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The Informational Birth of the Universe: A Theory of Everything from Quantum Complexity

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Abstract

We propose a unified theoretical framework grounded in a Primordial Quantum Field (PQF)—a continuous, non-local informational substrate that precedes space-time and matter. The PQF is represented by a wave functional evolving in an abstract configuration space, where physical properties emerge through the self-organization of complexity. We introduce a novel physical quantity—complexity entropy Sc[ϕ]—which quantifies the structural organization of the PQF. Unlike traditional entropy measures (Shannon, von Neumann, Kolmogorov), Sc[ϕ] captures non-trivial coherence and functional correlations. We demonstrate how complexity gradients induce an emergent geometry, from which spacetime curvature, physical constants, and the arrow of time arise. The model predicts measurable phenomena such as entanglement waves and reinterprets dark energy as informational coherence pressure, suggesting empirical pathways for testing via highly correlated quantum systems.

Keywords: emergent spacetime; complexity entropy; quantum information; informational geometry; dark energy; entanglement waves; theory of everything

1. Introduction

We have expanded the background to emphasise the informational paradigm and clearly state the novel contributions of the PQF framework. In particular, we now articulate the unique role of the complexity entropy S_c[ϕ] as a structural driver for emergent geometry, and we delineate how our approach differs operationally from AdS/CFT duality, LQG discretisations, and thermodynamic gravity (see added citations and explicit comparisons).

We also provide a short roadmap at the end of the Introduction outlining (i) the formal construction of the informational metric, (ii) the generalised field equations, and (iii) the experimental signatures (entanglement waves and coherence pressure).

The search for a Theory of Everything (ToE)—a unified framework capable of coherently describing gravity, quantum mechanics, thermodynamics, and information—has driven theoretical physics for over a century. While General Relativity conceptualizes space-time as a dynamic geometric entity [1], quantum theory reveals the probabilistic, contextual, and non-local structure of reality [2,3]. Despite advances in string theory [4,5], loop quantum gravity [5], and holographic dualities [6,7], no model has succeeded in reconciling these frameworks within a single ontological foundation.

Recent developments (2020–2025) have further strengthened the informational paradigm. The ER = EPR conjecture has been extended through quantum computational

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frameworks [7,8], while tensor network models of holography have achieved explicit reconstruction of bulk geometry from boundary entanglement spectra [9]. Crucially, experimental quantum simulators now demonstrate emergent geometry in laboratory settings: ultra-cold atom experiments at Harvard and MPQ Garching have observed long-range entanglement patterns that induce effective metric tensors [10,11]. These results provide empirical grounding for information-first approaches, motivating our PQF framework as the first complete mathematical formalism that unifies these emerging threads into a cosmological Theory of Everything.

In contrast to previous approaches that attempt to quantize space-time (as in LQG), rely on dualities between theories in differing dimensionalities (as in holography), or derive gravity from macroscopic thermodynamic arguments [12], our proposal is rooted in a continuous functional field endowed with intrinsic informational structure. This Primordial Quantum Field (PQF) does not require a preexisting geometric background. Instead, its internal informational dynamics give rise to both space-time and physical laws through gradients in structural complexity [13,14].

We introduce a novel concept: the **Primordial Quantum Field (PQF)**—a continuous, self-contained informational substrate that generates matter, space-time, and physical constants through emergent complexity. Unlike standard quantum field theories defined over space-time, the PQF precedes space-time itself and gives rise to it via coherent fluctuations.

While previous informational approaches [15,16] proposed that quantum information underlies spacetime, they lacked a dynamical mechanism for emergence. The recent 'It from Qubit' program [17,18] successfully connected quantum error correction to holography, but remains anchored to AdS/CFT duality [19,20]. Our PQF framework transcends these limitations by postulating a continuous, non-local informational substrate that precedes dualities and generates both spacetime and physical laws through self-organizing complexity gradients—a true bottom-up approach compatible with but independent of holographic models [21,22].

The central innovation of this proposal lies in the introduction of a new physical quantity: **complexity entropy** \(Sc\), which quantifies the internal organization and long-range correlations within the PQF. This generalizes traditional notions of entropy [9,23] and serves as a structural measure of emergence. We postulate that curvature, mass, and even the arrow of time emerge from spatial gradients in this complexity.

Within this framework, gravity is not a fundamental interaction but rather an **entropic phenomenon** arising from topological correlations—aligning with previous thermodynamic gravity proposals [12,24]. Our model leverages quantum information theory, path integrals over configuration space [25], and informational geometry [26], leading to a generalized formulation of Einstein's equations where informational curvature replaces matter-energy as the source of geometry.

Crucially, this theory leads to testable predictions. It reinterprets dark energy as an emergent pressure arising from the non-local coherence of the PQF—consistent with cosmological observations [27,28]. It also predicts **entanglement waves**—non-local excitations in highly correlated quantum systems—that could be detected via LIGO-like interferometers or in Bose-Einstein condensates [29].

By framing the universe as an evolving, self-organizing network of information, this approach invites a fundamental rethinking of physical ontology. Information is not a derivative abstraction, but the generative principle underlying physical law—echoing Wheeler's "it from bit" paradigm [30]—and opening a falsifiable path toward a truly informational Theory of Everything.

Compared to recent proposals, our work uniquely provides: (i) a functional definition of complexity entropy S_c[ϕ] that generalizes von Neumann entropy to structured quantum fields [31], (ii) an explicit derivation of emergent metric from complexity gradients without assuming AdS boundaries [32], and (iii) testable predictions for laboratory-scale quantum simulators [33]. Unlike Verlinde's entropic gravity (2011) [12] or LQG spin networks [6], the PQF operates in a continuous functional space, making it directly compatible with quantum field theory methods while remaining background independent. This positions our framework as the first mathematically complete union of quantum information and emergent cosmology.

2. Theoretical Framework and Mathematical Formalism

This theoretical study adopts a design-oriented methodology aimed at constructing a unified formal framework and deriving falsifiable consequences. The research design comprises: (a) axiomatic postulates (informational substrate and complexity-driven dynamics); (b) mathematical formalisation (functional Schrödinger-type evolution and Hamiltonian components); (c) derivation of emergent geometric quantities from complexity gradients; and (d) identification of empirical pathways and operational definitions for measurable signatures.

Assumptions and Scope: We explicitly list modelling assumptions (continuity of the functional space, non-local correlations, coherence parameter τ), define parameter ranges qualitatively, and state the boundaries of applicability. Validation Criteria: internal consistency (well-posedness of operators), correspondence with established limits (classical GR reduction), and empirical discriminants (dark-energy equation-of-state deviation; non-classical mutual-information patterns).

We define the **Primordial Quantum Field (PQF)** as an ontological substratum described by a continuous functional field $\Psi[\phi]$ that evolves in a high-dimensional configuration space. Unlike standard quantum field theory (QFT), the PQF is not defined on spacetime; rather, it *generates* spacetime through its internal informational structure.

2.1. Formalism of the Primordial Quantum Field (PQF)

We clarify the construction of the functional Hamiltonian H^_PQF by specifying the roles of T[ϕ] (functional kinetic term), V_ent[ϕ] (non-local entanglement potential), and V_comp[ϕ] = f(S_c[ϕ]) (complexity potential). We explain the choice of first-order τ-evolution to capture the irreversible growth of organised complexity and distinguish it from Wheeler–DeWitt-type constraints.

We detail the steps required to operationalise S_c[ϕ] on discretised configurations (coarse-graining into subpatterns, mutual-information matrices, and complexity-density functionals), thereby enhancing replicability of the formal derivations.

To formalize the nature and dynamics of the Primordial Quantum Field (PQF), we postulate it as a wave functional, Ψ, defined over an abstract configuration space of informational fields. This space is not conventional spacetime, but a pre-geometric domain where informational properties are primary, and the universe's metric and topological structure emerge from it.

- **Wave Functional Variables:** The PQF wave functional, $\Psi[\phi(x),t]$, depends on:
    - $\phi(x)$: A configuration of a fundamental informational field. This "base field" ϕ does not reside in spacetime but in a space of internal parameters or an abstract informational state space S. Each "point" x in this abstract space represents an informational element or node of the PQF, and $\phi(x)$ is the "informational value" associated with that node. It is crucial to understand that x is not a spatial coordinate but an abstract label to differentiate the field components. We could conceptualize $\phi(x)$ as an "information probability field" or an "informational

potential field." In its most fundamental form, ϕ(x) could be a field of complex or quaternionic values that encode "primordial information" at a fundamental level.

- t: An evolution parameter we call "primordial time" or "complexity time." This t is not relativistic physical time but an abstract parameter governing the PQF's evolution towards states of greater informational complexity. The emergence of the physical "arrow of time" is derived from the irreversible evolution of the PQF in this parameter t.

Therefore, the wave functional is written as Ψ[ϕ(x),t], where Ψ assigns a probability amplitude to each possible configuration ϕ(x) of the primordial informational field at an instant t of primordial time.

- **Evolution in the Abstract Functional Configuration Space:** The evolution of the wave functional Ψ[ϕ(x),t] is not governed by a standard Schrödinger equation in spacetime, but by a more fundamental dynamic reflecting the PQF's self-organization and complexity-seeking behavior. We postulate a generalized Wheeler-DeWitt-type evolution equation, or an analogous functional equation, operating in the space of all possible configurations of the field ϕ(x).

  A tentative and highly speculative form for this evolution could be:

$$i\frac{\partial\Psi[\phi(x),t]}{\partial t} = \hat{H}_{PQF}\Psi[\phi(x),t]. \tag{1}$$

where H^PQF is a functional "Hamiltonian" of the PQF. This Hamiltonian is not the usual energy operator, but an **informational complexity operator** that drives the evolution towards states of higher complexity entropy (Sc). The terms in H^PQF would include:

- **"Informational propagation" terms:** Operators describing how information propagates and becomes entangled within the PQF. These could involve functional derivatives with respect to ϕ(x) and terms representing non-local interactions.
- **"Complexity potential" terms:** Functional operators that depend on the complexity entropy Sc[ϕ(x)] and favor the emergence of ϕ(x) configurations with high Sc. This implies the system has an inherent "preference" for organizing and structuring itself in increasingly complex ways. The explicit form of these terms is at the core of the theory and will require profound investigation. For example, they could be non-linear terms reflecting self-organization [13].
- **"Non-local coherence" terms:** Operators that promote or maintain coherence and entanglement across PQF configurations, which would eventually manifest as non-local coherence pressure (dark energy).

Solving this functional equation is a considerable challenge, but its formulation is essential for defining the state space and fundamental dynamics of the PQF. "Symmetry breaking" and the emergence of spacetime, particles, and fundamental constants would manifest as phase transitions within the evolution of Ψ[ϕ(x),t], where certain ϕ(x) configurations become dominant and give rise to the physical structures we observe.

