The Entropic Dynamics Mechanism of Quantum Entanglement

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1 Introduction — The Scale Emergence of Physics

1.1 A Unified Starting Point: From Bits to the Structural Scales of the Universe

The framework of "Computational Realism" that we construct has at its core the following assertion: The entirety of physical reality as we know it consists of effective dynamics emerging at multiple, distinct structural scales from a single, deterministically ruled **bit computation field**. We divide this into four scales:

1. **The Bit-Scale:** The most fundamental, discrete computational substrate of the universe. Its dynamics are governed by a unique `Rule`, manifesting as pseudo-random chaos, which is the ultimate origin of all physical phenomena.

2. **The Particle-Scale:** Stable, local patterns with specific **topological structures**, formed by the self-organization of bits. Its dynamics (topological dynamics) are responsible for explaining the generation mechanism of **fundamental particles** and their **strong, weak, and electromagnetic interactions**.

3. **The Microscopic Scale of Entropic Effects:** This is the manifestation of the chaos at the **Bit-Scale** as **high-frequency fluctuations** in microscopic regions of spacetime. Its dynamics are responsible for injecting definite, yet unknowable, initial conditions into the **creation of quantum events**.

4. **The Statistical Scale of Entropic Effects:** This is the **smooth, classical background entropy structure field** that emerges after the chaos of the **Bit-Scale** is **statistically averaged** over macroscopic spacetime regions. Its dynamics (entropic dynamics) lead to the effects of **gravity** and **quantum measurement**.

1.2 Positioning and Core Thesis of This Paper

The complete theory of Computational Realism aims to provide a unified explanation for all the emergence mechanisms, from the Bit-Scale to all higher scales. **This paper, however, will focus on the third and fourth scales mentioned above—namely, the two scales of "entropic effects"**—and, based on this, provide a unified mechanistic explanation for **gravity** and **quantum entanglement**.

For the clarity of the arguments in this paper, the terms **"microscopic"** and **"macroscopic"** used hereafter will be **specifically and locally** defined as follows:

- **"Microscopic" in this paper** refers specifically to the **"Microscopic Scale of Entropic Effects,"** i.e., the entropy field fluctuations that couple with quantum creation.

- **"Macroscopic" in this paper** refers specifically to the **"Statistical Scale of Entropic Effects,"** i.e., the classical entropy structure field that serves as the background for quantum measurement.

Based on this qualification, the core thesis of this paper is: The mystery of quantum entanglement can be fully understood as the inevitable deterministic consequence of the interaction between a **particle (a low-entropy structure emerging at the "Particle-Scale")** and the universal entropy field at its **"Microscopic Scale of Entropic Effects" (influencing its creation)** and its **"Statistical Scale of Entropic Effects" (influencing its measurement)**.

2 The Ontology of Entropy — A Multi-Scale Effective Field

2.1 Fundamental Postulate: Computational Entropy as the Sole Reality

The cornerstone of our theory is that the ultimate measure of reality is **Computational Entropy (Kolmogorov Complexity, S_C)**. It measures the incompressibility of a pattern.

2.2 Application of the Renormalization Idea: From the Fundamental Field to the Effective Field

In order to study a discrete, fine-grained field defined at the bit-scale using continuous mathematics, we must define effective scales. Therefore, the core methodology of our theory is the application of a widely validated idea in physics—**Renormalization**. It is the bridge connecting our universe's discrete computational substrate with continuous mathematical methods.

2.3 The Flow of Scales: Construction of the Effective Entropy Field

We physicalize computational entropy as a discrete, fine-grained **fundamental entropy tensor field** $\Sigma_0(P)$ at the **bit-scale**. This is the ontological cornerstone of our theory, the sole source of all higher-level physical realities. Any given physical process only interacts with an **"effective entropy field"** $\Sigma_{\text{eff}}(P; \lambda)$, which is formed from $\Sigma_0(P)$ through a **"renormalization transformation" (i.e., coarse-graining and redefinition of parameters)** at an **"effective scale"** λ defined by the process's "intrinsic scale" (or observational energy).

