Review

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Adam Dakhil Nasser *

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Review

The Quantum Measurement Problem: Foundations, Interpretations, and Recent Developments

Adam Dakhil Nasser

Al-Mustaqbal university; std24471017@uomus.edu.iq

Abstract: Quantum mechanics famously posits two distinct evolution rules for the state of a system: a deterministic, unitary time evolution under the Schrodinger equation, and a probabilistic "collapse" of the wavefunction upon measurement as dictated by the Born rule. The apparent inconsistency of these two dynamical laws – one continuous and one discontinuous – constitutes the quantum measurement problem. This foundational problem, which underlies the emergence of definite out- comes from quantum superpositions, has persisted since the theory's inception. In this review, we present a comprehensive and rigorous examination of the measurement problem and survey the leading approaches that seek to resolve or circumvent it. We begin by formulating the measurement problem and its conceptual challenges. We then discuss in detail the major interpretations of quan- tum mechanics and theoretical frameworks addressing the problem: the Copenhagen interpretation, Everett's many-worlds interpretation, de Broglie–Bohm pilot-wave theory, objective collapse mod- els, the role of decoherence and environment-induced superselection, and epistemic approaches such as QBism. For each interpretation, we describe the core principles and mathematical formalism, assessing how (and whether) it attempts to solve the measurement problem. We also review modern developments and experiments relevant to quantum measurements, including tests of Bell inequali- ties, observations of decoherence and macroscopic superpositions, weak measurements and quantum eraser experiments, and thought experiments 'a la Wigner's friend. We highlight how these results inform the ongoing debate. Finally, we discuss open problems and challenges that remain in fully resolving the measurement problem.

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I. Introduction

Quantum mechanics has achieved unparalleled empirical success, yet the theory's interpretation remains fraught with conceptual difficulties. Chief among these is the quantum measurement problem, broadly speaking the puzzle of how and why definite classical outcomes emerge from quantum processes. In the textbook (Copenhagen) formulation of quantum theory, an isolated system evolves smoothly and reversibly according to the linear Schrodinger equation. However, when a measurement is performed, one must invoke an additional postulate: the wavefunction collapses irreversibly and randomly into an eigenstate of the observable being measured, with probabilities given by the Born rule. These two modes of evolution are radically different in character, yet the theory provides no clear criterion for when the deterministic evolution gives way to stochastic collapse. As John Bell memorably criticized, "measurement" in quantum mechanics is an ill-defined concept requiring an undesired departure from the normal

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unitary dynamics. The lack of a precise physical description of the measurement process and the ambiguity of the quantum-classical boundary have been a source of debate for decades.

Despite the pragmatic success of the Copenhagen interpretation in predicting experimental results, the measurement problem signals a profound gap in our understanding of quantum theory's foundations. Schrodinger's cat paradox (1935) and the Einstein-Podolsky-Rosen argument (1935) highlighted the unsettling implications of applying quan- tum superposition and entanglement to macroscopic systems. In Schrodinger's hypothetical scenario, a quantum superposition (a decaying atom) becomes entangled with a macroscopic object (a cat that is alive or dead), yielding an entangled state that quantum mechanics, in principle, treats as a coherent superposition. Yet when we open the box, we observe a single outcome – the cat is either alive or dead, not a superposition. Where and how does the superposition "collapse" into a single reality? Similarly, the EPR paradox questioned whether quantum mechanics can be considered a complete description of reality, given its inability to assign definite values to observables prior to measurement, unless one accepts nonlocal influence. Niels Bohr's response defended the completeness of quantum mechanics by emphasizing the role of the measuring apparatus and the classical context, but the debate underscored that quantum measurement raises deep questions about reality and knowledge.

Over the years, many distinguished physicists and philosophers have proposed resolutions to the measurement prob- lem. These proposals have given rise to a plethora of interpretations of quantum mechanics and modified theoretical frameworks. Broadly speaking, one can identify several schools of thought:

- The Copenhagen interpretation (and variants of "standard" quantum theory) which retains the special status of measurement as a primitive concept, positing an ultimate cut between the quantum system and classical apparatus.
- The many-worlds interpretation (Everettian quantum mechanics), which denies physical collapse and instead postulates that all outcomes in a quantum superposition are realized, each in a different branch of the universe.
- Hidden-variable theories, such as the de Broglie–Bohm pilot-wave theory, which introduce additional vari- ables or structures so that the measurement outcome is determined (in principle) by underlying deterministic dynamics, thus avoiding collapse at the expense of nonlocality.
- Ob jective collapse theories, which modify quantum dynamics by introducing spontaneous wavefunction collapses as physical processes, thereby providing a mechanism for quantum state reduction that is precise and observer-independent.
- Environment-induced decoherence approaches, which, while not interpretations per se, demonstrate how interactions with environmental degrees of freedom can effectively suppress interference and select a preferred basis of "classical" outcomes, thereby addressing part of the measurement problem.
- Epistemic and relational interpretations, such as QBism (quantum Bayesianism) and Rovelli's relational quantum mechanics, which hold that the quantum state does not represent objective reality but rather an observer's information or relationships; these frameworks essentially argue the measurement "problem" dissolves when quantum mechanics is viewed as a theory of inference or relations.

Each of these approaches attempts to resolve the measurement problem in a different way, and each comes with its own advantages and difficult trade-offs. To date, there is no consensus in the physics community as to which (if any) interpretation is correct. The proliferation of interpretations and their mutually incompatible ontologies has even been described as a "cacophony" , underscoring the unsettled nature of quantum foundations.

The stakes of the measurement problem are high: at root it asks what quantum theory says about reality itself. Does a quantum state represent something objectively real, or merely knowledge or information? Do we need to change the dynamics of quantum theory to account

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for observations, or can interpretation alone suffice? Is the linearity of quantum mechanics exact, or is there new physics (collapse dynamics or other) beyond the Schrodinger equation? These questions tie into broader issues such as locality, realism, and even the interface of quantum mechanics with gravity and consciousness.

In this review, we provide a detailed exposition of the quantum measurement problem and thoroughly examine the major proposed solutions and interpretations. In §II we define the measurement problem more rigorously, breaking it down into specific issues. In §III–VIII we devote separate sections to the interpretations listed above, discussing how each one addresses (or sidesteps) the core dilemma of collapse vs. unitary evolution. §IX is devoted to experimental and theoretical developments that inform the measurement problem, including tests of quantum foundations (Bell tests, Leggett-Garg tests, Wigner's friend scenarios), studies of decoherence, and other relevant experiments (weak measurements, quantum erasers, interference of macroscopic objects, etc.). In §X we discuss the comparative strengths and weaknesses of the different approaches and summarize remaining open problems. Finally, §XI offers concluding remarks on the outlook for resolving the measurement problem. Throughout, we cite key literature (both classic and recent) for further in-depth reading. Our aim is to provide an authoritative and up-to-date review that will be useful to both newcomers and specialists in quantum foundations.

II. The Quantum Measurement Problem

At its heart, the measurement problem arises from the tension between two postulates of quantum mechanics:

1. Unitary evolution : An isolated quantum system evolves according to the Schrodinger equation,

$$i\hbar \frac{d}{dt} |\Psi(t)\rangle = \hat{H} |\Psi(t)\rangle,, \qquad (1)$$

where $\hat{H}$ is the system Hamiltonian. This evolution is linear and deterministic; a pure state $|\Psi(t_0)\rangle$ at an initial time t_0 is mapped to a definite pure state $|\Psi(t)\rangle$ at any later time t by a unitary operator $|\Psi(t)\rangle = \hat{U}(t, t_0)|\Psi(t_0)\rangle$. If the system is initially in a superposition of some basis states, it remains in a correlated superposition as time progresses (save only for phase rotations of components).

2. Wavefunction collapse : Upon measurement of an observable A with eigenstates $|a_i\rangle$, the state of the system discontinuously and randomly "collapses" to one of the eigenstates $|a_i\rangle$. If just prior to measurement the system is described by the state $|\Psi\rangle = \sum_i c_i |a_i\rangle$ (expanded in the eigenbasis of A), then immediately after an ideal measurement yielding outcome a_k the state is

$$\Psi \; ; \; \text{measurement} \; ; \; a \qquad (2)$$

with probability $P(a_k) = |c_k|^2$ (the Born rule). The state change (2) is non-unitary and non-deterministic. Moreover, it is an irreversible process – once the outcome is obtained, the other components of the superposition are (apparently) eliminated.

The measurement postulate is essential for quantum theory to connect with experiments: it tells us how to obtain classical information from a quantum system and why repeated measurements yield the same result (after collapse, the system is in an eigenstate, giving the same eigenvalue if measured again). However, this postulate introduces a host of troubling questions:

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- **When/what triggers collapse?** Standard quantum mechanics does not specify what constitutes a "mea- surement" or when exactly the collapse occurs. In practice, a measurement involves a macroscopic apparatus or an irreversible amplification of a microscopic event to a classically observable scale. But in principle, if one considers the entire system (apparatus + microscopic system) as one big quantum system, then by postulate (1) the combined state should evolve unitarily. This leads to the infamous von Neumann chain or Heisenberg cut dilemma: one can keep enlarging the quantum system to include more of the measurement apparatus, and as long as one treats everything quantum-mechanically, there is no collapse – just a growing entangled state. Where does one draw the line and invoke collapse? von Neumann proved that the location of the cut between quantum and classical realms in principle does not affect final predictions, as long as one is inserted somewhere. But conceptually, the need to arbitrarily invoke a classical interface is unsatisfactory.
- **Definite outcomes (the "pointer basis" problem)**: In a measurement, we always observe a single, definite outcome (e.g. a single pointer position on a dial). Yet if the system plus apparatus evolve solely via Schrödinger's equation, the final state after their interaction will generally be an entangled superposition of different pointer positions correlated with different system eigenstates (as Schrodinger's cat exemplifies). Formally, if $|A_0\rangle$ is the initial "ready" state of the apparatus and $|s_i\rangle$ are eigenstates of the system observable being measured, the ideal measurement interaction leads to

$$\sum_i c_i |s_i\rangle \otimes |A_0\rangle \xrightarrow{\text{unitary}} \sum_i c_i |s_i\rangle \otimes |A_i\rangle, \quad (3)$$

where $|A_i\rangle$ is the apparatus state indicating outcome i. The result is an entangled superposition of pointer states $|A_i\rangle$. There is no term in the unitary dynamics (1) that "picks" one i and discards the others. The collapse postulate (2) was introduced to break this superposition, randomly projecting onto a single term of the sum.

