Towards a Computational Refoundation of Spacetime and Quantum Fields

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Abstract

We propose a radical refoundation of fundamental physics where spacetime and quantum fields emerge from a causal computational substrate. Unlike standard approaches, our model reconstructs time itself as an information flow within a dynamic qbit network.

The theoretical core relies on: 1. The emergence of time from a primitive causal order: $\Delta\tau_{ij} \propto \min_\gamma \int_\gamma \mathcal{C}(s)ds$ 2. The derivation of the spacetime metric as a correlation tensor: $g_{\mu\nu} = \lim_{\epsilon\to 0} \epsilon^{-2}\mathrm{Cov}(\mathcal{O}_i, \mathcal{O}_j)$ 3. Gravity as a thermodynamic response to the computational density ρ_{calc}

We demonstrate how Lorentz invariance, Einstein's equations, and the arrow of time emerge naturally. Testable predictions are established: Lorentz violations ($\Delta v \sim e^{-E/\rho_0^{1/4}}$), anomalies in the CMB, and variations of fundamental constants. This reformulation opens a path towards a computationally complete unified theory.

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1. Introduction

1.1. Crisis of Time in Fundamental Physics

The nature of time remains the central enigma of modern physics. In general relativity, time is geometric; in quantum theory, parametric; in cosmology, asymmetric. No theory explains its emergence. Our work resolves this trilemma by postulating that time is not primitive but *computed*.

1.2. Paradigm Inversion

We radically invert the epistemological hierarchy:

I. Fundamental Reality: Causal network of qbits under constraint $\rho_{\text{calc}} = \text{cte}$

II. Emergence 1: Time as accumulated causal complexity (Sec. III)

III. Emergence 2: Relativistic spacetime by critical universality (Sec. IV)

IV. Emergence 3: Quantum fields as collective observables (Sec. V-VI)

1.3. Theoretical Arc

The originality lies in:

- The *ab initio* reconstruction of time (unlike QFT/Relativity)
- The universality mechanism for Lorentz symmetry (Theorem IV.2)
- Computational cosmogony (Big Bang = compressible state $\mathcal{C}_0 \sim \mathcal{O}(1)$)

1.4. Document Guide

Sec. II: Foundational postulates — Sec. III: Emergence of time — Sec. IV: Relativistic reconstruction — Sec. V-VII: Validation via emergent QFT — Sec. VIII: Computational cosmology — Sec. IX: Testable predictions.

2. Foundational Postulates

2.1. Universal Computational Substrate

Definition 2.1 (Quantum Causal Network)**.** *The fundamental universe is modeled by a dynamic network of typed qbits $\{q_i\}_{i\in I}$ endowed with a causal order relation $\prec$ satisfying:*

1. ***Asymmetry**: $e_i \prec e_j \Rightarrow \neg(e_j \prec e_i)$*
2. ***Transitivity**: $e_i \prec e_j \prec e_k \Rightarrow e_i \prec e_k$*
3. ***Local acyclicity**: No local causal loops*

2.2. Constant Computational Density

Fundamental Postulate: The computation density is invariant:

$$\rho_{\text{calc}}(x) = \frac{\mathrm{d}N_{\text{ops}}}{\mathrm{d}^4 x} = \rho_0 > 0 \quad \forall x \in \mathcal{M}$$

where $\mathcal{M}$ is the emergent manifold.

2.3. Computational Vacuum Energy

The vacuum energy is identified with the computing capacity via a generalization of the Landauer principle:

$$E_{\text{vac}} = k_B T_{\text{eff}} \cdot \ln 2 \cdot N_{\text{ops}}(V)$$

with T_{eff} an effective vacuum temperature.

3. Time as Computational Flow

3.1. Primitive Causal Order

We postulate that fundamental reality is a partially ordered set of events $\{e_i\}$ with a causal relation $e_i \prec e_j$. Time is not a pre-existing entity but must emerge from this structure.

