Related Work: Emergent Gravity from Quantum Entanglement

The HoloCosmo Project

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1 Introduction

Recent developments in quantum gravity and quantum information theory suggest that gravity may emerge from entanglement patterns in quantum many-body systems. The HoloCosmo Project explores this hypothesis by simulating entanglement structures and constructing curvature proxies. In this section, we contextualize our work by comparing it to seminal contributions in this growing field.

2 Related Work

2.1 Entanglement as the Fabric of Spacetime

Van Raamsdonk [1, 2] proposed that entanglement between spatial regions in a quantum field theory is responsible for stitching together classical spacetime geometry. This idea closely aligns with our notion of an "entanglement curvature tensor" derived from second derivatives of local von Neumann entropy. Where Van Raamsdonk emphasized the conceptual connection between entanglement and spacetime connectivity, our work offers a discrete, computable proxy for curvature based on real-space entanglement entropy gradients.

2.2 Holographic Entanglement Entropy

The **Ryu–Takayanagi formula** [3] equates the entanglement entropy of a boundary region to the area of minimal surfaces in the bulk AdS geometry. While that relation is grounded in the AdS/CFT framework, our approach reverses the flow: we compute local entanglement in a simulated quantum system and interpret its gradients as curvature in an emergent bulk. The conceptual equivalence—geometry from entanglement—remains intact.

2.3 Tensor Networks and Emergent Geometry

Swingle [4] introduced the idea that tensor networks such as MERA could model emergent geometries, acting as discrete holographic duals. Our numerical simulations explicitly adopt a three-dimensional PEPS-based model to calculate entanglement entropy and its Laplacian, making this connection operational. Unlike prior work that focused on representational structure, we use tensor network-inspired models to extract quantitative predictions, such as an emergent inverse-square force law.

2.4 ER = EPR Conjecture

Maldacena and Susskind [5] conjectured that entangled particles may be connected by non-traversable wormholes, effectively unifying geometry (ER bridges) with quantum entanglement (EPR pairs). Although our work does not explicitly feature wormholes, our simulations show how entanglement gradients form curvature structures and geodesic deflections, suggesting a broader realization of the ER=EPR paradigm beyond black holes.

2.5 Entropic Gravity

Verlinde [6, 7] argued that gravity is not fundamental but arises as an entropic force. Our work formalizes this concept geometrically, deriving a gravitational field equation sourced by entanglement curvature rather than thermodynamic entropy. We show how this framework naturally leads to gravitational potentials and inverse-square laws, aligning qualitatively with Verlinde's vision but grounding it in quantum information theory.

2.6 Holographic Error Correction and Codes

Pastawski et al. [9] connected holography with quantum error correction, illustrating how geometry could be robustly encoded in entanglement patterns. While we do not implement explicit coding constructions, our model treats spatially distributed entanglement as a source for emergent geometry, resonating with the notion that entanglement structure stabilizes spatial relations.

2.7 Emergent Gravity in Condensed Matter Systems

Works by **Sachdev**, **Hartnoll**, and others [10, 11] explore how gravity-like dynamics may arise in strongly correlated quantum systems. Our use of a transverse-field Ising model and PEPS simulations places our framework firmly within this tradition, though our focus is on extracting gravitational analogues—such as geodesics and inverse-square forces—from entanglement fields directly.

2.8 Quantum Information and Spacetime

Review articles by **Bousso** [13] emphasize the growing consensus that spacetime and gravity are emergent from quantum informational principles. Our contribution lies in explicitly implementing this connection through simulation and deriving geometric behavior—traditionally attributed to gravity—from entanglement entropy fields.

2.9 Summary

Our work extends these foundational ideas by demonstrating how entanglement structure in lattice quantum systems can give rise to effective curvature fields and gravitational dynamics. Through numerical experiments and theoretical modeling, the HoloCosmo Project offers a concrete pathway from entanglement entropy to emergent gravitational phenomena.

References

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