But absent collapse, the state remains a superposition of macroscopically distinct outcomes – something we do not observe. This is sometimes called the problem of outcomes : why do we see a definite result, given the formalism yields a superposition of possibilities?

- **Probability and the Born rule**: Even if one accepts that perhaps all outcomes happen in some sense (as the many-worlds view suggests), one must still account for the apparent randomness of a particular observed outcome and the fact that outcomes occur with frequencies $|c_i|^2$. In other words, why the Born probability rule? In interpretations where collapse is fundamental, the Born rule is usually just an axiom (or can be shown to be the only consistent choice under certain symmetry assumptions). But in deterministic no-collapse interpretations, the Born rule must be derived or explained as something like a law of large numbers or a measure over branching worlds, etc. The status of the Born rule is thus another facet of the measurement problem. Even in many-worlds where all outcomes occur, observers perceive the world stochastically, so one must define a probability measure on the branches and justify why it is the $|c_i|^2$ norm-squared amplitude (this has been a non-trivial problem for Everettian theory).
- **Quantum-to-classical transition**: More generally, how do we reconcile the microscopic quantum behavior (where superpositions are rampant and interference phenomena are observable) with the macroscopic classical world of our experience (where objects have definite positions and quantum interference seems absent)? The measurement problem is essentially about this transition. Why do quantum effects become unobservable in large systems? Is it

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just a matter of practice (too many degrees of freedom to keep track of phase coherence), or is there a fundamental reason (e.g. the wavefunction collapses beyond a certain scale)? This overlaps with what is sometimes called the macro-objectification problem: how to define precisely under what conditions a system can be said to have a single classical outcome or property.

The measurement problem, as outlined above, is not merely a philosophical quibble; it points to a potential incompleteness or inconsistency in how we apply quantum theory to the whole universe. As Bell and others have emphasized, one cannot have it both ways: if the quantum state (the wavefunction or quantum state vector) is a complete description of a physical system, then the process of measurement should itself be describable as part of that physical system's evolution . But doing so (via Eq.,(3)) yields, in general, a superposition of outcomes rather than a single outcome. Hence, either:

1. The quantum state is not a complete description of reality (there are additional variables or structures deter- mining outcomes that the quantum state does not capture), or
2. The dynamics of quantum mechanics is not actually strictly linear when considering the full system including measuring devices (collapse is a real physical nonlinearity or new dynamical process), or
3. Our notion of "reality" or "outcome" needs modification (for example, all outcomes occur in separate branches, or outcomes are only personal experiences of observers and not global events).

Broadly speaking, these options correspond to the paths taken by the different interpretations: hidden-variable theories pursue option (1); objective collapse theories pursue option (2); Everett's many-worlds and QBism/relational approaches pursue option (3). Decoherence, as we will see, does not by itself add new dynamics or variables, but it greatly clarifies how option (3) can be tenable by showing that different outcomes (branches) become effectively non-interacting and appear classical under typical conditions.

It is worth noting that one may distinguish different aspects or "sub-problems" within the overall measurement problem. Some authors, for instance, delineate the problem of outcomes (or "preferred basis" problem) separately from the problem of statistics (probability rule), etc. . In this review we will not rigidly compartmentalize these facets, but we will touch on each: how a given interpretation produces (or explains) a unique outcome, how it justifies the probability rule, and how it delineates the boundary (if any) between quantum and classical.

In the following sections, we analyze the principal interpretations and modifications of quantum mechanics that attempt to solve the measurement problem. We will see that each approach provides a very different answer to the question "What actually happens in a quantum measurement?"

III. Copenhagen Interpretation and The Classical Cut

The Copenhagen interpretation, although not a single monolithic doctrine, refers to the standard textbook un- derstanding of quantum mechanics developed by Bohr, Heisenberg, and others in the 1920s and 30s. In this view, quantum mechanics is fundamentally a theory about observations obtained with classical measuring apparatus. It de- liberately eschews providing a microscopic "story" of what happens during measurement – instead, it posits a division between the quantum system (described by a wavefunction) and the classical world of the observer and apparatus. The act of measurement is an irreducible primitive in the theory: when a measurement is made, the wavefunction discontinuously collapses to an eigenstate corresponding to the observed outcome.

Niels Bohr emphasized the necessity of using classical terms to describe experimental setups and results. According to Bohr's principle of complementarity, certain properties (like the wave and particle aspects of quantum objects) are mutually exclusive yet both necessary for a complete description of phenomena. One cannot, in this view, speak of a quantum system having definite

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properties prior to measurement in any classical sense; the experimental context defines what aspect of the system is revealed (e.g. position or momentum, one at a time). In the Copenhagen interpretation, questions about what is "really" going on in the quantum realm between observations are considered meaningless – quantum mechanics only provides probabilities for the outcomes of experiments.

From the Copenhagen perspective, the measurement problem is not so much "solved" as it is sidestepped by a philosophical stance: quantum mechanics is a tool for calculating observable probabilities, and one should not demand a dynamical account of wavefunction collapse. Collapse is just a postulate that works; it happens when an "observer" interacts with the system, and trying to analyze the process beyond that is futile or outside the scope of physics. As Landau and Lifshitz famously put it, "in quantum mechanics there is no such thing as an isolated system," meaning any attempt to describe a measuring apparatus quantum-mechanically is contrary to the Copenhagen spirit. One must ultimately invoke a classical realm.

While this approach is operationally successful, it leaves many physicists and philosophers dissatisfied. It essentially says that quantum theory, as normally formulated, is fundamentally incomplete – not in the EPR sense of hidden variables, but in the sense that it deliberately refrains from describing how outcomes occur. Moreover, it raises the troublesome question: what exactly counts as a "measurement" or an "observer"? Is a Geiger counter enough, or must a conscious observer look at the Geiger counter? Some early framings (e.g. von Neumann–Wigner) even entertained the notion that consciousness might be what collapses the wavefunction. Such ideas, while historically notable, are not part of the mainstream Copenhagen interpretation, which typically treats any macroscopic, irreversible amplification device as sufficient to invoke classical concepts. Nonetheless, the lack of a clear criterion for when the quantum-to- classical transition occurs means the Copenhagen view does not offer a crisp resolution of the measurement problem – rather, it posits that the problem is outside the domain of the theory.

That said, the Copenhagen interpretation was never a single official doctrine, and there are nuanced differences in how its proponents viewed the collapse. Heisenberg spoke of the collapse as a change in the knowledge of the system (information update) rather than a physical process, whereas Bohr avoided even that, focusing on the completeness of phenomena once system and apparatus are considered together. In modern terms, one might reconcile this (to a degree) with an epistemic view: collapse represents our updating of information when we learn the outcome, not a literal physical wave crashing. Indeed, some later interpretations like QBism (discussed in §VIII) take inspiration from this, treating the quantum state as an observer's state of knowledge (or belief) and collapse as a Bayesian update.

In summary, the Copenhagen interpretation "solves" the measurement problem by fiat: it accepts the dual dynamics (unitary evolution vs. measurement collapse) as a fundamental given and restricts quantum theory's domain to the former, with the latter being an extrinsic rule connecting to classical experience. There is no deeper explanation for collapse – it is simply part of the axioms. The strength of this interpretation is its minimalism and its alignment with how quantum mechanics is actually used in the lab. Its weakness is that it leaves one wanting a more unified, universal theory where measurement is not a separate magical step. As Bell quipped, "our theorists . . . have constructed an exact and unambiguous theory only for the purpose of getting themselves to the laboratory door; once inside they content themselves with jargon" . The Copenhagen mindset essentially accepts the jargon ("collapse," "classical apparatus") as unavoidable.

Before moving on, we should acknowledge that environment-induced decoherence (to be discussed in §VII) has significantly sharpened the Copenhagen picture by explaining why certain observables (the "pointer" observables) behave classically for macroscopic systems. Decoherence can be seen as providing the mechanism that Copenhagen refused to seek explicitly: it shows how interactions with a large environment effectively cause a density matrix to diagonalize in a preferred basis . Some advocates of a modernized Copenhagen view argue that, with

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decoherence, one can understand why measurement outcomes are stable and effectively unique without needing to modify quantum mechanics. However, even with decoherence, one still typically interprets the emergent diagonal density matrix as representing an ignorance (classical mixture) of outcomes rather than a live superposition – and that step is akin to an epistemic collapse. Thus, Copenhagen+decoherence still ultimately relies on the traditional interpretation that a "measurement has occurred" to replace superposition by classical ignorance.

In the end, the Copenhagen interpretation remains an instrumentalist approach: it tells experimenters how to use quantum mechanics to calculate results, but deliberately remains agnostic or silent on what underlying reality produces those results. This stance avoids any internal inconsistency, but many find it unsatisfying as a final answer to the measurement problem, motivating the search for deeper interpretations or extensions, to which we now turn.

IV. Many-Worlds Interpretation (Everettian Quantum Mechanics)

The many-worlds interpretation, proposed by Hugh Everett III in 1957 , offers a radical shift in perspective: it asserts that the unitary evolution given by the Schrodinger equation is never violated. There is no wavefunction collapse at all. Instead, whenever a measurement-like interaction occurs, the total wavefunction of the universe (system + apparatus + environment + observers) splits or branches into a superposition of orthogonal components, each corresponding to a different outcome. In each branch, the measuring apparatus has recorded a definite result and the observer has perceived that result. Crucially, because the branches are effectively non-interacting (quantum interference between them vanishes due to decoherence), each branch behaves like a separate classical world in which a single outcome has occurred. Thus, all possible outcomes of a quantum measurement are realized, each in a different branch of the universal wavefunction. The collection of branches can be thought of as a multiverse of coexisting realities – hence the name "many-worlds."

