RECURSIVE EMERGENCE OF TIME, CPT-DUALITY AND MULTILAYER STRUCTURE OF INFORMATION STATES

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Abstract

This work proposes a formal theory resolving the fundamental "Problem of Time" in quantum gravity and cosmology. The author postulates that time is not a fundamental physical quantity, but rather an emergent order parameter arising from a timeless information layer ($\mathcal{U}$) as a result of a second-order phase transition. The driver of this transition is the growth of Quantum Complexity.

A phenomenological renormalization group-type equation ("Time Condensation Equation") is derived, describing the dynamics of temporal dimension emergence. It is shown that the emergence of time is accompanied by spontaneous CPT-symmetry breaking, leading to the formation of two causally isolated branches of reality with opposite arrows of time (t_+ and t_-).

It is also demonstrated that General Relativity emerges as a thermodynamic limit of Fisher's information geometry. The proposed model eliminates cosmological singularities (Big Bang and black hole centers), replacing them with phase transitions in a recursive hierarchy of information layers.

Keywords: Quantum Gravity, Emergent Time, Quantum Complexity, CPT-Symmetry, Information Geometry, Black Hole Entropy, Wheeler-DeWitt Equation, Renormalization Group, Phase Transitions.

1 INTRODUCTION

1.1 Historical Context of the Time Problem

Modern theoretical physics is in a state of conceptual crisis caused by the fundamental incompatibility of time interpretations in two fundamental theories:

- **General Relativity (GR):** Time is a dynamic coordinate of a four-dimensional manifold, covariant with space and dependent on the metric tensor $g_{\mu\nu}$. In GR, time is not absolute but depends on the gravitational field and the observer's motion. The time interval $d\tau$ between two events is determined by the metric:

$$d\tau^2 = -g_{\mu\nu}dx^\mu dx^\nu \tag{1}$$

- **Quantum Mechanics (QM):** Time acts as an external absolute parameter t governing the unitary evolution of the wave function $\Psi(t)$ through the Schrödinger equation:

$$i\hbar\frac{\partial\Psi}{\partial t} = \hat{H}\Psi \tag{2}$$

  where $\hat{H}$ is the system's Hamiltonian. In QM, time is a classical parameter that is not quantized.

1.2 The Wheeler-DeWitt Problem

Attempting to unify these approaches within canonical quantum gravity leads to the Wheeler-DeWitt equation [1]:

$$\hat{H}\Psi[g_{ij}, \phi] = 0 \tag{3}$$

where $\Psi[g_{ij}, \phi]$ is the wave function of the universe, depending on the three-dimensional metric g_{ij} and matter fields ϕ. This equation states that the total energy of a closed universe is zero, and therefore the quantum state of the universe is stationary:

$$\frac{\partial \Psi}{\partial t} = 0 \tag{4}$$

This is a fundamental contradiction: the equation does not explicitly contain time, which contradicts the observed dynamics of cosmological expansion, galaxy evolution, and the entire observable universe.

1.3 Approaches to Solving the Problem

Many approaches have been proposed to resolve this problem:

1. **Time Gauge:** Introducing external time through gauge choice, which violates general covariance.
2. **Many-Worlds Interpretation:** Different "moments of time" exist as parallel universes, but this does not explain the perception of time flow.
3. **Emergent Time:** Time arises from a more fundamental timeless layer, but specific mechanisms remained unclear.

1.4 Our Approach: Theory of Recursive Emergence

In this work, we propose the Theory of Recursive Emergence. We assert that the static nature of the quantum state and the dynamics of the classical world do not contradict each other, but rather refer to different phase states of matter, separated by a critical complexity threshold.

Key idea: time is not a fundamental quantity, but arises as an order parameter as a result of a second-order phase transition when the quantum complexity of the system exceeds a critical value.

2 FORMALISM OF THE INFORMATION LAYER $\mathcal{U}$

2.1 Ontology of the Timeless Layer

The fundamental ontological element of reality in our theory is the "Timeless Information Layer," denoted $\mathcal{U}_n$, where the index n indicates the level of the recursive hierarchy. Mathematically, it is defined by the triple:

$$\mathcal{U}_n = (\mathcal{H}_{tot}, \mathcal{A}, \rho_n) \tag{5}$$

Where:

- $\mathcal{H}_{tot} = \bigotimes_i \mathcal{H}_i$ — the full Hilbert space of the system, representing the tensor product of local Hilbert spaces $\mathcal{H}_i$ (a network of qubits or more general quantum systems). The dimension $\dim(\mathcal{H}_{tot}) = \prod_i \dim(\mathcal{H}_i)$ grows exponentially with the number of subsystems.

