an open technical challenge.

Closely related is the issue of coarse-graining. Irreversibility, and therefore constraint accumulation, is defined relative to a coarse-grained description. A central question is whether there exist natural or privileged coarse-graining schemes that yield observer-independent time accumulation, or whether time remains partially perspectival, tied to the informational and dynamical capacities of particular subsystems. Clarifying the degree of objectivity attainable in event-based time is essential for fully situating the proposal within fundamental physics.

A further open direction concerns the relationship between this framework and candidate theories of quantum gravity. Many such approaches posit that spacetime itself is emergent from more primitive structures. It remains to be seen whether irreversible constraint accumulation can be identified at this pre-geometric level and whether proper time, as reconstructed from event density, coincides with or helps explain the emergence of spacetime geometry in these models.

Finally, there is the question of how constraint accumulation interfaces with information-theoretic notions of complexity, computation, and memory. Since irreversible events are closely tied to information erasure, record formation, and loss of alternative histories, a deeper connection may exist between temporal accumulation and measures of algorithmic or thermodynamic complexity. Making this connection precise could further unify thermodynamics, information theory, and temporal ontology.

All of these questions concern the refinement and formalization of the present framework rather than its revision. They point toward future work aimed at sharpening the quantitative and conceptual tools required to fully articulate time as an emergent measure of irreversible constraint accumulation.

8 Conclusion

This work has proposed a conservative but conceptually reordering interpretation of time in physics. Proper time need not be treated as a primitive dimension or metaphysical substance. Instead, it may be understood as a scalar measure of irreversible constraint accumulation along a worldline, enabled and bounded by entropy production.

No empirical predictions of existing physical theories are altered by this reinterpretation. The metric definition of proper time in general relativity remains intact, as do the laws of thermodynamics, statistical mechanics, and quantum theory. What changes is the ontological ordering: irreversibility becomes physically prior to temporal measurement, and states become summaries of event histories rather than fundamental entities.

8.1 Summary of Core Claims

The argument developed in this work unfolded through a sequence of interconnected claims that together support a reinterpretation of time grounded in irreversibility rather than fundamentality. First, physical states were shown to function as representational summaries: they encode equivalence classes of underlying microhistories and therefore should not be treated as ontological primitives. What is physically primary is not the instantaneous state, but the structured history of transitions that give rise to it.

Within this framework, irreversible events were defined as transitions that permanently impose constraints on future evolution under a given coarse-graining. Such events are distinguished not by discontinuity, but by the exclusion of alternative microhistories that cannot be recovered without extraordinary intervention. Irreversibility thus emerges from the interaction between reversible microscopic dynamics and macroscopic descriptions that collapse many possibilities into fewer effective outcomes.

Entropy production was identified as a necessary condition for irreversible events. Rather than serving merely as a measure of disorder, entropy production functions as an enabling bound on persistent structure: it permits the local imposition of constraints while ensuring that the global accounting of possibilities remains consistent with the second law of thermodynamics. Without positive entropy production, no permanent constraint accumulation can occur.

On this basis, it was argued that all operational clocks necessarily rely on irreversible processes. Any system whose dynamics were perfectly reversible would be incapable of producing stable, distinguishable records of temporal passage. Time measurement, in practice, is inseparable from entropy production and information erasure.

Proper time was then reinterpreted as being proportional to the cumulative density of irreversible, constraint-imposing events along a worldline. This reinterpretation preserves the formal metric definition of proper time while supplying it with a physically grounded operational meaning. Within this view, gravitational and kinematic time dilation arise not from any alteration of time itself, but from the suppression of irreversible event rates due to gravitational redshift or relative motion.

As systems approach thermodynamic equilibrium, entropy production vanishes and the accu-

mulation of new constraints halts. In this limit, microscopic dynamics continue, but no further operational time is generated. Temporal advance ceases not because motion stops, but because no new irreversible distinctions are being formed.

Finally, cosmological heat death was reinterpreted as a state of maximal smoothness. In this regime, constraints are exhausted, distinctions have collapsed, and further differentiation is impossible. Heat death thus represents not stasis, but the completion of constraint accumulation.

Taken together, these claims resolve the apparent tension between reversible microdynamics and irreversible macrodynamics without introducing new physical laws. The reconciliation is achieved by reordering ontological priorities: irreversibility becomes physically prior to temporal measurement, and time itself emerges as a bookkeeping quantity that tracks the organized loss of possibility.

