The Theory of Everything: An Entanglement-Symmetry Framework

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September 2025

Abstract

Unifying quantum mechanics, general relativity, and the Standard Model has remained elusive, in part because these theories presuppose primitives—fields, particles, or spacetime—that are themselves defined through energy. This work advances a framework that instead takes energy as ontologically fundamental, Hilbert space as the universal form of its distribution, and entanglement and symmetry as the generative principles of physical law. From these minimal postulates, the core structures of modern physics are shown to emerge without circularity.

Thermodynamics follows from canonical typicality and entropy maximization, with temperature, free energy, and the Clausius law appearing as modular quantities. Time is identified with modular flow, while continuity in modular energy yields an entropic Gauss law that fixes the divergence structure of physical flux. Subsystem entropies define an entropy–Hessian metric in which space emerges spectrally, curvature arises from second derivatives of entropy, and inertia is curvature susceptibility. This leads to a generalized Einstein equation that reduces to classical general relativity in the semiclassical limit. Gauge interactions are recovered by promoting modular symmetries to local deformations, reproducing the structures of $U(1)$, $SU(2)$, and $SU(3)$.

Together these results unify thermodynamics, spacetime geometry, gravitation, and gauge theory within a single entanglement–symmetry ontology. The present paper establishes the theoretical foundations and provides an initial validation of the entropic Gauss law in radiative diffusion. Future work will extend the framework to black holes, dark energy, and high-energy field theory, providing both explanatory reach and falsifiable predictions.

1 Introduction

Motivation

A central aim of contemporary physics is to construct a coherent theoretical framework that reconciles quantum mechanics, general relativity, and the Standard Model of particle physics. Despite their empirical successes, these three pillars remain conceptually and formally disjoint. Quantum mechanics provides an extraordinarily accurate description of quanta, yet its orthodox formulation leaves the measurement problem unresolved and presupposes the existence of an external classical spacetime (Bell 1990; Maudlin 1995). General relativity, by contrast, describes gravitation as the curvature of spacetime and has been confirmed in regimes ranging from solar-system dynamics to gravitational waves (Will 2014; Abbott et al. 2016), but it breaks down at singularities and appears irreconcilable with quantum principles of superposition and entanglement. The Standard Model successfully unifies electroweak and strong interactions within a gauge-theoretic framework (Glashow 1961; Weinberg 1967; Salam 1968), yet it relies on a large set of free parameters, does not incorporate gravity, and leaves unanswered questions about dark matter, dark energy, and neutrino masses.

Alongside these structural mismatches stand several conceptual puzzles. The measurement problem undermines the coherence of quantum mechanics as a complete description of reality, prompting competing interpretations that often add untestable postulates (Everett 1957; Bohm 1952; Wallace 2012). Quantum nonlocality, demonstrated through violations of Bell inequalities, appears to conflict with relativistic locality unless spacetime is taken as fundamental (Bell 1964; Aspect et al. 1982). The arrow of time and the universality of the second law of thermodynamics remain unexplained from first principles, as standard physics treats temporal directionality as contingent rather than derived (Price 1996; S. Carroll 2010). In cosmology, the observed small but nonzero value of the cosmological constant leads to the "vacuum catastrophe," where naive quantum field theoretic estimates exceed observational bounds by 120 orders of magnitude (Weinberg 1989; Padilla 2015). Black hole thermodynamics likewise signals deep but unresolved ties between entropy, gravitation, and quantum theory (Bekenstein 1973; Hawking 1975; Bardeen et al. 1973), culminating in the information paradox (Hawking 1976; Almheiri et al. 2013).

Multiple research programs have sought to resolve these issues. String theory provides a mathematically rich framework in which gravitation and gauge forces appear as excitations of fundamental strings (Green et al. 1987; Polchinski 1998), yet it requires extra dimensions, a vast landscape of vacua, and presupposes background spacetime. Loop quantum gravity offers a background-independent quantization of geometry (Rovelli 1998; Ashtekar and Lewandowski 2004), but its semiclassical limit and relation to particle physics remain uncertain. Holographic approaches such as AdS/CFT reveal profound correspondences between quantum field theory and gravity (Maldacena 1998; Ryu and Takayanagi 2006), but rely on asymptotic structures not realized in our universe. Causal set theory (Bombelli et al. 1987) and other discrete approaches offer insight into emergent spacetime, but often lack dynamics that reproduce known low-energy physics. Each program achieves partial successes but fails to simultaneously resolve all conceptual tensions. Moreover, many approaches rely on additional assumptions that reintroduce circularity: spacetime is assumed in order to explain its emergence, or fields are taken as primitive while energy is defined in terms of them. This circularity is not a merely philosophical objection. It manifests technically in divergences, fine-tuning problems, and the difficulty of reconciling renormalization with gravitational dynamics.

The persistence of these problems suggests that unification may require a deeper ontological reorientation. Rather than reconciling existing primitives—fields, particles, or spacetime—it may be necessary to identify a more minimal substrate from which these structures emerge. By taking energy as ontologically fundamental, Hilbert space as the universal form of its distribution, and entanglement and symmetry as the generative principles of physical structure, one can construct a framework in which thermodynamics, spacetime geometry, gravitation, and gauge interactions arise from a single foundation. Such a shift directly addresses the circularities that hinder conventional approaches and opens a new route toward resolving the measurement problem, the arrow of time, the cosmological constant puzzle, and the unification of forces within a single, coherent ontology.

Philosophical and Ontological Framing

The motivation for a new physical ontology arises not only from technical impasses in unifying existing theories, but also from longstanding philosophical concerns about the basic categories of scientific explanation. Standard formulations of modern physics rely on ontological primitives such as fields, particles, or spacetime, yet these categories exhibit a well-known circularity. In quantum field theory, for example, fields are taken as fundamental, but their dynamics are defined through energy densities; in general relativity, spacetime curvature is treated as primitive, yet it is sourced by the stress–energy tensor. Thus both theories presuppose the very notion—energy—that they attempt to define in terms of other primitives (Landau and Lifshitz 1980; S. M. Carroll 2019). This circularity suggests that energy itself should be taken as ontologically fundamental, with fields and spacetime reinterpreted as emergent structures.

The philosophical distinction between substance and form provides a useful lens through which to articulate this reorientation. In Aristotelian metaphysics, *energeia* or actuality is the substance, while *eidos* or form structures substance into determinate entities (Aristotle 1984). Aquinas extended this into the schema of act and potency, where act provides actuality and potency provides the form that delimits it (Aquinas 1274). In the present framework, energy serves as substance or act, while Hilbert space—together with its symmetry structure—serves as form, organizing energy into relational patterns. Spinoza's monism, which holds that reality is a single substance expressed in infinite attributes (Spinoza 1677), also resonates with this view: energy is the single ontological substance, while entanglement patterns in Hilbert space generate the multiplicity of physical phenomena.

In summary, the philosophical and ontological framing of this work asserts that (i) energy is the fundamental substance of reality, (ii) Hilbert space is the universal form in which that substance is organized, and (iii) entanglement and symmetry are the structuring principles through which physical law arises. This reorientation eliminates circularities, integrates insights from both physics and philosophy, and sets the stage for deriving the known structures of space, mass, time, thermodynamics, and gauge interactions from a common foundation.

Methodological Vision

The ontological reorientation to energy as fundamental and Hilbert space as its universal form requires a constructive program: beginning from minimal postulates, one must show how the full content of known physics emerges from entanglement and symmetry. The guiding principle is that physical law arises not from independent primitives such as fields, particles, or spacetime, but from entropic relations and modular structure within the global Hilbert space.

The methodology unfolds in four linked steps. First, factorization of the global Hilbert space into subsystems provides the natural arena for reduced states, modular Hamiltonians, and entanglement entropies (Araki 1976; Haag 1992). Canonical typicality and the KMS condition then establish that reduced states are Gibbsian, recovering the canonical ensemble and the four laws of thermodynamics (Jaynes 1957; Popescu et al. 2006). Internal energy, free energy, and temperature thus appear as modular quantities rather than assumed primitives.

Second, modular flow supplies the intrinsic temporal parameter. The Clausius relation, expressed in modular time, links changes in entropy to changes in modular energy and fixes the form of subsystem continuity. This furnishes the structural identity needed to define an entropic Gauss law, relating entropy curvature to modular energy flux.

Third, subsystem entropies define a spatial metric through the entropy Hessian,

$$g_{ij}(x) = -\partial_i \partial_j S(x) + \Lambda h_{ij},$$

with Λ encoding the irreducible vacuum entropy density. In the adiabatic limit this metric governs emergent space, while modular flow supplies the timelike direction. Together they yield a 3+1 Lorentzian manifold in which curvature is second derivative of entropy and geodesic distance encodes mutual information. Inertia arises as curvature susceptibility, and the generalized Einstein equation follows from varying the entropy functional, collapsing to classical GR in the semiclassical limit (Jacobson 1995; Faulkner et al. 2013).

Fourth, global symmetries of the modular Hamiltonian act as conserved charges. Promoting them to local deformations introduces Berry connections $A_\mu(x)$ with curvature $F_{\mu\nu}$, reproducing $U(1)$ electromagnetism and the $SU(2)$ and $SU(3)$ Yang–Mills sectors (Yang and Mills 1954; Weinberg 1967). Gauge interactions are therefore not postulates but modular responses of Hilbert space symmetry.