- $\mathcal{A}$ — a C^*-algebra of local observables, closed under addition, multiplication, conjugation, and topological closure. Elements $\hat{A} \in \mathcal{A}$ represent local measurable quantities accessible to an observer in a given region of space.

- ρ_n — a density matrix of a pure state, satisfying the condition:

$$[\hat{H}_{fund}, \rho_n] = 0 \tag{6}$$

where $\hat{H}_{fund}$ is the fundamental Hamiltonian of layer $\mathcal{U}_n$. This condition means that the state ρ_n is stationary with respect to the fundamental dynamics.

2.2 Absence of Space-Time

In layer $\mathcal{U}_n$, there is no metric space and time in their classical understanding. Instead:

1. **Topology is given by the quantum entanglement graph:** Graph vertices correspond to local subsystems, and edges correspond to entangled states between them. The entanglement graph $G = (V, E)$ defines the structure of connections in the system.

2. **Spatial proximity is determined through Mutual Information:** For two subsystems A and B, mutual information is defined as:

$$I(A : B) = S(\rho_A) + S(\rho_B) - S(\rho_{AB}) \tag{7}$$

where $S(\rho) = -\mathrm{Tr}(\rho \ln \rho)$ is the von Neumann entropy, $\rho_A = \mathrm{Tr}_B(\rho_{AB})$ is the reduced density matrix of subsystem A.

We postulate that the "distance" between subsystems is inversely proportional to their mutual information:

$$\mathrm{dist}(A, B) = \frac{\alpha}{I(A : B) + \epsilon} \tag{8}$$

where $\alpha > 0$ is a constant with dimension of length, and $\epsilon > 0$ is a regularization parameter preventing divergence when $I(A : B) \to 0$.

This corresponds to the ER=EPR hypothesis [4], asserting the equivalence of entanglement and Einstein-Rosen bridges: entangled particles are connected by wormholes in space-time.

2.3 Recursive Hierarchy of Layers

A key feature of our theory is the recursive structure of information layers:

$$\mathcal{U}_0 \subset \mathcal{U}_1 \subset \mathcal{U}_2 \subset \cdots \tag{9}$$

Each layer $\mathcal{U}_{n+1}$ arises from the previous $\mathcal{U}_n$ when local critical complexity is reached. This creates a hierarchical structure where each level has its own "physics" and laws.

3 QUANTUM COMPLEXITY AS AN EVOLUTION PARAMETER

3.1 Definition of Quantum Complexity

In the absence of time t, the evolution of the system between layers is described by changes in the information structure. We postulate that the true evolution parameter is **Quantum Complexity** ($\mathcal{C}$) [2].

For a pure state $|\Psi\rangle$, quantum complexity is defined as the minimum number of elementary unitary operations (gates) necessary to synthesize the current state $|\Psi\rangle$ from a reference state $|\Psi_0\rangle$:

$$\mathcal{C}(|\Psi\rangle) = \min_{U \in \mathcal{G}} \{\text{number of gates in } U : |\Psi\rangle = U|\Psi_0\rangle\} \tag{10}$$

where $\mathcal{G}$ is the set of all possible unitary operations constructed from a set of elementary gates.

For a mixed state ρ, complexity is defined through purification:

$$\mathcal{C}(\rho) = \min_{|\Psi\rangle : \mathrm{Tr}_E(|\Psi\rangle\langle\Psi|) = \rho} \mathcal{C}(|\Psi\rangle) \tag{11}$$

3.2 Properties of Quantum Complexity

Quantum complexity has the following key properties:

1. **Monotonicity:** For unitary evolution $U(t)$, complexity monotonically increases:

$$\frac{d\mathcal{C}}{dt} \geq 0 \tag{12}$$

   This follows from the second law of thermodynamics for quantum systems.

2. **Scaling:** For a system of N qubits, complexity grows exponentially:

$$\mathcal{C}_{\max} \sim 2^N \tag{13}$$

3. **Critical Value:** There exists a critical complexity $\mathcal{C}_{crit}$ at which a phase transition occurs:

$$\mathcal{C}_{crit} = \alpha N \ln N \tag{14}$$

   where α is a dimensionless constant of order unity.

