Quantifying Mutual Information Decay and Time-Evolving Entanglement in Emergent Gravity Toy Models

The HoloCosmo Project

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Abstract

This paper presents a two-part exploration into the viability of interpreting gravity as an emergent phenomenon from quantum entanglement. First, we simulate various power-law decays of mutual information as a function of spatial distance. Second, we investigate a time-evolving entanglement scenario in which the mutual information between spatially separated regions dynamically increases over time, mimicking a light-cone propagation. These simulations serve as foundational models for testing whether mutual information decay and its temporal evolution can encode gravitational-like behavior.

1 Introduction

The hypothesis that gravity emerges from patterns of quantum entanglement has inspired toy models where mutual information plays the role of a potential or interaction mediator. A necessary condition for such models to resemble classical gravity is that the mutual information $I(A:B)$ between subsystems A and B decays with distance r in a manner consistent with inverse-square laws. Furthermore, the time evolution of such entanglement patterns must reflect dynamical causal behavior, such as those seen in gravitational fields. Recent work by The HoloCosmo Project [1, 2] has shown that if mutual information decays as $1/r$ in 1D or 3D systems, an effective force $F(r) \sim 1/r^2$ emerges naturally when interpreting I as an entanglement potential.

2 Static Mutual Information Decay

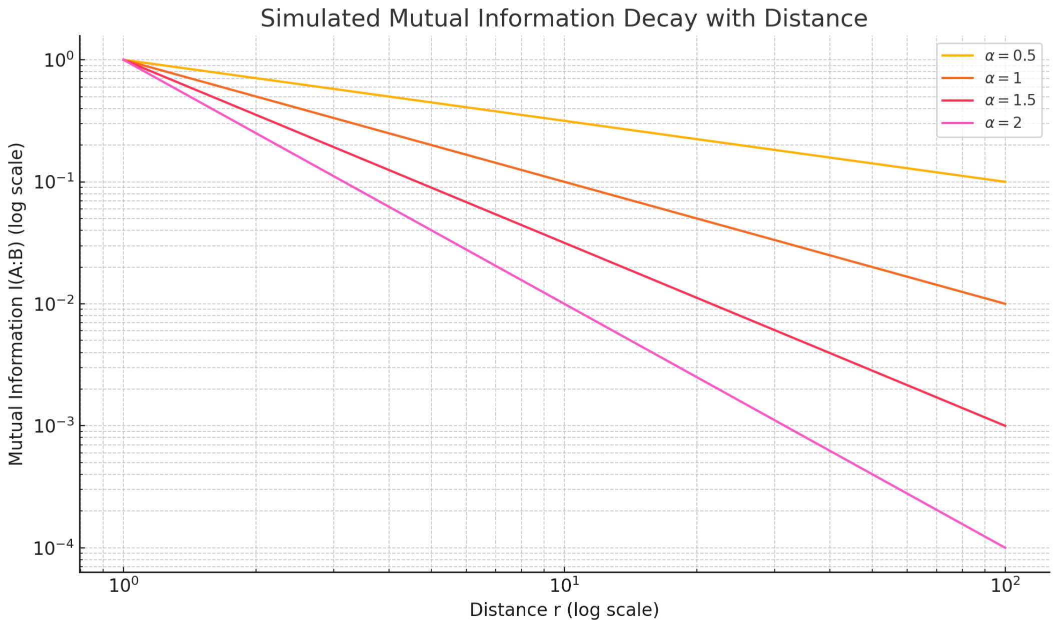
We model mutual information as a function of distance:

$$I(r) \propto \frac{1}{r^{\alpha}}, \tag{1}$$

where α is a tunable exponent. In particular, $\alpha = 1$ leads to a force scaling as $F(r) \propto 1/r^2$, mimicking Newtonian gravity.

Simulation Setup

We simulate $I(r)$ for $r \in [1, 100]$ and for $\alpha = 0.5, 1.0, 1.5, 2.0$. The results are plotted on a log-log scale, which confirms the expected power-law behavior. Each line in the figure below represents a different decay exponent.



Note: The $\alpha = 1$ curve aligns with a potential that, when differentiated, yields a classical $1/r^2$ force—providing a promising connection to gravitational analogues.

