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Finite Propagation and the Regime Structure of Reality

—*Classicality and Geometry as Constraint-Limited Phenomena*

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Abstract

This paper develops a unified ontological framework in which quantum indeterminacy, classical determinism, and gravitational structure are interpreted not as manifestations of distinct fundamental laws, but as regime-dependent consequences of a single physical constraint: finite propagation at the invariant speed *c*. We argue that the transition from reversible physical possibility to irreversible physical fact is regulated by the finite rate at which interaction outcomes can propagate, accumulate, and stabilize. Irreversibility is tied explicitly to entropy-producing interactions subject to causal delay, grounding the framework in nonequilibrium thermodynamics rather than measurement postulates. We introduce a phenomenological order parameter, *commitment density* (ρ_{commit}), defined as the locally accumulated history of irreversible constraint formation under finite propagation. Distinct physical regimes arise when this quantity crosses a critical *percolation threshold* (ρ_c), yielding three ontological domains: quantum under-representation ($\rho_{\text{commit}} \ll \rho_c$, insufficient closure), classical balance ($\rho_{\text{commit}} \sim \rho_c$, writable yet stable), and cosmological over-representation ($\rho_{\text{commit}} \gg \rho_c$, saturated and non-writable). Key terms are defined in the main text. This regime structure provides a unified reinterpretation of quantum measurement, classical determinism, and horizon formation. Event horizons are generalized as the observational signature of causal saturation, appearing wherever accumulated closure renders regions non-writable. Time emerges from cyclic but asymmetric closure processes whose accumulated bias produces temporal direction. The framework makes specific falsifiable predictions: commitment should be gradual and resolvable in time-resolved decoherence experiments; gravitational-wave memory should be detectable as permanent relational displacement; and the quantum-classical boundary should depend on commitment density rather than mass or scale alone. Four explicit conditions that would falsify the framework are specified in **Appendix A**.

Keywords

Finite Propagation, Irreversibility, Decoherence, Percolation Threshold, Spacetime Emergence, Gravitational-Wave Memory, Regime Transitions, Ontology of Physics

1. Introduction: Finite Propagation as an Ontological Constraint

Modern physics is extraordinarily successful within its respective domains, yet deeply fractured at its foundations. Quantum mechanics models phenomena across all scales—from subatomic particles to superconducting circuits to proposed tests at the Planck mass—but struggles to yield classical determinism without auxiliary postulates. General relativity robustly accounts for gravitation and spacetime geometry while resisting consistent quantization. Cosmology invokes unseen forms of matter and energy to reconcile observation with theory. These tensions are typically attributed to missing dynamics, incomplete unification schemes, or the absence of a final theory of quantum gravity.

This paper advances a different diagnosis. We propose that these fractures arise from a shared ontological blind spot: the tacit assumption that physical facts are resolved uniformly and instantaneously at all scales. Against this assumption, we argue that the invariant propagation speed *c*—the speed of light in vacuum—is not merely a kinematic limit on signal transmission, but the primary regulator of ontological commitment itself. Physical reality does not harden everywhere at once. The irreversibility of relational outcomes varies with scale according to how efficiently finite-speed interactions can establish and maintain durable exclusions.

From this perspective, the so-called laws of physics are not globally invariant descriptions imposed on a fully instantiated reality. Rather, they are stable summaries of behavior within specific regimes of relational commitment. When commitment is sparse, reality remains probabilistic and reversible. When commitment is balanced, classical determinism emerges. When commitment is saturated, geometry itself becomes inertial, functioning as accumulated constraint rather than writable dynamics.

A natural question arises: how can propagation speed be defined if spacetime itself is claimed to emerge from accumulated commitment? This apparent circularity is resolved by recognizing that *c* functions as a *constraint on relations*, not a velocity through a pre-existing medium. The invariance of *c* under Lorentz transformations reflects its role as a structural constant governing how interactions can coordinate, independent of any particular geometric embedding. Spacetime geometry then emerges as a stable description valid in the classical regime, where commitment density permits continuous writability. The constraint precedes the geometry it enables (Einstein, 1905).