8.2 Entropy Revisited

A central conceptual clarification concerns entropy. Entropy increase does not introduce disorder in any ontologically fundamental sense. Rather, it releases constraints. As entropy grows, more microstates become macroscopically equivalent; fewer distinctions matter; the system becomes smoother.

This perspective dissolves a common confusion. Entropy increase does not oppose structure per se. It opposes *persistent, differentiating constraints*. Dissipative structures exist precisely because they channel entropy production in a way that stabilizes constraints locally while releasing them globally.

In this light, time itself is not opposed to entropy. Time is the cumulative record of irreversible constraint release.

8.3 Time as Organized Forgetting

On the present view, time may be understood as a bookkeeping device for irreversible forgetting. Each event eliminates alternative futures that could otherwise have occurred. Proper time measures how much of the future has been rendered impossible.

This framing aligns time with other emergent thermodynamic quantities such as temperature or pressure. Like them, time is not fundamental but arises from collective behavior under coarse-graining. Unlike them, time tracks loss rather than magnitude: the organized disappearance of possibility.

8.4 Heat Death Reconsidered

The far-future heat death of the universe is often imagined as a frozen or meaningless end state. The present framework offers a different picture. Heat death is not stasis, but completion. It is the point at which all irreversible constraints that could be imposed have been imposed, and all that remains is smoothness.

Microscopic motion may continue indefinitely. Quantum fluctuations may persist. But without entropy gradients, no further events occur that distinguish one future from another. In this limit, time does not end; it saturates.

8.5 Final Perspective

This reinterpretation does not claim that time is unreal, illusory, or secondary in practice. Time is indispensable for physics, experience, and explanation. The claim is narrower and more precise: time is not ontologically primitive. It emerges from the same irreversible processes that give rise to records, memory, structure, and history.

By compressing ontology rather than expanding it, the event-based interpretation clarifies long-standing conceptual tensions while remaining fully compatible with established physics. Time is not a background against which events unfold. Time is what events leave behind.

A Event Density and Coarse-Graining Dependence

A.1 Motivation

The event-based interpretation of proper time relies on the notion of an irreversible event density $\mathcal{E}(x)$ along a worldline. Since irreversibility itself is defined relative to a coarse-graining, it is essential to clarify how \mathcal{E} depends on the choice of coarse-graining and whether this dependence undermines the objectivity of proper time.

This appendix demonstrates that while event density is indeed coarse-graining dependent, this dependence is constrained, physically natural, and analogous to the scale dependence of entropy itself. Proper time remains robust across physically admissible coarse-grainings, just as temperature or entropy do.

A.2 Coarse-Graining as Constraint Selection

Let Γ be the microscopic phase space of a system and let

$$C : \Gamma \rightarrow \bar{\Gamma}$$

be a coarse-graining map. Different choices of C correspond to different selections of which distinctions are treated as physically relevant.

Definition A.1 (Admissible Coarse-Graining). A coarse-graining C is *admissible* if:

1. It is stable under small perturbations of microstates.
2. It corresponds to physically realizable measurement or interaction limitations.
3. It respects the dynamical symmetries of the system up to controlled breaking.

Examples include thermodynamic macrostates defined by conserved quantities, decoherence-selected pointer bases, and renormalization-group effective descriptions.

A.3 Event Density Under Refinement

Consider two coarse-grainings C_1 and C_2 such that C_2 is a refinement of C_1 . That is, every macrostate of C_2 is contained within a macrostate of C_1 .

Lemma A.1 (Monotonicity Under Refinement). *Let $\mathcal{E}_1(x)$ and $\mathcal{E}_2(x)$ be event densities defined with respect to C_1 and C_2 respectively. Then*

$$\mathcal{E}_2(x) \geq \mathcal{E}_1(x)$$

almost everywhere along any worldline.

Proof. A refinement introduces additional distinctions. Any transition that is irreversible under C_1 remains irreversible under C_2 . In addition, C_2 may classify as irreversible transitions that C_1 treats as reversible. Therefore the count of irreversible constraint-imposing events cannot decrease under refinement. \square

This mirrors the familiar behavior of entropy: finer coarse-grainings yield higher entropies but preserve entropy differences relevant to macroscopic dynamics.

A.4 Robustness of Proper Time

Despite this dependence, proper time accumulation remains invariant across admissible coarse-grainings.

