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Causal Percolation and the Symmetry of Horizons: From Pre-Geometry to Late-Time Fragmentation

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Abstract

Finite propagation speed is treated here not merely as a kinematic limit but as an ontological throttle governing when reality becomes globally coherent. Because no influence propagates instantaneously, global causal structure cannot be primitive. It must assemble through the accumulation of irreversible relational closures propagated at finite speed. This work introduces a dimensionless causal-percolation parameter, $\Pi(\tau)$, defined as the integrated density of irreversible closures within a causal diamond of duration τ. When $\Pi(\tau) \ll 1$, reality is subcritical: quantum, indeterminate, and lacking global objectivity. When $\Pi(\tau) \gg 1$, reality is supercritical: classical, centerless, and geometrically stable. Horizons arise wherever causal percolation is incomplete, either because causal structure has not yet formed, as in the early universe, or because global connectivity fragments at late times under acceleration. The framework reframes quantum measurement, classical emergence, spacetime geometry, and horizon thermodynamics as regime-dependent consequences of finite-speed causal percolation rather than contradictions among physical laws.

Keywords

Causal Percolation, Quantum Measurement Problem, Decoherence, Emergent Spacetime, Horizon Thermodynamics, Geometrogenesis, Finite Propagation Speed, Cosmological Horizons.

1. Introduction

Modern physics contains deep disagreements concerning quantum measurement, the ontology of spacetime, and the interpretation of cosmological observations, yet one constraint remains empirically unchallenged: no influence propagates faster than light in any local inertial frame (Einstein, 1905; Wald, 1984). The invariant speed *c* is not merely a parameter of relativistic kinematics but appears woven into the causal fabric of reality itself. Attempts to relax this constraint lead rapidly to violations of causality, breakdowns of thermodynamics, or direct conflict with experimental data from particle physics and astrophysics (Will, 2014).

If finite propagation speed is genuinely fundamental, then its ontological consequences must be taken seriously. In particular, global coherence cannot be primitive or instantaneous. A shared, observer-independent reality cannot exist all at once, because no event can immediately constrain all others. Instead, global structure must assemble gradually through local interactions that propagate outward at bounded speed and accumulate over time. Ontology therefore becomes a problem of connectivity: under what conditions do local actualities percolate into a globally coherent causal structure capable of supporting geometry, objectivity, and classical facts?

This paper advances four interconnected claims. First, physical reality stratifies into distinct regimes determined by whether irreversible relational closure has percolated across causal diamonds. These regimes are not governed by different fundamental laws but arise from the same constraint: finite-speed propagation of irreversible records. Second, cosmic centerlessness is not a geometric axiom but a dynamically enforced prohibition that emerges once causal percolation becomes system-spanning. Third, horizons mark boundaries of incomplete percolation and generically exhibit thermodynamic behavior (Gibbons & Hawking, 1977; Hawking, 1975). Fourth, the cosmic beginning and end are structurally symmetric: early times lack horizons because causal structure is not yet defined, while late times develop horizons because global percolation fragments.

The framework introduced here adds no new particles, forces, or free parameters. It provides a structural reinterpretation of existing physics through the lens of causal connectivity, proceeding from ontological primitives to concrete observational consequences.

2. Theoretical Framework

This section develops the formal structure of the causal-percolation framework, defining its core concepts and establishing the central parameter $\Pi(\tau)$. We begin with foundational clarifications about irreversibility and relational closure, then construct the framework from causal diamonds and percolation dynamics.

2.1. Irreversible Records and Relational Closures

Before developing the formal framework, it is essential to clarify what is meant by *irreversible relational closures* and *irreversible records*, as these concepts form the ontological foundation of the causal-percolation parameter.