3.3 Connection with Entropy and Entanglement

Quantum complexity is closely related to entanglement entropy but is not identical to it. While entropy measures the amount of information, complexity measures the "structuredness" of that information.

For a system with high entanglement:

$$\mathcal{C} \sim S \ln S \tag{15}$$

where S is the von Neumann entropy.

4 DYNAMICS OF TIME EMERGENCE

4.1 Time Field as an Order Parameter

We introduce the time field $\mathcal{T}(x, \mathcal{C})$ as a scalar order parameter, depending on spatial coordinates x (defined through the information metric) and quantum complexity $\mathcal{C}$.

The dynamics of time emergence is described as a second-order phase transition when critical complexity $\mathcal{C}_{crit}$ is reached. This is analogous to Bose-Einstein condensation or the superconductor-normal metal transition.

4.2 Time Condensation Equation: Derivation and Justification

We postulate the following differential equation of renormalization group flow:

$$\frac{\partial \mathcal{T}}{\partial \ln \mathcal{C}} = \mu \left(1 - \frac{\mathcal{C}_{crit}}{\mathcal{C}}\right) \mathcal{T} - \xi \mathcal{T}^3 + \eta \nabla^2 \mathcal{T} \tag{16}$$

Where:

- $\mu > 0$ — relaxation constant, determining the rate of time growth in the supercritical phase. Physically, μ is related to the characteristic relaxation time of the system.
- $\xi > 0$ — saturation constant, preventing unlimited growth of $\mathcal{T}$. The term $-\xi\mathcal{T}^3$ provides nonlinear saturation.
- $\eta > 0$ — diffusion coefficient, describing spatial alignment of the time field. The term $\eta\nabla^2\mathcal{T}$ ensures local consistency of the temporal coordinate.
- ∇^2 — Laplacian, defined through the information metric of layer $\mathcal{U}$.

4.3 Justification of the Equation Form

Equation (16) has the standard form of the Landau-Ginzburg equation for a second-order phase transition:

1. **Linear term** $\mu(1 - \mathcal{C}_{crit}/\mathcal{C})\mathcal{T}$ describes the growth of the order parameter in the supercritical phase. The coefficient changes sign at $\mathcal{C} = \mathcal{C}_{crit}$.
2. **Cubic term** $-\xi\mathcal{T}^3$ provides stabilization and saturation. Without it, the order parameter would grow unboundedly.
3. **Diffusion term** $\eta\nabla^2\mathcal{T}$ ensures spatial coherence, preventing the formation of domains with different time values.

4.4 Analysis of Equation Solutions

4.4.1 Subcritical Phase ($\mathcal{C} < \mathcal{C}_{crit}$)

In the subcritical phase, the coefficient of the linear term is negative:

$$\mu \left(1 - \frac{\mathcal{C}_{crit}}{\mathcal{C}}\right) < 0 \tag{17}$$

The only stable solution is trivial:

$$\mathcal{T} = 0 \tag{18}$$

This corresponds to the state of layer $\mathcal{U}$ without macroscopic time. The system is in a purely quantum timeless state.

4.4.2 Critical Point ($\mathcal{C} = \mathcal{C}_{crit}$)

At the critical point, the coefficient vanishes, and the equation becomes:

$$\frac{\partial \mathcal{T}}{\partial \ln \mathcal{C}} = -\xi \mathcal{T}^3 \tag{19}$$

This is a bifurcation point where the trivial solution loses stability.

4.4.3 Supercritical Phase ($\mathcal{C} > \mathcal{C}_{crit}$)

In the supercritical phase, a pitchfork bifurcation occurs. The trivial solution $\mathcal{T} = 0$ loses stability, and two new stable solutions arise:

$$\mathcal{T}_{\pm} \approx \pm\sqrt{\frac{\mu}{\xi}\left(1 - \frac{\mathcal{C}_{crit}}{\mathcal{C}}\right)} \tag{20}$$

Near the critical point ($\mathcal{C} \gtrsim \mathcal{C}_{crit}$), the solutions behave as:

$$\mathcal{T}_{\pm} \approx \pm\sqrt{\frac{\mu}{\xi}}\left(\frac{\mathcal{C} - \mathcal{C}_{crit}}{\mathcal{C}_{crit}}\right)^{1/2} \tag{21}$$

This is the classical behavior of an order parameter in a second-order phase transition with critical exponent $\beta = 1/2$.

