Information-Energy Equivalence in Emergent Spacetime: A Generalization of Special Relativity for Post-Material Physics

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Abstract

We present a fundamental reinterpretation of Einstein's mass-energy equivalence within the framework of emergent spacetime theory. By recognizing spacetime as an error-correcting code emerging from quantum entanglement, we derive a generalized information-energy equivalence relation $E = Ic^2$, where I represents local information density and c^2 serves as a conversion factor through the error correction framework. This formulation reveals mass as a measure of information density rather than a fundamental property of matter, providing a bridge between quantum information theory and relativistic physics. Our approach suggests that the traditional material ontology underlying physics must be replaced by an informational substrate, with profound implications for cosmology, quantum gravity, and the nature of physical law itself.

Contents

1 Introduction

1.1 The Crisis of Material Ontology

Einstein's special theory of relativity established the equivalence of mass and energy through the iconic relation $E = mc^2$, fundamentally altering our understanding of matter and energy. However, this formulation assumes a material ontology where mass represents an intrinsic property of physical objects. Recent developments in quantum information theory, particularly the emergence of spacetime from entanglement [1, 2], suggest that this material foundation may be illusory.

The traditional interpretation of $E = mc^2$ faces several conceptual challenges when viewed through the lens of emergent spacetime:

1. Mass appears as a derived rather than fundamental quantity in theories where geometry emerges from entanglement

2. The speed of light c takes on new meaning as a property of the error-correcting code rather than a fundamental constant of spacetime

3. Energy itself becomes reinterpreted as the cost of maintaining informational coherence

1.2 Toward Information-Energy Equivalence

We propose that Einstein's mass-energy relation is a special case of a more general information-energy equivalence. In our framework, what we traditionally call "mass" is actually a measure of local information density within the error-correcting structure that gives rise to spacetime. This leads to the generalized relation:

$$E = Ic^2 \tag{1}$$

where I represents information density and c^2 provides the conversion between information units and energy units through the underlying error correction framework.

This reinterpretation has profound implications for our understanding of:

- The nature of matter and substance

- The origin of inertia and gravitational effects

- The relationship between quantum mechanics and general relativity

- The cosmological constant problem and dark energy

2   Theoretical Framework: Emergent Spacetime as Error Correction

2.1   Quantum Error Correction and Holographic Duality

The AdS/CFT correspondence demonstrates that gravity in the bulk can emerge from entanglement on the boundary [3]. More specifically, the Ryu-Takayanagi prescription shows that areas of minimal surfaces in the bulk correspond to entanglement entropy on the boundary [2]:

$$S_A = \frac{\text{Area}(\gamma_A)}{4G_N} \tag{2}$$

This relationship suggests that spacetime geometry itself can be understood as an error-correcting code, where the bulk reconstruction from boundary data follows quantum error correction protocols [4].

2.2   Information Density as Fundamental Quantity

In the error correction framework, the fundamental quantity is not mass but information density $I(x)$, defined as:

$$I(x) = \lim_{\epsilon \to 0} \frac{S(\mathcal{R}_\epsilon(x))}{V(\mathcal{R}_\epsilon(x))} \tag{3}$$

where $S(\mathcal{R}_\epsilon(x))$ is the entanglement entropy in a region $\mathcal{R}_\epsilon$ of volume V around point x.

This information density captures the local "computational cost" of maintaining the spacetime structure through error correction. Regions of high information density correspond to what we traditionally interpret as massive objects.

2.3   The Error Correction Metric

The error correction framework provides a natural metric structure through the fidelity of quantum state reconstruction. The effective metric tensor emerges as:

$$g_{\mu\nu}^{\text{eff}} = g_{\mu\nu}^{\text{flat}} + \alpha \frac{\partial^2 \log I}{\partial x^\mu \partial x^\nu} \tag{4}$$

where $g_{\mu\nu}^{\text{flat}}$ is the flat spacetime metric, α is a coupling constant, and $I(x)$ is the local information density.

3 Derivation of Information-Energy Equivalence

3.1 Energy as Error Correction Cost

In quantum error correction, maintaining coherent information requires continuous energy expenditure. The energy cost E of maintaining information density I in a region scales as:

$$E = \int \mathcal{E}_{\text{correction}}(I(x)) \, d^3x \tag{5}$$

For the case of uniform information density, this simplifies to $E = \mathcal{E}_{\text{correction}}(I) \cdot V$.

3.2 The Conversion Factor c^2

The speed of light c in our framework represents the characteristic speed of information propagation in the error-correcting code. The factor c^2 emerges from the dimensional analysis of converting information units to energy units.

Specifically, if information is measured in natural units (bits or nats), then the conversion to energy requires:

$$[E] = [I] \cdot [c]^2 \tag{6}$$

where the brackets denote dimensions. This gives:

$$\text{Energy} = \text{Information} \times \frac{\text{Length}^2}{\text{Time}^2} \tag{7}$$

The factor c^2 thus represents the square of the information propagation speed in the emergent spacetime.

3.3 General Information-Energy Relation

Combining these insights, we obtain the general information-energy equivalence:

Theorem 1 (Information-Energy Equivalence). *In emergent spacetime arising from quantum error correction, the energy E required to maintain a configuration with information density I is given by:*

$$E = Ic^2 \tag{8}$$

where c is the characteristic speed of information propagation in the underlying error-correcting code.