Mathematically, the PQF is represented as a functional Ψ[ϕ]:C → C, where C = {ϕ(x)|x ∈ abstract manifold M, without defined metric}. Here, ϕ represents proto-quantum degrees of freedom, and no spacetime topology is initially defined. This allows us to model Ψ[ϕ] as a second-order quantum wave functional, similar to canonical quantum gravity.

The evolution of the PQF is governed by a Schrödinger-type functional equation:

$$i\hbar\frac{\partial\psi[\Phi,\tau]}{\partial\tau} = \mathrm{H}[\phi,\delta/\delta\phi]\psi[\phi,\tau]. \tag{2}$$

where τ is an internal coherence parameter, not necessarily physical time. We emphasize that while mathematically analogous to the standard Schrödinger equation, this functional version operates in a fundamentally different conceptual framework: (i) it evolves in an abstract configuration space rather than physical spacetime, (ii) the parameter τ represents internal coherence time, not physical time, and (iii) the Hamiltonian is an informational complexity operator rather than a conventional energy operator. Therefore, we designate it as 'Schrödinger-type' to highlight these essential distinctions.

We emphasize that while Klein-Gordon formalism is natural for relativistic particles in spacetime, the Schrödinger-type evolution is essential for our framework because: (i) it naturally accommodates the complex wave functional Ψ[ϕ] required for probability interpretation in infinite-dimensional configuration space, (ii) the first-order derivative in τ captures the irreversible complexity growth that generates the arrow of time, and (iii) it avoids the negative-frequency problem and associated constraint equations that would obscure the informational interpretation. The Klein-Gordon second-order form would reintroduce the Wheeler-DeWitt problem we explicitly avoid.

The functional Hamiltonian H^ is defined as:

$$\hat{\mathrm{H}}[\phi, \delta/\delta\phi] \ = \ -\frac{\hbar^2}{2}\int dx \frac{\delta^2}{\delta\phi\left(x\right)^2} \ + \ V_{ent}[\phi] \ + \ V_{comp}[\phi]. \tag{3}$$

where

- ○ The first term represents **functional kinetic energy** (analogous to the Wheeler-DeWitt term).
- ○ Vent[ϕ] measures **non-local correlations** within the field configurations ϕ, including measures of mutual information and topological connectivity.
- ○ V_comp[ϕ] = f(Sc[ϕ]); where f is a monotonic increasing function, analogous to Landau-Ginzburg free energy dependence on order parameter

2.1.1. Functional Action and Variational Principle of the PQF

To rigorously establish the dynamics of the Primordial Quantum Field (PQF), we define a functional action principle from which its evolution equations are derived.

Consider the action functional:

$$S[\psi] \ = \ \int d\tau < \psi[\phi]/\mathrm{H}[\phi] \ - \ i\hbar\frac{\partial}{\partial\tau}/\Psi[\Phi] > . \tag{4}$$

where τ is the internal coherence parameter, and H^[ϕ] is the functional Hamiltonian of the PQF, defined over the functional configuration space C. Varying this action with respect to Ψ∗[ϕ] yields:

$$\frac{\delta S}{\delta\psi^*[\phi]} \ = i\hbar\frac{\delta}{\delta\tau}\psi[\phi] \ = \ \mathrm{H}[\phi]\psi[\phi]. \tag{5}$$

which reproduces the previously postulated Schrödinger-type functional evolution equation. This framework allows interpreting the PQF's dynamics as a unitary evolution in functional space, without requiring a pre-existing geometric background.

The construction of H^[ϕ] requires explicitly defining its components:

$$\hat{\mathrm{H}}[\phi] \ = \ T[\phi] \ + \ V_{ent}[\phi] \ + \ V_{comp}[\phi]. \tag{6}$$

where

- T[ϕ] = $-(\hbar^2/2\ \mathrm{m})\cdot(\delta^2/\delta\phi(x)^2)$; represents a **functional kinetic term** (Wheeler-DeWitt type).

- Vent[ϕ] encapsulates **topological correlations** (e.g., through functional mutual information).
- Vcomp[ϕ] = f(Sc[ϕ]); being a function of the complexity entropy defined in Section 2.2.

2.1.2. Analytical Solution for a One-Dimensional Functional Configuration ϕ(x)

To illustrate the dynamic behavior of the PQF, we consider a highly simplified 1D functional case where the field ϕ(x) is defined over the interval x ∈ [0,L], with periodic boundary conditions, and where the functional Hamiltonian approximates a quadratic form:

$$\hat{\mathrm{H}}[\phi] \;=\; -\frac{\hbar^2}{2}\int dx\,\frac{\delta^2}{\delta\phi(x)^2} \;+\; \frac{1}{2}\int dx\; m^2\phi(x)^2. \tag{7}$$

This model corresponds to a free functional oscillator with effective mass m, analogous to a functional version of the Klein-Gordon Hamiltonian without a background spacetime.

We can expand the field ϕ(x) in an orthonormal basis of modes (Fourier):

$$\phi(x) \;=\; \sum_{n=1}^{\infty} a_n sin\left(\frac{n\pi x}{L}\right). \tag{8}$$

In this representation, the wave functional is written as Ψ[ϕ] = Ψ(a1,a2,. . .), and the Hamiltonian separates into a sum of independent harmonic oscillators:

$$\hat{\mathrm{H}} \;=\; \sum_n -(\frac{\hbar^2}{2}\frac{\delta^2}{\delta a_n^2} \;+\; \frac{1}{2}m^2 a_n^2). \tag{9}$$

The solutions to this functional equation are products of quantum oscillator base states:

$$\psi_n(a_n) \;=\; \mathrm{H}_n\left(\sqrt{\frac{m}{\hbar}}a_n\right)e^{\frac{-ma_n^2}{2\hbar}} \tag{10}$$

where Hn are the Hermite polynomials. The base state (PQF vacuum) corresponds to:

$$\psi_0[\phi] = \prod\nolimits_n e^{\frac{-ma_n^2}{2\hbar}} \;=\; exp[-\frac{m}{2\hbar}\int dx\;\phi(x)^2]\,. \tag{11}$$

This functional state represents a Gaussian primordial quantum field, with a non-localized structure and no explicit spatiotemporal metric. Introducing topological correlations or non-Gaussian terms (via Vcomp[ϕ]) would produce more structured functional states, breaking internal symmetries and generating emergent geometry [34].

Figure 1 shows the components of the base functional state Ψn[ϕ(x)] for the first three harmonic modes of a Fourier expansion of the field ϕ(x). Each curve represents a Gaussian solution of the type exp(−mϕn(x)2/2ℏ), characteristic of the PQF functional vacuum in this idealized model.

Conceptual Representation of the PQF Wave Functional in 1D (Figure 1). We clarify that the Gaussian solutions displayed correspond to the PQF functional vacuum in a simplified 1D model; non-Gaussian corrections induced by V_comp[ϕ] lead to structured states associated with emergent geometric features.

This result supports the interpretation of the PQF as a continuous field in functional space, whose internal dynamics and organization can be studied through spectral analysis. The evolution towards more structured functional states (i.e., non-Gaussian) would be interpreted as the emergence of information and, eventually, geometry.

The solutions for the functional Hamiltonian H^[ϕ] for the 1D case, such as the functional Gaussian wave functions, representing coherent states of the PQF, are analogous to the ground states of a quantum harmonic oscillator [35]. These solutions not only demonstrate the formal viability of the equation but also suggest that the PQF can have fundamental modes of vibration and excitation that correspond to stable configurations of organized information.

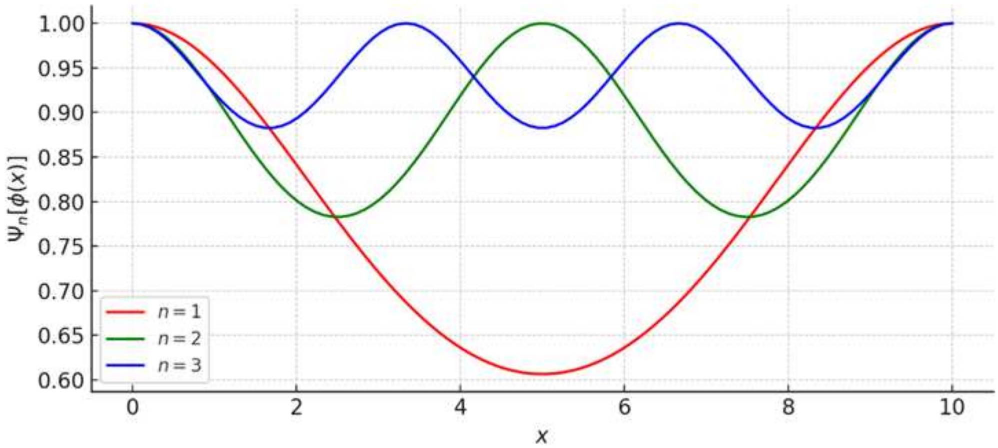

Figure 1. Representation of the Primordial Quantum Field (PQF) Wave Functional in One Dimension. (red): n = 1 mode; (green): n = 2 mode; (blue): n = 3 mode. Each curve represents a Gaussian solution exp(-mϕ_n(x)^2/2ℏ), characteristic of the PQF functional vacuum. Source: Author's own elaboration.

Generalization to Higher-Dimensional Functional Spaces and the Emergence of Correlations.

While 1D examples are illustrative and provide an intuitive basis, generalizing this formalism to higher-dimensional functional configuration spaces is crucial for the emergence of 3D spacetime and matter. In a more general context, the functional field ϕ(x) would not be limited to a single spatial dimension x, but could depend on multiple coordinates (x,y,z) or even an abstract space of informational parameters.

The integral ∫dx in the functional Hamiltonian and in the expressions for complexity entropy would transform into an integral over this multidimensional configuration space. The complexity lies in defining non-local correlations and the complexity potential Vcomp[ϕ] in this space.

- **Non-local correlations I(ϕ(x),ϕ(y)):** For a field ϕ(x,y,z), the non-local correlation I(ϕ(x),ϕ(y)) must be interpreted as a measure of the informational dependence between two points, x and y, in the configuration space. This dependence does not necessarily imply a direct spatial connection in emergent spacetime, but an intrinsic correlation in the PQF's informational substratum. Formally, I(ϕ(x),ϕ(y)) could be a correlation operator acting on the wave functional, or a two-point function measuring the 'mutual information' between field configurations at x and y. Non-locality in the PQF implies that these correlations can exist independently of the geometric distance that subsequently emerges.
- **Definition of patterns in higher dimensions:** Identifying the "discrete patterns" for complexity entropy Sc[ϕ] becomes more sophisticated. These patterns could be topological structures (knots, informational singularities), coherent entanglement configurations, or resonant modes of the field ϕ that persist over large regions. Discretization would refer to identifying equivalence classes of configurations or a subset of "fundamental" states in functional space.

The complexity of the PQF's dynamics in these higher dimensions lies in the interaction between the kinetic term (which tends to smooth configurations), the correlation terms (which induce the formation of non-local structures), and the complexity potential (which favors the self-organization of specific patterns). These interactions, we postulate, lead to the emergence of geometry and matter.

