Information-Copying Cosmology (ICC): Percolation-Induced Quantum-to-Classical Transition

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Abstract

The quantum measurement problem arises from the coexistence of unitary evolution and non-unitary collapse. Here we propose a dynamical framework — **Information-Copying Cosmology (ICC)** — in which collapse is not a fundamental postulate but an emergent phenomenon. Starting from a basis-dependent broadcasting channel, we derive a Lindblad-type master equation with rates that depend on the connectivity of an underlying information-copying network. When the copying density exceeds a critical threshold, the network percolates, and a giant connected component emerges. We show that the effective decoherence rate becomes proportional to the relative size of this giant component, identifying classicality as a percolation order parameter. The ICC model predicts critical slowing down with universal exponents ($\nu \approx 0.876$, $\beta \approx 0.418$ in 3D) and a power-law scaling of interference visibility with system size near the critical point, which is distinct from standard exponential decoherence. A concrete experimental protocol using trapped ions is proposed. Finally, a speculative extension to black hole horizons suggests a percolation-based mechanism for information retention within the ICC framework.

I. INTRODUCTION

The quantum measurement problem remains one of the deepest conceptual challenges in modern physics. Standard quantum mechanics provides two distinct dynamical rules:

- **Unitary evolution** described by the Schrödinger equation, which is deterministic, reversible, and linear.
- **Collapse postulate** (von Neumann / Born rule), which is probabilistic, irreversible, and non-linear.

No first-principles criterion specifies when to apply which rule. This logical gap prevents quantum mechanics from being a truly closed physical theory without invoking an external observer.

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A. Existing Approaches and Their Limitations

Decoherence theory [1, 2] explains the rapid suppression of off-diagonal density matrix elements through entanglement with environmental degrees of freedom. It successfully predicts the emergence of a preferred pointer basis. However, decoherence alone does not solve the measurement problem: it converts a superposition into an improper mixture, but does not explain why a *single* outcome is realized in an experiment. The off-diagonal terms become small but never strictly zero.

Spontaneous collapse models [3–5] modify the Schrödinger equation with stochastic non-linear terms. These models eliminate the measurement problem by construction but introduce phenomenological parameters (collapse rate λ_{GRW}, localization scale r_c) with no derivation from first principles.

Many-worlds interpretations avoid collapse entirely by positing that all outcomes coexist in a branching multiverse. While logically consistent, they struggle to provide a dynamical criterion for when branching occurs or how probabilities emerge in a strictly deterministic framework.

B. The Information-Copying Cosmology (ICC) Framework

This paper develops an alternative approach rooted in the observation that classical reality is characterized by the *redundant copying of information.* This insight is central to Quantum Darwinism [6–8], which explains the objectivity of classical reality through redundant information storage in the environment.

The core hypothesis of **Information-Copying Cosmology (ICC)** is:

> The emergence of classical behavior is not a mysterious collapse but a **phase transition** in the network of information-copying processes. A system behaves classically if and only if the copying of its state has reached a percolation threshold — that is, if there exists a giant connected component of degrees of freedom that have mutually copied information about the system.

This proposal transforms the measurement problem from a foundational puzzle into a problem of **statistical physics** and **network theory**.

C. Key Ideas of the Present Work

We construct a concrete dynamical model realizing the ICC hypothesis:

1. **Microscopic copying channel.** We define a CPTP map $\mathcal{E}_{\text{copy}}$ describing a single copying event in a preferred basis $\{|i\rangle\}$. The Kraus operators are $K_{ij} = \sqrt{\gamma_{ij}}|i\rangle\langle j|$, with $\sum_i \gamma_{ij} = 1$. This represents basis-dependent broadcasting, consistent with the no-cloning theorem.

2. **Continuous-time Lindblad generator.** By taking the limit of rare copying events, we derive a master equation $\dot{\rho} = -i[H, \rho] + \lambda(\mathcal{E}_{\text{copy}}(\rho) - \rho)$, where λ is the copying rate.

3. **Network dependence and emergent non-linearity.** The copying rate λ depends on the connectivity of an underlying information-copying graph G. This dependence arises from a mean-field coarse-graining of the total system+environment evolution. The resulting effective master equation is state-dependent and non-linear — an emergent property, not a fundamental violation of quantum mechanics.

4. **Percolation transition.** When the copying density exceeds a critical threshold p_c, the graph G develops a **giant connected component** containing the system.

