Derivation of Einstein Field Equations from Information-Geometric Variational Principles: An Outline of Quantum Gravity in EBOC–Causal Manifold Unification

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Abstract

Given the interplay framework between discrete–static block structure (EBOC) and continuous–causal manifolds, this paper proposes an information-geometric variational principle: on every sufficiently small timelike geometric ball (or local causal diamond), the **generalized entropy** S_{gen} is extremized subject to volume and reference vacuum constraints. Utilizing the first-order "first law" $\delta S_{\text{out}} = \delta\langle H_{\text{mod}}\rangle$ of relative entropy and area variation induced by geometric light beam convergence (Raychaudhuri), we prove that for all small balls and all shape deformations, the extremality condition implies Einstein field equations $G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G\,\langle T_{\mu\nu}\rangle$. At the semiclassical level, second-order variation and non-negativity of relative entropy yield information inequalities including quantum focusing and QNEC, constituting quantum corrections. On the discrete side, EBOC's static block–factor decoding semantics provides Regge-type discrete action and proves convergence to the above continuous field equations in the limit of mesh refinement and information-geometric consistency. The "readout–scale–causality" semantics of this work strictly align with the windowed group delay master scale $\varphi'/\pi = \rho_{\text{rel}} = (2\pi)^{-1}\mathrm{tr}\,\mathsf{Q}$, achieving closure under finite-order Nyquist–Poisson–Euler–Maclaurin error discipline.

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1 Introduction

The derivation of Einstein field equations from thermodynamic and information-theoretic principles has emerged as a fundamental research direction in quantum gravity. Jacobson's seminal work [?] demonstrated that Einstein equations can be viewed as equations of state arising from local thermodynamic equilibrium. Subsequent developments in holography [?] and entanglement entropy [?] have deepened this connection, suggesting that gravitational dynamics may fundamentally arise from information-geometric considerations.

In this work, we propose a rigorous information-geometric variational principle (IGVP) within the unified framework of EBOC (Eternal Block Observation Computation) and causal manifolds. Our approach differs from previous work in several key aspects:

- **Local variational principle**: We formulate generalized entropy extremization on local balls, avoiding global assumptions and enabling point-by-point derivation of field equations.
- **Information-geometric foundation**: We employ Fisher–Rao metrics and relative entropy structures from rigorous information geometry, ensuring uniqueness via Čencov's theorem [?] and monotonicity properties.
- **Discrete–continuous duality**: The EBOC discrete side provides Regge-type triangulation with factor decoding semantics, provably converging to continuous field equations.
- **Master scale alignment**: All constructions respect the trinity scale identity $\varphi'/\pi = \rho_{\mathrm{rel}} = (2\pi)^{-1}\mathrm{tr}\,\mathsf{Q}$ and double-time separation (causality from t_*, operational scales from T_γ).

The paper is organized as follows. Section 2 establishes notation, axioms, and conventions. Section 3 develops local statistical manifolds and relative entropy. Section 4 formulates the information-geometric variational principle (IGVP). Section 5 analyzes second-order variation and quantum energy conditions. Section 6 couples master scales, readouts, and information geometry. Section 7 develops discrete EBOC–Regge information action and continuous limit. Section 8 establishes consistency with the GLS–readout framework. Section 9 discusses quantum corrections and renormalization. Section 10 provides proof details. Section 11 discusses relationships with existing approaches. Section 12 presents typical corollaries and observational consequences. Section 13 concludes.

2 Notation, Axioms, and Conventions

2.1 Unit Convention

We adopt units $\hbar = c = 1$. Metric signature is $(-+++)$. For a small ball $B_\ell(x)$, the outward-pointing unit timelike vector is denoted u^μ, with corresponding spatial hypersurface element $d\Sigma^\nu = u^\nu d\Sigma$.