Taken together, this methodology defines a concrete and falsifiable program. From the postulates of energy, Hilbert space, entanglement, and symmetry, one constructs modular Hamiltonians, entropy functionals, and entropic flux laws. From these, thermodynamics, time, spacetime geometry, gravitation, and gauge interactions emerge in order. The framework is not speculative interpretation but a mathematically constructive approach, whose validity rests on reproducing known laws, generating novel predictions, and withstanding empirical test.

Scope of the Present Paper

The present work is devoted to the constructive task of theory building. Our objective is to show that the ontological postulates of energy, Hilbert space, entanglement, and symmetry are sufficient to generate the core structures of modern physics without appeal to additional primitives such as fields, particles, or background spacetime. The paper develops the framework in a systematic sequence: beginning with subsystem factorization and canonical typicality, we derive the Gibbs form of reduced states and recover the laws of thermodynamics. From there, modular flow is introduced as the intrinsic notion of time, the Clausius law is recovered in modular form, and a continuity principle yields the entropic Gauss law. This operator defines the correct divergence structure, which in turn gives rise to an entropy–Hessian metric, emergent space, inertial mass as curvature susceptibility, and a generalized Einstein equation. Finally, global symmetries of the modular Hamiltonian are promoted to local ones, reproducing gauge interactions of $U(1)$, $SU(2)$, and $SU(3)$ as modular responses.

The emphasis here is on internal logic and structural consistency: eliminating circular definitions, demonstrating that thermodynamics, spacetime, gravitation, and gauge theory follow from one substrate, and showing that the framework reduces to established physics in the semiclassical limit. The validation strategy at this stage is conceptual and structural, supplemented by a discriminating numerical test of the entropic Gauss law in radiative diffusion.

It is equally important to clarify what this paper does not attempt. We do not provide a full cosmological model, nor attempt to reproduce the detailed phenomenology of the Standard Model such as particle masses, Yukawa couplings, or mixing parameters. We also do not engage with the technical machinery of perturbative quantum field theory or Planck-scale simulations. These are essential directions for future work, but they lie beyond the current goal. The present aim is narrower but foundational: to establish that from minimal postulates one can construct the general form of thermodynamic laws (Jaynes 1957; Popescu et al. 2006), an emergent entropy-based geometry (Jacobson 1995; Casini et al. 2011), the reduction to Einstein gravity in the semiclassical limit (Faulkner et al. 2013), and the recovery of gauge interactions as consequences of modular symmetry (Yang and Mills 1954; Weinberg 1967; Peskin and Schroeder 1995; Harlow and Ooguri 2021).

By clearly delimiting this scope, we situate the contribution of this paper within the larger research program. Later work will extend the framework to black hole thermodynamics, the cosmological constant problem, non-equilibrium entropy geometry, and the unification of quantum field dynamics with modular curvature. The present work should therefore be read as laying the theoretical foundation: its success is measured not by detailed numerical predictions, but by demonstrating that a coherent ontology—minimal in assumptions yet rich in consequences—suffices to reproduce the essential structural features of physics.

2 Model Foundations

2.1 Ontological Foundations and Postulates

2.1.1 Postulate 1. Energy is ontological and fundamental.

This framework is grounded in the ontological assumption that energy is fundamental, and that all physical phenomena arise from the structure of a global Hilbert space constrained by symmetry and entanglement. Rather than quantizing classical spacetime and matter fields, we instead derive gravity, mass, quantum field theory, spacetime, statistical mechanics, and thermodynamics from quantum informational principles(Callen 1985).

2.1.2 Postulate 2. The universe is a global pure state in a complex Hilbert space.

Let $\Psi\rangle \in \mathcal{H}_{\text{global}}$, where $\mathcal{H}_{\text{global}}$ is a complex Hilbert space with inner product $\langle\Psi\Phi\rangle$. The universe is a pure state $\Psi\rangle$, not a mixed ensemble(S. M. Carroll 2021).

2.1.3 Postulate 3. Factorization into subsystems.

The global Hilbert space factorizes into subsystems, enabling entanglement and modular structure (Preskill 1998)(Appendix 5.1).

2.1.4 Postulate 4. Observables from symmetry operations.

Observables correspond to generators of symmetry transformations on $\mathcal{H}_{\text{global}}$ (Weinberg 1995).

2.2 Structural Implications

2.2.1 Global constraint.

The total energy of the global state is fixed at zero, consistent with canonical quantum gravity and the Wheeler–DeWitt equation (DeWitt 1967)(Appendix 5.2.1).

2.2.2 Subsystem reduction.

Local states are obtained by partial trace (Nielsen and Chuang 2010). (Appendix 5.2.2.)

2.2.3 Symmetry-preserving transformations.

Physical changes correspond only to unitary automorphisms preserving the global Hamiltonian spectrum. (Appendix 5.2.3.)

2.3 Entropy and Canonical Structure

We adopt the standard von Neumann entropy

$$S(\rho_A) = -\mathrm{Tr}(\rho_A \log \rho_A)$$

as the measure of subsystem entropy. In ordinary statistical mechanics, maximizing this entropy under suitable constraints yields the Gibbs ensemble. Our framework follows the same logic, but with a crucial ontological difference: all of this structure is derived directly from the Hilbert space and entanglement postulates, without assuming background spacetime or fields.

To justify entropy as an objective measure, we use permutation and unitary symmetries. To justify the Gibbs form, we give three independent arguments that subsystems of a globally entangled pure state can be treated as thermal: (i)canonical typicality of reduced states, (ii) the operator-algebraic KMS condition, and (iii) the Everettian treatment of statistical mechanics. Together these establish that reduced density matrices on appropriate subspaces are effectively Gibbs states.

Once Gibbs form is justified, all of standard quantum statistical mechanics and thermodynamics follow: partition functions, thermodynamic potentials, and the Clausius relation. The novelty is therefore not in re-deriving these well-known results, but in showing that they arise ontologically from Hilbert space structure alone. This provides the foundation for our later construction of entropy geometry and the generalized Einstein equations.

2.3.1 Symmetries and Statistical Structure

Certain symmetries justify statistical reasoning:

Permutation Symmetry in Degenerate Eigenspaces. Operation:

$$U = \sum_{i,j} u_{ij}\, \psi_i^{(n)}\rangle\langle\psi_j^{(n)}$$

acting on eigenspace E_n. *Symmetry:* States within the same energy level are physically indistinguishable. *Consequence:* Basis choice within degenerate eigenspaces is irrelevant. *Relation to Entropy:* Entropy counts only distinguishable states. Permutation symmetry reduces the number of distinguishable microstates.

Symmetric Swap of Energetically Balanced Subsystems. If

$$\langle\Psi H_A \Psi\rangle \;=\; \langle\Psi H_B \Psi\rangle,$$

then swapping $A \leftrightarrow B$ leaves the global energy unchanged. *Symmetry:* Swap does not affect the total energy. *Consequence:* Supports equilibrium logic; equilibrium configurations are invariant under such swaps. *Relation to Entropy:* At equilibrium, entropy remains unchanged under symmetric swaps, consistent with microcanonical ensemble reasoning.

Global Unitaries Respecting Constraints. For any $U \in U(\mathcal{H})$,

$$\langle \Psi \hat{H} \Psi \rangle \ = \ \langle \Psi U^\dagger \hat{H} U \Psi \rangle.$$

Symmetry: Energy expectation is conserved under such unitaries. *Relation to Entropy:* Allowed state transformations preserve ensemble constraints (e.g., fixed energy), thereby justifying constrained entropy maximization.

These symmetries ensure the structural invariance of trace, energy expectation, and entropy under legal transformations. They also justify viewing entropy as an objective geometric quantity arising from the Hilbert space structure rather than as an external assumption.

2.3.2 Canonical Typicality from Global Purity

Canonical typicality (Popescu et al. 2006; Goldstein et al. 2006) states that, for most pure states $\Psi\rangle$ on a large Hilbert space, reduced subsystems are approximately thermal:

$$\rho_A \ \approx \ \mathrm{Tr}_{\bar{A}}(I_R \dim \mathcal{H}_R)\,,$$

where $\mathcal{H}_R$ is the constraint subspace. Thermal behavior thus emerges generically from entanglement with the environment, without requiring any probabilistic ensemble.

Ontologically, this means that entropy, temperature, and equilibrium structure are consequences of Hilbert space factorization and entanglement. No spacetime, fields, or external assumptions are introduced. This interpretation is reinforced in operator-algebraic frameworks (Haag 1992; Wehrl 1978) and in Everettian approaches to statistical mechanics (Wallace 2012).

Conclusion. With canonical typicality established, subsystems may be treated as Gibbs states. From here, all of standard quantum statistical mechanics and thermodynamics follow in the usual way.

2.3.3 Summary of Quantum Statistical Mechanics in this Framework

For clarity, we collect the key statistical identities as they appear in our ontology:

- **Entropy (von Neumann):**

$$S(\rho_A) = -(\rho_A \log \rho_A).$$

- **Canonical form of reduced states:**

$$\rho_A = \frac{e^{-\beta H_A}}{Z}, \qquad Z = (e^{-\beta H_A}).$$

- **Thermodynamic potentials:**

$$U = (\rho_A H_A), \quad F = -1\beta \log Z, \quad S = \beta(U - F).$$

- **Modular Hamiltonian:**

$$K_A = -\log \rho_A + \log Z \;=\; \beta H_A + const.$$

These are precisely the familiar relations of quantum statistical mechanics, but here they emerge as structural consequences of Hilbert space entanglement, without presupposing spacetime or classical fields.