5. **Decoherence as order parameter.** We show that the effective decoherence rate becomes $\Gamma_{\text{dec}} = \Gamma_0 \cdot (C_{\text{giant}}/N)$, where C_{giant} is the size of the giant component. This identifies classicality as an emergent order parameter.

6. **Testable predictions.** The ICC model predicts critical slowing down, power-law scaling of visibility near the critical point, and finite-size scaling collapse.

II. MODEL: INFORMATION-COPYING DYNAMICS

A. Copying Channel

Let the system be described by a density matrix ρ in a preferred basis $\{|i\rangle\}$ selected by the environment (pointer basis). We define the copying channel:

$$\mathcal{E}_{\text{copy}}(\rho) = \sum_{i,j} K_{ij} \rho K_{ij}^{\dagger}, \tag{1}$$

with Kraus operators:

$$K_{ij} = \sqrt{\gamma_{ij}}\,|i\rangle\langle j|, \quad \gamma_{ij} \geq 0. \tag{2}$$

Trace preservation requires:

$$\sum_{i,j} K_{ij}^{\dagger} K_{ij} = \sum_{j} \left(\sum_{i} \gamma_{ij} \right) |j\rangle\langle j| = I, \tag{3}$$

hence the normalization condition:

$$\boxed{\sum_{i} \gamma_{ij} = 1 \quad \forall j.} \tag{4}$$

Physically, population in $|j\rangle$ is redistributed among $|i\rangle$ according to probabilities γ_{ij} — a basis-dependent broadcasting of information.

B. Continuous-Time Limit

Let copying events occur with rate λ (dimensions T^{-1}). Over a short time interval Δt, the system evolves as:

$$\mathcal{E}_{\Delta t} = (1 - \lambda \Delta t) I + \lambda \Delta t\, \mathcal{E}_{\text{copy}}. \tag{5}$$

In the limit $\Delta t \to 0$, we obtain the generator:

$$\mathcal{L}_{\text{copy}} = \lim_{\Delta t \to 0} \frac{\mathcal{E}_{\Delta t} - I}{\Delta t} = \lambda(\mathcal{E}_{\text{copy}} - I). \tag{6}$$

The full master equation including Hamiltonian evolution is:

$$\boxed{\dot{\rho} = -i[H, \rho] + \lambda\big(\mathcal{E}_{\text{copy}}(\rho) - \rho\big).} \tag{7}$$

This is a Lindblad-type generator *derived* from a CPTP map, not postulated ad hoc.

C. Consistency with No-Cloning

The copying channel is **not** a universal cloning map. It implements *basis-dependent broadcasting*: only information encoded in the preferred basis $\{|i\rangle\}$ is redundantly propagated. This is consistent with the no-cloning theorem because the environment is initialized in a fixed state, and the copies exist only as correlations, not as independent clones of arbitrary superpositions.

III. EMERGENT NONLINEARITY FROM NETWORK DEPENDENCE

A. Underlying Linear Dynamics and Mean-Field Factorization

At the fundamental level, the combined system (system + environment) evolves under a linear CPTP map: $\dot{\rho}_{\mathrm{tot}} = \mathcal{L}_{\mathrm{tot}}[\rho_{\mathrm{tot}}]$.

To obtain a closed equation for the system alone, we make a **mean-field approximation**:

$$\rho_{\mathrm{tot}}(t) \approx \rho_S(t) \otimes \rho_E[\rho_S(t)], \tag{8}$$

where the environment state ρ_E depends *functionally* on the system state ρ_S due to the continuous copying of system information into the environment. This is analogous to the Hartree approximation in many-body physics or the Born approximation in open quantum systems.

B. Justification of the Mean-Field Approximation

This factorization is justified in the regime of *weak system-environment coupling* and a *large environment*. Specifically:

1. Each environmental subsystem interacts with the system via a weak copying channel with rate $\lambda \ll \omega_S$ (system characteristic frequency).

2. The environment contains $N \gg 1$ subsystems, each initially in a fiducial state $|0\rangle_E$.

3. After copying, system-environment entanglement remains small because the copying channel is basis-dependent and does not create superpositions of macroscopically distinct states.

Under these conditions, the environment acts as a *classical record* of the system's state, and back-action on the system is negligible at leading order.

Limitation: The mean-field approximation breaks down when system-environment entanglement becomes significant (e.g., near the percolation threshold for very small N). Finite-size corrections can be systematically included via cluster expansions, but are beyond the scope of this work.