2.2 Causality–Readout Separation (Double-Time Separation)

Causality and no-signaling are determined solely by **frontier time** t_*. Windowed group delay readout $T_\gamma[w_R, h]$ serves only as measurable scale, with no universal magnitude comparison to t_*. All causal and partial order conclusions in this work depend only on t_* and lightlike cone structure; readout scales are used for information-geometric measures and calibration.

2.3 Scale Identity (Master Scale)

Under the global unitarity postulate,

$$\boxed{\frac{\varphi'(E)}{\pi} = \rho_{\rm rel}(E) = \frac{1}{2\pi}\,\mathrm{tr}\,\mathsf{Q}(E), \qquad \mathsf{Q}(E) = -i\,S^\dagger(E)\tfrac{dS}{dE}(E)}.$$

This master scale defines windowed readouts and energy-delay duality (redshift-time reciprocity).

2.4 NPE Finite-Order Error Discipline

All numerical implementations follow Nyquist–Poisson–Euler–Maclaurin tripartite decomposition with finite-order EM endpoint corrections. Singularities do not increase; poles provide master scales. All information quantities and readout discrete approximations close within this accounting framework.

2.5 Interplay Condition (GLS $\leftrightarrow$ Causal Manifold)

Reconstruct the conformal class of manifolds via frontier reachability preorder and light observation sets. Construct energy-differentiable unitary $S(E)$ from radiation field–scattering and return to master scales. At the categorical level, equivalence holds up to energy-dependent unitary gauge equivalence classes.

2.6 EBOC (Discrete Side)

The world is given by static blocks X_f and eternal graph–subshifts. Observation = factor decoding; information non-increasing. Brudno alignment of time sub-actions and information conservation of reversible CA constitute axiomatic foundations of discrete information geometry.

2.7 Information Geometry

On classical statistical manifolds $(\mathcal{P}, g^{\rm F})$, the Fisher–Rao metric is the unique metric satisfying Markov (data processing) monotonicity (Čencov's theorem) [?]. In the quantum case, the Hessian of Umegaki relative entropy yields the BKM monotone metric, belonging to the Petz family of monotone metrics (non-unique). Dual connection structure (∇, ∇^*) is induced by divergence families [?].

3 Local Statistical Manifolds and Relative Entropy

3.1 Local Balls and Modular Hamiltonians

In local Lorentz coordinates at point $x \in \mathcal{M}$, take a small ball $B_\ell(x)$. Let ρ_{B_ℓ} be the reduced state of matter fields in B_ℓ, and $\rho^{(0)}_{B_\ell}$ the reference state corresponding to the local maximally symmetric vacuum. The modular Hamiltonian for the vacuum in conformal theory can be locally written as

$$H^{(0)}_{\rm mod} = 2\pi \int_{B_\ell} \xi^\mu T_{\mu\nu}\, d\Sigma^\nu, \qquad \xi^\mu = \frac{\ell^2 - r^2}{2\ell}\, u^\mu + O(\ell^3),$$

so that first-order variation of relative entropy satisfies the "first law"

$$\delta S(\rho_{B_\ell}\|\rho^{(0)}_{B_\ell}) = \delta\left\langle H^{(0)}_{\text{mod}}\right\rangle - \delta S_{\text{out}} = 0.$$

This equality holds universally in perturbations and small ball limits, systematically clarified in holographic and field theory contexts [?].

3.2 Information-Geometric Perspective

On statistical manifolds parametrized by metric deformations $g \mapsto g + \delta g$ and state deformations $\rho \mapsto \rho + \delta\rho$, second-order variation of relative entropy defines the Fisher–Rao metric, whose uniqueness is characterized by Čencov monotonicity and sufficiency invariance. We take the relative entropy $D(\rho_{B_\ell}\|\rho^{(0)}_{B_\ell})$ induced by local ball families $\{B_\ell(x)\}$ as the fundamental divergence of information geometry, with its first-order balance (extremality) and second-order positive-definiteness as content of the variational principle [?].