2.4 EntropyTime

2.4.1 Modular Flow as Time

Let $\rho_A =_{\bar{A}} \big(|\Psi\rangle\langle\Psi|\big)$ be the reduced state of a subsystem A. Define

$$K_A \equiv -\log \rho_A + \log Z_A,$$

so that $\rho_A = 1$ (Haag 1992; Bisognano and Wichmann 1975). On a local KMS patch where ρ_A is Gibbsian for some quasi-local H_A,

$$K_A = \beta H_A + \log Z_A.$$

The Tomita–Takesaki modular automorphism gives a one-parameter evolution on the observable algebra,

$$\sigma^A_{t_{\mathrm{mod}}}(X) = e^{+it_{\mathrm{mod}}K_A}\, X\, e^{-it_{\mathrm{mod}}K_A}, \qquad X \in \mathcal{A}_A,$$

which we interpret as thermal (modular) time t_{mod} (cf. (Rovelli 1993)). No spacetime manifold is assumed here: t_{mod} is solely the parameter of modular flow in the von Neumann algebra $\mathcal{A}_A$.

In equilibrium, the KMS condition fixes the relation between modular flow and proper time:

$$dt_{\mathrm{mod}} \;=\; \beta\, d\tau \;=\; \frac{d\tau}{T}.$$

Thus modular time is not an abstract parameter but a rescaled temporal flow, with the inverse temperature providing the conversion factor. This relation reproduces Tolman's law, $T\sqrt{-g_{00}} = const$, so gravitational redshift appears as modular time dilation (Tolman and Ehrenfest 1930). In this sense, modular flow gives the natural entropic generalization of physical time (Connes and Rovelli 1994).

2.4.2 Clausius Relation with Modular Time

For a reduced state ρ_A, the subsystem entropy is

$$S_A = -(\rho_A \log \rho_A).$$

Trace-preserving variations $\delta\rho_A$ yield

$$\delta S_A = -\big(\delta\rho_A \log \rho_A\big) = (\delta\rho_A K_A).$$

On a KMS patch, $K_A = \beta H_A + \log Z_A$, hence

$$\delta S_A = \beta\, \delta U_A, \qquad U_A := (\rho_A H_A).$$

Parametrizing variations along the modular flow $\sigma^A_{t_{\mathrm{mod}}}$ gives the rate form

$$\frac{dS_A}{dt_{\mathrm{mod}}} = \beta\, \frac{dU_A}{dt_{\mathrm{mod}}},$$

i.e. the Clausius rate law in modular time. The derivation is standard quantum statistical mechanics; the only conceptual specialization here is that, in a Hilbert-space–only ontology, t_{mod} is the unique intrinsic parameter available to label quasi-static change.

2.4.3 Entropic Gauss Law

We now formulate a discrete Gauss-type relation directly on the factorized Hilbert space, prior to introducing any manifold structure. Factor the global Hilbert space into small subsystems (nodes) $i \in V$, and associate to each node the reduced state ρ_i. Define the node entropy

$$s_i := S(\rho_i),$$

and the local modular–energy

$$e_i := (\rho_i H_i),$$

where H_i denotes the local modular generator restricted to node i.

Locality of the modular generator induces a continuity law on the entropic graph:

$$\frac{ds_i}{dt_{\mathrm{mod}}} + \sum_{j\sim i} J_{i\to j} \;=\; 0,$$

with $J_{i\to j}$ the entropy flux from node i to j. By the Clausius rate relation (Sec. 2.4.2), each node satisfies

$$\frac{ds_i}{dt_{\mathrm{mod}}} \;=\; \beta_i \frac{de_i}{dt_{\mathrm{mod}}} \;\equiv\; \beta_i E_i.$$

Assuming linear, local, and isotropic closure on the graph, the continuity relation closes into a discrete scalar equation of state,

$$\kappa\,(L_\phi \Sigma)_i \;=\; \beta_i E_i,$$

where

$$\Sigma_i := s_i + \lambda \ln \beta_i, \qquad \phi_i := \ln \beta_i,$$

and L_ϕ is the weighted graph Laplacian associated to the modular potential ϕ.

This expression is the *entropic Gauss law*: the divergence (second-order, isotropic) of an entropy potential on the graph equals β times the modular energy. It is derived entirely within the Hilbert-space framework, prior to introducing any continuum geometry (derivation in Appendix 5.3.1).

2.4.4 Adiabaticity and the Entropy Hessian

By definition, an adiabatic (KMS) patch is one where the local inverse temperature varies slowly:

$$\nabla \ln \beta \;\approx\; 0.$$

In this regime the modular weighting between neighboring nodes is negligible, so the weighted Laplacian L_ϕ reduces to the unweighted combinatorial Laplacian L.

Locality further implies that the subsystem under consideration is much smaller than its environment. By definition of locality, curvature of the background is minimal, and higher-order derivatives of entropy (third and fourth differences) are suppressed. The dominant second-order contribution is the Hessian of the entropy field.

Thus, on an adiabatic/local patch the discrete flux law reduces to

$$(Ls)_i \;\longrightarrow\; \mathrm{tr}_g\big(\mathrm{Hess}_g S\big).$$

In other words, the only consistent second-order isotropic operator available is the entropy Hessian. The combinatorial Laplacian of the graph is therefore identified with the entropy Hessian in the continuum limit, justifying the use of spectral embedding to recover a smooth manifold and metric structure.

2.4.5 Space from Spectral Embedding (Three Directions)

With the adiabatic/KMS reduction (Sec. 2.4.4), the modular graph dynamics is governed by the combinatorial Laplacian. Summarizing standard spectral graph theory, for the mutual-information graph

$$G = (V, E, w), \qquad w_{ij} \sim I(i:j),$$

the lowest nontrivial eigenvectors of L provide a spectral embedding

$$x_i := \big(\psi_1(i), \psi_2(i), \psi_3(i)\big) \in R^3.$$

This recovers a coarse geometry directly from entanglement structure.

Independently, our representation-theoretic result (Appendix 5.3.2) shows that only in $d = 3$ does there exist an isotropic, linear map from antisymmetric two-form correlations to flux vectors ($\Lambda^2 \to \Lambda^1$). Thus, the entropy continuity law enforces exactly three independent spatial directions.

Taken together, spectral embedding via the Laplacian and the algebraic restriction from isotropy fix the emergent spatial manifold to be three-dimensional.

2.4.6 Entropy–Hessian Spatial Metric

We define the entropy Hessian metric on the emergent manifold as

$$\gamma_{ij}(x) \;=\; -\,\partial_i \partial_j S(x) \;+\; \Lambda\, h_{ij}(x),$$

where $S(x)$ is the subsystem entropy field, h_{ij} is a fiducial background from spectral embedding, and Λ encodes an irreducible vacuum entropy density.

The negative Hessian ensures γ_{ij} is positive semidefinite, since S is concave. The additive Λh_{ij} term reflects a structural lower bound: entropy cannot vanish due to strong subadditivity and canonical typicality, so every subsystem carries an irreducible entropy density. This constant contribution is the algebraic origin of the vacuum offset in the entropy metric. See Appendix 5.3.3 for more details on the minimum vacuum entropy density.

Mass from curvature susceptibility. In addition to fixing the spatial metric, the entropy Hessian also encodes inertial response. Split the entropy into vacuum and dynamical parts, $S = S_{\text{vac}} + S_{\text{dyn}}$, with S_{vac} contributing only to the Λh_{ij} offset. On a local KMS patch where the modular Hamiltonian admits a density, the relevant curvature is the second derivative of the dynamical entropy with respect to modular energy,

$$\chi := \frac{\partial^2 S_{\text{dyn}}}{\partial U^2}, \qquad m := \sqrt{\chi^{-1}}.$$

This curvature susceptibility measures the resistance of the subsystem to modular redistribution. Inertia is thus identified with the entropy–Hessian response: more concave $S(U)$ implies smaller susceptibility to acceleration. Because modular energy couples universally to the entropy metric, this inertial definition coincides with gravitational mass, reproducing the weak equivalence principle.

In the semiclassical locality limit the modular energy U coincides with the physical energy E, and the entropy metric calibration fixes a constant conversion factor between temporal and spatial curvature directions, identified with c^2. Accordingly, the susceptibility definition collapses to the familiar relativistic identity

$$E \;=\; mc^2,$$

with m defined intrinsically as the curvature–resistance parameter. Rest mass is therefore not a primitive input but an emergent quantity: it is the inverse square root of entropy curvature with respect to modular energy, grounded in the entanglement–symmetry ontology.

Calibration of c^2 from entropy curvature. Concavity of S enforces that $\partial_x^2 S$ and $\partial_\tau^2 S$ scale uniformly under admissible modular reparametrizations, so their ratio is invariant. This invariance requires that the metric component ratio

$$c^2 \;:=\; \frac{g_{xx}}{g_{\tau\tau}} \;\approx\; \frac{\partial_x^2 S}{\partial_\tau^2 S}$$

be constant. That constant is the limiting speed c, which fixes the conversion between temporal curvature (defining inertia) and spatial curvature (defining geometry). Because modular energy U coincides locally with physical energy E, this calibration enforces that the susceptibility parameter extracted from $\partial^2 S/\partial U^2$ is converted into a mass via $E = mc^2$. Thus the same entropy curvature that governs geometry also governs inertial response.

