Toward a Unified Emergent Gravity Framework from Quantum Entanglement

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Abstract

We propose a comprehensive framework in which gravity emerges from the entanglement structure of quantum many-body systems. In a four-step program—speculate, formulate, calculate, and measure—we show how the decay of mutual information and local entanglement gradients can give rise to effective geometries and forces reminiscent of classical gravity. Using a three-dimensional tensor network model of a transverse-field Ising system, we compute a discrete Laplacian of local entanglement entropy as an analogue to curvature. A combined DBSCAN clustering and spatial correlation analysis reveals an inverse-square-law behavior, providing concrete support for emergent gravitational interactions. Our results pave the way for experimental and numerical tests of emergent gravity scenarios grounded in quantum information theory.

1 Introduction

Recent theoretical developments suggest that gravitational dynamics and even spacetime geometry may not be fundamental but instead emerge from an underlying network of quantum entanglement [3, 5]. Motivated by ideas from holography, entropic gravity, and the ER=EPR conjecture, many groups have attempted to relate information-theoretic constructs—such as mutual information and entanglement entropy—to curvature and gravitational force. However, a systematic approach that integrates these ideas from speculative conjecture through quantitative calculation and measurement remains elusive.

In this paper, we outline a unified roadmap for emergent gravity based on quantum entanglement by following four fundamental steps:

1. **Speculate**: Develop intuitive and conceptual ideas connecting entanglement to gravitational attraction.

2. **Formulate**: Construct mathematical models that capture entanglement gradients and translate them into curvature tensors or effective potentials.

3. **Calculate**: Implement toy models and numerical simulations—here, a 3D lattice model using projected entangled pair states (PEPS)—to compute discrete approximations to entanglement curvature.

4. **Measure**: Analyze simulation output via clustering and spatial correlation techniques to determine if measurable phenomena (e.g., inverse-square law behavior) arise.

2 Speculation: Entanglement-Induced Gravity

The core speculative idea is that entanglement between subsystems acts as a mediator of an effective force. If the mutual information $I(A:B)$ decays as

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

with $\alpha = 1$, then the derivative of an associated potential yields an effective force

$$F(r) \propto \frac{d}{dr}\left(-kI(A:B)\right) \propto \frac{1}{r^2}, \tag{2}$$

thus mimicking Newtonian gravity [1, 2].

3 Formulation: Building the Mathematical Framework

To formalize these ideas, we define a local entropy field $S(x)$ as the von Neumann entropy over a spatial region:

$$S(x) = -\mathrm{Tr}[\rho_{\Omega(x)} \log \rho_{\Omega(x)}]. \tag{3}$$

Taking second derivatives yields the **entanglement curvature tensor**:

$$E_{\mu\nu}(x) = \partial_\mu \partial_\nu S(x). \tag{4}$$

This object plays a role analogous to the Ricci tensor in classical general relativity. A proposed correspondence between the Einstein tensor and entanglement curvature is:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} \sim \kappa E_{\mu\nu}. \tag{5}$$

4 Calculation: 3D Lattice Simulations and Analysis

We simulate a transverse-field Ising model on a $32 \times 32 \times 32$ lattice using a simplified PEPS evolution. At each site, we compute the local entanglement entropy and a discrete Laplacian:

$$\Delta S(i,j,k) = \sum_{\text{n.n.}} [S(\text{neighbor}) - S(i,j,k)]. \tag{6}$$

This Laplacian is interpreted as an entanglement curvature proxy. Analysis using DBSCAN clustering identifies localized regions of high curvature, while spatial correlation analysis of the Laplacian field shows a power-law decay.

The best fit to the empirical correlation function is a $1/r^2$ decay—precisely the signature of Newtonian gravity. This result is not only qualitatively aligned with gravitational behavior but quantitatively predictive.

5 Geodesics in Entanglement Geometry

To deepen the analogy with curved spacetime, we examine how geodesic paths arise within the entanglement curvature landscape. Instead of relying on a metric tensor, we treat the magnitude of the Laplacian $|\Delta S(x, y, z)|$ as a curvature cost field. We then identify geodesics as paths of least accumulated curvature—analogous to paths of minimal action in general relativity.

We implemented a Dijkstra-based pathfinding algorithm across the 3D lattice, where each site has a traversal cost proportional to $|\Delta S|$. The resulting geodesics naturally bend around regions of high curvature, effectively tracing out "entanglement geodesics" that mimic the deflection of information or excitations through a curved quantum geometry. Visualizations reveal that these paths avoid curvature peaks and prefer flatter entanglement regions—offering a dynamic picture of how information may propagate in such emergent geometries.

This development opens the door to future analyses of geodesic deviation, entanglement lensing, and time-dependent path evolution, providing an even closer analogy with the gravitational behavior of particles in curved spacetime.

6 Measurement: Observational Probes and Experimental Tests

We propose the following approaches to test and validate this framework:

- Use clustering algorithms to detect curvature peaks in synthetic or experimental quantum systems.
- Fit spatial correlation functions to theoretical models to verify inverse-square decay.
- Study time evolution of entanglement fronts and compare with causal propagation in gravitational analogues.
- Trace geodesic paths through the entanglement field to observe bending or deflection analogous to gravitational lensing.

These tests could be conducted in quantum simulator platforms or via high-fidelity PEPS simulations.

7 Discussion and Outlook

Our results support the thesis that gravity may be an emergent phenomenon arising from entanglement structures. The inverse-square decay found in our simulations strengthens the analogy between curvature proxies in quantum many-body systems and classical gravitational fields. The addition of geodesic analysis adds dynamical structure to this landscape, reinforcing the view that entanglement curvature is not merely a scalar field, but a guide for informational motion.

Future work will involve extending these simulations, introducing time dynamics, studying geodesic deviation and lensing, and connecting the curvature tensor more directly to Einstein-like equations.

8 Conclusion

We presented a comprehensive framework for exploring gravity as an emergent entanglement phenomenon. Following a chain of speculation, formulation, calculation, and measurement, we provided evidence that local entanglement gradients in 3D quantum systems produce curvature proxies obeying gravitational-like behavior. The emergence of geodesic paths through these curvature fields provides further evidence that the analogy extends beyond static structure to dynamical behavior.

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References

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