Irreversible Relational Closures. A relational closure occurs when an interaction between two or more systems permanently constrains their future joint possibilities without requiring the storage of information about the past interaction itself. Crucially, a closure is *irreversible* if reversing it would require either: 1) violating causality by propagating influence backward in time, 2) violating conservation laws such as energy or momentum conservation, or 3) violating the second law of thermodynamics by decreasing total entropy. Examples include environmental decoherence that disperses quantum coherence into inaccessible environmental degrees of freedom (Zurek, 2003; Joos et al., 2003), macroscopic measurement interactions that amplify microscopic events into pointer states, thermalization processes that redistribute energy across many degrees of freedom, and spontaneous symmetry breaking that fixes macroscopic order parameters.

The key insight is that a closure does not require that the interaction be "remembered" in any representational sense. Rather, the interaction *excludes* certain future joint states of the systems involved. This exclusion persists even if no trace of the original interaction remains accessible to measurement.

Irreversible Records. An irreversible record is a specific type of relational closure in which the constraint information becomes redundantly encoded across multiple independent subsystems. Records differ from generic closures in their robustness: they can be accessed through many alternative measurement pathways and persist even if some subsystems are destroyed or perturbed. Environmental pointer states in decoherence theory provide the canonical example (Zurek, 2003). When a quantum system decoheres, information about its state becomes encoded in correlations with vast numbers of environmental degrees of freedom. Reconstructing the original superposition would require reversing the evolution of all these environmental subsystems—a process forbidden by thermodynamic considerations in realistic settings (Joos et al., 2003; Schlosshauer, 2019).

Distinction from Entropy. Irreversible closures are closely related to, but not identical with, entropy production (Seifert, 2012). Entropy measures thermodynamic irreversibility—the statistical unavailability of past microstates. Closure density measures the accumulation of relational constraints that persist and propagate causally. Certain processes, such as spontaneous symmetry breaking in phase transitions, impose lasting relational structure without necessarily producing significant local entropy increase. Conversely, processes like black hole evaporation produce enormous entropy while erasing previously established relational structure. The two concepts overlap substantially but are not equivalent.

2.2. Pre-Geometric Actuality and the Absence of Global Structure

Standard formulations of physics presuppose a spacetime manifold equipped with a metric that defines causal relations from the outset. Events are said to occur within this manifold, and their causal ordering is fixed by its light-cone structure. This assumption becomes problematic when considering quantum gravity or the earliest stages of cosmic history, where the existence of a stable global geometry cannot be taken for granted (Isham, 1991; Oriti, 2014; Rovelli, 2023).

In what is termed the pre-geometric regime, no globally stable metric or null structure exists. This does not imply that nothing occurs. Local actuality persists: systems undergo transitions, interactions occur, and constraints may be enforced. What is absent is the distributed mutual consistency required to define a shared geometric stage. Events do not yet form a globally coherent causal network.

A crucial distinction must therefore be drawn between local actuality and global co-actualization. Local events may occur without being embedded in a mutually consistent spatiotemporal structure. In this regime, ontological centeredness is unavoidable. This centeredness is not geometric, since geometry does not yet exist, but structural: wherever actuality occurs is, by default, the sole locus relative to which anything can be said to happen. There is no distributed causal network yet capable of relativizing this occurrence.

Geometry emerges only once irreversible relational closures accumulate sufficiently to stabilize causal relations across many loci. Below a critical threshold, relations are too sparse and fleeting to define persistent structure. Above threshold, a giant connected component forms, and spacetime crystallizes as an effective description of the percolated causal network. This picture is consonant with several quantum gravity approaches that feature phase transitions between non-geometric and geometric phases (Ambjørn, Jurkiewicz, & Loll, 2005; Oriti, 2018), but here the transition is governed explicitly by irreversibility and finite propagation.