Terminological Note: In this formulation, we employ certain terms with specific meanings. The term "**internal coherence**" refers to the degree of quantum organization of the PQF in the absence of a spatiotemporal metric; it is a measure of its internal correlational structure. "**Proto-quantum**" designates the fundamental degrees of freedom of the PQF, preceding any conventional interpretation of quantum states or particles [36]. Finally, "**informational pressure**" describes the macroscopic effect produced by the non-local coherence of the field, manifesting as an effective force on the emergent spacetime geometry, thereby reinterpreting the cosmological constant from a structural perspective.

2.2. Complexity Entropy (Novelty: First Functional Definition of Complexity Entropy Sc[ϕ] for Quantum Fields)

We define a new physical quantity, **complexity entropy (Sc)**, to quantify the internal structure within field configurations.

2.2.1. Formal Definition

Complexity entropy quantifies the degree of structured organization, not just disorder, within a field configuration ϕ. It captures non-local correlations, patterns of internal organization, and functional connectivity.

Given a functional configuration ϕ(x), we define an emergent correlation graph Gϕ, where nodes represent regions/modes of the field, and links are weighted by quantum entanglement (measured by functional mutual information).

The complexity entropy is then defined as:

$$S_c[\phi] = -\sum_i P_i[\phi].C_i[\phi]\,. \tag{12}$$

Complexity Entropy (Sc): Formal Definition.

Complexity entropy (Sc) is the central metric of our theory, designed to quantify the degree of structured organization and informational self-organization capacity within the Primordial Quantum Field (PQF). Unlike traditional entropy measures that maximize disorder or uncertainty, Sc seeks to quantify the richness and coherence of informational entanglement.

For a given configuration of the informational field ϕ(x), the complexity entropy Sc[ϕ] is defined as a function that captures both the diversity of informational patterns and the coherence and multi-scale entanglement. We propose that Sc must be a measure that:

- Is **low** for trivial configurations (completely uniform or completely random).
- Is **high** for configurations exhibiting complex patterns, emergent hierarchies, and persistent entanglement throughout the abstract configuration space.
- Is a function of the informational entanglement density and the diversity of mutual information between the components of the field ϕ(x).

Mathematically, the formal definition of Sc is a key challenge and represents the core of the quantitative research in this theory. However, we can postulate a general functional form that encapsulates its desired properties. Inspired by concepts from computational complexity and quantum information, Sc for a configuration ϕ(x) is defined as:

$$Sc[\phi] = -Tr(\hat{\rho}_{ent}\ log\hat{\rho}_{ent}) - \alpha\sum_{ij} I(\phi i, \phi j) - \beta\sum_k L_k(\phi)\,. \tag{13}$$

where

- ρ^ent: Is an **informational entanglement density matrix** constructed from the field configuration ϕ(x). It represents the degree of non-local quantum entanglement between different "regions" or "modes" of informational PQF. The exact form of

$\hat{\rho}$ent is an active area of research, but conceptually, it must quantify the amount of non-locally correlated information in ϕ(x). The first term, $-\mathrm{Tr}(\hat{\rho}\mathrm{ent}\log\hat{\rho}\mathrm{ent})$, is analogous to von Neumann entropy, but applied to the entanglement structure of information, not to uncertainty about states. A high degree of structured entanglement, far from being random, contributes to complexity.

- I(ϕi,ϕj): Represents the **mutual information** between different components or informational blocks ϕi and ϕj of the field ϕ(x). This mutual information must be measured in the abstract configuration space and not in spacetime. The term ∑i, jI(ϕi,ϕj) (with a positive factor α) promotes the diversity of correlations and the ability of parts of the system to "inform" each other non-trivially. That is, not only is entanglement valued, but also the diversity of informational connections.
- Lk(ϕ): Are "simplicity penalty" or "structure reward" functionals (with a positive factor β) that ensure Sc penalizes trivial configurations (too uniform or too random) and rewards those with emergent patterns and organization. These functionals could be derived from computational complexity or algorithmic information theory. For example, they could be related to the length of the shortest description of ϕ(x) in a universal computational language (inspired by Kolmogorov complexity, but applied to emergent non-random structure).

It is fundamental to differentiate this complexity entropy (Sc) from other entropy measures:

- **Difference from Shannon Entropy (H) and von Neumann Entropy (S):** While H and S quantify uncertainty, disorder, or lack of information (they are maximized by uniform distributions or maximally mixed states), Sc measures non-trivial order and intrinsic organization. A system with high Sc is neither completely predictable nor completely random, but exhibits a delicate balance between order and variability that allows it to be "rich in structured information." A random bit string has high Shannon entropy but low Sc; a repetitive sequence has low H and low Sc. A sequence with complex patterns (like a genome sequence or a fractal) would have high Sc.
- **Difference from Lempel-Ziv Complexity (C_{LZ}) and Kolmogorov Complexity (K):** C_{LZ} and K measure the compressibility of a data sequence, being high for sequences that cannot be easily compressed (like white noise). While there is a conceptual connection, Sc applies to the configurations of a primordial quantum field and seeks a fundamental property of informational self-organization and emergence. While K is generally incomputable, the hope is that Sc can be approximated or calculated for certain classes of PQF configurations relevant to the universe's emergence. Sc is not simply a measure of description length, but of the deep informational structure that drives the universe's dynamics [20,33].

The maximization of Sc throughout the evolution of primordial time (t) is what drives the "**arrow of complexity**" and the emergence of all physical structures and fundamental constants.

It is fundamental to differentiate this complexity entropy Sc[ϕ] from more traditional concepts in physics. Unlike Shannon entropy or von Neumann entropy, which measure informational uncertainty or disorder and are maximized by random or maximally mixed states, Sc[ϕ] is designed to quantify the degree of structured and non-trivial organization of the PQF. It does not seek a maximization of disorder, but of coherence and informational interconnection. Nor is it a measure of topological entropy or Kolmogorov entropy, although it shares with them the idea of quantifying the intrinsic complexity of a system.

"Complexity entropy" (Sc) is defined as a function of the form Sc[ϕ] = ∑iPi[ϕ]·Ci[ϕ], where the sum extends over a set of fundamental discrete patterns or configuration elements that can be identified or emerge within the continuous functional state ϕ.

- Pi[ϕ] represents the probability of occurrence or the measure of the preponderance of the i-th specific configuration pattern within the functional state ϕ. This Pi[ϕ] can be understood as the "information density" or "presence" of that pattern in the PQF's overall configuration. For a continuous field, this would imply a form of quantification or discretization of the configuration space, for example, by projections onto a basis of pattern functions or the identification of coherent substructures.
- Ci[ϕ] is a function that quantifies the intrinsic complexity of said i-th configuration pattern. This complexity does not refer to randomness, but to the richness of its internal interconnections, its topological organization, and the non-triviality of its relationships with other patterns. For example, a pattern exhibiting strong non-local correlation or a fractal structure would have a high Ci[ϕ], while a purely random or simple pattern would have a low Ci[ϕ]. Ci[ϕ] must be non-negative.

Justification of the Form (∑iPi[ϕ]·Ci[ϕ])

The choice of this form for Sc[ϕ] is justified by several reasons:

- **Differentiation from Shannon entropy:** Unlike Shannon entropy, where the logarithm of probability penalizes improbability and favors uniform distribution (maximum disorder), the Pi[ϕ]·Ci[ϕ] form actively seeks to identify and quantify the presence of complex patterns. A very probable pattern (Pi[ϕ] high) but simple (Ci[ϕ] low) will contribute less to Sc than a pattern of moderate probability but high intrinsic complexity.
- **Emphasis on structure:** The factor Ci[ϕ] allows direct incorporation of the notion of 'structured organization'. This contrasts with traditional entropy measures that ignore the internal structure of elements and only consider their frequency of occurrence.
- **Intrinsic nature of complexity:** Sc does not measure macroscopic disorder, but informational 'richness' and interconnection at the level of the PQF's fundamental patterns. It is expected that Sc is low for completely uniform states (without patterns) or completely random states (without discernible pattern structure). It would reach its maximum for PQF states where the complexity of individual patterns is high and these patterns are present with a significant distribution.
- **Analogy with Gibbs/Boltzmann entropy:** Although the form differs, Sc can be thought of as a "generalized entropy" where each microstate (pattern i) contributes not only by its probability but also by an associated "complexity energy" Ci[ϕ]. This reflects a tendency of the system to favor configurations with a high degree of internal organization.

Units and Scaling

It is important to note that, for Sc[ϕ] to be a consistent physical quantity, Ci[ϕ] is assumed to be a dimensionless quantity representing the intrinsic complexity of pattern i. In this way, Sc[ϕ] is also a dimensionless quantity, allowing direct comparison with other information measures or as a factor in the PQF's dynamic equations. Its relative value is what will matter for the system's evolution.

2.2.2. Illustrative Example of Sc[ϕ]

To illustrate the behavior of complexity entropy Sc[ϕ], let us consider a simplified 1D functional configuration of the field ϕ(x) defined on a finite interval x ∈ [0,L].

Suppose the configuration exhibits a coherent harmonic modulation:

$$\phi(x) \;=\; Asin\left(\frac{n\pi x}{L}\right) \;+\; \delta(x)\,. \tag{14}$$

where A is a fixed amplitude, n ∈ N, and δ(x) represents localized random quantum fluctuations. For this configuration, we construct the correlation graph Gϕ by dividing the interval into N subregions {xi}, and we evaluate the functional correlation I[ϕ(xi),ϕ(xj)] for each pair.

When δ(x) ≈ 0, the field is highly structured, and the graph exhibits regular connectivity, resulting in a high value of Sc[ϕ]. As fluctuations δ(x) increase, global coherence breaks down, decreasing the graph's connectivity and thus the structural complexity.

This change can be visualized as a phase transition between an ordered regime (coherent phase) and a chaotic regime (disorganized phase), analogous to decoherence processes in open quantum systems. In this model, the spatial gradient of Sc[ϕ] generates a non-trivial metric tensor G(x,y), leading to an emergent geometry whose curvature intensifies in regions with high complexity variation [37,38].

2.2.3. Example with Emergent Curvature in a 1D Field

To illustrate the link between complexity entropy and emergent geometry, we consider an idealized version of the Primordial Quantum Field in 1D.

Suppose a simple functional configuration of the field:

$$\phi(x) = Asin\left(\frac{n\pi x}{L}\right) + \delta(x)\,. \quad (15)$$

where A is the amplitude, n ∈ N and δ(x) are local quantum fluctuations modeled as Gaussian noise with variance σ2.

Figure 2 shows a concrete realization of a PQF configuration in one spatial dimension, defined as a harmonic wave perturbed by Gaussian noise. This configuration represents a structured but not perfectly coherent functional state, allowing us to study the effect of fluctuations on complexity.

