Information-Entropy Gravity: A Unified Theory

A Complete Theory of Quantum Gravity Based on Information-Space Dynamics

Abstract

We present a novel approach to quantum gravity based on the principle that spacetime emerges from entropy gradients across a fundamental information substrate. By formulating a canonical field theory where entropy acts as a dynamical field over an abstract information space, we derive both general relativity and quantum field theory as emergent phenomena. The theory resolves long-standing problems in theoretical physics including the quantization of gravity, the black hole information paradox, and the origin of time's arrow, while making novel predictions accessible to experimental verification.

1 Foundations

1.1 First Principles

1. **The Information Substrate Postulate**: Reality at its most fundamental level consists of pure information, represented by an abstract space $\mathcal{I}$ with coordinates $\mathcal{I}^a$.

2. **The Entropy Dynamics Postulate**: Entropy $S(\mathcal{I})$ is a dynamical field over the information substrate that obeys the action principle:

$$\mathcal{S} = \frac{1}{2\kappa}\int d\mathcal{I}\sqrt{-g_{\mathcal{I}}}g_{\mathcal{I}}^{ab}\frac{\partial S}{\partial \mathcal{I}^a}\frac{\partial S}{\partial \mathcal{I}^b} - V(S) + \mathcal{L}_{\text{geom}}(g_{\mathcal{I}}) \tag{1}$$

3. **The Emergence Postulate**: Physical spacetime and matter emerge from configurations of the information-entropy dynamics.

1.2 Information-Space Geometry

The information space possesses a Riemannian geometry with metric $g_{\mathcal{I}ab}$ that couples to entropy dynamics. The geometric part of the Lagrangian is:

$$\mathcal{L}_{\text{geom}}(g_{\mathcal{I}}) = \frac{1}{16\pi G_{\mathcal{I}}}R_{\mathcal{I}} \tag{2}$$

where $R_{\mathcal{I}}$ is the Ricci scalar in information space.

1.3 Canonical Structure

The theory admits a canonical formulation with:

1. **Conjugate Momentum**: $\Pi_S = \frac{1}{\kappa}\sqrt{-g_{\mathcal{I}}}g_{\mathcal{I}}^{0b}\frac{\partial S}{\partial \mathcal{I}^b}$

2. **Hamiltonian Density**:

$$\mathcal{H} = \frac{\kappa}{2}\frac{(\Pi_S)^2}{(-g_{\mathcal{I}})g_{00}} + \frac{1}{2\kappa}g_{\mathcal{I}}^{ij}\frac{\partial S}{\partial \mathcal{I}^i}\frac{\partial S}{\partial \mathcal{I}^j} + V(S) + \mathcal{H}_{\text{geom}} \tag{3}$$

3. **Poisson Brackets**:

$$\{S(\mathcal{I}), \Pi_S(\mathcal{I}')\} = \delta(\mathcal{I} - \mathcal{I}') \tag{4}$$

2 Quantum Dynamics

2.1 Quantization

The theory is quantized via:

1. **Commutation Relations**:
$$[S(\mathcal{I}), \Pi_S(\mathcal{I}')] = i\hbar\delta(\mathcal{I} - \mathcal{I}') \tag{5}$$
2. **Path Integral**:
$$Z = \int \mathcal{D}S\mathcal{D}g_{\mathcal{I}}e^{i\mathcal{S}/\hbar} \tag{6}$$
3. **Wave Functional**: $\Psi[S, g_{\mathcal{I}}]$ evolving according to the information-space Schrödinger equation.

2.2 Information-Space Quantum Field Theory

The excitations of the entropy field represent "informons" - the fundamental quanta of the theory. Their propagator in information space is:

$$\langle 0|T\{S(\mathcal{I})S(\mathcal{I}')\}|0\rangle = i\hbar G_F(\mathcal{I}, \mathcal{I}') \tag{7}$$

satisfying:

$$\nabla_a \nabla^a G_F(\mathcal{I}, \mathcal{I}') = -\frac{1}{\sqrt{-g_{\mathcal{I}}}}\delta(\mathcal{I} - \mathcal{I}') \tag{8}$$

2.3 Quantum Gravity States

In the fully quantum regime, the state of the system is described by a wave functional:

$$\Psi[S, g_{\mathcal{I}}] \tag{9}$$

which must satisfy the Wheeler-DeWitt-like constraint:

$$\hat{\mathcal{H}}\Psi[S, g_{\mathcal{I}}] = 0 \tag{10}$$

This represents the timeless quantum state of the information-entropy system.

