Saturated Entanglement as the Interface Transition Criterion

Author: James (JD) Longmire **ORCID:** 0009-0009-1383-7698 **Status:** Final Draft for Review **Version:** 2.10 **Date:** 2025-12-04 **Context:** Proposed physical criterion for the LRT interface (IIS → Boolean Actuality)

Abstract

Logic Realism Theory (LRT) identifies the quantum-to-classical transition as an interface between non-Boolean possibility (IIS) and Boolean actuality, but leaves the precise physical criterion for this transition as an open empirical question. This document proposes a specific criterion: the interface transition completes when (C1) system-environment entanglement entropy reaches a stable plateau near its maximum, AND (C2) pointer-basis coherences are irretrievably suppressed. This "plateau-plus-pointer" criterion builds on standard decoherence theory without adding new physics, provides testable predictions, and has survived initial theoretical evaluation.

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1. The Hypothesis

1.1 The Problem

LRT's main paper identifies the interface criterion as an open question: > "The precise physical criterion marking the interface (decoherence threshold, gravitational criterion, information-theoretic saturation) remains an empirical question."

This document proposes a specific answer.

1.2 The Criterion (Dual Condition)

The interface transition completes when two conditions are jointly satisfied:

> **(C1) Entropy Saturation:** The von Neumann entropy of the reduced system state reaches a dynamically stable plateau near its maximum:
>
> $$S(\rho_{\text{system}}) \geq \log(d) - \epsilon$$
>
> where d is the system Hilbert space dimension and ε is determined by environment structure and conservation laws.
>
> **(C2) Pointer-Basis Decoherence:** Coherences in the pointer basis are irretrievably suppressed:
>
> $$|\rho_{ij}^{\text{pointer}}| < \delta \quad \text{for } i \neq j$$
>
> with no recoherence on operationally relevant timescales.

1.3 Why Two Conditions?

Condition Alone	Problem
C1 only	High entropy doesn't guarantee pointer-basis structure; system could be maximally mixed in the "wrong" basis
C2 only	Pointer decoherence could occur with residual entanglement permitting recoherence

Condition Alone	Problem
C1 + C2	Information has flowed to environment (C1) into stable Boolean records (C2)

1.4 Physical Interpretation

- **C1** measures global information export: how much of the system's distinguishability has been transferred to the environment
- **C2** ensures this information exists as stable, mutually exclusive records compatible with 3FLL enforcement
- **Together:** The interface occurs when all operationally accessible interference between outcome branches has vanished and cannot return

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2. Theoretical Basis

2.1 LRT Framework

In Logic Realism Theory: **- IIS** (Infinite Information Space): Contains non-Boolean, indeterminate states; superpositions exist here **- Boolean Actuality**: Permits only determinate, 3FLL-compliant outcomes; measurement results exist here **- The Interface**: Mediates between these domains; where collapse/actualization occurs

The interface must enforce: 1. **Totality** (Excluded Middle): Every state yields a definite outcome 2. **Single-valuedness** (Non-Contradiction): No contradictory outcomes 3. **Exclusivity** (Identity): Each outcome is self-identical and distinct

2.2 Connection to Standard Decoherence

The plateau-plus-pointer criterion extends (not replaces) standard decoherence:

Decoherence Theory	This Hypothesis Adds
Environmental scattering suppresses off-diagonals	Completion criterion: when suppression is sufficient
Pointer states emerge via einselection	Explicit condition C2 on pointer coherences
Rate ∝ coupling × environment density	Time-to-threshold prediction: $\tau \propto 1/(g^2N)$
Asymptotic approach to classicality	Sharp(ish) threshold at plateau + decoherence

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3. Experimental Support

3.1 Decoherence Timescales (Joos & Zeh 1985)

Object	Environment	Decoherence Time
Dust grain (10^{-3} cm)	Air at STP	10^{-36} s
Dust grain (10^{-3} cm)	Laboratory vacuum	10^{-27} s
Dust grain (10^{-3} cm)	Interstellar space	10^{-18} s
Large molecule	Cosmic background radiation	10^{6} s
Electron	Air at STP	10^{-13} s

These timescales show decoherence rate scales with environmental density, consistent with $\tau \propto 1/(g^2N)$.

3.2 Haroche's Progressive Decoherence (1996)

Brune et al. directly observed progressive decoherence in cavity QED: - Created Schrödinger cat state (coherent field superposition) - Watched it decay into statistical mixture in real-time - Confirmed theoretical decoherence timescales

This demonstrates collapse is a process with measurable dynamics, not instantaneous.

