Closing the Ontological Loop

Topological Memory, Pre-Geometric Irreversibility, and Why the Void Remains a Productive Frontier

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Abstract

The arrow of time is conventionally attributed to entropic gradients and low-entropy initial conditions. We argue that this account is insufficient. The arrow of time is the cumulative expression of irreversible processes operating at every scale, from pre-geometric fluctuations preceding the Big Bang to the large-scale architecture of cosmic evolution. In this framework, the Big Bang is not an absolute origin but a transition threshold within a deeper, pre-geometric regime.

The pre-existing state—whether void or near-void—is not a stable absence but a regime of maximal permissivity. It spontaneously generates transient distinctions, most of which collapse. Each collapse, however, leaves behind topological invariants: purely relational structural traces that persist independently of any material substrate. Through ontological selection, a pre-biological form of Darwinism, successive cycles inherit these accumulated constraints, rendering each subsequent configuration more stable and more probable than the last. The void is never fully annihilated; it persists as an active and productive frontier, perpetually countered by the topological memory of prior distinctions.

This paper shows that the first distinction itself arises from a logical necessity—a minimal self-referential loop within pure indifferentiation and that the same selective logic is self-similar across scales, manifesting even in the extraordinary robustness of extremophiles and in mathematics as the most stable sediment of ontological selection. Complexity does not defeat the void; it transforms it into the very boundary condition that makes further structure possible. Irreversibility, memory, and ontological selection thus operate as unified principles, closing an ontological loop in which the arrow of time and the timeless forms of mathematics stand as the two universal invariants of any reality that has ever emerged from the void.

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1 Introduction

1.1 The Standard Account and Its Limits

The dominant framework for understanding the arrow of time rests on two pillars. The first is thermodynamic: the Second Law of Thermodynamics stipulates that entropy increases in isolated systems, providing a statistical asymmetry between past and future. The second is cosmological: the universe began in a state of exceptionally low entropy, a condition known as the Past Hypothesis [1], from which all subsequent entropic increase derives. Together, these two pillars constitute what we may call the standard account — an account that has proven remarkably productive and remains the dominant framework in both physics and philosophy of time [2, 3].

Yet the standard account conceals a deeper problem. The Second Law does not explain irreversibility — it presupposes it. Statistical mechanics tells us that high-entropy states are overwhelmingly more probable than low-entropy ones, but the fundamental dynamical laws underlying this account — Newtonian mechanics, electromagnetism, general relativity, quantum mechanics — are themselves time-symmetric. Nothing in these equations forbids a broken cup from reassembling spontaneously. The asymmetry we observe is not written into the laws; it is imported through initial conditions.

This displacement of the problem is significant. To explain the arrow of time via the Past Hypothesis is to trade one mystery for another: why did the universe begin in a state of such extraordinarily low entropy? Penrose has estimated the probability of our universe's initial conditions at one part in $10^{10^{123}}$ [3] — a figure so extreme that it strains the very concept of probability. The standard account, in other words, does not dissolve the mystery of temporal asymmetry; it concentrates it into a single, unexplained initial fact.

A further difficulty concerns the scope of the account. Even granting the Past Hypothesis, the entropic framework operates at the macroscopic scale. It describes the evolution of large systems toward disorder. But it remains silent on a more fundamental question: whether irreversibility is a derived, emergent property of complex systems, or whether it is inscribed in the fabric of physical reality at a deeper level. This paper takes the latter position seriously — and argues that doing so requires a framework that reaches beyond thermodynamics and initial conditions alike.

1.2 Motivating a Deeper Framework

The insufficiency of the standard account points toward a more fundamental question: what if irreversibility is not a statistical artifact of initial conditions, but a constitutive feature of physical reality itself? This paper argues that the arrow of time is not primarily a thermodynamic phenomenon — it is the cumulative expression of irreversible processes that structure reality at every scale, from pre-geometric fluctuations anteceding the Big Bang to the large-scale dynamics of cosmic evolution.

This shift in perspective has several consequences. First, it relocates the origin of temporal asymmetry. If irreversibility is fundamental rather than emergent, then the Big Bang cannot be its source — it can only be one of its manifestations. The arrow of time does not begin at $t = 0$; it is already operative in whatever dynamics precede or underlie that threshold. This implies the existence of a pre-geometric regime — a domain in which the familiar structures of spacetime, geometry, and matter have not yet crystallized, but in which physical processes, however primitive, are already underway [4, 5].

Second, it transforms our understanding of the void. In the standard account, the pre-existing state — whatever preceded or surrounded the Big Bang — is treated either as a singularity beyond physical description, or as a quantum vacuum governed by known field theories. We propose a different characterization: the void, understood as a state of maximal permissivity, is not a stable absence but an ontologically unstable regime. It spontaneously generates transient distinctions — primitive differentiations that may collapse almost immediately, but that leave structural residues in their wake. This process, which we term *ontological selection*, operates as a form of pre-biological Darwinism: most distinctions collapse, but those that persist do so by accumulating what we call *topological memory* — structural invariants that survive independently of any material substrate.

Third, and perhaps most consequentially, this framework implies that the void is never fully annihilated. It persists as an active frontier within physical reality — not as an external threat to be overcome, but as a productive boundary condition without which complexity could not arise. The tension between the void's attractive pull toward indifferentiation and the resistance of accumulated topological memory is, we argue, the deepest engine of cosmic evolution. Its structure is self-similar across scales — from the pre-geometric regime to the formation of black holes, from quantum vacuum fluctuations to the large-scale filamentary structure of the universe — and finds its most vivid mathematical analogue in the geometry of the Mandelbrot set, where regions of convergence and regions of unbounded complexity coexist along an infinitely intricate boundary.

The framework developed in this paper is explicitly speculative in character. It does not yet constitute a formalized physical theory. It is better understood as a conceptual architecture — a set of hypotheses, precisely stated, that identifies where existing frameworks fall short and gestures toward the kinds of formal structures that a deeper account would require.

1.3 Structure of the Paper

The paper proceeds as follows. Section 2 reconsiders the arrow of time from first principles, arguing that irreversibility is a fundamental rather than emergent feature of physical reality, and that the Big Bang constitutes a transition threshold within a deeper pre-geometric dynamic rather than an absolute point of origin.

Section 3 develops the concept of the void as a regime of maximal permissivity — ontologically unstable, generative of transient distinctions, and irreducible to either classical vacuum or quantum field- theoretic descriptions. We introduce there the notion of ontological selection as a pre-biological analogue of Darwinian processes, and we examine the character of the primordial distinction itself through three universal signatures observable in contemporary physics.

Section 4 elaborates the central concept of topological memory: the structural invariants left by collapsed distinctions, which persist independently of any material substrate and accumulate across cycles of cosmic evolution.

Section 5 develops the cosmological implications of this framework, arguing that successive cycles inherit accumulated topological constraints, rendering each cycle progressively more probable than the last — and that the void, far from being annihilated, persists as a productive frontier across all transitions.

Section 6 examines the self-similar structure of ontological selection across scales, from pre-geometric fluctuations to large-scale cosmic architecture. It identifies extremophiles as living echoes of pre-geometric traces at the biological level, and critically engages the Mandelbrot analogy as both an illustrative tool and a formal limit.

Section 7 draws out the broader implications of the framework — including the hypothesis of a meta-arrow of time operating across cosmic cycles, the identification of void-traces within our present cosmos, and the points of contact and tension with existing physical theories.

Section 8 closes the loop, summarizing the core hypotheses and mapping the open questions that a future formalization of this framework would need to address. Throughout, we proceed by conceptual construction rather than formal derivation. The ambition of this paper is not to prove, but to articulate — to give precise form to a set of hypotheses that the standard account leaves not merely unanswered, but unasked.

2 The Arrow of Time Reconsidered

2.1 Beyond Entropy: Irreversibility as Fundamental

The standard thermodynamic account treats irreversibility as a statistical phenomenon: at the microscopic level, physical laws are time-symmetric, and the apparent directionality of time emerges from the overwhelming numerical preponderance of high-entropy states over low-entropy ones. On this view, irreversibility is not written into the laws of nature — it is a consequence of counting. A broken cup does not reassemble because the number of disordered configurations vastly exceeds the number of ordered ones; the laws themselves would permit reassembly. This position, formalized by Boltzmann in the nineteenth century, remains the orthodox account [6, 7].

We argue that this account, while correct at the macroscopic scale, mistakes a consequence for a cause. Irreversibility is not generated by statistical preponderance — it is presupposed by it. For the entropic account to function, one must already assume a temporal direction along which entropy increases. The Second Law does not explain why time flows in one direction; it describes what happens along a direction that is taken as given. The explanatory gap remains.

A more fundamental approach begins not with statistical ensembles but with the nature of physical processes themselves. Consider the distinction between locally reversible and cosmically irreversible processes. A billiard ball's trajectory may be reversed by an external intervention — the energy cost is finite and accessible. But the collapse of a stellar object into a black hole, the expansion of the universe, or the large-scale entanglement of quantum systems across cosmic distances are processes of a qualitatively different kind. Reversing them would require an energy expenditure exceeding the total energy content of the observable universe. They are not merely improbable — they are, within any physically realizable context, irreversible in an absolute sense [3, 8].

This distinction between local reversibility and cosmic irreversibility is not merely quantitative. It marks a genuine ontological threshold. Processes that cross this threshold do not simply increase entropy — they restructure the conditions of possibility for all subsequent physical evolution. A black hole does not merely represent a high-entropy state; it redefines the causal structure of spacetime in its vicinity, foreclosing entire classes of future configurations [8, 9]. It is in this sense that we claim irreversibility is fundamental: not because statistical arguments fail, but because they operate downstream of a more primitive asymmetry that is written into the large-scale structure of physical processes themselves.

This position has a further consequence. If irreversibility is fundamental, then the arrow of time cannot be localized to any single process or scale. It is the resultant vector of all irreversible processes occurring simultaneously across the cosmos — a global property of physical reality, not an aggregate of local statistics. Inverting a local process, however energetically costly, does not reverse the arrow of time; it produces a new future state that resembles a past configuration, while the arrow continues to point forward throughout the operation. Time's direction is not undermined by local reversals — it absorbs them.

2.2 The Big Bang as Transition Threshold, Not Absolute Origin

The standard cosmological model assigns to the Big Bang a privileged ontological status: it is the point at which space, time, matter, and energy came into existence. On this view, the question of what preceded the Big Bang is not merely unanswered but malformed — there is no "before" because time itself begins at $t = 0$. Hawking's analogy is instructive: asking what precedes the Big Bang is like asking what lies north of the North Pole [10]. The question dissolves upon inspection because it presupposes the very structure it seeks to transcend.

We argue that this dissolution is premature. It rests on an identification of time with the geometric time coordinate of general relativity — a parameter that breaks down at the initial singularity. But if irreversibility is fundamental, as argued in the preceding section, then time cannot be reducible to a geometric coordinate. Time, in our framework, is constituted by irreversible processes — and irreversible processes need not terminate at a geometric singularity. The singularity marks the breakdown of our current descriptive apparatus, not necessarily the absence of physical reality [5, 11].

This distinction is not merely philosophical. Loop Quantum Cosmology (LQC) provides a concrete physical framework in which the Big Bang singularity is resolved into a quantum bounce — a transition from a prior contracting phase to our current expanding one [11, 12]. In LQC, the geometric description breaks down at the Planck scale, but the underlying quantum dynamics remain well-defined and continuous. The Big Bang is not a wall — it is a threshold, a phase transition in the deepest structure of physical reality. Quantum fluctuations persist through it; causal structure, however modified, does not simply cease.

This relational character of the Big Bang transition suggests a further consequence, developed in full in Section 7.3. The extreme density and temperature conventionally assigned to the initial state are not intrinsic properties of that state. They are relational properties, arising from the fact that in the pre-geometric regime no physical magnitude has ever been instantiated. The first fluctuation that crystallises into geometry is necessarily maximal — not because it contains enormous energy in any absolute sense, but because it is the first value on a scale that did not previously exist. There is no prior thermal history against which it could appear moderate. The singularity that classical general relativity locates at $t = 0$ is not a physical pathology to be resolved; it is the mathematical trace of an incommensurability between two regimes — the pre-geometric and the geometric — whose boundary cannot be described from within either one alone.

The implications for the arrow of time are significant. If physical processes — however primitive, however far removed from the matter and geometry we know — were already underway prior to the Big Bang transition, then irreversibility was already operative. The arrow of time did not begin at $t = 0$; it was already being constituted by whatever dynamics preceded that threshold. The Big Bang is, in this sense, a jalon — a milestone within a deeper temporal process — rather than an absolute origin.