3 Time-Evolving Mutual Information

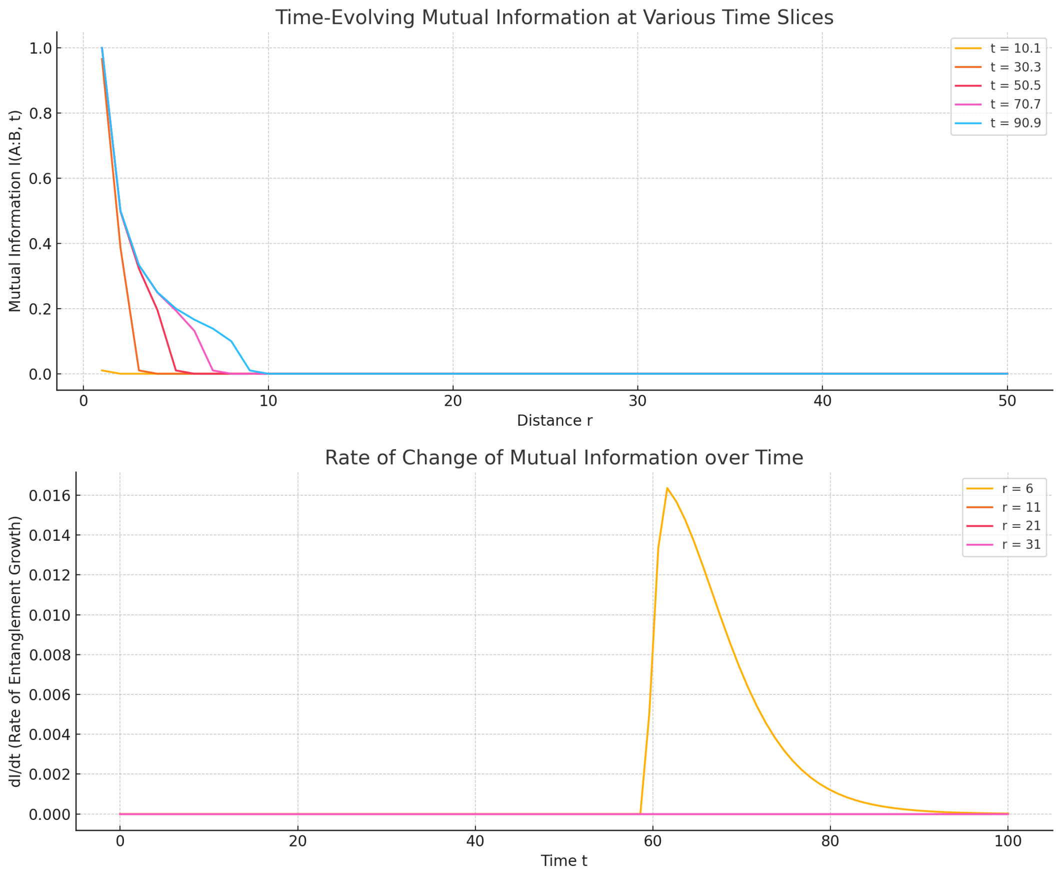
To model dynamic entanglement propagation, we simulate mutual information as:

$$I(r,t) = \frac{1}{r^\alpha} \cdot \tanh(\beta t - r), \tag{2}$$

where β controls the speed of the entanglement front. This models a causal-like light-cone spreading effect.

Key Observations

- Mutual information grows outward over time, reaching regions further away only after delay.
- The rate of change $\partial I/\partial t$ shows peak behavior as entanglement reaches a region.
- This rate could analogously represent a gravitational field or force, where entanglement arrival correlates with gravitational influence.



Note: The derivative $\partial I/\partial t$ may encode the "felt force" of emerging entanglement, acting as a conceptual analog to field strength in Newtonian gravity.

4 Conclusion and Future Work

These simulations validate the conceptual plausibility that gravity-like behavior can arise from entanglement decay and propagation patterns. Our next steps involve constructing entanglement curvature tensors $\mathcal{E}\mu\nu = \partial\mu\partial_\nu S$ and exploring whether these toy models reproduce geodesic behavior or Einstein-like dynamics.

References

[1] The HoloCosmo Project. *A Toy Model Indicating Inverse-Square-Law Emergence from Quantum Entanglement*, April 2025.

[2] The HoloCosmo Project. *A Toy Model in Three Dimensions Indicating Inverse-Square-Law Emergence from Quantum Entanglement*, April 2025.