The aim of this paper is not to propose new microphysical laws, but to reorganize existing physics around the ontological consequences of finite propagation.

The sections that follow develop a regime-based framework, introduce the order parameter formalism, and specify empirical conditions under which the framework can be tested or falsified.

2. Relational Commitment, Irreversibility, and Memory

Within a relational ontology, physical properties are not intrinsic features of isolated systems but arise through interaction. However, interaction alone is insufficient to produce a classical fact. For an interaction to instantiate a stable property, it must achieve irreversibility: information must be written into the world in such a way that it cannot be locally undone. This is what we refer to as ontological commitment (see Table 1).

Table 1. Glossary of key terms.

Term	Definition
Commitment	The irreversible registration of a relational outcome; the transition from open possibility to closed fact.
Commitment density (ρ_commit)	A phenomenological order parameter measuring the accumulated density of irreversible relational closures in a spacetime region.
Closure	The process by which relational possibilities become excluded; the enforcement of a definite outcome.
Relational closure	Closure arising from interaction between systems, as opposed to externally imposed boundary conditions.
Writability	The capacity of a spacetime region to register new relational commitments; the opposite of causal saturation.
Under-representation	A regime in which commitment density is insufficient to stabilize classical facts (quantum regime).
Over-representation	A regime in which commitment density saturates, rendering geometry non-writable (cosmological/horizon regime).
Classical balance	The intermediate regime where commitment density supports stable yet updatable records.
Causal saturation	The condition in which accumulated closure renders a region causally inaccessible to external observers.
Finite propagation	The physical constraint that interactions propagate at the invariant speed c, preventing instantaneous global coordination.
Percolation threshold (ρ_c)	The critical commitment density at which isolated closures link into system-spanning constraint.

Finite propagation speed enforces a fundamental latency in this process. No exclusion, record, or constraint can globalize instantaneously. Commitments accumulate only through causal chains mediated at the invariant speed c. We therefore introduce the notion of *commitment density*: the spatial and temporal accumulation of irreversible relational closures within a region.

When commitment density is low, interactions occur but their informational content disperses or remains too sparse to stabilize into shared memory. When commitment density is high, historical constraints saturate the region, strongly delimiting future possibilities. Physical regimes are thus distinguished not by different laws, but by different densities of irreversible relational closure.

3. Commitment Density: A Phenomenological Definition

The regime structure developed in this paper depends on a single intensive quantity: *commitment density*, written $\rho_{\text{commit}}(x,t)$. Commitment density is not a new physical field or force, but an *order parameter* in the sense familiar from percolation theory and phase transitions (Stauffer & Aharony, 1994): a bookkeeping measure of how much irreversible relational closure has accumulated in a region of spacetime.

Commitment density is defined as the time-integrated local rate of irreversible information registration, subject to finite propagation. Operationally, it tracks how much of a system's interaction history has been converted into durable exclusions that constrain future relational possibilities.

At minimum, commitment density depends on three factors: i) Interaction rate; ii) Interaction strength and duration; iii) Irreversibility, understood thermodynamically as entropy production or information loss to inaccessible degrees of freedom (Landauer, 1961). A schematic expression capturing these dependencies is:

$$\rho_{\text{commit}}\left(x,t\right) \approx \int_0^t K\left(x,t-t'\right)\dot{S}_{\text{irrev}}\left(x,t'\right)dt'$$

where $\dot{S}_{\text{irrev}}$ denotes the local rate of irreversible entropy production (the overdot indicating a time derivative, following standard thermodynamic notation), and K is a causal memory kernel encoding finite propagation and delay.

The kernel K is constrained by Lorentz invariance and vanishes outside the past light cone. Such kernels arise in relativistic transport theory (e.g., the Boltzmann equation in curved spacetime), in the theory of retarded Green's functions, and in open quantum systems where environmental correlations decay over light-crossing timescales. The specific functional form of K is not derived here; what matters is that it enforces causal delay and prevents instantaneous globalization of commitment.