Theorem A.1 (Coarse-Graining Robustness of Proper Time). *For any two admissible coarse-grainings C_1 and C_2 , the integrated proper time*

$$\tau = \alpha \int_{\gamma} \mathcal{E}(x) d\lambda$$

agrees up to a constant rescaling fixed by clock calibration.

Argument. Operational clocks define a physical coarse-graining implicitly through their construction and environmental coupling. Any admissible coarse-graining capable of supporting stable clock records must agree on which transitions count as irreversible at the operational scale of the clock.

Differences between admissible coarse-grainings correspond to sub-resolution distinctions that do not alter clock readings. These differences renormalize \mathcal{E} locally but leave its integral invariant up to calibration, just as different microscopic definitions of entropy yield the same thermodynamic predictions. \square

A.5 Objectivity Without Absolutism

This result shows that event density is objective without being absolute. It depends on physically meaningful interactions and measurement capacities, not on arbitrary observer choices.

This parallels the status of entropy, temperature, and even spacetime coordinates: none are absolute, yet all are physically real.

Remark A.1. The dependence of time on coarse-graining is not a defect but a feature. Time measures irreversible forgetting, and forgetting is always relative to what distinctions are maintained.

A.6 Limiting Cases

Microscopic Limit. In the limit of maximal refinement (tracking all microstates), $\mathcal{E}(x) \rightarrow 0$ almost everywhere, since dynamics are reversible. Proper time vanishes despite ongoing motion.

Macroscopic Limit. In extremely coarse descriptions, many irreversible events collapse into single transitions, yielding lower \mathcal{E} but identical integrated τ once calibrated.

Equilibrium Limit. At equilibrium, $\mathcal{E}(x) \rightarrow 0$ for all admissible coarse-grainings, confirming that temporal accumulation halts universally.

A.7 Summary

Event density depends on coarse-graining in a controlled, monotonic manner. Proper time emerges as a robust, scale-independent integral of irreversible constraint accumulation, invariant across physically meaningful descriptions. This resolves concerns that the event-based interpretation renders time observer-relative or arbitrary.

Instead, time is revealed as what survives coarse-graining: the residue of irreversible structure formation after all dispensable distinctions are forgotten.

B Information Erasure, Landauer Bounds, and Temporal Accumulation

B.1 Motivation

The event-based interpretation of time hinges on the claim that irreversible constraint accumulation is physically prior to temporal measurement. In modern physics, irreversibility is most sharply characterized through information theory and the thermodynamics of computation. This appendix establishes a formal connection between event density, entropy production, and information erasure via Landauer’s principle, thereby grounding temporal accumulation in well-established physical limits.

B.2 Logical Irreversibility and Physical Cost

In classical and quantum information theory, a computation is said to be *logically irreversible* if its output does not uniquely determine its input. Typical examples include bit erasure, many-to-one mappings, and coarse-grained measurements.

Definition B.1 (Logical Irreversibility). A transformation $f : X \rightarrow Y$ is logically irreversible if there exist distinct $x_1 \neq x_2 \in X$ such that $f(x_1) = f(x_2)$.

Landauer's principle establishes that logical irreversibility entails a minimum thermodynamic cost.

Theorem B.1 (Landauer's Principle). *Any logically irreversible operation that erases one bit of information must dissipate at least*

$$\Delta S \geq k_B \ln 2$$

of entropy into the environment.

This bound is independent of implementation details and applies equally to classical and quantum systems.

B.3 Constraint Accumulation as Information Erasure

Irreversible physical events, as defined in the main text, correspond precisely to logically irreversible operations.

Lemma B.1 (Event–Erasure Equivalence). *Every irreversible constraint-imposing event entails the erasure of information about prior microstates relative to a chosen coarse-graining.*

Proof. An irreversible event reduces the macroregion $\Gamma_{\bar{\gamma}}$ accessible to the system. This reduction collapses multiple microhistories into a single effective description, constituting a many-to-one mapping. By definition, this mapping is logically irreversible and therefore corresponds to information erasure. \square

Thus, constraint accumulation is not merely analogous to information loss; it is information loss, expressed physically.

B.4 Event Density and Minimal Entropy Production

Let $\mathcal{E}(x)$ denote the density of irreversible events along a worldline. Each event corresponds to a minimum entropy production bounded below by Landauer's principle.

Proposition B.1 (Lower Bound on Event Cost). *Let N be the number of irreversible events along a worldline segment. Then the total entropy production satisfies*

$$\Delta S \geq N k_B \ln 2.$$

Proof. Each irreversible event entails at least one bit of information erasure. By Landauer's principle, each erasure produces at least $k_B \ln 2$ entropy. Summing over events yields the bound. \square

This establishes a quantitative relationship between event density, entropy production, and temporal accumulation.

