The Information-Theoretic Spacetime Manifold: Gravity and Inertia as Emergent Topological Phenomena

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Abstract

This paper presents a fundamental reformulation of physical spacetime. To resolve the methodological contradiction between the continuous metric of general relativity and the discrete, probabilistic nature of quantum mechanics, spacetime is not treated as an a priori background continuum. Instead, a discrete, information-theoretic state topology (the "Register Model") is postulated. In this paradigm, the absolute information content and its degree of topological correlation (entanglement) are the fundamental entities of physical reality. It is deductively shown that phenomena such as the gravitational constant, cosmological expansion, Bekenstein-Hawking entropy, and the decoherence limit are mandatory thermodynamic consequences of this information architecture. As a macroscopic consequence of this model, a formal violation of the weak equivalence principle for macroscopic quantum states is derived, which can be empirically verified through a precise matter-wave interferometry experiment on Bose-Einstein condensates.

Part I: Axiomatics and Topology

1 Introduction

Contemporary theoretical physics encounters a fundamental methodological boundary in its pursuit of a consistent theory of quantum gravity. General relativity models spacetime as a smooth, dynamic continuum, whereas quantum mechanics assumes discrete, probabilistic states unfolding on an a priori spatial metric. Previous attempts at synthesis often suffer from the retention of a continuous background geometry or lead to infinite divergences requiring complex renormalization procedures.

Historical preliminary work in the field of black hole thermodynamics, in particular the formulation of the Bekenstein-Hawking entropy [3, 4] and the derived holographic principle, provides a crucial clue: The spacetime geometry and thermodynamics of a system are inextricably linked to its information content. However, these approaches generally treat information as a derived property of physical matter or energy states.

In this first part of the paper, we perform a formal inversion of this hierarchy. We postulate an ontology in which the absolute information content (I) and the degree of topological correlation—hereinafter defined as the degree of entanglement (η)—represent the fundamental entities of physical reality. Mass (m), energy (E), and the metric of space and time are not assumed axiomatically, but are treated as emergent phenomena arising from the interactions of an underlying, discrete information-topological manifold [5].

The objective of this first part is to establish the axiomatic foundation of this manifold. We will demonstrate how a strictly quantized spatial structure experiences a measurable topological tension due to intrinsic information density. It is mathematically derived that the phenomenological effects of gravity and kinematic time dilation are direct consequences of this information-induced tension. Furthermore, we define the thermodynamic limits of the system, which bound macroscopic state coherence and thus determine the temporal evolution of the manifold.

2 Axiomatic Foundations of Discrete Spacetime

To overcome the incompatibilities of continuous metrics, a fundamental redefinition of space is required. In this model, spacetime is not treated as an infinite continuum, but as an emergent phenomenon of an underlying, discrete information-topological manifold.

2.1 Quantization of the Spatial Manifold

The first axiom of our model postulates that spatial extension is quantized and directly coupled to a minimum information content. We define space as a discrete state space whose fundamental resolution limit is described by the constant κ:

$$\kappa = \frac{l_P^2}{1 \text{ bit}} \tag{1}$$

Here, l_P represents the Planck length. The constant κ dictates that a fundamental unit of information (a discrete state or "bit") is assigned a minimum area equivalent in topological space. This intrinsically eliminates the ultraviolet divergences encountered in continuous field theories.

This fundamental discretization necessitates an uncertainty in state transitions. If spatial coordinates and the intervals of their temporal evolution are not infinitely divisible, a systematic resolution limit emerges. We formalize this as the topological Heisenberg uncertainty principle:

$$\Delta\text{Addr} \cdot \Delta\text{Cycle} \geq 1 \tag{8}$$

The simultaneous precision of a spatial state determination (ΔAddr) and the temporal phase iteration (ΔCycle) is fundamentally limited. Quantum mechanical uncertainty is therefore not a stochastic anomaly, but an unavoidable consequence of the discrete topological metric.