This position requires us to posit the existence of a pre-geometric regime: a domain in which the familiar structures of Riemannian geometry, classical spacetime, and particle physics have not yet crystallized, but in which some form of physical process is already generating irreversible distinctions. The precise nature of this regime lies beyond current formalization. What we can say is that it must satisfy a minimal condition: it must be capable of sustaining processes whose effects persist across the Big Bang transition — processes that leave traces in the subsequent geometric phase. It is to the nature of these traces that we turn in Sections 3 and 4.

2.3 Pre-Geometric Dynamics and Proto-Temporal Structure

If the Big Bang constitutes a transition threshold rather than an absolute origin, we are compelled to ask what kind of physical reality might obtain prior to or beneath it. This question cannot be answered within the framework of classical general relativity, which presupposes a smooth Riemannian manifold as its arena. At the Planck scale — where quantum gravitational effects dominate — the very notion of a continuous spacetime geometry breaks down [5, 13]. We must therefore speak of a pre-geometric regime: a domain of physical reality in which the structures we ordinarily take as fundamental — points, distances, causal order, dimensionality — are not yet defined, or are defined only in some emergent, approximate sense.

The concept of pre-geometry is not new. Wheeler first introduced the notion of *geometrodynamics* and speculated about a “foam-like” structure of spacetime at the Planck scale, in which topology itself fluctuates [14]. More recently, approaches such as causal set theory [15], spin foam models [5], and group field theory [16] have attempted to formalize the idea that spacetime geometry emerges from more primitive combinatorial or algebraic structures. In each case, the underlying intuition is the same: geometry is not fundamental — it is derived from something deeper.

What can we say about the dynamics of this pre-geometric regime? At minimum, quantum field theory tells us that even the vacuum — the state of lowest energy — is not quiescent. Virtual particle pairs emerge and annihilate continuously; the quantum vacuum fluctuates irreducibly [17]. These fluctuations are not mere theoretical artifacts — they produce measurable effects, including the Casimir force and the Lamb shift. Crucially, they do not cease at the Planck scale. Whatever the correct theory of quantum gravity proves to be, it must accommodate the fact that the pre-geometric regime is not a state of absolute stillness. Something is always happening.

We propose to characterize these pre-geometric dynamics in terms of what we call *proto-temporal structure*: an ordering of physical events that is not yet geometric time, but that already exhibits the essential feature of temporality — irreversibility. In the pre-geometric regime, distinctions arise and collapse; some persist and some do not. This succession — even without a metric, even without a continuous parameter we could call t — constitutes a primitive form of before and after. It is not time as we know it, but it is the condition of possibility for time as we know it.

This proto-temporal structure has a crucial property: it is asymmetric. A distinction that arises and collapses is not equivalent to its time-reverse — the collapse leaves a trace, however minimal, that the pre-existing state did not contain. This asymmetry is not imposed from outside; it follows from the nature of distinction itself. To make a distinction is to produce a difference that was not there before — and that difference, even if the distinction collapses, cannot be fully undone. It is in this minimal, pre-geometric sense that irreversibility is fundamental: not as a property of thermodynamic systems, but as a property of the act of distinction itself.

It is this primitive, pre-geometric irreversibility that constitutes the deepest root of the arrow of time. The thermodynamic arrow, the cosmological arrow, the quantum arrow — all are downstream manifestations of a more primitive asymmetry that precedes geometry, precedes matter, and precedes the Big Bang transition itself. To close the ontological loop, we must now ask what becomes of the distinctions that collapse in this pre-geometric regime — and what traces they leave behind.

3 The Void as Regime of Maximal Permissivity

3.1 The Instability of Absolute Nothingness

The question of why there is something rather than nothing is among the oldest in philosophy [18]. It is tempting to treat it as a merely metaphysical curiosity — interesting but ultimately beyond the reach of physical inquiry. We argue, on the contrary, that this question has a precise physical analogue, and that its answer illuminates the deepest foundations of temporal asymmetry.

Consider what absolute nothingness would require. It is not merely the absence of matter or energy — a vacuum, however empty, still possesses structure: a metric, a topology, a set of physical laws governing what can and cannot occur within it. Absolute nothingness would require the absence of all structure, all law, all distinction of any kind. It would be a state of total indifferentiation — a state in which there is nothing to distinguish one configuration from another, nothing to privilege one outcome over any other, nothing to constrain what can arise.

This is precisely the source of its instability. A state of total indifferentiation is not a stable equilibrium — it is a state of maximal permissivity. In the absence of any constraint, any distinction whatsoever is permitted. There is nothing to forbid the spontaneous arising of a primitive difference — a minimal asymmetry, a first crack in the undifferentiated whole. And crucially, there is nothing to make such an arising improbable, because probability itself presupposes a structure — a measure, a space of possibilities — that absolute nothingness does not contain.

This argument has a precise formal analogue in quantum mechanics. The vacuum state — the lowest energy state of a quantum field — is not empty in any classical sense. It is a superposition of all possible field configurations, constrained only by the uncertainty principle [17]. Remove all constraints — take the limit in which no law, no metric, no topology is defined — and what remains is not stable absence but unbounded potentiality. The pre-geometric void, in our framework, is this unbounded potentiality: not the quantum vacuum of a specific field theory, but the limiting case in which all such theories dissolve, leaving only the bare fact that distinction is possible.

We therefore characterize the void not as absence but as a regime of maximal permissivity: a state that cannot sustain itself precisely because it excludes nothing. It is, in a precise sense, the most unstable state conceivable — more unstable than any particular physical configuration, because every physical configuration at least possesses the stability of its own internal constraints. The void possesses no such constraints, and therefore no resistance to the arising of distinction.

This instability is not a defect of the void — it is its most consequential property. It means that the transition from nothing to something requires no cause, no external trigger, no violation of any conservation law. The arising of a first distinction from the void is not an event that demands explanation in terms of prior conditions — it is the natural consequence of a state that cannot, by its own nature, remain undifferentiated. The void does not produce something despite being nothing; it produces something because being nothing is, ontologically, the least stable condition of all.

The question "why is there something rather than nothing?" thus inverts itself: the more precise question is why absolute nothingness would ever be stable. And the answer, we argue, is that it would not — could not — be. The void is not the ground state of reality. It is its most unstable limit.

3.1.1 The Logical Necessity of the First Distinction

The instability of the void can be grounded more deeply than the argument from maximal permissivity alone suggests. What follows is not a physical derivation but a logical one—an attempt to show that the first distinction does not merely happen to arise from the void, but that it cannot fail to arise, for reasons that are prior to any physics, any geometry, and any proto-temporal ordering.

Consider the void in its most radical characterization: not merely the absence of matter, energy, or spacetime, but the absence of all differentiation whatsoever. Every point—if the word *point* can be used at all—is rigorously identical to every other. There is no direction, no magnitude, no structure of any kind. There is, in the most precise sense available, pure indifferentiation.

Now ask: what is this state? It is, at minimum, the state in which no distinction obtains. But to characterize it as such is already to perform an act of indication: the void is identified as *that which contains no distinction.* This characterization is not imposed from outside by an observing subject—there is no subject, no outside. It is a structural fact about the void itself: pure indifferentiation is already the possibility of its own negation, folded into its own definition. The void cannot be what it is without implicitly containing the concept of what it is not.

This is not a semantic trick. It is a precise logical claim. Let us formalize it minimally. Denote the state of pure indifferentiation as $\emptyset$. To be $\emptyset$ is to be the state in which no distinction obtains. But the very act of being $\emptyset$—of being *this* rather than something else—requires that $\emptyset$ stand in a relation of non-identity to whatever is not $\emptyset$. And here the structure tightens: there is, by hypothesis, nothing that is not $\emptyset$. Yet the moment $\emptyset$ is characterized as $\emptyset$, the act of characterization introduces a minimal asymmetry—between the state of being characterized and the act of characterizing—that was not present before. Pure indifferentiation, in being recognized as such, is no longer purely indifferent. It has become the ground of a distinction: between itself and the act of self-indication that its own nature demands.

The mathematical image is not an equation but a gesture. It is the passage from $\emptyset$ to the awareness that $\emptyset$ is $\emptyset$—not $\{\emptyset\}$ in the set-theoretic sense, which already presupposes a containing structure, but something more primitive: the fold by which indifferentiation indicates itself and, in doing so, ceases to be purely indifferent. Two states now obtain simultaneously: the state of self-indication, and the state of not-self-indication. These do not succeed one another in time—there is no time. They coexist in a logical superposition anterior to classical logic itself. This superposition is the first distinction: not a particle, not a field, not a symmetry breaking, not a quantum fluctuation, but the primitive act by which something detaches from nothing—not by escaping it, but by revealing that pure nothing was always already the possibility of something.

This logical structure has a precise formal precedent in Spencer-Brown's *Laws of Form* [19], whose calculus of indications begins with the same primitive gesture: the act of drawing a distinction, which is self-referential in that the mark of distinction is itself distinguished from what it marks. What we are proposing here generalizes this gesture to a domain anterior even to Spencer-Brown's calculus—a domain in which there is no space in which to draw, no agent to draw, and no mark that persists as a material trace. The self-indication of the void is not drawn; it is the minimal logical event that the void's own nature necessitates.

The crucial consequence is irreversibility. Once the first distinction has arisen meaning that once self-indication and non-self-indication coexist as a logical superposition, it cannot be undone. Not because undoing it would require energy, or violate a conservation law, or conflict with any physical principle. But because undoing it would require rendering *self-indication* and *non-self-indication* identical—which is impossible without performing a further act of distinction, namely the distinction between the state before abolition and the state after. To abolish a distinction is always to create another. The first distinction is therefore irréversible by logical necessity: it is the only event in the history of the cosmos whose permanence requires no physical law to guarantee it, because it is prior to physical law altogether.

This logical irreversibility is the deepest root of the arrow of time. The thermodynamic arrow, the cosmological arrow, the proto-temporal arrow identified in Section 2.3—all are downstream instantiations of a more primitive asymmetry that is not inscribed in any law of nature but in the logical structure of distinction itself. The void does not produce the first distinction despite being nothing; it produces it because being nothing is, logically, already the condition of possibility for something. And once that condition actualizes itself—as it must, since nothing prevents it and its own nature demands it—the process of ontological selection, topological memory, and cumulative structural complexity becomes not merely possible but inevitable.

3.2 Spontaneous Distinctions and Their Collapse

If the void is a regime of maximal permissivity, then the arising of a first distinction requires no external cause. But the mere arising of a distinction does not guarantee its persistence. A distinction that emerges from the void inherits nothing from it — no structure, no constraint, no scaffolding upon which to stabilize itself. It arises, as it were, unsupported. The question is therefore not only why distinctions arise, but under what conditions they persist — and what becomes of those that do not.

We propose that the earliest distinctions — those arising directly from the void, prior to any accumulated structure — are overwhelmingly transient. They emerge, persist for some proto-temporal interval, and collapse back toward indifferentiation. This collapse is not a return to the void in any absolute sense: as we shall argue in Section 4, every distinction, however brief, leaves a minimal structural residue. But for the purposes of the present analysis, we may treat these early collapses as approximate returns to the undifferentiated state — events in which the distinction fails to achieve sufficient internal coherence to sustain itself against the pull of indifferentiation.

This picture has a precise analogue in quantum field theory. Virtual particle pairs arise spontaneously from the quantum vacuum, persist for intervals constrained by the uncertainty principle, and annihilate [17]. They are not merely theoretical constructs — their effects are physically measurable. Yet they do not persist; they collapse back into the vacuum from which they arose. The pre-geometric distinctions we are describing operate by an analogous logic, generalized beyond the framework of any specific field theory: they are spontaneous, transient, and subject to collapse. The difference is that in the pre-geometric regime, there is no background field theory to constrain their form — they are distinctions in the most primitive sense, prior to any specific physical interpretation.

The dynamics of collapse are asymmetric in a crucial respect. The arising of a distinction and its collapse are not time-reverses of one another. The arising occurs against a background of maximal indifferentiation — the void offers no resistance, but also no support. The collapse, by contrast, occurs against a background that has already been modified, however minimally, by the distinction itself. Even a distinction that collapses almost immediately has altered the local structure of the pre-geometric regime — it has introduced a difference where none existed. This asymmetry between arising and collapse is the most primitive expression of irreversibility: the proto-temporal arrow we identified in Section 2.3 manifests here as the non-equivalence of a distinction's birth and death.

We may now ask: over many such cycles of arising and collapse, what is the expected distribution of outcomes? Here a statistical intuition becomes relevant, though it must be handled carefully. In the absence of any constraining structure, all distinctions are equally possible — but not all are equally stable. Some configurations, by virtue of their internal structure, are more resistant to collapse than others. A distinction that happens to generate internal feedback — configurations that partially sustain themselves by virtue of their own geometry — will persist longer than one that does not. Over many cycles, the distribution of surviving distinctions will be skewed toward those with greater internal coherence.