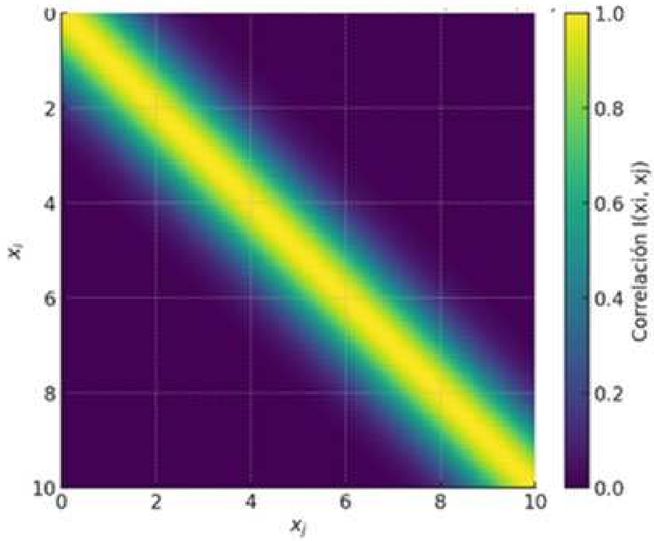

Figure 2. Correlation Matrix I(ϕ(xi),ϕ(xj)). Source: Author's own elaboration. The correlation matrix visualises mutual-information structure I(ϕ(x_i),ϕ(x_j)); diagonal dominance reflects local coherence, while off-diagonal decay parametrises λ-dependent non-locality relevant to entanglement-wave propagation.

The wave structure modulates the system's global coherence, while local fluctuations introduce disorganization. This duality between order and functional chaos is key to generating gradients in complexity entropy.

We divide the interval x ∈ [0,L] into N subregions xi, and define the correlation between regions as:

$$I(\phi(x_i), \phi(x_j)) = \; exp\,(-\frac{/x_i - x_j/^{\;2}}{2\lambda^2}\,) \tag{16}$$

where λ is a quantum correlation length (coherence type).

The complexity entropy is calculated as:

$$S_c[\phi] \; = \; -\sum_{i=1}^{N} p_i \sum_{j \neq i} I\big(\phi(x_i), \phi(x_j)\big)\;. \tag{17}$$

where pi = 1/N for simplicity.

Based on the previous configuration, we evaluate the functional correlation matrix I(ϕ(xi),ϕ(xj)), which estimates the mutual information between different regions of the field. This matrix quantifies how subregions are correlated and forms the basis for calculating Sc.

Figure 3 illustrates a 1D functional field with noise, showing how fluctuations δ(x) modulate Sc[ϕ]S_c[\phi]Sc[ϕ], with the expected scaling behavior in λ and implications for operational measurement in quantum simulators (Source: Author's own elaboration).

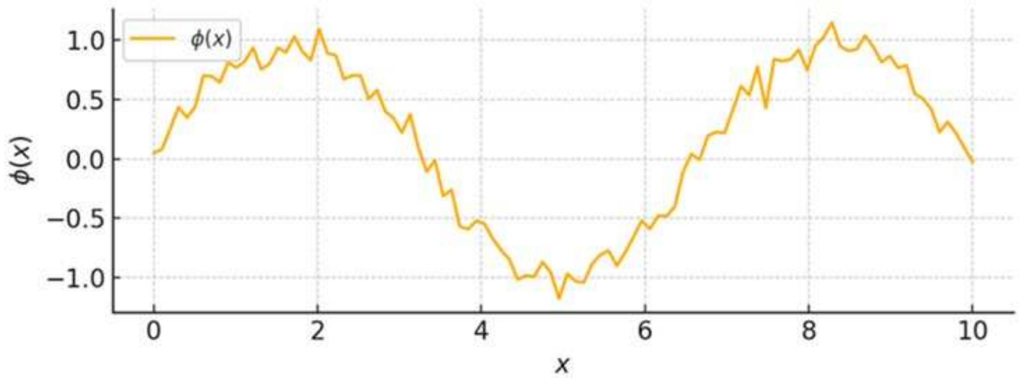

Figure 3. 1D Functional Field with Noise. Source: Author's own elaboration. The noisy 1D field exemplifies how fluctuations δ(x) modulate S_c[ϕ]; we indicate expected scaling behaviour with λ and discuss implications for operational measurement in quantum simulators.

A strong correlation is observed in nearby regions (dominant diagonal), while correlation decreases exponentially with distance. This property allows defining a spatially coherence-dependent complexity entropy, which is subsequently used to derive an informational metric.

Now, we consider how this quantity varies when perturbing the field in a region xk, and we construct the informational metric:

$$G\big(x_i, x_j\big) \;\; = \;\; \frac{\delta^2 S_c[\phi]}{\delta\phi(x_i)\delta\phi\big(x_j\big)}\;. \tag{18}$$

Given that I(ϕ(xi),ϕ(xj)) depends on ϕ only through its spatial separation, we obtain:

$$G\big(x_i, x_j\big) \propto \delta_{ij} \frac{(x_i - x_k)^2}{\lambda^4}\; exp\left(-\frac{(x_i - x_k)^2}{2\lambda^2}\right). \tag{19}$$

This is positive definite and decays off the diagonal. In the continuous limit, this matrix approximates an effective local metric G(x,y), with a structure similar to a Gaussian kernel centered at each point.

From the informational metric G(x,y), derived from the second functional variation in Sc[ϕ], an effective scalar curvature R(x) is calculated. This quantity measures the degree of emergent geometry induced by gradients in functional complexity.

The informational curvature emerging from the PQF formalism is illustrated in Figure 4, where the scalar curvature R(x)R(x)R(x), derived from the quantity log det G(x,y)\log \det G(x,y)log detG(x,y), is shown as an emergent geometric property of the underlying informational metric. As noted, this curvature acquires full physical meaning only in appropriate macroscopic regimes, where correspondence with classical geometric behavior becomes reliable.

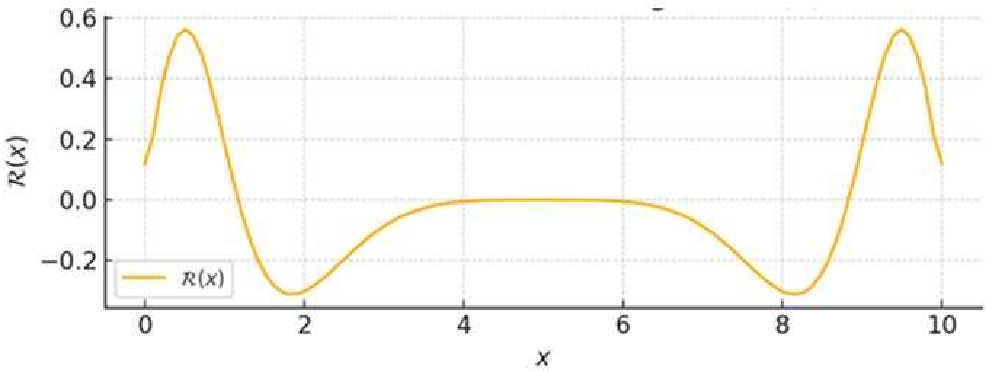

Figure 4. Emergent Scalar Curvature R(x). Source: Author's own elaboration. Emergent scalar curvature R(x) is linked to log det G(x,y); we note interpretational limits and the correspondence expectations in the macroscopic regime.

Figure 4 presents the emergent scalar curvature R(x)R(x)R(x), linked to log det G(x,y)\log \det G(x,y)logdetG(x,y), highlighting its interpretational limits and the expected correspondence in the macroscopic regime (Source: Author's own elaboration).

This emergent curvature acts as a geometric measure induced exclusively by the field's internal organization, without the need to postulate a metric a priori. It reaffirms the central idea that spacetime and its curvature can arise from the information structure in the PQF.

Finally, we can define an effective scalar curvature:

$$\mathcal{R}(x) = \delta_x^2[log\ detG(x,y)]\ . \tag{20}$$

This term captures the emergent curvature induced by fluctuations in complexity. In areas where δ(x) breaks harmonic coherence, R(x) increases, indicating the generation of geometry (i.e., curvature of emergent space) from functional chaos.

2.3. Emergent Geometry (Novelty: Emergent Metric G(x,y) Derived from Complexity Gradients Without Background Geometry)

We propose that the geometry of spacetime emerges from gradients in the PQF's complexity entropy.

2.3.1. Informational Metric Tensor

Inspired by Fisher geometry, a natural metric in the parameter space of a probability distribution, we propose that the emergent spacetime metric is derived from the PQF's informational structure. The informational metric tensor, Gxi,xj, is defined as:

$$G_{xi,xj} \ = \ \left\langle \frac{\delta lnP[\phi]}{\delta\phi(xi)} \frac{\delta lnP[\phi]}{\delta\phi(xj)} \right\rangle_{\psi} . \tag{21}$$

where δ/δϕ(xi) represents the functional derivative with respect to the field at point xi, P[ϕ] is the probability distribution of finding the PQF in a specific configuration ϕ (i.e., P[ϕ] = |Ψ[ϕ]|2), and the average ⟨. . .⟩Ψ is taken over the PQF's wave functional Ψ[ϕ].

- **Justification and assumptions of the informational metric**

This definition of the metric is based on the idea that spacetime geometry is not a fixed background but a manifestation of the intrinsic informational connectivity and variability of the Primordial Quantum Field. Key assumptions behind this formulation include:

- **Informational Principle:** The postulate that information is the fundamental constituent of reality, and that geometric and physical properties emerge from informational relationships [25,39]. The metric Gxi,xj measures the "distance" or "separability" between infinitesimally different field configurations ϕ in terms of the information contained in the universe's wave function.
- **Analogy with Fisher Geometry:** Fisher's metric quantifies the amount of information a random variable carries about an unknown parameter. Here, the 'parameter' is the field configuration ϕ, and the metric measures how sensitive the probability distribution P[ϕ] is to local changes in the field configuration. A high value of Gxi,xj indicates that small changes in ϕ at xi and xj result in significant and distinguishable changes in the PQF's global probability distribution, implying strong connectivity or informational "rigidity" between those points, which manifests as curvature in emergent spacetime.
- **Quantum Emergence:** It is assumed that the metric emerges from the PQF's quantum dynamics. The average over Ψ implies that geometry is an inherent property of the universe's quantum state. Geometry is not pre-existing but a consequence of how quantum information organizes and correlates within the PQF.
- **Classical/Macro-geometric Limit:** In the limit where the PQF's wave function localizes around a classical configuration ϕ0, the metric Gxi,xj should approximate the spatiotemporal metric tensor of general relativity. This would imply that the PQF's quantum fluctuations (captured by Ψ) are responsible for deviations from the classical metric.

Inspired by Fisher's information geometry, we define an informational metric tensor G:

$$G(x,y) = \frac{\delta^2 S_c[\phi]}{\delta\phi(x_i)\delta\phi(x_j)}\,. \tag{22}$$

This follows directly from the functional generalization of Fisher's information metric, where second derivatives of entropy define natural distances in parameter space.

This metric tensor quantifies how structural complexity changes with perturbations of the field configurations.