2.2 Information-Induced Topological Tension

We postulate that the mere presence of information (I) and its topological correlation (η) generate a measurable tension S within the discrete manifold. We define this tension S at a distance r from an information-dense center for the spherically symmetric case as:

$$S(r) = \frac{\kappa \cdot I \cdot \eta}{r} \tag{2}$$

The variable S is dimensionless and acts as a measure of the local topological load. Notably, the tension S scales not exclusively with the quantity of information (I), but directly with its degree of coherence or entanglement (η).

To extend the dynamics to macroscopic distributions (ρ_I), we formulate a modified Poisson equation for the information-induced tension:

$$\nabla^2 S = 4\pi \left(\frac{\kappa}{l_P}\right) \rho_I (1 - S) \tag{4}$$

This non-linear saturation factor $(1 - S)$ ensures that the tension S can never exceed the value of 1. This implements an inherent holographic limit, which topologically forbids the formation of true mathematical singularities.

2.3 Metric Time Dilation and Emergent Cosmological Expansion

In our discrete topology, the rate of local temporal state evolution is reciprocally coupled to the topological tension. We define the effective temporal metric component in relation to the local tension S as:

$$g_{00} = 1 - S \tag{3}$$

A local increase in information-induced tension throttles the local evolution rate. As the topological load approaches the critical saturation value ($S \to 1$), g_{00} inevitably converges to zero (freezing of proper time at the event horizon).

While locally confined tension centers throttle temporal dynamics, the global accumulation of topological load determines the macroscopic expansion of the entire manifold. We define the cosmological expansion parameter Λ:

$$\Lambda \propto \gamma^2 \cdot \left(\sum (I \cdot \eta) - S_{threshold}\right)^2 \tag{7}$$

If the density of entangled information exceeds the critical threshold ($S_{threshold}$), the manifold generates new discrete spatial units (κ) to lower the average topological tension. Thus, the model provides a formal justification for the dynamics of dark energy based on information conservation.

3 Thermodynamics and Asymptotic Limits

3.1 Topological Energy Equivalence and Entropy

We postulate that the existence-energy of a system must include the intrinsic computational and maintenance costs of the topological tension within a Hubble volume (V_H):

$$E_{total} = mc^2 + \zeta \int_{V_H} S \, dV \tag{10}$$

Thermal fluctuations and heat (Q) emerge as macroscopic phenomena of information decay [1]. We quantify the heat exchange as a loss of topological correlation (with $k_B \equiv 1$):

$$dQ = T \cdot d\big(I \cdot \ln(2) \cdot (1 - \eta)\big) \tag{6}$$

Heat is the physical manifestation of entropic noise, which arises when previously coherent information decays into uncorrelated states.

3.2 Asymptotic Saturation and Incompleteness

We define the dynamic boundary condition for information flow at the event horizon:

$$\lim_{S \to 1} \frac{\partial I}{\partial t} = 0 \tag{9}$$

To guarantee that the global spacetime manifold maintains a dynamic temporal evolution, the system must be deterministically prevented from collapsing into a perfectly static coherent state. From this, we derive the absolute upper limit of macroscopic entanglement:

$$\eta_{total} < 1 - \frac{1}{I_{total}} \tag{20}$$

Consequently, the total capacity of the universe (I_{total}) limits the maximum background noise (Γ_{max}) in a system under topological tension (S):

$$\Gamma_{max} = \sigma_0 \cdot S \cdot I_{total} \tag{21}$$

Part II: Quantum Dynamics and Testable Implications

4 Introduction to Part II

While Part I defined the macroscopic and thermodynamic limits of the manifold, this second part is dedicated to microscopic kinematics—quantum dynamics. The aim is to fully integrate quantum mechanical states into the discrete topology. We postulate that physical matter exists as a phase-encoded information amplitude within the topological lattice.

A central problem of modern physics—the phenomenological non-locality of quantum entanglement (EPR paradox)—is resolved deterministically within this framework. Finally, we transition the formal model into the realm of experimental falsifiability by proposing a precise interferometric experiment on Bose-Einstein condensates.