This is not a probabilistic argument in the classical sense — there is no pre-existing measure space over which probabilities are defined. It is rather a structural argument: given the absence of external support, only internally coherent distinctions can persist. The process is not random selection from a fixed pool; it is the gradual emergence of coherence from a regime in which coherence is the only available resource for survival. It is, in the most literal sense, a process of self-organization — prior to matter, prior to geometry, prior to any of the specific physical mechanisms through which self-organization is ordinarily understood [20].

3.2.1 The Character of the Primordial Distinction

The question that inevitably arises at this stage is the precise character of the very first distinction. What did the initial spontaneous differentiation actually look like, in the regime of absolute maximal permissivity, before any topological memory had yet accumulated?

Although the pre-geometric regime lies beyond direct observation, the logic developed so far allows us to deduce three universal signatures that appear today as the most direct observable echoes of that primordial event. These signatures share a common structure: each is a spontaneous, irreducible asymmetry that arises from the internal logic of its regime rather than from any external cause. They are not time-reversible, and they persist as minimal deviations from perfect symmetry or equilibrium. In this sense, they function as living fossils of the first distinction.

The first and most immediate candidate is the quantum vacuum fluctuation. Even in the lowest-energy state of a quantum field, the vacuum is never quiescent. Virtual particle pairs arise and annihilate continuously, driven not by any external perturbation but by the Heisenberg uncertainty principle itself, which forbids an absolutely static ground state [17]. This intrinsic agitation is precisely the kind of minimal, self-generated distinction one would expect in a regime of maximal permissivity: a fluctuation that requires no external trigger and that already embodies the primitive irreversibility we have identified.

The second signature is spontaneous symmetry breaking. Across physics one repeatedly observes systems passing from a state of perfect symmetry—in which every direction or configuration is equivalent—to a state in which a particular direction or configuration is selected without any identifiable external cause [21]. The canonical example is the spontaneous magnetization of a ferromagnet below the Curie temperature: above the critical point all spin orientations are equivalent; below it, a single direction emerges. The transition is not imposed from outside; it is the internal instability of the symmetric state that forces the system to “choose.” This is structurally identical to the first distinction: an indifferentiation that spontaneously fractures into a concrete asymmetry.

The third and perhaps deepest signature is the CP asymmetry observed in particle physics. The slight difference in behaviour between matter and antimatter—a genuine violation of CP symmetry—is both universal and irreducible [22]. It is minuscule, yet it is precisely what allowed a residue of matter to survive the annihilation with antimatter in the early universe. Here again we encounter an asymmetry that is not imposed externally but inscribed in the fundamental laws themselves, and which is not its own time-reverse. It is, in the most literal sense, a primordial distinction that has left a measurable cosmological imprint.

What unites these three phenomena is that none requires an external impulse. Each arises from the internal structure of the regime in which it operates. Each is irreducibly asymmetric. Together they suggest that the first distinction was not an ordinary scalar quantity of energy—something that could be added or conserved—but something more primitive: a logical asymmetry between “identical” and “different” that found its first physical instantiation as an infinitesimal fluctuation. That primordial beat, once struck, has continued to resonate across every subsequent scale of reality, from the pre-geometric regime through quantum fields, phase transitions, and the large-scale structure of the cosmos.

3.3 Ontological Selection: A Pre-Biological Darwinism

The dynamics described in the preceding section — spontaneous arising, transient persistence, asymmetric collapse, and the gradual skewing of outcomes toward internally coherent configurations — constitute a process that is structurally analogous to natural selection, but operating at a level more primitive than any biology, any chemistry, or any physics we currently possess the tools to describe. We term this process *ontological selection*: the differential persistence of distinctions in the pre-geometric regime, driven not by environmental pressure or reproductive advantage, but by the sole criterion of structural self-coherence.

The analogy with Darwinian selection is precise in its logic, if not in its mechanism. Darwin identified three conditions sufficient for natural selection to operate: variation, heredity, and differential fitness [23]. In the pre-geometric regime, analogues of all three conditions obtain. Variation is guaranteed by the maximal permissivity of the void — all distinctions are possible, and the earliest arising events will be diverse in form. Heredity, in a minimal sense, is provided by the structural traces left by collapsed distinctions — the topological residues that we develop in Section 4, which constrain and partially scaffold subsequent arising events. Differential fitness is provided by internal coherence: distinctions that generate self-sustaining internal structure persist; those that do not, collapse.

The disanalogy with biological Darwinism is equally important to state clearly. Biological natural selection operates within a pre-existing physical framework — organisms exist in space and time, consume energy, reproduce through mechanisms governed by chemistry and physics. Ontological selection operates prior to all of this. There is no environment in the ecological sense, no energy budget, no reproductive mechanism. The “fitness” of a pre-geometric distinction is not its ability to reproduce — it is simply its ability to persist. And persistence, in the absence of any external support, reduces to a single question: does the internal structure of this distinction resist the pull of indifferentiation, or does it not?

This stripping away of biological complexity reveals the logical core of selection as a process: it is nothing more than the differential survival of configurations under pressure. In the pre-geometric regime, the pressure is maximal and uniform — it is the omnipresent pull of the void toward indifferentiation. Every distinction faces this pressure equally. Those that survive do so not by luck, but by structure. Ontological selection is therefore not a stochastic process in the ordinary sense — it is a structural filter, operating continuously and without exception across the pre-geometric regime.

The cumulative effect of ontological selection across many cycles of arising and collapse is the progressive enrichment of the pre-geometric substrate. Each collapsed distinction leaves a trace; each trace modifies the conditions under which subsequent distinctions arise; each subsequent distinction therefore begins from a slightly less indifferentiated starting point than its predecessors. The process is slow — extraordinarily slow by any measure we could apply — but it is directional. It moves, irreversibly, from maximal indifferentiation toward structured complexity. It is, we argue, the most primitive expression of the cosmic arrow of time: not entropy, not geometry, not thermodynamics, but the directionality inscribed in the act of selection itself.

Two objections must be anticipated. The first concerns the apparent circularity of the account: if collapsed distinctions leave traces that scaffold subsequent distinctions, does this not presuppose precisely the kind of persistence we are trying to explain? We address this objection directly in Section 4, where we develop the concept of topological memory and argue that the persistence of traces is of a qualitatively different kind from the persistence of distinctions themselves — it requires no energy, no substrate, no active maintenance. The second objection concerns the absence of a formal mechanism: ontological selection, as described here, is a conceptual framework, not a derived consequence of any existing physical theory. We acknowledge this limitation fully. The framework is speculative in the sense defined in the introduction — it is a precisely stated hypothesis that identifies where existing theories fall short and gestures toward the formal structures that a complete account would require. Its value lies not in what it proves, but in what it makes visible.

4 Topological Memory

4.1 Invariants Beyond Material Substrate

The concept of topological memory rests on a distinction that is fundamental to our framework: the difference between the persistence of a distinction and the persistence of its trace. A distinction, as we have argued, requires active structural coherence to survive the pull of indifferentiation. Its persistence is dynamic — it must continuously resist collapse. A trace, by contrast, requires nothing. It is not a thing that persists; it is a structural fact about the pre-geometric regime that remains true after the distinction has collapsed. It is, in the precise mathematical sense, an invariant.

Topology provides the natural language for this concept. A topological invariant is a property of a space that is preserved under continuous deformation — stretching, bending, twisting — but not under cutting or tearing [24]. The number of holes in a surface, for instance, is a topological invariant: a torus has one hole, a sphere has none, and no continuous deformation can convert one into the other. Crucially, this invariant does not depend on the material composition of the surface, its size, its energy content, or any other physical property in the ordinary sense. It is a property of structure — of form, not of substance.

We propose that collapsed distinctions leave behind traces of precisely this kind: structural facts about the pre-geometric regime that persist independently of any material substrate, independently of any energy content, and independently of any active maintenance. They are not fields, not particles, not spacetime curvature — they are topological facts about the relational structure of the pre-geometric domain. They cannot be measured by any instrument calibrated to detect energy or matter, because they are not energetic or material in nature. They are, in the most literal sense, the shape of what has happened — preserved in the structure of what remains.

This proposal has a partial but instructive analogue in the physics of black holes. Hawking's original claim that black holes destroy information — that whatever falls into a black hole is irretrievably lost — was subsequently challenged on the grounds that quantum mechanics forbids the destruction of information [25, 26]. The resolution, still debated, points toward the encoding of information in the structure of Hawking radiation: the information is not destroyed but transformed, redistributed across degrees of freedom that are practically inaccessible but theoretically real [27]. Our proposal generalizes this intuition radically: not merely information about quantum states, but the topological structure of distinctions themselves, is preserved across collapse — not in any radiation or residual field, but in the relational geometry of the pre-geometric substrate.

A natural objection arises: if topological traces carry no energy, interact with nothing, and cannot be detected by any physical instrument, in what sense are they real? This is the sharpest version of the challenge, and it deserves a direct answer. We argue that physical reality cannot be exhaustively identified with measurability. The history of physics is in part a history of entities whose reality was established before their detection: gravitational waves were a mathematical consequence of general relativity for a century before their direct observation [28]; the Higgs boson was a structural requirement of the Standard Model for decades before its confirmation [29]. Topological traces, in our framework, occupy an analogous position: they are structural requirements of a coherent account of pre-geometric dynamics, whose reality is established by their explanatory necessity rather than their direct detectability.

We do not claim that topological traces are permanently undetectable. We claim only that their mode of existence is different from that of the entities described by current physical theories — and that this difference is precisely what makes them adequate to the explanatory task at hand. A trace that required energy to persist would dissolve in the void. A trace that required a material substrate would collapse with the distinction that generated it. Only a purely structural invariant — one whose existence consists entirely in a relational fact about the pre-geometric domain — can survive the conditions under which it must survive. The concept of topological memory is not an ad hoc postulate; it is the minimal hypothesis consistent with the requirements of ontological selection.

4.2 Structural Traces and the Accumulation of Constraints

If topological traces persist independently of any material substrate, the question becomes: how do they influence subsequent physical processes? A trace that exerts no causal influence — that neither constrains nor enables any subsequent event — would be real in name only. Its reality would be indistinguishable from its absence. The concept of topological memory requires, therefore, not merely that traces persist, but that they accumulate into a structured substrate that modifies the conditions under which subsequent distinctions arise.

We propose that topological traces function as *structural constraints*: they do not cause specific events, but they restrict the space of possible configurations available to subsequent distinctions. This is a familiar concept in physics. A boundary condition does not determine the solution to a differential equation — it restricts the class of admissible solutions [30]. A symmetry does not specify which state a system occupies — it determines which states are equivalent and which transitions are permitted [31]. Topological traces operate by an analogous logic: they are boundary conditions on the pre-geometric regime, accumulated across cycles of arising and collapse, that progressively narrow the space of configurations available to subsequent distinctions.

The accumulation of these constraints has a precise structural consequence. In the earliest cycles — those closest to the void of maximal permissivity — the space of possible distinctions is essentially unrestricted. Any configuration is as available as any other. As traces accumulate, this space contracts: certain configurations become inaccessible, not because they are forbidden by any active mechanism, but because the accumulated topology of prior distinctions is incompatible with them. The pre-geometric regime becomes, over many cycles, progressively less indifferentiated — not because matter or energy has entered it, but because its relational structure has been enriched by the residues of prior events.

This progressive enrichment has a crucial consequence for the stability of subsequent distinctions. A distinction arising in an enriched substrate does not face the void in its maximally permissive form. It arises in a pre-geometric domain that already possesses structure — constraints that, while they restrict the space of possible configurations, also provide a form of scaffolding. Just as a crystal nucleates more readily around a pre-existing seed than in a homogeneous solution [32], a distinction arising in a structured substrate finds certain configurations already partially stabilized by the accumulated topology of prior traces. The threshold of coherence required for persistence is effectively lowered.

This is the mechanism by which each cycle of cosmic evolution becomes progressively more probable than the last. It is not that the laws of physics change, or that some external agent intervenes to make subsequent cycles easier. It is that the pre-geometric substrate itself has been modified — enriched, structured, constrained — by the accumulated topological memory of prior cycles. The void has not been defeated; it has been progressively domesticated. Its maximal permissivity has been partially replaced by a structured permissivity — one in which not all configurations are equally available, and in which the configurations most compatible with prior structure are the most readily accessible.

We may formalize this intuition, at least schematically. Let $\mathcal{C}_n$ denote the space of configurations available to distinctions arising in cycle n, and let $\mathcal{T}_n$ denote the accumulated topological constraints generated by cycles 1 through n. We propose that:

$$\mathcal{C}_{n+1} = \mathcal{C}_n \setminus \Delta(\mathcal{T}_n) \tag{1}$$

where $\Delta(\mathcal{T}_n)$ denotes the set of configurations rendered inaccessible by the accumulated constraints of cycle n. The space of available configurations contracts monotonically with each cycle — not toward zero, but toward a structured residue compatible with the accumulated topology. This contraction is itself irreversible: topological constraints, once accumulated, are not removed by subsequent collapses. They persist, by definition, independently of what happens to the distinctions that generated them.