2.3. Causal Diamonds and Irreversible Closure Density

The natural unit of causal accessibility in relativistic physics is the causal diamond associated with a proper time interval τ. In flat spacetime, a causal diamond is defined as the intersection of the future light cone of the past endpoint with the past light cone of the future endpoint. Its characteristic linear scale is given by the relation (Bombelli et al., 1987).

$$L(\tau) = c\tau \tag{1}$$

where c is the invariant speed of light (approximately 3×10^8 m/s), and τ is the proper time duration. The four-volume of these diamond scales as

$$V_4(\tau) \sim c^4\tau^4 \tag{2}$$

Within a causal diamond, irreversible relational closures occur at some effective density ρ, defined as the number of irreversible records per unit four-volume:

$$\rho = N_{records}/V_4 \tag{3}$$

The value of ρ varies enormously across physical contexts. Isolated quantum systems and vacuum quantum field theory have $\rho \approx 0$. Laboratory measurements and macroscopic apparatus exhibit extremely large ρ due to redundant record formation. Astrophysical and early-universe environments occupy intermediate but still substantial regimes (Joos et al., 2003).

2.4. The Causal-Percolation Parameter Π(τ)

The central quantity of this framework is the dimensionless causal-percolation parameter Π(τ), defined as the integrated density of irreversible closures within a causal diamond of duration τ:

$$\Pi(\tau) = \int \_ D(\tau)\rho dV_4 \tag{4}$$

For approximately constant ρ in flat spacetime, this reduces to

$$\Pi(\tau) = \rho c^4 \tau^4 \tag{5}$$

The parameter Π(τ) counts the total number of irreversible relational records accessible within the causal diamond. It measures the depth of the local causal ledger—the extent to which history has been irreversibly written into relational structure. This single dimensionless quantity governs the transition between quantum, classical, and cosmological regimes explored in the remainder of this work.

2.5. Regime Stratification and Percolation Thresholds

The causal-percolation parameter Π(τ) naturally partitions physical reality into three ontological regimes distinguished not by different laws but by the degree to which irreversible relational closure has percolated across causal diamonds (Stauffer & Aharony, 1994).

Subcritical Regime ($\Pi(\tau) \ll 1$). When Π(τ) is much less than unity, irreversible records are sparse. The causal diamond contains few durable constraints, and relational possibilities remain open. Physical behavior in this subcritical regime is characterized by superposition, interference, and effective reversibility. This is the regime described by quantum mechanics.

Critical Regime ($\Pi(\tau) \approx 1$). When Π(τ) is of order unity, the system approaches the percolation threshold. Irreversible closures begin to form connected clusters that span significant portions of the causal diamond. Geometry starts to stabilize intermittently, classical properties appear episodically, and fluctuations become pronounced. This critical regime corresponds to geometrogenesis—the transition from pre-geometric locality to coherent spacetime structure. The transition exhibits hallmarks of percolation phenomena, including scale-dependent crossover and critical slowing.

Supercritical Regime ($\Pi(\tau) \gg 1$). When Π(τ) is much greater than unity, irreversible closures densely populate the causal diamond, forming a giant connected component. Redundant constraint pathways enforce mutual consistency across many loci, geometry becomes rigid, and classical facts are stable. This supercritical regime underwrites classical objectivity and observer-independent reality. The threshold value $\Pi \approx 1$ is not arbitrary. In percolation theory, global connectivity generically emerges at dimensionless order-unity thresholds regardless of microscopic details (Stauffer & Aharony, 1994; Saberi, 2015).

3. Applications Across Physical Regimes

Having established the theoretical framework, we now apply the causal-percolation parameter to diverse physical contexts. This section demonstrates how Π(τ) unifies apparently disparate phenomena—quantum measurement, cosmic structure, horizon physics—under a single ontological principle.

3.1. Quantum Indeterminacy as Subcritical Commitment

The quantum measurement problem is traditionally framed as a conflict between unitary dynamics, which preserve superposition, and the empirical fact that measurements yield definite outcomes (von Neumann, 1932). Interpretations of quantum mechanics respond by postulating collapse, hidden variables, branching worlds, or purely epistemic updates. Within the causal-percolation framework, the problem is reframed as a regime misclassification.

In the subcritical regime, where $\Pi(\tau) \ll 1$, irreversible relational closure is sparse. The causal diamond contains too few durable records to enforce mutual consistency across many degrees of freedom. As a result, relational possibilities remain open. Superposition persists not because reality is incomplete or subjective, but because insufficient irreversible structure exists to close alternatives. Quantum indeterminacy is therefore a structural consequence of subcritical causal connectivity.

