The Measurement Problem (Technical)

Quantum Foundations · Module 10 — Foundations And Open Problems

Node 10.5

Position in Knowledge Graph

System: Quantum Foundations **Structural Domain:** Foundations and Open Problems **Node:** 10.5

This node is the technical companion to the framing lesson of 6.1. The measurement problem is the most persistent open question in quantum foundations: what happens when a measurement "occurs"? Why does a coherent superposition give way to a single observed outcome? Node 6.1 stated the problem structurally and introduced the vocabulary of interpretations. Node 10.5 equips itself with the results of the intervening modules — decoherence (10.4), no-go theorems (10.1, 10.2, 10.3), open-systems dynamics (8.x) — and asks what, precisely, remains unresolved, and what modern proposed solutions look like.

Formal Statement

The measurement problem decomposes into three distinct sub-problems, which are often conflated in introductory treatments but which have very different statuses:

Sub-problem 1: Preferred basis. Why does measurement pick out a particular observable to resolve, rather than an arbitrary basis of the system's Hilbert space? *Status:* Resolved by **einselection** (5.5). The system-environment coupling selects a pointer basis as the basis that is stable under interaction with the environment.

Sub-problem 2: Non-observation of macroscopic superpositions. Why are macroscopic "Schrödinger cat" states not observed? *Status:* Resolved by **decoherence** (10.4). Decoherence timescales for macroscopic objects are vastly shorter than any observational timescale, so macroscopic coherences are destroyed before they can be detected.

Sub-problem 3: Definite outcome selection. Why does any single run of an experiment produce one specific outcome, rather than the mixed ensemble of outcomes that the reduced density matrix describes? *Status:* **Unresolved.** The reduced density matrix $\rho_S = \sum_i p_i |i\rangle\langle i|$ represents a probabilistic mixture, but in a single run an observer sees a single i. The transition from "mixture over outcomes" to "one outcome" has no description within the unitary formalism.

The unresolved sub-problem 3 is what the contemporary literature calls "the measurement problem" in the strict sense. Modern proposed solutions fall into four classes:

1. **No-collapse** (MWI, Everett): there is no outcome selection; all branches are equally real. The appearance of a single outcome is subjective to each branch-local observer. Dispenses with the problem by denying its premise.
2. **Hidden variable** (Bohmian): the outcome is determined by a pre-existing hidden variable (particle position in configuration space). No physical collapse; the outcome is simply what the hidden variable always pointed to.
3. **Dynamical collapse** (GRW, CSL, Diósi, Penrose): modify the Schrödinger equation with a stochastic non-linear term that *localizes* wavefunctions at rates depending on mass/size. Makes the collapse a physical process subject to empirical test.

4. **Epistemic** (Copenhagen, QBism, Relational QM): the wavefunction is not a physical state but an agent's information or belief. Measurement is a Bayesian update, not a physical process. Empirical predictions are unchanged; the "problem" dissolves by reinterpretation.

Only option 3 makes experimentally distinct predictions from standard quantum mechanics and is therefore testable.

Intuition

The fundamental tension is this. The Schrödinger equation is deterministic and linear. If you feed it an initial superposition $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ and a measurement apparatus in state $|\text{ready}\rangle$, unitary evolution produces

$$|\Psi\rangle \to \alpha|0, \text{sees } 0\rangle + \beta|1, \text{sees } 1\rangle.$$

This is a superposition of two macroscopically distinct situations: the apparatus is in two configurations at once. Decoherence tells you that the two branches become dynamically uncorrelated and cannot interfere, but both branches are still in the wavefunction. The math never selects one.

Yet in the lab, you see one outcome per run. This is an empirical fact: the experimentalist records either 0 or 1, not both. The wavefunction "collapses" to a single branch — or something happens that acts like collapse.

The measurement problem asks: what is that something? The no-collapse view says "nothing — you're one of many observers, and each of you sees their own outcome." The hidden-variable view says "the outcome was always determined, you just didn't know it." The collapse view says "the wavefunction really does collapse, via a physical process we can model stochastically." The epistemic view says "the wavefunction was never a physical thing, so nothing collapses."

These four positions make dramatically different metaphysical commitments. But only the collapse view predicts experimentally new things — specifically, a breakdown of unitarity at macroscopic scales, testable via interference experiments with larger and larger objects.