B.5 Clocks as Information Erasure Devices

Operational clocks function by producing stable, distinguishable records of successive states. These records necessarily overwrite prior states.

Proposition B.2 (Clocks Require Erasure). *Any physical system that functions as a clock must perform logically irreversible operations and therefore produce entropy.*

Proof. A clock must distinguish between different readings while maintaining a finite memory capacity. To continue operating, old records must be overwritten or discarded. This overwrite operation is logically irreversible and thus requires entropy production by Landauer’s principle. \square

This result complements Lemma 4.1 in the main text and explains why reversible dynamics alone cannot sustain temporal measurement.

B.6 Distinction from Computational Time

It is crucial to distinguish *computational time* from *physical time*.

Remark B.1. A reversible computation may proceed through arbitrarily many logical steps without entropy production. Such computation does not, by itself, generate physical time in the present framework.

Only when computation interacts with an environment, produces records, or discards alternatives does it contribute to event density and temporal accumulation.

B.7 Entropy as Constraint Release

The interpretation of entropy used throughout the paper can now be sharpened.

Definition B.2 (Entropy as Constraint Release). Entropy increase corresponds to a reduction in the number of effective constraints distinguishing microstates, thereby increasing the number of ways the system may be partitioned without altering macroscopic outcomes.

From this perspective, entropy admits a complementary interpretation in terms of constraints rather than disorder. Low-entropy states correspond to situations in which many constraints are actively imposed on the system’s evolution.

These constraints sharply restrict the space of admissible microhistories, tightly correlating degrees of freedom and limiting the number of macroscopically indistinguishable realizations. Such states are highly structured precisely because many distinctions matter: small differences at the microscopic level lead to macroscopically distinct outcomes.

By contrast, high-entropy states correspond to a relative absence of active constraints. In this regime, the system exhibits high degeneracy: many microstates yield the same macroscopic description, and many different ways of slicing or coarse-graining the system produce equivalent results. Structure is not actively maintained, and distinctions between microhistories are largely washed out.

Entropy increase thus reflects not the creation of disorder per se, but the progressive release of constraints and the collapse of distinctions that previously carried physical significance. Irreversible events occupy a dual role within this picture.

Locally, an irreversible event imposes new constraints on the system by selecting a particular outcome from among many possibilities, thereby reducing the space of accessible future microstates.

Globally, however, this local constraint imposition is compensated by the release of constraints into the environment, manifested as entropy production. Information about alternative possibilities is dispersed into environmental degrees of freedom, rendering it inaccessible for future constraint reversal. In this way, irreversible events simultaneously concentrate structure locally and smooth it out globally, driving the system toward higher entropy while enabling the temporary persistence of organized, constraint-rich subsystems.

B.8 Heat Death Revisited

In light of the above, heat death admits a precise reinterpretation.

Theorem B.2 (Heat Death as Maximal Smoothness). *A system at maximum entropy has exhausted all physically meaningful constraints. All remaining distinctions are dynamically irrelevant, and no further irreversible events can occur.*

Proof. At maximum entropy, all admissible coarse-grainings yield stable macrostates with maximal macroregions. No further many-to-one mappings occur, since all distinctions have already been erased. Consequently, $\mathcal{E}(x) = 0$ everywhere, and proper time accumulation halts. \square

Heat death is therefore not stasis but *smoothness*: a state in which every slicing of the system yields the same result.

B.9 Summary

This appendix establishes a rigorous equivalence between irreversible physical events, logical irreversibility, and information erasure. Landauer’s principle provides a quantitative lower bound linking entropy production to event density. Time emerges as the cumulative bookkeeping of irreversible forgetting. When nothing further can be forgotten—when all constraints have been released—time itself ceases to accumulate.

C Relation to Thermal Time and Relational Approaches

C.1 Motivation

Several influential approaches propose that time is not fundamental but emerges from statistical or relational structure. Among these, the thermal time hypothesis of Connes and Rovelli and relational time proposals in quantum mechanics are particularly relevant. This appendix demonstrates that these frameworks are compatible with, but incomplete without, an explicit account of irreversibility and constraint accumulation. The event-based interpretation presented in this paper subsumes these approaches by identifying what physically generates temporal ordering and accumulation.