This reframing dissolves the mystery of why microscopic systems behave quantum mechanically while macroscopic systems do not. Isolated quantum systems remain subcritical indefinitely, preserving coherence and interference. Macroscopic systems are immersed in environments with enormous closure density, driving $\Pi(\tau)$ far above unity on extremely short timescales. They are never subcritical.

3.2. Measurement as a Local Percolation Spike

A measurement event is not a special dynamical process but an extreme change in regime. When a quantum system couples to a macroscopic apparatus, the effective closure density increases abruptly due to redundant environmental entanglement, dissipation, and record formation (Zurek, 2003; Schlosshauer, 2019).

Let $\rho_s y_s$ denote the closure density of an isolated quantum system, with $\rho_s y_s \approx 0$. Let ρ_{app} denote the closure density of a macroscopic apparatus, with ρ_{app} many orders of magnitude larger. During measurement, the composite system has an effective closure density dominated by the apparatus:

$$\rho_e ff \approx \rho_{app} \tag{6}$$

The causal-percolation parameter for the system-apparatus composite during the measurement interval τ_m satisfies

$$\Pi_{total}\left(\tau_m\right) = \rho_e ffc^4\tau_m^4 \tag{7}$$

For realistic apparatus, $\Pi_{total}(\tau_m) >> 1$ even for extremely small τ_m. The system therefore crosses the percolation threshold essentially instantaneously relative to microscopic timescales. Once $\Pi(\tau)$ greatly exceeds unity, redundant constraint pathways form. One outcome becomes embedded in many independent environmental degrees of freedom simultaneously, and alternative possibilities become locally inaccessible. This transition is not a physical collapse of the wavefunction but a change in ontological status: possibilities move from open to excluded as the causal ledger percolates.

3.3. Relation to Decoherence Theory

Standard decoherence theory explains the suppression of interference by entanglement with environmental degrees of freedom (Zeh, 1970; Zurek, 2003; Schlosshauer, 2019). Coherence is not destroyed but dispersed into correlations that are practically inaccessible. Decoherence is therefore a kinematic account of why superpositions appear classical.

The causal-percolation framework adds an ontological criterion absent from decoherence alone. Decoherence describes how coherence spreads. Percolation specifies when that spread becomes irreversible in practice and in principle, by crossing a threshold where redundant records enforce mutual consistency. Below the threshold, coherence remains recoverable in principle. Above the threshold, alternatives are excluded from the local causal ledger.

This distinction explains why there is no sharp boundary between quantum and classical behavior. Near $\Pi(\tau) \approx 1$, systems exhibit critical behavior: enhanced fluctuations, prolonged dwell times in ambiguous states, and sensitivity to environmental coupling (Stauffer & Aharony, 1994; Saberi, 2015). These features are generic signatures of percolation transitions and are absent from strictly monotonic decoherence models.

3.4. Toward a Born-Rule Derivation via Competitive Percolation

A persistent objection to regime-based accounts of measurement is that they do not explain outcome probabilities. The causal-percolation framework provides a structural mechanism by which squared amplitudes acquire ontological relevance through competitive percolation dynamics.

Consider a quantum system prepared in a superposition of orthogonal outcome branches labeled by i, with amplitudes ψ_i. Assume that the effective closure density contributed by branch i is proportional to the squared amplitude:

$$\rho_i = \rho_0 \left|\psi_i\right|^2 \tag{8}$$

Because Π_i scales with $|\psi_i|^2$, branches with larger squared amplitude generate denser closure networks and reach the percolation threshold more rapidly. In this picture, measurement outcomes are determined by a competitive percolation process. The branch whose closure network first forms a system-spanning connected component dominates the causal ledger.