4 Information-Geometric Variational Principle (IGVP)

Principle 4.1 (IGVP)**.** For each point x and sufficiently small $B_\ell(x)$, subject to volume $\mathrm{Vol}(B_\ell)$ and reference vacuum constraints, the **generalized entropy**

$$S_{\text{gen}}(B_\ell) := \frac{A(\partial B_\ell)}{4G} + S_{\text{out}}(\rho_{B_\ell})$$

is extremized at first order with non-negative second-order variation. Equivalently, letting $\sigma_{B_\ell} = \rho^{(0)}_{B_\ell}$,

$$\delta S_{\text{gen}} = 0, \qquad \delta^2 S(\rho_{B_\ell}\|\sigma_{B_\ell}) \geq 0.$$

The first equation yields linearized field equations in first-order perturbative neighborhoods; under Assumption A below, it upgrades to complete field equations. The second equation provides stability and quantum energy inequality (QNEC) families. This extremality hypothesis is consistent with "maximal vacuum entanglement/entropic equilibrium" frameworks [?].

Lemma 4.2 (First Law)**.** *In the small ball limit and first-order perturbations,*

$$\delta S_{\text{out}} = \delta\left\langle H^{(0)}_{\text{mod}}\right\rangle = 2\pi\int_{B_\ell} \xi^\mu\,\delta\langle T_{\mu\nu}\rangle\,d\Sigma^\nu.$$

Proof. See cited literature [?]. □

Lemma 4.3 (Area Variation)**.** *Fixing ball volume while changing shape (or equivalently changing background metric while preserving center and radius), boundary area variation satisfies*

$$\delta\left(\frac{A}{4G}\right) = -2\pi\int_{B_\ell} \xi^\mu\,\frac{1}{8\pi G}\,\delta\big(G_{\mu\nu} + \Lambda g_{\mu\nu}\big)\,d\Sigma^\nu + O(\ell^{d+1}),$$

using standard small ball geometry of Raychaudhuri and geodesic expansion. Comparing this term with Lemma **??** *closes the first variation. (Derivation follows Jacobson-type local thermodynamic/entropic equilibrium arguments in small ball version) [?].*

Theorem 4.4 (IGVP $\Rightarrow$ Linearized; Upgrades to Complete Equations under Assumptions)**.** *If for all x and sufficiently small $B_\ell(x)$ we have $\delta S_{\text{gen}} = 0$, then in first-order neighborhoods of reference geometry,*

$$\boxed{\delta\big(G_{\mu\nu} + \Lambda g_{\mu\nu} - 8\pi G\,\langle T_{\mu\nu}\rangle\big) = 0}.$$

Furthermore, if ***Assumption A*** *holds:*

(i) The above equation holds for arbitrary background points and arbitrary perturbation families;

(ii) $C_{\mu\nu} := G_{\mu\nu} + \Lambda g_{\mu\nu} - 8\pi G\,\langle T_{\mu\nu}\rangle$ is a local, covariant, at-most-second-order tensor functional;

then under local Lorentz covariance and absence of external background structure, uniqueness implies $C_{\mu\nu} = C\,g_{\mu\nu}$. By Bianchi identity $\nabla^\mu G_{\mu\nu} = 0$ and energy-momentum conservation $\nabla^\mu\langle T_{\mu\nu}\rangle = 0$, we obtain $\nabla^\mu C_{\mu\nu} = 0$, hence $\partial_\nu C = 0$. Absorbing constant C into Λ, we obtain

$$G_{\mu\nu} + \Lambda_{\text{eff}}\, g_{\mu\nu} = 8\pi G\,\langle T_{\mu\nu}\rangle, \qquad \Lambda_{\text{eff}} = \Lambda + C.$$

Proof. This derivation is consistent with the equivalence spectrum "entanglement equilibrium $\Rightarrow$ Einstein equations", obtaining linearized and nonlinear extensions in holography and general field theory [?]. □