Structural Role

10.5 sits at the apex of the foundations module. All prior no-go theorems (Bell, KS, PBR) constrain *which* of the four options is viable, and decoherence (10.4) determines *what* those options must still explain. The final verdict:

- **No-collapse (MWI)** survives Bell, KS, PBR by accepting branching and denying outcome selection as a real event. Costs: ontological extravagance.
- **Bohmian** survives by being non-local (allowed by Bell), contextual (allowed by KS), and ψ-ontic (allowed by PBR). Costs: hidden variables need a pilot wave.
- **Dynamical collapse** survives by modifying quantum mechanics slightly. Costs: experimental constraints from macromolecule interferometry are tightening.
- **Epistemic** survives PBR by rejecting preparation independence (QBism) or by declaring ψ non-physical (strict Copenhagen). Costs: "what is the ontology, then?"

10.5 is also the empirical frontier: unlike 10.1–10.3, which are settled no-gos, 10.5 identifies a question that is **experimentally open** and being actively pursued.

Mathematical Development

GRW model

The Ghirardi–Rimini–Weber model (1986) modifies the Schrödinger equation by adding **spontaneous localizations**: at random times distributed as a Poisson process with rate λ_{GRW}, the wavefunction of each particle is multiplied by a Gaussian centered at a random position drawn from $|\psi|^2$:

$$\psi(x_1, ..., x_N) \to N_j\, e^{-(x_j - x_0)^2/(2r_C^2)}\, \psi(x_1, ..., x_N).$$

Parameters: $\lambda_{\text{GRW}} \approx 10^{-16}\,\text{s}^{-1}$ per particle, $r_C \approx 10^{-7}\,\text{m}$. For a single particle, localizations are rare (once per 10^{16} seconds), so atomic physics is unaffected. For a macroscopic object of 10^{23} particles, localizations occur at rate $10^7\,\text{s}^{-1}$, effectively continuously — so macroscopic superpositions collapse in microseconds.

CSL (Continuous Spontaneous Localization)

CSL (Pearle 1989, Ghirardi–Pearle–Rimini 1990) replaces the discrete jumps of GRW with a continuous stochastic process:

$$d|\psi\rangle = \left[-\frac{i}{\hbar} H\, dt + \sum_k (A_k - \langle A_k \rangle) dW_k - \frac{1}{2} \sum_k (A_k - \langle A_k \rangle)^2 dt \right] |\psi\rangle,$$

where W_k are independent Wiener processes and A_k are position-localization operators. The effective localization rate is the same as GRW in the single-particle limit but scales with mass density rather than particle count, resolving some issues with identical particles.

Both GRW and CSL predict **predictable deviations from unitarity**: the more massive / the more particles, the faster the collapse. This is the empirical fingerprint of dynamical collapse theories.

Penrose gravitational collapse

Penrose (1996) proposed that gravitational self-energy limits how long a superposition can persist:

$$\tau_{\text{Penrose}} \approx \hbar / E_G,$$

where E_G is the gravitational self-energy of the mass-density difference between the two branches of the superposition. For a 10^{-18} kg nanoparticle superposed over 10^{-7} m, $\tau_{\text{Penrose}} \sim 10^{-3}$ seconds — within reach of ongoing experiments.

Experimental constraints

Molecular interference experiments (Arndt group) have observed interference of C_{60}, C_{70}, and larger molecules up to ~ 2000 amu. Non-observation of collapse at these scales places upper bounds on λ_{GRW} and lower bounds on r_C. Current bounds are consistent with original GRW parameters but increasingly constrain the allowed parameter space.

The "gold-standard" test would be to observe interference of an object of mass $\sim 10^{-14}$ kg — just inside the regime where GRW predicts observable collapse. This is the target of several ongoing experiments (optically trapped nanoparticles, levitated microspheres).

Worked Example

GRW-modified double-slit for a macroscopic object

Take a mass $M = 10^{-14}$ kg ($\sim 10^{10}$ atoms) prepared in a superposition of two slits separated by $\Delta x = 100\,\text{nm}$. In standard quantum mechanics, the coherence time is set only by environmental decoherence (10.4) and can be made arbitrarily long by isolating the system.