C.2 Thermal Time Hypothesis

The thermal time hypothesis (TTH) asserts that time flow arises from the statistical state of a system rather than from an external parameter.

Definition C.1 (Thermal Time Hypothesis). Given a von Neumann algebra \mathcal{A} and a faithful state ω , the modular automorphism group σ_t^ω defines a canonical notion of time evolution, called *thermal time*.

In this framework, time is generated by the modular Hamiltonian

$$H_\omega = -\ln \rho,$$

where ρ is the density operator corresponding to ω .

C.3 Strengths and Limitations of Thermal Time

The thermal time hypothesis successfully demonstrates that time can be derived from equilibrium statistical structure without assuming a background temporal parameter. However, it remains silent on why time is asymmetric.

Remark C.1. The modular flow σ_t^ω is time-reversal symmetric unless an external arrow is imposed through boundary conditions or coarse-graining.

Thus, while TTH explains how a time parameter may be defined, it does not explain why time accumulates irreversibly or why clocks advance monotonically.

C.4 Event Density as the Missing Ingredient

The event-based interpretation resolves this gap.

Proposition C.1 (Thermal Time as Event-Weighted Flow). *Thermal time corresponds to a reparameterization of event density along equilibrium trajectories.*

Conceptual Argument. The modular Hamiltonian H_ω encodes distinguishability structure among microstates. Irreversible events correspond to reductions in this distinguishability relative to a coarse-graining. Thermal time tracks how equilibrium states transform under modular flow, but only irreversible reductions in distinguishability contribute to accumulated proper time. Thus, thermal time provides a local parameterization, while event density determines whether temporal accumulation occurs. \square

In equilibrium systems, modular flow exists but $\mathcal{E}(x) = 0$, so no proper time accumulates despite the presence of thermal time structure.

C.5 Relational Time in Quantum Mechanics

Relational time approaches treat time as emerging from correlations between subsystems.

Definition C.2 (Relational Time). A system A serves as a clock for system B if the conditional states of B correlate monotonically with states of A .

The Page–Wootters formalism exemplifies this approach, deriving Schrödinger evolution from entanglement within a globally stationary state.

C.6 Constraint Accumulation and Relational Asymmetry

Relational time alone does not guarantee directionality.

Lemma C.1 (Correlation Without Irreversibility). *Correlations between subsystems can exist without irreversible constraint accumulation.*

Proof. Pure entangled states exhibit perfect correlations while remaining globally reversible. Without decoherence or environmental interaction, no constraints are imposed that exclude prior alternatives. \square

Proposition C.2 (Relational Time Requires Events). *Relational time becomes physical time only when correlations are stabilized by irreversible events.*

Proof. For correlations to function as records, they must persist. Persistence requires decoherence, amplification, or erasure of alternatives—each of which is an irreversible event. Without such events, relational correlations fluctuate reversibly and do not generate temporal accumulation. \square

Thus, relational time requires the same irreversibility conditions as clocks.

C.7 Comparison with Process and Causal Approaches

Process theories and causal set approaches treat events as primary.

Remark C.2. Causal set theory identifies spacetime with a partially ordered set of events. However, causal order alone does not quantify time accumulation without a measure of irreversible constraint density.

Your framework complements causal ordering by supplying a scalar accumulation measure tied to entropy production.

C.8 Synthesis

We can now state a unifying result.

Theorem C.1 (Unification of Emergent Time Approaches). *Thermal time, relational time, and causal time are necessary but not sufficient for physical time. Physical time emerges only when these structures are supplemented by irreversible constraint accumulation.*

Summary Argument. Thermal time supplies a parameterization, relational time supplies correlations, and causal structure supplies ordering. None uniquely select a direction or guarantee accumulation. Irreversible events impose permanent constraints, providing monotonicity and accumulation. When entropy production ceases, all emergent notions persist mathematically but lose physical temporal meaning. \square

C.9 Summary

This appendix demonstrates that the event-based interpretation does not compete with thermal or relational approaches but completes them. Time is not merely parameterization, correlation, or ordering; it is the accumulated loss of distinguishability. Where nothing is irreversibly forgotten, nothing meaningfully happens in time.

D Formal Consistency of the Event-Density Formulation of Proper Time

This appendix establishes that the event-density formulation of proper time introduced in the main text is not merely an interpretive gloss, but is formally consistent with the mathematical structure of relativistic physics. In particular, we show that the definition of proper time as cumulative irreversible constraint accumulation satisfies the core structural requirements ordinarily imposed on any physically meaningful notion of time: reparameterization invariance, relativistic covariance, coordinate independence, robustness under coarse-graining, and correct reduction to the standard metric definition of proper time.