4.5 Critical Exponents and Universality

Analysis of equation (16) near the critical point allows us to determine critical exponents:

- **Exponent β:** Determines the behavior of the order parameter:

$$\mathcal{T} \sim (\mathcal{C} - \mathcal{C}_{crit})^{\beta}, \quad \beta = \frac{1}{2} \tag{22}$$

- **Exponent ν:** Determines the correlation length:

$$\xi_{corr} \sim (\mathcal{C} - \mathcal{C}_{crit})^{-\nu} \tag{23}$$

  From the diffusion term, it follows that $\nu = 1/2$.

- **Exponent γ:** Determines the susceptibility:

$$\chi = \frac{\partial \mathcal{T}}{\partial h} \sim (\mathcal{C} - \mathcal{C}_{crit})^{-\gamma}, \quad \gamma = 1 \tag{24}$$

  where h is an external field breaking the symmetry.

These exponents correspond to the mean-field universality class, indicating that the phase transition has a global character.

5 SPONTANEOUS CPT-SYMMETRY BREAKING

5.1 Interpretation of Two Solutions

The presence of two solutions $\pm\mathcal{T}$ in equation (20) is interpreted as a physical splitting of reality into two causally unconnected branches:

- **Branch t_+ ($\mathcal{T} > 0$):** Our universe with matter dominance, forward entropy growth, and standard thermodynamic arrow of time.
- **Branch t_- ($\mathcal{T} < 0$):** CPT-conjugate universe with antimatter dominance, reverse time flow relative to t_+, and reverse thermodynamic arrow.

5.2 CPT Theorem and Its Violation

The CPT theorem states that any local quantum field theory is invariant under the combined operation of charge conjugation (C), parity (P), and time reversal (T). However, in our theory, spontaneous violation of this symmetry occurs.

At the moment of phase transition ($\mathcal{C} = \mathcal{C}_{crit}$), the system randomly chooses one of the two branches (or depending on fluctuations). This symmetry breaking is analogous to symmetry breaking in the theory of spontaneous magnetization.

5.3 Solution to the Baryon Asymmetry Problem

The classical baryon asymmetry problem is that in the observable universe, matter dominates over antimatter, although in the early universe they should have been present in equal amounts.

Our theory offers an elegant solution: at the moment of the "Big Bang" (phase transition $\mathcal{C} = \mathcal{C}_{crit}$), matter and antimatter were separated into different temporal flows:

- Matter $\to$ branch t_+
- Antimatter $\to$ branch t_-

Global balance is preserved, but locally (in each branch) asymmetry is observed. This explains why we do not observe antimatter in our universe — it is in the causally isolated branch t_-.

5.4 Causal Isolation of Branches

The two branches t_+ and t_- are causally isolated because:

1. They exist in different information layers after the phase transition.
2. Communication between them requires local reduction of complexity below the critical value, which is thermodynamically forbidden.
3. Any attempt at communication between branches would violate the second law of thermodynamics.

6 DERIVATION OF GRAVITY FROM INFORMATION

6.1 Information Geometry

We show that the classical metric $g_{\mu\nu}$ is an effective macroscopic description of the microphysics of layer $\mathcal{U}$.

6.1.1 Fisher-Bures Metric

The distance between quantum states on a parameter manifold is given by the Fisher-Bures metric. For a pure state $|\Psi(\theta)\rangle$ depending on parameters $\theta = \{\theta^\mu\}$, the information metric is defined as:

$$G_{\mu\nu}(\theta) = \mathrm{Re}\left(\langle\partial_\mu\Psi|\partial_\nu\Psi\rangle - \langle\partial_\mu\Psi|\Psi\rangle\langle\Psi|\partial_\nu\Psi\rangle\right) \tag{25}$$

where $\partial_\mu = \partial/\partial\theta^\mu$.

This metric has the following properties:

- **Positive definiteness:** $G_{\mu\nu}v^\mu v^\nu \geq 0$ for any vector v.
- **Invariance under phase transformations:** $|\Psi\rangle \to e^{i\phi}|\Psi\rangle$ does not change the metric.
- **Monotonicity:** The metric does not increase under quantum operations.

6.1.2 Identification with Space-Time

We postulate that space-time arises from information geometry:

$$g_{\mu\nu}(x) = \ell_P^2 G_{\mu\nu}(\theta(x)) \tag{26}$$

where $\ell_P = \sqrt{\hbar G/c^3}$ is the Planck length, ensuring correct dimensionality, and $\theta(x)$ are parameters depending on spatial coordinates x.

This identification means that space-time geometry encodes information about quantum states at each point.