5 Second-Order Variation and Quantum Energy Conditions

Proposition 5.1 (Relative Entropy Non-Negativity and QNEC)**.** *Along any torsion-free null geodesic bundle k^μ through x, perform local cutting deformations and define*

$$s''_{\text{out}}(x) := \lim_{\mathcal{A}\to 0} \frac{1}{\mathcal{A}} \frac{d^2 S_{\text{out}}}{d\lambda^2},$$

where λ is the affine parameter of k^μ and $\mathcal{A}$ is the cross-sectional area of the deformation patch. Convexity of relative entropy yields

$$\boxed{\langle T_{kk}(x)\rangle \;\geq\; \frac{1}{2\pi}\, s''_{\text{out}}(x)},$$

the quantum null energy condition (QNEC). Proof families (field theory/holographic) all take convexity of relative entropy as core input [?].

Corollary 5.2 (Quantum Focusing and Generalized Entropy Monotonicity)**.** *The quantum focusing conjecture and quantum Bousso bound follow from the above inequality and non-increase of generalized entropy, compatible with second-order stability of IGVP [?].*

6 Master Scale, Readouts, and Information-Geometric Coupling

6.1 Windowed Group Delay and Fisher Density

For each observer window-kernel (w_R, h), define the in-band distribution $p(E|x) \propto (w_R * \check{h})(E)\, \rho_{\mathrm{rel}}(E; x)$. Define the local Fisher tensor

$$\mathcal{I}_{\mu\nu}(x) = \int \partial_\mu \ln p(E|x)\, \partial_\nu \ln p(E|x)\, p(E|x)\, dE,$$

and by Čencov–Amari uniqueness, take this as the calibration object between **readout–information geometry** and **background metric**: in the vacuum–alias-free limit and redshift-reciprocity rescaling, the constraint $\mathcal{I}_{\mu\nu} \propto g_{\mu\nu}$ can serve as an additional Lagrange multiplier term in IGVP, ensuring consistency between readout coordinates and geometric coordinates. This calibration is covariant under redshift-time reciprocity scaling laws.

6.2 Readout–Geometry Consistent Variation

Take the action

$$\mathcal{S}[g;\rho] = \frac{1}{16\pi G}\int \sqrt{-g}\,(R - 2\Lambda)\, d^4x - \int \sqrt{-g}\, \Phi(\rho\|\rho^{(0)})\, d^4x + \int \sqrt{-g}\, \lambda^{\mu\nu}(\mathcal{I}_{\mu\nu} - \kappa\, g_{\mu\nu}) d^4x,$$

where Φ is a local density with relative entropy as potential (reducible to volume integral form of $\delta\langle H_{\mathrm{mod}}\rangle - \delta S_{\mathrm{out}}$ in small ball limit). Variation with respect to $g_{\mu\nu}$ yields

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G \left(\langle T_{\mu\nu}\rangle + T^{(\mathrm{IG})}_{\mu\nu}\right),$$

while readout-geometry calibration $\mathcal{I}_{\mu\nu} = \kappa g_{\mu\nu}$ ensures the trace of $T^{(\mathrm{IG})}_{\mu\nu}$ and vacuum energy are absorbed into Λ, returning to the form of Theorem **??**. When using "first law" formulation, this is equivalent to taking $\delta S_{\mathrm{gen}} = 0$ as Euler–Lagrange condition. (Specific choice of information potential and Fisher–relative entropy equivalence in small ball limit guaranteed by standard information geometry) [**?**].

7 Discretization: EBOC–Regge Information Action and Continuous Limit

7.1 Static Block–Triangulation

On EBOC static blocks X_f, select lightlike-cone-consistent leaf stratification and triangulation. Let each 2-skeleton (triangle) h carry discrete area A_h and define deficit angle ε_h at h. The Regge action

$$S_{\mathrm{Regge}} = \frac{1}{8\pi G}\sum_h A_h\, \varepsilon_h - \frac{\Lambda}{8\pi G}\sum_\sigma V_\sigma$$

yields discrete Einstein equations under variation. On the information-geometric side, for each discrete small ball cell c, define **discrete generalized entropy**

$$S^{\mathrm{disc}}_{\mathrm{gen}}(c) = \frac{A(\partial c)}{4G} + S^{\mathrm{disc}}_{\mathrm{out}}(c).$$

First variation $\delta S_{\text{gen}}^{\text{disc}} = 0$ is compatible with Regge variation and converges to continuous IGVP under mesh refinement [?].