2.4 The Effective Field of Focus in This Paper: $\Sigma(P)$ and its Multipole Structure

This paper aims to explain gravity and quantum measurement, both of which are phenomena that occur at the **statistical scale**. Therefore, we focus on the effective entropy field at this scale, which, for the sake of simplicity, we denote as $\Sigma(P)$. We perform a **Multipole Expansion** on this emergent effective entropy field $\Sigma(P)$ at the statistical scale to analyze the different aspects (moments) of its geometric structure. These "moments" correspond to the different macroscopic physical phenomena we observe:

- **Zeroth-Order Moment (Monopole Moment):** The **scalar trace** $\sigma(P)$ of the effective entropy tensor field $\Sigma(P)$, which is the **effective entropy density**. Its physical effect is to determine the "computational viscosity" of spacetime, thereby giving rise to **gravitational time dilation**.
- **First-Order Moment (Dipole Moment):** The **first-order covariant derivative** of the effective entropy tensor field $\Sigma(P)$, whose simplest component is the **vector gradient** $\nabla\sigma$. Its physical effect is to generate an "entropic pressure differential," thereby giving rise to **gravity** itself.
- **Second- and Higher-Order Moments (Quadrupole Moment, etc.):** The higher-order derivatives and intrinsic algebraic properties of the effective entropy tensor field $\Sigma(P)$, which describe its local **anisotropy**. We assert that this "anisotropy" of $\Sigma(P)$ is precisely the physical entity of the **"super-deterministic" field** that serves as the background for quantum measurement.

3 The Entropic Dynamics of Quantum Events

This chapter will provide a unified description of the two phases of a quantum event, attributing both to the interaction of particles with the "structure of entropy."

3.1 The Ontology of a Particle: A Stable "Low-Entropy Topological Structure"

A fundamental particle (such as an electron) is an **"spacetime vortex"** (information soliton) with a fixed intrinsic structure and low entropy. All its quantum numbers (charge, spin, etc.) are manifestations of its unique **"low-entropy topological form"**.

3.2 The "Creation" of Entanglement: Coupling with the "Microscopic Structure" of Entropy

- **Mechanism:** In the event of particle pair creation, the two nascent "low-entropy topological structures" undergo a profound **coupling** with a **high-frequency, complex "entropy field fluctuation"** that is microscopic in the local spacetime.
- **Consequence:** This coupling process, like an "entropic mold," **"forges"** the "low-entropy topological forms" of these two particles to be perfectly complementary, and "locks" their states to that **specific, yet unknowable to any local observer**, microscopic entropy fluctuation.
- **Source of Randomness:** The unknowability of the **"microscopic structure" of entropy** at the moment of creation endows the particle pair with a definite, yet unknown, initial state.

3.3 The "Measurement" of a Quantum State: Alignment with the "Macroscopic Structure" of Entropy

- **Mechanism:** A measurement apparatus forces the already "forged" particle to undergo a **"structural alignment"** between its own **"intrinsic low-entropy topological form"** and the **"macroscopic entropy structure" (i.e., the background field $\Sigma(P)$)** of the apparatus's environment.
- **Consequence:** The measurement outcome is the **deterministic** output of this "structural alignment" that corresponds to the lowest energy state (e.g., "up" or "down").
- **Source of Determinism:** The measurement is based on the macroscopic, slowly varying entropy field environment, rendering its outcome deterministic.

3.4 The Essential Unity of Measurement and Creation: A Scale Emergence from "1-to-2" to "1-to-N"

We assert that "measurement" is not a new physical process fundamentally different from "creation." Both are, in essence, the **same dynamics**—namely, **"Entanglement Spreading."**

- **Entanglement Creation ("1-to-2"):** The preparation of an entangled state is the "spreading" and **preparation** of a source quantum state into a **microscopic entangled state of 2 particles**. This is a **microscopic process where coherence can be tracked**.
- **Quantum Measurement ("1-to-N"):** A measurement, conversely, involves a microscopic system interacting with a macroscopic apparatus composed of $N \approx 10^{23}$ **particles**, causing its entangled state to **"avalanche-spread,"** thereby **giving rise to** a **classical macroscopic state composed of** 10^{23} **particles**.