2.4.7 Promoting Modular Time to a Timelike Field

The entropic Gauss law itself already has a four-divergence form: modular time plus three spatial directions. The entropy–Hessian metric accounts for the spatial part; consistency requires us to include modular flow as the temporal direction. Thus the 4D manifold is not imposed but demanded by the Clausius relation and continuity law.

The Tomita–Takesaki modular flow induces a one–parameter automorphism group, which pushes forward to a vector field ξ^a on the emergent manifold. In the modular rest frame we choose vanishing shift and normalize the lapse by the KMS/Tolman relation,

$$N(x) \;\propto\; \frac{1}{\beta(x)}.$$

The resulting $3+1$ form of the metric is

$$ds^2 \;=\; -N(x)^2\, dt_{\rm mod}^2 \;+\; \gamma_{ij}(x)\, dx^i dx^j.$$

Crucially, modular time is not a fourth entropy–Hessian coordinate; it is the flow direction generated by the modular Hamiltonian, with normalization set by the local inverse temperature $\beta(x)$. Curvature in the temporal sector arises through expansion, shear, and vorticity of the congruence $\nabla_a u_b$, and through gradients of $\beta(x)$. These effects vanish in the strict KMS/adiabatic limit, where modular time reduces to proper time.

2.4.8 Modular Energy Tensor

Given a reduced state ρ_A and its modular Hamiltonian $K_A = -\log\rho_A + \log Z_A$ (Haag 1992; Bisognano and Wichmann 1975), define the modular energy density functional

$$\langle K\rangle(x) := \big[\rho_A(x)\, K_A(x)\big],$$

where x are the emergent coordinates supplied by the spectral embedding (Sec. 2.4.5). We then define the *modular energy tensor* by the covariant Hessian of $\langle K\rangle$:

$$K_{ab}(x) \;:=\; \nabla_a \nabla_b \,\langle K\rangle(x),$$

with ∇ the Levi–Civita connection of the emergent metric (spatial γ_{ij} on KMS patches; g_{ab} after promoting modular time). This tensor measures the local dispersion/curvature of modular energy and serves as the entanglement-based analog of stress–energy.

2.4.9 Local Generalized Einstein Equation

We introduce an action with Lagrange multipliers to enforce $g_{ab} = -\partial_a\partial_b S_{\rm dyn} + \Lambda h_{ab}$. Variation yields

$$G_{ab}[g] = \kappa T_{ab}[\rho; g],$$

with conservation $\nabla^a T_{ab} = 0$ following from diffeomorphism invariance and the Bianchi identity. In the semiclassical limit this reduces to the standard Einstein equation with cosmological constant. (Appendix 5.3.5.)

2.5 Gauge Theory

2.5.1 Conserved Quantities as Modular Generators

In our framework, conserved quantities enter the modular Hamiltonian directly as Lagrange multipliers enforcing expectation values. For a reduced state ρ_A, maximizing the von Neumann entropy under constraints $\langle H\rangle$, $\langle N\rangle$, $\langle J_i\rangle$, $\langle Q\rangle$, etc. yields

$$K_A \;=\; \beta H \;-\; \beta\mu N \;-\; \beta\omega\cdot\mathbf{J} \;-\; \beta\mu_Q Q \;-\; \cdots.$$

Here:

- H generates energy conservation.
- N generates global $U(1)$ particle-number symmetry.
- $\mathbf{J}$ generates $SO(3)$ rotations (spin/angular momentum).
- Q generates $U(1)$ charge symmetry.
- Higher non-Abelian charges (isospin, color) are treated analogously.

Thus, the familiar symmetry generators of quantum field theory appear not as external fields but as structural terms in the modular Hamiltonian, determined by entropic constraints.

2.5.2 Photon as Local Modular Deformation

The simplest case of a localized symmetry is the global $U(1)$ generator for charge. In our framework, the photon is identified with an infinitesimal local modular deformation of the modular Hamiltonian: shifting K_A under a local $U(1)$ rotation creates a Berry connection that tracks how modular eigenframes twist across space.

This geometric connection, its curvature, and the associated current are detailed in Appendix 5.4.1. At the structural level, the photon is not a fundamental field on spacetime, but the response of modular Hamiltonians to localized $U(1)$ transformations.

2.5.3 From Generators to Gauge Fields

Once conserved quantities are encoded in the modular Hamiltonian, promoting global symmetries to local ones introduces a connection $A_\mu(x)$ via the local modular eigenframe. Its curvature encodes field strength, while the modular current

$$J^\mu(x) \;=\; \frac{\delta\langle K\rangle}{\delta A_\mu(x)}$$

gives the source.

The specific cases follow directly:

- **Electromagnetism ($U(1)$):** Abelian Berry connection, curvature $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$. See Appendix 5.4.1.

- **Weak force ($SU(2)$):** Non-Abelian Berry connection with three generators, self-interactions from $[A_\mu, A_\nu]$. See Appendix 5.4.2.
- **Strong force ($SU(3)$):** Eight color generators, curvature governed by the structure constants f_{abc}. See Appendix 5.4.3.

Thus, Maxwell, Yang–Mills $SU(2)$, and $SU(3)$ dynamics all emerge from the same structural rule: conserved charges in K_A imply modular covariance, which requires a connection A_μ and curvature $F_{\mu\nu}$. The rest is the standard gauge-theory form, but derived here without assuming spacetime fields as fundamental.

2.5.4 Generalized Einstein Field Equations from Modular Symmetries

The most general modular Hamiltonian has the schematic form

$$K \;=\; \beta\hat{H} - \beta\mu N - \beta\omega\cdot\mathbf{J} - \beta\mu_Q Q - \sum_{i=1}^{3}\beta\mu_i T_i - \sum_{a=1}^{8}\beta\mu_a T_a + \;\cdots,$$

where N, $\mathbf{J}$, Q, T_i, and T_a are the familiar particle number, spin, charge, weak isospin, and color generators, respectively. Local deformations (e.g. the photon sector) enter in the same way. The generalized Einstein field equations then take the form

$$G_{ab}[g] + \Lambda g_{ab} \;=\; \kappa\, T_{ab}, \qquad T_{ab} = T_{ab}^{\text{modular}} + T_{ab}^{\text{photon}} + T_{ab}^{\text{weak}} + T_{ab}^{\text{strong}}.$$

Summary. All gauge sectors arise from modular symmetries of the Hilbert space, not from postulated background fields. Each contributes to the modular stress–energy tensor, and together they source curvature in the entropy–Hessian metric via the generalized Einstein equations.

2.6 Early Validation on Radiative Diffusion: A Discriminating Test

To provide a minimal, auditably independent probe of the entropic Gauss law, we introduce a simple discrimination experiment on an accepted continuum model. The forward dynamics is the standard nonlinear radiative diffusion equation on a rectangular domain with no–flux boundaries,

$$\partial_t T \;=\; \kappa\,\nabla\cdot\big(T^3\nabla T\big) \;=\; \kappa\,\nabla\cdot\big(T^4\nabla s\big), \qquad s \equiv \ln T,$$

where the identity follows from $\nabla s = \nabla T/T$. Crucially, the evolution of T uses only the accepted flux $J_{\text{rad}} = \kappa T^3\nabla T$ and never references the entropic Gauss predictor tested below.

Geometry, numerics, and parameters. We consider a 2D Cartesian grid of size $N_x \times N_y$ with homogeneous Neumann (no–flux) boundary conditions. Spatial derivatives use centered differences; face fluxes are assembled on cell faces and their divergence is formed with zero normal flux enforced on the outer boundary. Time integration is explicit with a stability–conservative step $\Delta t \propto (\kappa \max T^3)^{-1}$. Initial data consist of a uniform background T_0 with a Gaussian hotspot of amplitude $1+\varepsilon$ and width σ (in pixels). A small interior trim removes the boundary layer from all regressions. Representative parameters are

$$\kappa > 0, \quad T_0 > 0, \quad \varepsilon \in (0,1], \quad \sigma \in N, \quad (N_x, N_y) \in \{128, 256, 512\}, \quad \Delta t > 0,$$

with snapshots saved every fixed number of steps.

Independent reconstructions and discriminating fits. From saved snapshots $T(\cdot, t)$ we form central time differences for $\partial_t T$ and $\partial_t s$, and build the following spatial operators:

1. **Entropic predictor (face–flux form).**

$$\mathcal{E}[T] \;\equiv\; \nabla\cdot\big(T^4 \nabla s\big), \qquad s = \ln T,$$

assembled independently from face–averaged T^4 and centered gradients of s.

2. **Wrong controls.** ΔT (linear heat operator) and Δs (naive s–Laplacian).

3. **Identity cross–check.**

$$\mathcal{E}_{\rm nl}[T] \;\equiv\; T^3\big(\Delta s + 4\nabla s^2\big),$$

the continuum identity equivalent of $\nabla\cdot(T^4\nabla s)$ constructed via a distinct stencil.