Everett originally called his idea the "relative state" formulation: the key insight is that after a measurement, the state of the observer is only defined relative to the state of the system. For example, in the entangled state (3) (with system states $|s_i\rangle$ and apparatus states $|A_i\rangle$), one can say that the apparatus is in state $|A_i\rangle$ relative to the system being in $|s_i\rangle$. There is no collapse to a single $|s_k\rangle \otimes |A_k\rangle$; instead the total state contains all such terms. However, an observer within one branch (say the term with $i = k$) will only see the outcome k and will not be aware of the other components of the wavefunction. Those other components constitute different worlds that have, for all practical purposes, no interaction with the observer's world post-measurement.

The many-worlds interpretation thus addresses the measurement problem by denying the need for a special measure- ment postulate. The Schrodinger equation (1) is assumed to govern everything, including the measurement devices and observers. There is only quantum evolution, and the appearance of collapse is an illusion that comes from the perspective of an observer who becomes entangled with the measured system. In effect, the measurement problem is "solved" by taking the quantum formalism at face value, but redefining the notion of reality: reality is the full wave- function of the universe, which contains simultaneous multiple outcomes. Observers perceive a stochastic outcome only because they themselves are localized within one branch.

A crucial ingredient in making many-worlds viable is decoherence. Everett's original work predated the full development of decoherence theory, but modern Everettian interpretations heavily invoke decoherence to explain why branches do not interfere and why they can be treated as separate worlds. When a macroscopic measurement apparatus becomes entangled with a microscopic system, environmental interactions (with air molecules, photons, etc., or internal degrees of freedom) will very rapidly decohere the entangled superposition in the pointer basis

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. This means the off-diagonal terms in the density matrix (interference between different outcome branches) become negligibly small. Each branch then evolves approximately independently. The outcome states $|A_i\rangle$ become stable (they "einselect" into pointer states), and the observers in distinct branches have no means to communicate or interact. In effect, decoherence provides the mechanism for the "splitting" of worlds. It ensures that once macroscopically different outcomes are recorded, the branches decouple. Without decoherence, one might in principle recombine branches and see interference between what we would call different worlds, which would call into question their status as separate realities. Decoherence thus gives many-worlds a solid physical footing by showing that branch autonomy is a natural consequence of quantum dynamics in a high-dimensional environment .

However, many-worlds is not without its conceptual challenges. Foremost among them is the probability problem: If all outcomes occur, in what sense is an outcome "random" and why do we assign the Born rule probabilities $|c_i|^2$ to them? In the deterministic mathematics of many-worlds, the wavefunction evolution is completely causal and there is no fundamental probability. The appearance of probability must be an emergent, subjective phenomenon. Everett and others have argued that an observer should rationally assign subjective probabilities equal to branch weight $|c_i|^2$ to being in a given branch, essentially because if you imagine many identical setups, the branch frequency will follow $|c_i|^2$. More formally, several derivations have been attempted: for example, Deutsch and Wallace have advanced a decision-theoretic derivation that if an observer values future outcomes in a certain consistent way, they must act as if the Born rule holds in a branching universe . Others (Zurek) have given an argument from envariance (environment-assisted invariance) that recovers the Born rule from symmetries of entangled states . While these arguments are interesting, not everyone finds them fully convincing, and the issue of justifying probability in a deterministic multiverse is still debated . In practice, most Everettian proponents simply assume that an agent who knows the wavefunction (and thus the squared amplitudes) will treat those as probabilities for their experienced outcome, consistent with the Born rule, and this assumption yields results in agreement with experiment. The success of quantum predictions then empirically justifies the identification of $|c_i|^2$ as probabilities in the theory.

Another point of contention is the ontology of many-worlds. What exactly are these "worlds," and when do they split? The theory, at its core, has just a wavefunction (or quantum state of the universe) obeying linear dynamics. The term "world" is an emergent concept, corresponding to a decohered branch that contains approximate classical reality (people, objects, etc.). Some have questioned whether this is a sufficient ontology for a fundamental theory. For example, the theory has no explicit notion of particles or fields or localized matter – all is in the wavefunction. Yet in each branch, it appears as if there are particles and objects. This leads to philosophical questions about derivation of the classical world from the wavefunction ontology. Many-worlds advocates like David Wallace have written extensively on how classical structures and the appearance of a quasi-classical world emerge within the wavefunction of the universe . Generally, thanks to decoherence, each "world" can be characterized by a roughly definite configuration (or history) in terms of classical degrees of freedom.

There is also the issue of "splitting" vs. "continuous branching". It is somewhat misleading to talk of a discrete splitting event; in reality, as interactions with an environment happen continuously, branches continuously diffuse and decohere. The number of "worlds" is not well-defined and typically grows exponentially with time as more and more distinctions are recorded in the environment. Some critics argue this makes the theory ontologically extravagant (the famous "reality multiplies too fast" objection). Proponents counter that one should not think of literal universes popping into existence, but rather recognize that the wavefunction's complexity simply increases, and what we call different worlds are just an emergent structure in that complexity. Since the theory is fully deterministic and unitary, it actually does not have any stochastic process of world creation; it's all implicit in the unitary evolution. Despite these

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philosophical challenges, the many-worlds interpretation has gained a significant following for its elegance in addressing the measurement problem. It requires no new physical postulates beyond the Schrodinger equation; it is a universal quantum mechanics that applies at all scales without exception. There is no need for a collapse mechanism or hidden variables. It is also fully local in its dynamics (the nonlocality in Bell's theorem is manifested as correlations between branches rather than superluminal influences). Many-worlds thus preserves the formal simplicity of quantum theory at the price of accepting a vastly expanded notion of reality.

From an experimental standpoint, many-worlds makes the same predictions as standard quantum mechanics for all practical purposes. It is empirically indistinguishable from quantum theory with collapse, since any experiment's outcome frequencies will obey the Born rule in either case. One might wonder if the existence of other branches could ever be detected. In principle, interference between branches could be observed if the decoherence were somehow prevented or reversed. In practice, once decoherence has set in for a macroscopic system, reversing it is effectively impossible (it would require control of an astronomically large number of degrees of freedom). There have been pro- posals (mostly thought experiments) to witness signs of many-worlds by measuring interference in carefully controlled scenarios with conscious observers (Wigner's friend setups). So far, no such evidence exists, and many-worlds fully predicts we won't see other branches except through interference experiments that are essentially identical to verify- ing quantum superposition. One interesting implication is that if one could maintain coherence in larger and larger systems (e.g. Schrodinger cat states of truly macroscopic objects), one would in effect be "creating parallel outcomes" and in principle could recombine them. Experiments have pushed the envelope of superposition to ever larger systems , but always within the regime of quantum theory's expected validity. These do not prove many-worlds, but they show that the world does behave quantumly even for objects comprising thousands of atoms , lending credence to the idea that, in absence of collapse, superpositions of entire organisms (in principle) are not absurd, just very quickly decohered in practice.

In summary, the many-worlds interpretation resolves the measurement problem by discarding wavefunction collapse entirely and asserting that all possible outcomes occur in a vast multiverse described by the universal wavefunction. It provides a clear conceptual framework in which the Schrodinger equation is never violated. The definite outcomes are explained as being observer-specific: an observer becomes entangled and thereby "selects" a branch. Probability is reinterpreted as subjective expectation across branches. Many-worlds is appealing to those seeking a deterministic and complete account of quantum phenomena, but it remains controversial to others due to its counterintuitive ontological implications. Whether one accepts many-worlds often comes down to a judgment of whether it is more troubling to have unobservable parallel worlds or to have an inherently indeterministic, collapse-postulate-based physics. In any case, many-worlds stands as one of the most prominent attempted solutions to the measurement problem.

V. Bohmian Mechanics (Pilot-Wave Theory)

Bohmian mechanics, also known as the deBroglie–Bohm theory or pilot-wave theory, is a hidden-variable formu- lation of quantum mechanics that provides a concrete mechanism for the emergence of definite outcomes. Initially proposed by Louis deBroglie in 1927 and later developed by David Bohm in 1952 , this interpretation introduces ad- ditional degrees of freedom – usually taken to be the exact positions of particles – which supplement the wavefunction description. In Bohmian mechanics, the wavefunction never collapses; it always evolves according to the Schrodinger equation. However, particles have well-defined trajectories at all times, guided by the wavefunction. Thus, even if the wavefunction is a superposition of different outcomes, each particle will actually follow one particular path and end up in a definite position, providing a unique measurement result.

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The mathematical core of the pilot-wave theory can be illustrated for simplicity with spinless particles. Suppose we have N particles with positions $x_1, x_2, \ldots, x_N$. Bohmian mechanics says:

- The system is described by a wavefunction $\Psi(x_1, \ldots, x_N, t)$ which obeys the usual N-body Schrodinger equation
  $$i\hbar \frac{\partial \Psi}{\partial t} = \hat{H}\Psi.$$
  In addition to the wavefunction, each particle has at any time a definite position $X_i(t)$ in real space. The collection $X_i(t)$ constitutes the actual configuration of the system.
  The motion of the particles is determined by the wavefunction via the so-called guiding equation. For example, for a single particle,
  $$\frac{dX(t)}{dt} = \frac{\hbar}{m}\Im \frac{\nabla\Psi(x,t)}{\Psi(x,t)}\bigg|_{x = X(t)}, \tag{4}$$

which can be derived from writing the wavefunction in polar form $\Psi = Re^{iS/\hbar}$ (with R and S real) and identifying $v = \frac{1}{m}\nabla S$ as the velocity field. Equation (4) means the particle velocity is proportional to the quantum probability current. In effect, the wavefunction acts like a "pilot wave" that directs the particle along specific trajectories.