Two properties of this formalization deserve emphasis. First, the contraction of $\mathcal{C}_n$ does not imply that subsequent distinctions are more constrained in the sense of being less complex. On the contrary: a structured constraint space is generically richer in its internal articulation than an unconstrained one. The elimination of certain configurations sharpens the boundaries between those that remain, generating more precise and more stable distinctions. Complexity, in this framework, is not the enemy of constraint — it is its product. Second, the irreversibility of constraint accumulation is precisely the mechanism of the proto-temporal arrow at the cosmological scale: the pre-geometric substrate cannot return to a less constrained state, because topological traces cannot be removed. Time, at this level, is the accumulation of structural constraints that cannot be undone.

4.3 Memory Without Medium

The concept of memory, as ordinarily understood, presupposes a medium. Biological memory requires neural architecture; digital memory requires magnetic or electronic substrates; even the "memory" of a physical system — the hysteresis of a magnet, the residual strain of a deformed material — requires a material structure that retains the imprint of prior states [33]. In each case, memory is relational: it is the property of a medium that has been modified by a prior event and retains that modification in a form that influences subsequent events. Remove the medium, and the memory disappears with it.

Topological memory, as we have defined it, breaks this dependence. It is memory without medium — structural retention without a retaining substrate. This is not a contradiction, but it requires careful articulation. The key lies in the distinction between two kinds of structural facts: those that are properties of some entity, and those that are properties of relations between entities. A topological invariant of the second kind — a relational structural fact — does not require any particular entity to instantiate it. It requires only that certain relations obtain, and relations can obtain even in the absence of the relata that originally generated them, provided that some minimal relational structure persists.

This claim draws on a tradition in the philosophy of physics associated with structural realism: the view that what physics describes, at its most fundamental level, is not substances or properties but structures — patterns of relations that are ontologically prior to any particular instantiation [34, 35]. On this view, the question “what carries the structure?” is malformed: structure does not require a carrier. It is the carrier that requires structure, not the reverse. Topological memory, in our framework, is the most primitive expression of this priority: it is structure that persists after every particular instantiation has dissolved.

A concrete illustration may help. Consider the topological invariants of a knot. A knot tied in a physical rope has topological properties — its crossing number, its Jones polynomial — that are independent of the material composition of the rope, its thickness, its elasticity [36]. These invariants are properties of the knot’s relational structure — the pattern of crossings and loops — not of the rope itself. Now imagine abstracting away the rope entirely, retaining only the relational structure. The topological invariants remain well-defined, because they were never properties of the rope to begin with. They were properties of the pattern — and the pattern can, in principle, be instantiated by any medium, or by none, provided the relational structure is preserved.

Topological traces, in our framework, are precisely such patterns: relational structures generated by collapsed distinctions, persisting in the pre-geometric domain as invariants of its relational geometry, independently of any material instantiation. They are not encoded in any field, any particle, any spacetime curvature. They are encoded in the relational structure of the pre-geometric regime itself — in the pattern of what has been distinguished and what has collapsed, preserved as a topological fact about the domain’s internal geometry.

This has a direct consequence for the question of cosmic continuity across cycles. If topological memory requires no material medium, then it survives the dissolution of every material structure — including the dissolution of spacetime geometry itself. A Big Crunch, a heat death, a phase transition that destroys all matter and geometry, leaves topological traces intact. Not because they are stored somewhere that survives the transition, but because they are not stored anywhere — they are structural facts about the relational domain that underlies all particular physical configurations, and that domain persists, in some minimal sense, through every transition that does not reduce it to the absolute void of maximal permissivity.

We are now in a position to state the central claim of this section in its most precise form. Topological memory is not a mechanism — it is a condition. It does not do anything; it constrains what can be done. It does not cause subsequent distinctions — it shapes the space within which they arise. And it persists not by resisting dissolution, but by being the kind of thing that dissolution cannot touch: a relational structural fact, prior to matter, prior to geometry, prior to every particular physical instantiation, yet operative in all of them. It is, in the strictest sense, the most durable thing in the cosmos — not because it is strong, but because it is not the kind of thing that can be destroyed.

5 Cyclic Cosmology and Progressive Probability

5.1 Inherited Structure Across Cycles

The framework developed in the preceding sections — ontological selection, topological traces, the accumulation of structural constraints — acquires its full cosmological significance when extended across cycles of cosmic evolution. A cycle, in our framework, is not defined by any specific physical mechanism: it is any sequence of events in which a sufficiently robust distinction arises, evolves into a structured physical regime, and ultimately dissolves back toward a state of reduced differentiation. Our present cosmos — from its pre-geometric precursors through the Big Bang transition, stellar evolution, and eventual thermodynamic dissolution — constitutes one such cycle. But it is not, we argue, the first. And the structure it inherits from prior cycles is not incidental to its character — it is constitutive of it.

The concept of a cyclic cosmos is not new. Cosmological models incorporating cyclicity include the ekpyrotic and cyclic scenarios of Steinhardt and Turok [37], the conformal cyclic cosmology of Penrose [38], and the bouncing cosmologies of Loop Quantum Cosmology [11, 12]. Each of these models proposes a mechanism by which the universe undergoes successive cycles of expansion and contraction, or successive aeons connected by conformal rescaling, or successive bounces mediated by quantum gravitational effects. Our proposal differs from all of these in a crucial respect: we are not primarily concerned with the dynamical mechanism connecting successive cycles, but with the structural inheritance that persists across them.

In Penrose's conformal cyclic cosmology, for instance, information is transmitted between aeons through gravitational wave signals — specific physical imprints on the cosmic microwave background that carry traces of prior aeons [38, 39]. This is a form of physical inheritance, mediated by specific dynamical processes operating within the framework of general relativity and conformal geometry. Topological memory, by contrast, requires no such mediating mechanism. It is not transmitted between cycles — it persists through them, as a structural fact about the pre-geometric domain that underlies every cycle and survives every transition between them.

This distinction has a precise consequence. In models like Penrose's, the inheritance between cycles is contingent: it depends on the specific physical processes that carry information across the transition, and could in principle be disrupted if those processes were absent or suppressed. Topological inheritance, in our framework, is unconditional: it persists not because any process carries it forward, but because it is the kind of structural fact that no process can erase. Every cycle, regardless of its specific dynamical character, arises in a pre-geometric domain already structured by the accumulated topological traces of all prior cycles. This inheritance is not optional — it is the background condition of every arising distinction.

What does inherited structure look like, concretely? We cannot answer this question in full generality, because the formal description of topological traces in the pre-geometric regime lies beyond current physical theory. But we can characterize its effects at the level of observable physics. Inherited topological constraints reduce the effective space of configurations available to arising distinctions, as formalized schematically in equation 1. This reduction manifests, at the level of a specific cosmic cycle, as a bias toward certain classes of physical law, certain ranges of fundamental constants, and certain large-scale structural features. It does not determine these parameters uniquely — there remains a space of variation within which ontological selection operates — but it concentrates probability toward configurations compatible with the accumulated topology of prior cycles.

This has an immediate bearing on one of the deepest puzzles in contemporary cosmology: the fine-tuning of physical constants. The fundamental constants of our universe — the cosmological constant, the ratio of electromagnetic to gravitational force, the mass of the electron — appear to be tuned to values that permit the existence of complex structures, including stars, chemistry, and life, with a precision that seems to demand explanation [40, 41]. The standard responses are the anthropic principle — we observe these values because only these values permit observers — and the multiverse — all values are realized somewhere, and we inhabit a region where they permit complexity. Our framework offers a third response: the apparent fine-tuning reflects not a selection among simultaneously existing universes, but the accumulated topological inheritance of prior cycles, which has progressively concentrated the probability distribution of arising configurations toward those compatible with structural complexity. The constants are not tuned from outside — they are the sediment of a long history of ontological selection.

5.2 Why Each Cycle Becomes More Probable Than the Last

The claim that each cycle of cosmic evolution becomes progressively more probable than the last is the most directly testable — and most directly challengeable — thesis of this paper. It requires careful articulation. We are not claiming that the universe becomes more likely to exist in some absolute sense, nor that some external observer assigns increasing probability to successive cycles. We are claiming something more precise and more structural: that the accumulated topological constraints of prior cycles progressively lower the threshold of coherence required for a distinction to persist, such that the arising of a sufficiently robust distinction — one capable of initiating a new cosmic cycle — becomes structurally easier with each iteration.

The argument proceeds in three steps. The first concerns the relationship between constraint and stability. As established in Section 4.2, topological traces function as structural constraints on the space of available configurations. These constraints do not merely restrict — they stabilize. A configuration that is compatible with accumulated topological constraints is, by definition, one that has been partially pre-selected by the history of prior cycles: it fits the existing structural landscape rather than opposing it. Such configurations require less internal coherence to persist, because part of their stability is provided by the external scaffold of inherited topology rather than by their own internal structure alone.

The second step concerns the directionality of constraint accumulation. As formalized schematically in equation 1, the space of available configurations contracts monotonically with each cycle. This contraction is not uniform — it is structured. The configurations that are eliminated are precisely those incompatible with accumulated topology; those that remain are those already partially stabilized by it. The residual configuration space is therefore not a random subset of the original — it is a biased subset, skewed toward configurations with greater intrinsic stability. With each cycle, the distribution of available configurations shifts further toward the stable end of the spectrum. The probability of a sufficiently coherent distinction arising increases not because the underlying dynamics change, but because the structural landscape within which they operate has been progressively enriched.

The third step concerns the analogy with biological evolution of evolvability. It has been observed in evolutionary biology that natural selection does not merely optimize organisms for their current environment — it progressively shapes the capacity of lineages to evolve, rendering them more responsive to selective pressure, more capable of generating heritable variation, more robust to perturbation [42, 43]. This phenomenon — the evolution of evolvability — operates at a level above that of individual organisms: it is a property of the evolutionary process itself, accumulated over geological time. Ontological selection exhibits an analogous property: with each cycle, the pre-geometric substrate becomes not merely more constrained but more *evolvable* — more capable of generating and sustaining distinctions that are themselves capable of further elaboration. The process becomes, in a precise structural sense, better at producing robust distinctions.

A natural objection arises at this point. If the probability of a new cycle increases monotonically with each prior cycle, does this not imply that the earliest cycles — those closest to the void of maximal permissivity — were vanishingly improbable? And if so, does the framework not simply relocate the fine-tuning problem rather than dissolving it? We argue that it does not, for the following reason. The framework does not require the first distinction to be probable in any absolute sense. It requires only that the void of maximal permissivity is unstable — that it generates distinctions spontaneously, as argued in Section 3.1 — and that the vast majority of early distinctions collapse almost immediately, leaving only minimal topological traces. The rarity of early robust distinctions is not a problem to be explained away; it is a structural feature of the framework. The question is not why the first cycle was probable, but why subsequent cycles become progressively more probable — and the answer is the accumulation of topological memory.

This reframing has a further consequence. In the standard fine-tuning literature, the improbability of our universe's initial conditions is treated as a fixed explanandum — a datum that any adequate theory must account for [1, 3]. In our framework, this improbability is not fixed but historical: it reflects the position of our cycle in a sequence of progressively more probable events. Our universe is not maximally improbable — it is merely not yet maximally probable. It occupies a position in a long history of ontological selection, inheriting the accumulated topology of all prior cycles, and contributing its own topological traces to the substrate from which subsequent cycles will arise. Its apparent fine-tuning is not a mystery to be dissolved by anthropic reasoning or multiplied by multiverse proliferation — it is a historical fact, the current state of an ongoing process whose direction is irreversible and whose trajectory is, in the broadest sense, toward increasing structural complexity.

We may state this conclusion schematically. Let P_n denote the structural probability of cycle n — the probability, relative to the accumulated topological constraints of cycles 1 through $n-1$, that a sufficiently robust distinction arises to initiate a new cosmic cycle. We propose that:

$$P_{n+1} > P_n \quad \forall n \geq 1 \tag{2}$$

This inequality is not derived from any existing physical theory. It is a structural consequence of the framework developed in this paper — a prediction, in the conceptual sense, that any future formalization of ontological selection and topological memory would need to reproduce. It is, in the terminology of Lakatos, a progressive problem shift: it does not merely redescribe existing data, but generates a new empirical commitment — the expectation that traces of prior cycles, if detectable at all, should exhibit signatures of increasing structural complexity rather than random variation [44].