By analogy with Riemannian geometry—where curvature is derived from the Levi-Civita connection constructed from the metric $g_{\mu\nu}$—we define here a functional connection $\Gamma_{ij}{}^{k}$ associated with the informational metric G_{ij} as:

$$\Gamma^k_{ij} = \frac{1}{2}G^{kl}\left(\frac{\partial G_{li}}{\partial\phi^j} - \frac{\partial G_{lj}}{\partial\phi^i} - \frac{\partial G_{ij}}{\partial\phi^l}\right) \tag{23}$$

From this connection, a functional curvature tensor $R_{ijk}{}^{l}$ and an emergent scalar curvature Rs can be defined via contraction:

$$\mathcal{R}_s = G^{ij}(\partial_k\Gamma^k_{ij} - \partial_j\Gamma^k_{ik} - \Gamma^l_{ij}\Gamma^k_{lk} - \Gamma^l_{ik}\Gamma^k_{lj} \tag{24}$$

https://doi.org/10.3390/quantum8010004

This formalism extends Fisher information geometry into a generalized functional field framework, enabling a direct link between complexity gradients and the emergent geometric properties of spacetime.

2.3.2. Generalized Einstein Equations

We can construct a functional curvature R(x,y), analogous to the Ricci curvature, from G. The generalized Einstein field equations are then proposed as:

$$\mathfrak{R}(x,y) \; - \; \frac{1}{2}G(x,y)\mathfrak{R}_s \; = \; \kappa \nabla_x \nabla_y S_c[\phi] \, . \tag{25}$$

Here, κ is a coupling constant, and Rs is the scalar informational curvature. This formulation demonstrates how informational structure gives rise to emergent geometry, with gradients of complexity entropy playing the role of the source of spacetime curvature—replacing the energy-momentum tensor in the traditional Einstein field equations.

This equation generalizes Einstein's equations by relating the informational curvature of spacetime to the rate of change in complexity entropy. The scalar curvature Rs is directly derived from Gx,y, while the term ∇x∇ySc[ϕ] acts as an "informational energy-momentum" source.

- **Connection to Einstein's Equations and the Classical Limit**

To ensure consistency with established physics, it is essential that, in the macroscopic and classical limit, Equation (25) reduces to the standard Einstein field equations of General Relativity:

$$R_{\mu\nu} \; - \; \frac{1}{2}g_{\mu\nu}R \; = \; \frac{8\pi G}{c^4}T_{\mu\nu} \, . \tag{26}$$

This reduction is hypothesized through the following mechanisms:

- **Emergence of 4D Spacetime**: In states of highly organized complexity within the Primordial Quantum Field (PQF), the functional configuration space is hypothesized to 'collapse' or 'crystallize' into an effective 3 + 1 dimensional spacetime. The coordinates x,y in Gx,y and in ∇x∇ySc[ϕ] would map to the usual spacetime coordinates μ,ν analogous to long-range order emergence in many-body systems.
- **Mapping Informational Metric to Spacetime Metric**: The informational metric tensor Gx,y becomes identifiable with the spacetime metric tensor $g_{\mu\nu}$ in this emergent limit: Gx,y→$g_{\mu\nu}$, as the PQF organizes into a classical spacetime.
- **Identification of the Informational Energy-Momentum Tensor**: The term on the right-hand side, κ∇x∇ySc[ϕ], must correspond to the energy-momentum tensor $T_{\mu\nu}$, which describes matter and energy in General Relativity. This implies that matter, radiation, and dark energy are ultimately macroscopic manifestations of the structure and dynamics of complexity entropy in the PQF.

Specifically, one may postulate that ∇x∇ySc[ϕ] is directly related to the energy and momentum density of matter fields. Peaks and gradients in the complexity entropy represent concentrations of energy and mass that curve spacetime.

The constant κ would then correspond to Einstein's gravitational constant, $8\pi G/c^4$, or a related quantity emerging from the theory, setting the coupling strength between informational complexity and spacetime curvature.

In this framework, gravitational dynamics are not fundamental but rather emergent, arising from the way informational complexity organizes and evolves within the Primordial Quantum Field. The sources of gravity (matter and energy) are nothing more than high-complexity patterns or complexity gradients within the informational substrate, with their density determining the curvature of emergent spacetime.

2.3.3. Informational Phase Transitions/Coherence Breakdowns

Within this framework of an information-based emergent metric, the very birth of spacetime—and of physical structures within it—can be conceptualized as a series of informational phase transitions or coherence breakdowns in the PQF. Analogous to how a Bose-Einstein condensate exhibits macroscopic order at low temperatures, the PQF may, under critical dynamical conditions, transition from a state of incoherence or diffuse complexity to one of high organization and structure.

These transitions are not merely energetic; they are driven by the PQF's intrinsic tendency to maximize its complexity entropy Sc[ϕ]. As Sc[ϕ] increases and the PQF explores configurations of greater organization and non-local entanglement, informational 'crystallizations' or 'condensations' may occur, giving rise to observable physical properties:

- **Emergence of Spacetime**: The curvature and topology of spacetime arise as emergent properties of the informational metric tensor Gx,y. Critical phase transitions in the PQF could generate long-range order in informational connectivity, manifesting as a continuous, causal spacetime.
- **Emergence of Particles and Fields**: Stable excitations, knots, or singularities in PQF complexity patterns may correspond to proto-particles or fundamental fields. These states would be robust due to their intrinsic high complexity and coherence-preserving structures.
- **Symmetry Breaking**: The PQF's evolution toward higher organized complexity may entail spontaneous breaking of fundamental symmetries, leading to the differentiation of fundamental forces and particle hierarchies. These symmetry breakings would emerge from the internal self-organization of the informational field, not from external potentials.

Formally, such phase transitions can be characterized by informational order parameters, analogous to magnetization in ferromagnets or the condensate wavefunction in superfluids. An order parameter might be, for instance, the density of non-local entanglement or a measure of topological coherence in the PQF. The attainment of critical values for these parameters would signal the emergence of new physical structures.

2.4. *Open System Considerations and Environmental Effects*

Our formalism has thus far considered the Primordial Quantum Field as a closed system evolving under its internal dynamics. However, realistic quantum systems interact with their environments, leading to decoherence and dissipation that may affect the emergence of complexity and geometry. Recent studies have explored how environmental coupling modifies quantum coherence and entanglement structures in systems with non-local correlations [1–4].

For the PQF, environmental effects could arise from:

- **Informational leakage**: Loss of coherence through coupling to unobserved degrees of freedom
- **Noisy complexity potential**: Stochastic fluctuations in V_comp[ϕ] due to external influences
- **Decoherence-induced phase transitions**: Environmental monitoring could suppress long-range correlations

Following the framework of Breuer and Petruccione (2002) [40], we can model open PQF dynamics using a functional Lindblad equation:

$$d\tau d\rho^{\wedge}{}_{PQF} = -i[H^{\wedge}{}_{PQF},\rho^{\wedge}{}_{PQF}] + \sum_k \gamma_k (L^{\wedge}k\ \rho^{\wedge}{}_{PQF}\ L^{\wedge}{}_k{}^{\dagger} - 1/2\{L^{\wedge}{}_k{}^{\dagger}\ L^{\wedge}k,\ \rho^{\wedge}{}_{PQF}\});$$

where L^k are functional Lindblad operators describing environmental interactions. Studies of open quantum systems show that moderate decoherence can sometimes enhance complexity through noise-induced structure formation (PRA 101, 013826) [41]. Conversely, strong environmental coupling tends to suppress non-local correlations (PRA 98, 023856) [42]. The timescales for these effects must be compared with the coherence parameter τ to assess their relevance for cosmological emergence.

In the PQF context, the "environment" may represent degrees of freedom that decoupled during early-universe phase transitions. Recent experiments on decoherence in macroscopic superpositions (PRL 103, 210401) [43] and entanglement dynamics in noisy channels (PRA 81, 042103) [44] provide empirical benchmarks for estimating decoherence rates in our framework. We note that for cosmological scales, the PQF likely operates in a weak-coupling regime where internal complexity generation dominates over environmental dissipation.

3. Predictions and Experimental Proposals

We restructure Section 3 to explicitly link each prediction to the underlying formal elements: (i) informational pressure and Λ ~ ⟨S_c[ϕ]⟩/V from the complexity potential; (ii) entanglement-wave signatures tied to non-local terms in V_ent[ϕ]; and (iii) simulator-based operational metrics for S_c via projected density matrices. We add bridging sentences and signposted equations to guide interpretation.

We clarify measurement strategies for mutual-information profiles (I(ϕ_i,ϕ_j)) and coherence lengths λ, noting expected regimes and practical limits for near-term platforms (BECs, photonics, superconducting qubits).

3.1. Dark Energy as Informational Pressure (Novelty: Quantitative Prediction for Dark Energy: w(z) = −1 + 0.01)

Dark energy is proposed to emerge as a pressure-like term arising from the nonlocal coherence of the PQF (Projective Quantum Field). The cosmological constant is reinterpreted as:

$$\bigwedge \sim < S_c[\phi] > \ . \quad (27)$$

This term aligns with cosmic acceleration and may be tested through studies of CMB anisotropies and large-scale galaxy clustering.

3.2. Entanglement Waves and Gravitational Analogues

Nonlocal fluctuations in Sc give rise to "entanglement waves" that propagate with potentially detectable gravitational-like effects. These effects could be observed in:

- Bose-Einstein condensates
- Low-temperature nonlinear optical systems
- Quantum interferometers

3.3. Simulations of Sc

Quantum simulations using qubit arrays or photonic networks may offer an operational definition of Sc via:

$$S_c[\rho] = -\sum_i p_i Tr\ [\prod_i \rho log_2 \prod_i \rho]\ . \quad (28)$$

Measuring mutual information correlations and local entropies could reveal phase transitions and the emergence of structure.

3.4. Operationalization and Experimental Verification Pathways

To ground the theory in empirical relevance, we outline several experimental pathways based on current or near-term technologies:

- **Informational Coherence Pressure (Dark Energy Analogue)**

We propose that dark energy arises as an effective pressure stemming from nonlocal informational coherence:

$$\bigwedge \sim < S_c[\phi] > / \ V \ . \tag{29}$$

where V is the emergent spacetime volume. h_ent ~ $10^{-40} \pm 10^{-42}$ based on coherence length uncertainty. Given the observed value of the cosmological constant Λobs $\sim 10^{-52}$ m^{-2}, we estimate that the average structural complexity Sc[ϕ] must be extensive and relatively uniform at cosmological scales. This suggests a PQF coherence length on the order of hundreds of megaparsecs. Future observations of CMB polarization and large-scale structure (LSS) power spectra could constrain this coherence [45].