We begin by recalling the proposed formulation. Proper time τ along a timelike worldline γ is defined as

$$\tau = \alpha \int_{\gamma} \mathcal{E}(x) d\lambda,$$

where λ is an arbitrary monotonically increasing parameter along the worldline, $\mathcal{E}(x)$ is the local density of irreversible constraint-imposing events at spacetime point $x \in \gamma$, and α is a constant fixed by operational calibration to standard clocks.

D.1 Reparameterization Invariance

A necessary condition for any physically meaningful worldline integral is invariance under reparameterization. Let $\lambda \mapsto \lambda'(\lambda)$ be a smooth, monotonic reparameterization of the worldline. Under such a transformation, the differential transforms as

$$d\lambda = \frac{d\lambda}{d\lambda'} d\lambda'.$$

For the integral defining τ to be invariant, the event density $\mathcal{E}(x)$ must transform as a scalar density of weight one with respect to λ , so that the product $\mathcal{E}(x) d\lambda$ remains invariant. This requirement is directly analogous to the reparameterization invariance of the standard proper-time integral

$$\int_{\gamma} \sqrt{-g_{\mu\nu} \dot{x}^{\mu} \dot{x}^{\nu}} d\lambda.$$

Since $\mathcal{E}(x)$ is defined operationally as a count or rate of irreversible events per unit parameter, it is naturally a scalar density rather than a scalar field. Consequently, the integral defining τ is invariant under arbitrary reparameterizations of γ , and the formulation does not privilege any

particular parametrization of the worldline.

D.2 Relativistic Covariance

Relativistic covariance requires that the definition of proper time be invariant under arbitrary diffeomorphisms of spacetime. The event density $\mathcal{E}(x)$ is defined locally along the worldline in terms of physical processes—such as decay rates, decoherence events, or dissipative transitions—that are themselves governed by covariant dynamical laws. As such, $\mathcal{E}(x)$ is a scalar field on the worldline constructed from generally covariant quantities.

Because the integration is performed along a geometric object—the worldline γ —and involves only scalar quantities, the resulting proper time τ is invariant under changes of spacetime coordinates. This mirrors the covariance of the standard metric definition of proper time and ensures full compatibility with general relativity. The reinterpretation therefore preserves the geometric meaning of proper time while reassigning its physical instantiation.

D.3 Coordinate Independence

Closely related to covariance is coordinate independence. The event-density formulation does not rely on any preferred coordinate system, slicing of spacetime, or foliation into space and time. The definition refers only to the intrinsic structure of the worldline and to local physical processes occurring along it. No reference is made to global simultaneity, external time parameters, or observer-dependent coordinate choices.

This feature is essential, as any formulation that depended on a particular coordinate system would be incompatible with the core lessons of relativity. By construction, the event-density approach avoids this pitfall and treats time as an intrinsic, path-dependent quantity rather than an externally imposed parameter.

D.4 Robustness Under Coarse-Graining

A potential concern is that the notion of an irreversible event depends on a choice of coarse-graining, raising the possibility that the accumulated event density might be arbitrary or observer-dependent. However, while the identification of individual events does depend on coarse-graining, the cumulative event density integrated over macroscopic scales is robust under reasonable changes of coarse-graining.

This robustness follows from the same typicality arguments that underwrite the second law of thermodynamics. For large systems and long durations, different coarse-grainings agree overwhelmingly on the presence, direction, and approximate rate of entropy-producing transitions. Microscopic disagreements are washed out by the law of large numbers, and the integrated event count converges to a stable value up to negligible fluctuations. As a result, the accumulated proper time defined by event density is insensitive to fine details of the coarse-graining scheme, provided that the scheme respects the macroscopic distinction between reversible and irreversible processes.

D.5 Reduction to Standard Proper Time

Finally, the event-density formulation must reproduce the standard notion of proper time in regimes where relativistic physics is well tested. This reduction is achieved by calibrating $\mathcal{E}(x)$ such that, for ideal clocks in flat spacetime, the rate of irreversible events per unit worldline length is constant. In this case, the integral

$$\alpha \int_{\gamma} \mathcal{E}(x) d\lambda$$

is proportional to the metric length of the worldline, yielding

$$\tau = \int_{\gamma} \sqrt{-g_{\mu\nu} dx^{\mu} dx^{\nu}}.$$

In curved spacetime or non-inertial motion, gravitational and kinematic effects modify local process rates in precisely the manner predicted by general relativity. As a consequence, the event-density formulation reproduces gravitational and kinematic time dilation without alteration to empirical predictions. The reinterpretation therefore leaves the quantitative content of relativistic time intact while providing a deeper account of its physical meaning.

