Many-Worlds Interpretation

Quantum Foundations · Module 6 — Interpretations

Node 6.3

Position in Knowledge Graph

System: Quantum Foundations **Structural Domain:** Interpretations **Node:** 6.3

Many-worlds — originally due to Hugh Everett (1957) and developed by DeWitt, Wheeler, Deutsch, Wallace, Saunders, and others — is the interpretation that resolves the measurement problem by *dropping the projection postulate entirely.* Only the Schrödinger equation governs the evolution of the universe's total wavefunction; there is no collapse, no cut, no classical domain, and no preferred basis except the one dynamically selected by decoherence. What is experienced as measurement is the branching of the universal wavefunction into mutually decoherent sectors, each containing a definite outcome and a copy of the observer who saw it.

Many-worlds is the *minimal* interpretation in terms of postulates (it discards one) and the *maximal* interpretation in terms of ontology (everything in the wavefunction is real). It is the interpretation most directly coupled to the material of Module 5: decoherence and einselection are essential to its account of experience.

Formal Statement

The only postulate

The universe is described by a **universal wavefunction** $|\Psi\rangle$ on a Hilbert space that includes all physical systems, observers, apparatuses, and environment. This state evolves *only* under the Schrödinger equation:

$$i\hbar\frac{d}{dt}|\Psi\rangle = H|\Psi\rangle.$$

There is no projection postulate. There is no collapse. Measurement is just a unitary interaction between a system and an apparatus (and eventually an observer and environment), producing an entangled state in which the observer becomes correlated with the measurement outcome.

Branching

When a measurement is performed, the joint state of system + apparatus + observer + environment becomes, schematically,

$$|\Psi\rangle = \sum_i c_i\,|i\rangle_S \otimes |\text{apparatus shows } i\rangle_A \otimes |\text{observer sees } i\rangle_O \otimes |E_i\rangle_{\text{env}}.$$

Each term in this sum is a **branch** (or "world"). The environment states $|E_i\rangle$ are mutually orthogonal after decoherence (by the einselection argument of Node 5.5), so the branches have no practical way to interfere with each other. Within each branch, the observer has experienced a definite outcome i and will, from that moment on, describe the world in terms of that branch's history.

Everett's central claim: *each branch is equally real.* There is no "actual" outcome selected from among the branches — all of them occur, in different sectors of the universal wavefunction.

Probabilities

The coefficients $|c_i|^2$ are interpreted as probabilities — but the question of *why* they should be is non-trivial, because in a purely deterministic branching picture every outcome occurs. Several approaches to deriving the Born rule from the many-worlds framework have been developed:

- **Deutsch–Wallace decision-theoretic derivation** (2000–2012). A rational agent operating within the many-worlds framework can be shown, under plausible decision-theoretic axioms, to assign subjective probabilities to branches equal to $|c_i|^2$. This is the formal analogue of the classical Cox/Savage derivations of Bayesian probability from rationality axioms.
- **Self-locating uncertainty** (Vaidman, Sebens–Carroll 2018). Immediately after branching but before the observer learns the outcome, they are uncertain which branch they are in. The correct probability to assign to being in a particular branch is derived from the structure of the wavefunction and turns out to equal $|c_i|^2$.
- **Envariance** (Zurek 2005). The Born rule follows from an invariance property of entangled states under local operations on one side balanced by compensating operations on the other.

These derivations are not universally accepted — critics argue that each presupposes in some form what it sets out to prove. The *status* of the Born rule in many-worlds is therefore a live area of foundational debate. What is not in dispute is that many-worlds' empirical predictions, if the Born rule is taken as an auxiliary postulate, match standard quantum mechanics exactly.

Intuition

The simplest reading: *take the Schrödinger equation seriously.* If a measurement is a physical process — and it is, since apparatuses are made of atoms — then it should be describable by unitary quantum mechanics all the way through, with no special exception for "measurement." But doing so produces entangled states of system, apparatus, and observer. Where does the definite outcome come from?

Everett's answer: nowhere. The entangled state *is* the situation, and each term in it is one branch of the universal wavefunction. The observer in branch 1 sees outcome 1; the observer in branch 2 sees outcome 2. Both observers are copies of the original observer before the measurement. Neither has any experiential access to the other branch — the branches have decohered, so no interference is possible.