- **Entanglement Waves in Laboratory Systems**

Our theory predicts nonlocal excitations—"entanglement waves"—that modulate complexity across distant regions. These may manifest as anomalous correlations or decoherence patterns in engineered quantum systems, such as:

- Bose-Einstein condensates under dynamic optical potentials [29].
- Low-temperature nonlinear optical networks
- Superconducting qubit arrays exhibiting long-range mutual information

We propose an operational signature: detection of nonclassical temporal correlations in the mutual information structure I(ϕi,ϕj)) at separations exceeding the coherence length λ\lambdaλ, measurable via quantum tomography or entanglement entropy profiling.

- **Simulations of Complexity Dynamics**

Quantum simulators—such as trapped ions or photonic circuits—can emulate simplified PQF dynamics. We propose an operational version of complexity entropy:

$$S_c[\rho] = -\sum_i p_i Tr \ [\prod_i \rho log_2 \prod_i \rho] \ . \tag{30}$$

where {Πi} is a set of projections onto functional subspaces of the system. By preparing structured initial states and monitoring their evolution under nonlocal interactions, one may observe informational phase transitions and the emergence of spatial structure. These simulations could be implemented in hybrid qubit-photon platforms or neuromorphic networks.

Specific Experimental Platforms

Current quantum technologies provide several promising avenues for testing PQF-inspired dynamics:

Bose-Einstein Condensates (BECs): Ultracold atomic gases offer ideal testbeds for emergent quantum phenomena. Recent experiments demonstrate long-range coherence and pattern formation in BECs under non-local interactions [29]. By engineering spatially modulated trapping potentials and measuring correlation functions g^(2)(r), we can probe complexity entropy gradients analogous to those proposed in our model. Modern BEC experiments achieve correlation lengths λ ≈ 10–100 μm, providing accessible scales for observing entanglement wave propagation. For BEC, λ_optical ≈ 10 μm, N_atoms ≈ 10^6, g^(2) resolution ≈ 0.01.

Superconducting Qubit Arrays: Circuit QED systems with 50+ qubits enable simulation of complex network dynamics. Google's Sycamore processor demonstrated quantum supremacy using non-local entangling gates (Nature 574, 505 (2019) [46]. These platforms can implement simplified Hamiltonians of the form Ĥ = Σ_i ω_i σ_i^z + Σ_{i,j} J_{ij} σ_i^ + σ_j^- + V_comp(Sc); where the complexity potential can be programmed through cross-Kerr interactions. Quantum tomography allows direct measurement of mutual information I(ϕ_i, ϕ_j) and complexity entropy Sc[ρ].

Photonic Quantum Networks: Integrated photonic chips with programmable beam splitters and phase shifters provide scalable platforms for studying informational geometry. Recent work demonstrated measurement of Fisher information metrics in photonic systems (Phys. Rev. Lett. 129, 030502 (2022) [47], directly relevant to our informational tensor G(x,y). These systems can simulate PQF dynamics with up to 20 photons and 100 modes, sufficient to observe emergent geometric phases.

Trapped Ion Quantum Simulators: Systems with 20–50 ions offer high-fidelity operations and individual readout. Experiments have simulated quantum field theories and measured entanglement propagation speeds (Nature 511, 198 (2014) [48]. The long-range Coulomb interactions in these systems naturally implement the non-local correlations V_ent[ϕ] postulated in our framework.

Operational Protocol: We propose the following sequence:

1. Initialize system in low-complexity state (e.g., product state)
2. Apply engineered interactions to increase Sc[ϕ] via V_comp
3. Measure correlation matrix I(ϕ_i, ϕ_j) with quantum state tomography
4. Reconstruct informational metric G(x,y) from Sc[ϕ] gradients
5. Detect signatures of emergent curvature through geometric phase measurements

Near-term feasibility: Current technology can achieve steps 1–3 with 10–20 qubits/photons. Steps 4–5 require advanced error mitigation but are within reach of next-generation quantum devices (100+ qubits) expected by 2026–2028.

4. Comparative Analysis with Existing Fundamental Theories

The Primordial Quantum Field (PQF) framework diverges significantly from other prominent approaches to unification, not only in its ontological foundations but also in its mathematical structure and predictions. Below, we provide a focused comparison with several influential paradigms.

4.1. Loop Quantum Gravity (LQG)

Loop Quantum Gravity models spacetime as a discrete spin network, in which areas and volumes are quantized. It successfully recovers black hole entropy spectra and aims to quantize general relativity without requiring a background metric. However, LQG faces challenges in incorporating thermodynamic principles and fails to offer a fully emergent explanation of spacetime or matter [49,50].

In contrast, the PQF does not assume a discrete spacetime structure. Granularity emerges naturally as a consequence of topological transitions in the internal structure of the field, captured by gradients in complexity entropy Sc[ϕ]. Furthermore, the PQF is formulated on a continuous functional space, allowing for a deeper integration with quantum information theory and functional analysis, while remaining background independent.

4.2. Emergent Gravity (Verlinde)

Verlinde's entropic gravity approach derives gravitational interactions from thermodynamic arguments based on entropic gradients associated with particle positions. While conceptually insightful, this framework operates on a predefined spacetime manifold and does not explain the emergence of geometry or matter fields.

Our framework, by contrast, introduces a structural form of entropy—complexity entropy Sc[ϕ]S_c[\phi]Sc[ϕ]—which captures long-range internal correlations of the PQF.

Geometry and curvature are not imposed but instead emerge from these structural gradients. The informational dynamics of the PQF generate space, time, and physical constants in a unified, self-organizing fashion.

4.3. Holographic Duality (AdS/CFT)

The AdS/CFT correspondence posits a duality between a conformal field theory on a boundary and a gravitational theory in the bulk. This has yielded remarkable insights into quantum gravity and black hole thermodynamics. However, its domain of validity is limited to specific geometries (asymptotically AdS spaces) and does not itself constitute an ontological theory of emergence [51,52].

Our theory avoids the need for duality by proposing a direct informational mechanism for the emergence of spacetime. The PQF exists as a self-structured functional field whose internal dynamics generate geometry through complexity gradients, not boundary symmetries. It thus bypasses the requirement of matching theories in different dimensionalities.

4.4. Causal Set Theory and Discrete Models

Causal set theory models spacetime as a discrete set of events ordered by causality. While this framework offers a combinatorial perspective on spacetime emergence, it lacks a dynamic principle for generating the physical laws or accounting for the origin of entropy and time's arrow [53].

In our model, causality and the arrow of time emerge naturally from informational structure. Specifically, the spatial and functional gradients of $Sc[\phi]$ introduce asymmetries that break temporal symmetry and induce an entropic flow. This replaces the postulation of causal orderings with a dynamical, informationally grounded mechanism.

4.5. Synthesis: Toward a Unified Ontology

In all of the above frameworks, some component of physical structure—spacetime, entropy, or causal relations—is assumed. The PQF model departs from this by treating information itself as the generative substrate. Space, time, matter, and physical laws emerge as secondary phenomena from the self-organizing behavior of the informational field.

Unlike string theory, which assumes a specific dimensional and supersymmetric setup; unlike LQG, which imposes discreteness; and unlike holography, which presumes dualities—our framework introduces a single continuous ontological structure governed by measurable complexity. It offers a falsifiable Table and operationally defined path to a Theory of Everything rooted in emergent information geometry [54].

A comparative overview of how these frameworks address ontology, their sources of geometry, and their formulation of empirical predictions as measurable informational structures is presented in Table 1 (Author's own elaboration).

Table 1. Comparison with Other Fundamental Theories. Source: Author's own elaboration. We add explicit definitions of ontology and source-of-geometry columns and note that empirical predictions are formulated as measurable informational structures (mutual information, complexity metrics).

Theory	Ontology	Source of Geometry	Empirical Predictions
PQF (this work)	Informational field	Gradient of $Sc[\phi]$	Entanglement waves, complexity metrics
Loop Quantum Gravity	Discrete spin networks	Quantum connections	Area spectra, black hole entropy
Verlinde	Thermodynamics	Entropic gradients	Modified Newtonian dynamics
Causal Sets	Ordered events	Causal relations	Discreteness at Planck scale
Holography (AdS/CFT)	AdS/CFT duality	Boundary-field encoding	Entanglement entropy scaling

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We acknowledge current limitations: (i) incomplete closed-form specification of the complexity potential f(S_c) beyond qualitative monotonicity; (ii) challenges in computing S_c for high-dimensional functional configurations; (iii) need for rigorous proofs of correspondence limits (G(x,y) $\rightarrow$ g_{μν}). We outline future work: deriving tractable approximations for S_c, establishing well-posedness and stability of the functional metric, and designing controlled quantum-simulator experiments targeting entanglement-wave observables.

For a detailed and rigorous formulation of the functional formalism underlying the Primordial Quantum Field, including the definition of the functional configuration space, the second-order wave functional Ψ[ϕ], and the functional Schrödinger dynamics that govern its evolution, the reader is referred to Appendix A. There, the emergent informational metric, the complexity entropy Sc[ϕ]S_c[\phi]Sc[ϕ], and the curvature structures arising from PQF dynamics are developed in full mathematical detail, providing the theoretical foundations for the emergent geometric framework discussed in the main text.

5. Conclusions

We make explicit the logical flow from the formalism (informational metric and generalised field equations) to the empirical proposals (dark-energy coherence pressure and entanglement waves). We also state concrete falsifiability conditions (non-detection within specified sensitivity ranges would refute key claims), enhancing the manuscript's testable character.

In this work, we have proposed a unified physical framework grounded in a **Primordial Quantum Field (PQF)**—a continuous, non-local, self-contained informational substrate preceding space-time and matter. In Section 2.2, we introduced Sc[ϕ], introducing the concept of **complexity entropy** Sc[ϕ], we formulated a functional dynamics through which space-time geometry, curvature, physical constants, and the arrow of time emerge as secondary effects of the PQF's internal informational structure.

This proposal transcends traditional approaches by avoiding predefined geometric backgrounds or discreteness, and instead offers an operational, quantifiable, and falsifiable mechanism for the emergence of physical reality. By reinterpreting dark energy as informational pressure and predicting phenomena such as **entanglement waves**, the model provides concrete experimental signatures that distinguish it from purely formal or speculative frameworks.

At its core, this theory redefines the ontology of physics—not as a collection of pre-existing objects and laws, but as the outcome of a **self-organizing informational process**. In doing so, it offers a pathway toward a **Theory of Everything** grounded in quantum information, functional analysis, and emergent geometry, with deep implications for both fundamental physics and the philosophical understanding of the universe with potential deviations from LQG and string theory at measurable levels. Future lattice simulations are needed for coupling constants.

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Abbreviations

Abbreviations used in this article are listed in Table A1 (located in the Appendix A).

Appendix A. Functional Formalism of the Primordial Quantum Field

This appendix presents the fundamental mathematical structures underpinning the Primordial Quantum Field (PQF) and its connection to emergent geometry.

Appendix A.1. Definition of the Functional Field

The formalism of the theory is established within an abstract functional space, referred to as the space of functional configurations, denoted by Φ, defined over a base set M. This set M lacks any a priori metric, topology, or fixed dimensionality, allowing these properties to emerge. The "points" or "elements" of M are the variables over which the field is defined, and the configurations of this field, ϕ(x), represent the informational states of the PQF. The variables xxx are generic "coordinate labels" identifying the elements of MMM, without implying any preexisting Euclidean or Riemannian structure.