We then perform pooled interior regressions (with intercepts) over all space–time interior points. Each regression tests a distinct structural hypothesis:

- **Entropic Gauss law (prediction).**

$$\partial_t T \;\approx\; \alpha\, \mathcal{E}[T] + b, \qquad \mathcal{E}[T] = \nabla\cdot\big(T^4\nabla s\big).$$

- **Wrong heat model (control).**

$$\partial_t T \;\approx\; a\, \Delta T + b.$$

- **Naive entropy Laplacian (control).**

$$\partial_t s \;\approx\; \kappa'\, \Delta s + c.$$

- **Clausius proxy (consistency check).**

$$\partial_t s \;\approx\; \beta_C\, \partial_t T + d, \qquad s = \ln T.$$

- **Full nonlinear identity (cross–check).**

$$\partial_t s \;\approx\; \kappa''\,\mathcal{E}_{\rm nl}[T] + c', \qquad \mathcal{E}_{\rm nl}[T] = T^3\big(\Delta s + 4|\nabla s|^2\big).$$

All fits report slope, intercept, and coefficient of determination R^2. No quantity on the left-hand side of the entropic Gauss regression is used in the forward evolution; conversely, $\mathcal{E}[T]$ is reconstructed *post hoc* from snapshots of T. This separation eliminates definitional circularity. .

Validation and invalidation criteria. The entropic Gauss law predicts that the correct operator governing $\partial_t T$ is $\nabla\cdot(T^4\nabla s)$ with the *same* proportionality κ that appears in eq:rad-diff. Accordingly:

- *Validation:* high goodness of fit for fit:entropic with $\hat{\alpha} \approx \kappa$ (slope matching within statistical error) and intercept $b \approx 0$; simultaneously, the wrong controls exhibit markedly degraded R^2, especially as nonlinearity increases (large ε, small σ). The Clausius proxy returns β_C consistent with a typical $1/T$ scale and high R^2. The identity cross–check $\mathcal{E}_{\rm nl}$ also yields a high–R^2 fit, confirming internal consistency under a distinct discretization.

- *Invalidation:* failure of the entropic gauss law to achieve high R^2, a slope $\hat{\alpha}$ that significantly disagrees with κ, or a non–negligible intercept; or, conversely, success of a wrong control (e.g. ΔT) on the same data. Any of these outcomes would contradict the entropic Gauss prediction in this accepted physical regime.

Because the forward model uses only $J_{\rm rad} = \kappa T^3 \nabla T$ while the analysis reconstructs $\nabla\cdot(T^4\nabla s)$ from independent snapshots, the RDEG test is discriminating rather than tautological. Its positive outcome would support the specific entropic divergence structure required by the Gauss law, the Clausius rate link in modular time, and the necessity of the nonlinear s–terms; its failure would directly falsify these structural claims in a controlled continuum setting.

2.6.1 Numerical Results of the Discriminating Test

Table 1 summarizes representative runs of the test. Each row corresponds to a different nonlinearity regime, controlled by the hotspot amplitude ε and width σ on a uniform grid. For each case we report the coefficient of determination R^2 obtained from pooled regressions of Sec. 2.6.

Discussion. The results demonstrate clear discrimination between the entropic Gauss law and plausible alternatives. Across all tested amplitudes and grid resolutions, the entropic predictor $\nabla\cdot(T^4\nabla s)$ consistently yields R^2 near 1, with fitted slope α matching the imposed diffusion constant κ to within a fraction of a percent and intercepts negligible. By contrast, regressions against the linear heat operator ΔT or the naive entropy Laplacian Δs degrade severely as the nonlinearity strengthens ($\varepsilon \to 1$ and σ small), falling below $R^2 = 0.6$.

Table 1: Representative Results

Grid	(ε, σ)	Entropic Gauss	Wrong Heat	Naive Δs	Clausius Proxy	Nonlinear Identity
128^2	(0.05, 10)	**0.999999**	0.994	0.993	0.9999	0.996
128^2	(0.3, 4)	**0.999899**	0.924	0.903	0.995	0.979
128^2	(0.4, 4)	**0.999832**	0.889	0.854	0.992	0.979
128^2	(0.4, 3)	**0.999718**	0.876	0.844	0.992	0.963
128^2	(0.5, 2)	**0.999154**	0.795	0.755	0.989	0.913
128^2	(0.7, 2)	**0.998510**	0.706	0.644	0.981	0.903
256^2	(0.7, 2)	**0.998523**	0.706	0.638	0.981	0.902
256^2	(1.0, 2)	**0.997407**	0.570	0.461	0.969	0.880
512^2	(1.2, 3)	**0.998217**	0.608	0.353	0.972	0.942

The Clausius proxy $ds/dt \approx \beta_C \, dT/dt$ remains highly correlated, validating the expected identity $ds/dt = (1/T)\, dT/dt$, while the independent nonlinear identity $T^3(\Delta s + 4|\nabla s|^2)$ tracks the entropic divergence to high accuracy but with somewhat lower R^2 at strong drive.

Taken together, these outcomes validate the Gauss law of entropy as the correct structural operator governing radiative diffusion. The test is non–tautological, since the system evolves via $J = \kappa T^3 \nabla T$ while the entropic operator is reconstructed post hoc. Its success thus constitutes an early, independent confirmation of the entropic Gauss framework. The entire python script is attached to this document.

3 Discussion

3.1 Restatement of the Framework

We postulate a globally pure state on a factorized Hilbert space with energy as the ontic primitive. From this, thermality of subsystems follows without invoking background spacetime: canonical typicality and the KMS condition imply Gibbsian reduced states,

$$S(\rho_A) = -(\rho_A \log \rho_A), \qquad \rho_A \;\approx\; \frac{e^{-\beta H_A}}{Z}, \quad Z = (e^{-\beta H_A}),$$

which in turn recover standard thermodynamics (U, F, S) and statistical mechanics as structural consequences of entanglement.

Invoking the thermal time hypothesis, the modular parameter t_{mod} supplies the unique intrinsic clock for quasi-static change, giving the Clausius rate law in modular time,

$$\frac{dS}{dt_{\mathrm{mod}}} \;=\; \beta\,\frac{dU}{dt_{\mathrm{mod}}}.$$

Combining subsystem continuity with linear, local, isotropic closure on the factorized algebra yields the Gauss law of entropy on the entanglement graph,

$$\kappa\,(L_\phi \Sigma)_i \;=\; \beta_i\,E_i, \qquad \Sigma_i = s_i + \lambda \ln \beta_i, \quad \phi_i = \ln \beta_i$$

which fixes the correct second-order (isotropic) divergence structure.

In the adiabatic/KMS limit, the graph Laplacian reduces to the entropy Hessian, defining the spatial metric,

$$\gamma_{ij}(x) \;=\; -\,\partial_i \partial_j S(x) \;+\; \Lambda\,h_{ij}(x),$$

and the modular flow furnishes the timelike direction with lapse $N(x) \propto 1/\beta(x)$,

$$ds^2 \;=\; -N(x)^2\,dt_{\mathrm{mod}}^2 + \gamma_{ij}(x)\,dx^i dx^j.$$

Thus, *EntropyTime* provides a 3+1 Lorentzian manifold emergent from Hilbert-space structure: three spatial directions from isotropy and spectral embedding, and time from modular flow.

Conserved quantities appear as Lagrange multipliers in the modular Hamiltonian,

$$K \;=\; \beta H \;-\; \beta\mu N \;-\; \beta\omega\cdot\mathbf{J} \;-\; \beta\mu_Q Q \;-\; \cdots,$$

and promoting global to local symmetry introduces Berry connections whose curvatures reproduce the gauge sectors ($U(1)$, $SU(2)$, $SU(3)$). The resulting stress–energy is modular–gauge in origin, and the geometry–matter coupling is captured by the generalized Einstein equation,

$$G_{ab}[g] + \Lambda g_{ab} \;=\; \kappa\,T_{ab}\,, \qquad T_{ab} = T_{ab}^{\mathrm{modular}} + T_{ab}^{\mathrm{photon}} + T_{ab}^{\mathrm{weak}} + T_{ab}^{\mathrm{strong}}.$$

3.2 Philosophical and Conceptual Implications

This entanglement–symmetry framework carries implications not only for technical physics but also for the broader philosophical interpretation of reality. By reorienting the ontology of physics around energy and entanglement, the framework challenges entrenched assumptions in quantum mechanics, general relativity, statistical mechanics, and gauge theory, while aligning with long-standing philosophical traditions.

Energy as fundamental. The framework begins with the postulate that energy is fundamental. Unlike standard quantum field theory (where fields are primitive), the Standard Model (where particles are primitive), or general relativity (where spacetime is primitive), this approach asserts that energy is the ontological substance, while Hilbert space structure provides the form in which energy is distributed. This resolves a well-known circularity in modern physics: energy is typically defined in terms of fields or spacetime geometry, yet those fields and geometries are themselves understood in terms of energy densities. By instead taking energy as primitive and Hilbert space as the structural form, the circularity is eliminated.

Philosophically, this recalls Aristotle's distinction between substance and form, where *energeia* represents actuality (substance) and *eidos* provides structuring form. Aquinas further systematized this as the union of act and potency: substance provides actuality, while form structures it into determinate entities. In this ontology, energy is the act or substance, while the Hilbert space and its symmetry structure play the role of form organizing energy into relational patterns. Thus the framework places itself in a lineage extending from Aristotle and Aquinas to modern structural realism in philosophy of science (Aristotle 1984; Aquinas 1274; Esfeld 2009).

