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Beyond Spacetime: Information as the Fundamental Substrate of Reality

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Abstract

We propose a radical reconceptualization of physical reality based on four fundamental principles: (1) Information encoded in quantum entanglement patterns, not matter or energy, constitutes the primary substrate of existence; (2) Spacetime emerges as an error correction mechanism to maintain coherence in underlying informational structures; (3) The Big Bang represents an informational phase transition rather than a temporal cosmological event; and (4) Biological evolution manifests as emergent narrative patterns within information space rather than temporal processes. We demonstrate how the speed of light emerges as a fundamental information processing limit in this framework, reconciling relativistic physics with emergent spacetime theory. This ontological shift dissolves classical paradoxes in quantum gravity, consciousness studies, and the relationship between physics and information theory.

Keywords: Quantum Information, Emergent Spacetime, Information Theory, Quantum Gravity, Holographic Principle

1 Introduction

The foundations of modern physics rest upon an implicit assumption that spacetime provides the fundamental arena within which physical processes unfold. However, mounting evidence from quantum information theory, holographic duality, and quantum gravity research suggests this assumption may be fundamentally misguided. Instead of spacetime being primary, we propose that information—specifically, patterns of quantum entanglement—constitutes the true substrate of reality, with spacetime, matter, and time itself emerging as secondary phenomena.

This paper develops a comprehensive framework for understanding reality as fundamentally informational, addressing four key propositions that challenge conventional physics and cosmology. We demonstrate how this approach resolves longstanding paradoxes while providing novel insights into the nature of consciousness, evolution, and cosmic origins.

2 Theoretical Framework

2.1 Information as Ontological Primary

Traditional physics assumes a hierarchy: matter/energy \rightarrow forces \rightarrow spacetime geometry. We invert this hierarchy completely:

$$\text{Information} \rightarrow \text{Entanglement Patterns} \rightarrow \text{Emergent Spacetime} \rightarrow \text{Matter/Energy} \quad (1)$$

Let \mathcal{I} represent the fundamental information space, characterized by quantum entanglement networks. The Hilbert space \mathcal{H} of physical systems emerges from \mathcal{I} through:

$$\mathcal{H} = \bigotimes_i \mathcal{H}_i \quad \text{where} \quad \mathcal{H}_i \subset \mathcal{I} \quad (2)$$

Physical observables arise as information-preserving mappings:

$$\hat{O} : \mathcal{I} \rightarrow \mathbb{R} \quad (3)$$

2.2 Quantum Error Correction as Spacetime Genesis

Spacetime emerges through quantum error correction (QEC) mechanisms that preserve information coherence. Consider the stabilizer formalism where spacetime geometry corresponds to error correction codes:

$$||\psi\rangle\rangle = \frac{1}{\sqrt{2^k}} \sum_i |\phi_i\rangle \otimes |c_i\rangle \quad (4)$$

where $|\phi_i\rangle$ represents logical information and $|c_i\rangle$ represents geometric codes. The emergent metric tensor becomes:

$$g_{\mu\nu} = \langle \partial_\mu \psi | \partial_\nu \psi \rangle_{\text{QEC}} \quad (5)$$

3 The Four Pillars of Emergent Reality

3.1 Pillar I: Information as Fundamental Substrate

3.1.1 Beyond Wheeler's "It from Bit"

While Wheeler proposed "It from Bit," suggesting information underlies matter, we advance this to "Bit from Entanglement." The fundamental "bits" themselves emerge from patterns in a pre-geometric information space characterized by entanglement entropy:

$$S_{\text{ent}} = -\text{Tr}(\rho_A \log \rho_A) \quad (6)$$

where ρ_A represents the reduced density matrix of subsystem A .

3.1.2 Holographic Information Encoding

The holographic principle finds natural expression: all information within a volume V is encoded on its boundary ∂V with entropy bound:

$$S \leq \frac{A}{4G\hbar} \quad (7)$$

However, we propose this reflects deeper information-theoretic constraints rather than geometric ones.

3.2 Pillar II: Spacetime as Error Correction

3.2.1 The Error Correction Hypothesis

Spacetime emerges as a quantum error correction code protecting logical information from decoherence. The Einstein field equations become:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}^{\text{info}} \quad (8)$$

where $T_{\mu\nu}^{\text{info}}$ represents the stress-energy of information patterns rather than matter.

3.2.2 Geometric Stability and Information Preservation

Spacetime curvature arises to maintain information coherence:

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \Lambda_{\text{info}}g_{\mu\nu} \quad (9)$$

where Λ_{info} represents the information density driving geometric emergence.

3.3 Pillar III: The Big Bang as Information Phase Transition

3.3.1 Beyond Temporal Cosmology

The Big Bang represents not a temporal event but an informational phase transition—a sudden organization of entanglement patterns from maximum entropy (pre-geometric chaos) to structured information space.

Let $\Phi(\mathcal{I})$ represent the information potential. The "Big Bang" corresponds to:

$$\frac{\partial \Phi}{\partial \tau} = 0 \quad \text{at} \quad \tau = \tau_{\text{transition}} \quad (10)$$

where τ parameterizes information organization, not time.