C. Connectivity-Dependent Rates

Under the mean-field approximation, the effective copying rate becomes state-dependent:

$$\lambda_{\text{eff}} = \lambda\big(C[\rho_S]\big), \tag{9}$$

where $C[\rho_S]$ is the size of the connected component in the information-copying graph, which depends on the system's state through the copying history. The reduced master equation becomes:

$$\dot{\rho}_S = -i[H, \rho_S] + \lambda\big(C[\rho_S]\big)\big(\mathcal{E}_{\text{copy}}(\rho_S) - \rho_S\big). \tag{10}$$

This equation is **nonlinear** in ρ_S due to the functional dependence $\lambda(C[\rho_S])$, even though the underlying dynamics is linear.

D. The Preferred Basis Problem

ICC assumes the existence of a preferred basis $\{|i\rangle\}$ in which copying occurs. This basis is typically selected by the system–environment interaction Hamiltonian — the **pointer basis** of standard decoherence theory [1].

Complementarity with decoherence theory: ICC does not *derive* the preferred basis from first principles; it *presupposes* it to keep the model tractable. However, once the basis is selected (by standard decoherence), ICC explains why superpositions in this basis irreversibly collapse — namely, when the copying network percolates. Decoherence selects the basis; ICC explains the irreversibility.

IV. INFORMATION PERCOLATION TRANSITION

A. Definition of the Copying Graph

We construct an undirected graph $G = (V, E)$ as follows:

- **Vertices** V: set of all relevant degrees of freedom (the system + N environmental subsystems).

- **Edges** E: an edge (i, j) exists if information has been successfully copied between i and j within a characteristic timescale τ_{copy}.

The per-edge probability per time step Δt is $p_{\text{copy}} = 1 - e^{-\lambda_{\text{local}}\Delta t}$, where λ_{local} is the local copying rate.

B. Percolation Threshold and Order Parameter

A **giant connected component** emerges when $p_{\text{copy}} > p_c$. For 3D spatial networks (natural dimensionality of local interactions), $p_c \approx 0.3116$ (site percolation on a cubic lattice). For Erdős–Rényi random graphs (mean-field limit), $p_c^{(\text{ER})} = 1/(N-1)$.

Define the percolation order parameter:

$$P_\infty(p) = \lim_{N\to\infty} \frac{\langle C_{\text{giant}}\rangle}{N}. \tag{11}$$

Near the critical point, $P_\infty(p) \sim (p - p_c)^\beta$ for $p \to p_c^+$. For the 3D percolation universality class, $\beta \approx 0.418$ and $\nu \approx 0.876$.

C. Derivation of $\Gamma_{\text{dec}} \propto C_{\text{giant}}/N$

Consider a system coupled to N environmental qubits. The total microscopic copying rate is $\lambda_{\text{total}} = N\lambda_0$, where λ_0 is the single-qubit copying rate.

However, not all copies are independent. If the system belongs to a connected component of size C in the copying graph, the C qubits in this component share redundant information. The *effective number of independent copies* is determined by the information capacity of the component. For a connected graph with C vertices, the number of independent degrees of freedom scales as C (in the mean-field limit, where internal correlations are neglected).

Thus, the effective decoherence rate is:

$$\Gamma_{\text{eff}} = \lambda_0 \cdot \frac{C}{N} \cdot N = \Gamma_0 \cdot \frac{C}{N}, \tag{12}$$

where $\Gamma_0 = N\lambda_0$ is the maximum decoherence rate when all N qubits are independent (no percolation).

Physical interpretation:

- For $p < p_c$: $C \sim \log N \implies \Gamma_{\text{eff}} \sim \Gamma_0 \frac{\log N}{N} \to 0$ (coherence preserved in the thermodynamic limit).
- For $p > p_c$: $C \sim N \cdot P_\infty(p) \implies \Gamma_{\text{eff}} \sim \Gamma_0 \cdot P_\infty(p)$ (finite decoherence rate).

We can therefore write the central relation:

$$\boxed{\Gamma_{\text{dec}} = \Gamma_0 \cdot \frac{C_{\text{giant}}}{N} \cdot \Theta(p - p_c),} \tag{13}$$

where Θ is the Heaviside step function (smoothed near the critical point). The transition at $p = p_c$ marks the onset of *irreversible decoherence*.

D. Finite-Size Scaling

For finite system size N, the percolation transition is smoothed into a crossover. Using finite-size scaling theory:

$$\frac{C_{\text{giant}}(N,p)}{N} = N^{-\beta/\nu} \cdot f\big((p - p_c)N^{1/\nu}\big), \tag{14}$$

where f is a universal scaling function. For $N \sim 10$–100 (accessible in trapped-ion experiments), this scaling function can be precomputed numerically.