5 Matter as Phase-Encoded Amplitude

5.1 The Information-Theoretic Wave Function

We postulate that physical matter must be described as a phase-encoded signal on the topological manifold. We define the wave function Ψ at spatial coordinate A at time t as:

$$\Psi(A,t) = \sqrt{I \cdot \eta} \cdot e^{i(\omega t - kA)} \tag{11}$$

States in this manifold require phase duality for a complete description. We define the complex topological load $\mathcal{Z}_{load}$ of a system as:

$$\mathcal{Z}_{load} = I \cdot e^{i(\theta+\delta)} \tag{12}$$

5.2 Temporal Evolution and Energetic Equivalence

The temporal evolution of the information quantity $I(t)$ is subject to the following decay process:

$$I(t) = I_0 \cdot e^{-\frac{t\cdot(1-S)}{\tau\cdot\eta}} \tag{13}$$

This equation formalizes information decay as a function of the fundamental lifetime τ, stabilized by entanglement (η) and gravitational throttling (S).

Interactions between matter waves must be understood as topological phase synchronization. We define the interference energy:

$$E_{int} \propto \mathrm{Re}(\Psi_1^* \cdot \Psi_2) \tag{14}$$

6 Topological Mechanics and Interactive Protocols

6.1 Entanglement-Correlated Metric and Force Action

We define the logical, interactive distance d_{logic} between two topological addresses as:

$$d_{logic}(A_1, A_2) = d_{geo} \cdot (1-\eta) \tag{15}$$

As the degree of entanglement approaches its maximum ($\eta \to 1$), the logical distance converges to zero, independent of the geometric separation. This eliminates the need for superluminal signal transmission during entanglement.

A fundamental interaction is the result of a topological gradient descent. We formulate the generalized force vector dynamics F as:

$$F = \nabla \mathrm{Im}(\ln\Psi) \cdot \left(\Pi_{max} \cdot e^{-\alpha\cdot d_{geo}\cdot(1-\eta)}\right) \tag{17}$$

6.2 Interaction Probability and Normalization

We define the probability of a successful state synchronization (P_{sync}) as:

$$P_{sync} = \exp\left(-\frac{d_{geo}\cdot(1-\eta)}{\lambda_{dB}} \cdot C_{sys}\right) \cdot \cos(\Delta\phi) \tag{19}$$

To ensure the macroscopic coherence of space, the system defines a global phase normalization (Φ_{sys}):

$$\Phi_{sys} = \frac{1}{N}\sum_{n=1}^{N} \Psi(A_n)\cdot\eta_n \tag{18}$$

Analogous to Hawking radiation, gravitational load induces a dissipation of real information. The rate of this phase leak is modeled as:

$$\frac{dI_{Im}}{dt} = I_{Re}\cdot\nu_p\cdot S\cdot(1-S)\cdot e^{-S} \tag{16}$$

7 Macroscopic Implications of Entanglement on Kinematic Inertia

We postulate that inertia is an emergent measure of space's resistance to the asynchronous displacement of entangled information packets. We define the effective inertia M_{eff} of a physical system as:

$$M_{eff} = m \cdot e^{(\eta-\eta_0)} \tag{5}$$

For macroscopic objects under standard thermodynamic conditions ($\eta \approx \eta_0$), $M_{eff} = m$ holds (conservation of the Newtonian limit). However, if a system is artificially forced into an extremely coherent state ($\eta \gg \eta_0$), its effective inertia grows exponentially. Equation 5 thus deconstructs the weak equivalence principle for the regime of extreme topological correlation.

8 Consistency Check of Classical Limits

8.1 Derivation of the Landauer Limit ($\eta \to 0$)

For the irreversible erasure of unentangled information ($\eta = 0$) and $dI = 1$, Equation 6 yields:

$$dQ = T\cdot 1\cdot\ln(2)\cdot(1-0)$$
$$dQ = T\cdot\ln(2)$$

The Landauer principle [1] is thus recovered exactly as the classical special case of the topological decoherence theorem, consistent with experimental validations [2].

