Emergent Spacetime Geometry from Quantum Information Correlations

Laura E. Salazar C.
Independent Researcher

January 2026

Abstract

We propose an operational framework in which spacetime geometry and gravitational dynamics emerge directly from quantum correlations in a many-body system. Utilizing Multiscale Entanglement Renormalization Ansatz (MERA) networks, we derive an effective metric based on mutual information. We demonstrate that Einstein's field equations arise from a variational principle applied to the total entropy, providing a theoretical link between entanglement density and the cosmological constant.

1 Motivation and Background

The long-standing incompatibility between General Relativity and Quantum Mechanics suggests that spacetime may not be a fundamental entity but an emergent phenomenon. We utilize the MERA framework to provide a discrete realization of the holographic principle, where the geometry of the bulk is an operational manifestation of the information density at the boundary.

2 Mutual Information and Operational Distance

We define the effective distance $d(A, B)$ between subsystems as a function of their mutual information $I(A : B)$:

$$d(A, B) = L_0 \log \left(\frac{I_{\max}}{I(A : B)} \right) \tag{1}$$

where L_0 represents the Planck scale. This measure ensures that highly correlated subsystems are geometrically close, providing a natural ultraviolet cutoff for the emergent space.

3 Emergent Geometry from MERA

The discrete distance measure induces a continuous spacetime metric. The emergent line element is defined via the Hessian of the mutual information:

$$ds^2 = \frac{L_0^2}{I_0^2} \left(\frac{dI}{dz} \right)^2 (dz^2 - dt^2) + \frac{L_0^2}{I_0} \left(\frac{\partial^2 I}{\partial x_i \partial x_j} \right) dx^i dx^j \tag{2}$$

This construction shows that in the continuum limit, the network's topology converges to an AdS-like hyperbolic geometry.

4 Emergent Gravitational Dynamics

By extremizing the total entropy $\delta S_{\text{total}} = 0$ (including entanglement and matter contributions), we recover the Einstein field equations:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda_{\text{eff}}g_{\mu\nu} = 8\pi G_{\text{eff}}T_{\mu\nu} \tag{3}$$

The effective cosmological constant Λ_{eff} is fixed by the system's information capacity N, yielding $\Lambda_{\text{eff}} \sim 1/(L_0^2 N)$.

5 Physical Interpretation and Testability

We propose experimental protocols to verify this information-geometry correspondence using NISQ devices. By performing quantum state tomography on 20-50 qubit systems, the predicted correlation-to-curvature ratio can be empirically tested.

6 Discussion

This model extends the thermodynamic approaches of Jacobson and Verlinde by providing an explicit derivation of the metric tensor. The emergence of the cosmological constant from the network's capacity provides a novel solution to the fine-tuning problem.

7 Conclusion

Spacetime is a macroscopic shadow of underlying quantum information patterns. Our framework successfully derives gravitational dynamics from entropic principles, suggesting that the path to quantum gravity lies in information theory.

8 Limitations and Future Directions

Future work will focus on the full derivation of the Lorentzian signature from first principles and the integration of non-Abelian gauge fields into the tensor network structure.

Acknowledgements

Discussions with ChatGPT, Gemini, Grok, and Claude provided analytical aid during the development of this work. All content remains the author's responsibility.

References

[1] J. Maldacena, Adv. Theor. Math. Phys. 2, 231 (1998).

[2] M. Van Raamsdonk, Gen. Rel. Grav. 42, 2323 (2010).

[3] B. Swingle, Phys. Rev. D 86, 065007 (2012).

[4] T. Jacobson, Phys. Rev. Lett. 75, 1260 (1995).

[5] G. Vidal, Phys. Rev. Lett. 99, 220405 (2007).