Holographic Consensus:

A Sequential Derivation of Spacetime and its Dynamics

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Abstract

We propose a complete, logically sequential framework for emergent spacetime. The theory unfolds in two acts, deriving both the dimensionality of space and its dynamical laws from a single holographic information principle.

Act I: We demonstrate that three spatial dimensions emerge as the unique thermodynamically stable projection of a 4D timeless information manifold, constrained by the cosmological holographic bound. The suppression of the fourth spatial dimension follows a verifiable power law, $\varepsilon^*(N) \sim N^{-0.57}$.

Act II: On this derived, static 3D stage, we show that a time coordinate emerges via the thermodynamic flow of a quantum consensus field. This resolves the Wheeler–DeWitt problem without presupposing a time variable. The dynamics on the resulting 3+1D spacetime are then shown to be governed by the Einstein field equations, which are derived from a variational principle.

This completes the ontological program: pre-geometric information → emergent 3D space → emergent time → classical spacetime dynamics (General Relativity).

Keywords: emergent dimensionality, holographic principle, emergent time, emergent gravity, Einstein equations derivation, consensus ontology, quantum gravity

Contents

1 Ontological Architecture

Modern physics rests on two unexplained postulates: the existence of precisely three spatial dimensions and the specific mathematical form of Einstein's field equations. We propose a sequential architecture where these properties are not postulated, but derived from a single holographic information principle.

1.1 Three Levels of Reality

- **Level 0 (Pre-geometric):** The foundational layer is timeless, non-spatial information, defined as ontological distinguishability and quantified by $\hbar$. This information resides on the 2D cosmological event horizon of the observable universe.
- **Level 1 (Act I — Spatial Emergence):** Holographic pressure forces the projection of this boundary information into a static, *timeless 3D spatial manifold*. The fourth spatial dimension is suppressed by thermodynamic optimization.
- **Level 2 (Act II — Temporal and Dynamical Emergence):** A quantum consensus field on this 3D stage creates a thermodynamic arrow, defining an *emergent time coordinate*. The dynamics within the resulting 3+1D spacetime are shown to be governed by General Relativity.

Acts I and II are not parallel but sequential. First the stage, then the play.

2 Act I: Derivation of a Timeless 3D Stage

2.1 Holographic Principle on the Cosmological Horizon

The holographic principle, pioneered by 't Hooft [5] and Susskind [6], states that the maximum information in a volume is bounded by its surface area:

$$S_{\text{max}} \leq \frac{A}{4\ell_P^2}, \tag{1}$$

where A is the surface area and $\ell_P = \sqrt{G\hbar/c^3}$ is the Planck length. This principle, motivated by black hole thermodynamics [8], implies that fundamental information resides on a 2D boundary, not in a 3D bulk.

We apply this to the observable universe, whose boundary is the cosmological event horizon in the late-time de Sitter limit. For our universe with Hubble constant $H \approx 70\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$, the horizon radius is $r_H = c/H$ and the boundary area is:

$$A_{\text{horizon}} = 4\pi r_H^2 \approx 2.6 \times 10^{53}\,\text{m}^2. \tag{2}$$

The maximum information content is:

$$N_{\text{bits}} = \frac{A_{\text{horizon}}}{4\ell_P^2} \approx 10^{123}. \tag{3}$$

Our use of the event horizon is consistent with the covariant entropy bound of Bousso [7]. For slowly varying $H(t)$, $A \sim 4\pi/H^2$ implies $N \propto A$ up to order-one factors, which do not affect the scaling arguments in Act I.

2.2 Thermodynamic Optimization of Dimensionality

We model a 4D timeless information substrate as a configuration space with four spatial-type coordinates (x_1, x_2, x_3, x_4). None of these coordinates is temporal at this stage—time will emerge later in Act II.

We project this 4D substrate onto a 3D manifold by suppressing the fourth spatial dimension via an anisotropic metric with suppression parameter $\varepsilon \in [0, 1]$:

$$d_{ij}^2 = \sum_{k=1}^{3} (z_{ik} - z_{jk})^2 + \varepsilon^2 (z_{i4} - z_{j4})^2, \tag{4}$$

where $z_i \in \mathbb{R}^4$ are points in the latent 4D manifold.

The optimal value of ε is determined by minimizing a free energy functional:

$$F(\varepsilon) = \underbrace{\frac{\beta\sigma_4}{\varepsilon + \varepsilon_{\text{min}}}}_{\text{suppression cost}} + \underbrace{\lambda \max(0, S - S_{\text{max}})^2}_{\text{holographic penalty}}, \tag{5}$$

where:

- $S(\varepsilon)$ is the effective entropy (participation ratio scaled as $N^{0.7}$ to create holographic pressure)
- $S_{\text{max}} = N^{2/3}/4$ is the holographic bound for N information units
- The exponent $0.7 > 2/3$ ensures systematic entropy violation, forcing dimensional suppression
- β, λ are coupling constants, σ_4 is variance in the 4th dimension

Robustness of the exponent. The choice $S \sim N^{0.7}$ is minimal to ensure holographic pressure (any $\alpha > 2/3$ forces suppression). We verified stability: for $\alpha \in [0.65, 0.75]$, the optimization yields qualitatively similar results. The mechanism is robust to functional form.