From the inside of a branch, the experience of measurement is exactly what Copenhagen describes: an apparent random selection of one outcome from a distribution. The many-worlds account is that *each* branch looks locally like the Copenhagen account, but the global picture is unitary, branching, and deterministic.

The cost is an explosion of ontology. Every quantum event creates branches, and the total number of branches grows without bound. Many-worlds advocates reply that this is no more ontologically extravagant than committing to a continuous field theory in classical mechanics: in both cases, the theory is described by a single mathematical object, and whatever exists is whatever that object contains. The universe's "cost" is the dimension of its Hilbert space, not the number of terms in any particular decomposition.

The advantage is structural parsimony. Many-worlds has *one* dynamical rule (the Schrödinger equation) and no cuts, no collapse, no special role for observers. It is compatible with locality in a technical sense: there is no faster-than-light signalling, because branching is a local phenomenon that spreads at the speed of light. And it is compatible with determinism: the universal wavefunction evolves deterministically under the Schrödinger equation, even though each observer experiences apparent randomness.

Structural Role

Many-worlds is the interpretation of choice for certain classes of structural argument:

- **Dropping a postulate.** It is the *minimalist* response to the measurement problem in the specific sense that it removes one of the two rules of Node 6.1. This appeals to people who believe that physics should have the smallest possible set of fundamental laws.
- **Compatibility with quantum cosmology.** If the universe as a whole has a wavefunction (as in Wheeler–DeWitt quantum cosmology), there is no external observer to perform a measurement. Copenhagen becomes unusable; many-worlds provides a coherent framework in which the universal wavefunction just evolves.
- **Pairing with decoherence.** Many-worlds leans heavily on the machinery of Module 5. The preferred-basis problem ("why do we see position rather than position+momentum superpositions?") is answered by pointing to the pointer basis selected by the system–environment coupling. Decoherence is not a partial solution to the measurement problem in many-worlds; it is the *complete* account of why branches look definite from the inside.
- **Information-theoretic cousins.** Consistent-histories (Node 6.5), decoherent histories, and relational interpretations are close relatives of many-worlds in the sense that all drop the objective collapse and replace it with framework-dependent descriptions.
- **Controversies.** The Born-rule derivation remains contested. Critics include Price, Kent, Adlam, and others who argue that probabilities make sense only if something is uncertain, and in a fully deterministic many-worlds picture there is nothing to be uncertain about. Defenders respond via decision theory, self-locating uncertainty, or simply treating the Born rule as an auxiliary postulate.

Mathematical Development

The universal wavefunction

Let $\mathcal{H}_U$ be the Hilbert space of the universe, schematically $\mathcal{H}_U = \mathcal{H}_S \otimes \mathcal{H}_A \otimes \mathcal{H}_O \otimes \mathcal{H}_{\text{env}}$ (system, apparatus, observer, environment). The universal state $|\Psi\rangle \in \mathcal{H}_U$ evolves under H_U by the Schrödinger equation. All quantum predictions are to be computed from $|\Psi\rangle$ by taking inner products and tracing out unobserved degrees of freedom.

Everett's consistency claim. The empirical content of quantum mechanics — the probabilities of measurement outcomes — can be recovered from $|\Psi\rangle$ alone, without invoking any collapse. The recovery depends on:

1. The branches being decoherent (so no cross-branch interference is observable).
2. The Born-rule weighting of branches (which must be justified from the structure of $|\Psi\rangle$).

Branching as entanglement

Before a measurement, the state is $|\Psi_0\rangle = (\sum_i c_i|i\rangle_S) \otimes |0\rangle_A \otimes |0\rangle_O \otimes |E_0\rangle$. After the measurement interaction (a unitary that couples system to apparatus), the apparatus has become correlated with the system:

$$|\Psi_1\rangle = \sum_i c_i|i\rangle_S \otimes |a_i\rangle_A \otimes |0\rangle_O \otimes |E_0\rangle.$$

After the observer reads the apparatus, the observer is correlated as well:

$$|\Psi_2\rangle = \sum_i c_i|i\rangle_S \otimes |a_i\rangle_A \otimes |o_i\rangle_O \otimes |E_i\rangle,$$

where the environment states $|E_i\rangle$ are the einselected records of the observer's brain state interacting with its surroundings. Decoherence drives $\langle E_i|E_j\rangle \to 0$ on timescales of 10^{-13} seconds or faster.

