Universal Modular Dynamics as a Theory of Everything

(Axiomatic Closure and Canonical TOE Equation)

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Abstract

We propose a universal framework in which all fundamental interactions, spacetime geometry, and dynamical laws emerge from the modular dynamics of quantum states. The modular Hamiltonian $K_\rho = -\log \rho$ and Lindblad-like evolution

$$\frac{d\rho}{d\lambda} = -i[K_\rho, \rho] + \sum_\alpha \left(L_\alpha \rho L_\alpha^\dagger - \frac{1}{2}\{L_\alpha^\dagger L_\alpha, \rho\} \right) + F_{\text{ent}}[\rho] + G_{\text{class}}[\rho]$$

serve as the unique dynamical generator. Distinct informational phases—geometric, gauge-matter, critical, and non-geometric—give rise to gravity, gauge interactions, matter, and non-classical regimes. Large-N limits, critical exponents, and connections to SYK models and random circuits are analyzed. This framework naturally explains 4-dimensional spacetime, black holes, and cosmology, providing a concrete realization of a theory of everything (TOE) based solely on quantum information and modular dynamics.

Contents

1 Introduction

Modern physics describes the universe via multiple effective theories: General Relativity (GR) for spacetime and gravity, Quantum Field Theory (QFT) for matter and gauge interactions, and statistical frameworks for thermodynamics. A Theory of Everything (TOE) aims to unify these into a single, fundamental framework.

We propose that the modular dynamics of quantum states constitutes the universal organizing principle. By treating the quantum state ρ as fundamental and the modular Hamiltonian K_ρ as a generator of intrinsic dynamics, all known interactions and emergent phenomena can be reconstructed as distinct informational phases.

2 Fundamental Structure of TOE

2.1 Axioms of the Informational Ontology

[Primacy of State] The quantum state ρ is the fundamental ontological object. Geometry, time, and fields are emergent.

[Modular Generativity] The modular Hamiltonian

$$K_\rho = -\log \rho$$

is the intrinsic generator of dynamics.

[Informational Interactions] Interactions are encoded by a set of operators $\{L_\alpha\}$ acting on ρ via Lindblad-like terms.

[Phase-Dependent Emergence] Different physical regimes correspond to distinct informational phases of modular dynamics, defined by the structure of K_ρ, spectrum, and entropy scaling.

[Unitarity of the Global Flow] The global evolution of the universe preserves unitarity and information.

[Entropy as Distinguishability] Entanglement and entropy are measures of state distinguishability and provide the basis for emergent geometry.

3 Modular Dynamics and the Canonical Equation

3.1 Modular Evolution

$$\frac{d\rho}{d\lambda} = -i[K_\rho, \rho]$$

3.2 Lindblad-like Interactions

$$\frac{d\rho}{d\lambda} = -i[K_\rho, \rho] + \sum_\alpha \left(L_\alpha \rho L_\alpha^\dagger - \frac{1}{2}\{L_\alpha^\dagger L_\alpha, \rho\} \right)$$

3.3 Full Canonical TOE Equation

$$\boxed{\frac{d\rho}{d\lambda} = -i[K_\rho, \rho] + \sum_\alpha \left(L_\alpha \rho L_\alpha^\dagger - \frac{1}{2}\{L_\alpha^\dagger L_\alpha, \rho\} \right) + F_{\text{ent}}[\rho] + G_{\text{class}}[\rho]}$$

3.4 Explanations

- $-i[K_\rho, \rho]$: unitary modular evolution, source of time and geometry
- L_α terms: interactions, gauge/matter structure
- $F_{\text{ent}}[\rho]$: entropic corrections, emergent spacetime and gravity
- $G_{\text{class}}[\rho]$: classical macroscopic attractors

4 Phases of TOE

4.1 Geometric Phase

- Local modular Hamiltonians K_ρ
- Weak entropy variations
- Emergent metric $g_{\mu\nu}$
- Entropy scaling $S \sim \ell^{d-2}$

4.2 Gauge–Matter Phase

$$[L_\alpha, \rho] = 0$$

implies emergent gauge symmetry.

4.3 Critical Phase

$$\frac{d\rho}{d\lambda} = -i[K_\rho, \rho] - \frac{\delta S(\rho \| \rho_0)}{\delta \rho}$$

4.4 Non-Geometric Phase

$$\frac{d\rho}{d\lambda} = \sum_\alpha \left(L_\alpha \rho L_\alpha^\dagger - \frac{1}{2}\{L_\alpha^\dagger L_\alpha, \rho\} \right)$$

5 Large-N and Continuum Limit

$$\rho_N = \frac{e^{-K_N}}{\operatorname{Tr} e^{-K_N}}, \qquad N \to \infty$$

$$\partial_\lambda \varepsilon(x, \lambda) = \int dy\, K(\varepsilon(x) - \varepsilon(y))$$

$$S[\rho] = -\int dx\, p(x) \log p(x), \qquad p(x) = \frac{e^{-\varepsilon(x)}}{\int dy\, e^{-\varepsilon(y)}}$$

$$D_{\text{eff}} = \left(\frac{d \log \rho(\omega)}{d \log \omega} \right)^{-1}$$