- When a measurement is made, one ultimately is concerned with where the particles (e.g. those making up a pointer or a detector flash) end up. Since the particles have definite positions, the outcome is determined by their final configuration. The appearance of collapse comes from the fact that once the particles become entangled with the wavefunction's different branches, only one branch ends up containing the particles (the others have no particles in them, hence no realized outcome in those branches).

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In the pilot-wave picture, the randomness of quantum outcomes originates from ignorance about the exact initial positions of particles (the hidden variables). Bohmian mechanics postulates a quantum equilibrium hypothesis: if the particle configuration is initially distributed according to $|\Psi(x, 0)|^2$, then it will continue to be distributed according to $|\Psi(x, t)|^2$ at all times . This property ensures that observers who know only the wavefunction (and not the hidden variables) will make predictions in agreement with the Born rule. In other words, Bohmian mechanics reproduces all statistical predictions of standard quantum mechanics, provided one assumes that the actual positions are randomly distributed according to the wavefunction's $|\Psi|^2$ density. This is analogous to how in classical statistical mechanics one assumes a probability distribution over microstates (e.g. molecules' positions/velocities) to derive thermodynamic behavior. The quantum equilibrium condition can be argued to arise dynamically (through a kind of "ergodic" mixing in configuration space) or simply taken as an additional postulate.

By construction, Bohmian mechanics provides a clean solution to the measurement problem's core issue: there is always a single, well-defined outcome. For instance, consider a particle going through a two-slit apparatus and then hitting a screen. The wavefunction may pass through both slits and create an interference pattern, but the actual particle goes through one specific slit and hits the screen at a single point. If one "measures which slit," the measuring device becomes entangled with the wavefunction branches, but the measuring device itself consists of particles that follow trajectories. So the device will end up with a definite pointer position corresponding to whichever branch has the particles in it. The other branch of the wavefunction, lacking the particles, is often termed an empty wave: it still exists as a solution of the Schrodinger equation, but it has no influence because the particles are not there (except subtle cases where an empty wave could, in principle, still affect particle motion if recombined, but environment- induced decoherence tends to prevent such recombination in practice). Thus, in Bohm's theory, wavefunction collapse is not a physical process; instead, the effective collapse is simply our knowledge updating that the particles are only in one branch.

Another attractive feature of Bohmian mechanics is that it is explicitly nonlocal, which actually aligns well with Bell's theorem. Bell's inequality (1964) proved that no local hidden-variable theory can reproduce the predictions of quantum entanglement . Bohmian mechanics evades this by being manifestly nonlocal: the guiding equation (4) for particle i can depend on the positions of other particles instantaneously, since the wavefunction lives in configuration space. For example, in an EPR experiment with two entangled particles separated by a great distance, the wavefunction is entangled and the velocity of particle 1 can depend on the position of particle 2 via the common wavefunction. This nonlocal influence does not allow signaling (because one cannot control the hidden positions to send a message), but it ensures the theory can produce the correct quantum correlations in line with Bell tests. Thus, Bohm's theory accepts what quantum mechanics demands: if we want definite outcomes determined by hidden parameters, we must sacrifice locality. John Bell himself was quite sympathetic to Bohmian mechanics as a lucid example of how to "be serious" about quantum mechanics . He famously wrote that Bohm's 1952 papers were ignored for too long, remarking "in 1952 I saw the impossible done" in reference to a deterministic completion of QM .

While Bohmian mechanics solves the measurement problem by construction, it faces other challenges:

- Extension to quantum fields and relativity: The pilot-wave theory as described deals with non-relativistic quantum mechanics of particles. Extending it to relativistic quantum field theory is non-trivial. There have been successful extensions in some cases (e.g., Bohmian models for quantum electrodynamics, or using parti- cle densities for fields), but maintaining Lorentz invariance is delicate. Typically, one introduces a preferred foliation of spacetime (an absolute time or a preferred frame) for the dynamics, which is conceptually at odds with relativity. Some argue this is no worse than having an advanced vs retarded potential, etc., but it is a philosophical cost. Recent work has made progress in pilot-wave

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models for fields and even an analogue of Bohmian photons and electrons, but a fully satisfactory relativistic version is still an area of research .

- Empirical indistinguishability: Bohmian mechanics makes the same empirical predictions as standard quan- tum mechanics (as long as quantum equilibrium holds). Therefore, it cannot be experimentally distinguished by statistical tests. This leads some to argue it is a redundant addition to quantum theory ("why add hidden variables if they don't change predictions?"). However, proponents respond that the value is in the conceptual clarity: it provides a coherent picture of reality that avoids paradox (no cats in limbo) and it could, in prin- ciple, suggest new insights (for example, in understanding quantum chaos or defining quantum trajectories in chemistry).
- Simplicity and elegance: By introducing a second ontology (particles positions in addition to the wavefunc- tion), some feel Bohmian mechanics is less elegant. It also has an asymmetry: the wavefunction influences the particles, but the particles do not back-react on the wavefunction (except via their contributions to the total wavefunction's Schrodinger equation as sources if one includes particle positions as boundary conditions in some field equation formulation). This one-way influence (often called the quantum potential or pilot-wave acting on particles) is peculiar, though not logically inconsistent. The wavefunction itself lives in a high-dimensional con-figuration space, which some find less palatable ontologically than fields in real 3D space. Recent philosophical work has explored viewing the wavefunction as a multi-field in 3D space to make the ontology more compact .

In the context of the measurement problem, however, Bohmian mechanics stands as a working solution: each measurement has a definite result determined by the initial configuration (unknown to us, hence seemingly random). The collapse axiom is not needed; after a measurement interaction, the wavefunction may remain a superposition, but only one branch contains the actual configuration. Thus one can interpret the formalism as if the wavefunction "collapsed" to that branch (because the empty branches can be ignored henceforth). Indeed, one can derive an effective collapse law under Bohmian dynamics: when decoherence from the environment is taken into account, the empty wave branches separating from the occupied branch have no effect on the occupied branch's particles, so it is as if the wavefunction has collapsed onto the branch where the particles reside.

One interesting aspect of Bohmian mechanics is that it provides an explanation for why measurements have the particular outcomes they do – in terms of the trajectories. For example, consider an electron spin measurement in a

Stern-Gerlach apparatus. In standard quantum mechanics, if the electron spin is $|\uparrow_x\rangle = (|\uparrow_z\rangle + |\downarrow_z\rangle)/\sqrt{2}$ and one

measures S_z, the outcome is randomly up or down. In Bohmian mechanics, one can analyze the electron as a particle with position going through the Stern-Gerlach magnet's magnetic field gradient. The wavefunction splits into two packets (corresponding to the spin-up vs spin-down paths), and the particle goes into one of those wavepacket paths depending on its initial position and velocity. So the outcome "up" vs "down" is predetermined by the trajectory, even though to a experimenter it appears random because they don't know the initial conditions. In this way, Bohm's theory removes ontological randomness – the unpredictability is just epistemic.

In summary, Bohmian mechanics solves the measurement problem by introducing a dual structure: a continuously evolving wavefunction and actual particle positions. Measurements yield definite outcomes because particles always have definite states (positions, and by extension definite values for any "beable" being measured such as pointer position) even when the wavefunction is in a superposition. The theory reproduces all the usual quantum statistics (given appropriate initial conditions) while providing an intelligible mechanism for collapse-like phenomena. It is a nonlocal hidden-variable theory, fully consistent with Bell's inequality constraints. The cost is a more elaborate ontology and the challenge of merging with relativity. Many find the gain in clarity to be worth these costs , while others prefer to stick with the minimal

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statistical interpretation. Nonetheless, pilot-wave theory remains one of the best-studied realistic interpretations of quantum mechanics, and a viable solution to the measurement problem.

VI. Objective Collapse Theories (Dynamical Reduction Models)

Objective collapse theories, also known as dynamical reduction models, take a different tack on the measurement problem: they modify the standard quantum dynamics by introducing additional physical processes that cause the wavefunction to collapse, without the need for an observer. In these theories, the collapse is a genuine physical phenomenon – a random but well-defined dynamical process – rather than just an update of information. The goal is to have a unified theory in which microscopic systems follow the Schrodinger evolution nearly exactly (preserv- ing quantum behavior), but larger systems spontaneously and rapidly collapse to classical definite states (ensuring macroscopic objects never remain in embarrassing superpositions like Schrodinger's cat). This way, the measurement problem is resolved because the theory itself specifies when and how superpositions are destroyed to yield single outcomes. Collapse becomes an objective, observer-independent process in nature.

The prototype of objective collapse models is the Ghirardi–Rimini–Weber (GRW) model proposed in 1986 . GRW postulated that each elementary particle has a small probability per unit time (~ 10^{-16} per second) of undergoing a spontaneous localization ("hit"). When a hit occurs, the particle's wavefunction $\psi(x)$ is multiplied by a narrow Gaussian function [$g(x-r) = \frac{1}{(\pi r_C^2)^{3/4}} \exp\left(-\frac{|x-r|^2}{2r_C^2}\right)$] of width $r_C \sim 10^{-7}$ m (a chosen localization length on the order of 100 nm). This localization is equivalent to a rapid collapse of the particle's wavefunction to a localized wavepacket centered around some random position **r** (drawn according to the $|\psi|^2$ distribution, so that probabilistic consistency with Born's rule is maintained). Between such collapse events, the wavefunction evolves according to Schrodinger's equation as usual. The collapse rate for one particle is extremely low (10^{-16}/s corresponds to one collapse in about 10^{16} seconds, or 3×10^8 years, on average). Thus an isolated electron or atom would essentially never spontaneously collapse and would behave just like standard quantum theory. However, for a macroscopic object containing N particles, the chance of at least one particle collapsing in a given time is amplified by N . For example, an object with 10^{23} particles (of order Avogadro's number) would have ~ $10^{23} \times 10^{-16} = 10^7$ collapses per second among its constituents – effectively a continuous monitoring that keeps the object's center-of-mass wavefunction sharply localized. As a result, macroscopic superpositions are suppressed extremely rapidly. Any would-be Schrodinger-cat state (superposition of significantly different center-of-mass configurations) will trigger collapses almost immediately, selecting one configuration.

