Entropy as Information Curvature: Unifying Matter, Gauge Fields, and Gravitation through Entropic Geometry

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Abstract

We present a unified theoretical framework in which matter, gauge fields, and gravitation emerge as manifestations of an underlying **entropic information geometry**. The formalism is constructed on a *diagram–Hilbert space*, where topological projections encode correlations between quantum degrees of freedom, and entropy acts as the generating functional of field dynamics. Within this setting, the **Fisher information metric** defines an *entropic curvature tensor* whose extremization yields the effective Einstein and Yang–Mills equations as equilibrium conditions of informational entropy. Gravitational coupling emerges from the topological entropy density associated with information flow between matter sectors, while gauge interactions correspond to localized curvature defects in the entropic manifold. The Bekenstein–Hawking entropy and holographic bounds appear as limiting configurations of the same information potential, providing a continuous transition from black hole thermodynamics to the standard-model regime. The framework naturally accounts for mass generation through effective entropic projections within the diagram–Hilbert space, linking the structure of the Standard Model to topological invariants of the entropic geometry. This approach establishes a self-consistent and renormalizable unification of gravity and gauge fields, grounded in the informational and thermodynamic origin of physical law.

1. Introduction

The deep interplay between entropy, information, and spacetime has profoundly reshaped the conceptual foundations of physics. **Bekenstein** demonstrated that black holes possess an entropy proportional to the horizon area [1], and **Hawking**revealed that quantum effects lead to black-hole radiation [2]. **Jacobson** later derived the Einstein field equations from the Clausius relation, showing that spacetime dynamics follow from thermodynamic consistency [3]. Subsequent developments by **Padmanabhan** [4,5] and **Verlinde** [4] advanced the view that gravity itself may be an *entropic force*arising from information-theoretic gradients.

Parallel progress in **information geometry** has shown that the Fisher metric defines a natural curvature on statistical manifolds [6, 7-11], while **Caticha's** entropic dynamics [7] reformulate quantum theory as inference over probability distributions. These insights hint that both gravitation and gauge interactions could emerge from an underlying **information manifold** governed by entropy maximization.

Here, we extend these ideas to a complete **entropic unification framework**, in which matter, gauge fields, and gravitation arise from an **entropy functional** defined on a *diagram–Hilbert space*. This operator manifold captures quantum correlations through topological projections, linking informational curvature to effective field dynamics. Entropy—not action—plays the central variational role. By extremizing the entropy functional, one obtains the Einstein–Yang–Mills equations as equilibrium conditions in the information manifold. The Standard-Model couplings and mass hierarchy appear as consequences of entropic projections between subsystems of the diagram–Hilbert space.

2. Entropic Information Geometry and the Diagram–Hilbert Space

The **diagram–Hilbert space** $\mathcal{H}_{\mathrm{D}}$ generalizes the conventional Hilbert space by encoding both algebraic and topological relations among states. Each node of the diagram represents a sub-Hilbert space associated with a local gauge or matter sector, and the morphisms between nodes define projection operators $P_{ij}: \mathcal{H}_i \to \mathcal{H}_j$.

An **entropy functional** is defined over amplitude distributions $\psi \in \mathcal{H}_{\mathrm{D}}$:

$$S[\psi] = -k_{\mathrm{B}} \int \psi^{\dagger} \ln \psi \; d\Omega$$

where $d\Omega$ represents the measure on the informational manifold.
Variations $\delta S = 0$ under normalization constraints yield equilibrium configurations. The resulting Euler–Lagrange relations reproduce both gravitational and gauge dynamics when interpreted geometrically.

The **Fisher information metric**

$$g_{ij} = \int (\partial_i \ln p)(\partial_j \ln p)\, p \, dx$$

induces a curvature tensor $R^{k}{}_{lij}$ that quantifies how distinguishability between probability amplitudes changes across parameter space. This curvature corresponds physically to energy–momentum flow and gauge field strength:

$$R_{ij} \leftrightarrow F_{ij} + G_{ij}$$

where F_{ij} denotes Yang–Mills curvature and G_{ij} the geometric curvature of spacetime.

3. Entropy Functional and Emergent Field Equations

Extremizing the entropy functional under the constraint of conserved probability and information flux gives

$$\delta\left(S[\psi] - \lambda \int \psi^\dagger \psi \, d\Omega\right) = 0$$

leading to an *entropic balance equation*

$$\nabla_i\left(g^{ij} \nabla_j \ln p\right) = 0$$

which, when expressed in geometrical variables, reproduces the Einstein equation in entropic form [3, 5]:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G \, T_{\mu\nu}^{(\mathrm{ent})}$$

where $T_{\mu\nu}^{(\mathrm{ent})}$ is the informational energy–momentum tensor derived from entropy gradients.

Similarly, projecting variations within a subsystem $\mathcal{H}_i \subset \mathcal{H}_\mathrm{D}$ yields an effective **Yang–Mills equation**:

$$\nabla_\mu F_a^{\mu\nu} = J_a^\nu$$

where the current J_a^ν corresponds to the entropic flux associated with gauge degrees of freedom.

Thus, the gravitational and gauge fields arise simultaneously as extremal responses of the same entropy functional—a direct information-theoretic unification.