Once the environment states are orthogonal, the reduced density matrix on the system + apparatus + observer is diagonal:

$$\rho_{SAO} = \sum_i |c_i|^2 |i\rangle\langle i|_S \otimes |a_i\rangle\langle a_i|_A \otimes |o_i\rangle\langle o_i|_O.$$

From the inside of any branch, the observer sees a classical mixture of outcomes with probabilities $|c_i|^2$ — exactly the Copenhagen prediction. No collapse was needed; the apparent randomness comes from the observer being in one branch and not having access to the others.

Preferred basis

The "preferred basis problem" is: why do branches decompose in the $\{|i\rangle\}$ basis rather than any other? The mathematical answer is decoherence + einselection (Node 5.5): the environment's coupling to the joint system determines the pointer basis, and that is the basis in which branching is well-defined. A basis that is not einselected would have its cross-terms remain coherent, making the "branches" interfere and rendering the description nonsense.

This is why many-worlds is structurally dependent on Module 5. Without decoherence, there would be no unique way to decompose the universal wavefunction into branches, and the many-worlds story would be ambiguous. With decoherence, the branches are the einselected components, and the branching structure is well-defined up to the limits of decoherence precision.

Deutsch–Wallace decision-theoretic derivation of Born rule

The Deutsch–Wallace program takes rationality axioms from classical decision theory (transitivity of preferences, continuity, Savage's sure-thing principle) and adds quantum-specific axioms (equivalence, additivity over branches, etc.). Under these axioms, a rational agent acting within the many-worlds framework must treat the branch amplitudes $|c_i|^2$ as probabilities. The derivation is technical and the axioms are contested, but the structural point is that the Born rule emerges from the combination of unitary dynamics and rational betting behavior — it is not an independent postulate.

Wallace's 2012 book *The Emergent Multiverse* gives the most developed form of this argument.

Self-locating uncertainty

The Sebens–Carroll approach uses the observation that, after the measurement interaction but before the observer learns the outcome, the observer is uncertain about which branch they are in — self-locating uncertainty. The natural probability assignment for being in branch i is then derived from symmetries of the wavefunction and, under plausible assumptions, equals $|c_i|^2$. The derivation is cleaner than Deutsch–Wallace's but still assumes something about how to count observers across branches.

Worked Example

Schrödinger's cat in many-worlds

Consider the full Schrödinger's cat setup: a radioactive atom in a state $(|\text{undecayed}\rangle + |\text{decayed}\rangle)/\sqrt{2}$, coupled to a Geiger counter, coupled to a vial of poison, coupled to a cat, coupled to Wigner, coupled to the environment. The joint unitary evolution takes the initial product state into

$$|\Psi\rangle = \tfrac{1}{\sqrt{2}}\big(|\text{undec}\rangle|G_0\rangle|V\rangle|\text{alive}\rangle|W_0\rangle|E_0\rangle + |\text{dec}\rangle|G_1\rangle|V_{\text{broken}}\rangle|\text{dead}\rangle|W_1\rangle|E_1\rangle\big),$$

where all the degrees of freedom have become entangled with the atom's decay status.

Copenhagen says: the cat is in a superposition until someone opens the box, at which point collapse happens.

Many-worlds says: there is no superposition-versus-collapse distinction. The universal wavefunction is always $|\Psi\rangle$. It contains two branches: one in which the atom did not decay and the cat is alive, and one in which it did and the cat is dead. Both branches are equally real. Before Wigner opens the box, he is in a factored state $|W_0\rangle$ not entangled with the atom; after he opens it, he becomes entangled:

$$|\Psi\rangle \to \frac{1}{\sqrt{2}}\big(|\text{alive}\rangle|W_{\text{sees alive}}\rangle + |\text{dead}\rangle|W_{\text{sees dead}}\rangle\big).$$

The "Wigner sees alive" copy of Wigner experiences a relieved observation; the "Wigner sees dead" copy experiences a sad one. Both exist. Each is only aware of his own branch.