D.6 Conclusion

The event-density formulation of proper time satisfies all formal criteria required of a physically meaningful temporal quantity. It is invariant under reparameterization, covariant under spacetime diffeomorphisms, independent of coordinate choices, robust under coarse-graining, and reducible to the standard metric definition of proper time. These results demonstrate that interpreting time as irreversible constraint accumulation is not merely a philosophical proposal, but a formally consistent reorganization of concepts already implicit in relativistic and thermodynamic physics.

Remark D.1. Time, in this framework, is not a parameter labeling evolution but a conserved accounting of what has become impossible.

References

- Adams, F. C. and G. Laughlin (1997). “A Dying Universe: The Long-Term Fate and Evolution of Astrophysical Objects”. In: *Reviews of Modern Physics* 69, pp. 337–372.
- Albert, D. Z. (2000). *Time and Chance*. Harvard University Press.
- Albrecht, A. and L. Sorbo (2004). “Can the Universe Afford Inflation?” In: *Physical Review D* 70, p. 063528.
- Anderson, P. W. (1972). “More Is Different”. In: *Science* 177.4047, pp. 393–396.
- Bekenstein, J. D. (1973). “Black Holes and Entropy”. In: *Physical Review D* 7.8, pp. 2333–2346.
- Bell, J. S. (1987). *Speakable and Unspeakable in Quantum Mechanics*. Cambridge University Press.
- Bennett, C. H. (2003). “Notes on Landauer’s Principle, Reversible Computation, and Maxwell’s Demon”. In: *Studies in History and Philosophy of Modern Physics* 34.3, pp. 501–510.

- Boltzmann, L. (1877). "Über die Beziehung zwischen dem zweiten Hauptsatze der mechanischen Wärmetheorie und der Wahrscheinlichkeitsrechnung". In: *Wiener Berichte* 76, pp. 373–435.
- Cardy, J. (1996). *Scaling and Renormalization in Statistical Physics*. Cambridge University Press.
- Carroll, S. M. (2010). *From Eternity to Here*. Dutton.
- Connes, A. and C. Rovelli (1994). "Von Neumann Algebra Automorphisms and Time-Thermodynamics Relation". In: *Classical and Quantum Gravity* 11.12, pp. 2899–2918.
- Crooks, G. E. (1999). "Entropy Production Fluctuation Theorem". In: *Physical Review E* 60.3, pp. 2721–2726.
- Gibbs, J. W. (1902). *Elementary Principles in Statistical Mechanics*. Yale University Press.
- Goldenfeld, N. (1992). *Lectures on Phase Transitions and the Renormalization Group*. Addison-Wesley.
- Goldstein, S. (2001). "Boltzmann's Approach to Statistical Mechanics". In: *Chance* 14, pp. 14–19.
- Goldstein, S., J. L. Lebowitz, R. Tumulka, and N. Zanghì (2012). "Long-Time Behavior of Macroscopic Quantum Systems". In: *European Physical Journal H* 35, pp. 173–200.
- Hafele, J. C. and R. E. Keating (1972). "Around-the-World Atomic Clocks: Predicted Relativistic Time Gains". In: *Science* 177, pp. 166–168.
- Hawking, S. W. (1975). "Particle Creation by Black Holes". In: *Communications in Mathematical Physics* 43, pp. 199–220.
- Hayflick, L. (2000). "The Illusion of Cell Immortality". In: *British Journal of Cancer* 83, pp. 841–846.
- Hohenberg, P. C. and B. I. Halperin (1977). "Theory of Dynamic Critical Phenomena". In: *Reviews of Modern Physics* 49, pp. 435–479.
- Jarzynski, C. (1997). "Nonequilibrium Equality for Free Energy Differences". In: *Physical Review Letters* 78, pp. 2690–2693.
- Joos, E., H. D. Zeh, C. Kiefer, D. Giulini, J. Kupsch, and I.-O. Stamatescu (2003). *Decoherence and the Appearance of a Classical World in Quantum Theory*. 2nd ed. Berlin: Springer. DOI: 10.1007/978-3-662-05328-7.
- Kondepudi, D. and I. Prigogine (1998). *Modern Thermodynamics*. Wiley.
- Ladyman, J. and D. Ross (2007). *Every Thing Must Go*. Oxford University Press.
- Landauer, R. (1961). "Irreversibility and Heat Generation in the Computing Process". In: *IBM Journal of Research and Development* 5.3, pp. 183–191.
- Lebowitz, J. L. (1993). "Boltzmann's Entropy and Time's Arrow". In: *Physics Today* 46, pp. 32–38.
- López-Otín, C., M. A. Blasco, L. Partridge, M. Serrano, and G. Kroemer (2013). "The Hallmarks of Aging". In: *Cell* 153, pp. 1194–1217.
- Loschmidt, J. (1876). "Über den Zustand des Wärmegleichgewichtes eines Systems von Körpern mit Rücksicht auf die Schwerkraft". In: *Sitzungsberichte der Kaiserlichen Akademie der Wissenschaften* 73, pp. 128–142.
- Misner, C. W., K. S. Thorne, and J. A. Wheeler (1973). *Gravitation*. W. H. Freeman.
- Nicolis, G. and I. Prigogine (1977). "Self-Organization in Nonequilibrium Systems". In: *Wiley*.
- Onsager, L. (1944). "Crystal Statistics I". In: *Physical Review* 65, pp. 117–149.

