The Attralucian Essays: Exploring the Finite

First Edition

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Quantum Decoherence and Classicality: A Geofinitist Reinterpretation

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Overview

Quantum decoherence describes how interactions with an environment suppress quantum coherence, leading to the emergence of classical behavior. While widely accepted as a key mechanism in the quantum-to-classical transition, decoherence does not by itself resolve foundational questions such as outcome selection or the measurement problem.

This paper does not propose a new interpretation of quantum mechanics. Instead, it offers a Geofinitist reinterpretation: decoherence is treated as an *operational, measurable phenomenon*, grounded in finite systems, uncertainty, and reproducible experimental procedures. Classicality is reframed as a *stability band*—a regime in which coherence is suppressed, records become redundant, and quantum effects are no longer recoverable within experimental limits.

From Idealised Dynamics to Measured Processes

Standard quantum theory models systems in a Hilbert space with density operators ρ evolving under unitary or open-system dynamics. These models are powerful abstractions. However, experimental access is always finite:

- states are reconstructed via tomography with uncertainty,
- dynamics are inferred from finite data,
- measurements are coarse-grained and noisy.

Geofinitism treats these limitations not as imperfections, but as defining features of the problem.

Geofinitist Principles Applied

1. Finite Container Space

Hilbert-space models provide a continuous, often high-dimensional description. In practice, experiments probe finite subspaces determined by preparation, measurement, and energy constraints. Observed dynamics are therefore trajectories within a finite, measurable container.

2. Measurement and Uncertainty

Quantum states are not directly accessible. They are reconstructed as measured objects:

$$\rho_t^{\mathbb{M}} = (\rho_t, \varepsilon_{\rho,t}),$$

with uncertainties arising from sampling noise, calibration error, and finite statistics.

3. Layered Emergence

Classical behavior does not arise in a single step. It emerges through a cascade:

- microscopic quantum dynamics,
- interaction with environment,
- formation of macroscopic records,
- observation and interpretation.

4. Contextual Validity

Concepts such as "wavefunction collapse" or "preferred basis" depend on experimental context. Geofinitism treats them as operational constructs, defined by measurement and stability rather than metaphysical necessity.

5. Finite Constraints

All observations occur under finite time resolution, energy bounds, and measurement precision. Continuous-time and infinite-precision descriptions are limiting abstractions.

Operational Decoherence

Let $\rho_t^{\mathbb{M}}$ be a measured density operator at time t, and $\Lambda_{\Delta t}^{\mathbb{M}}$ a measured dynamical map.

Define coherence relative to a basis $B = \{b_i\}$:

$$C_B(t) = \sum_{i \neq j} |\rho_t^{(ij)}| \;\pm\; \varepsilon_{C,t}.$$

Define a basis-invariant alternative via relative entropy:

$$C_{\text{rel}}(t) = S(\rho_t^{\text{diag}}) - S(\rho_t) \;\pm\; \varepsilon_{S,t}.$$

Pointer Basis Selection

Rather than assuming a preferred basis, we define it operationally.

Let B be a candidate basis. Define a robustness functional:

$$\mathcal{R}(B) = \mathbb{E}_{t \in \mathcal{T}} \left[\sum_i \text{Var}_t(b_i \rho_t b_i) - \lambda \sum_{i \neq j} |\rho_t^{(ij)}|^2 \right].$$

The pointer basis $B^\star$ maximizes $\mathcal{R}(B)$ within measurement tolerances.

Operational Decoherence Criterion

Fix thresholds (τ_C, τ_S) and a time window $\mathcal{W}$.

A system is said to decohere in basis B over $\mathcal{W}$ if:

$$\max_{t\in\mathcal{W}} C_B(t) \lesssim \tau_C, \quad \max_{t\in\mathcal{W}} C_{\mathrm{rel}}(t) \lesssim \tau_S.$$

Environmental Redundancy and Classicality

Let $\{E_k\}$ be environmental fragments. Define redundancy:

$$\mathcal{R}_O(t) = \left|\{k : I_{\mathbb{M}}(O : E_k)_t \geq \iota\}\right|,$$

where $I_{\mathbb{M}}$ is measured mutual information.

Large redundancy indicates the emergence of objective classical records.

Recoverability and Irreversibility

Define recoverability under intervention:

$$\mathsf{Rec}(\Delta) = F(\rho_t, \rho_{t+\Delta}^{\mathrm{echo}}) \ \pm\ \varepsilon_{\mathrm{rec}}.$$

- High recoverability $\Rightarrow$ reversible coherence loss,

- Low recoverability $\Rightarrow$ effective decoherence.

Classicality Band

Classical behavior is defined as a stability regime where:

- coherence is suppressed ($C_B \leq \tau_C$),
- observables are stable,
- environmental redundancy is high,
- recoverability is low.

If these conditions are not jointly satisfied within uncertainty bounds, the system is classified as INDETERMINATE.

Interpretation

In this framework:

- Decoherence is not a metaphysical collapse,
- Classicality is not a binary event,
- Measurement is a finite, auditable process.

Quantum-to-classical transition is thus a measurable pattern of:

- coherence suppression,
- basis stability,
- redundancy of records,

- irreversibility under intervention.

Conclusion

The standard theory of decoherence remains intact as an abstract framework. Geofinitism reframes it within finite, measurable regimes.

This yields a practical methodology: identify classical behavior through measurable thresholds, robustness criteria, and reproducible experiments, without committing to a particular interpretation of quantum mechanics.

Context. Decoherence is treated as an operational phenomenon: suppression of coherence, stabilization of basis, and emergence of classical records under finite measurement conditions.

Measured States.

$$\rho_t^{\mathbb{M}} = (\rho_t, \varepsilon_{\rho,t})$$

Measured Dynamics.

$$\Lambda_{\Delta t}^{\mathbb{M}} = (\Lambda_{\Delta t}, \varepsilon_{\Lambda})$$

Coherence.

$$C_B(t) = \sum_{i \neq j} |\rho_t^{(ij)}|$$

Decoherence Criterion.

$$C_B(t) \leq \tau_C, \quad C_{\mathrm{rel}}(t) \leq \tau_S$$

Pointer Basis.

$$B^\star = \arg\max_B \mathcal{R}(B)$$

Redundancy.

$$\mathcal{R}_O(t) = |\{k : I(O : E_k) \geq \iota\}|$$

Recoverability.

$$\mathsf{Rec}(\Delta) = F(\rho, \rho^{\mathrm{echo}})$$

Decision. Classicality holds within tolerance; otherwise abstain.