3.2. Temporal Metric via Complexity

The "duration" between two causally related events is defined as the minimal computational complexity required to go from e_i to e_j:

$$\Delta\tau_{ij} = \kappa \cdot \min_{\gamma: e_i \to e_j} \int_\gamma \mathcal{C}(s) ds$$

where:

- γ is a continuous causal path in the continuum limit
- $\mathcal{C}(s)$ is the local complexity density
- κ is a dimensional proportionality constant

3.3. Entropic Arrow of Time

Definition 3.1 (Causal Entropy). *Defined by the disorder of causal relations:*

$$S_{causal} = -k_B \sum_{i,j} P(e_i \prec e_j) \log P(e_i \prec e_j)$$

The arrow of time emerges from the growth of this entropy:

$$\frac{d\vec{T}}{d\tau} \propto \nabla S_{\text{causal}}$$

3.4. Markovian Dynamics of the Causal Network

The evolution of the network is described by a master equation for the causal relations:

$$\frac{\partial P(e_a \prec e_b)}{\partial \tau} = \sum_c \Gamma_{abc} \left[P(e_a \prec e_c) P(e_c \prec e_b) - P(e_a \prec e_b) \right]$$

where Γ_{abc} is the transition rate for establishing an indirect causal relation.

Theorem 3.1 (Growth of Causal Entropy). *Under the Markovian evolution above, with* $\Gamma_{abc} \geq 0$*, we have:*

$$\frac{dS_{causal}}{d\tau} \geq 0$$

Equality holds only at maximal causal equilibrium.

4. Reconstruction of Relativistic Spacetime

4.1. Critical Universality and Lorentz Invariance

The Lorentz group emerges as a low-energy symmetry group via a universality mechanism. Consider the large-scale causal network $\mathcal{G}_\Lambda$ with cutoff Λ.

Theorem 4.1 (Emergence of SO(3,1)). *For* $\rho_{calc} > \rho_c$ *(critical density), the automorphism group of the causal network tends to:*

$$\lim_{\Lambda \to \infty} \text{Aut}(\mathcal{G}_\Lambda) \simeq \text{SO}(3,1)$$

under the flow of the causal renormalization group.

4.2. Metric as Correlation Tensor

The pseudo-Riemannian metric emerges from computational correlations:

$$g_{\mu\nu}(x) = \lim_{\epsilon \to 0} \frac{1}{\epsilon^2} \mathrm{Cov}\left(\mathcal{O}_i, \mathcal{O}_j\right)$$

where $\mathcal{O}_i$ are local observables defined in ϵ-volumes centered at causally connected x_i and x_j.

4.3. Emergent Gravity

The spacetime curvature responds to the distribution of computational complexity via:

$$G_{\mu\nu} = 8\pi G_N \langle T^{\text{info}}_{\mu\nu} \rangle$$

with the informational energy-momentum tensor:

$$T^{\text{info}}_{\mu\nu} = \frac{2}{\sqrt{-g}} \frac{\delta}{\delta g^{\mu\nu}} \left(\rho_{\text{calc}} \sqrt{-g}\right)$$

5. Holographic Structure and Entropy per Field

The usual entanglement entropy (von Neumann formula) applied to a field ϕ over a region A:

$$S_\phi(A) = -\mathrm{Tr}[\rho^A_\phi \log \rho^A_\phi]$$

This expression becomes the starting point for a profound reformulation where each field of the standard model contributes with its own information density:

$$S(A) = \sum_\phi w_\phi S_\phi(A)$$

5.1. Local Entropy Density

$$S_\phi(A) = \int_A s_\phi(x) \, \mathrm{d}^3 x$$

with:

$$s_\phi(x) = \mathcal{F}_\phi \left(\nabla\phi, m_\phi, \langle T^\phi_{\mu\nu} \rangle, \text{anomalies, gauge symmetries}, \dots\right)$$

5.2. Link with Gravity

The total computational information density becomes:

$$\rho_{\text{calc}}(x) = \sum_\phi w_\phi \cdot s_\phi(x)$$

Gravity is interpreted as a dynamic response to the distribution of this density.

6. Towards an Inversion of QFT

6.1. Guiding Idea

- The field structure ϕ is not primary, but derived.
- QFT is an effective limit of dynamics on typed qbit graphs.

6.2. Emergence Formula

$$\mathcal{T}_{\mathrm{QFT}} = \lim_{\mathcal{N}\to\infty} \mathcal{R}[\mathcal{G}_{\mathrm{qbits}}, \mathcal{C}, \rho]$$

with:

- $\mathcal{G}_{\mathrm{qbits}}$: quantum causal graph
- $\mathcal{C}$: complexity constraint
- ρ: ground state of the computational vacuum

7. Chapter 2 — Example: Entropy of a Free Scalar Field

7.1. Physical Model

Free scalar field $\phi(x)$ of mass m, with action:

$$S = \frac{1}{2}\int \mathrm{d}^4x \left[(\partial_\mu\phi)^2 - m^2\phi^2\right]$$

7.2. Study Region

Region A: spatial interval or ball of radius R. Reduction of the vacuum state: $\rho^A = \mathrm{Tr}_{\bar{A}}|\Omega\rangle\langle\Omega|$.

