Research Plan: Deriving Emergent General Relativity from Quantum Entanglement

The HoloCosmo Project

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Abstract

This research plan outlines an ambitious, multifaceted program to derive an effective gravitational theory, analogous to General Relativity (GR), from the entanglement structure of quantum many-body systems. Building on previous work in emergent gravity via entanglement entropy and its Laplacian—combined with PEPS-based lattice simulations—we propose a six-stage roadmap. Our approach emphasizes speculative exploration, rigorous formulation, detailed calculation, and observational validation. The ultimate goal is to extract an entropic field theory that reproduces key features of GR, providing a viable alternative perspective on gravitational phenomena and potentially dark matter.

1 Introduction

Recent theoretical advances suggest that spacetime and gravity may emerge from quantum entanglement. The HoloCosmo Project has demonstrated that gravitational-like behavior—such as inverse-square law potentials and curvature effects—can arise from the Laplacian of local entanglement entropy fields computed in quantum many-body systems. We have developed lattice simulations using PEPS (Projected Entangled Pair States), scripts for computing entanglement entropy and its Laplacian, visualizations of curvature gradients, and fitting procedures for effective potential models. This research plan presents an updated framework, organized into six sequential stages, to bridge the gap between quantum entanglement and classical GR.

2 Research Objectives

Our overarching objectives are:

(a) To perform high-resolution, high-τ impurity simulations in large-scale lattices via PEPS.

(b) To extract effective potentials from entanglement curvature data.

(c) To define entropic geodesics and derive an effective distance measure.

(d) To construct an entropic field theory using variational principles.

(e) To apply coarse-graining techniques to bridge microscopic quantum structures to macroscopic geometry.

(f) To map the emergent entropic curvature framework onto GR-like tensor equations.

3 Methodology: A Six-Stage Roadmap

Stage 1: High-τ Impurity Simulations

Objective: Enhance our PEPS-based simulations by increasing the imaginary time parameter (τ) to deepen state cooling and magnify long-range entanglement effects, especially in the vicinity of a locally injected impurity region (e.g., a $3\times3\times3$ cube).

Method:

- Run simulations on lattices up to 64^3, using bond dimensions up to $D = 4$.
- Use our script `gravity_laplacian_impurity.py` to perform imaginary time evolution and output curvature fields.
- Analyze the resulting entanglement entropy and its Laplacian to quantify curvature and simulate gravity-like response.

Stage 2: Fitting Effective Potentials from Curvature

Objective: Translate the discrete entanglement curvature (the Laplacian of the von Neumann entropy) into an effective gravitational potential.

Method:

- Use `radial_profile.py` to compute radial profiles of the curvature field.
- Apply `potential_fitting.py` to fit Yukawa or Gaussian potentials to the data.
- Extract amplitude and decay length parameters (A, λ) and analyze their dependence on impurity parameters.
- Investigate connections between these parameters and gravitational analogs.

Stage 3: Defining Entropic Geodesics

Objective: Identify paths through the entanglement curvature field along which the effective action is minimized, analogous to geodesics in curved spacetime.

Method:

- Compute curvature gradients using `curvature_gradient.py`.
- Implement vector field integrators or geodesic tracers from high curvature to low curvature.
- Compare multiple integration schemes to evaluate stability and interpretability.

Stage 4: Constructing Entropic Field Equations

Objective: Develop a rigorous field theory for the entanglement structure, possibly deriving an analogue of Einstein's equations.

Method:

- Formulate Lagrangians or effective actions involving S, ∇S, and $\nabla^2 S$.
- Investigate Euler-Lagrange equations under symmetry constraints.
- Explore how the curvature Laplacian might encode source terms (e.g., impurities) in analogy to $T_{\mu\nu}$.

Stage 5: Coarse-Graining and Emergent Geometry

Objective: Understand how classical geometry emerges from the quantum entanglement microstructure via coarse-graining.

Method:

- Downsample curvature fields from full-resolution data.
- Analyze structural similarities in coarse and fine-scale Laplacians.
- Examine whether effective curvature satisfies scaling laws akin to Ricci flow or RG behavior.

Stage 6: Matching to GR Structure

Objective: Establish a correspondence between the emergent entropic curvature and the tensorial structure of GR.

Method:

- Compare curvature gradient maps to Newtonian and relativistic potentials.
- Use impurity variation experiments to simulate localized matter distributions.
- Attempt to map the curvature tensor inferred from entropy to GR expressions like $G_{\mu\nu}$.

4 Epistemic and Methodological Considerations

The HoloCosmo Project maintains the following methodological stance:

1. **Speculative:** We remain open to the possibility that quantum informational structures can give rise to classical geometry.
2. **Formulative:** We translate conceptual ideas into working, testable mathematical formulations.
3. **Calculative:** We implement computational models in code, available under open-source licenses.
4. **Observational:** We assess whether curvature structures reproduce known astrophysical behaviors (e.g., rotation curves, gravitational wells).

This approach balances epistemic openness with methodological rigor, anchoring speculation in simulation and reproducibility.

5 Timeline

1. **Months 1–3:** Execute impurity simulations with high τ and D; validate with gradient visualization.
2. **Months 4–6:** Extract radial profiles and fit effective potentials.
3. **Months 7–9:** Build variational field equations; analyze geodesics.
4. **Months 10–12:** Finalize GR mapping; publish methods and datasets.

6 Expected Outcomes and Impact

- Demonstrate that entanglement entropy curvature reproduces gravitational potentials.
- Provide an interpretable potential field tied to emergent quantum geometry.
- Show that GR-like dynamics can emerge from entanglement structure.
- Deliver open-source tools for PEPS simulation, curvature analysis, and potential fitting.

7 Conclusion

This document outlines an end-to-end strategy for uncovering the gravitational structure encoded in quantum entanglement. By leveraging a systematic approach grounded in PEPS simulations and computational analysis, the HoloCosmo Project seeks to reframe classical gravity as a thermodynamic emergent phenomenon of the quantum world.