3.3 Weak vs. Strong Measurement Crossover

Superconducting qubit experiments show:

Measurement Type	Coupling	Observed Behavior
Strong	High	Quantum jumps, definite states
Weak	Low	Stochastic trajectories, partial information
Very strong	Very high	Quantum Zeno freezing

This supports the prediction that measurement strength affects time-to-threshold.

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4. Testable Predictions

4.1 Entropy-Interference Correlation

Prediction: Interference vanishes when S(ρ_system) reaches the plateau near log(d), not before.

Test: In cavity QED or circuit QED: 1. Prepare superposition state 2. Allow controlled interaction with apparatus 3. Monitor both entanglement entropy and interference visibility 4. Correlate disappearance of interference with entropy saturation

Expected: Sharp correlation between S reaching plateau and interference vanishing.

4.2 Collapse Time Scaling

Prediction:

$$\tau_{\text{collapse}} \propto \frac{1}{g^2 N}$$

where g = coupling strength, N = apparatus degrees of freedom.

Test: Vary g systematically in cavity QED; measure time to definite outcome.

Expected: Doubling g should quarter collapse time.

4.3 Quantum Eraser Consistency

Prediction: Recoherence (quantum eraser) succeeds only when C1 or C2 is violated—i.e., before plateau is reached or before pointer records are stable.

Test: Attempt quantum eraser at various delays after measurement interaction.

Expected: Eraser succeeds for short delays (C2 not yet satisfied), fails for long delays (stable pointer records).

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5. Relationship to Other Approaches

Approach	Mechanism	Relationship to This Hypothesis
Decoherence (Zurek)	Environmental entanglement	We add completion criterion to their rate
GRW/CSL	Spontaneous localization (new physics)	We use only standard QM; no new dynamics
Penrose-Diósi	Gravitational self-energy	Could contribute to g in our $\tau \propto 1/g^2N$
Relational QM	Observer-relative facts	Compatible; interface is relational
QBism	Agent's beliefs update	Different; we claim ontic transition

Key distinction: We identify a threshold of standard quantum processes (entanglement + decoherence) as the interface criterion—no new physics required.

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6. Theoretical Evaluation Summary

The hypothesis was evaluated against known quantum information theory. Results:

6.1 Issues Addressed

Objection	Resolution
Page's theorem: Exact $S = \log(d)$ is measure-zero	Changed to plateau: $S \geq \log(d) - \varepsilon$
Classicality before max entropy	Added C2 (pointer decoherence) as independent condition
Entropy is basis-independent but pointers aren't	Hybrid criterion: global (C1) + local (C2)

6.2 Evaluator Verdict

> "Saturated entanglement + pointer suppression is a strong, consistent, and promising proposal for filling the one major gap LRT openly leaves—the concrete, physical interface rule."

6.3 Remaining Open Questions

1. **ε and δ values:** What sets these thresholds? Candidates: spectral gaps, recurrence times, information-theoretic bounds
2. **Continuous variables:** How to formulate for infinite-dimensional systems?
3. **Stability timescale:** What counts as "operationally relevant"? May be context-dependent
4. **Cut dependence:** Different system/environment splits may shift where conditions are satisfied

These are refinement issues, not fundamental problems.

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7. Summary

The Criterion

The LRT interface transition (IIS → Boolean Actuality) completes when:

C1: S(ρ_system) ≥ log(d) - ε (entropy plateau)

C2: |ρ_ij^pointer| < δ with no recoherence (pointer decoherence)

What It Explains

- Why definite outcomes occur (3FLL enforced when both conditions met)
- Why collapse time depends on measurement strength (affects time to plateau)
- Why weak measurements give partial collapse (conditions partially satisfied)
- Why quantum erasers work (conditions not yet fully satisfied)
- Why pointer basis is special (explicitly referenced in C2)

What It Predicts

- Threshold behavior at entropy plateau + pointer decoherence
- Collapse time $\tau \propto 1/(g^2N)$
- Testable in cavity QED, superconducting qubits, trapped ions

What It Doesn't Explain

- Why *this* outcome vs *that* (may be irreducibly stochastic)
- Precise values of ε and δ (may be context-dependent or require deeper theory)

Status

A mathematically coherent, experimentally testable, LRT-compatible hypothesis for the interface criterion. Ready for detailed theoretical modeling and experimental design.

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