The GRW model is a simple, stochastic modification of quantum mechanics. It successfully gives a mathematical mechanism for wavefunction collapse and yields the Born rule probabilities by construction of the collapse probabil- ity density. However, it has some idealizations: the collapse events (hits) are assumed to happen in a Markovian (memoryless) way with a fixed rate, and the position basis is privileged (collapses are postulated in position space). Later refinements led to the Continuous Spontaneous Localization (CSL) model , which makes the collapse process continuous in time rather than as sudden jumps. In CSL, one adds nonlinear and stochastic terms to the Schrodinger equation that effectively accomplish a similar localization effect but in a smooth way. Schematically, the Schrodinger equation is modified to: $d|\Psi_t\rangle = \left[-\frac{i}{\hbar}\hat{H}\,dt + \sum_j \hat{A}_j\,dW_j(t) - \frac{1}{2}\lambda\hat{A}^2\,dt\right]|\Psi_t\rangle$, where $\hat{A}_j$ are collapse-generating op-

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$i \quad \hbar \quad 2 \quad j \quad j \quad -$

erators (often taken as particle position operators), dW_j are independent Wiener processes (noise terms), and λ sets the strength/rate of collapse. This is a stochastic nonlinear Schrodinger equation (also known as a quantum state diffusion or Belavkin equation in mathematical literature). It can be shown to approximately reproduce GRW's discrete jumps in the appropriate limit, but with the benefit of a well-defined continuous dynamics.

In objective collapse theories, the Born rule is not an extra axiom but emerges from the statistics of the random collapse process. These theories are thus falsifiable – they deviate from standard quantum mechanics in regimes that are intermediate between microscopic and macroscopic. Specifically, they predict that sufficiently isolated mesoscopic superpositions might collapse spontaneously at a certain rate, producing slight deviations from the Schrodinger evolution. If these deviations (such as spontaneous heating, radiation, or loss of coherence) can be observed or constrained experimentally, one can set limits on the parameters of the collapse model (like λ and r_C).

Indeed, there is a growing body of experimental work setting bounds on collapse models . One avenue is to search for spontaneous emission of radiation: if a charged particle's wavefunction collapses, it effectively jostles the particle and could cause it to emit a photon. Experiments with sensitive detectors have looked for unexplained X-ray or gamma-ray emission that could be attributed to spontaneous collapses of ambient matter. For instance, experiments at the Gran Sasso underground laboratory (e.g. the ICARUS and GRANIT experiments, and a dedicated one by Curceanu et al.) have set limits that push λ (collapse frequency per nucleon) to be below $\sim 10^{-17}$–$10^{-8}\,s^{-1}$ for r_C around 10^{-7},m . Another class of experiments involves interferometry with macromolecules or nanoparticles: by creating superpositions of increasingly massive objects and seeing if interference visibility is maintained, one can test whether spontaneous localization kicks in at some scale . So far, interference has been seen with objects up to $\sim 10^4$ amu in mass , with no sign of collapse, thereby affirming that any collapse mechanism (if it exists) must occur beyond this scale or at rates small enough not to have shown up. Future proposals involve nanocrystal interferometry and optomechanical systems, which could reach superposition masses of 10^9–10^{11} amu, significantly expanding the testing ground.

Some prominent models in the objective collapse category include: • GRW (1986) with discrete hits . • CSL (Pearle 1989, Ghirardi et al. 1990) continuous version . • Diosi–Penrose (DP) gravity-induced collapse: Proposed independently by Lajos Diosi (1989) and Roger Penrose (1996) , this idea ties collapse to gravity. Penrose argued that placing a mass in superposition of two locations creates a superposition of two different spacetime geometries, which might be unstable. He estimated a collapse time $T \sim \hbar/(\Delta E_G)$ where ΔE_G is the gravitational self-energy difference between the two mass configurations . In effect, gravity might provide an objective measure for when superpositions become too "heavy" and should collapse. The DP model is not as sharply formulated as GRW/CSL (Penrose's is more a conjecture than a defined stochastic equation, though Diósi gave a dynamical model). It suggests a localization rate that increases with mass and separation. Experiments with isolated macroscopic superpositions (like a tiny mirror in a superposition of two locations) are conceptually proposed to test this in the future. Recent work has aimed to refine and test DP, and some experimental bounds (from for instance LIGO mirror fluctuations or matter-wave interferometry) already challenge the simplest gravity-collapse estimates . • Continuous gravity-related decoherence (not exactly objective collapse but related): Some approaches consider that gravity or other fundamental fields might induce decoherence (like fluctuations in spacetime metric causing phase randomization). However, these often result in decoherence (suppressing interference) rather than true collapse (selecting an outcome).

An attractive feature of objective collapse theories is that they can in principle account for the Born rule as a natural consequence of the dynamics. The theory is genuinely stochastic, so the "probabilities" are objective frequencies of random events. If constructed properly (as GRW/CSL are) to collapse onto position eigenstates with probability density $|\psi|^2$, they automatically give Born rule for position measurements. For other observables, one can show that dynamical collapses in space tend to produce outcomes consistent with the Born rule as well, especially when combined with environmental decoherence which pushes the wavefunction into localized "pointer" states before collapse completes .

One must also consider energy conservation: collapse mechanisms often inject energy into the system (the local- ization "jolt"). For GRW, one can estimate a very tiny but nonzero heating of matter. The chosen GRW rates were originally set such that this heating is negligible. Nonetheless, precision experiments (like cold atom gas heating or spontaneous photon emission) can sometimes constrain such effects. Modern CSL models introduce a correlation in the noise (colored noise) to mitigate energy production , preserving thermodynamic consistency better.

Conceptually, objective collapse theories are satisfying to those who want an observer-free resolution of measure- ment. In these theories, even if no conscious observer ever looks at a system, if it is sufficiently macroscopic the wavefunction will collapse (e.g., a latent image forms on a photographic plate even without an observer, because the silver atoms collapse to either developed or not). This fits with our intuition that an event like a radioactive decay "really happens" even if not observed, and triggers collapse of a Geiger counter state. Standard quantum mechanics could only say it becomes entangled with environment; collapse models say it actually collapses by itself after a short time.

The downside is that we have introduced new physics without direct evidence so far – we have to choose parameters like collapse rate λ and localization scale r_C somewhat arbitrarily (guided by "what would solve the measurement problem without conflicting known facts"). The canonical values ($\lambda \sim 10^{-16}\,\mathrm{s}^{-1}$, $r_C \sim 10^{-7}\,\mathrm{m}$) were suggested by GRW as a reasonable guess that avoids conflict with electron diffraction and latent image formation, etc. . These values are not sacred; experimental bounds have since tightened the window for such parameters . If experiments keep finding no deviation, collapse models will face pressure – either the parameters must be pushed to limits where collapse happens so rarely that the theory is almost indistinguishable from ordinary quantum mechanics except for absurdly large systems, or one might conclude nature doesn't use that mechanism.

It's worth mentioning that objective collapse theories are intrinsically nonlinear and non-unitary, which means they do not fit into the standard Hamiltonian paradigm. This raises issues of compatibility with special relativity (nonlocal and nonlinear often implies potential for superluminal signaling unless carefully formulated). Ensuring relativistic consistency is a major open problem. Some progress via relativistic CSL and field-theoretic models exists (e.g., Tumulka's "flash" ontology for GRW in relativistic context) , but a generally accepted relativistic collapse theory remains elusive.

In summary, objective collapse models provide a well-defined mechanism for wavefunction collapse, thereby offering a straightforward solution to the measurement problem: wavefunctions of macroscopic systems just don't remain in superposition for long, thanks to an underlying physical collapse process. Measurements are just a special case where the collapse is essentially guaranteed by the interaction of microscopic and macroscopic, causing the latter to collapse and hence registering a definite result. These theories are experimentally testable (and indeed being tested at the boundary of quantum and classical) . They do add new physics and thus far lack direct confirmation, but they stand as a serious attempt to complete quantum mechanics by removing the privileged role of "observer" and making the dynamics universal. If eventually an experiment sees an anomalous loss of coherence or spontaneous noise consistent with collapse parameters, it would revolutionize physics and validate this approach. Until then, objective collapse remains a bold and intriguing proposal on the table, often considered alongside many-worlds and Bohmian mechanics as one of the primary solutions to the measurement puzzle.

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VII. Decoherence and Emergence of Classicality

Decoherence is not an interpretation of quantum mechanics per se, but rather a physical process that has become central to understanding how classical behavior emerges from quantum systems . Any discussion of the measurement problem today must incorporate the insights from decoherence theory, because decoherence provides a mechanism whereby environmental interactions effectively produce the appearance of wavefunction collapse (or at least the suppression of interference) in a system.