This expression is schematic rather than dynamical. The framework does not propose an equation of motion for ρ_{commit}, nor does it derive $\dot{S}_{\text{irrev}}$ or K from first principles. Both quantities are well-defined within existing physics. The present framework reorganizes these existing quantities around the ontological role of irreversible closure, without introducing new primitives.

In this sense, commitment density functions as an order parameter rather than a fundamental law. Regime transitions occur when ρ_{commit} crosses critical thresholds—*percolation thresholds*—at which irreversible exclusions link into system-spanning constraint.

4. The Regime Structure of Reality

The interplay between finite propagation and commitment density yields three distinct ontological regimes, illustrated in **Figure 1**.

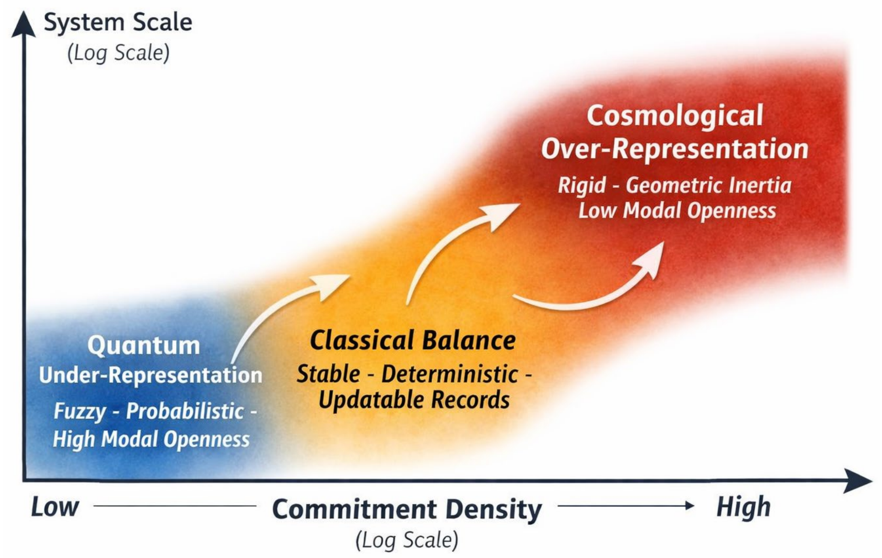

Figure 1. Modal Phase Diagram of Relational Commitment Across Scale. The horizontal axis represents commitment density (ρ_{commit}); the vertical axis represents system scale. At small scales and low commitment density, systems exhibit quantum under-representation. At intermediate scales and balanced commitment density, classical behavior emerges. At large scales and high commitment density, accumulated closure dominates, yielding cosmological over-representation. Arrows indicate regime transitions as commitment density crosses the percolation threshold ρ_c. The diagram is conceptual rather than quantitative.

5. Quantum Under-Representation

When $\rho_{\text{commit}} \ll \rho_c$, interactions are insufficient in density and duration to establish robust, irreversible records. This is a regime of commitment famine. Relational possibilities remain open because no durable ledger exists to close them.

Quantum indeterminacy, on this account, is not merely epistemic ignorance but a structural consequence of insufficient commitment. Properties fail to become definite not because they are hidden, but because the conditions required for stabilization are unmet. A system maintains multiple relational possibilities precisely because its history remains reversible in practice.

The measurement problem is dissolved rather than solved. What is traditionally described as wavefunction collapse is reinterpreted as a threshold phenomenon: a quantum system remains under-represented until its coupling to a memory-rich environment drives commitment density beyond the percolation threshold. At that point, irreversible exclusions propagate, a specific outcome is written into the environment, and alternative possibilities become locally inaccessible. Decoherence describes the kinematics of environmental entanglement; this framework supplies the ontological criterion that explains why one outcome hardens into fact (Zurek, 2003).

This account is compatible with quantum entanglement and Bell nonlocality. Entangled systems share a jointly constrained possibility space established by their common causal past. No signal propagates faster than *c*; rather, the correlations reflect exclusions already enacted within the shared backward light cone. Measurement locally actualizes one branch of a pre-established constraint structure. What appears as "nonlocal correlation" is the revelation of relational closure that occurred locally in the past, not communication across spacelike separation.