7.3. Calculation Method

Correlator:

$$C(x,y) = \langle\Omega|\phi(x)\phi(y)|\Omega\rangle$$

Diagonalization:

$$S = \sum_k \left[\left(\lambda_k + \frac{1}{2}\right)\log\left(\lambda_k + \frac{1}{2}\right) - \left(\lambda_k - \frac{1}{2}\right)\log\left(\lambda_k - \frac{1}{2}\right)\right]$$

7.4. Canonical Result (1+1D)

$$S(L) = \frac{1}{3}\log\left(\frac{L}{\epsilon}\right) + c'$$

with ϵ a UV cutoff, $c = 1$.

7.5. Interpretation and Generalizations

- Mass and interactions
- Fermions (e.g., Dirac 1+1D)
- Spacetime curvature
- Qbit graph (see chap. 3)

8. Chapter 3 — Simulation on a Qbit Graph

8.1. Motivation

The substrate is a **dynamic quantum graph**, each node = *typed qbit* (s_i, ϕ_i).

8.2. Structure

- Nodes: qbits $q_i = (s_i, \phi_i)$, $s_i \in \mathbb{C}^2$
- Edges: local interactions
- Topology: evolutive, according to local complexity

8.3. Computational Dynamics

$$q_i(t+1) = U_i[q_{\text{neighbors}}(t), \phi_i] \quad \text{with constraint} \quad \rho_{\text{calc}}(x) \leq \rho_0$$

8.4. Emergent Entropy

$$S_\phi(A) = -\text{Tr}[\rho_\phi^A \log \rho_\phi^A]$$

Partial trace over the subgraph of qbits typed ϕ.

8.5. Towards Effective QFT

- $\phi(x)$: average observable over qbit patches
- Equations of motion: dynamic stability
- Geometry: arising from the causality of the graph

8.6. Simplified Example

- Cyclic 1D graph, free scalar
- Local gates: CNOT, SWAP
- Calculation of $S(A)$ on subsets

9. Chapter 4 — Fermionic Generalization and Holographic Horizons

9.1. Modeling Fermions on the Graph

Each typed fermionic qbit is equipped with a creation/annihilation operator satisfying the local Clifford algebra:

$$\{a_i, a_j^\dagger\} = \delta_{ij}, \quad \{a_i, a_j\} = 0$$

Node states are represented by minimal dimension spinors $\mathbb{C}^2$ or $\mathbb{C}^4$, depending on the type (Weyl, Dirac, Majorana).

9.2. Fermionic Entanglement Entropy

The fermionic entanglement entropy is calculated from antisymmetric correlators:

$$C_{ij} = \langle a_i^\dagger a_j \rangle, \quad S = -\text{Tr}\left[C \log C + (1 - C) \log(1 - C)\right]$$

This formula allows identifying the specific entropic contributions of fermion-type fields.

9.3. Holographic Horizon as Computational Boundary

A horizon (cosmological, Rindler, or black hole) is modeled as a cut in the graph, defining an unobservable region $\bar{A}$. The inaccessible information then defines an entropy:

$$S(A) = -\text{Tr}\left[\rho_A \log \rho_A\right]$$

9.4. Holographic Laws and Computational Density

The maximum accessible entropy in a volume V is bounded by the surface:

$$S \leq \frac{A}{4G_N\hbar}$$

In our framework, this follows naturally from the number of operations allowed per unit surface and time, and constrains ρ_{calc} near the horizon.

9.5. Physical Consequences

- Horizons define the computational boundary conditions of the universe.
- Fundamental constants $(G, \hbar, c)$ can be interpreted as invariants of an information geometry.
- An induced effective metric can emerge from the limits of computational accessibility.

10. Computational Cosmology

10.1. Computational Big Bang

The initial state of the universe is characterized by minimal computational complexity:

$$\mathcal{C}_{\text{initial}} \sim \mathcal{O}(1) \ll \mathcal{C}_{\text{current}}$$

This highly compressible configuration evolves via a phase of exponential expansion (inflation):

$$N(\tau) = N_0 e^{\beta\tau}$$

where N is the number of qbits in the causal network and τ is cosmological time.