4   Recovery of Classical Mass-Energy Equivalence

4.1   Mass as Information Density

In the traditional formulation $E = mc^2$, mass m can be reinterpreted as a measure of information density through the relation:

$$m = \kappa I \tag{9}$$

where κ is a proportionality constant that depends on the specific error correction scheme.

This interpretation suggests that what we call "rest mass" is actually the information density of a localized pattern in the error-correcting code that gives rise to spacetime.

4.2   Inertia from Information Conservation

The inertial properties of massive objects arise naturally from information conservation laws in the error correction framework. Accelerating a massive object requires redistributing information density, which costs energy according to the correction protocols.

The principle of least action in this context becomes a principle of minimal information processing:

$$\delta \int \mathcal{L}_{\text{info}}(I, \partial_\mu I) \, d^4x = 0 \tag{10}$$

where $\mathcal{L}_{\text{info}}$ is the information-theoretic Lagrangian density.

5   Implications and Predictions

5.1   Modified Dispersion Relations

The information-energy equivalence predicts modifications to standard dispersion relations at high energies where the discrete structure of the error-correcting code becomes apparent:

$$E^2 = (Ic^2)^2 + \epsilon(I)(pc)^2 \tag{11}$$

where $\epsilon(I)$ is an information-dependent correction factor and p is momentum.

5.2   Dark Energy as Error Correction Overhead

The cosmological constant problem may find resolution in our framework. The observed dark energy density corresponds to the baseline energy cost of maintaining spacetime through error

correction:

$$\rho_\Lambda = I_0 c^2 \tag{12}$$

where I_0 is the minimum information density required for spacetime stability.

5.3 Quantum Gravity and Information

Our framework provides a natural bridge between quantum mechanics and general relativity through the information-energy equivalence. Gravitational effects arise from gradients in information density:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}^{\text{info}} \tag{13}$$

where $T_{\mu\nu}^{\text{info}}$ is the information stress-energy tensor derived from local information density variations.

6 Experimental Consequences

6.1 Violations of Equivalence Principle

At extremely high information densities, our theory predicts small violations of the weak equivalence principle due to the discrete structure of the error-correcting code. These effects might be observable in:

- Precision tests with ultradense materials

- Behavior of information-rich quantum systems in gravitational fields

- High-energy particle interactions near black holes

6.2 Modified Black Hole Thermodynamics

Black hole entropy in our framework becomes:

$$S_{BH} = \frac{A}{4G} = \int_{BH} I(x)\, d^3x \tag{14}$$

This suggests that black holes are regions of maximum information density consistent with error correction stability.

7   Philosophical and Ontological Implications

7.1   The Collapse of Material Substance

Our framework implies a fundamental ontological shift from material to informational substrate. Physical objects are not "made of" matter but are rather stable patterns in an information-processing system. This aligns with Wheeler's "it from bit" hypothesis while providing a concrete mathematical framework.

7.2   Consciousness and Information Density

If consciousness involves high-density information processing, our framework suggests that conscious systems should exhibit gravitational effects proportional to their information density. This provides a potential bridge between physics and neuroscience.

7.3   Time and Causality

Since spacetime emerges from error correction, our framework supports a view where time is not fundamental but arises from the sequential nature of information processing. This resolves various paradoxes in quantum mechanics and relativity.

8   Cosmological Applications

8.1   Big Bang as Information Phase Transition

In our framework, the Big Bang represents a phase transition in the error-correcting code rather than a temporal beginning. The universe "began" when the code achieved sufficient complexity to support stable information patterns.

8.2   Evolution as Information Selection

Biological evolution becomes reinterpreted as a process of information pattern selection within the error-correcting substrate. Darwin's mechanism operates at the level of information density optimization rather than material adaptation.

9   Future Directions

9.1   Computational Verification

Our theory suggests several computational approaches for verification:

1. Quantum error correction simulations with emergent geometry

2. Information density calculations for known particle configurations

3. Numerical studies of modified dispersion relations

9.2 Experimental Tests

Key experimental signatures to search for include:

- Deviations from $E = mc^2$ at quantum scales

- Information-dependent gravitational effects

- Correlations between information processing and energy consumption in quantum systems

10 Conclusion

We have presented a fundamental reinterpretation of Einstein's mass-energy equivalence within the framework of emergent spacetime. Our derivation of $E = Ic^2$ reveals mass as a measure of information density rather than a fundamental property of matter. This formulation provides:

1. A bridge between quantum information theory and relativistic physics

2. Natural explanations for dark energy and quantum gravity

3. A path toward resolving the measurement problem in quantum mechanics

4. Support for information-based ontologies in fundamental physics

The implications extend beyond physics to philosophy, consciousness studies, and our understanding of reality itself. If correct, our framework suggests that the universe is fundamentally computational, with physical law emerging from information processing constraints rather than governing material substance.

This work opens new avenues for theoretical development and experimental investigation, potentially leading to a unified theory that encompasses quantum mechanics, relativity, and consciousness within a single informational framework.

Acknowledgments

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