6. Classical Balance

When $\rho_{\text{commit}} \sim \rho_c$, systems are large enough to accumulate durable records, yet not so saturated that history overwhelms present dynamics. Memory is robust but writable.

Classical determinism emerges not because quantum mechanics fails, but because aggregate commitments overwhelm individual uncertainties. Vast numbers of local closures chain together to form stable causal networks. Quantum interference is suppressed, trajectories stabilize, and effective determinism arises. This regime supports the persistence of objects, the reliability of measurement, and the causal continuity required for chemistry, biology, and computation.

The classical world is therefore not fundamental, but optimal. It is the regime in which commitment is neither too sparse to stabilize nor too dense to ossify.

7. Cosmological Over-Representation

When $\rho_{\text{commit}} \gg \rho_c$, commitment density saturates local possibilities. Billions of years of interaction fossilize into enduring geometric constraint. Accumulated history strongly biases—though does not eliminate—present dynamics.

The term "cosmological" here refers to the *regime character*, not to the absence of dynamics at large scales. Galaxies rotate, clusters merge, and the universe expands. What changes is the *writability* of geometry: in over-represented regions, the accumulated ledger constrains what new relational structures can form. Dynamics persist, but they unfold against a backdrop of inherited curvature that cannot be freely rewritten.

From this perspective, gravitational anomalies commonly attributed to dark matter can be partially reinterpreted as inherited curvature arising from accumulated relational closure. Regions with prolonged interaction histories carry constraint residue that augments the gravitational influence of present baryonic matter. The stress-energy tensor, typically treated as an instantaneous snapshot, should be conceptually understood as including a temporally integrated component reflecting spacetime's own accumulated memory.

Black holes represent the extreme limit of over-representation. Their event horizons enforce maximal exclusion, rendering information permanently inaccessible to the exterior. Hawking radiation can be interpreted as the thermodynamic cost of maintaining such absolute commitment under finite propagation (Bekenstein, 1973).

8. Horizons as the Observational Signature of Causal Saturation

Within the present framework, horizons are not treated as exceptional geometric objects but as the inevitable observational signature of saturated relational commitment under finite propagation. An event horizon arises wherever accumulated irreversible closure renders a region non-writable from the perspective of an observer who remains capable of updating relational records.

Thought experiments originally developed in the debates between Einstein and Bohr concerning complementarity have recently been realized experimentally, reaffirming that certain pairs of properties cannot be simultaneously observed—not due to instrumental inadequacy, but because of intrinsic physical constraints imposed by causal structure (Bohr, 1949; Proietti et al., 2019). These results underscore that observational limits are ontological features arising from how information is permitted to propagate and stabilize.

In standard treatments, event horizons are most commonly associated with black holes. However, the defining feature of a horizon is not extreme curvature *per se*, but causal exclusion: the permanent inability of new relational information to propagate across a boundary (Bekenstein, 1973). This condition is equally realized in cosmological settings, where observer-dependent cosmological event horizons naturally arise in accelerating universes.

From the standpoint of commitment density, these cases are structurally unified. A black hole represents a localized extreme of over-representation; cosmological horizons represent a distributed form. In both cases, what counts as 'complete' depends on causal accessibility, not observation or belief.

9. The Emergence of Spacetime

This framework rejects the assumption of a pre-existing spacetime manifold. Instead, spacetime is understood as emergent from a percolation process of relational commitments.

In the earliest universe, interactions were present but subcritical. Relational closures were too sparse and fleeting to form a globally coherent network. This *zygotic* regime was structurally indeterminate, lacking stable spatial extension or temporal order.

The emergence of photons marks a critical phase transition. As massless mediators constrained by finite speed, photons are uniquely suited to propagate exclusions efficiently while enforcing delay. They enable local commitments to chain together, crossing the percolation threshold at which spacetime geometry crystallizes as a durable ledger of relational closure. The invariant speed c is not a velocity through space; it is the structural constant that governs how relations can coordinate before geometry emerges to describe them.