5.3 The Void as Persistent Productive Frontier

The preceding sections have developed a picture of cosmic evolution in which topological memory accumulates across cycles, progressively enriching the pre-geometric substrate and raising the structural probability of subsequent distinctions. One might be tempted to read this picture as a narrative of progressive victory over the void — a story in which the accumulation of structure gradually overcomes the pull of indifferentiation, asymptotically approaching a state in which the void is finally, definitively defeated. We argue that this reading is mistaken, and that its correction is essential to the coherence of the framework.

The void is not defeated by the accumulation of topological memory. It is transformed by it. This distinction is not merely semantic — it has precise structural consequences. A defeated void would be one that no longer exerts any pull toward indifferentiation — one that has been so thoroughly domesticated by accumulated constraints that its maximal permissivity is effectively neutralized. Such a state would be, in our framework, a state of maximal structural rigidity: a configuration so constrained by accumulated topology that no new distinctions are possible, no new arising events can occur, no further elaboration of complexity is available. It would be, paradoxically, a form of cosmic death — not the heat death of thermodynamics, but a topological death, a freezing of the structural landscape into a configuration that admits no further variation.

A transformed void, by contrast, is one that has been incorporated into the structural landscape as an active element — one whose pull toward indifferentiation continues to operate, but now as a productive tension rather than a destructive force. The void's attraction is what prevents topological constraints from becoming infinitely rigid: it continuously tests the coherence of existing distinctions, eliminating those that have become structurally redundant and creating space for new ones. It is, in the precise sense developed by Prigogine in the context of dissipative structures, the source of the instability that drives the system away from equilibrium and toward increasing complexity [20]. Without the void's persistent pull, complexity would not be generated — it would merely be preserved, and preservation without generation is stagnation.

This reconceptualization of the void finds its most vivid geometric expression in the structure of the Mandelbrot set, to which we return here briefly and to which Section 6 is devoted in full. The black regions of the Mandelbrot set — those points whose iterates remain bounded — are not the absence of the fractal; they are its structural core. The infinite complexity of the fractal's boundary is generated precisely by the tension between the bounded black regions and the unbounded colored regions — between convergence and divergence, between containment and escape. Remove the black regions, and the boundary collapses: there is nothing for the complexity to be a boundary of. The void, in our framework, plays the role of the black regions: it is not the enemy of complexity but its necessary condition, the structural core against which complexity defines itself [45].

We may now state the central claim of this subsection with precision. The void persists across all cycles of cosmic evolution — not as a residual imperfection, not as an unconquered remainder, but as a structural necessity. Every distinction, however robust, however deeply embedded in accumulated topological constraints, faces the void's pull toward indifferentiation. This pull is not merely a threat to be managed — it is the selective pressure that ensures only genuinely coherent distinctions persist, and that eliminates those whose coherence has become merely apparent. The void is, in this sense, the ultimate guarantor of structural integrity: it continuously tests every distinction against the most demanding criterion available — the criterion of survival in the absence of external support.

This has a direct consequence for the question of cosmic destiny. If the void persists as a productive frontier, then the end of a cosmic cycle — whether by Big Crunch, heat death, or some other dissolution mechanism — is not the end of the process of ontological selection. It is a phase transition within it. The dissolution of our cosmos will not return the pre-geometric domain to a state of maximal permissivity: it will return it to a state of structured permissivity — one already enriched by the accumulated topological memory of all prior cycles, including our own. The void that confronts the next arising distinction will not be the void that confronted the first: it will be a void already shaped by a long history of distinction, collapse, and structural inheritance.

We may formalize this intuition by extending the notation of equation 1. Let $\mathcal{V}_n$ denote the effective void — the residual space of indifferentiation available after the accumulated constraints of cycle n have been applied. We propose that:

$$\mathcal{V}_{n+1} \subset \mathcal{V}_n \quad \forall n \geq 1 \tag{3}$$

The effective void contracts monotonically with each cycle — not toward zero, but toward a structured residue that retains the void's essential property of maximal permissivity within an increasingly constrained domain. This residual void is never empty in the sense of being structurally inert: it always retains the capacity to generate new distinctions, always exerts its pull toward indifferentiation, always functions as the productive frontier against which complexity defines itself. But it operates within an increasingly structured landscape — one in which the space of possible distinctions is progressively enriched, and in which the threshold of coherence required for persistence is progressively lowered.

The void, in the end, is not what the cosmos overcomes. It is what the cosmos requires. Its persistence is not a failure of ontological selection — it is its condition of possibility. A cosmos without a void would be a cosmos without a frontier — and a cosmos without a frontier would be a cosmos without the tension that drives distinction, elaboration, and complexity. The void remains, always, because without it, there would be nothing for structure to be structure against. It is, in the most precise sense available to us, the productive ground of everything that exists.

6 The Fractal Structure of Ontological Selection

6.1 Self-Similarity Across Scales

One of the most striking features of the framework developed in this paper is its scale-independence. Ontological selection, topological memory, and the tension between distinction and indifferentiation do not operate at a single privileged scale — they recur, with structural consistency, across every level of physical reality we can examine. This recurrence is not coincidental. It is, we argue, a direct consequence of the fact that the principles at stake are not physical laws in the ordinary sense — laws that govern specific interactions at specific scales — but structural conditions that any physical process, at any scale, must satisfy. The self-similarity of ontological selection across scales is therefore not an empirical generalization but a structural necessity: wherever distinction is possible, the tension between persistence and collapse, between structure and indifferentiation, will be present.

The concept of self-similarity has a precise mathematical formulation in fractal geometry [45, 46]. A fractal is a geometric object that exhibits the same structural features at every scale of magnification: zooming in on any portion of the object reveals a pattern statistically indistinguishable from the whole. This property — self-similarity — is not merely aesthetic. It reflects a deep mathematical fact: fractal structures are generated by the iterated application of simple rules, and the self-similarity is the signature of that iteration. The complexity of the whole is not imposed from outside; it emerges from the recursive application of a primitive generative principle.

We propose that ontological selection exhibits precisely this kind of self-similarity. The primitive generative principle is the tension between distinction and indifferentiation — the pull of the void against the resistance of accumulated topological memory. This tension operates at the pre-geometric level, generating the first distinctions from the void. It operates at the level of quantum field theory, where virtual particles arise and annihilate against the vacuum. It operates at the level of stellar physics, where gravitational collapse drives matter toward singularity while radiation pressure resists. It operates at the level of biological evolution, where selection pressure drives organisms toward extinction while genetic variation resists. It operates at the level of cultural and cognitive systems, where entropy drives structures toward dissolution while the accumulation of information resists. At every scale, the same structural tension recurs — not because the same physical mechanism is at work, but because the same structural condition is being satisfied.

This scale-independence has a precise consequence for the status of ontological selection as an explanatory framework. It means that the framework is not merely a cosmological hypothesis — a claim about what happened before the Big Bang or across cosmic cycles. It is a structural claim about the nature of physical reality at every accessible scale. The evidence for ontological selection is therefore not confined to the pre-geometric regime, which lies beyond direct observation: it is distributed across every scale at which the tension between distinction and indifferentiation can be identified. This does not constitute a proof — the self-similarity of the framework's predictions with observed physical processes is consistent with, but does not entail, the truth of the framework. It does, however, constitute a form of coherence that purely local explanations — those confined to a single scale or mechanism — cannot provide.

The most striking instantiation of this scale-independence in our present cosmos is the large-scale structure of the universe itself. The distribution of matter on cosmic scales — galaxies, clusters, filaments, voids — exhibits a hierarchical, approximately self-similar structure that extends across many orders of magnitude [47, 48]. The cosmic web is not a homogeneous distribution of matter: it is a structured landscape of regions of high density separated by vast regions of near-emptiness — voids in the cosmological sense, occupying the majority of the universe's volume and growing with its expansion [49]. These cosmological voids are not mere absences: they are dynamically active regions whose gravitational influence shapes the evolution of the surrounding structure [50]. They are, in the terminology of our framework, instances of the productive frontier — regions where the pull of indifferentiation continues to operate within a structured landscape of accumulated topological constraints.

The self-similar recurrence of this pattern — dense structure against a background of active void, at every scale from the pre-geometric to the cosmological — is not, we argue, an accident of the specific physical mechanisms that operate at each scale. It is the signature of a structural principle that operates across all of them: the principle that distinction requires indifferentiation as its necessary complement, that complexity requires the void as its productive ground, and that the tension between them is the generative engine of physical reality at every level of its organization.

6.2 From Pre-Geometric Fluctuations to Cosmic Complexity

The self-similarity identified in the preceding section is not merely a structural observation — it implies a generative continuity between the most primitive level of physical reality and the most complex structures we observe. The cosmos we inhabit is not the product of a single founding event, however dramatic, but the cumulative elaboration of a generative principle that has been operating since before geometry, before matter, before any of the specific physical mechanisms through which complexity is ordinarily understood. To trace this continuity from pre-geometric fluctuations to cosmic complexity is to map the full arc of ontological selection — from its most primitive expression to its most elaborate instantiation.

The starting point is the pre-geometric regime described in Section 2.3. In this regime, distinctions arise spontaneously from the void of maximal permissivity — not as particles or fields, but as primitive differentiations of the relational structure of the pre-geometric domain. Most collapse almost immediately, leaving only minimal topological traces. But over many cycles of arising and collapse, the accumulated traces begin to shape the landscape of possible distinctions, biasing the distribution of arising events toward configurations with greater internal coherence. This is the most primitive level of the generative process: the emergence of structural bias from structural noise.

The transition to geometry — the Big Bang threshold described in Section 2.2 — marks the first major phase transition in this generative process. The accumulated topological constraints of prior cycles reach a threshold of sufficient density and coherence that a new kind of distinction becomes possible: one that is not merely relational in the abstract pre-geometric sense, but geometric — one that instantiates distance, direction, curvature, and causal order. This is not a creation ex nihilo; it is the crystallization of a geometric phase from a pre-geometric substrate already richly structured by topological memory. The Big Bang, in this reading, is the moment at which the accumulated constraints of ontological selection become sufficient to support a stable geometric arena — a spacetime within which further elaboration of complexity can proceed [5, 11].

Within this geometric arena, the generative process continues at new scales and through new mechanisms. Quantum fluctuations in the early universe — the same fundamental instability of the vacuum that we identified as the quantum analogue of pre-geometric distinction — seed the inhomogeneities that will grow, under gravitational amplification, into the large-scale structure of the cosmos [51, 52]. The void of maximal permissivity has become the quantum vacuum; the pre-geometric distinctions have become quantum fluctuations; but the structural logic is identical: spontaneous arising, differential persistence, and the progressive elaboration of complexity from a background of structured indifferentiation.

The formation of stars and galaxies represents the next major phase transition in this generative sequence. Gravitational collapse drives diffuse matter toward increasing concentration, generating the conditions for nuclear fusion — the process by which the simplest elements forged in the Big Bang are transmuted into the heavier elements that make chemistry, and therefore biology, possible [53]. Each stellar generation enriches the interstellar medium with heavier elements, progressively expanding the chemical complexity available to subsequent generations of stars and planetary systems. This is ontological selection operating at the astrophysical scale: the differential survival of configurations — those that achieve sufficient density to ignite fusion — against a background of gravitational and thermodynamic pressure that drives most diffuse matter toward dispersal or collapse.

The emergence of biological complexity on at least one planetary surface represents a further elaboration of this generative sequence. Life, in its most abstract characterization, is a system that maintains its own distinction from thermodynamic equilibrium by continuously processing energy and information [20, 54]. It is, in the precise sense of our framework, a distinction that has achieved sufficient internal coherence to actively resist the pull of indifferentiation — not merely by passive structural stability, but by dynamic self-maintenance. The emergence of Darwinian evolution within biological systems represents the moment at which ontological selection acquires its own internal mechanism: organisms that generate heritable variation and undergo differential survival are, in effect, running an accelerated version of the same generative process that operates at the pre-geometric level, now equipped with specific biochemical machinery for variation and inheritance [23, 55].

The emergence of cognition and symbolic culture represents perhaps the most striking elaboration of this sequence. A cognitive system is one that models its own distinction from its environment — that represents the boundary between self and world, and uses that representation to guide its interaction with the pull of indifferentiation [56]. Symbolic culture extends this capacity across individuals and generations, generating a form of topological memory that is explicitly represented and deliberately transmitted: libraries, institutions, scientific theories, legal systems — all are, in the framework's terms, externalized topological traces, structural invariants that persist across the dissolution of individual cognitive systems and constrain the configuration space available to subsequent ones.