V. EXPERIMENTAL PREDICTIONS

A. Interference Visibility

For a superposition state $|\psi\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$, the visibility after time t is $V(t) = |\rho_{01}(t)|$. Within the ICC framework:

$$V(t) = \exp\left(-\frac{\Gamma_{\text{eff}}}{2}t\right) = \exp\left(-\frac{\Gamma_0}{2} \cdot \frac{C_{\text{giant}}}{N} \cdot t\right). \tag{15}$$

B. Power-Law Scaling and Distinction from Standard Decoherence

In a typical experimental setup, the copying probability p is controlled by the interaction strength. To observe the transition, we consider tuning the system to reach the critical point at a specific system size N_c, such that $p(N_c) = p_c$. Near this critical point, $P_\infty(p(N)) \sim |N - N_c|^\beta$.

Thus, for fixed evolution time t:

$$V(N) \approx 1 - \text{const} \cdot |N - N_c|^\beta \quad \text{for } N \approx N_c. \tag{16}$$

Model	**Visibility decay**	**Signature**
Standard decoherence	$V \sim e^{-\Gamma N t}$	Exponential in N
ICC (general)	$V \sim \exp(-\Gamma_0 t \cdot P_\infty(p))$	Phase transition at p_c
ICC (near critical N_c)	$V \sim \exp(-\text{const} \cdot \lvert N - N_c\rvert^\beta)$	Power-law near N_c

TABLE I. Comparison of visibility decay signatures.

Test: Measure $V(N)$ for fixed t. Standard decoherence gives $-\ln V \propto N$. ICC gives $-\ln V \propto P_\infty(N) \sim (N - N_c)^\beta$ near the critical point — a markedly different functional form.

C. Experimental Protocol for Trapped Ions

Setup. A single trapped ion (system qubit) is coupled to N identical ions (environment) via laser-induced dipole–dipole interactions. The ions are confined in a linear Paul trap. The qubit states $\{|0\rangle, |1\rangle\}$ are encoded in long-lived hyperfine ground states.

Control parameter. The copying probability p is tuned by varying the interaction time τ_{int} or the laser intensity I:

$$p = 1 - e^{-\kappa I \tau_{\text{int}}}, \tag{17}$$

where κ is a coupling constant determined by the dipole matrix element d_{01}, the laser detuning Δ, and the spontaneous emission rate γ: $\kappa \sim |d_{01}|^2/(\hbar^2\Delta^2) \cdot \gamma$.

For typical parameters in $^{171}\text{Yb}^+$ ions ($d_{01} \sim 10^{-29}\,\text{C}\cdot\text{m}$, $\Delta \sim 2\pi \times 10\,\text{GHz}$, $\gamma \sim 2\pi \times 20\,\text{MHz}$), we estimate $\kappa \sim 10^{-3}\,\text{W}^{-1}\text{s}^{-1}$. Thus, for laser intensity $I \sim 1\,\text{W/m}^2$ and interaction time $\tau_{\text{int}} \sim 1\,\text{ms}$, we obtain $p \sim 10^{-3}$, which is in the weak-copying regime suitable for observing the percolation transition.

Measurement protocol.

1. Prepare the system ion in a superposition state $|\psi\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$.

2. Turn on the coupling laser for a controlled time τ_{int}, allowing copying interactions with the N environment ions.

3. After evolution time t, perform Ramsey interferometry to extract the visibility $V(t)$.

4. Repeat for different values of N (e.g., 5, 10, 20, 50) and different interaction times τ_{int} (tuning p).

Current trapped-ion experiments can achieve $N \sim 10$–50 environment ions with high-fidelity control [9, 10]. The required coherence times ($\sim 100\,\mu$s to $10\,$ms) are routinely achieved, making this proposal feasible with current technology.

VI. OUTLOOK: BLACK HOLES AS A PERCOLATION SURFACE (SPECULATIVE)

The ICC framework naturally extends to horizons, where the local copying density $\lambda(r)$ may reach criticality. If the horizon forms a 2D surface with a null direction, the effective dimensionality of the information network is $d_{\text{eff}} = 3$. This suggests that information about infalling matter is copied into a giant connected component on the horizon. This provides a speculative resolution of the black hole information paradox without violating unitarity: information is not lost but stored in the percolated horizon network and later released during evaporation. A detailed analysis, including reconciliation with the fast scrambling bound ($t_{\text{scramble}} \sim M \log M$ vs. ICC's $t_{\text{scramble}} \sim M^{\nu/d_f}$), is left for future work (see companion paper in preparation).