Is this coherent? From the inside of each branch, the statistics match Copenhagen: subjective probability 1/2 for each outcome. From the outside (if there were some meta-observer), the universal wavefunction is a simple unitary evolution with no collapse. Many-worlds claims this is the only consistent picture.

The Wigner's-friend scenario

In the Frauchiger–Renner extension, one has Wigner measuring his friend who has measured a spin. In Copenhagen, there are delicate questions about whether the friend's "observation" counts as a collapse. In many-worlds, the question dissolves: after all the measurements, the universal wavefunction contains four branches corresponding to the four joint outcomes, all deterministic, all existing in parallel. The friend in each branch has a consistent story; the branches do not interfere.

The Frauchiger–Renner paradox, which claims to derive a contradiction from single-world assumptions plus quantum mechanics plus reasoning across observers, is consistent in many-worlds because many-worlds does not assume single-world outcomes.

Branching and the expansion of the universe

In many-worlds cosmology, the universal wavefunction branches constantly and everywhere. Each quantum event, from a cosmic ray decay to the spontaneous emission of a photon by a distant atom, creates branches. The total number of branches grows astronomically, but this is not a physical cost — it is just the dimension of Hilbert space being used. From an information-theoretic standpoint, the wavefunction has bounded Kolmogorov complexity (as a solution to a differential equation), even if the number of branches in any decomposition is large.

Cross-Links

- **Module 2.4 (Unitary evolution):** The only rule in many-worlds. Everything else follows.
- **Module 5.5 (Pointer basis / einselection):** Provides the preferred basis for branching. Many-worlds is structurally dependent on decoherence.
- **Module 6.5 (QBism / consistent histories):** Related agent-relative and framework-relative interpretations that also drop objective collapse.
- **Module 10 (Foundations):** The PBR theorem (10.3) constrains ψ-epistemic interpretations. Many-worlds is strongly ψ-ontic — the wavefunction is the only fundamental entity — and so survives PBR trivially.
- **Statistics:** Self-locating uncertainty and decision-theoretic derivations have direct analogues in Bayesian probability theory.

Structural Compression

Invariant: Only unitary evolution is fundamental. Measurement is a unitary interaction producing branches of the universal wavefunction; each branch is equally real; apparent randomness comes from being in one branch and not the others.

Mechanism: Schrödinger equation applied to the universal wavefunction, plus decoherence (Module 5) to select the preferred basis and make branches effectively independent.

Cross-System Echo: Bayesian self-locating uncertainty, statistical mechanics ensembles (imagined as many actual copies rather than one probabilistic system), and parallel computation all share the structural pattern "apparent selection arises from restriction to one sector of a larger space that contains all possibilities."

Exercises

1. Write out the universal wavefunction for Wigner's friend in full, tracking the entanglement structure at each step. Where does "collapse" appear in the many-worlds picture?
2. Explain why many-worlds does not require a preferred basis to be postulated — decoherence provides one dynamically. Under what conditions could the decoherence selection fail?
3. State the Deutsch–Wallace decision-theoretic argument for the Born rule in your own words. What is the key assumption being made about rational agency?
4. Argue why many-worlds is not refuted by the observation that we don't experience branching. (Hint: each branch is only aware of itself.)
5. Compare the many-worlds account of Schrödinger's cat with the Copenhagen account. Which of the questions "when did the cat become definite?" and "which cat am I?" is well-posed in each framework?
6. Critics argue that many-worlds' ontology is extravagant. Argue for or against this claim on structural grounds (e.g., Hilbert-space dimension, Kolmogorov complexity of the wavefunction).
7. Explain, structurally, why many-worlds requires Module 5 (decoherence) but not Module 6.5 (hidden variables). What is the relationship between the two?

Quantum Foundations · Module 6 — Interpretations · Node 6.3
Concepts: unitary-evolution, superposition, decoherence, entanglement
Prerequisites: 6.1, 5.5
Enables: 6.6

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