The basic idea of environment-induced decoherence, developed by Zeh, Zurek, Joos and others in the 1970s–1990s , is that when a quantum system becomes entangled with a large environment (including, for example, the many degrees of freedom of a measuring apparatus), the reduced state of the system (obtained by tracing out the environment) loses its quantum coherence. Specifically, consider the system-apparatus entangled state from Eq.,(3): $\sum_i c_i |s_i> \otimes |A_i>$. Now include an environment E (photons, air molecules, etc.), which will typically interact slightly differently with the apparatus in state $|A_i>$ versus $|A_j>$. As a result, the total state becomes $[-\Psi_{S+A+E} >= \sum_i c_i, |s_i> \otimes |A_i> \otimes |E_i>,]$ where $-E_i>$ are (un-normalized) environment states that got correlated with the apparatus state $|A_i>$. Because the environment has a huge number of degrees of freedom, the states $|E_i>$ for $i = j$ are practically orthogonal (their overlap $<E_j|E_i>$ is extremely small for $i = j$, meaning the environment states encodes a record of which outcome occurred). Now, if you look at the reduced density matrix of the system+apparatus (tracing out E): $[\varrho_{S+A} = \mathrm{Tr}_E |\Psi>!<\Psi| = \sum_{ij} c_i c^*, |s_i, A_i>!<s_j, A_j|, <E_j|E_i>.]$ Since $<E_j|E_i> \approx \delta_{ij}$, all the off-diagonal terms $(i = j)$ in ϱ_{S+A} are suppressed. In the idealized limit of $<E_j|E_i> = 0$ for $i = j$, ϱ_{S+A} becomes $[\varrho_{S+A} \approx \sum_i |c_i|^2, |s_i, A_i>!<s_i, A_i|,]$ which is a statistical mixture of different outcomes, with probabilities $-c_i|^2$. This is exactly as if the wavefunction had collapsed with the Born rule. Interference between the $|s_i, A_i>$ terms is gone for all practical purposes (one cannot observe interference without carefully recohering the environment, which is practically impossible). The basis $|s_i, A_i>$ that retains coherence internally but not between each other is sometimes called the pointer basis , because these are the states that the apparatus (pointer) gets "stuck" or "pointing" in due to environment monitoring. They are typically approximately the eigenstates of whatever macroscopic quantity the environment continually measures (like position of a grain of dust via scattering of photons, etc.). Zurek has formalized selection of the pointer basis by stability criteria (the pointer states are those robust to environmental Heisenberg-picture perturbations, i.e. that become minimally entangled with the environment) .

The concept of decoherence thus addresses the preferred basis problem and the apparent quantum-classical tran- sition: why we don't see superpositions of macroscopic states. It shows that even if the state of the universe is a giant superposition, it is as if each branch has collapsed when viewed locally, because interference between branches is destroyed exponentially fast by decoherence. For a macroscopic superposition, the decoherence timescale can be absurdly short (e.g., a dust grain at atmospheric pressure decoheres from a spatial superposition on the order of 10^{-31} seconds !). Even in intergalactic space, stray photons would decohere a grain in $\sim 10^{-7}$ s . In laboratory conditions, mesoscopic superpositions (like in SQUID flux states or BECs) might decohere in microseconds or less, unless extreme isolation is maintained.

Does decoherence solve the measurement problem? In a strict sense, not by itself. Decoherence explains why superpositions become impractical to observe, and why definite-looking outcomes emerge in each branch, but it does not explain why a particular branch is realized to the exclusion of others. After decoherence, one is left with a still-entangled state of system+apparatus+environment, albeit one that is for all practical purposes a mixture of classical alternatives. If one takes an Everettian view, one says: indeed all alternatives exist, decoherence just prevents them from interfering (splitting worlds). If one takes a Copenhagen or collapse view, one would say: at this point, it is safe to update our description to a collapsed density matrix (since interference is gone), and treat it as "now the system is in one of those eigenstates, we just don't know which." In other words, decoherence pushes the burden of collapse from the microlevel to the macrolevel: the collapse problem is greatly ameliorated, because the system has effectively already diagonalized in a stable basis, but if one insists on a single outcome, one still might need to say that the quantum state has collapsed into one term of the mixture. However, one could argue that this last step is more a matter of interpretation. If one is content with the ensemble interpretation or with Everett's interpretation, decoherence basically does all the work needed: it provides a mechanism for emergent classicality and the appearance of wavefunction collapse.

One important offshoot of decoherence theory is the idea of Quantum Darwinism proposed by Zurek and colleagues . Quantum Darwinism posits that the objective reality of certain observables arises because the environment acts as a communication channel that proliferates (broadcasts) information about the system to many fragments of the environment . In effect, multiple observers can indirectly access a system by intercepting bits of the environment (photons, etc.) and will all agree on the outcome because the environment has redundantly imprinted the same information (the pointer state of the system) across many degrees of freedom. Only certain states can be recorded in this redundant fashion (the pointer states). Those states are the ones that "survive" Darwinian selection by the environment; hence the term Darwinism. This framework explains why we see a classical objective world: the environment has selected for stable states and made their information widely available, so everyone observes the same classical outcome, not a subjective or varying one. There have been experiments in quantum optics that observe the spread of information into environment subspaces consistent with Quantum Darwinism predictions (seeing that observers can independently pick up the same information from different fractions of the environment) .

Another extension is Consistent (or decoherent) histories formulated by Griffiths, Omnès, Gell-Mann, and Hartle. This interpretation uses decoherence to define sets of alternative histories of a system that are mutually exclusive and have well-defined classical probabilities (because interference between those histories is suppressed) . Each such consistent set of histories can be considered a logical framework where normal probability rules apply. One does not need wavefunction collapse; instead one analyzes quantum events in terms of these histories. However, consistent histories suffers from non-uniqueness (multiple incompatible sets of histories can exist) and it remains more of a formalism than a compelling physical interpretation for many.

From a practical perspective, decoherence has been enormously successful. It has been quantitatively confirmed in numerous experiments. For example, the classic experiments by Brune et al. (1996) observing decoherence of a "Schrodinger cat" state of a few photons in a cavity by using Rydberg atoms ; or the works with fullerene molecules showing how interference disappears as one introduces background gas (which decoheres the molecular position) . Quantum computing as a field is essentially the engineering struggle against decoherence: qubits need to be isolated to preserve coherence, or actively corrected faster than decoherence destroys the information. The success of classicality in our everyday world is entirely attributed to rapid decoherence of relevant degrees of freedom.

In context of interpretations: • In Copenhagen, decoherence provides justification for where to put the Heisenberg cut: large systems decohere, so by the time a signal is amplified to a macroscopic scale, one can safely say it has resulted in a definite classical record. • In many-worlds, decoherence is the mechanism of world branching and ensures worlds do not interact.

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• In Bohmian mechanics, decoherence is also important: it explains why particles get funneled into effective trajectories corresponding to classical outcomes. (Bohmian particles still have trajectories regardless, but decoherence ensures that empty wave packets don't later interfere and cause weird deviations. It explains the emergence of classical Newtonian paths as those guided by robust branches of the wavefunction). • In objective collapse theories, decoherence from environment often works in tandem with collapse. Collapse models typically need to be calibrated such that they overwhelm decoherence only when needed. Also, environment itself can induce effectively a collapse by measuring the system; collapse theories may consider collapses of environment plus system, etc.

Thus, while decoherence alone might not be a full interpretation, it resolves large parts of the puzzle: it solves the preferred-basis problem and shows that the measurement apparatus will always have a pointer basis in which it is effectively classical. It also shows that as soon as a microscopic superposition "leaks" information into the environment, it will not remain a coherent superposition from any practical viewpoint. What remains, arguably, is just the "inverted commas" problem: whether one needs to interpret the remaining mixture as truly "either/or" (with one realized) or as "both, but don't interfere." That separates interpretations like collapse vs many-worlds vs epistemic.

In summary, decoherence provides the mechanism by which quantum possibilities decohere into apparent classical realities. It is an essential part of any modern resolution of the measurement problem, often serving as the bridge between the quantum and classical descriptions. It shifts focus from wavefunction collapse to the entangling role of environments. With decoherence in hand, the measurement problem is far less mysterious: we understand that a macroscopic measuring device cannot remain in a coherent superposition due to unavoidable environmental coupling

. The "collapse" effectively happens through environmental monitoring. The only question is whether one declares that process by itself sufficient (as many would, following Everett or consistent histories), or one still adds a collapse postulate on top (as collapse models do to remove even the formal existence of the other branches), or one says that it's simply an update of knowledge once decoherence has happened (Copenhagen modern view). Regardless of interpretation, decoherence is a crucial ingredient that any satisfactory theory must incorporate to account for the emergence of the classical world.

VIII. Qbism and Epistemic Interpretations

QBism (Quantum Bayesianism) and related epistemic or information-theoretic interpretations offer a very different perspective on the measurement problem: they argue that the problem largely dissolves if one understands the quantum wavefunction not as a literal physical object, but as an expression of an observer's information, beliefs, or betting commitments about the outcomes of experiments . In this view, the supposed "collapse" of the wavefunction is nothing mysterious at all – it is simply the Bayesian updating of an agent's state of knowledge after acquiring new data (the measurement result). There is no physical collapse happening in the world, just a logical change in the agent's information.

QBism, championed by Christopher Fuchs, Rüdiger Schack, N. David Mermin and others , is an explicitly agent- centric interpretation. It asserts that quantum probabilities (via the Born rule) are subjective degrees of belief (Bayesian probabilities) that an agent assigns to possible outcomes of measurements. The quantum state (wave- function or density matrix) is thus a compendium of these personal probabilities; it does not exist "out there" in the external world, but in the agent's mind (or notebook). When a measurement is made, the agent updates their quantum state in accordance with the result – this is a standard Bayesian conditioning (the analog of collapse). According to QBism, there is no measurement problem because quantum theory never intended to describe an objective process of wavefunction collapse. It is a tool for an agent to organize their expectations. The "outcome" is a personal experience for the agent. Of course, different agents can communicate their experiences and update their states accordingly, so it's not solipsism, but QBism emphasizes that quantum theory strictly only gives an individual agent's expectations for their own experiences.

By taking this stance, QBism avoids any need for a special mechanism for collapse. The Born rule itself is viewed not as a law of nature, but as an empirical addition to Dutch-book coherence or a consistency requirement on how an agent should assign probabilities to different outcomes given a quantum state and an experimental apparatus. In fact, Fuchs and Schack derived the Born rule within QBism by considering a consistency (or symmetry) condition on an agent's probability assignments (called the "urgleichung") . The measurement problem is reframed: the question is not "how does nature pick an outcome?" but "how does an agent update their beliefs correctly when they see an outcome?"