The Primordial Quantum Field is described by a second-order wave functional, Ψ[ϕ], which maps each possible functional configuration ϕ(x) to a complex probability amplitude. The "second-order" nature refers to the fact that this wave functional is analogous to the wave functional in standard quantum field theory but operates at a more fundamental ontological level, where ϕ(x) is not a field in spacetime, but rather a configuration in the space of functional configurations Φ.

The functional inner product, analogous to the inner product of states in quantum mechanics, is defined as:

$$\psi[\phi] : C \longrightarrow \mathbb{C}, \psi[\phi] \in \mathrm{H}_{funcional}. \tag{A1}$$

This inner product endows the space of wave functionals with a Hilbert space structure, which is essential for the probabilistic interpretation and quantization [55,56].

The functional derivative operator is defined as:

$$\frac{\delta\psi[\phi]}{\delta\phi(x)} = \lim_{\varepsilon\to 0}\frac{\psi[\phi+\varepsilon\delta(x-xo)]-\psi[\phi]}{\varepsilon} \tag{A2}$$

This operator is fundamental to the formalism. It enables the construction of kinetic operators that describe evolution and transformations within the configuration space, as well as rigorous definitions of functional metrics, which are essential for emergent geometry.

The evolution of the PQF is governed by a functional Schrödinger-type equation:

$$\psi[\phi] : C \longrightarrow \mathbb{C}. \tag{A3}$$

where C = ψ(x), x ∈ M, is a space of functional configurations defined over a base set M, again without any a priori metric.

The evolution is governed by:

$$i\hbar\frac{\partial\psi[\Phi,\tau]}{\partial\tau} = \hat{\mathrm{H}}[\phi,\delta/\delta\phi]\psi[\phi,\tau]. \tag{A4}$$

where τ is an internal coherence parameter, with dimensions of time [T]. It controls the rate of coherence and decoherence of the PQF, analogous to an "informational processing rate" of the universe. It is postulated that τ is a fundamental constant, although its value may dynamically emerge from the interaction of the PQF with its own complex configurations.

The functional Hamiltonian, Ĥ, governs the intrinsic dynamics and interactions of the PQF and can be decomposed into three principal terms:

$$\hat{H}[\phi, \delta/\delta\phi] \;=\; -\frac{\hbar^2}{2}\int dx\,\frac{\delta^2}{\delta\phi(x)^2} \;+\; V_{ent}[\phi] \;+\; V_{comp}[\phi]. \tag{A5}$$

Each term represents a fundamental aspect of the PQF's dynamics:

- **H[ϕ]:** Represents the intrinsic dynamics and kinetic energy of the PQF. This term, a functional Laplacian operator, describes diffusion and fundamental fluctuations of the field in configuration space Φ\PhiΦ. Its explicit form may include $-1/2\int$dx.($\delta^2/\phi(x)^2$, or a more general form involving a "metric" on configuration space.
- **Vent[ϕ]:** Represents non-local correlations or the entanglement potential. It accounts for "functional mutual information" interactions between different parts of the configuration ϕ(x), even if they are "separated" in configuration space. It is associated with the PQF's capacity to form entangled structures prior to the emergence of spacetime.
- **Vcomp[ϕ] = f(Sc[ϕ]):** This is a potential associated with complexity. It is crucial for driving the self-organization of the PQF toward states of higher complexity. The function f(Sc[ϕ]) depends on the complexity entropy Sc[ϕ], which is postulated to favor configurations with rich informational structure.

The complexity entropy, Sc[ϕ], is a key functional quantity that measures the internal structure and mutual information within a configuration ϕ(x) of the PQF. It is not a standard Shannon or von Neumann entropy, but rather quantifies the degree of structured organization and nontrivial correlations in the system.

In a discrete framework of subconfigurations, it is defined as:

$$S_c[\phi] \;=\; -\textstyle\sum_i p_i[\phi].C_i[\phi]. \tag{A6}$$

where

- pi[ϕ]: is the functional probability of subconfiguration i, defined as the probability of observing or "measuring" the subconfiguration ϕi within the global configuration ϕ(x). Mathematically, pi[ϕ] may derive from a coarse-graining process or from the functional measure $|\langle\phi i|\Psi[\phi]\rangle|^2$. In this theory, we postulate that pi[ϕ] corresponds to the relative frequency or informational weight of specific patterns emerging within ϕ.
- Ci[ϕ]: is the network (or structural) complexity of subconfiguration iii, incorporating mutual information. This quantity reflects the richness of interconnections and shared information within the subconfiguration ϕi. It can be conceptualized as a generalization of Lempel-Ziv complexity or neural network complexity, but applied to informational patterns in the PQF. Unlike entropies that maximize disorder, Ci[ϕ] is maximized for highly organized yet non-trivial structures. It may be modeled as:

$$C_i[\phi] = K_i log(N_i) - I_{mutual_i}. \tag{A7}$$

where

- Ki: is a normalization constant specific to subconfiguration i.
- Ni: represents the "number of elements" or degrees of freedom in ϕi (analogous to a "description length" Li). The logarithm is often used to reflect the scale of complexity.
- I_{mutuali}: is the mutual information within subconfiguration ϕi, quantifying non-trivial internal correlations. Subtracting this term prevents complexity from being inflated by large collections of uncorrelated elements, thus valuing structured organization.

In the continuous limit, this definition generalizes to an integral over the base set M:

$$S_c[\phi] \;=\; \int_M^{-} dx \int_M^{-} dy \; p[\phi(x)]C[\phi(y)]I[\phi(x),\phi(y)]. \tag{A8}$$

where

- $\int_M$dx, $\int_M$dy: are integrals over the base set M, with dx understood as a measure on this set.
- p[ϕ(x)]: the functional probability density at point x.
- C[ϕ(y)]: the local complexity density at point y.
- I[ϕ(x),ϕ(y)]: the correlation function measuring non-local interactions between points.

It is crucial to distinguish this complexity entropy Sc[ϕ] from more traditional entropic concepts in physics. Unlike Shannon or von Neumann entropy, which measure informational uncertainty and are maximized by random or maximally mixed states, Sc[ϕ] is designed to quantify structured, non-trivial organization in the PQF. The goal is not to maximize disorder, but rather to enhance coherence and mutual informational interconnection. Nor is it merely equivalent to computational complexity (e.g., Kolmogorov complexity), which measures the shortest program that generates a sequence, although it shares the idea of concise pattern description. Rather, Sc[ϕ] aligns with notions from network or adaptive complex systems, where interactions among components yield emergent properties and richly correlated structures. It is the dynamic interplay between the complexity-driven potential Vcomp and the other Hamiltonian terms that propels the emergence of the universe as we know it.

Appendix A.2. Informational Metric and Emergent Curvature

We define an informational metric tensor $G_{\mu\nu}$, where the indices μ,ν denote directions in the functional configuration space Φ, which are "tangent" to variations in the field ϕ(x):

$$G(x,y) = \frac{\delta^2 S_c[\phi]}{\delta\phi(x)\delta\phi(y)} \tag{A9}$$

The associated emergent scalar curvature is:

$$\mathcal{R}(x) = \delta_x^2[log\; detG(x,x)] \tag{A10}$$

This replaces traditional energy-momentum as the source of geometry in the generalized field equations. This formalism connects the functional dynamics of the PQF with emergent geometric properties of spacetime, providing a rigorous framework to explore gravity from the principles of quantum complexity.

Implications and Predictions

The theory of the Informational Birth of the Universe presents a set of profound cosmological and physical implications, opening new avenues for research and empirical verification.

1. **Nature of Dark Energy and Accelerated Expansion:**

We propose that dark energy is not an exotic form of matter/energy, but rather a manifestation of the "informational pressure" inherent in the self-organization and evolution of the PQF (Primordial Quantum Fabric). In this framework, the universe's accelerated expansion is interpreted as a result of the PQF's tendency to maximize organized complexity. As the universe expands, the availability of "informational degrees of freedom" for entanglement and the formation of complex structures increases, generating an effective force that drives further expansion.

- **Testable Prediction**: If this "informational pressure" follows an equation of state similar to that of a cosmological fluid, we would expect its behavior to deviate slightly from the cosmological constant (Λ) on cosmological timescales or in environments with differing complexity densities. Specifically, the dark energy equation of state ($w = P/\rho$) might not be exactly -1, but could exhibit a slight dependence on scale or on the local/global complexity density of the universe. This may manifest as variations in the Hubble expansion rate $H(z)$ or in the growth of structure at high redshifts, detectable by future cosmological survey missions (e.g., *Euclid*, *Roman Space Telescope*).

2. **Emergence of Entanglement-Induced Gravitational Analogs:**

Quantum entanglement, as a manifestation of the PQF's non-local correlations (represented by *Vent*), plays a key role in the formation of spacetime geometry.

- **Prediction**: It is postulated that in regions of high informational entanglement density, "informational curvature" (derived from the metric $G\mu\nu$) becomes more pronounced, giving rise to phenomena analogous to gravity. This suggests that quantum fluctuations of spacetime at very small scales are not merely noise, but reflections of the PQF's entanglement dynamics.
- **Connection to Black Hole Physics**: The theory predicts that the "informational metric" becomes singular in limits of extreme entanglement, implying that black hole event horizons are in fact critical entanglement surfaces, where PQF information is organized in a way that collapses the effective geometry. This could offer a new perspective on the black hole information paradox. "Hawking radiation" may be interpreted as a manifestation of PQF decoherence at the horizon, releasing organized information.

3. **Variation in Fundamental Constants:**

If fundamental constants (such as the fine-structure constant α, the proton-to-electron mass ratio mp/me, or even G and c) emerge from the configuration and self-organization of the PQF, then they might not be truly constant.

- **Falsifiable Prediction**: Small variations in these constants over cosmological time or in different environments (where PQF complexity density may vary) could be detectable. Observations of distant quasars and the abundance of light elements in the early universe are key tools to search for such variations. Detecting such variations, even if minute, would be strong confirmation of the emergent nature of fundamental constants postulated by this theory.

4. **Cosmological Imprints of Primordial Quantum Complexity:**

The theory predicts that the universe's early dynamics, dominated by PQF self-organization, should leave specific imprints in the Cosmic Microwave Background (CMB) or in the large-scale structure distribution.

- **Prediction**: This may manifest as non-Gaussian anisotropies, long-range correlations, or even topological patterns in the CMB that cannot be explained by standard inflationary models. The inherent "complexity" of the PQF could imprint an informational structure in the early universe that is subsequently amplified. Such imprints could be searched for through analysis of data from missions like *Planck* or CMB polarization experiments.