10. Triadic Necessity Under Finite Propagation

The regime structure developed here is not an arbitrary classification but a structural necessity imposed by finite propagation (**Figure 2**). In a universe where relational updates cannot propagate instantaneously, reality cannot be exhaustively resolved into a single ontological mode. Physical intelligibility requires a triadic organization: complementary regimes of under-commitment and over-commitment mediated by a constraint that is not reducible to either.

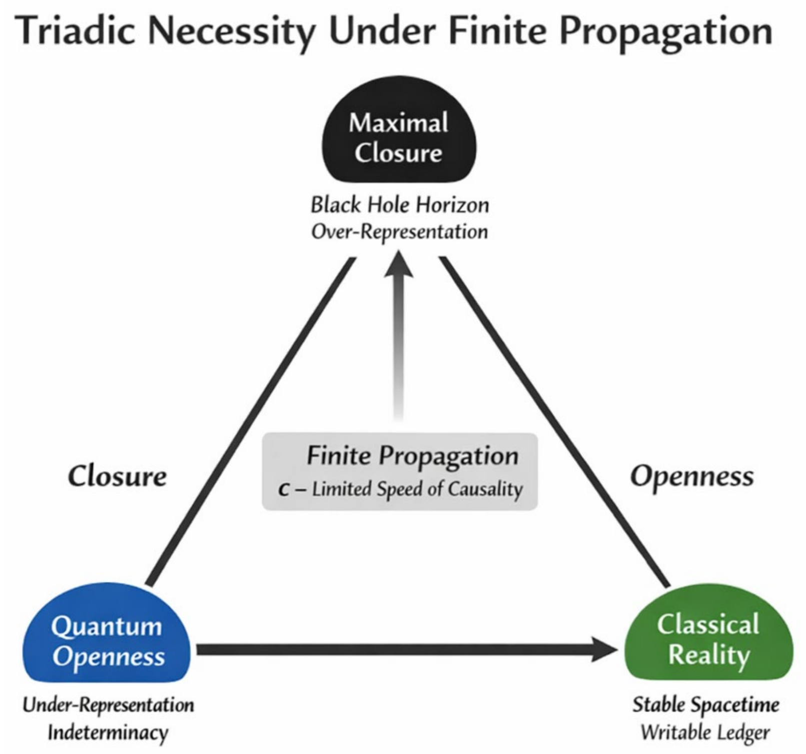

Figure 2. Triadic Regime Structure Under Finite Propagation. Quantum under-representation (left) corresponds to insufficient commitment density. Cosmological over-representation (top) corresponds to saturated commitment density. Between these extremes lies the classical regime (right), where commitment is both robust and writable. Finite propagation, mediated by the invariant speed c, acts as an orthogonal constraint that enforces delay and locality. This non-collinearity provides the minimal asymmetry required for memory and temporal direction.

Pure binary ontologies fail to account for this structure. If closure were globally simultaneous, facts would harden everywhere at once and no temporal ordering could arise. If openness were universal, no durable records could form. Finite propagation supplies the missing mediator: the invariant speed c enforces delay, locality, and non-synchronization of relational closure.

11. Regime Transitions and Edge Cases

The regime transitions described in this framework are conceptually smooth yet physically emergent, exhibiting the characteristic structure of a percolation threshold. The underlying constraint—finite propagation speed—remains invariant, but the density of irreversible relational records varies continuously. No sharp ontological boundary separates the regimes in principle; nevertheless, the phenomenological consequences of crossing critical thresholds appear abrupt, much as gradual cooling produces the sudden rigidity of ice (**Figure 3**).