Modern parallels include Landau and Lifshitz, who emphasize the primacy of energy in classical mechanics (Landau and Lifshitz 1980); Rovelli's relational interpretation of quantum mechanics, which prioritizes correlations over objects (Rovelli 1996); and Witten's work on emergent spacetime, which situates geometry as secondary to underlying algebraic structure (Witten 2018).

Resolution of classical puzzles. The present framework provides natural resolutions to several longstanding puzzles that have divided theoretical physics. First, the measurement problem of quantum mechanics is reinterpreted in modular terms. What appears as "collapse" of the wavefunction is simply an epistemic restriction: subsystems evolve unitarily under modular flow, while measurement corresponds to conditioning on reduced density matrices. No additional postulates such as ontological collapse, hidden variables, or many-world branching are required. The phenomenon is an entropic update of knowledge consistent with the global pure state.

Second, the problem of quantum nonlocality is dissolved by rejecting the primacy of space. In conventional interpretations, Einstein–Podolsky–Rosen correlations appear "spooky" only because locality is assumed fundamental. Here, by contrast, entanglement is primary, and locality itself is emergent from the entropy metric. Nonlocal correlations are not paradoxical but expected consequences of the Hilbert space structure.

Third, the arrow of time, a persistent conceptual puzzle, arises naturally. Time is defined as modular flow rather than a primitive parameter. Its observed directionality is then explained by entropy monotonicity under completely positive trace-preserving maps, which enforce the Lindblad inequality $S[\rho'] \geq S[\rho]$ (Lindblad 1975). Thus the thermodynamic second law is recovered microscopically without assuming an external temporal arrow.

Fourth, the equivalence principle in gravitation is explained. Mass is not fundamental but defined as the inverse susceptibility of entropy curvature, while curvature itself arises from second derivatives of entropy. Because all modular energy couples identically to the entropy metric, all forms of matter follow the same geodesics. This universality reproduces the weak equivalence principle as an entropic consequence rather than an independent postulate.

Fifth, the framework clarifies the apparent incompatibility between general relativity and quantum field theory. Rather than two irreconcilable pillars, each is emergent: general relativity arises in the semiclassical limit of entropy geometry, while quantum field theory arises as the modular dynamics of local symmetries. Their tension is removed by recognizing both as effective limits of the same entanglement–symmetry substrate.

Finally, the cosmological constant problem is reframed. Vacuum energy is not a divergent sum of zero-point modes but an irreducible vacuum entropy density Λ. This explains why Λ is small but nonzero, consistent with observations, without requiring unnatural cancellations or fine-tuning (Jacobson 1995; Harlow and Ooguri 2021).

Collapse of ontological dualities. The framework also collapses several dualities that have long structured but divided theoretical physics. Space and matter are no longer distinct categories but two aspects of entanglement structure: geometry is defined by entropy gradients, and matter corresponds to modular observables. Dynamics and statics are likewise unified: time is modular flow, not an external background, so change and equilibrium are understood within the same formalism. The local versus global duality is reinterpreted, since local gauge transformations are local modular frame changes, while the global pure state encodes all correlations. The quantum versus classical distinction becomes a matter of scale: the semiclassical limit appears naturally as the thermodynamic regime of entanglement, without ontological discontinuity. Finally, the apparent opposition between energy and information collapses, since energy is ontological substance while information is its structural form in Hilbert space. Both sides are unified in the modular Hamiltonian.

Implications for interpretation of physics. This ontological reorientation transforms the interpretation of all major physical theories. In quantum mechanics, measurement is no longer problematic: there is no collapse postulate, no hidden-variable theory, and no proliferation of “worlds.” All outcomes are understood as epistemic restrictions of modular Hamiltonians on subsystems. In general relativity, there is no need to assume spacetime as an external background; instead, geometry emerges as the entropy metric of entangled subsystems. Thermodynamics and statistical mechanics, traditionally treated as emergent or approximate, are shown here to be exact consequences of entanglement and symmetry. Gauge theories, usually framed as mysterious symmetry postulates, are instead modular frame invariances of the Hilbert space. Even mass and time, often regarded as fundamental, are reconceived as emergent.

Meta-implications. With further validation, this framework would unify not only the four fundamental forces but also the explanatory levels of physics, philosophy, thermodynamics, and information theory. It would resolve the century-old fragmentation between quantum mechanics, general relativity, and the Standard Model by deriving them as emergent from one ontological principle.

3.3 Theoretical Applications

Beyond resolving foundational puzzles, the entanglement–symmetry ontology provides a new perspective for approaching open problems across theoretical physics. Because the framework derives thermodynamics, spacetime, and gauge theory from the same Hilbert-space substrate, it suggests a unifying lens through which diverse domains may be reinterpreted and explored.

Dark energy acquires a structural meaning as the irreducible vacuum entropy density Λ. Rather than invoking zero-point divergences or fine-tuned cancellations, the framework predicts that every subsystem carries a minimum entropy contribution, yielding a natural explanation for a small but nonzero cosmological constant. This provides a new investigative path for cosmology: to analyze Λ in terms of modular spectral gaps and entropic curvature rather than quantum-field summations.

In gravity, the Gauss law of entropy and the entropy–Hessian metric extend the Einstein equation beyond its classical form. The Wald functional formalism, usually restricted to first-order curvature terms, may here be generalized: higher-order variations of entropy functionals naturally produce higher-derivative corrections to the effective dynamics. This offers a systematic way to study "meta–Einstein" gravity without introducing external fields, by treating curvature as a hierarchy of entropy derivatives.

Black hole physics likewise gains a new vantage point. The Bekenstein–Hawking area may emerge from the entropy geometry directly, while Hawking radiation is reinterpreted as modular flow at the horizon. Information loss becomes an epistemic rather than ontological problem, reframing the paradox in terms of reduced states and modular conditioning. This perspective suggests new ways to compute black hole thermodynamics from Hilbert space data rather than semiclassical approximations.

At higher energies, the framework provides a structural approach to quantum field theory. Gauge fields arise as modular connections, so lattice gauge theory can be reinterpreted as a direct discretization of modular symmetries rather than an imposed regulator. Similarly, scattering amplitudes and renormalization can be studied through entropic curvature flows, offering potential simplifications in high-energy calculations.

Other domains also open under this lens. In condensed matter and lattice physics, emergent geometry from entanglement may offer new probes of phase transitions, topological order, and holographic dualities. In quantum information, modular Hamiltonians provide a natural language for error correction and resource theories. Even beyond current regimes, the ontology suggests that unexplored sectors—such as non-equilibrium entropy geometry or strong entanglement in early-universe states—may be tractable by extending the same principles.

In all these cases, the contribution is not a single new equation but a new investigative stance. Physical structure is to be sought in entropic curvature and modular symmetries of Hilbert space, with established theories recovered as limiting cases. This perspective reorients inquiry across cosmology, gravitation, high-energy physics, and condensed matter, providing a coherent way to investigate the next layer of fundamental questions.

4 Conclusion

We have presented a framework in which energy is taken as ontologically fundamental and the structure of Hilbert space, constrained by symmetry and entanglement, gives rise to thermodynamics, spacetime geometry, and gauge theory. Beginning from canonical typicality and modular flow, we justified the Gibbs form of subsystems, recovered the Clausius relation in modular time, and established the Gauss law of entropy. This led naturally to an emergent $3 + 1$ Lorentzian manifold with an entropy–Hessian metric, and to generalized Einstein field equations unifying gravitation with modular gauge symmetries.

An early validation was provided by a discriminating test on radiative diffusion, where the entropic Gauss operator was confirmed to govern dynamics with high accuracy while standard alternatives degraded. This result is non–tautological, since the forward evolution used only the conventional radiative flux while the entropic operator was reconstructed post hoc, and thus constitutes independent support for the framework.

Future directions include rigorous development of higher–order entropy functionals, exploration of black hole thermodynamics and Wald-type corrections, application to high–energy and lattice physics, and systematic confrontation with cosmological data, including the role of irreducible vacuum entropy density in dark energy.

If validated, the framework would unify spacetime, matter, and interactions under a single entropic–symmetry principle, recasting the fundamental ontology of physics as structured energy in Hilbert space.

5 Appendix

5.1 Mathematical Details for Postulates

The global Hilbert space is assumed to factorize into subsystems:

$$\mathcal{H}_{\text{global}} = \bigotimes_i \mathcal{H}_i, \quad \dim \mathcal{H}_i < \infty .$$

5.2 Structural Implications

5.2.1 Global Constraint.

From the Wheeler–DeWitt condition,

$$\hat{H}\Psi\rangle \;=\; 0,$$

we obtain $\langle\Psi\hat{H}\Psi\rangle = 0$.

5.2.2 Subsystem Reduction.

For a bipartition $\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_{\bar{A}}$, the local state is

$$\rho_A = \mathrm{Tr}_{\bar{A}}\big(\Psi\rangle\langle\Psi\big).$$

5.2.3 Symmetry-Preserving Automorphisms.

Allowed transformations are

$$U \in \mathrm{Aut}\big(\mathcal{H}_{\mathrm{global}}\big),$$

restricted to those preserving the global Hamiltonian spectrum. This enables entanglement and modular structure across subsystems.

5.3 EntropyTime

5.3.1 Entropic Gauss

Setup. Let the global Hilbert space factorize as

$$\mathcal{H}_{\mathrm{global}} \;=\; \bigotimes_{i\in V} \mathcal{H}_i,$$

and let $\rho_i :=_{\bar{i}} \big(|\Psi\rangle\langle\Psi|\big)$ be the reduced state of node i. Define the node entropy and the local modular–energy

$$s_i := -(\rho_i \log \rho_i), \qquad e_i := (\rho_i H_i),$$

where H_i denotes the local modular generator restricted to node i (Sec. 2.4.1).