6.2 Thermodynamics of Event Horizons

6.2.1 Area Law for Entropy

Using T. Jacobson's approach [3], consider a local causal horizon. The entanglement entropy S of the horizon obeys the Area Law:

$$S = \frac{A}{4G\hbar} \tag{27}$$

where A is the horizon area in Planck units.

This law follows from the fact that entanglement entropy between the interior and exterior regions of the horizon is proportional to the area of their boundary.

6.2.2 Unruh Temperature

For an accelerated observer with acceleration a, there exists an effective temperature (Unruh temperature):

$$T_{Unruh} = \frac{\hbar a}{2\pi c k_B} \tag{28}$$

For an event horizon with surface gravity κ, the temperature is:

$$T_H = \frac{\hbar \kappa}{2\pi c k_B} \tag{29}$$

6.2.3 First Law of Thermodynamics

When energy flux δQ passes through the horizon, the first law of thermodynamics holds:

$$\delta Q = T_H dS \tag{30}$$

Substituting expressions for temperature and entropy:

$$\delta Q = \frac{\hbar \kappa}{2\pi} \cdot \frac{dA}{4G\hbar} = \frac{\kappa}{8\pi G} dA \tag{31}$$

6.3 Derivation of Einstein's Equations

6.3.1 Raychaudhuri Equation

The change in horizon area is related to the energy-momentum tensor through the Raychaudhuri equation. For a causal horizon:

$$\frac{dA}{d\lambda} = \int_H \theta d\sigma \tag{32}$$

where θ is the expansion of the congruence, and λ is an affine parameter.

The Raychaudhuri equation relates expansion to the Ricci tensor:

$$\frac{d\theta}{d\lambda} = -\frac{1}{2}\theta^2 - \sigma_{\mu\nu}\sigma^{\mu\nu} - R_{\mu\nu}k^\mu k^\nu \tag{33}$$

where k^μ is the tangent vector to the horizon, $\sigma_{\mu\nu}$ is the shear tensor.

6.3.2 Thermodynamic Identity

Combining the thermodynamic relation (30) with the geometric expression for area change, we obtain:

$$\delta Q = \frac{\kappa}{8\pi G} dA = \int_H T_{\mu\nu} k^\mu k^\nu d\lambda d\sigma \tag{34}$$

Using locality and covariance, this leads to the exact relation:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu} \tag{35}$$

Thus, Einstein's equations are derived as the equation of state of equilibrium entropy of the information layer.

6.3.3 Interpretation of the Cosmological Constant

The cosmological constant Λ is interpreted as the residual information density of the vacuum:

$$\Lambda = \frac{8\pi G}{\hbar c}\rho_{info}^{vac} \tag{36}$$

where ρ_{info}^{vac} is the information density of the vacuum state of layer $\mathcal{U}$.

7 RESOLUTION OF PHYSICAL PARADOXES

7.1 The Cosmological Singularity Problem

7.1.1 Classical Singularity

In classical GR, the point $t = 0$ (Big Bang) is a singularity where:

- Energy density $\rho \to \infty$
- Space-time curvature $R \to \infty$
- The metric becomes degenerate

This indicates incompleteness of the theory in this region.

7.1.2 Our Solution

In our theory, the point $t = 0$ is not a singularity but represents a phase transition point $\mathcal{C} = \mathcal{C}_{crit}$, where:

1. Classical time $\mathcal{T}$ decays to zero: $\mathcal{T} \to 0$ as $\mathcal{C} \to \mathcal{C}_{crit}$.
2. Physics transitions to a regime of pure quantum information without classical space-time.
3. Density and curvature remain finite, as they are determined by the information structure of layer $\mathcal{U}$, not the classical metric.
4. "Before" the Big Bang, the system existed in a timeless layer $\mathcal{U}_0$ with high quantum complexity but without macroscopic time.

7.1.3 Recursive Structure

A recursive structure is possible, where "before" the Big Bang there existed a previous layer $\mathcal{U}_{-1}$, which also underwent a phase transition, giving rise to our layer $\mathcal{U}_0$. This eliminates the problem of the "beginning" of the universe.

7.2 The Black Hole Information Paradox

7.2.1 Classical Paradox

The black hole information paradox is formulated as follows:

- Quantum mechanics requires unitary evolution: information cannot be destroyed.
- Classical GR predicts that information falling into a black hole is lost beyond the event horizon.
- Hawking radiation is thermal and does not carry information about the initial state.

