

Quantum-Entropy Field Theory

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Abstract

We present a framework in which the dynamics of bulk spacetime and the Standard Model of particle physics emerge from a single master equation of quantum entropy. Using the Quantum-Entropy Field (QEF) master equation, together with an Infinite-Order Entanglement-Preserving (IOEP) symmetry, we show that bulk fields, their stress-energy tensor, and their gauge structure arise naturally from boundary entanglement constraints. This provides a unified entanglement-first derivation of geometry, gravity, and matter fields.

1 Introduction

The interplay between quantum information and spacetime geometry suggests that gravity and matter may emerge from quantum entanglement. Here, we formalize this intuition using a Quantum-Entropy Field (QEF) master equation:

$$\delta S_{\text{geom}} + \delta S_{\text{matter}} = 0, \quad (1)$$

where δS_{geom} is the variation of geometric entropy (proportional to the boundary area of causal diamonds), and δS_{matter} is the variation of matter entanglement entropy on the boundary. This principle asserts that total generalized entropy is stationary, providing constraints on both spacetime geometry and bulk matter fields.

2 Boundary Entanglement and the Emergence of Bulk Stress-Energy

Using the entanglement first law, the variation of matter entropy in a small causal diamond of radius R is:

$$\delta S_{\text{matter}} = \delta \langle K \rangle, \quad (2)$$

where K is the modular Hamiltonian associated with the boundary. For approximately flat spacetime,

$$\delta \langle K \rangle = 2\pi \int_{\Sigma} \langle T_{ab} \rangle \xi^a d\Sigma^b, \quad (3)$$

with ξ^a the approximate boost Killing vector and Σ the boundary surface. The QEF master equation then imposes

$$\delta S_{\text{geom}} + 2\pi \int_{\Sigma} \langle T_{ab} \rangle \xi^a d\Sigma^b = 0. \quad (4)$$

Any fluctuation of entanglement on the boundary requires a corresponding bulk energy-momentum distribution to preserve stationarity of total entropy.

3 Emergence of Bulk Spacetime

Assuming δS_{geom} depends linearly on small variations of the boundary area:

$$\delta S_{\text{geom}} = \frac{1}{4G} \delta \text{Area}[\Sigma] \approx \frac{1}{4G} \int_{\Sigma} \theta d\Sigma, \quad (5)$$

where θ is the expansion of null generators on the boundary. Plugging into the QEF equation, we recover a linearized Einstein equation in the bulk:

$$G_{ab} + \Lambda g_{ab} = 8\pi G \langle T_{ab} \rangle. \quad (6)$$

Thus, spacetime geometry emerges as the solution to boundary entanglement constraints, with bulk curvature sourced by the emergent stress-energy tensor.

4 Emergence of Bulk Fields

The bulk stress-energy tensor is generated by matter fields:

$$\langle T_{ab} \rangle = \sum_i -\frac{2}{\sqrt{-g}} \frac{\delta \mathcal{L}_i[\phi_i, g]}{\delta g^{ab}}, \quad (7)$$

where ϕ_i represents all allowed bulk fields (fermions, scalars, gauge bosons).

The functional emergence principle is

$$\{\phi_i(x)\}_{\text{emergent}} = \arg \min_{\phi_i} \left| \delta S_{\text{geom}} + 2\pi \int_{\Sigma} \langle T_{ab}[\phi_i] \rangle \xi^a d\Sigma^b \right|, \quad (8)$$

i.e., only field configurations whose stress-energy satisfies the boundary entanglement constraint exist. Bulk fields thus emerge as solutions to a functional equation imposed by QEF.

5 IOEP Symmetry and the Standard Model

The Infinite-Order Entanglement-Preserving (IOEP) symmetry imposes

$$S_{\text{matter}}[U_{\text{IOEP}} \rho U_{\text{IOEP}}^\dagger] = S_{\text{matter}}[\rho]. \quad (9)$$

Only bulk fields that preserve boundary entanglement under IOEP transformations are allowed. Consequences:

1. Gauge group selection: Only $SU(3) \times SU(2) \times U(1)$ gauge fields satisfy entanglement preservation.
2. Chirality constraints: Left- and right-handed fermions are selected.
3. Interactions: Yukawa couplings, gauge interactions, and scalar potential are determined by minimal solutions consistent with QEF + IOEP.

The full Standard Model field content and interactions emerge naturally as the minimal set of fields consistent with boundary entanglement and symmetry.

6 Examples of Emergent Fields

6.1 Fermion Field

$$\mathcal{L}_\psi = i\bar{\psi}\gamma^a\partial_a\psi, \quad T_{ab}[\psi] = \frac{i}{2}(\bar{\psi}\gamma_{(a}\partial_{b)}\psi - \partial_{(a}\bar{\psi}\gamma_{b)}\psi) \quad (10)$$

QEF requires that the integrated T_{ab} over the boundary balances δS_{geom} , implying the fermion must exist in the bulk. IOEP symmetry selects allowed chirality and gauge charges.

6.2 Gauge Field

$$\mathcal{L}_A = -\frac{1}{4}F_{ab}F^{ab}, \quad F_{ab} = \partial_a A_b - \partial_b A_a, \quad T_{ab}[A] = F_{ac}F_b{}^c - \frac{1}{4}\eta_{ab}F_{cd}F^{cd} \quad (11)$$

Functional equation:

$$\int_{\Sigma} \xi^a T_{ab}[A] d\Sigma^b = -\frac{1}{2\pi} \delta S_{\text{geom}} \quad (12)$$

Gauge fields emerge as minimal excitations whose stress-energy satisfies boundary constraints. IOEP selects allowed gauge groups.

6.3 Scalar Field (Higgs)

$$\mathcal{L}_H = |\partial_\mu H|^2 - V(H) \quad (13)$$

T_{ab} contributes to δS_{matter} , ensuring boundary entanglement balance, and is selected by IOEP symmetry.

7 Full Emergence Scheme

Boundary Entanglement (QEF) \rightarrow Functional Constraint $\delta S_{\text{total}} = 0$
 \rightarrow Bulk Stress-Energy T_{ab} Required \rightarrow Functional Solution \rightarrow Bulk Fields ϕ_i
 (ψ, H, A_μ)
 \rightarrow IOEP Symmetry Selection \rightarrow Emergent Standard Model Fields & Interactions

QEF + IOEP together determine which fields exist, their interactions, and spacetime geometry. Bulk spacetime and Standard Model are emergent phenomena arising from fundamental quantum entropy principles.

8 Conclusion

Starting from the QEF master equation, we derive:

1. Bulk spacetime geometry from boundary entanglement.
2. Stress-energy tensor T_{ab} as the source of geometry.
3. Emergence of bulk matter fields whose stress-energy satisfies QEF.
4. IOEP symmetry selection of allowed gauge groups, representations, and interactions, reproducing the Standard Model.

This provides a unified entanglement-first derivation of spacetime, gravity, and matter.

References

1. T. Jacobson, “Thermodynamics of Spacetime: The Einstein Equation of State,” *Phys. Rev. Lett.* 75, 1260 (1995).
2. M. Van Raamsdonk, “Building up spacetime with quantum entanglement,” *Gen. Rel. Grav.* 42, 2323 (2010).
3. D. Harlow, “Jerusalem Lectures on Black Holes and Quantum Information,” *Rev. Mod. Phys.* 88, 015002 (2016).
4. J. Maldacena, “The Large N Limit of Superconformal Field Theories and Supergravity,” *Adv. Theor. Math. Phys.* 2, 231 (1998).
5. L. Susskind, “The World as a Hologram,” *J. Math. Phys.* 36, 6377 (1995).