7.2 Observation = Decoding and Information Non-Increase

Visible language of discrete states is generated by factor decoding π, satisfying

$$K(\pi(x|_W)) \ \leq \ K(x|_W) + K(\pi) + O(1).$$

Thus discrete $S_{\text{out}}^{\text{disc}}$ converges to continuous S_{out} in the refinement limit, ensuring $S_{\text{gen}}^{\text{disc}} \to S_{\text{gen}}$ and stability of IGVP.

8 Consistency with GLS–Readout Framework

8.1 Frontier–No-Supercone Propagation and Readout Independence

From frontier lower bound $t_* \geq L_g/c$ and gauge covariance/relative invariance of windowed readouts: IGVP ball selection and readout dictionary selection are mutually independent. Ball-deformation is anchored only on causal structure and metric; readouts provide only Fisher calibration and energy-delay scales.

8.2 Redshift–Reciprocity and Fisher Scaling

Under spectral scaling $E \mapsto E/(1+z)$, Fisher tensor and readout scales in small balls transform covariantly as $(1+z)^{-2}$. Volume-preserving IGVP condition is consistent with Jacobson/entanglement equilibrium volume constraints.

9 Quantum Corrections, Renormalization, and Verifiable Conditions

9.1 One-Loop/$1/N$ Corrections

In holography and field theory, the "area + bulk entanglement" structure of generalized entropy is compensated by bulk entanglement at one loop. This correction is precisely the origin of quantum extremal surface (QES) conditions for S_{gen}, ensuring IGVP remains valid at semiclassical level [?].

9.2 QNEC and Relative Entropy Convexity

Second-order variation positivity yields

$$\boxed{\langle T_{kk}(x)\rangle \geq \frac{1}{2\pi}\, s_{\text{out}}''(x)},$$

proven in field theory and holographic contexts, constituting stability criteria and verifiable conditions for IGVP [?].

10 Proof Details

10.1 Small Ball Geometry and Area Expansion

In normal coordinates, small ball boundary area is

$$A(\partial B_\ell) = \Omega_{d-2}\,\ell^{d-2}\left[1 - \frac{\ell^2}{6(d-1)}\,R + O(\ell^4)\right].$$

Volume-preserving variation eliminates $\delta\ell$, leaving $\delta A \propto \delta R$. Pairing with Lemma **??** and using $G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu}$ yields Theorem **??**.

10.2 "First Law" and Modular Hamiltonian

Ball modular Hamiltonian is locally a linear functional of energy-momentum tensor for conformal vacuum, so $\delta S_{\mathrm{out}} = \delta\langle H_{\mathrm{mod}}\rangle$ holds. Corrections for non-conformal fields are provided in subsequent literature without affecting conclusion form [**?**].

11 Relationships with Existing Approaches and Advantages

11.1 Jacobson (Thermodynamic/Entanglement Equilibrium) Line

This work restates "local thermodynamic/entropic equilibrium" as **information-geometric extremality**, replacing specific thermal closures with universal Fisher–relative entropy structures, viewing gravity as "geometric response maintaining local information balance" [**?**].

11.2 Holographic "First Law" Line

This work reproduces "first law ⇒ field equations" logic at local ball level without holographic assumptions. When gravitational duals exist, it rigorously interfaces with holographic derivations (linearized Einstein equations) [**?**].

11.3 EBOC–GLS Unification

Discrete–decoding and continuous–causality unify under IGVP: discrete-side information non-increase and static block consistent expansion ensure $S_{\mathrm{gen}}^{\mathrm{disc}} \to S_{\mathrm{gen}}$. Continuous-side master scale–readout–Fisher calibration seamlessly aligns measurable scales with geometric dimensions.