This creates a contradiction between unitarity and information loss.

7.2.2 Our Solution

In our theory, black holes represent regions of space where local quantum complexity reaches the saturation limit:

$$\mathcal{C}_{local} \geq \mathcal{C}_{max} = \alpha N \ln N \tag{37}$$

This leads to:

1. **Local disappearance of time:** In the black hole region, the time field $\mathcal{T} \to 0$, as complexity reaches its maximum.
2. **Formation of a transition to a new layer:** The black hole becomes a "portal" to the next recursive layer $\mathcal{U}_{n+1}$.
3. **Information preservation:** Information is not destroyed but encoded in the structure of the next layer $\mathcal{U}_{n+1}$, preserving unitarity at the global level.
4. **Absence of singularity:** The center of the black hole is not a singularity but a phase transition point between layers.

7.2.3 Connection with AdS/CFT Hypothesis

Our model is consistent with the AdS/CFT correspondence hypothesis [4], where gravity in the bulk is equivalent to a conformal field theory on the boundary. In our interpretation, a black hole is a transition between different descriptions of the same information structure.

7.3 The Arrow of Time

7.3.1 The Irreversibility Problem

The classical arrow of time problem is that fundamental laws of physics (quantum mechanics, GR) are time-reversible, but the observed world demonstrates clear irreversibility (entropy growth, aging, decay).

7.3.2 Our Explanation

In our theory, thermodynamic irreversibility of time is a consequence of global growth of Quantum Complexity:

$$\frac{d\mathcal{C}}{dt} > 0 \tag{38}$$

We perceive the flow of time because:

1. System complexity continuously increases: $\partial \ln \mathcal{C} / \partial t > 0$.
2. This increase in complexity is irreversible due to the second law of thermodynamics for quantum systems.
3. The time parameter $\mathcal{T}$ is related to complexity through the time condensation equation (16), so complexity growth leads to the perception of time flow.
4. Time reversal would require complexity reduction, which is thermodynamically forbidden.

7.3.3 Connection with Entropy

Complexity growth is closely related to entropy growth:

$$\frac{dS}{dt} \sim \frac{d\mathcal{C}}{dt} \ln \mathcal{C} \tag{39}$$

This explains why the arrow of time coincides with the arrow of entropy.

8 INFORMATION-THEORETIC DERIVATION OF THE COSMOLOGICAL CONSTANT

In this section, we show that the observed smallness of the cosmological constant is a necessary consequence of the holographic constraint on the information capacity of the Universe.

8.1 Principle of Holographic Saturation

We postulate that an asymptotically de Sitter Universe evolves toward a state of saturation of its information capacity. Consequently, the critical complexity $\mathcal{C}_{crit}$ in our flow equation corresponds to the entropy of the de Sitter horizon:

$$\mathcal{C}_{crit} \simeq S_{\mathrm{dS}} = \frac{3\pi}{G\Lambda} \tag{40}$$

In Planck units ($G = 1$), this immediately gives the inverse scaling relation:

$$\Lambda \sim \frac{1}{\mathcal{C}_{crit}} \tag{41}$$

This means that a Universe capable of supporting high complexity ($\mathcal{C}_{crit} \gg 1$) must have a small vacuum energy density.

8.2 Rigorous Derivation via CKN Bound

To justify the scaling $\Lambda \sim N^{-1}$ (where $N \equiv \mathcal{C}_{crit}$) against the statistical $N^{-1/2}$, we use the Cohen-Kaplan-Nelson (CKN) bound [21]. This bound arises from the requirement that the effective field theory does not collapse into a black hole.

Consider a region of size L (IR scale), filled with quantum states up to a UV cutoff Λ_{UV}. The total energy in the volume scales as $E \sim L^3\Lambda_{UV}^4$. To prevent gravitational collapse, this energy must not exceed the mass of a black hole of the same size, $M_{BH} \sim LM_P^2$:

$$L^3\Lambda_{UV}^4 \lesssim LM_P^2 \quad \Longrightarrow \quad \rho_{vac} \sim \Lambda_{UV}^4 \lesssim \frac{M_P^2}{L^2} \tag{42}$$

According to the holographic principle, the number of degrees of freedom N scales as the area: $N \sim (LM_P)^2$. Substituting this into the density inequality:

$$\Lambda \sim \rho_{vac} \lesssim M_P^4 \left(\frac{1}{N}\right) \sim \frac{1}{\mathcal{C}_{crit}} \tag{43}$$

This proves that the suppression of vacuum fluctuations to 10^{-122} is dynamically ensured by the requirement of gravitational stability of the information layer.