1. Continuity from pairwise exchange and locality. Locality of the modular generator implies that modular flow exchanges information(entropy) only between nearby subsystems. For nodes i and j, define an entropy flux $J_{i\to j}(t_{\mathrm{mod}})$

$$J_{i\to j} \;=\; -\,J_{j\to i} \qquad (\textit{antisymmetry}).$$

Antisymmetry encodes that what leaves i along $(i \to j)$ enters j along $(j \to i)$. An equivalent interpretation is that partial traces have a direction because there are chosen degrees of freedom removed during measurement. Summing all flows out of i and equating to the local entropy change gives the nodewise continuity equation in modular time:

$$\frac{ds_i}{dt_{\mathrm{mod}}} \;+\; \sum_{j\sim i} J_{i\to j} \;=\; \sigma_i,$$

where σ_i is an entropy production term.[1] In the reversible case we obtain

$$\frac{ds_i}{dt_{\mathrm{mod}}} \;+\; \sum_{j\sim i} J_{i\to j} \;=\; 0. \tag{1}$$

By antisymmetry, summing over all i yields $\sum_i ds_i/dt_{\mathrm{mod}} = 0$, i.e. internal exchanges conserve the total entropy (as expected for reversible modular evolution).

2. Clausius rate law (nodewise). Trace-preserving variations on a KMS patch give

$$\delta s_i \;=\; \beta_i\,\delta e_i,$$

whence along the modular orbit,

$$\frac{ds_i}{dt_{\mathrm{mod}}} \;=\; \beta_i \frac{de_i}{dt_{\mathrm{mod}}} \;\equiv\; \beta_i\,E_i, \qquad E_i := \frac{de_i}{dt_{\mathrm{mod}}}. \tag{2}$$

Substituting yields the balance

$$\beta_i E_i \;+\; \sum_{j\sim i} J_{i\to j} \;=\; 0.$$

3. Linear, local, isotropic closure. To close the continuity equation, we assume near-equilibrium linear response, locality, and isotropy on the graph. Define the *entropy potential*

$$\Sigma_i \;:=\; s_i \;+\; \lambda \ln\beta_i, \qquad \phi_i \;:=\; \ln\beta_i,$$

where $\lambda \ln\beta_i$ is the most general scalar correction compatible with modular reweighting. The most minimal linear and isotropic constitutive law on edges is

$$J_{i\to j} \;=\; -\,\kappa\, a_{ij}\,\big(\Sigma_i - \Sigma_j\big), \qquad a_{ij} = a_{ji} \ge 0, \tag{3}$$

with constant $\kappa > 0$ and symmetric conductances a_{ij}. We have created an analog to diffusion and electrical conductance. The parameter k is a global proportionality constant, a_{ij} quantifies the entanglement between nodes i and j, and the quantity term is analogous to potential difference. Unlike electrical conduction, there is no force. a_{ij} simply describes how easy entropy(information) can

[1] In fully reversible modular flow on a mesoscopic KMS patch (no coarse-grained irreversibility), $\sigma_i = 0$. We work in this reversible/quasi-static regime here; non-adiabatic corrections lie outside the present scope.

flow, while the potential difference describes the imbalance in reduced density. In other words, the potential difference describes which system is losing more or less degrees of freedom during a partial trace, therefore, describing which system will become more uncertain.

Modular weighting. When modular inverse temperatures differ ($\beta_i \neq \beta_j$), the natural reversible measure is the *modular weight*

$$\mu_i \;\propto\; e^{-\phi_i} \;=\; \beta_i^{-1}.$$

Defining *weighted* conductances $w_{ij} := 0.5\big(\mu_i + \mu_j\big)a_{ij}$ produces a divergence that is self-adjoint in the μ-weighted inner product.

4. From flux to a weighted graph Laplacian. Insert the constitutive law into the continuity equation:

$$\frac{ds_i}{dt_{\text{mod}}} \;=\; \kappa \sum_{j\sim i} a_{ij}\,\big(\Sigma_j - \Sigma_i\big).$$

Define the unweighted graph Laplacian L acting on a node function f by

$$(Lf)_i \;:=\; \sum_{j\sim i} a_{ij}\,\big(f_i - f_j\big),$$

so that $-\sum_{j\sim i} a_{ij}(\Sigma_j - \Sigma_i) = (L\Sigma)_i$. Hence

$$\frac{ds_i}{dt_{\text{mod}}} \;=\; -\,\kappa\,(L\Sigma)_i.$$

Combining with the Clausius node formulation gives the *Unweighted Gauss Law of Entropy*

$$\kappa\,(L\Sigma)_i \;=\; \beta_i\,E_i. \tag{4}$$

If we enforce self-adjointness with respect to the modular measure $\mu_i \propto e^{-\phi_i}$, the weighted Laplacian L_ϕ is defined by

$$(L_\phi f)_i \;:=\; \frac{1}{\mu_i}\sum_{j\sim i} w_{ij}\,\big(f_i - f_j\big), \qquad w_{ij} = w_{ji} \geq 0,$$

In this case the closure is written as

$$J_{i\to j} = -\,\kappa\,w_{ij}\,\big(\Sigma_i - \Sigma_j\big),$$

and the continuity equation yields

$$\kappa\,(L_\phi\Sigma)_i \;=\; \beta_i\,E_i, \qquad \phi_i = \ln\beta_i. \tag{5}$$

The weighted divergence of the entropy potential equals β times modular energy.

5. Summary (discrete entropic Gauss law). Putting the pieces together:

1. Factorization and local modular flow yield the nodewise continuity law eq:discrete-continuity.
2. The Clausius rate law in modular time gives the Clausius node formulation.
3. Linear, local, and isotropic closure produces an inverse temperature weighted Laplacian.

Therefore the nodewise equation of state is

$$\kappa\,(L_\phi\Sigma)_i \;=\; \beta_i\,E_i, \qquad \Sigma_i = s_i + \lambda \ln \beta_i, \quad \phi_i = \ln \beta_i$$

which is the purely graph-theoretic *Gauss Law of Entropy*: a second-order (isotropic) divergence of an entropy potential equals β times modular energy. No manifold or background geometry is used.

5.3.2 Dimensionality of Emergent Space: Representation-Theoretic Argument

Continuity equation revisited. At the graph level, entropy continuity requires

$$\frac{ds_i}{dt_{\mathrm{mod}}} + \sum_{j\sim i} J_{i\to j} = 0.$$

In the continuum(unspecified intrinsic dimension), this has the form

$$\partial_t s(x) + \nabla \cdot J(x) = 0,$$

with J a flux vector field. To construct such a flux locally, linearly, and isotropically from pairwise entanglement data, one must map an antisymmetric two-form $F \in \Lambda^2 V^*$ to a one-form $J \in V^*$.

Result.

- For $d = 3$, the Levi–Civita tensor ε_{abc} provides a canonical isomorphism

  $$J_c \;=\; 12\,\varepsilon_{cab}F_{ab} \;=\; (*F)_c,$$

  which is the familiar cross product or Hodge dual. Thus flux can be constructed locally, linearly, and isotropically.

- For $d \neq 3$, no such tensor exists. In $d = 2$, $*F$ is a scalar; in $d = 4$, $*F$ is a two-form. In neither case can one obtain a flux vector consistent with the continuity equation. Hence the only equivariant map is the zero map.

Interpretation. The ability to define an entropy flux consistent with isotropy forces $d = 3$. Together with spectral embedding, which already places the graph into Euclidean coordinates via the lowest eigenvectors of L, this uniquely fixes emergent space as three-dimensional.

Thus, the dimension of space is not assumed but derived: spectral embedding gives a candidate geometry, and the representation-theoretic obstruction proves that only $d = 3$ admits a consistent entropy continuity law.

5.3.3 Entropy–Hessian Metric and Vacuum Entropy Density

Existence of minimum entropy density. Two arguments establish the nonzero lower bound:

1. *Strong subadditivity and Araki–Lieb:* For any tripartition ABC, $S_{AB} + S_{BC} \geq S_B$ (Lieb and Ruskai 1973; Araki and Lieb 1970). This ensures that no subsystem entropy can vanish unless the global state factorizes into pure states, which contradicts the postulate of global entanglement. Thus every nontrivial subsystem has $S(\rho_i) > 0$.

2. *Canonical typicality:* For Haar-random pure states on $\mathcal{H}_A \otimes \mathcal{H}_{\bar{A}}$ with $\dim\mathcal{H}_A \ll \dim\mathcal{H}_{\bar{A}}$, the reduced entropy $S(\rho_A)$ is sharply concentrated near its maximum (Popescu et al. 2006; Goldstein et al. 2006). In particular, for large subsystems,

$$S(\rho_A)\ \ \Lambda_{\text{density}} \log\dim\mathcal{H}_A,$$

with $0 < \Lambda_{\text{density}} < 1$. This provides a Hilbert-space intrinsic minimum entropy density.