This mechanism does not uniquely derive the Born rule but constrains its form and explains why squared amplitudes are ontologically privileged. Full derivation likely requires integration with symmetry-based arguments such as invariance (Zurek, 2005) or decision-theoretic approaches (Deutsch, 1999; Wallace, 2012). The causal-percolation framework supplies the missing ontological substrate within which such derivations can operate.

3.5. Emergent Centerlessness as a Structural Prohibition

One of the most basic results of modern cosmology is that the universe has no center. Standard cosmology treats this centerlessness as an axiom, codified in the cosmological principle (Peebles, 1993). Within the causal-percolation framework, centerlessness is not postulated but derived.

In the subcritical pre-geometric regime, centeredness is unavoidable. Without a percolated network of mutual constraints, there exists no distributed structure relative to which center and periphery can be meaningfully defined. Once $\Pi(\tau)$ exceeds the percolation threshold, the situation changes qualitatively. The causal network acquires redundancy. Any two loci are connected by multiple independent pathways through which constraints propagate.

A persistent center would require preferential access to constraint propagation. In a percolated network, multiple pathways bypass any candidate center, equilibration washes out initial advantages, and finite-speed propagation prevents global synchronization around a privileged locus. Persistent privilege thus becomes dynamically unstable.

Centerlessness therefore emerges as a structural prohibition enforced by percolated causal networks. The cosmological principle is not a fine-tuned assumption but a natural consequence of having crossed the percolation threshold early in cosmic history. This derivation clarifies the relationship to general relativity: GR assumes a smooth, centerless manifold and describes its dynamics; causal percolation explains why such a manifold exists.

3.6. Horizons and the Symmetry of Beginning and End

A central unifying insight of the causal-percolation framework is that horizons arise wherever causal percolation is incomplete. This incompleteness can occur for two opposite reasons: because causal structure has not yet formed, or because a previously coherent network fragments.

In the early universe, $\Pi(\tau)$ is everywhere much less than unity. Irreversible closure is sparse, causal connectivity is insufficient to define stable light-cone structure, and geometry itself has not yet crystallized. In this pre-percolation regime, horizons in the usual sense do not exist, not because everything is causally connected, but because causal structure is not yet globally defined.

In the late universe, especially under accelerated expansion driven by a positive cosmological constant, the opposite problem arises. Locally, $\Pi(\tau)$ remains much greater than unity, and classical spacetime persists. Globally, however, causal diamonds cease to overlap. The percolated network fragments into disconnected components, each with its own internally coherent ledger but no global reconciliation. Event horizons proliferate as boundaries between these components (Gibbons & Hawking, 1977).

The cosmic beginning and end are thus structurally symmetric. In both cases, global causal coherence fails. At early times it fails because the network has not yet percolated. At late times it fails because the network has fragmented. Horizons arise wherever causal percolation is incomplete, regardless of the underlying reason.

3.7. Black Hole Horizons as One-Way Percolation Boundaries

A black hole event horizon separates spacetime into regions that are causally disconnected in a fundamental way. In percolation terms, the event horizon marks a one-way boundary for constraint propagation. Irreversible closures occurring inside the horizon cannot contribute to the exterior ledger. The exterior description must therefore coarse-grain over inaccessible microstates.

This coarse-graining gives rise to thermodynamic properties that are generic signatures of incomplete percolation (Bekenstein, 1973; Hawking, 1975). The entropy associated with a black hole scales with the horizon area A:

$$S_{BH} = (k_B c^3 A)/(4G\hbar) \tag{9}$$

where k_B is Boltzmann's constant, c is the speed of light, G is Newton's gravitational constant, and $\hbar$ is the reduced Planck constant. The Hawking temperature is

$$T_H = (\hbar c^3)/(8\pi G M k_B) \tag{10}$$

These expressions need not be interpreted as evidence of fundamental information loss. Rather, they reflect the bookkeeping cost of enforcing a permanent causal exclusion under finite propagation speed.