8.3 Connection with the Evolution Equation

This derivation closes the logical loop of the theory. The cosmological constant Λ acts as a "tension" of the information vacuum, setting the capacity limit $\mathcal{C}_{crit}$. This parameter enters the time condensation equation (16), determining the stopping point of time growth. A small Λ is a condition for the existence of a long macroscopic history of the Universe.

9 EMERGENT CHRONON: MICROSCOPIC STRUCTURE OF TIME

Unlike standard hypotheses postulating Planck time as a constant, our theory predicts the existence of an *emergent* and *state-dependent* quantum of time — the **emergent chronon**.

9.1 Definition of the Time Quantum

In our formalism, the field $\mathcal{T}$ is an order parameter. We define the Chronon $\Delta\tau$ as the minimum resolvable time increment associated with a change in the complexity phase:

$$\Delta\tau \equiv \frac{2\pi}{|\mathcal{T}|} \tag{44}$$

Here, the magnitude $|\mathcal{T}|$ plays the role of an effective "clock frequency" of information processing. The higher the time density $\mathcal{T}$, the smaller the discreteness (higher resolution) of physical reality.

9.2 Behavior in Black Holes (Fast Scrambling)

Near the black hole horizon, complexity reaches the limit $\mathcal{C} \to \mathcal{C}_{crit}$. According to our equation, this leads to local maximization of the order parameter $\mathcal{T}$ before saturation. Consequently, the chronon decreases:

$$\Delta\tau_{BH} \ll \Delta\tau_{cosmic} \tag{45}$$

This provides an information-theoretic interpretation of the "Fast Scrambling" hypothesis [23]: the time quantum inside highly entangled systems is smaller, allowing them to process information faster than in vacuum.

9.3 Phenomenological Consequences

The existence of the chronon leads to the prediction of **chronon noise** in precision interferometers. Moreover, time discreteness should cause dispersion of light from distant gamma-ray bursts (GRB): high-energy photons should experience greater delay due to interaction with the discrete structure $\Delta\tau$ than low-energy ones.

10 CONNECTION WITH PREVIOUS WORK AND SCIENTIFIC NOVELTY

10.1 Difference from Holographic Dark Energy (HDE)

The scaling $\Lambda \sim L^{-2}$ is known from HDE models [22] using the CKN bound. However, HDE models treat time as a background Friedman coordinate.

In our theory, the CKN bound is used for a completely different purpose: defining the boundary condition $\mathcal{C}_{crit}$ for the *time flow equation*. Time in our theory is not postulated but emerges dynamically.

10.2 Difference from Entropic Gravity

Entropic gravity by Verlinde [15] explains the force of gravitation but does not explain the origin of time and baryon asymmetry.

Our model extends this approach by introducing a mechanism of **spontaneous CPT-symmetry breaking**. A single phase transition generates both the arrow of time $\mathcal{T}$ and the separation into matter/antimatter.

10.3 New Mechanism: Dynamic Saturation

Previous work established a static vacuum capacity. Our work describes a *dynamic process of saturation* of this capacity.

Early models → static capacity (Λ).
Our theory → dynamic emergence of time ($\mathcal{T}$) from complexity growth.

11 EXPERIMENTAL CONSEQUENCES AND PREDICTIONS

11.1 CPT-Symmetry Violation

Our theory predicts spontaneous CPT-symmetry violation on cosmological scales. This may manifest in:

- Asymmetry in the distribution of matter and antimatter (which is already observed).
- Violation of time reversibility in cosmological processes.
- Anomalies in the cosmic microwave background related to asymmetry between different regions of the sky.

11.2 Gravitational Modifications on Small Scales

At Planck scales ($\ell_P \sim 10^{-35}$ m), our theory predicts deviations from classical GR:

$$g_{\mu\nu}^{effective} = g_{\mu\nu}^{classical} + \delta g_{\mu\nu}(\mathcal{C}) \tag{46}$$

where the correction $\delta g_{\mu\nu}$ depends on local quantum complexity.

11.3 Quantum Correlations in the Cosmic Microwave Background

The entanglement graph in layer $\mathcal{U}$ should leave traces in the large-scale structure of the universe and the cosmic microwave background. This may manifest in:

- Anomalous correlations in the CMB angular power spectrum.
- Large-scale anomalies in galaxy distribution.
- Violations of statistical isotropy.