12 Typical Corollaries and Observable Consequences

1. **Field equations ⇒ local entropicity**: If $G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G\,\langle T_{\mu\nu}\rangle$ is known, $\delta S_{\mathrm{gen}} = 0$ can be directly verified in small ball limit [**?**].

2. **QNEC/quantum focusing**: Second-order deformations in any null direction yield energy lower bounds, providing consistency checks and numerical verification metrics for semiclassical gravity [**?**].

3. **Redshift–reciprocity clock and Fisher capacity**: In observation-timing experiments, bandwidth–resolution–redshift reciprocity scaling manifests explicitly in IGVP Lagrange constraints, serving as direct posterior for experimental calibration layers.

13 Conclusion (Outline Form)

- In small ball limit, first-order extremality of **generalized entropy** S_{gen} (combined with relative entropy first law) is equivalent to linearized Einstein equations; under Assumption A, complete nonlinear Einstein equations follow.
- Second-order variation non-negativity yields QNEC/quantum focusing and other **quantum consistency** constraints.
- EBOC discrete–decoding semantics and Regge triangulation provide **discrete action–extremality** compatible realization, converging to continuous IGVP in refinement limit.
- Master scale–windowed readout–Fisher calibration **uniformly align** "measurable scales" with geometric metrics, maintaining scale hierarchy separation of causality-readout and finite-order closure of numerical error accounting.

A Interface Details with GLS–EBOC Unification (Outline)

1. **Master scale and Fisher alignment**: Construct $p(E|x)$ from $\rho_{\text{rel}} = (2\pi)^{-1}\text{tr}\,\mathsf{Q}$ and define $\mathcal{I}_{\mu\nu}$. Constrain $\lambda^{\mu\nu}(\mathcal{I}_{\mu\nu} - \kappa g_{\mu\nu})$ to pull readout coordinates back to geometric coordinates.
2. **Causality–readout stratification**: IGVP balls and relative entropy anchor only causality and metric; windowed group delay serves only statistical manifold scales and observation dictionary, not participating in partial order definition.
3. **Discrete–limit**: Define $S_{\text{gen}}^{\text{disc}}$, Regge action, and factor decoding on EBOC static blocks and eternal graphs, satisfying $\delta S_{\text{gen}}^{\text{disc}} = 0 \Rightarrow$ Regge equations. Refinement limit returns to Theorem **??**.
4. **Categorical equivalence and covariance**: GLS $\leftrightarrow$ causal manifold interplay ensures functoriality and naturality of "geometry–readout–information". IGVP remains invariant under this equivalence.

B Information Geometry–First Law Equivalent Formulations

Write small ball relative entropy as

$$S(\rho_{B_\ell}\|\sigma_{B_\ell}) = \text{Tr}(\rho_{B_\ell}\ln\rho_{B_\ell}) - \text{Tr}(\rho_{B_\ell}\ln\sigma_{B_\ell}),$$

with first-order variation yielding

$$\delta S = -\delta S_{\rm out} + \delta\langle H^{(0)}_{\rm mod}\rangle, \qquad H^{(0)}_{\rm mod} := -\ln \sigma_{B_\ell},$$

the "first law". For conformal vacuum, $H^{(0)}_{\rm mod}$ is a local functional of energy flow density. For non-conformal cases, operator expansion corrections in small ball limit do not change extremality condition form [**?**].

C Numerical Implementation and NPE Error Accounting (Readout Side)

In any readout integral implemented with window-kernel (w_R, h), only apply sampling/truncation/EM endpoint corrections to integrand $f(E) = w_R(E)\,[h\star\rho_{\rm rel}](E)$. IGVP ball-deformation and field equation derivation are unaffected by this numerical accounting.

Note: All formula metric–readout–causality scale hierarchies and master scale, interplay consistency have been systematically characterized in the preceding unified framework. This work provides rigorous formulation of "gravity = generalized entropy extremality (combined with relative entropy first law)" and provides continuous–discrete dual realization.

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