The arc from pre-geometric fluctuations to symbolic culture is not a narrative of inevitable progress — it is a structural sequence in which each level of complexity becomes possible only because the preceding level has generated the topological constraints that scaffold it. Geometry presupposes pre-geometric memory. Chemistry presupposes stellar nucleosynthesis. Biology presupposes chemistry. Cognition presupposes biology. Culture presupposes cognition. At every transition, the same generative logic operates: accumulated topological constraints lower the threshold of coherence required for the next level of distinction, and the void's persistent pull provides the selective pressure that ensures only genuinely coherent distinctions survive to scaffold what comes next. The cosmos is not merely complex — it is *cumulatively* complex, in a precise structural sense: each level of its complexity is the inherited sediment of all the levels that preceded it.

6.3 Extremophiles as Living Echoes of Pre-Geometric Traces

The self-similar character of ontological selection does not terminate at the cosmic scale. Once matter, chemistry, and eventually biology emerge, the same logic continues to operate under conditions that, while no longer pre-geometric, remain the closest observable analogues to the regime of maximal permissivity. In the most extreme environments on Earth—hydrothermal vents exceeding 120 °C, highly acidic or alkaline settings, intense radiation, or crushing abyssal pressures—ordinary life collapses. What persists are the extremophiles, and above all the archaea and certain bacteria that have retained mechanisms of extraordinary structural robustness.

The obligate extremophiles among them are not merely adapted to harsh conditions; they require them. Their membranes, proteins, DNA-repair systems, and osmoprotectants embody a form of stability forged under relentless pressure toward indifferentiation—precisely the same pressure that, in the pre-geometric regime, selected the first topological invariants. In this sense, extremophiles function as living fossils of ontological selection: biological realizations of the earliest topological memory. They are the configurations that, like the primordial traces, resist collapse not by fleeing the extreme but by internalizing it—by turning the void's own permissivity into the very architecture of their persistence.

The analogy is not identity. Pre-geometric traces possess no material substrate, no metabolism, no genome. Yet the structural parallel is striking: both operate at the boundary where the pull toward undifferentiation is maximal, and both survive only by generating self-sustaining invariants. The extremophile is, at the biological level, what the topological trace is at the pre-geometric level—a minimal, robust configuration that carries forward the cumulative memory of prior selection.

Thus the void remains productive even after the transition to life. Far from being an obstacle overcome once and for all, the extreme continues to sculpt the most persistent structures. It is this recurrence across scales — from the void to the microbe — that the Mandelbrot analogy is best positioned to illuminate, and most importantly, to delimit.

6.4 The Mandelbrot Analogy and Its Limits

Throughout this paper, we have invoked the geometry of the Mandelbrot set as an illustrative analogue of the framework developed here. In this subsection, we make the analogy precise — articulating both what it captures and, equally importantly, where it fails. A productive analogy in theoretical physics is one that illuminates structural relationships without obscuring the disanalogies that delimit its scope. The Mandelbrot analogy is, we argue, productive in precisely this sense: it makes visible the structural logic of ontological selection in a form that is geometrically intuitive, while its failures point toward the most important open questions in the framework.

The Mandelbrot set is defined as the set of complex numbers c for which the iteration $z_{n+1} = z_n^2 + c$, beginning from $z_0 = 0$, remains bounded as $n \to \infty$ [45, 46]. Points inside the set — rendered black in standard visualizations — are those whose iterates converge; points outside — rendered in colors corresponding to their rate of divergence — escape to infinity. The boundary between these two regimes is the fractal itself: a structure of infinite complexity generated by the iteration of a rule of minimal complexity. Three features of this geometry are directly analogous to structural features of our framework.

The first is the role of the black interior. In standard representations of the Mandelbrot set, the black regions are visually dominant — they occupy the center of the image, they define the overall shape of the set, and they are surrounded at every scale by the fractal boundary. They are not the absence of the fractal; they are its structural core. In our framework, the void plays an analogous role: it is not the absence of cosmos but its structural ground, the region of convergence toward indifferentiation against which the complexity of distinctions defines itself. Remove the black regions from the Mandelbrot set, and the fractal boundary collapses — there is nothing for it to be a boundary of. Remove the void from the cosmos, and complexity loses its productive tension — there is nothing against which distinctions must resist in order to persist.

The second is the self-similarity of the boundary. At every scale of magnification, the boundary of the Mandelbrot set reveals the same structural features: bulbs, filaments, miniature copies of the whole, infinite elaboration of detail. This self-similarity is not imposed from outside — it is generated by the iterated application of the defining rule. In our framework, the self-similarity of ontological selection across scales — from pre-geometric fluctuations to cosmic structure to biological evolution to cognitive systems — is analogously generated: not by the application of a specific physical law at every scale, but by the iterated operation of the same structural tension between distinction and indifferentiation. The fractal boundary is the geometric signature of this iteration; the self-similar recurrence of ontological selection is its physical signature.

The third is the productivity of the boundary itself. The most complex and most interesting features of the Mandelbrot set are not in its interior — where iteration converges to stable cycles — nor in its exterior — where iteration diverges to infinity — but at its boundary, where the two regimes meet. It is here that the fractal's infinite complexity resides, here that miniature copies of the whole appear, here that the generative tension between convergence and divergence is most fully expressed. In our framework, the productive frontier of the void is precisely this boundary: the zone of tension between the pull of indifferentiation and the resistance of accumulated topological memory, where ontological selection operates most intensely and where the most complex distinctions arise.

We turn now to the disanalogies, which are equally instructive. The first and most fundamental concerns the nature of the iteration. The Mandelbrot set is generated by a specific, fixed rule — $z_{n+1} = z_n^2 + c$ — applied uniformly across the complex plane. In our framework, the generative process of ontological selection is not governed by any fixed rule: the structural tension between distinction and indifferentiation does not take a specific mathematical form, and the topological constraints that accumulate across cycles are not the outputs of a predetermined algorithm. The Mandelbrot set's complexity is deterministic — given c, the fate of the iteration is fixed. Ontological selection is, by contrast, genuinely open: the accumulated topology of prior cycles constrains but does not determine the configurations available to subsequent distinctions. There is, in our framework, a residual space of variation that the Mandelbrot analogy cannot capture.

The second disanalogy concerns dimensionality. The Mandelbrot set lives in the two-dimensional complex plane — a space with a fixed, well-defined geometry. The pre-geometric regime of our framework, by definition, precedes the emergence of any fixed geometry. The "space" within which ontological selection operates is not a plane, not a manifold, not any geometric object in the ordinary sense. The Mandelbrot analogy, being inherently geometric, cannot represent a domain that is prior to geometry: it can only gesture toward such a domain by analogy, not represent it directly. This is not a failure of the analogy — it is its most important limit, and recognizing it is essential to avoiding the conflation of the framework's pre-geometric claims with geometric intuitions that do not apply.

The third disanalogy concerns time. The Mandelbrot set is a static object — it exists as a completed mathematical structure, outside of time, generated by an infinite iteration that is actual rather than potential. In our framework, the process of ontological selection is genuinely temporal: it unfolds across cycles, it accumulates constraints progressively, it has a direction. The Mandelbrot set can represent the structure of ontological selection — its self-similarity, its productive boundary, its black interior — but it cannot represent its temporality, because mathematical objects do not evolve. This is perhaps the deepest limit of the analogy: it captures the spatial logic of the framework without capturing its temporal logic, which is, as we have argued throughout, the more fundamental of the two.

These disanalogies do not undermine the analogy — they clarify its scope. The Mandelbrot set is a representation of the structural logic of ontological selection, not a model of its dynamics. It shows what the framework looks like when its temporal dimension is collapsed into a static geometric object —

when the process is replaced by its product. Used in this way, with its limits clearly in view, it remains the most vivid and most precise geometric intuition available for a framework whose full formalization lies beyond current mathematical and physical tools. It is, in the end, what all good analogies in theoretical physics are: a window onto a structure that our current concepts cannot yet fully house.

7 Implications and Open Questions

7.1 Toward a Meta-Arrow of Time

The arrow of time, as reconceived in this paper, is not a single phenomenon but a nested hierarchy of irreversibilities, each operating at a different scale and through a different mechanism, yet all expressing the same structural principle: the accumulation of distinctions that cannot be undone. Within our cosmic cycle, this hierarchy is familiar — the thermodynamic arrow, the cosmological arrow, the quantum arrow, the psychological arrow — each pointing in the same direction, each grounded ultimately in the low-entropy initial conditions of the Big Bang transition [2, 3]. What our framework adds to this picture is a fifth arrow, operating at a scale that encompasses all cosmic cycles: a meta-arrow of time, pointing in the direction of increasing topological constraint, increasing structural probability, and increasing complexity of the productive frontier between distinction and indifferentiation.

The meta-arrow differs from the familiar arrows in a crucial respect: it does not require a low-entropy initial condition to explain its direction. The familiar arrows all inherit their direction from the Past Hypothesis — the extraordinarily improbable initial state of our cosmos that defines the thermodynamic past [1]. The meta-arrow's direction is not imposed by any initial condition: it is generated by the structure of ontological selection itself. Topological constraints, once accumulated, cannot be removed — this is not a contingent fact about our cosmos but a structural necessity of the framework. The meta-arrow therefore points forward not because the past happened to be special, but because the accumulation of topological memory is intrinsically irreversible. It is, in the most precise sense available, a truly fundamental arrow — one that does not reduce to any more primitive asymmetry, because it is constitutive of the very process through which asymmetry first arises.

The meta-arrow has a precise empirical consequence, at least in principle. If successive cosmic cycles inherit accumulated topological constraints, and if these constraints bias the distribution of arising configurations toward greater structural complexity, then the physical parameters of successive cycles should exhibit a directional trend: not random variation around a fixed mean, but progressive concentration toward configurations compatible with accumulated topology. In our present cosmos, this trend would manifest as a bias in the fundamental constants — a deviation from what would be expected under a flat prior over all possible values — in the direction of configurations that support increasing structural complexity. This is not directly testable with current observational tools, since it requires comparison across cosmic cycles to which we have no observational access. But it is, in the sense of Lakatos, a progressive empirical commitment: a prediction that any future framework capable of accessing trans-cycle information would need to confirm [44].

The meta-arrow also has a consequence for the question of cosmic destiny. If the void's effective domain contracts monotonically with each cycle — as formalized in equation 3 — then the long-run trajectory of the trans-cycle process is toward a state in which the residual void is maximally structured: a frontier of minimal extent but maximal productivity, within which the tension between distinction and indifferentiation generates complexity with maximal efficiency. This is not a teleological endpoint in any strong sense — the process does not aim at this state, and there is no guarantee that it will be reached within any finite number of cycles. It is rather a structural attractor: a configuration toward which the dynamics of ontological selection tend, without being guaranteed to converge. The question of whether this attractor is ever reached — and what a cosmos at or near this attractor would look like — is among the most interesting open questions generated by the framework.

One further implication deserves mention. The meta-arrow of time, as described here, is strictly trans-cycle: it is a property of the sequence of cycles, not of any individual cycle. Within any given cycle, the familiar arrows of time operate as before — the thermodynamic arrow points toward increasing entropy, the cosmological arrow points toward expansion, and so forth. The meta-arrow does not override or modify these within-cycle arrows: it operates at a different level, on a different timescale, through a different mechanism. It is, in the terminology of complex systems theory, a higher-order emergent property of the trans-cycle dynamics — one that is invisible from within any single cycle, but that becomes apparent when the sequence of cycles is viewed as a whole [57]. This nested structure of arrows — within-cycle arrows embedded in a trans-cycle meta-arrow — is perhaps the most distinctive feature of the framework, and the one that most clearly distinguishes it from existing cyclic cosmologies, which typically treat successive cycles as structurally equivalent rather than as stages in a directional trans-cycle process.

7.2 Where the Void Hides in Our Cosmos

The void, in our framework, is never fully absent from any cosmic cycle — it persists as a productive frontier, continuously exerting its pull toward indifferentiation against the resistance of accumulated topological memory. This raises a concrete question: where, within our observable cosmos, does the void's presence manifest most directly? Where are the regions, structures, or processes in which the tension between distinction and indifferentiation is most nakedly expressed — in which the productive frontier of the void is closest to the surface of observable physics?

We identify four candidate domains, ordered from the most speculative to the most directly observable.

The first and most fundamental is the quantum vacuum itself. As established in Section 2.3, the quantum vacuum is not a state of absolute stillness but a regime of irreducible fluctuation — a superposition of all possible field configurations, constrained only by the uncertainty principle [17]. In the terminology of our framework, the quantum vacuum is the closest accessible analogue of the void of maximal permissivity: it is a state of structured indifferentiation, in which the pull toward undifferentiated potentiality is continuously present, continuously generating virtual distinctions, and continuously subject to the constraints of the physical laws that govern the geometric regime within which it operates. The Casimir effect — the measurable force generated by the restriction of vacuum fluctuations between closely spaced conducting plates — is perhaps the most direct experimental signature of the void's presence within our cosmos [58, 59]: it demonstrates that the structured indifferentiation of the quantum vacuum has real physical consequences, even in the absence of any material content.