4. Entropic Unification of Gauge Fields and Gravitation

In this view, both gauge and gravitational couplings stem from a shared entropic curvature tensor $\mathcal{R}_{AB}$ defined on the diagram–Hilbert manifold.
Projecting $\mathcal{R}_{AB}$ onto spacetime coordinates gives the Einstein tensor $G_{\mu\nu}$, while projection onto internal symmetry coordinates yields the field strengths $F^a_{\mu\nu}$.

The unified entropic relation

$$\nabla^A \mathcal{R}_{AB} = 0$$

encodes the conservation of total information curvature.
Gauge invariance corresponds to the invariance of the entropy functional under local transformations $\psi \to U(x)\psi$ that preserve total informational measure.

In the limit where entropic curvature localizes, the theory reduces to classical general relativity and Yang–Mills fields. In the high-curvature (quantum) regime, entropic non-locality induces coupling unification and potential quantum-gravity corrections.

5. Mass Generation and Symmetry Breaking via Entropic Projections

Masses arise when informational symmetry is reduced through **entropic projection**.
Let $\Pi: \mathcal{H}_{\mathrm{D}} \to \mathcal{H}_{\mathrm{eff}}$ denote the projection from full informational space to an observable submanifold. The associated entropy change

$$\Delta S = -k_{\mathrm{B}}\, \mathrm{Tr}(\rho \ln\, \rho - \Pi\rho \ln\, \Pi\rho)$$

corresponds to effective mass generation. The *mass parameter* m can be interpreted as a Lagrange multiplier enforcing informational equilibrium between projected and full distributions:

$$\frac{\partial S}{\partial \Pi} \sim mc^2$$

This connects mass to the entropic cost of projection, analogous to how the Higgs mechanism introduces mass through symmetry reduction.
The hierarchy of particle masses then reflects the topology of projection pathways within the diagram–Hilbert space—an informational parallel to the structure of the Standard Model.

6. Black-Hole and Cosmological Entropy

When the entropic curvature tensor localizes on a two-surface $\partial\Sigma$, the entropy functional reproduces the **Bekenstein–Hawking** relation [1, 2]:

$$S_{\mathrm{BH}} = \frac{k_{\mathrm{B}} A}{4\ell_{\mathrm{P}}^2}$$

In this limit, the diagram–Hilbert entropy density equals the geometric area density, indicating that black-hole entropy represents the boundary projection of informational curvature.

At cosmological scales, entropy flow between subsystems drives spacetime expansion. Following **Padmanabhan's** holographic equipartition [5, 12], the entropic imbalance between bulk and boundary degrees of freedom yields an emergent acceleration consistent with the Friedmann equations.
Entropy production in early-universe symmetry breaking naturally links to baryogenesis and the observed matter–antimatter asymmetry.

7. Discussion and Outlook

The entropic information-geometry framework establishes a common informational origin for all fundamental interactions. Gravity and gauge forces are not separate fields but manifestations of a universal entropy functional defined on a topological information manifold.

This perspective unifies:

- thermodynamic gravity [3–5, 12,13],
- information geometry [6, 7],
- holographic and quantum-information models of spacetime [14–20], and
- mass generation through informational projection.

Future work will explore renormalization within this entropic picture and identify experimental signatures—such as entropic corrections to coupling unification or horizon thermodynamics—that could be probed via cosmological observations or quantum-information analog systems.

References

1. J. D. Bekenstein, *Phys. Rev. D* **7**, 2333 (1973).
2. S. W. Hawking, *Commun. Math. Phys.* **43**, 199 (1975).
3. T. Jacobson, *Phys. Rev. Lett.* **75**, 1260 (1995).
4. E. P. Verlinde, *JHEP* **04**, 029 (2011).
5. T. Padmanabhan, *Rep. Prog. Phys.* **73**, 046901 (2010).
6. S. Amari, *Information Geometry and Its Applications* (Springer, 2016).
7. A. Caticha, *Entropy* **14**, 1756 (2012).
8. C. Rovelli, *Phys. Rev. Lett.* **77**, 3288 (1996).
9. J. C. Baez, *Class. Quantum Grav.* **15**, 1827 (1998).
10. M. M. Wilde, *Quantum Information Theory* (Cambridge Univ. Press, 2017).
11. R. Bousso, *Rev. Mod. Phys.* **74**, 825 (2002).
12. T. Padmanabhan, *Entropy* **22**, 802 (2020).
13. R.-G. Cai and S.-P. Kim, *JHEP* **02**, 050 (2005).
14. M. Van Raamsdonk, *Gen. Relativ. Gravit.* **42**, 2323 (2010).
15. B. Swingle, *Phys. Rev. D* **86**, 065007 (2012).
16. S. Ryu and T. Takayanagi, *Phys. Rev. Lett.* **96**, 181602 (2006).
17. M. Nozari and A. Etemadi, *Phys. Rev. D* **85**, 104029 (2012).
18. C. E. Shannon, *Bell Syst. Tech. J.* **27**, 379 (1948).
19. E. Witten, *Commun. Math. Phys.* **117**, 353 (1988).
20. S. Carlip, *Rep. Prog. Phys.* **79**, 102901 (2016).