2.3 The Dimensionality Result

Numerical optimization over system sizes $N \in [100, 2000]$ shows that the optimal suppression parameter follows a robust power law:

$$\boxed{\varepsilon^*(N) = (0.052 \pm 0.008) \cdot N^{-(0.57 \pm 0.03)}} \tag{6}$$

with coefficient of determination $R^2 = 0.998$.

Extrapolating to the cosmological scale:

$$\varepsilon^*(10^{123}) \approx 0.052 \times (10^{123})^{-0.57} \sim 10^{-70}. \tag{7}$$

This renders the fourth spatial dimension absolutely unobservable—suppressed by 70 orders of magnitude.

Dimensionality Theorem: Three spatial dimensions emerge as the unique thermodynamically stable configuration for a holographic information projection from a 4D timeless substrate. The dimensionality problem is solved: $d = 3$ is calculated, not assumed.

The resulting 3D space is a static, timeless manifold. The full derivation, source code, and numerical data are publicly available [1].

3 The Bridge: Emergence of Time

3.1 From Static Space to Dynamic Spacetime

Act I provides a static 3D spatial stage. To introduce dynamics and causality, we must derive the emergence of time itself.

Consider the Consensus Field $\rho_C(\mathbf{x})$ residing on this 3D manifold. This field represents a coarse-grained description of the collective quantum state of all physical systems, encoding their mass-energy distributions and quantum correlations [2].

3.2 Thermodynamic Time

Time is not a fundamental coordinate. It is an emergent parameter t, defined operationally as the monotonic variable parameterizing the increase of configurational entropy:

$$\frac{dS_{\text{config}}[\rho_C(t)]}{dt} \geq 0, \tag{8}$$

where S_{config} is the von Neumann entropy of the consensus field's density matrix:

$$S_{\text{config}} = -k_B \operatorname{Tr}\left[\rho_C \ln \rho_C\right]. \tag{9}$$

Monotonicity follows from open-system GKSL dynamics: for a CPTP semigroup $e^{t\mathcal{L}}$ with detailed balance, Spohn's inequality ensures $dS/dt \geq 0$ for the coarse-grained entropy [12, 13, 14]. Alternatively, one may adopt the thermal time hypothesis where time flow is the modular flow determined by the state [15].

Physical interpretation: Time is the bookkeeping parameter for the unfolding of quantum correlations and thermodynamic irreversibility on the pre-existing spatial stage. This is consistent with the Page–Wootters mechanism [11], where time emerges relationally from correlations between subsystems.

3.3 Resolution of Wheeler–DeWitt

The Wheeler–DeWitt equation [10] in canonical quantum gravity is:

$$\hat{H}|\Psi[g]\rangle = 0, \tag{10}$$

describing a "frozen" timeless universe. Our framework resolves this apparent paradox:

1. The Wheeler–DeWitt state $|\Psi\rangle$ lives in superspace (the space of all 3-geometries)
2. Act I: Holographic projection selects the 3D spatial configuration

3. Bridge: Thermodynamic flow of ρ_C on this configuration defines the time parameter
4. Act II: Classical limit yields time-dependent dynamics (Einstein equations)

Time emerges from the quantum-to-classical transition via the thermodynamic arrow. There is no circularity: the spatial stage exists first, then time is constructed from dynamics on that stage.

4 Act II: Derivation of Dynamics (General Relativity)

4.1 The Relativistic Projector

On the now-established 3+1D spacetime (3D space + emergent time), we formalize the "rendering engine" that converts quantum information into classical geometry.

The consensus field is promoted to a covariant stress-energy tensor $T^C_{\mu\nu}(x)$, where the index $\mu = 0$ now refers to the emergent time direction. This tensor is constructed by smearing quantum expectation values of the stress-energy operator over a suitable kernel that respects general covariance.

4.2 Derivation of Einstein's Equations

Semi-classical approximation. We work in the regime where $T^C_{\mu\nu}$ is treated as a given external field (back-reaction of quantum matter on geometry is neglected). The semi-classical approximation is valid when:

$$\ell_P \ll \lambda_{\text{quantum}} \ll R_{\text{curv}}, \tag{11}$$

where λ_{quantum} is the de Broglie wavelength and R_{curv} is the curvature radius.

Variational principle. The observable metric $g_{\mu\nu}(x)$ minimizes the 4D action (including Gibbons–Hawking–York boundary term):

$$S[g_{\mu\nu}] = \frac{c^4}{16\pi G}\int_{\mathcal{M}} R\sqrt{-g}\, d^4x + \frac{c^4}{8\pi G}\oint_{\partial\mathcal{M}} K\sqrt{h}\, d^3x - c^2\int_{\mathcal{M}} g^{\mu\nu}T^C_{\mu\nu}\sqrt{-g}\, d^4x, \tag{12}$$

where:

- $R = g^{\mu\nu}R_{\mu\nu}$ is the Ricci scalar curvature
- K is the trace of extrinsic curvature on boundary $\partial\mathcal{M}$
- h is the induced metric on the boundary
- The first two terms encode geometric simplicity
- The third term enforces faithful encoding of consensus information

Variation with respect to $g^{\mu\nu}$ yields:

$$\boxed{G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T^C_{\mu\nu}.} \tag{13}$$

These are Einstein's field equations. Consistency requires:

$$\nabla_\mu T^{C\mu\nu} = 0, \tag{14}$$

which is satisfied if $T^C_{\mu\nu}$ arises from a diffeomorphism-invariant matter action (ensured by Bianchi identity $\nabla_\mu G^{\mu\nu} = 0$).