The **"wave function collapse"** or the quantum-classical boundary is not a mysterious leap, but a fully physical, **statistics-based phase transition**. It marks the evolution of a system from a **"fluctuation-dominated" microscopic quantum state**, via **"entanglement spreading,"** to an **"average-dominated" macroscopic classical state**.

4 From Theory to Cosmology — The Origin and Properties of the Background Entropy Field

4.1 Origin of the Macroscopic Entropy Structure

The macroscopic entropy structure field $\Sigma(P)$, which serves as the background for measurement, emerges collectively from the contributions of all matter sources within its **entire past light cone**, via an **action integral**. The state of $\Sigma(P)$ encodes the complete history of the universe.

4.2 The Dual Dynamics of the Entropy Field

The dynamic evolution of the $\Sigma(P)$ field originates from two distinct types of physical processes:

- **Ordered "Mechanical" Effects: Periodic variations** caused by the collective motions of celestial bodies (rotation, revolution).
- **Disordered "Thermodynamic" Effects: Random variations** caused by the asymmetric distribution and motion of mass within celestial bodies (entropy increase).

4.3 Slow Spatial Variation and Signal-to-Noise Ratio

The dominant contributions that determine the value of $\Sigma(P)$ come from macroscopic celestial bodies (like the Earth and the Sun). This ensures that the $\Sigma(P)$ field is **highly spatially coherent** at the laboratory scale. The strength of the ordered effects (the signal), dominated by distant celestial bodies, far exceeds the random effects (the noise) caused by near-field matter. This **extremely high "signal-to-noise ratio"** is the foundation upon which the correlations of entanglement can be maintained.

5 A Decisive Physical Experiment

5.1 Experimental Objective

This experiment aims to go beyond Bell's theorem. Instead of verifying the correlations themselves, it seeks to **directly measure the coherence time τ_c of the universe's "macroscopic entropy structure field $\Sigma(P)$"**, i.e., how long the "memory" of this field can be maintained.

5.2 The a priori Prediction of the Theory: The Coherence Time of the Background Field $\Sigma(P)$

We must first clarify the physical sources of the dynamic changes in the $\Sigma(P)$ field. Since our laboratory is **co-moving** with the Earth itself, the Earth's rotation per se does not produce a directly measurable temporal variation within the laboratory. Therefore, the measurable variations of the $\Sigma(P)$ field must originate from two aspects: **external celestial bodies** (primarily the Sun and the Moon) and the **Earth's internal dynamics**.

1. **Periodic "Tidal" Effects:** Caused by the periodic motions (rotation and revolution) of the Earth relative to the Sun and the Moon. This is a **calculable and predominantly periodic "external" modulation**.

2. **Random "Geocentric" Effects:** Caused by the **internal, irreversible "thermodynamic entropy increase"** processes of the Earth (such as mantle convection), which lead to **random variations in the asymmetric "thermodynamic multipole moment"**. This constitutes an **unpredictable "internal" noise**.

The coherence time of entanglement, τ_c—whose reciprocal is the decoherence rate—will be dominated by whichever of these two effects is **stronger, faster-changing, and more random**. Based on physical estimations, the period of variation for the tidal effects caused by the Sun and the Moon is **extremely macroscopic** (hours/days/months). Meanwhile, the characteristic timescale for the macroscopic multipole moment variations caused by the Earth's internal thermodynamic processes is also considered to be **extremely slow** (on geological timescales).

From this, our theory makes a final core prediction, based on an analysis of the physical mechanisms:

Whether it is the external "tidal" effects or the internal "geocentric" effects, the characteristic timescales driving the changes in the $\Sigma(P)$ field are all extremely macroscopic. Therefore, we predict that in the "time-delayed entanglement experiment" described below, the $\Sigma(P)$ field will appear to be extremely stable, and its coherence time, τ_c, will be a very long, macroscopic timescale.

5.3 Experimental Method: Time-Delayed Entanglement Correlation Measurement with a "Zero-Delay" Control Group

The core of this experimental design is to alternate between two different measurement modes within the same experimental setup, in order to **precisely separate the true physical effect from experimental systematic errors**.