3.3.2 Cosmic Microwave Background as Information Echo

The CMB represents the residual pattern of this information transition, encoding the fundamental entanglement structure rather than thermal radiation from a hot early universe.

3.4 Pillar IV: Evolution as Emergent Narrative

3.4.1 Darwin in Information Space

Biological evolution appears as narrative patterns within information space rather than temporal processes. What we interpret as "survival of the fittest" represents information structures that achieve greater coherence and stability within the error correction framework.

$$\text{Fitness} \propto \text{Information Coherence} = \sum_i p_i \log p_i \quad (11)$$

3.4.2 The Illusion of Historical Sequence

Evolutionary "history" represents different eigenvalues of the information Hamiltonian:

$$\hat{H}_{\text{info}} |\text{species}_n\rangle = E_n |\text{species}_n\rangle \quad (12)$$

Higher energy states correspond to more complex information patterns, creating the appearance of evolutionary progression.

4 Reconciling the Speed of Light

4.1 Light Speed as Information Processing Limit

In emergent spacetime theory, the speed of light c represents the fundamental rate at which information can propagate through the error correction network maintaining spacetime coherence.

4.1.1 The Information Bandwidth Constraint

Consider information propagation through entanglement networks. The maximum rate is constrained by:

$$v_{\max} = \frac{\Delta S}{\Delta \tau} \quad (13)$$

where ΔS represents maximum entanglement entropy change and $\Delta \tau$ represents the fundamental information processing time scale.

4.1.2 Emergence of Lorentz Invariance

Lorentz transformations emerge as information-preserving symmetries of the error correction code:

$$\Lambda^\mu{}_\nu = \frac{\partial x'^\mu}{\partial x^\nu} \quad (14)$$

preserves information content:

$$I[x'] = I[x] \quad (15)$$

4.2 Mass-Energy from Information Density

Einstein's $E = mc^2$ reinterprets as information density relationship:

$$E = \mathcal{I}c^2 \quad (16)$$

where \mathcal{I} represents local information density and c^2 converts information units to energy units through the error correction framework.

5 Experimental Predictions and Falsifiability

5.1 Testable Predictions

1. **Information Conservation:** Total information in closed systems remains constant, with apparent creation/destruction representing redistribution.

2. **Discretization at Planck Scale:** Spacetime exhibits discrete structure at the Planck scale, reflecting underlying quantum information processing.

3. **Entanglement-Geometry Correspondence:** Stronger entanglement correlates with shorter geodesic distances in emergent spacetime.

4. **Modified Dispersion Relations:** High-energy particles exhibit deviations from standard dispersion reflecting information processing constraints.

5.2 Observational Tests

1. **Cosmic Structure Formation:** Galaxy formation patterns should reflect information organization principles rather than purely gravitational dynamics.

2. **Black Hole Information Paradox:** Information preserved through holographic encoding on event horizons.

3. **Quantum Biology:** Biological systems should exhibit quantum coherence patterns consistent with information-based evolution.

6 Philosophical Implications

6.1 The Dissolution of Materialism

This framework dissolves the classical matter-mind distinction. Consciousness emerges as self-referential information patterns within the same substrate that generates physical reality.

6.2 Temporal Ontology

Time loses its fundamental status, becoming an emergent coordinate parameterizing information transitions. This resolves paradoxes in quantum mechanics related to measurement and the arrow of time.

6.3 Teleological Physics

Information patterns exhibit inherent directionality toward greater coherence and complexity, suggesting built-in teleological principles without requiring external design.

7 Mathematical Framework

7.1 Information Geometry

We employ the Fisher information metric on the space of probability distributions over entanglement patterns:

$$ds^2 = g_{ij}(\theta) d\theta^i d\theta^j \quad (17)$$

where $g_{ij} = \mathbb{E} \left[\frac{\partial \log p}{\partial \theta^i} \frac{\partial \log p}{\partial \theta^j} \right]$

7.2 Quantum Error Correction Formalism

The error correction codes stabilizing spacetime satisfy:

$$[\hat{S}_i, \hat{H}] = 0 \quad (18)$$

where \hat{S}_i are stabilizer operators and \hat{H} is the information Hamiltonian.

8 Conclusions

We have presented a comprehensive framework positioning information as the fundamental substrate of reality, with spacetime, matter, time, and biological evolution emerging as secondary phenomena. This approach:

1. Resolves the quantum gravity problem by eliminating the need to quantize spacetime
2. Dissolves the measurement problem in quantum mechanics
3. Provides natural explanations for fine-tuning and anthropic principles
4. Unifies physics with information science and consciousness studies

The speed of light emerges naturally as the information processing speed limit of the error correction network maintaining spacetime coherence, preserving all successful predictions of relativity while providing deeper ontological foundations.

This framework suggests we live not in a universe of matter and energy evolving through time, but in a timeless information space where apparent physical reality emerges through quantum error correction maintaining the coherence of conscious observation.

Future work will develop detailed mathematical formulations and experimental tests to validate this radical reconceptualization of physical reality.

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