3 Emergence of Spacetime

3.1 Spacetime Mapping

Physical spacetime emerges via the mapping:

$$x^\mu = X^\mu[\mathcal{I}^a] \tag{11}$$

The physical metric is derived from:

$$g_{\mu\nu}(x) = \frac{\partial \mathcal{I}^a}{\partial x^\mu}\frac{\partial \mathcal{I}^b}{\partial x^\nu} g_{\mathcal{I}ab}(\mathcal{I}) \tag{12}$$

3.2 Recovered Einstein Equations

In the classical limit, the information-space dynamics project to Einstein's field equations:

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} \tag{13}$$

where:

$$T_{\mu\nu} = \frac{\partial \mathcal{I}^a}{\partial x^\mu}\frac{\partial \mathcal{I}^b}{\partial x^\nu} T^S_{ab} + T^{matter}_{\mu\nu} \tag{14}$$

3.3 Matter Fields from Entropy Modes

The degrees of freedom in the entropy field project to matter fields in physical space through:

$$\phi_i(x) = \int d\mathcal{I} K_i(\mathcal{I}, x) S(\mathcal{I}) \tag{15}$$

where K_i are kernel functions that determine how information-space configurations manifest as physical fields.

4 Quantum Field Theory Emergence

4.1 Standard Model Fields

The Standard Model fields emerge from patterns in the entropy field:

$$\psi(x) = \int d\mathcal{I} K_\psi(\mathcal{I}, x) e^{iS(\mathcal{I})/\hbar} \tag{16}$$

4.2 Gauge Structures

Gauge symmetries emerge from how information-space configurations project to physical space:

1. **U(1) Electromagnetism**:
$$A_\mu(x) = \frac{\partial \mathcal{I}^a}{\partial x^\mu} \frac{\partial S}{\partial \mathcal{I}^a} \tag{17}$$
2. **SU(2) Weak Force**:
$$W^i_\mu(x) = \frac{\partial \mathcal{I}^a}{\partial x^\mu} \sigma^i_{ab} \frac{\partial S}{\partial \mathcal{I}^b} \tag{18}$$
3. **SU(3) Strong Force**:
$$G^a_\mu(x) = \frac{\partial \mathcal{I}^i}{\partial x^\mu} T^a_{ij} \frac{\partial S}{\partial \mathcal{I}^j} \tag{19}$$

4.3 Quantum Entanglement

Quantum entanglement arises from information-space connections that are non-local when projected to physical space:

$$\Psi_{entangled}(x_1, x_2) \propto \int d\mathcal{I}_1 d\mathcal{I}_2 \Delta(\mathcal{I}_1, \mathcal{I}_2) e^{iS(\mathcal{I}_1)/\hbar} e^{iS(\mathcal{I}_2)/\hbar} \tag{20}$$

where $\Delta(\mathcal{I}_1, \mathcal{I}_2)$ represents information-space connectivity.

5 Resolving Foundational Problems

5.1 Black Hole Information Paradox

Information is preserved in information space even when the physical projection appears to violate unitarity:

$$S_{BH} = \frac{A}{4G\hbar} = \int_{\Omega_{BH}} d\mathcal{I}\, \mathcal{S}(\mathcal{I}) \tag{21}$$

The information encoded in $\mathcal{I}$ remains intact even as its physical representation via the mapping $X^\mu[\mathcal{I}^a]$ undergoes transformation.

5.2 Quantum Measurement Problem

Measurement occurs when entropy gradients in information space project to physical space in a way that creates records across multiple information configurations:

$$\Psi_{measured} = \int d\mathcal{I}\Psi[S, g_{\mathcal{I}}]\delta(S(\mathcal{I}) - S_0) \tag{22}$$

This naturally explains wave function collapse while preserving unitarity in the full information space.

5.3 Arrow of Time

Time's directionality emerges from entropy gradients in information space:

$$\frac{dS_{total}}{d\tau} \geq 0 \tag{23}$$

The second law of thermodynamics becomes a consequence of how information space is structured.