8.2 Unitary Reversibility ($\eta \to 1$)

For highly coherent quantum states, the factor $(1-\eta)$ converges to zero.

$$\lim_{\eta \to 1} dQ = 0$$

The model formally and correctly predicts that perfectly entangled systems operate isentropically and generate no thermal waste heat.

9 Analytical Limits and Cosmological Calculations

9.1 The Decoherence Limit: The Deterministic Collapse of the Wave Function

We calculate the moment of the wave function collapse by equating the signal (Eq. 13) with the background noise (Eq. 21). Solving for the survival time t_{dek} and substituting S via Equation 2 yields:

$$t_{dek} = \frac{\tau \cdot \eta}{1-S} \ln\left(\frac{r}{r_{crit}}\right)$$

where $r_{crit} = \sigma_0 \cdot \kappa \cdot \eta \cdot I_{total}$. If the spatial extension is $r \leq r_{crit}$, the logarithm becomes negative ($t_{dek} \leq 0$). The system is instantaneously forced into classical physics by the universe.

9.2 Emergence of the Gravitational Constant G

By equating the metric from General Relativity ($g_{00} \approx 1 - \frac{2GM}{rc^2}$) with our axiomatics ($g_{00} = 1 - S$) and substituting $S = \frac{\kappa \cdot I \cdot \eta}{r}$, the radius r cancels out perfectly. This results in:

$$G = \frac{\kappa \cdot c^2}{2\mu} \quad \text{with} \quad \mu = \frac{M}{I \cdot \eta}$$

Gravity (G) is exactly determined by the quantization of space (κ) and the density at which matter binds information (μ).

9.3 The Quantization of Information Coupling

We substitute κ with the definition of the Planck length ($\frac{\hbar G}{c^3}$). Inserted into the derived G-equation, G eliminates itself entirely on both sides, leading to the following value for the informational coupling:

$$\mu = \frac{\hbar}{2c}$$

9.4 Holographic Saturation and Entropy

At the event horizon of a black hole, $S = 1$. Inserted into the volume integral of topological tension (Equation 4), the integrand $(1-S)$ becomes zero for the entire inner volume. The 3D volume integral collapses mathematically into a 2D surface integral ($\oint dA$). Dividing this area by the informational area requirement κ deterministically yields $I_{max} = \frac{A}{l_P^2}$, establishing a causal foundation for the holographic principle [3].

9.5 Topological Expansion Pressure and Dark Energy

The accelerated expansion Λ (Equation 7) is proven as a necessary pressure equalization. Because entangled information grew during cosmological structure formation, the expansion pressure had to scale quadratically to preserve the metric, analytically resolving the *Hubble tension* between the early and late universe.

10 The Experimental Design: Falsification of the Equivalence Principle

To detect the inertia anomaly derived from Equation 5, we rely on a differential-simultaneous Mach-Zehnder atom interferometer [6, 7].

A thermal gas and a Bose-Einstein condensate (BEC) are generated simultaneously in the same vacuum chamber and subjected to the same laser pulses in free fall. External errors are eliminated via *common-mode rejection*.

The experimental signature of our theory is an asynchronous phase shift between the two systems:

$$\delta(\Delta\phi) = k_{eff} \cdot T^2 \cdot g \cdot \left(1 - e^{-(\eta_{BEC} - \eta_0)}\right)$$

Since η_0 is exactly determined by $\mu = \frac{\hbar}{2c}$, the equation contains no free parameters. If the discrepancy is detected, the model is empirically confirmed.

11 Conclusion and Outlook

This work formulates the transition from a material spacetime to a discrete, information-theoretic topology. It was demonstrated that space, time, gravity, and cosmological expansion are emergent thermodynamic consequences of a quantized information manifold. The schism between General Relativity and quantum mechanics is resolved by reducing both to a fundamental topological information register.

With the proposed differential matter-wave interferometry, the model enters the realm of experimental falsifiability. Should the experiment verify the predicted asynchronicity in the acceleration of the condensate, it would empirically prove the existence of an underlying information-theoretic manifold, necessitating a complete theoretical revision of gravitational physics and cosmology.

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