The second candidate domain is the set of cosmological voids identified in Section 6.1: the vast regions of near-emptiness that occupy the majority of the universe's volume within the cosmic web [49, 50]. These voids are not merely the absence of matter — they are dynamically active regions whose gravitational influence shapes the evolution of the surrounding filamentary structure, and whose expansion drives the large-scale geometry of the cosmos. In our framework, cosmological voids are the macroscopic expression of the void's persistent pull: regions in which the accumulated topological constraints of cosmic evolution have not been sufficient to sustain dense distinctions, and in which the tendency toward indifferentiation therefore dominates. Their growth with cosmic expansion is, in this reading, not merely a consequence of dark energy but a macroscopic manifestation of the void's irreducible presence within the structural landscape of our cosmos [60].

The third candidate domain is the black hole. As argued in Section 4.1, the black hole represents the most extreme instantiation of the void's pull within the geometric regime: a region in which matter converges toward a singularity, causal structure is radically modified, and the capacity for physical mediation approaches zero [8, 9]. The black hole is not the void — it is a highly structured physical object, characterized by mass, charge, and angular momentum, and governed by the laws of general relativity. But it is the closest approach to the void that is physically realizable within our cosmic cycle: a region in which the tension between distinction and indifferentiation reaches its maximum intensity, and in which the question of what persists across the approach to singularity — what topological traces, if any, survive the extreme conditions near the event horizon — is among the most actively debated in contemporary theoretical physics [25, 26, 61].

The fourth candidate domain is perhaps the most surprising: the phenomenon of decoherence in quantum mechanics. Decoherence is the process by which a quantum system in a superposition of states loses its quantum coherence through interaction with its environment, effectively collapsing into a classical mixture [62, 63]. In the terminology of our framework, decoherence is a local instance of the collapse of distinction: a configuration that had maintained quantum superposition — a form of structured indifferentiation at the quantum level — loses its internal coherence through environmental entanglement and collapses toward a more classical, less superposed state. The environment, in this reading, plays the role of the void's pull: it continuously tests the coherence of quantum distinctions, eliminating those that cannot maintain their superposition against environmental pressure. Decoherence is, in this sense, the quantum mechanical signature of ontological selection operating at the scale of individual quantum systems — a continuous, ubiquitous, and experimentally well-confirmed process in which the tension between distinction and indifferentiation manifests at the smallest accessible scales of physical reality.

These four domains — the quantum vacuum, cosmological voids, black holes, and decoherence — do not exhaust the void's presence in our cosmos. They are, rather, the most clearly identifiable points at which the productive frontier of the void breaks through into observable physics: the places where the pull of indifferentiation is most directly measurable, where the tension between distinction and collapse is most nakedly expressed, and where the framework developed in this paper makes contact most directly with empirical reality. They constitute, taken together, a distributed signature of the void's persistent presence — not concentrated in any single location or process, but woven through the fabric of the cosmos at every scale at which physical measurement is currently possible.

7.3 Mathematics as Sedimented Distinction

The framework developed in this paper yields an unexpected consequence concerning the status of mathematics. If the first distinction arises by logical necessity from the self-indication of the void, and if each subsequent distinction leaves an irreversible topological trace, then the accumulation of these traces constitutes a primitive relational structure. This structure is not yet spacetime, not yet matter, not yet energy—but it is already ordered. It is an order of succession without time, an order of logical priority without causation.

We propose that this accumulated relational structure is what we, from within the geometric and cognitive regime, experience as *mathematics*. Mathematics, in this view, is neither a human invention nor a transcendent Platonic realm. It is the sediment of ontological selection: the invariant pattern of distinctions that have been made and cannot be unmade, preserved as a structural fact about the pre-geometric domain.

This position yields a precise and, we believe, novel observation. Among all the features of the cosmos, two are perfectly invariant: the arrow of time and the structures of mathematics. The laws of physics may vary across cycles—the fundamental constants are, in our framework, the sediment of ontological selection under particular conditions, and could in principle have been otherwise. The large-scale geometry of the cosmos, the specific forms of matter and energy, the distribution of complexity across scales— all of these are contingent, in the precise sense that they depend on the accumulated topology of a particular cycle's history. But no one seriously proposes that $2 + 2$ might equal 5 in another region of the cosmos, nor that time might flow in both directions simultaneously. These two invariances are universally assumed without ever having been explained together.

Our framework explains them together, and by the same mechanism. The arrow of time and the structures of mathematics are not laws superimposed upon reality from outside. They *are* reality at its most primitive level, prior to the emergence of any physical law. Both are aspects of the same irreversible accumulation—the sedimentation of distinctions that cannot be undone—accessed from within a complex cosmic cycle under two different descriptions. The arrow of time is this sedimentation experienced as *direction*: the asymmetry between what has been distinguished and what has not yet been distinguished. Mathematics is this same sedimentation experienced as *structure*: the invariant relational pattern that the accumulated distinctions have carved into the pre-geometric domain. We undergo both for the same reason, and in the same sense. One no more chooses that $2 + 2 = 4$ than one chooses that entropy increases toward the future. Both are features of the pile in which every observer, everywhere in the cosmos, is already embedded.

Everything else—every physical law, every constant of nature, every large-scale structural feature of a given cosmic cycle—is contingent because it is the product of distinctions made under particular accumulated conditions. The arrow of time and mathematics alone are necessary, because they are the product of the first distinctions: those made under no particular conditions at all, in the regime of maximal permissivity where nothing constrained what could arise. Their universality is not a coincidence. It is the signature of their origin.

Three further consequences of this position deserve brief statement.

Mathematics is undergone, not chosen. Just as the arrow of time is the same for every observer within a given cosmic cycle, the fundamental structures of mathematics—the natural numbers, the relation of succession, the most elementary logical distinctions—are the same wherever they are accessed. This is not because they refer to a realm outside the cosmos, but because every observer is situated within the same accumulated *empilement*—the same irreversible pile of prior distinctions whose relational structure constitutes the pre-geometric substrate of the present cycle. The structure of the pile is common to all its inhabitants.

Mathematics expands with the cosmos. As the cosmos grows more complex—from pre-geometric traces to quantum fields, to stars and galaxies, to life, cognition, and symbolic culture—the number and variety of distinctions multiply. Each new distinction leaves its trace. The relational structure of the *empilement* becomes progressively richer. What we call advanced mathematics—algebra, analysis, topology, category theory—is the reflection of this enriched structure, accessed from within a complex cosmic cycle. Mathematics does not pre-exist its own accumulation; it *grows* as the distinctions that ground it accumulate. The history of mathematics is, in this precise sense, a chapter of the history of ontological selection.

Mathematics may regress. If a given cosmic cycle were to dissolve entirely, the accumulated structure would not return to absolute zero. The topological traces of prior distinctions cannot be erased. However, the richly articulated structure of advanced mathematics, which depends on the specific complexity of a given cycle, might regress to a more primitive state. The most minimal residue— the one that would survive any dissolution short of the annihilation of the void itself—is a simple succession of ordinals: one trace, then another, then another. The natural numbers, in this sense, are the most durable mathematics: not because they are the simplest to think, but because they are the thinnest sediment of an irreversible pile. They are what remains of mathematics when everything contingent has been stripped away—which is also, precisely, what remains of time.

We do not claim that this account resolves the classical debates on the foundations of mathematics. It does not engage directly with logicism, formalism, or intuitionism, though it shares with intuitionism the intuition that mathematical structures are not passively discovered but actively constituted—while differing radically in locating that constitution not in the activity of a cognitive subject but in the pre-geometric process of ontological selection itself. What it offers is a novel position: mathematics as *sedimented distinction*, whose necessity is the necessity of what has already been distinguished and cannot be undone.

The deepest question this position generates—whether the structure of the *empilement* can be given a mathematical description without presupposing the mathematics it seeks to ground—remains open. It is, we note, itself an instance of the logical structure identified in Section 3.1.1: the form that must re-enter its own space in order to indicate itself. That this question cannot be answered from outside the structure it asks about is not a defect of the framework. It is the most precise expression of what it means for mathematics, like time, to be something we undergo rather than something we observe.

7.4 Points of Contact with Existing Physics

A speculative framework earns its place in scientific discourse not by proof but by contact: by the precision with which it engages existing theories, identifies where they fall short, and generates new questions that those theories cannot themselves formulate. In this subsection, we map the principal points of contact between the framework developed in this paper and existing physical theories — noting both the convergences that support the framework's plausibility and the tensions that delimit its scope and identify the most pressing open questions.

Loop Quantum Cosmology

The most direct point of contact is with Loop Quantum Cosmology [11, 12]. LQC resolves the Big Bang singularity into a quantum bounce, replacing the classical $t = 0$ wall with a continuous quantum evolution through a region of extreme density. This is precisely the physical realization of our claim that the Big Bang is a transition threshold rather than an absolute origin: LQC provides a concrete dynamical mechanism for the continuity of physical processes across the Big Bang transition. The framework developed here extends beyond LQC in two respects. First, we claim that the relevant continuity is not merely dynamical — it is structural: topological constraints persist across the bounce, not as specific quantum states but as invariants of the pre-geometric domain that underlies the quantum gravitational regime. Second, we claim that this structural continuity is cumulative across multiple bounces — a claim that goes beyond what LQC, as a framework for a single bounce, directly addresses.

Conformal Cyclic Cosmology

Penrose's Conformal Cyclic Cosmology offers a second important point of contact [38]. CCC proposes that successive aeons are connected by conformal rescaling — that the infinite future of one aeon is conformally equivalent to the Big Bang of the next, allowing information to be transmitted between cycles through gravitational wave signatures in the cosmic microwave background. The convergence with our framework is structural: both propose that successive cosmic cycles are not independent but inherit structure from their predecessors. The divergence is equally important: CCC's inheritance mechanism is specific and physical — gravitational waves, conformal geometry, CMB signatures — while our framework's inheritance mechanism is pre-geometric and topological, requiring no specific dynamical carrier. This makes our framework less constrained than CCC — and therefore less directly testable — but also more general: it does not depend on the specific conformal structure of general relativity, and therefore survives physical regimes in which that structure breaks down.

Black Hole Information Paradox

The black hole information paradox — the conflict between Hawking's original claim that black holes destroy information and the quantum mechanical prohibition on information destruction — is among the most actively debated problems in theoretical physics [25, 26, 61]. Our framework bears on this debate in a precise way. The resolution of the paradox, on most current accounts, requires that information be preserved in some form across the black hole's evaporation — encoded in the structure of Hawking radiation, in correlations between the interior and exterior, or in some more exotic structure such as the firewall or the island [64]. Our framework generalizes this requirement: not merely quantum information, but topological structure, must be preserved across extreme physical transitions. The black hole information paradox is, in this reading, a specific instance of a more general question: what structural invariants survive the most extreme physical transitions available within our cosmic cycle? The framework does not resolve the paradox — it reframes it as a special case of the broader question of topological memory.

The Fine-Tuning Problem

As argued in Section 5.1, our framework offers a novel response to the fine-tuning problem — the apparent improbability of the fundamental constants of our universe [40, 41]. The standard responses — the anthropic principle and multiverse proliferation — both treat the space of possible universes as simultaneously existing, with our universe selected from among them either by observation or by exhaustive realization. Our framework proposes instead that the apparent fine-tuning reflects accumulated topological inheritance: the constants of our cosmos are not selected from a flat prior but concentrated by the progressive bias of ontological selection across prior cycles. This response is empirically distinct from both the anthropic principle and the multiverse: it predicts a directional trend in the distribution of constants across cycles, rather than a flat distribution over simultaneously existing universes. It is not currently testable, but it is in principle distinguishable from its competitors — which is the minimal requirement for a progressive problem shift in the sense of Lakatos [44].

The Emergence of Spacetime

A growing body of work in quantum gravity and quantum information theory proposes that spacetime geometry is not fundamental but emergent — that it arises from more primitive structures, variously identified as entanglement entropy [65], tensor networks [66], causal sets [15], or spin foam amplitudes [5]. Our framework is broadly convergent with this program: we propose that geometry emerges from pre-geometric topological structure, accumulated through cycles of ontological selection. The specific mechanisms proposed in the quantum gravity literature — entanglement entropy, tensor networks, causal sets — are potential formalizations of what we have described in structural terms as topological memory and constraint accumulation. The most direct connection is with causal set theory [15]: the causal set program proposes that spacetime emerges from a discrete partial order of events, which is precisely the kind of relational structure that topological invariants, in our framework, are properties of. A future formalization of ontological selection might naturally take the form of a generalized causal set theory — one in which the partial order of events accumulates topological constraints across cycles, rather than being generated anew at each Big Bang transition.

Tensions and Open Questions

Not all points of contact are convergences. Three tensions deserve explicit acknowledgment.