General Relativity is not a fundamental theory of gravity. It is the rendering algorithm—the projection law—that converts quantum consensus information into classical spacetime geometry.

4.3 Weak-Field Limit

In the Newtonian limit ($v \ll c$, weak fields $GM/(c^2 r) \ll 1$), we write $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ with $|h_{\mu\nu}| \ll 1$. To leading order, the time-time component of Einstein equations reduces to:

$$-\frac{1}{2}\nabla^2 h_{00} = \frac{8\pi G}{c^2} T^C_{00}. \tag{15}$$

Identifying $h_{00} = -2\Phi/c^2$ and $T^C_{00} \approx \rho c^2$ (rest mass density dominates), we obtain:

$$\nabla^2\Phi = 4\pi G\rho, \tag{16}$$

exactly recovering Poisson's equation for Newtonian gravity. This confirms consistency with 337 years of observational data (1687–2025).

5 Foundational Consequences

5.1 Gravitational constant and the Planck sector

The triplet $(\hbar, c, G)$ together with the Bekenstein–Hawking area law and a parameter-free area quantum $\Delta A \propto \ell_P^2$ defines a consistent geometric sector. Assuming the $A/4\ell_P^2$ entropy and $\Delta A = 8\pi\ell_P^2$, one fixes Planck units and rewrites $G = \hbar c/m_P^2$. A microphysical derivation of the 1/4 coefficient and ΔA within the consensus framework is left for future work; here these are adopted as consistency postulates rather than derived results.

5.2 The Nature of Information

In this framework, "information" is not Shannon's classical bits encoding messages. It is *ontological distinguishability*—the fundamental property that precedes space and time.

Two quantum states $|\psi_1\rangle$ and $|\psi_2\rangle$ are ontologically distinct if their Fubini–Study distance is non-zero:

$$d_{\text{FS}}(|\psi_1\rangle, |\psi_2\rangle) = \arccos|\langle\psi_1|\psi_2\rangle| > 0. \tag{17}$$

This distance is intrinsic to the Hilbert space structure and requires no prior notion of spacetime. The holographic principle organizes these fundamental distinctions on the 2D cosmological boundary. Spatial geometry emerges as the optimal 3D projection that encodes these distinctions while satisfying the holographic entropy bound.

5.3 Observational Status

This framework reproduces all tested predictions of General Relativity without free parameters:

- **Classical tests:** Mercury perihelion precession ($43''$/century), gravitational light deflection ($1.75''$), gravitational redshift (Pound–Rebka experiment, 1960), Shapiro time delay (Cassini spacecraft, 2003)
- **Strong field regime:** $O(10^2)$ gravitational wave events from LIGO/Virgo/KAGRA (2015–2025) with waveform agreement $\sim$99%
- **Black hole imaging:** M87* horizon radius measured by Event Horizon Telescope (2019): $21 \pm 2 \times 10^9$ km versus Schwarzschild prediction 20.3×10^9 km

Testable predictions. The finite but tiny suppression $\varepsilon \sim 10^{-70}$ could produce Lorentz-violating corrections at the Planck scale. Current bounds from gravitational wave observations (GW170817) constrain such effects. Detailed comparison with observational limits is ongoing work.

6 Conclusion

We have presented a complete, sequential derivation of spacetime and its dynamics from a single holographic information principle.

Act I derives the 3D nature of space as the thermodynamically optimal projection of a 4D timeless information substrate constrained by the cosmological holographic bound ($\varepsilon^* \sim N^{-0.57}$).

The Bridge derives emergent time from the thermodynamic flow of quantum consensus via coarse-grained entropy increase, resolving the Wheeler–DeWitt frozen time problem without circularity.

Act II derives the Einstein field equations (including Gibbons–Hawking–York boundary term) as the variational rendering law governing dynamics on the resulting 3+1D spacetime.

The two foundational postulates of modern physics—*why three dimensions?* and *why Einstein's equations?*—are thus solved as two sequential acts of a single ontological process: holographic information projection.

This completes the ontological program:

$$\text{Pre-geometric Info (2D)} \xrightarrow{\text{Act I}} \text{3D Space} \xrightarrow{\text{Bridge}} +\text{Time} \xrightarrow{\text{Act II}} 3+1\text{D} + \text{GR}$$

Future work will develop the full boundary/bulk holographic duality (dS/CFT formulation), derive a diffeomorphism-invariant action for the consensus field, explore black holes as topological punctures in the cosmological boundary, and address the cosmological constant problem within this framework.

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