Epistemic interpretations akin to QBism often draw an analogy between quantum collapse and the classical Bayesian update. For example, if I have a probability distribution for tomorrow's weather (30

One might ask: in QBism, what is the ontology? If the wavefunction is just an agent's belief, what is actually happening in the world? QBism deliberately stays quiet on the ontology of reality. It accepts a kind of pragmatism: quantum theory is a tool for making wise decisions (placing bets) about experimental outcomes, not a mirror of reality itself. The "world" that lies beyond our experiences is taken as potentially too nebulous to describe; all we have are our interventions (measurements) and the consequences (outcomes). Quantum theory provides a map from the former to probabilities of the latter. That said, QBists like Fuchs often invoke the idea that each measurement event is a creative act: the outcome is not predetermined but is something new that comes into being (some echo of Wheeler's "participatory universe" idea). But they stop short of giving a mechanistic picture of what happens at measurement – it's simply an interaction between agent and system, and the outcome is an experience for the agent.

Another epistemic interpretation is Relational Quantum Mechanics (RQM) proposed by Carlo Rovelli . RQM suggests that the quantum state of a system is always relative to another system (typically the observer or measuring apparatus). There is no absolute state of a system; different observers can give different accounts. For instance, in Wigner's friend scenario, the Friend has seen an outcome (so relative to Friend, the system's state is collapsed), but Wigner (outside) can still consider the friend+system in a superposition. Both are correct, each relative to their frame of information . In RQM, a "fact" (outcome) is only such relative to a system that interacts. This avoids paradoxes like Wigner's friend by rejecting the notion of a single, observer-independent reality for quantum events. The measurement problem in RQM is handled by saying: when a quantum event (interaction) happens between two systems, it establishes a relation (correlation) that is a fact between those two systems, but not necessarily for others. Thus, each "collapse" is perspective-dependent. There is no universal collapse or single world, but also no branching worlds; rather a mesh of interrelated facts between systems. RQM is philosophically intriguing, but it can be challenging to digest. It effectively says the quantum state and outcome only have meaning when specifying "as seen by which observer." This is consistent with a relational view of reality (somewhat like special relativity taught us time is observer-dependent, RQM suggests outcomes are observer-dependent). Provided no contradictions arise when observers communicate (and RQM claims there are none, each will update their description upon interaction, aligning facts), the theory is consistent .

In both QBism and RQM, the collapse is not a physical, problematic process: it is either an update of information or a transition from being a superposition relative to one observer to being definite relative to another, via interaction. The "problem" of which outcome occurs is answered trivially: whichever one the agent experiences (QBism), or whichever one becomes relationally defined in the interaction (RQM). Why the Born rule? In QBism, because it's the rational way to assign probabilities (and it has been derived from operational desiderata) ; in RQM, because standard quantum conditional probabilities apply within each frame.

A common criticism of these interpretations is that they seem to “give up” on describing reality. They are sometimes branded as anti-realist or instrumentalist. QBists embrace that to a degree: they say quantum theory’s role is not to picture reality but to help us navigate it . They emphasize the personalist Bayesian view where probability is degree of belief, and there is no “god’s eye view.” RQM tries to remain realist but makes reality relational (no absolute facts, only relational ones), which some find hard to swallow. Both approaches also have to contend with the question: if the wavefunction is subjective, how come different observers can eventually agree on outcomes? QBism says observers have to update based on communication; if Alice sees result and Bob later asks her, Bob must update his state to be consistent with Alice’s experience. The formalism allows this easily (via Bayesian conditionalization). No inconsistency arises as long as one carefully accounts that the quantum state assignments are observer-dependent . Still, it feels unusual compared to classical physics where we assume an objective state of affairs exists that all can in principle observe.

Nevertheless, QBism has provided fruitful insights and resolved some puzzles: for example, it rejects counterfactual questions like “what would have happened if a different measurement were made” as meaningless in a single-agent context, which dovetails with the idea that unperformed experiments have no results. It also handles well the scenario of Wigner’s friend by noting that Wigner’s state assignment and the Friend’s state assignment are different, but each is a valid reflection of their own information . There is no contradiction because in QBism the quantum state isn’t a single real thing to be either collapsed or not; it’s just each agent’s catalog of expectations.

Another viewpoint worth mentioning is the information-theoretic interpretation (Zeilinger, Brukner) which posits that the quantum state represents information (maybe in terms of yes/no questions that can be asked of a system) . These interpretations often tie quantum probabilities to fundamental limits on information. They share with QBism the idea that quantum mechanics is about knowledge and information constraints, not about objective wavefunctions.

In summary, epistemic interpretations like QBism effectively neutralize the measurement problem by declaring that the wavefunction collapse is simply the normal updating of an observer’s knowledge upon obtaining new data. There is no mysterious physical collapse to explain, because the wavefunction was never a physical wave to begin with, but a mathematical encapsulation of knowledge. The question “which outcome occurs in reality?” is answered: the outcome is an experience, and quantum mechanics only speaks to the probabilities of those experiences for an agent. There is only one outcome per agent (so no many-worlds multiplicity), and the probability rule is a normative rule for rational agents (to be consistent in their betting behavior or degrees of belief).

While some physicists find this approach liberating (removing the philosophical baggage of the measurement problem), others find it unsatisfactory or incomplete (it doesn’t tell us what is really happening or why these rules, aside from pragmatic reasons). It is, however, a consistent viewpoint, and it reminds us that ultimately any “measurement” involves an interaction and an observer who interprets the result; hence, maybe the cut was always between quantum formalism and our Bayesian inference, not between quantum and classical hardware.

Epistemic interpretations dovetail interestingly with advances in quantum information and quantum foundations, where people try to derive quantum theory from axioms about information (e.g. no faster-than-light signaling, prob- ability theory generalized by complex amplitudes, etc.). If quantum mechanics is fundamentally about information, then the measurement postulates might be seen as just rules in an inferential system, not physical dynamics.

In conclusion, QBism and similar interpretations resolve the measurement problem by a paradigm shift: they treat the wavefunction as an abstract computational tool tied to observers, and they equate collapse to the mundane act of updating information. In doing so, they bypass

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the need for physical collapse or parallel universes or additional variables, at the cost of giving up on an observer-independent quantum state reality. Whether one finds this compelling may depend on one's philosophical inclination regarding scientific realism and the role of the observer in physics. Regardless, these interpretations contribute a valuable perspective: they emphasize carefully what quantum theory actually says (and doesn't say) about the world and highlight that some of the "problems" might arise from forcing an interpretation of the formalism that the formalism itself doesn't mandate.

IX. Experimental Tests and Modern Developments

The quest to understand the quantum measurement problem has been significantly informed by experimental ad- vances and theoretical no-go theorems. While interpretations often make identical experimental predictions (being interpretations of the same theory), there are certain experimental contexts that illuminate the weirdness of measure- ment and, in some cases, constrain possible resolutions. Here we review several key categories of experiments and results:

A. Bell Tests and the Reality of Quantum Nonlocality

Perhaps the most important experimental developments in quantum foundations have been the series of Bell tests starting from the 1970s through the present. John Bell's theorem (1964) showed that any local hidden-variable theory (a possible approach to explain measurement outcomes deterministically) is at odds with quantum mechanics. Specifically, Bell derived inequalities that must hold for any local realist theory, and quantum mechanics predicts violations of those inequalities for certain entangled states. The prototypical scenario involves a pair of entangled particles (e.g. in the singlet spin state) shared between two distant observers (Alice and Bob) who each choose one of several measurement settings (different polarization or spin-axis angles) to measure. The statistics of their outcomes, when compared, can violate Bell's inequality.

Starting with Freedman and Clauser's test in 1972 and especially Alain Aspect's landmark experiments in 1982 , physicists have observed clear violations of Bell inequalities, in agreement with quantum predictions and contradicting local hidden variables. Over the decades, experiments have closed various "loopholes." In 2015, several groups (Hensen et al. at Delft , Giustina et al., Shalm et al.) conducted almost simultaneously the first loophole-free Bell tests, which closed both the locality loophole (ensuring measurements are spacelike separated, so no subluminal communication) and the detection loophole (ensuring a high fraction of pairs are detected so sampling bias can't explain results). For example, Hensen et al. used entangled electron spins in diamond separated by 1.3 km and achieved a statistically significant Bell inequality violation . These experiments strongly support that if there are hidden variables determining outcomes, they must be nonlocal (allowing instantaneous correlations beyond light-speed signals). In other words, they rule out a large class of "classical-like" theories where measurement outcomes pre-exist and are merely revealed.

The implications for the measurement problem: Bell tests show that any interpretation which tries to restore realism (definite outcomes determined by hidden variables) cannot maintain locality. Bohmian mechanics and collapse theories can accommodate this (they are explicitly nonlocal). Many-worlds skirts the issue by not having hidden variables at all but does imply a form of nonlocality in that the wavefunction of the two particles is entangled across space (though it doesn't allow signaling). Epistemic interpretations like QBism say Bell correlations are just observational facts we update on, but they don't provide a "reason" for the correlation beyond "that's how our probabilities work." Beyond Bell's original inequality, experiments have tested related concepts: • Leggett's nonlocal hidden- variable models: Some nonlocal models not identical to quantum predictions were ruled out by experiments (e.g. Aspect, Groblacher 2007). • Leggett-Garg inequality: Tests of macroscopic

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realism (whether a single system's properties can be considered definitively either/or at different times). Experiments with superconducting qubits, for example, violate Leggett-Garg inequalities, suggesting that a macroscopic system cannot be assigned definite values independent of measurement (similar in spirit to Bell but in time-domain). This supports the quantum view that superpositions are real even for larger systems. • Kochen-Specker contextuality: Another theoretical result shows that hidden variables, if they exist, must be contextual (the outcome must depend on which other compatible ob- servables are measured together). Experiments on trapped ions and photons have confirmed quantum contextuality . This again underscores that any underlying classical-like description of measurement outcomes would be very exotic (contextuality defies classical intuition where measurement of one property shouldn't care about what else is measured alongside).