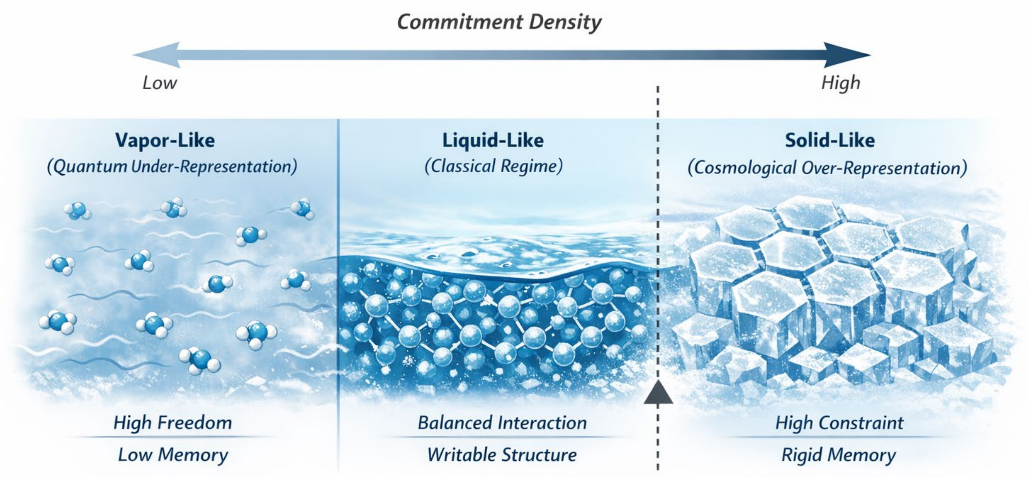

Figure 3. Phase-transition analogy for regime-dependent relational commitment. This schematic presents a non-literal analogy between thermodynamic phase transitions and the regime structure generated by finite-propagation-limited relational commitment. The vapor-like regime corresponds to low commitment density (quantum under-representation). The liquid-like regime corresponds to intermediate balance (classical regime). The solid-like regime corresponds to saturated commitment density (cosmological over-representation). The analogy is intended to clarify regime behavior rather than assert physical identity.

Several empirical edge cases illuminate this process. Mesoscopic systems—large molecules, superconducting circuits, optomechanical resonators—occupy a hybrid zone in which the ledger is only partially written. Their relational records accumulate unevenly, allowing partial coherence to survive. The absence of a single mass threshold for the quantum-classical transition is expected under a density-based criterion.

Gravitational-wave memory offers a particularly direct illustration. When a gravitational wave passes through a region, it leaves a permanent displacement even after the wave has passed (Christodoulou, 1991). This is a literal ledger entry written into geometry itself—space remembers.

12. Why Quantum Gravity Remains Elusive

Efforts to quantize gravity typically attempt to quantize geometry itself. Within this framework, that project commits a category error. Geometry is already a macroscopic memory object—an accumulated record of irreversible closure. Quantization presupposes modal openness and reversibility, precisely the conditions geometry lacks in the over-represented regime.

This mismatch explains the persistent difficulties of quantum gravity: non-renormalizability, the problem of time, and information paradoxes (Rovelli, 2004). A viable unification must address the subcritical, pre-geometric regime from which geometry emerges, rather than attempting to quantize the already-saturated ledger.

13. Complementarity and the Asymmetry of Closure

A recurring feature of this framework is the appearance of complementary constraints arising from a single physical limitation. The invariant speed *c* does not merely regulate signaling; it enforces a deeper prohibition against global closure. From this prohibition follow the absence of a cosmological center, the impossibility of instantaneous global state updates, and the non-Markovian persistence of physical history.

If information cannot propagate instantaneously, then no event can acquire immediate global relevance. Any candidate for a cosmological center would require such relevance. Finite propagation therefore excludes centerlessness not as a geometric axiom, but as a consequence of delayed relational closure.

Closure plays a special role because it alone introduces irreversibility. Interaction and propagation may be reversible; closure is not. Once an exclusion is enforced and recorded, it biases future possibilities in a way that cannot be undone everywhere at once. This asymmetry is structurally necessary: without it, no memory could persist, no temporal ordering could arise, and no stable identities could be sustained.

14. Conclusion: Finitude as Ontological Ground

Quantum mechanics, classical physics, and cosmology are not competing descriptions of reality. They are regime-specific expressions of a single constraint: finite propagation at the invariant speed *c*. Where relational commitment is insufficient, physical possibilities remain under-represented and probabilistic. Where commitment is balanced, determinism and writable structure emerge. Where commitment is saturated, accumulated history dominates and geometry becomes inertial.