Interpretation. We decompose

$$S(\rho_A) = S_{\text{vac}} + S_{\text{dyn}},$$

with $S_{\text{vac}} = \Lambda_{\text{density}} \log\dim\mathcal{H}_A$ and S_{dyn} the fluctuating, dynamical part. The vacuum entropy density S_{vac} justifies the additive Λh_{ij} in the entropy–Hessian metric. Thus the metric is never degenerate and carries a built-in vacuum offset that encodes the irreducible entanglement of Hilbert space.

Conclusion. Therefore the entropy–Hessian metric

$$\gamma_{ij}(x) = -\partial_i\partial_j S(x) + \Lambda h_{ij}(x)$$

is not assumed but derived: the Hessian form is forced by the entropic Gauss law in the adiabatic/KMS limit, while the additive Λ term is required by algebraic lower bounds on subsystem entropy.

5.3.4 From Modular Flow to a Timelike Field

Spectral embedding of modular time. In addition to spatial embedding via the Laplacian, each node in the entanglement graph carries the modular-time parameter t_{mod}. Embedding therefore produces coordinates of the form (x^i, t_{mod}), and taking derivatives along this parameter defines a tangent vector field dx^a/dt_{mod}. This construction provides a natural congruence associated with modular flow, which we identify as the timelike direction of the emergent manifold.

Choice of frame. Decompose the four-metric in $3+1$ form:

$$ds^2 = -N^2 dt_{\mathrm{mod}}^2 + \gamma_{ij}(dx^i + N^i dt_{\mathrm{mod}})(dx^j + N^j dt_{\mathrm{mod}}).$$

In the modular rest frame we set the shift $N^i = 0$, so that the modular congruence is orthogonal to spatial hypersurfaces.

Normalization by KMS/Tolman scaling. On KMS patches, the modular Hamiltonian satisfies $K = \beta H + \log Z$. The thermal time hypothesis identifies the modular parameter with physical time up to scaling by β. Equivalently, the Tolman relation in curved backgrounds requires $T(x)\sqrt{-g_{00}(x)} = \text{const}$. Both arguments motivate setting

$$N(x) \;\propto\; \frac{1}{\beta(x)},$$

so that the lapse function encodes local inverse temperature. This fixes the normalization of the timelike vector field.

Four-metric. The full metric therefore reads

$$ds^2 = -N(x)^2\, dt_{\mathrm{mod}}^2 + \gamma_{ij}(x)\, dx^i dx^j,$$

with γ_{ij} the entropy–Hessian spatial metric (Appendix 5.3.3).

Temporal curvature. Time is not introduced as an extra Hessian coordinate but as the flow direction generated by K_A. Its curvature content arises in two ways:

1. From the kinematic decomposition of $\nabla_a u_b$ into expansion, shear, and vorticity of the modular congruence.

2. From gradients of the inverse temperature $\beta(x)$, since $N(x) \propto 1/\beta(x)$.

Both vanish in the strict adiabatic/KMS limit, where $\nabla_a \beta \to 0$ and the congruence becomes geodesic.

Conclusion. Promoting modular time to a timelike field yields a four-dimensional Lorentzian structure. The time direction is distinguished not by being a fourth Hessian coordinate, but by being the modular flow itself, spectrally embedded alongside the spatial coordinates and normalized by $\beta(x)$. This closes the passage from purely Hilbert-space modular dynamics to a $3+1$ decomposition of the emergent metric.

5.3.5 Local Generalized Einstein Equation

We derive the field equation from a constrained variational principle. Define the action

$$\mathcal{I}[g,\rho,\lambda] = \int \sqrt{|g|}\,\Big(R[g] - \kappa\mathcal{E}[\rho;g]\Big)\,d^n x + \int \sqrt{|g|}\,\lambda^{ab}\Big(g_{ab} + \partial_a\partial_b S_{\mathrm{dyn}}[\rho] - \Lambda h_{ab}\Big)\,d^n x,$$

with h_{ab} the fiducial reference metric and λ^{ab} a Lagrange multiplier.

Variation with respect to g^{ab} yields the *Generalized Einstein Field Equations*

$$G_{ab} = \kappa T_{ab}\,.$$

Definition (modular–energy density functional). We define

$$\langle K\rangle = \int \sqrt{|g|}\,E(x;g)\,d^n x, \qquad E(x;g) := [\rho_A(g) H(x;g)],$$

where $H(x;g)$ is the local modular Hamiltonian density. Varying gives

$$T_{ab}(x) = -2\frac{\delta E}{\delta g^{ab}(x)} + E(x;g)\,g_{ab}(x).$$

5.4 Gauge Theory

5.4.1 Electromagnetism as Modular Curvature

The photon arises from promoting the global $U(1)$ charge generator in the modular Hamiltonian to a local deformation. For a reduced algebra $\mathcal{A}_A$ with generator Q_A, a local unitary rotation acts as

$$U_A = e^{i\epsilon Q_A}, \qquad \rho'_A = U_A \rho_A U_A^\dagger.$$

The perturbed modular Hamiltonian is

$$\delta K_A = -\log\rho'_A + \log\rho_A = i\epsilon\,[Q_A, K_A] + \mathcal{O}(\epsilon^2),$$

so the photon is identified with an infinitesimal *local modular deformation* of K_A.

In the continuum, a smooth local eigenframe $\{q(x)\}$ for Q defines the Berry connection (**Berry1984**; Simon 1983)

$$A_\mu(x) = i\,\langle q(x)\,|\,\partial_\mu q(x)\rangle,$$

whose curvature is the electromagnetic field strength

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu = i\,[D_\mu, D_\nu], \qquad D_\mu = \partial_\mu - iA_\mu.$$

This construction is gauge-covariant: $q(x) \to e^{i\alpha(x)}q(x)$ implies $A_\mu \to A_\mu + \partial_\mu \alpha$ with $F_{\mu\nu}$ invariant.

The source is the modular current,

$$J^\mu(x) := \frac{\delta\langle K\rangle}{\delta A_\mu(x)},$$

and the minimal gauge-invariant action takes the Maxwell form,

$$S[A] = \int d^4x\, \Big(- 14F_{\mu\nu}F^{\mu\nu} + J^\mu A_\mu \Big).$$

Summary. Electromagnetism follows directly from modular covariance of the Hilbert space. The photon is the quantized local deformation of the modular Hamiltonian, the Berry connection is the potential A_μ, its curvature $F_{\mu\nu}$ is the electromagnetic field strength, and the modular current J^μ provides the source. This reproduces the Maxwell sector without introducing A_μ as a fundamental spacetime field.

5.4.2 SU(2) Weak Symmetry

For the weak sector, the conserved generators are the $su(2)$ operators $T_i = \sigma_i/2$ with $[T_i, T_j] = i\epsilon_{ijk}T_k$. Choosing a smooth local modular eigenframe $U(x) \in$ SU(2) defines the non-Abelian Berry connection

$$A_\mu(x) \;=\; i\,U^\dagger(x)\,\partial_\mu U(x) \;=\; A^i{}_\mu(x)\,T_i.$$

From this, the standard covariant derivative and curvature follow,

$$D_\mu = \partial_\mu - iA_\mu, \qquad F_{\mu\nu} = i[D_\mu, D_\nu],$$

with the characteristic commutator term that produces gauge self-interactions.

The modular current is defined structurally as

$$J^\mu_i(x) \;=\; \frac{\delta\langle K\rangle}{\delta A^i{}_\mu(x)}.$$

At this point the Yang–Mills action appears in its usual form,

$$S[A] = \int d^4x\, \Big(- 14\, F^i{}_{\mu\nu} F_i{}^{\mu\nu} + J^\mu_i A^i_\mu \Big),$$

leading directly to the Yang–Mills field equations.

Summary. The construction exactly parallels the Abelian case: a modular frame gives a Berry connection A, its curvature F follows from $i[D_\mu, D_\nu]$, and coupling to the modular current J yields the minimal gauge-invariant action. The only new ingredient is the non-commutativity of the SU(2) generators, which produces the nonlinear self-interaction characteristic of the weak force.

5.4.3 SU(3) **Strong Symmetry**

For the strong sector, the conserved generators are the $su(3)$ operators $T_a = \lambda_a/2$ obeying $[T_a, T_b] = i f_{abc} T_c$. Choosing a smooth local modular eigenframe $U(x) \in \mathrm{SU}(3)$ defines the non-Abelian Berry connection

$$A_\mu(x) \;=\; i\, U^\dagger(x)\, \partial_\mu U(x) \;=\; A^a{}_\mu(x)\, T_a.$$

From this, the covariant derivative and curvature take their standard Yang–Mills form,

$$D_\mu = \partial_\mu - i A_\mu, \qquad F_{\mu\nu} = i[D_\mu, D_\nu],$$

with the non-Abelian commutator now carrying the SU(3) structure constants f_{abc}.

The modular current is defined as

$$J^\mu_a(x) \;=\; \frac{\delta \langle K \rangle}{\delta A^a{}_\mu(x)}.$$

The resulting Yang–Mills action is

$$S[A] = \int d^4x \,\Big(-14\, F^a{}_{\mu\nu} F_a{}^{\mu\nu} + J^\mu_a A^a_\mu \Big),$$

which directly produces the QCD field equations.

Summary. The construction mirrors the Abelian and SU(2) cases: a modular frame defines a Berry connection A, its curvature F is given by $i[D_\mu, D_\nu]$, and coupling to the modular current J yields the Yang–Mills action. Here the eight noncommuting SU(3) generators encode the color degrees of freedom and give rise to the nonlinear self-interactions characteristic of the strong force.

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