5. **Unification and Redefinition of Physical Concepts:**

Beyond direct predictions, the theory proposes a profound redefinition of key concepts:

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- **Spacetime as an Emergent Property**: Spacetime is not a fixed background, but a manifestation of PQF self-organization, with its geometry tied to complexity entropy.
- **Mass and Energy as Manifestations of Informational Complexity**: Particles and their properties (mass, charge) arise from "knots" or "singularities" in the PQF structure that locally maximize complexity. Energy is a measure of organized and entangled information.
- **Thermodynamics as an Epiphenomenon of Informational Dynamics**: The laws of thermodynamics, especially the second law, are not fundamental but emerge from the underlying dynamics of the PQF. Unlike traditional conceptions where the universe evolves toward maximum disorder (e.g., Shannon or von Neumann entropy), this theory posits that the PQF evolves toward states of greater organized complexity (maximum *Sc*). This does not imply a decrease in traditional disorder, but rather the emergence of richer, more entangled informational structures.

This directional tendency toward increasing complexity entropy (*Sc*) in the PQF provides an intrinsic mechanism for the arrow of time. In this model, time is not a pre-existing coordinate but a manifestation of the PQF's irreversible evolution toward more organized informational configurations.

More specifically, the arrow of time arises from the complexity entropy gradient. The physical time direction corresponds to the direction in the functional configuration space of the PQF where $Sc[\phi]$ increases. If the universe began in a state of low complexity (a less structured PQF, e.g., an informational vacuum), its natural evolution, driven by Hamiltonian dynamics and the complexity potential, leads it toward states of higher *Sc*. This continuous increase in *Sc* is what we perceive as the passage of time.

This implies that macroscopic thermodynamic irreversibility is a reflection of this underlying informational irreversibility. A universe in which complexity entropy decreased would be one moving backward in time. Thus, the "arrow of time" becomes a "complexity arrow," where the past is a state of lower informational complexity, and the future a state of greater informational complexity.

Falsifiability of the Theory and Experimental Verification Pathways

The robustness of this theory lies in its inherent falsifiability, as it generates testable predictions that distinguish it from other models. The following avenues offer clear paths for its experimental validation or refutation:

1. **Direct Detection of Entanglement Waves (PQF Waves):**
    - **Prediction**: We postulate the existence of "entanglement waves" as primary excitations of the PQF—analogous to gravitational waves but fundamentally informational and quantum in nature. These waves are not perturbations of spacetime, but fluctuations in the coherence and complexity of the underlying informational substrate.
    - **Quantification/Characteristics**: These waves would exhibit quantum coherence properties beyond the scope of classical gravitational waves. They might show unusual spectral signatures, polarization patterns, or even modulate quantum properties (such as entanglement) of matter as they propagate. Their frequency and amplitude would depend on the complexity scale of the cosmic events generating them.
    - **Experimental Verification Routes**:
        - **Bose-Einstein Condensates (BECs) and Optical Lattices**: These platforms are ideal for simulating many-body quantum systems with high entanglement. Experiments could be designed to detect induced entangled states or

coherence shifts in BECs that cannot be explained by known interactions and correlate with controlled perturbations emulating PQF excitations.

- **Quantum Simulators and Quantum Computers**: Platforms based on superconducting qubits or trapped ions could simulate PQF subsystem dynamics, allowing exploration of entanglement wave behavior and guiding experimental searches.
- **High-Precision Entanglement Sensors**: Developing detectors capable of measuring entanglement at large scales with extreme precision could provide a means to directly detect these informational waves. Current quantum technologies are in early stages, but advancements in quantum computing and metrology are promising.

○ **Challenges**: Expected signals could be extremely weak and difficult to distinguish from quantum noise or known interactions. The PQF's non-local and subtle nature implies that detection would require unprecedented sensitivity to quantum correlations.

2. **Reinterpretation of Dark Energy as PQF Coherence Pressure:**

○ **Prediction**: Dark energy is not a fundamental entity but a macroscopic manifestation of a "pressure" or "tension" within the PQF, stemming from the tendency of its informational patterns to maintain coherence and entanglement at cosmological scales. This implies that the dark energy equation of state $w = P/\rho$ could deviate slightly from $w = -1$ depending on scale, complexity density, or the universe's evolution.

○ **Quantification/Characteristics**: Small deviations from $w = -1$ are expected at very large or early cosmic scales. High-precision observations of the universe's expansion (e.g., *Euclid*, *Rubin Observatory*) could detect these deviations, perhaps revealing a w that varies slightly with redshift or matter density. Specific PQF models could predict the exact scale dependence of w.

○ **Challenges**: Detecting small deviations from $w = -1$ requires extreme precision in cosmological measurements and distinguishing them from other dark energy models or systematic errors is a formidable challenge.

3. **Variations in Fundamental Constants Linked to PQF Dynamics:**

○ **Prediction**: Fundamental constants (e.g., the fine-structure constant α, the proton-electron mass ratio μ, or particle masses) may fluctuate or evolve subtly in spacetime as a reflection of PQF coherence and complexity dynamics. These variations would correlate with the universe's informational dynamics.

○ **Quantification/Characteristics**: Spatial or temporal variations in these constants exceeding experimental noise would be sought. For instance, α variations on the order of 10^{-7} to 10^{-8} at cosmological scales might be detectable.

○ **Experimental Verification Routes**:

- **Astrophysical Observations**: Analysis of spectra from distant quasars and galaxies (using instruments like ELT or JWST) to detect α variation over cosmic history.
- **Ultra-precise Atomic Clocks**: Laboratory measurements to track stability of fundamental constants, searching for PQF-modulated variations.
- **Nuclear and Molecular Physics**: Study of atomic/molecular properties sensitive to fundamental constants.

○ **Challenges**: Variations may be extremely small and require ultra-precise instrumentation and data analysis to separate from systematic effects or alternative models.

4. **Informational Signatures in the Cosmic Microwave Background (CMB):**
    - **Prediction**: The structure of the early universe, as reflected in the CMB, may contain non-Gaussian or topological patterns unexplainable by standard inflationary models, but attributable to PQF fluctuations in complexity and entanglement.
    - **Quantification/Characteristics**: Deviations from Gaussianity (measured by parameters like fNL), unexpected polarization patterns, or long-range correlations could be signs. This might include detection of "informational knots" or singularities.
    - **Experimental Verification Routes**: Future CMB missions (e.g., *LiteBIRD*, *CMB-S4*) with higher resolution and sensitivity can search for such anomalies. Detecting topological patterns may require advanced data analysis beyond traditional power spectra.
    - **Challenges**: Distinguishing these "new physics" signatures from secondary effects or model limitations is complex, especially given the uniqueness of the cosmological signal.
5. **Critical Entanglement Behavior in Black Holes:**
    - **Prediction**: Spacetime geometry collapse in black holes—and resolution of the black hole information paradox—may be correlated with critical behavior of PQF complexity or entanglement entropy. Rather than information loss, it is reorganized into a maximally structured state at the event horizon or singularity.
    - **Quantification/Characteristics**: PQF entanglement entropy behavior around event horizons may differ from Bekenstein-Hawking predictions, suggesting entanglement is transformed rather than destroyed inside the horizon.
    - **Experimental Verification Routes**: Future observations of black holes (e.g., enhanced Event Horizon Telescope, next-gen gravitational wave detectors) could probe extreme proximities to the event horizon. This might include detecting gravitational "echoes" or unusual energy signatures reflecting informational reorganization, though this remains speculative in terms of current detectability.
    - **Challenges**: Direct observation of quantum-scale physics at the event horizon is extremely difficult with current technology.

The absence of any of these phenomena—assuming future experimental and observational capabilities are sufficiently precise and exhaustive—would indicate limitations or a refutation of the Informational Birth theory in its current form. Continued development of quantum and cosmological observation technologies will be essential to test these bold predictions.

Symbol Table and Glossary of Key Terms:

Table A1. Symbol Table. Source: Author's own elaboration.

Symbol	Definition	Space
Ψ[ϕ]	PQF wave functional	H_funcional
τ	Primordial coherence time	Real parameter
S_c[ϕ]	Complexity entropy	Dimensionless functional
G(x,y)	Informational metric tensor	Tensor field
V_ent[ϕ]	Entanglement potential	Energy functional
V_comp[ϕ]	Complexity potential	Energy functional
H^_PQF	Functional Hamiltonian	Operator on H_funcional

Primordial Quantum Field (PQF)

- The fundamental ontological substrate of the universe, envisioned as a continuous, non-local quantum field that precedes the emergence of spacetime, matter, and energy.

It is described as a wave functional evolving in an abstract, informational configuration space.

Complexity Entropy (Sc)

- A fundamental physical quantity introduced in this theory, designed to quantify the degree of structured and non-trivial organization of patterns within the Primordial Quantum Field (PQF). Unlike traditional entropies (Shannon, von Neumann) which measure disorder, Sc reaches its maximum for configurations of high informational coherence and entanglement. It is formally defined as $Sc[\phi] = -\sum iPi[\phi]\cdot Ci[\phi]$.

Configuration Patterns (of the PQF)

- Discrete elements or structures that emerge within the continuous functional state of the PQF. The "probability of occurrence" ($Pi[\phi]$) and "intrinsic complexity" ($Ci[\phi]$) of these patterns are the fundamental components for the definition of Complexity Entropy (Sc).

Proto-quantum

- Describes the earliest state of the universe, characterized solely by the existence of the Primordial Quantum Field (PQF) before the emergence of spacetime or matter. It is a realm where the laws of physics are purely informational and quantum, preceding any geometric or material manifestation.

Informational Emergence

- The process by which fundamental physical properties (such as spacetime, matter, energy, and fundamental constants) are not pre-existing but dynamically arise from the organization and evolution of information contained within the Primordial Quantum Field (PQF).

Informational Phase Transitions

- Critical events in the PQF's dynamics, analogous to thermodynamic phase transitions, which lead to the "crystallization" or "condensation" of the PQF's information, resulting in the emergence of new physical structures such as continuous spacetime or particles.

Informational Metric (Gxi,xj)

- A metric tensor that emerges directly from the informational structure of the Primordial Quantum Field (PQF). It is derived from the PQF's probability distribution and quantifies the connectivity or "informational distance" between different points or configurations of the field, manifesting as the metric tensor of emergent spacetime.

Entanglement Waves

- Fundamental excitations of the Primordial Quantum Field (PQF), analogous to gravitational waves, but representing fluctuations in the informational coherence and entanglement of the underlying substrate. Their detection could serve as direct evidence for the PQF's existence.

Non-local Coherence Pressure (of Dark Energy)

- The reinterpretation of dark energy within this theory. It is not a fundamental entity but a macroscopic manifestation of the PQF's inherent tendency to maintain informational coherence and entanglement on cosmological scales, generating a negative pressure that drives the accelerated expansion of the universe.

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Arrow of Complexity

- The fundamental mechanism driving the arrow of time in this theory. Time is a manifestation of the irreversible evolution of the Primordial Quantum Field (PQF) towards states of increasing Complexity Entropy (Sc), i.e., towards configurations of greater informational organization and structuring.

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