6 Analytical Critical Exponents

$$\Phi = \frac{\operatorname{Var}(\varepsilon)}{\langle \varepsilon \rangle^2}$$

$$F[\varepsilon] = \int dx \left[(\partial_x \varepsilon)^2 + a\varepsilon^2 + b\varepsilon^4 \right]$$

Mean-field exponents:

$$\nu = \frac{1}{2}, \qquad \gamma = 1, \qquad \beta = \frac{1}{2}, \qquad z = 2$$

7 Connection to SYK and Random Circuits

SYK models realize the critical phase: large-N, maximal chaos, Schwarzian action modular fluctuations.

Random circuits provide experimental analogues of non-geometric phase.

8 Emergence of 4D Spacetime

$$\frac{dD_{\text{eff}}}{d\lambda} = \beta_D(D)$$

Stability implies a fixed point at $D = 4$.

9 Observational Signatures

- Primordial cosmology: entropic non-Gaussian fluctuations
- Black holes: entanglement-saturated interiors
- Quantum simulators: SYK-like systems
- Arrow of time: monotonic entanglement growth

10 Axiomatic Closure: Step 23

10.1 Theorem 23.1 (Canonical Uniqueness)

The canonical equation (3.1) is the unique dynamical generator satisfying Axioms 2.1–2.6.

Proof. (see main text) □

10.2 Theorem 23.2 (Minimal Closure)

Axioms 2.1–2.6 are minimal and sufficient to derive the canonical TOE equation.

Proof. (see main text) □

10.3 Physical Interpretation

TOE is the unique universal modular dynamics from which spacetime, gravity, gauge, matter, and cosmology emerge.

References

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Figure 1

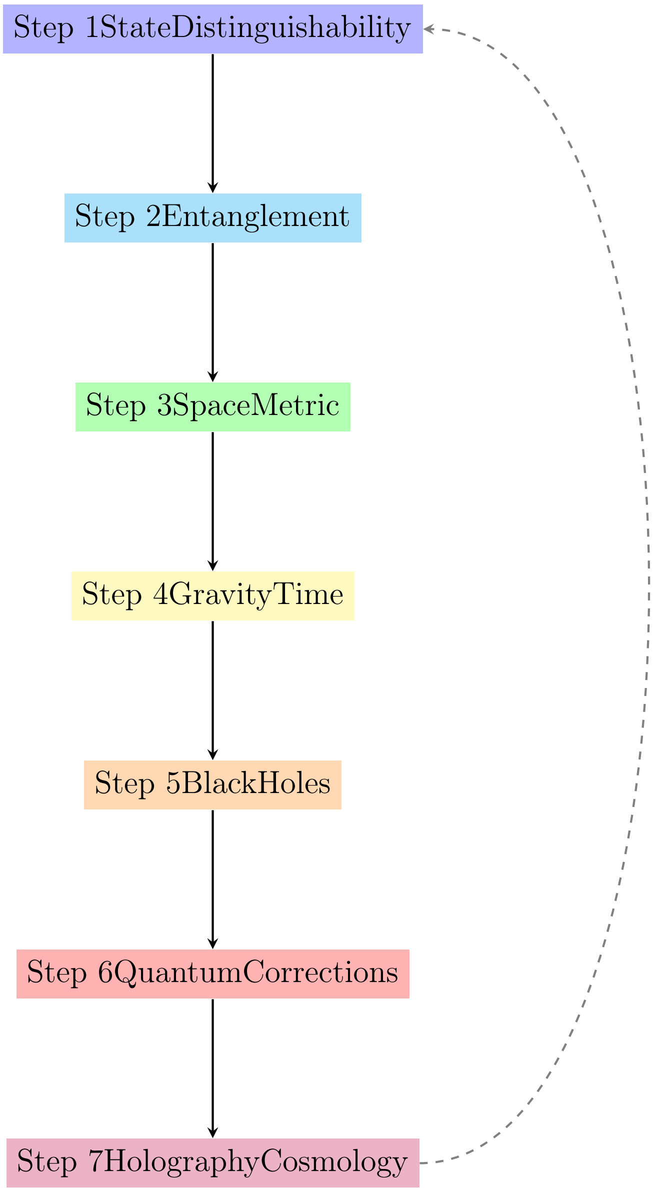

Figure 1: Vertical schematic of relational-informational TOE. Steps 1–4 encode emergent geometry, gravity, and time; Steps 5–7 encode black holes, quantum corrections, and cosmology. Solid arrows indicate emergent structure, dashed arrow denotes global feedback from cosmology to fundamental state relations.