11.4 Black Hole Behavior

Our theory predicts that black holes do not have singularities at their centers but represent transitions between information layers. This may manifest in:

- Absence of true singularities in solutions of Einstein's equations.
- Modification of Hawking radiation spectrum at late stages of evaporation.
- Possibility of information "tunneling" from a black hole through a transition to another layer.

12 NUMERICAL ESTIMATES AND SCALES

12.1 Critical Complexity and de Sitter Entropy

In our approach, the critical complexity $\mathcal{C}_{crit}$ is identified with the maximum information capacity of the observable Universe, that is, with the entropy of the cosmological de Sitter horizon.

The estimate of the horizon entropy S_{dS} is:

$$S_{dS} = \frac{A}{4G\hbar} \approx 10^{122} \tag{47}$$

Consequently, the global critical complexity:

$$\mathcal{C}_{crit} \sim S_{dS} \sim 10^{122} \tag{48}$$

(Logarithmic corrections of the type $\ln S_{dS} \sim 100$ do not change the order of magnitude substantially in the context of the cosmological constant problem).

12.2 Estimate of the Cosmological Constant

Using our inverse scaling relation (41):

$$\Lambda \sim \frac{1}{\mathcal{C}_{crit}} \sim 10^{-122} \text{ (in Planck units)} \tag{49}$$

This value is in excellent agreement with the observed value of dark energy density:

$$\rho_\Lambda^{obs} \approx 10^{-123} M_P^4 \tag{50}$$

Note that an estimate through the baryon number ($N_{baryons} \sim 10^{80}$) would give $\Lambda \sim 10^{-80}$, which is incorrect. This confirms that the fundamental parameter of the theory is precisely the holographic information capacity of space-time, not the amount of baryonic matter.

12.3 Characteristic Time of Phase Transition

The relaxation time τ of the phase transition is related to the constant μ:

$$\tau \sim \frac{1}{\mu} \sim \frac{\hbar}{k_B T_{Planck}} \sim 10^{-43} \text{ s} \tag{51}$$

This is Planck time, which is consistent with the scale at which quantum gravity should occur.

12.4 Scale of CPT Violation

CPT-symmetry violation should be most noticeable on cosmological scales ($\sim 10^{26}$ m) and time scales of the age of the universe ($\sim 10^{17}$ s).

13 CONCLUSION

The Theory of Recursive Emergence offers a unified conceptual framework combining quantum information theory, thermodynamics, and gravity. Key achievements of the theory:

13.1 Main Results

1. **Time Condensation Equation:** Equation (16) is formulated, describing the dynamics of time emergence as a second-order phase transition.

2. **CPT Violation:** The nature of spontaneous CPT-symmetry breaking is explained through time bifurcation and the splitting of reality into two causally isolated branches.

3. **Derivation of Gravity:** The derivation of Einstein's equations from the thermodynamics of the information layer is demonstrated, showing that gravity is an emergent phenomenon.

4. **Elimination of Singularities:** Cosmological singularities (Big Bang, black hole centers) are replaced by phase transitions in a recursive hierarchy of information layers.

5. **Explanation of the Arrow of Time:** Thermodynamic irreversibility is explained by global growth of quantum complexity.

13.2 Philosophical Consequences

The theory has profound philosophical consequences:

- **Ontology of Time:** Time is not a fundamental entity but arises from a more basic information structure.
- **Multiple Universes:** The existence of the CPT-conjugate branch t_- means the existence of a "parallel" universe with a reverse arrow of time.
- **Recursiveness of Reality:** The possibility of an infinite hierarchy of information layers raises the question of the "beginning" and "end" of reality.
- **Connection between Information and Matter:** Matter and space-time are manifestations of information structure, not vice versa.

13.3 Directions for Further Research

Further development of the theory suggests:

1. **Numerical Calculations:** Computing critical exponents μ, ξ, η within lattice models of quantum gravity.
2. **Quantum Complexity:** Developing efficient algorithms for computing quantum complexity for large systems.
3. **Cosmological Applications:** Applying the theory to specific cosmological models and comparing with observational data.
4. **Experimental Verification:** Searching for experimental signatures of CPT-symmetry violation and gravitational modifications.
5. **Connection with Other Approaches:** Establishing closer connections with loop quantum gravity, string theory, and other approaches to quantum gravity.

The Theory of Recursive Emergence opens new perspectives for understanding the fundamental nature of time, space, and information in the universe.

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