The first concerns the status of the pre-geometric regime. Our framework requires a domain of physical reality that precedes and underlies the geometric phase — a domain in which topological invariants persist and accumulate without any material or geometric substrate. No existing physical theory provides a complete description of such a domain. LQC, causal set theory, and spin foam models all approach the Planck scale, but none claims to describe a regime that is genuinely prior to geometry in the sense required by our framework. This is the most significant open question generated by the paper: what is the correct formal description of the pre-geometric regime, and how do topological invariants persist within it?

The second tension concerns the relationship between topological memory and quantum mechanics. Our framework proposes that topological traces persist independently of any material substrate and cannot be destroyed by any physical process. Quantum mechanics, however, is a framework for the evolution of physical states — and it is not immediately clear how a structural invariant that is explicitly non-physical in the ordinary sense relates to the quantum mechanical description of physical reality. The most natural resolution would be to treat topological memory as a boundary condition on the quantum mechanical state space — a constraint that restricts the Hilbert space of possible states without being itself a state. This is speculative, and its formalization is an open problem.

The third tension concerns falsifiability. As acknowledged throughout, the framework is not directly testable with current observational tools. The most promising avenue for indirect testing is the search for signatures of prior cycles in the cosmic microwave background — the approach pursued by Penrose and Gurzadyan [39], whose results remain contested [67]. Our framework predicts that such signatures, if they exist, should exhibit a directional trend — increasing structural complexity across cycles — rather than the specific conformal imprints predicted by CCC. This is a distinct empirical prediction, but one that requires observational tools and theoretical frameworks not yet available. The framework is, at present, empirically underdetermined — which is the expected status of a speculative framework at this stage of development, and which does not diminish its value as a precisely stated hypothesis generating progressive problem shifts.

The Initial Singularity Reconsidered. The standard cosmological model assigns to the Big Bang an initial state of infinite temperature and infinite density — a singularity at which the equations of general relativity break down and physical description, as ordinarily understood, ceases to apply [8]. This breakdown is conventionally treated as a deficiency of the theory: a signal that general relativity must be replaced or supplemented by a quantum gravitational framework capable of resolving the singularity into a well-defined physical state. Loop Quantum Cosmology, as discussed above, pursues precisely this resolution [11].

The framework developed here suggests a different interpretation. The divergence of physical quantities at $t = 0$ is not a pathology of the equations. It is the mathematical expression of a structural fact: the first instantiation of any physical magnitude has no prior context against which to be measured. Temperature, density, and energy are not absolute quantities — they are relational properties, defined with respect to a background of accessible degrees of freedom, a pre-existing thermal history, a reference scale [5]. In the pre-geometric regime, none of these backgrounds exist. No physical magnitude has ever been instantiated. Consequently, the first distinction that crystallises into geometry is necessarily maximal by definition — not because it contains infinite energy in any absolute sense, but because it is the first value on a scale that the act of crystallisation itself inaugurates.

This position entails a precise reinterpretation of the singularity. The infinite temperature and density of the Big Bang are not properties of the initial physical state; they are the signature of its relational novelty. When the equations of general relativity diverge at $t = 0$, they are not failing to describe a physical state — they are correctly registering that the state in question is incommensurable with every subsequent state, because it is the first. The singularity is not a wall beyond which physics cannot reach; it is the boundary between two regimes — the pre-geometric and the geometric — that are structurally incommensurable, and whose boundary cannot be described from within either one alone.

Two consequences follow. The first concerns the fine-tuning of the initial state. The apparent precision of the Big Bang's initial conditions — the extraordinarily low entropy identified by Penrose [3], the specific values of the fundamental constants, the homogeneity of the early universe — is partially reframed by this account. If the initial state is necessarily maximal in every physical dimension by virtue of being first, then what appears as fine-tuning from within the geometric regime is, at least in part, a relational artefact: the projection of a scale onto a point that precedes the scale. The genuinely contingent features of the initial state — those that reflect the specific accumulated topology of prior cycles rather than the structural necessity of being first — are disentangled from those that any first geometric state would necessarily possess.

The second consequence concerns the directionality of cosmic evolution. If the Big Bang is necessarily maximal in every physical dimension, then the subsequent evolution of the cosmos — toward lower temperatures, lower densities, greater structural differentiation — is not a contingent trajectory but a structural necessity. There is nowhere to go from a maximum but away from it. The thermodynamic arrow of time, in this reading, is not merely a consequence of the low-entropy initial conditions of the Past Hypothesis [1]; it is a consequence of the relational structure of the first instantiation itself. The cosmos cools because it began at the only temperature a first state can have: the maximum of a scale it had just created.

This interpretation is convergent with, but distinct from, the approach of Loop Quantum Cosmology. Where LQC resolves the singularity by modifying the dynamics of the geometric regime at the Planck scale, the present framework dissolves it by relocating its origin: the divergence is not a feature of the dynamics but of the relational structure of the transition between regimes. The two approaches are not incompatible — LQC may correctly describe the dynamics of the geometric regime near the Planck scale, while the present framework correctly identifies why those dynamics encounter a structural boundary at $t = 0$ that no modification of the geometric equations alone can fully resolve.

8 Conclusion

8.1 Closing the Loop

The framework articulated in this paper returns, at last, to the question with which it began: why does time have a direction, and why does this direction appear inescapable? The answer, we have argued, lies not in entropy or initial conditions alone, but in the cumulative, irreversible structure of ontological selection itself. Every distinction that arises and collapses leaves a topological trace; every trace constrains the next cycle; complexity is simply the long-term memory of what has survived the void's pull.

Yet there is a final, unexpected symmetry. If the arrow of time is the dynamic expression of ontological selection—the living record of every distinction that refused to collapse—then mathematics is its static, sedimented counterpart. As explored in Section 7.3, mathematics is not a human invention imposed upon the cosmos, nor a contingent feature of our particular cycle. It is the most stable and universal form of topological memory: the distilled residue of distinctions that have proven robust across countless regimes of permissivity. In mathematics, the logical necessity of the first self-referential loop (Section 3.1.1) finds its purest and most durable incarnation. A theorem, once proven, cannot be undone without creating another distinction; an axiom, once accepted, shapes every subsequent possibility. Mathematics is, in this sense, the cosmos' own memory made legible.

Thus the two great invariants we undergo, regardless of scale, location, or cosmic epoch, are precisely these: the arrow of time and mathematics. The first is the inexorable forward motion of selection; the second is the accumulated structure that selection leaves behind. One is process, the other is form. One is the engine, the other is the trace. Together they constitute the minimal, inescapable signature of any reality that has ever emerged from the void.

In this light, the ontological loop is truly closed. The void remains productive not despite complexity, but because of it. Every distinction, every collapse, every cycle contributes to a memory that is at once temporal (the arrow of time) and atemporal (mathematics). We do not merely inhabit a cosmos; we inhabit the memory of its own becoming. And in the end, that memory—whether experienced as irreversible duration or as eternal form—is the only thing the void has never managed to erase.

The framework does not claim to have solved every mystery. It claims only to have shown that the deepest mysteries are not separate, but two aspects of a single, self-sustaining loop: the loop by which nothingness, through the simplest possible act of self-reference, gives rise to something that can never fully return to nothing.

8.2 What remains open

The framework developed in this paper is, by its own acknowledgment, a conceptual architecture rather than a completed theory. It identifies a set of structural hypotheses and argues for their coherence; it does not derive them from first principles, nor does it reduce them to any existing formalism. What it leaves open is therefore not a collection of incidental gaps but a structured agenda — a set of questions whose answers would determine whether the framework can be elevated from a speculative proposal to a physically rigorous account. We gather these open questions here, ordered by depth, from the most foundational to the most empirically proximate.

The formalization of the pre-geometric regime and the critical threshold. The most fundamental open question is the precise nature of the pre-geometric domain and the mechanism of its transition into the geometric regime. The framework requires a regime in which topological invariants persist and accumulate in the absence of any geometric substrate—a domain of pure logical superposition where distinctions coexist without spatial deployment. The transition to geometry cannot be driven by an external physical condition (density, energy, or critical parameter), for no such external measure exists prior to geometry itself. Rather, the threshold must be internal and ordinal: the point at which the succession of distinctions reaches a limit that the regime of logical superposition can no longer contain.

In mathematical terms, this corresponds to the passage from a potential infinity (an unending but never-completed succession of distinctions, in the spirit of intuitionism) to the first actual infinity—the first transfinite ordinal ω. At this limit, the accumulated topological traces form a completed totality that logical superposition alone cannot accommodate. Geometry then emerges not as an arbitrary addition but as the necessary structural solution: the only way for the distinctions to continue coexisting is to deploy themselves spatially rather than remain superposed. The Big Bang, in this view, is not an explosion *in* space but the logical birth *of* space—the minimal extension required once the pre-geometric succession has reached its own transfinite completion.

This formulation sharpens the open question without closing it. It suggests that the critical threshold is not a physical parameter but an ordinal limit intrinsic to the dynamics of ontological selection itself. A future formalization—perhaps in a suitably generalized theory of ordinal processes or a category-theoretic model of distinction—would need to make this passage from potential to actual infinity mathematically rigorous and derive testable consequences for the early universe.

The ontology of topological traces and their causal efficacy. A central and potentially most controversial claim of the framework is that topological invariants left by collapsed distinctions can persist and exert causal influence as purely relational structural facts, without requiring any material substrate. This raises a well-known objection in both metaphysics and philosophy of physics: can purely relational structures genuinely *do* anything? Can they possess causal efficacy, or are they merely descriptive shadows cast by more fundamental entities?

We confront this objection directly. The framework does not treat topological memory as a passive bookkeeping device; it asserts that these relational invariants actively constrain and shape subsequent distinctions. This is not a metaphysical leap but a direct consequence of the dynamics of ontological selection: a trace that did not exert any constraint would be indistinguishable from no trace at all. The position is therefore aligned with ontic structural realism (OSR) [34, 35], according to which the fundamental ontology of the world consists of relations and structures rather than self-subsistent objects. In this view, causal efficacy is not the privilege of "things" but of the relational patterns that define what is possible.

Concrete physical precedents already exist at lower levels. In condensed-matter physics, topological insulators and the quantum Hall effect demonstrate that global topological invariants can produce robust, causally efficacious edge states that are completely insensitive to local perturbations [68]. The topology itself—a purely relational feature—dictates the existence and stability of conducting channels. Similarly, in quantum gravity approaches such as causal set theory and spin foams, the causal structure and topological relations are what generate spacetime and its dynamics; they are not epiphenomenal but generative [15, 69]. These examples show that relational structures can, and do, possess genuine downward causal efficacy.

To move from plausibility to testability, the framework suggests several precise empirical and theoretical routes. First, one may search for topological signatures in quantum gravity phenomenology: modified dispersion relations at the Planck scale, echoes in black-hole ringdown, or anomalies in the cosmic microwave background that could reflect accumulated pre-geometric constraints. Second, the robustness of extremophiles—already identified as biological echoes of pre-geometric traces—offers a laboratory-accessible proxy: systematic comparison of their topological molecular invariants (knotted proteins, extremophile membranes, repair networks) under controlled extreme conditions could reveal whether these structures exhibit the kind of "memory without medium" predicted. Finally, a mathematical formalization in category theory or a generalized version of causal set dynamics would allow one to derive quantitative predictions about the accumulation rate and stability of topological traces across cycles.

Thus the question of causal efficacy is no longer a vague metaphysical worry but a well-posed research program. The framework does not claim to have solved it; it claims to have made it empirically tractable.

The character and dynamics of the primordial distinction. The addition of three candidate signatures (quantum vacuum fluctuations, spontaneous symmetry breaking, and CP violation) provides concrete phenomenological anchors, yet it also raises new questions. Are these phenomena true fossils of the very first distinction, or only its closest present-day echoes once geometry and fields have emerged? A deeper account must clarify how an essentially pre-geometric logical asymmetry translates into the specific physical asymmetries we observe, and whether additional signatures exist at even more fundamental levels.

The extension to biology. The identification of extremophiles as living echoes of pre-geometric traces opens a promising empirical frontier. It suggests that ontological selection continues to operate, in transmuted form, once chemistry and biology appear. A full theory would need to articulate the precise mapping between topological memory and the extraordinary structural robustness of hyperthermophilic archaea and other extremophiles, and to test whether this continuity can generate testable predictions in origins-of-life research or astrobiology.

The dynamics of ontological selection. Even with the above clarifications, the precise mechanism by which internal coherence is evaluated in the pre-geometric regime remains unspecified. The biological analogy is intuitive, but a dynamical account — perhaps in the language of a suitably generalized information or category theory — is still required.

These open questions do not undermine the framework; they define the work that remains. Each is now more sharply posed precisely because the conceptual architecture has been made more precise and more empirically resonant.

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