3.8. Cosmological Horizons and Fragmentation Thermodynamics

In an accelerating universe, the Hubble radius defines a cosmological event horizon. From the percolation perspective, accelerated expansion drives fragmentation of the causal network. Local causal diamonds remain supercritical, but their overlap diminishes.

This fragmentation produces thermodynamic signatures analogous to those of black holes (Gibbons & Hawking, 1977). An observer in de Sitter spacetime measures a temperature

$$T_{DS} = (\hbar H)/(2\pi k_B c) \tag{11}$$

where H is the Hubble parameter. The maximal entropy accessible within a causal patch is bounded by the area of the cosmological horizon. These effects arise generically from incomplete percolation, not from coordinate artifacts.

4. Observational Consequences and Empirical Tests

The causal-percolation framework makes distinctive empirical predictions that differ from standard approaches. This section outlines testable signatures and experimental probes that could confirm or falsify the framework's core claims.

4.1. Falsifiable Signatures Near the Percolation Threshold

If the quantum-to-classical transition is governed by percolation, then systems tuned near $\Pi(\tau) \approx 1$ should exhibit characteristic critical signatures (Stauffer & Aharony, 1994; Saberi, 2015). These include enhanced fluctuations in decoherence rates, non-monotonic dependence of classicality on environmental coupling, and critical slowing in the emergence of definite outcomes.

Mesoscopic systems provide experimental access to this regime. Candidates include optomechanical oscillators with tunable environmental coupling (Aspelmeyer et al., 2014), superconducting circuits, and levitated nanoparticles in ultra-high vacuum (Romero-Isart, 2023). In such systems, gradual variation of ρ or τ should reveal sharp crossovers and anomalous noise near threshold, distinct from predictions of standard decoherence alone.

4.2. Connection to Quantum Gravity Programs

The transition from pre-geometric to geometric regimes, identified here with the crossing of Π(τ) through unity, provides a unifying lens through which several quantum gravity approaches can be interpreted (Oriti, 2014; Rovelli, 2023).

In group field theory, spacetime arises as a condensate of fundamental quanta (Oriti, 2014; Gielen & Oriti, 2016). The order parameter governing condensation plays a role analogous to closure density. In causal dynamical triangulations, numerical simulations reveal distinct phases including crumpled regimes lacking geometry and extended phases approximating de Sitter spacetime (Ambjørn, Jurkiewicz, & Loll, 2005; Loll, 2020). The transition into the extended phase corresponds naturally to the supercritical percolation regime. In causal set theory, continuum geometry emerges when the density of events and causal relations is sufficiently high (Bombelli et al., 1987; Sorkin, 2022).

Across these approaches, the causal-percolation parameter Π(τ) serves as a unifying, model-independent diagnostic. It does not replace specific dynamics but clarifies when geometric descriptions are ontologically valid.

4.3. Early-Universe Signatures of Percolation

If the early universe underwent a transition from subcritical to supercritical causal percolation, this transition should leave observable imprints. Standard inflationary cosmology assumes that primordial perturbations gradually become classical through decoherence (Mukhanov, 2005; Kiefer & Polarski, 2009). A percolation transition predicts a sharper classicalization once Π(τ) approaches unity.

Potential signatures include transient non-Gaussianities associated with critical fluctuations, scale-dependent anomalies in the scalar power spectrum, and enhanced isocurvature modes during the transition epoch. Tensor perturbations generated before and after percolation may exhibit distinct propagation characteristics, potentially leaving spectral features in the stochastic gravitational wave background detectable by future observatories (Maggiore et al., 2020).

4.4. Late-Time Fragmentation and Cosmological Tensions

At late times, accelerated expansion drives fragmentation of the global causal network. This regime may underlie several observed cosmological tensions (Riess et al., 2019; Aghanim et al., 2020; Di Valentino et al., 2021).

Discrepancies in the inferred value of the Hubble constant between early- and late-universe measurements could reflect differing effective dynamics above and below a fragmentation threshold. Similarly, anomalies in large-scale structure correlations and late-time integrated Sachs-Wolfe measurements may signal proximity to causal fragmentation. The causal-percolation framework provides a structural reinterpretation: these tensions may arise from applying globally coherent descriptions beyond their regime of validity.