In GRW, each atom has a collapse rate of $10^{-16}\,\text{s}^{-1}$. With $N = 10^{10}$ atoms, the collective collapse rate is

$$\lambda_N = N\lambda_{\text{GRW}} = 10^{-6}\,\text{s}^{-1}.$$

The expected coherence time is $\tau \sim \lambda_N^{-1} \sim 10^6$ seconds. So over a 1-second experiment, collapse is unlikely. But for $M = 10^{-11}$ kg $\to N = 10^{13}$, $\lambda_N = 10^{-3}\,\text{s}^{-1}$, and coherence is lost within milliseconds — well within the range of an interference experiment.

If such an experiment observes interference with high visibility for $M > 10^{-13}$ kg over ~ 1 second, then GRW with original parameters is ruled out. Experiments are approaching this threshold.

CSL mass-density scaling

Under CSL, the scaling is with mass density rather than particle count. A solid with mass density $\rho \approx 10^3\,\text{kg/m}^3$ collapses faster than an equivalent gas of the same total mass. Experiments with micro-oscillators (silicon beams) test the mass-density scaling, and the latest bounds place CSL's collapse rate at most $\sim 10^{-8}\,\text{s}^{-1}$ per nucleon — two orders of magnitude tighter than GRW's original proposal.

Falsification criterion

Dynamical collapse theories make a concrete, falsifiable prediction: **unitarity breaks down at sufficiently large scales**. If an experiment ever observes persistent interference of an object of mass $\gg 10^{-13}$ kg over ~ 1 second, dynamical collapse (as currently parameterized) is falsified. If, conversely, an experiment observes faster-than-environmental decoherence at that scale, it is confirmed. This is the sharpest empirical frontier in quantum foundations today.

Cross-Links

- **6.1 Measurement problem (framing)** — conceptual introduction; 10.5 is the technical version.
- **10.4 Quantum-to-classical transition** — decoherence resolves sub-problems 1 and 2; sub-problem 3 is what 10.5 is about.
- **6.2 MWI**, **6.4 Bohmian**, **6.5 QBism**, **GRW/CSL literature** — the four families of proposed solutions.
- **10.1, 10.2, 10.3** — no-go theorems constraining which solutions are viable.
- **8.x Open-systems** — the Lindblad and stochastic formalisms underlie both decoherence and dynamical collapse.
- **Experimental physics** — macromolecule interferometry, levitated nanospheres.

Structural Compression

Invariant: The transition from "unitary superposition" to "single observed outcome" is not accounted for by the unitary formalism alone.

Mechanism: None within standard quantum mechanics. Proposed mechanisms: many-worlds branching, Bohmian hidden variables, dynamical collapse, epistemic reinterpretation. Only the third is experimentally distinct.

Cross-System Echo: All foundational theories of physics face *underdetermination* — multiple consistent ontologies fit the same empirical data. The measurement problem is underdetermination at its sharpest: the math is finished, the experiments are done, and multiple incompatible pictures remain viable.

Exercises

1. State the three sub-problems of the measurement problem explicitly and identify, for each, which mechanism (if any) resolves it within standard quantum mechanics plus decoherence.
2. Compute the expected GRW collapse rate for a 10^{-12} kg silica microsphere (composed of SiO_2, $\sim 10^{13}$ nucleons), and compare to the expected decoherence rate from thermal photons at 300 K.
3. Show that CSL, in the limit where $r_C \to \infty$, reduces to a deterministic modification of the Schrödinger equation, and argue why this limit is experimentally ruled out by atomic interference experiments.
4. Derive the Penrose collapse time $\tau \approx \hbar/E_G$ for a 1 kg mass superposed over 1 mm, and explain why this scale is inaccessible to current experiments.
5. A many-worlds advocate argues that the measurement problem "dissolves" because all outcomes happen. Identify the residual problem of deriving the **Born rule** in MWI and explain why this is considered its most serious remaining challenge.
6. Compute the expected number of collapse events per second in a cubic centimeter of water under GRW, and comment on whether this is detectable in principle.
7. **Argue, structurally**, why only dynamical collapse theories, among the four families of proposed solutions, make experimentally distinguishable predictions. Identify precisely what empirical signature would distinguish MWI from Bohmian from epistemic views — if any exists at all.

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Concepts: unitary-evolution, born-rule, density-matrix, superposition
Prerequisites: 6.1, 10.4

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