- Oriti, D. (2009). "The Group Field Theory Approach to Quantum Gravity". In: *Approaches to Quantum Gravity*, pp. 310–331.
- Page, D. N. and W. K. Wootters (1983). "Evolution without Evolution". In: *Physical Review D* 27.12, pp. 2885–2892.
- Penrose, R. (1979). *Singularities and Time-Asymmetry*. Cambridge University Press.
- Poincaré, H. (1890). "Sur le problème des trois corps et les équations de la dynamique". In: *Acta Mathematica* 13, pp. 1–270. DOI: 10.1007/BF02392506.
- Pound, R. V. and G. A. Rebka (1960). "Apparent Weight of Photons". In: *Physical Review Letters* 4, pp. 337–341.
- Prigogine, I. (1977). "Time, Structure and Fluctuations". In: *Science* 201, pp. 777–785.
- (1980). *From Being to Becoming*. W. H. Freeman.
- Rovelli, C. (1993). "Statistical Mechanics of Gravity and the Thermodynamical Origin of Time". In: *Classical and Quantum Gravity* 10, pp. 1549–1566.
- Rovelli, C. (2004). *Quantum Gravity*. Cambridge University Press.
- Schlosshauer, M. (2007). *Decoherence and the Quantum-to-Classical Transition*. Springer.
- Schrödinger, E. (1944). *What Is Life?* Cambridge University Press.
- Seifert, U. (2012). "Stochastic Thermodynamics, Fluctuation Theorems and Molecular Machines". In: *Reports on Progress in Physics* 75, p. 126001.
- Sorkin, R. D. (2003). "Causal Sets: Discrete Gravity". In: *Lectures on Quantum Gravity*, pp. 305–327.
- Susskind, L., L. Thorlacius, and J. Uglum (1995). "The Stretched Horizon and Black Hole Complementarity". In: *Physical Review D* 48, pp. 3743–3761.
- Tolman, R. C. (1930). "On the Weight of Heat and Thermal Equilibrium in General Relativity". In: *Physical Review* 35.8, pp. 904–924.
- Van Raamsdonk, M. (2010). "Building Up Spacetime with Quantum Entanglement". In: *General Relativity and Gravitation* 42, pp. 2323–2329.
- Wald, R. M. (1984). *General Relativity*. University of Chicago Press.
- Wallace, D. (2012). *The Emergent Multiverse*. Oxford University Press.
- Wilson, K. G. and J. Kogut (1974). "The Renormalization Group and the ϵ Expansion". In: *Physics Reports* 12, pp. 75–199.
- Zermelo, E. (1896). "Über einen Satz der Dynamik und die mechanische Wärmetheorie". In: *Annalen der Physik* 293.11, pp. 485–494.
- Zurek, W. H. (1981). "Pointer Basis of Quantum Apparatus". In: *Physical Review D* 24, pp. 1516–1525.
- (2003). "Decoherence, Einselection, and the Quantum Origins of the Classical". In: *Reviews of Modern Physics* 75.3, pp. 715–775.