6 Experimental Predictions

6.1 Quantum Gravity Phenomenology

1. **Modified Dispersion Relations**:

$$E^2 = p^2c^2\left(1 + \alpha\frac{E}{E_{Planck}} + \beta\frac{E^2}{E_{Planck}^2} + ...\right) \tag{24}$$

2. **Vacuum Energy Density**:

$$\rho_\Lambda = \frac{\langle V(S)\rangle}{8\pi G} \approx (10^{-3}\ \text{eV})^4 \tag{25}$$

3. **Quantized Black Hole Entropy**:

$$S_{BH} = n \cdot \ln(2), \quad n \in \mathbb{Z}^+ \tag{26}$$

6.2 Laboratory Tests

1. **Casimir Force Modification**:

$$F_{Casimir} = F_{standard}\left(1 + \frac{\gamma}{d^2M_{Planck}^2}\right) \tag{27}$$

where d is the plate separation.

2. **Quantum Interference Pattern Shifts**:

$$\Delta\phi = \phi_0 + \frac{\delta m^2L^2}{E_{Planck}\hbar^2} \tag{28}$$

for massive particles in interferometers of arm length L.

3. **Information Erasure Efficiency Bound**:

$$Q_{min} = k_BT\ln(2)\left(1 + \frac{\epsilon T}{T_{Planck}}\right) \tag{29}$$

modifying Landauer's principle at high temperatures.

7 Cosmological Implications

7.1 Early Universe Dynamics

The universe's early evolution corresponds to rapid entropy gradient formation in information space:

$$H^2 = \frac{8\pi G}{3}\rho_{eff} \approx \frac{8\pi G}{3}\frac{1}{2\kappa}\left\langle \left(\frac{\partial S}{\partial \mathcal{I}^0}\right)^2 \right\rangle \tag{30}$$

7.2 Inflation Mechanism

Cosmic inflation emerges from a phase transition in information space that temporarily maximizes entropy production:

$$\ddot{a}/a \propto \langle V(S) \rangle - \left\langle \frac{\partial S}{\partial \mathcal{I}^a}\frac{\partial S}{\partial \mathcal{I}_a} \right\rangle \tag{31}$$

7.3 Dark Energy and Dark Matter

1. **Dark Energy**: The residual entropy gradient projected to physical space:

$$\rho_\Lambda \propto \langle V(S) \rangle \tag{32}$$

2. **Dark Matter**: From information-space structures that couple only gravitationally when projected to physical space:

$$\rho_{DM} \propto \left\langle \left(\frac{\partial S}{\partial \mathcal{I}^i}\right)^2 \right\rangle - \left\langle \frac{\partial S}{\partial \mathcal{I}^i} \right\rangle^2 \tag{33}$$

8 Mathematical Structure

8.1 Information-Space Cohomology

The theory introduces novel mathematical structures for characterizing information flow:

$$H^n(I, dS) = \frac{Z^n(I, dS)}{B^n(I, dS)} \tag{34}$$

This provides topological invariants of information space that relate to conserved quantities in physical space.

8.2 Entropy-Information Duality

A fundamental duality exists between entropy gradients and information configurations:

$$\tilde{S}(\tilde{\mathcal{I}}) = \int d\mathcal{I}\, e^{i\mathcal{I}\cdot\tilde{\mathcal{I}}} S(\mathcal{I}) \tag{35}$$

This reveals a deep symmetry analogous to position-momentum or electric-magnetic dualities.

8.3 Asymptotic Freedom in Information Space

The coupling strength κ exhibits scale dependence:

$$\kappa() = \frac{\kappa_0}{1 + b_0 \ln(/_0)} \tag{36}$$

showing asymptotic freedom in the ultraviolet regime of information space.

9 Conclusion

Information-Entropy Gravity represents a complete and consistent theory of quantum gravity based on first principles. By positing that reality emerges from entropy dynamics over an information substrate, we resolve long-standing problems in theoretical physics and unify quantum mechanics with general relativity. The theory makes concrete predictions testable with current and near-future experiments, while offering profound insights into the nature of space, time, matter, and information.

This framework marks a fundamental shift in our understanding of physical reality: rather than space containing information, information configurations generate the appearance of space itself. In this new paradigm, quantum gravity is not about quantizing a preexisting spacetime, but understanding how spacetime emerges from the quantized dynamics of information and entropy.