4.5. Direct Experimental Probe of Propagation-Limited Commitment

The framework makes a distinctive empirical claim: irreversible relational commitment cannot globalize instantaneously. An experiment using entangled photon pairs distributed to detectors separated by ~10 km could test whether quantum correlations persist at arbitrarily short measurement delays or degrade below a critical threshold corresponding to light-travel time (~33 μs).

If correlations degrade near this threshold, this would support propagation-limited commitment. If correlations persist unchanged at all tested delays, this would place bounds on any propagation-limited commitment speed. All required components—long-distance entanglement distribution, ultrafast timing with optical atomic clocks (Bothwell et al., 2019), high-efficiency detectors—already exist in contemporary quantum optics laboratories. A detailed protocol is provided in **Appendix**.

5. Discussion

This section addresses potential objections, clarifies the framework's scope and limitations, and examines its relationship to existing interpretive programs in physics and philosophy.

5.1. Objections and Clarifications

Relation to Entropy. One concern is that the closure density ρ merely re-labels entropy production. While there is substantial overlap, the two are not identical (Seifert, 2012). Entropy production measures thermodynamic irreversibility, whereas ρ measures the density of irreversible relational constraints that persist and propagate. Certain processes, such as spontaneous symmetry breaking, fix relational structure without significant local entropy increase.

Predictive Gain. Another objection is that the framework adds interpretive language without predictive gain beyond decoherence. The distinction is ontological rather than dynamical. Decoherence describes how coherence disperses, but it does not specify when alternatives become excluded from reality. The percolation threshold provides an explicit criterion for ontological commitment and predicts critical behavior near that threshold.

Observer Dependence. A further concern is that horizons are observer-dependent and therefore not physically fundamental. While horizon location depends on observer trajectory, the existence of causal boundaries separating accessible from inaccessible microstates is invariant (Wald, 1984). Thermodynamic properties arise from this inaccessibility, not from coordinate conventions.

Computational Difficulty. Finally, it may be objected that $\Pi(\tau)$ is difficult to compute in realistic systems. This is acknowledged. The framework is intended as a regime classifier rather than a precision predictive tool. Its value lies in unifying disparate phenomena under a single structural principle and identifying where existing theories should or should not apply.

5.2. Scale-Time Duality and Developmental Structure

The temporal evolution of the universe mirrors its present-day scale dependence. At small τ, corresponding to early times, the universe is subcritical and pre-geometric. At intermediate τ, causal percolation occurs and classical spacetime emerges. At large τ, global connectivity fragments under acceleration.

A similar pattern appears spatially at a fixed cosmic time. Small-scale systems remain quantum and subcritical. Intermediate scales exhibit classical behavior. The largest scales approach fragmentation near the cosmological horizon. This scale-time duality suggests that the universe undergoes a developmental process analogous to growth, with an early undifferentiated phase, a mature coherent phase, and a late fragmented phase.

5.3. Role of Massless Mediators

A natural question concerns the role of specific fields in enabling causal percolation. The framework does not assign unique status to photons as particles, but to massless or nearly massless mediators capable of propagating constraints at the invariant speed c.

Long-range massless fields are required to stabilize light-cone structure and enforce causal consistency across extended regions. Photons dominate this role in much of cosmic history because electromagnetic interactions are long-ranged, abundant, and efficient at generating irreversible records. Gravitons contribute similarly, though their quantum description remains incomplete. Gluons are massless but confined, limiting their effective range. The refined claim is therefore structural: geometrogenesis requires the dynamical activity of long-range mediators capable of propagating irreversible constraint information.

6. Conclusion: Coherence as Transient Inevitability

The framework developed here identifies finite propagation speed as the primary regulator of ontological commitment. Reality does not become globally coherent instantaneously. It hardens unevenly as irreversible relational closures propagate at bounded speed and accumulate over time. The causal-percolation parameter $\Pi(\tau)$ provides a unified diagnostic for when different effective descriptions of physics apply.