10.2. Global Cosmological Time

Cosmological time is defined as the accumulated computational complexity:

$$\tau_{\text{cosmo}} = \frac{1}{\rho_0} \int_{\mathcal{V}} \mathcal{C}(x)\sqrt{-g}d^4x$$

where $\mathcal{V}$ is the past causal volume.

10.3. Computational Dark Energy

The cosmic acceleration is interpreted as a residual computational cost:

$$\Lambda = \alpha \frac{\rho_{\text{calc}} c^4}{E^2_{\text{Planck}}}$$

with α an algorithmic efficiency factor.

11. Testable Predictions

11.1. Lorentz Violations

At high energies ($E \gg \rho_0^{1/4}$), violations of Lorentz invariance are predicted:

$$\Delta v(E) = v_g(E) - c \sim c\, e^{-E/E_{\text{comp}}}, \quad E_{\text{comp}} = \rho_0^{1/4}$$

11.2. Anomalies in the CMB

The angular power spectrum shows deviations from the ΛCDM model:

$$C_\ell = C_\ell^{\Lambda\mathrm{CDM}} + \delta_\ell, \quad \delta_\ell = A\ell^{-3/2}e^{-\gamma\ell}$$

with A, γ parameters derived from ρ_0.

11.3. Variation of Fundamental Constants

The computational density decreases with expansion, inducing slow variations:

$$\frac{d\ln\alpha}{dt} = \eta\,\rho_{\mathrm{calc}}^{1/2} \sim 10^{-19}\,\mathrm{yr}^{-1}$$

where α is the fine structure constant.

Appendices

.1. Appendix A — Annotated Bibliography

- **Ryu, S., Takayanagi, T.** *Holographic Derivation of Entanglement Entropy from AdS/CFT.* Phys. Rev. Lett. 96, 181602 (2006).
  Introduces the Ryu–Takayanagi formula relating entanglement entropy to the minimal area in AdS space. Starting point for many reflections on holographic entropy laws.

- **Susskind, L., Uglum, L.** *Black Hole Entropy in Canonical Quantum Gravity and Superstring Theory.* Phys. Rev. D50 (1994).
  Proposes a microcanonical interpretation of black hole entropy from the vacuum density of states. Precursor to the idea of holography.

- **Jacobson, T.** *Thermodynamics of Spacetime: The Einstein Equation of State.* Phys. Rev. Lett. 75, 1260 (1995).
  Demonstrates that Einstein's equations can be seen as a thermodynamic equation of state, relating entropy, heat, and local horizon.

- **Lloyd, S.** *Ultimate Physical Limits to Computation.* Nature 406, 1047 (2000).
  Defines the fundamental limits of computing power based on energy and volume. Basis of the link between physics and information.

- **Bombelli, R., Koul, R. K., Lee, J., Sorkin, R. D.** *Quantum source of entropy for black holes.* Phys. Rev. D34, 373 (1986).
  One of the first calculations of entanglement entropy in a QFT on curved spacetime. Highlights the role of the partial trace and inaccessible degrees of freedom.

- **Bianchi, E., Myers, R. C.** *On the Architecture of Spacetime Geometry.* Class. Quant. Grav. 31, 214002 (2014).
  Explores the idea that spacetime geometry stems from informational principles (entropy, entanglement, surface).

.2. Appendix B — Diagram of a Holographic Computational Horizon

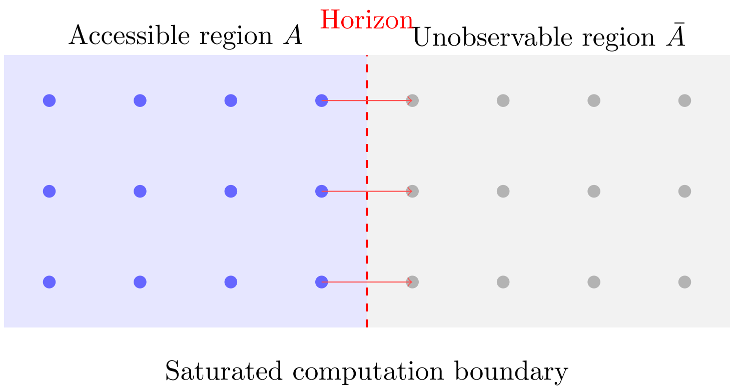

Figure 1: Modeling of a horizon as a computational boundary in a qbit graph. The interaction between A and $\bar{A}$ is bounded by the maximum computational density allowed by holographic laws.