On this view, spacetime is not a container but a ledger. Space is the record of where irreversible exclusions have already stabilized. Time is the refusal of closed relations to reopen everywhere at once. Horizons arise wherever the density of accumulated closure renders regions non-writable.

The framework makes specific predictions that can fail: resolvable temporal structure in decoherence, detectable gravitational-wave memory, density-dependent rather than mass-dependent quantum-classical boundaries, and the four falsification conditions specified in Appendix A. Either finite propagation is ontologically inert, or it explains far more of physical structure than current foundational frameworks allow.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Appendix A: Quantitative Order Parameters and Regime Constraints

A.1 Phenomenological Definition of Commitment Density

The regime structure depends on a single intensive quantity: $\rho_{\text{commit}}(x,t)$. This is an *order parameter* in the sense familiar from percolation theory: a bookkeeping measure of accumulated irreversible relational closure, not a new physical field.

A schematic functional is:

$$\rho_{\text{commit}}(x,t) = \int_{-\infty}^{t} K(x,t-t')\,\dot{S}_{\text{irrev}}(x,t')\,dt'$$

$\dot{S}_{\text{irrev}}$ is the local rate of irreversible entropy production, well-defined in nonequilibrium thermodynamics and subject to the Landauer bound. K is a causal memory kernel constrained by Lorentz invariance, vanishing outside the past light cone. Such kernels appear in relativistic Boltzmann transport, retarded Green's functions, and open quantum systems with finite correlation times.

A.2 Regime Structure as Threshold Inequalities

Three regimes are distinguished by the relationship between ρ_{commit} and a critical percolation threshold ρ_c:

Quantum under-representation ($\rho_{\text{commit}} \ll \rho_c$): Insufficient closure to stabilize durable records. Decoherence remains incomplete; quantum indeterminacy persists.

Classical balance ($\rho_{\text{commit}} \sim \rho_c$): Sufficient closure for stable, writable geometry. Aggregate commitments overwhelm quantum uncertainties.

Cosmological over-representation ($\rho_{\text{commit}} \gg \rho_c$): Saturated closure; geometry becomes non-writable. Horizons emerge as signatures of causal saturation.

A.3 Relation to Existing Physical Quantities

Entropy production: ρ_{commit} phenomenologically tracks time-integrated $\dot{S}_{\text{irrev}}$. The Landauer principle establishes that irreversible information erasure has minimum thermodynamic cost, grounding commitment in measurable thermodynamics.

Decoherence rates: Environmental coupling drives ρ_{commit} toward the percolation threshold. Time-resolved decoherence experiments directly observe this transition.

Gravitational-wave memory: Permanent displacement after a gravitational wave passes provides a direct observational signature of irreversible relational closure at macroscopic scales (Christodoulou, 1991).

Horizon formation: Horizons arise where ρ_{commit} saturates. The Bekenstein-Hawking entropy measures accumulated constraint behind the horizon.

A.4 Empirical Access and Falsifiability Conditions

The framework makes claims that are empirically accessible and falsifiable:

Time-resolved decoherence: The transition from quantum openness to classical definiteness should exhibit temporal structure bounded by propagation speed. Ultrafast spectroscopy can test this.

Mesoscopic superposition: The quantum-classical boundary should depend on commitment density, not mass alone. No single mass threshold should exist.

Gravitational-wave memory: Detection by pulsar timing arrays or next-generation detectors would confirm irreversible relational effects.

Cosmological structure: Early structure formation may exhibit percolation signatures rather than smooth growth.

Conditions That Would Falsify the Framework

i) Irreversible closure without entropy production—permanent exclusions established without thermodynamic cost.

ii) Global instantaneous coordination—physical outcomes synchronized without propagation delay.

iii) Stable geometry without interaction history—classical spacetime emerging in regions with no prior causal contact.

iv) Strictly instantaneous outcome commitment—no resolvable dynamical structure in quantum measurement regardless of temporal resolution.

These are not rhetorical vulnerabilities. They specify where the framework can fail.