VII. DISCUSSION

A. Relation to Other Interpretations

Interpretation	**Status of collapse**	**ICC contribution**
Copenhagen	Postulated	Provides dynamical mechanism
Many-worlds	No collapse (branching)	Criterion for irreversible branching
Bohmian mechanics	No collapse (hidden variables)	No hidden variables; effective collapse
GRW / CSL	Stochastic collapse (free parameters)	Derives collapse rate from connectivity
ICC (this work)	Emergent from percolation	Phase transition, critical exponents

TABLE II. Comparison of ICC with other quantum interpretations.

Key distinguishing features of ICC are: (1) the collapse rate is derived from network connectivity, not introduced as a free parameter; (2) it predicts universal scaling with testable critical exponents; (3) it requires no observer; and (4) it is complementary to decoherence theory.

B. Does ICC Solve the Measurement Problem?

A natural objection is that ICC merely reformulates decoherence without addressing why a single outcome is realized.

Response: Standard decoherence converts a pure state into an **improper mixture**, where off-diagonal terms become small but never strictly zero. ICC goes further through the **percolation transition**. Above the threshold ($p > p_c$), the system becomes part of a **giant connected component** of copies. Within this component, all copies are correlated and "agree" on a single classical state. From the perspective of any observer who is also part of this component, the system is in a *definite* classical state. This is analogous to spontaneous symmetry breaking in statistical mechanics, where a definite order parameter is selected.

Caveat regarding probabilities: The copying channel $\mathcal{E}_{\text{copy}}$ is constructed to be consistent with the Born rule at the microscopic level. Specifically, the Kraus operators are chosen such that the probability of copying state $|j\rangle$ to $|i\rangle$ aligns with $|\langle i|\psi\rangle|^2$ for an initial state $|\psi\rangle$. ICC assumes the Born rule as input and explains the *irreversibility* of outcome selection, not the fundamental origin of probabilities themselves. Whether this constitutes a full "solution" to the measurement problem depends on one's philosophical stance, but it undeniably provides a dynamical, testable mechanism for the emergence of classical reality.

VIII. CONCLUSIONS

We have constructed a dynamical model in which the quantum-to-classical transition arises from a percolation transition in an information-copying network. Starting from a CPTP copying channel, we derived an effective Lindblad master equation with state-dependent rates. When the copying density exceeds a threshold, a giant connected component emerges, and the decoherence rate becomes proportional to the relative size of this component — identifying classicality as an order parameter.

Key predictions include critical slowing down with $\nu \approx 0.876$, power-law scaling of visibility near the critical point, and a clear distinction from exponential decoherence. Experimental tests are feasible with trapped ions, cold atoms, or superconducting qubits. If confirmed, ICC would transform the measurement problem from a conceptual puzzle into a domain of statistical physics.

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DATA AVAILABILITY

The Python code for numerical simulations of the finite-size scaling is available at `https://github.com/yourusername/icc-percolation` (to be made public upon publication) and archived on Zenodo.

Appendix A: Numerical Scheme for Finite-Size Scaling

The following algorithm can be used to compute $V(N)$ for finite N:

1. Choose total number of nodes $N_{\text{tot}} = N + 1$ (system + environment).

2. Choose edge probability p (controls copying density).

3. Generate an Erdős–Rényi graph $G(N_{\text{tot}}, p)$.

4. Identify the connected component containing the system node. Let C be the size of that component.

5. Compute effective decoherence rate: $\Gamma_{\text{eff}} = \Gamma_0 \cdot C/N_{\text{tot}}$.

6. Compute visibility: $V = \exp(-\Gamma_{\text{eff}} t)$ for fixed t.

7. Repeat for many graph realizations (typically 10^3–10^4) and average $\langle V \rangle$ as a function of p and N.

Expected results:

- For $p < p_c$: $C \sim \log N_{\text{tot}} \implies V \approx 1$ (coherence preserved).
- For $p > p_c$: $C \sim N_{\text{tot}} \cdot P_\infty(p) \implies V \sim \exp(-\text{const} \cdot N_{\text{tot}})$ (exponential decay).
- At $p = p_c$: $V \sim \exp(-\text{const} \cdot t \cdot N_{\text{tot}}^{-\beta/\nu})$ (anomalous scaling).

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