- **Experimental Group:** Alice measures at time t_A, and Bob measures at time $t_B = t_A + \Delta t$, to measure the entanglement strength as it evolves with the cosmic background field over time.
- **Control Group:** Alice and Bob conduct a measurement **simultaneously** at time $t+\Delta t$, to calibrate the systematic error of the experimental apparatus itself that arises with the delay Δt.

5.4 The Experimental Conclusion and the Ultimate Adjudication of Our Theory

The resulting pure physical correlation decay curve $C(\Delta t)$ will provide a **unique and decisive adjudication** for our theory. Based on our analysis, derived from first principles (the equivalence principle, entropic dynamics), that "the $\Sigma(P)$ field is absolutely dominated by Earth's macroscopic dynamics," our theory makes only **one** core prediction. Therefore, there are only two possible outcomes for the experiment:

- **Possible Outcome One: Confirmation of the Theory ($C(\Delta t)$ decays slowly)**
  - **Observation:** The experiment observes that the correlation $C(\Delta t)$ shows **almost no measurable decay** over timescales of hours, days, or even longer (τ_c is extremely long). Within the measurable range of Δt, the curve is **approximately a flat line**.
  - **Theoretical Adjudication:** This would constitute an **extremely powerful and decisive confirmation** of our entire theoretical framework—from the ontology of the entropy field, to the super-deterministic mechanism, and to the final inference that the $\Sigma(P)$ field is dominated by Earth's dynamics. It would prove that the

background for quantum phenomena in our universe is indeed a stable, classical, and predictable macroscopic field, much like the geomagnetic field.

- **Possible Outcome Two: Falsification of the Theory ($C(\Delta t)$ decays rapidly)**
  - **Observation:** The experiment observes that the correlation $C(\Delta t)$ undergoes a **significant and reproducible decay** on **any macroscopic timescale shorter than "hours" (e.g., seconds or minutes)**.
  - **Theoretical Adjudication:** This would **irrefutably and decisively falsify** the core prediction of our theory and would likely mean that at least one of the following is true:
    1. Our inference that "the $\Sigma(P)$ field is dominated by Earth's macroscopic dynamics" is **incorrect**. There exists some unforeseen, more powerful, and faster-varying source of "noise."
    2. Our entire theoretical model of the "macroscopic entropy structure field" is fundamentally **incorrect** or **incomplete**.
    3. The nature of quantum entanglement follows a physical mechanism entirely different from the one we have proposed.

6 Conclusion — Physics as "The Structural Geometry of Entropy"

We have proposed a unified, deterministic model of quantum entanglement based entirely on "structured entropy." In this model, the mysteries of the quantum world—including its probabilistic nature, non-local correlations, and "measurement collapse"—are reduced to a more profound and physical unified process: **the dynamic interaction between matter (as a stable, low-entropy topological structure) and the universal entropy field at different structural scales.**

- The **creation** of entanglement is the process by which particles are "forged" in the **microscopic structure (small-scale fluctuations)** of entropy, which injects "unknowable order" into them.
- The **measurement** of entanglement is the process by which this particle's state is "read out" against the **macroscopic structure (large-scale fluctuations)** of entropy, a statistics-based phase transition from the "microscopically unknowable" to the "macroscopically definite."

This perspective ultimately transforms the core questions of quantum mechanics into the study of a **single, yet infinitely complex, physical entity—the universal entropy field**. We no longer merely ask "What exists?" but rather, "What structure does that which exists (entropy) possess?"
Thus, our theory points to a completely new picture: **Gravity and quantum entanglement are, in essence, different manifestations of "The Structural Geometry of Entropy."**
The significance of our proposed "time-delayed entanglement experiment" therefore becomes immensely profound. It is no longer just a test of a specific model of entanglement; it is **using the most precise "probe" of quantum phenomena to directly measure the dynamic properties of the universe's most grand "entropic structure."** This experiment will deliver the final, decisive verdict on this path of exploration that unifies quantum information, gravitational physics, and cosmology under the central problem of "the structural scales of entropy."