Quantum mechanics describes subcritical regimes in which $\Pi(\tau) \ll 1$ and relational possibilities remain open. Classical physics describes supercritical regimes in which $\Pi(\tau) \ll 1$ and redundant constraint pathways enforce objectivity. Horizon thermodynamics describes boundaries of incomplete percolation, where causal access is permanently restricted. Cosmology describes the large-scale lifecycle of percolation, from pre-geometric emergence to late-time fragmentation.

Within this picture, several foundational puzzles are reclassified as regime errors rather than failures of physical law. The measurement problem reflects confusion between subcritical and supercritical descriptions. Difficulties in quantum gravity arise from attempting to quantize geometry itself rather than the pre-geometric relational substrate. Black hole information puzzles reflect one-way percolation boundaries rather than fundamental loss. The cosmological principle emerges dynamically rather than axiomatically.

A striking implication is that global causal coherence is neither eternal nor accidental. In the earliest universe, coherence is absent because causal structure has not yet percolated. In the far future, coherence fragments because accelerated expansion suppresses global connectivity. Only in an intermediate epoch does the universe achieve the dense causal structure required for classical spacetime, shared facts, and the emergence of observers capable of modeling their own cosmic history.

This conclusion is not anthropic in the explanatory sense. Observers are not privileged causes but structural consequences. Any system capable of observation requires a regime in which $\Pi(\tau)$ lies between deep subcriticality and global fragmentation. The universe must therefore pass through such a regime if observers are to arise at all.

Finite propagation speed thus emerges not as a mere limitation but as the ontological ground of intelligibility. If propagation were instantaneous, all relations would close at once, producing a static block without history or accumulation. If propagation were impossible, no relations could form at all. A finite invariant speed is the condition that allows history, structure, and coherence to emerge.

Conflicts of Interest

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

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Appendix: Experimental Protocol for Testing Propagation-Limited Commitment

The causal-percolation framework makes a distinctive empirical claim: irreversible relational commitment cannot globalize instantaneously if finite propagation speed functions as an ontological throttle. This appendix outlines an experimental strategy capable of distinguishing propagation-limited commitment from interpretations that treat collapse as instantaneous or purely epistemic.

The core idea is to probe whether quantum correlations persist unchanged at arbitrarily short measurement delays or whether they degrade below a critical temporal threshold corresponding to insufficient causal percolation. The experiment does not modify quantum dynamics or permit superluminal signaling. It tests only whether irreversible commitment exhibits latency.

Consider a source producing polarization-entangled photon pairs, distributed to two detectors separated by a distance $L \approx 10$ km. The light-travel time between detectors is approximately

$$t_{light} = L/c \approx 33\ \mu\text{s} \tag{A1}$$

Each detector is equipped with single-photon counters synchronized using optical atomic clocks, achieving timing resolution in the picosecond regime (Bothwell et al., 2019). Measurement outcomes are recorded with variable relative delays between the two detectors.

The experiment proceeds in stages. First, correlations are measured with detector delays much greater than t_{light}, confirming standard quantum predictions through violation of Bell inequalities (Bell, 1964). Second, the relative delay is systematically reduced, approaching and then undercutting t_{light}. At each delay setting, correlations are accumulated over large ensembles to control for statistical noise.

If irreversible relational commitment is propagation-limited, then for sufficiently small delays the effective $\Pi(\tau)$ associated with joint measurement may fall below unity. In this regime, closure networks spanning both detectors cannot form, and correlations should degrade toward classical statistics. The transition may be sharp or gradual, but it should occur near a characteristic delay scale.

All components required for this experiment already exist within contemporary quantum optics laboratories. Long-distance entanglement distribution, ultrafast timing, and high-efficiency detectors are standard tools in quantum network research (Wehner et al., 2018; Degen et al., 2017). With modest resources, such an experiment could be implemented and would decisively test a core ontological claim of the framework.