These fundamental tests collectively reinforce the stance that quantum measurement outcomes cannot be explained by any local realist picture. They put strong pressure on interpretations: if one had hopes of an underlying local deterministic story (like Einstein might have), those hopes are experimentally untenable. Instead, one must embrace nonlocality (as Bohm did) or the irreducible randomness of quantum mechanics (Copenhagen, collapse models) or the reality of many worlds or relationism.

B. Wigner's Friend and the Nature of Observer and Facts

As our ability to manipulate quantum systems advanced, thought experiments that were once only philosophical are becoming experimentally relevant. The Wigner's friend scenario, proposed by Eugene Wigner in 1961, imagines a friend in a lab performing a quantum measurement, while Wigner outside treats the entire lab (friend + system) as a quantum state. Quantum mechanics would allow Wigner to describe an entangled state where the friend is in a superposition of having seen outcome A and outcome B. But from the friend's perspective, she definitely saw a single outcome and perhaps even collapsed the wavefunction in her analysis. This raises the question: whose description is "correct"? Traditional interpretations would say Wigner's superposed state is only a description prior to him opening the door; once he interacts, there must be consistency where he too sees a definite outcome. Others (Everett) would say both are correct in their own frame, and become correlated when they meet.

Recent works have extended this to propose actual experiments. For example, in 2018, a theorem by Frauchiger and Renner argued that if quantum theory is universally valid (for friend and Wigner) and certain assumptions about logic of reasoning hold, one reaches a contradiction – suggesting that one of the assumptions (like observer-independent facts) must give . This was a theoretical "no-go theorem" that if interpreted strongly, challenges the idea of a single objective reality in quantum context. A subsequent experiment by Proietti et al. (2019) implemented a simplified Wigner's friend scenario with entangled photons, demonstrating in effect that two observers can arrive at inconsistent facts if they both use quantum mechanics naively . The experiment's logic followed a proposed inequality (by Bong et al. 2020) analogous to Bell's, which was violated. The interpretation of this is subtle: it doesn't mean reality is inconsistent, but it means that one of the assumptions (like "an observation yields a single fact that is the same for all observers") must fail if quantum mechanics holds. Indeed, relational QM and QBism would say "observer-independent fact" is the assumption to drop.

While these friend-style experiments are still small (with photons as "friends"), they lend support to interpretations where the wavefunction's collapse can be observer-dependent (RQM) or to many-worlds (where Wigner and friend end up in different branches). They pose a challenge to any interpretation that tries to maintain a classical objective reality for outcomes in an all-encompassing way.

C. Weak Measurements and Quantum Erasers

Weak measurement is a technique introduced by Aharonov, Albert, and Vaidman (1988) that allows one to gain partial information about a quantum system without causing a full collapse. In a weak measurement, the coupling between the system and measuring device is so weak that the system state is only slightly disturbed for each run, and only a very uncertain reading is obtained (so uncertain that many repetitions are needed to get useful info). By performing weak measurements both before and after a strong (projective) measurement, one can even infer conditional expectations called weak values. These can sometimes lie outside the usual eigenvalue range, which initially caused much debate.

Weak measurements have demonstrated seemingly paradoxical effects: for instance, Kocsis et al. (2011) weakly measured the momentum of photons passing through a double-slit and then post-selected on the interference pattern position, reconstructing average trajectories of photons that resemble the flow lines of the Bohmian pilot-wave theory. This suggests one can speak of an "average trajectory" without each photon having a well-defined path (no single photon's path is measured definitively). While weak measurements don't violate quantum principles, they give an empirical way to peek into a system without collapsing it entirely, offering insight into what happens during measurement. They support a picture of gradual decoherence and collapse, rather than an instant jump (though standard theory fully accounts for them via the density matrix formalism).

Another famous experiment is the quantum eraser. In the delayed-choice quantum eraser (Scully and Drühl 1982; Kim et al. 2000) , one can set up a situation where a particle goes through a two-slit setup and is detected, but a separate quantum system (e.g. a photon) carries "which-slit" information. If that information is left intact, interference disappears (decoherence due to entanglement). But one can later "erase" the information (e.g. by measuring the photon in a way that doesn't reveal which slit, like projecting onto an entangled basis), and condition on that, the interference pattern is recovered among those sub-ensembles. The striking part is the eraser can be done at a time after the particle hit the screen, giving the impression that one can choose to retroactively decide whether the particle behaved like a wave (interference) or particle (which-path). In reality, there's no retro-causation; the particle always had an entangled state with the which-path marker, and only when one examines joint correlations do the patterns emerge. But it reinforces Bohr's point: "No phenomenon is a phenomenon until it is a recorded (observed) phenomenon." The outcome (interference or not) depends on what you do with the information.

These experiments emphasize the role of information and knowledge in quantum measurement. They suggest the "collapse" is not an instantaneous irreversible event at the time of particle detection per se, but relative to the available information in the universe (if which-path info is still out there, interference is lost; if that info is erased, coherence is effectively restored for the conditioned sub-ensembles). For interpretations: • Many-worlds: the quantum eraser is just following unitary evolution of entangled particles; nothing surprising, just that if you entangle and then un-entangle (erase info), interference returns. • Copenhagen: complementarity is demonstrated; depending on experimental arrangement (i.e. whether which-path info is observed or erased), you either get interference or not.

• Information-based: it's about what the experimenter knows or could know. • Bohmian: the particle had a definite path, but the interference pattern is caused by the pilot wave which is impacted by whether the which-path photon is measured or not. Bohmian accounts exist that replicate the results (pilot wave carries phase information, etc.). • Collapse models: if collapse truly happened at detection, you might think interference couldn't be recovered, but since the detection is of one half of an entangled pair, collapse models would say either the whole entangled state collapses (which would ruin interference permanently) or some consistent approach must treat the erasure measurement as causing a new collapse that effectively sorts out subensembles that reveal interference. These subtleties mean collapse models must be carefully applied, but usually they are formulated to mimic QM in these scenarios, so they wouldn't contradict the observations.

D. Macroscopic Superpositions and Collapse Tests

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A direct way to approach the measurement problem experimentally is to push the boundary of superposition to larger and larger systems. If standard quantum mechanics holds, even huge objects can in principle be placed in superposition (the difficulty is isolating them from decoherence). If some new physics (like objective collapse) kicks in at some scale, experiments might see a deviation (loss of interference beyond what environmental decoherence predicts, or spontaneous localization events).

Interference experiments with large molecules have progressed remarkably. Starting with fullerene C_{60} in 1999 (Zeilinger's group), up to molecules of mass 2.5×10^4 amu in 2019 (Fein et al.) , showing beautiful interference fringes, confirming quantum coherence for objects composed of thousands of atoms . These experiments often use far- field diffraction or interferometers, and ensure that the internal temperature is low enough that thermal decoherence doesn't wash out the interference. The fact that interference persists sets constraints on collapse theories. The largest of these molecules still did not spontaneously collapse according to GRW/CSL within the experimental observation time, which helped rule out more aggressive collapse parameters. Proposed experiments aim to reach masses $> 10^6$ amu or even use nanoparticles (which could have 10^{10} atoms). There are serious proposals to use optomechanical systems where a tiny mirror or dielectric bead is prepared in a spatial superposition of two locations differing by say tens of nanometers, and then see if interference can be observed or if an anomaly (like DP gravity collapse) intervenes. So far, such a quantum superposition of a truly "macroscopic" object (visible to naked eye scale) hasn't been realized, but the field is advancing with quantum control of mechanical oscillators (LIGO mirrors have been put in near-ground-state, etc.).

Relatedly, experiments also search for spontaneous collapse signals. The aforementioned X-ray detection experi- ments (e.g. Curceanu et al., Donadi et al.) looked for radiation that would be emitted if nuclei experienced random collapse kicks. The absence of such X-rays at predicted levels has ruled out original GRW rates for certain parameter ranges, forcing collapse model proponents to adjust parameters or consider that maybe gravity (which wouldn't cause electromagnetic radiation in same way) is needed to cause collapse.

One interesting reported anomaly: In 2019, a team (Catalina Curceanu et al.) reported an unexpected excess noise in a cantilever experiment that could hint at CSL noise, but it's far from confirmed (and could be mundane). This shows such tests are ongoing.

Another cutting-edge idea: Interferometry with living organisms (like viruses, or perhaps eventually a small bacterium) to see if quantum superposition persists. That remains speculative for now due to technical challenges and the fact that living things are extremely decoherent internally (warm, many DOF).

On the theoretical side, results like Pusey-Barrett-Rudolph (PBR) theorem (2012) have impacted interpre- tations. PBR argued that if quantum predictions hold and if two different quantum states (for the same system) correspond only to subjective knowledge (psi-epistemic), then one can derive a contradiction unless those states cor- respond to actually different physical states (psi-ontic). In plain terms, PBR provided evidence that the wavefunction might be more than just knowledge; it suggested that epistemic interpretations face difficulties (unless they abandon an assumption like preparation independence). Proponents of QBism have pointed out that they indeed abandon the idea that quantum states have objective existence that different agents must agree upon without communicating, thus evading PBR. But PBR has been influential in convincing some people that the wavefunction is "real" (ontic) in some sense. Follow-up work by Matthew Leifer and others has expanded on distinctions between psi-ontic and psi-epistemic models .

Finally, a nod to quantum computing: building a quantum computer with many qubits is effectively demonstrating that tens or hundreds of two-level systems can maintain superposition and entanglement (so a superposition over 2^{100} basis states) without collapsing. As qubit counts rise, we're effectively testing quantum mechanics in larger Hilbert spaces than

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ever. If collapse were to occur spontaneously at some complexity threshold, it would become evident as we scale up quantum processors (assuming error rates are due solely to ordinary decoherence sources). So far, no deviation; errors in quantum computers are fully consistent with environmental decoherence and control imperfections, not spontaneous collapse.

X. Discussion and Open Problems

Despite tremendous theoretical and experimental progress, the quantum measurement problem is not universally regarded as "solved." Each interpretation or modification of quantum mechanics has its pros and cons, and none has achieved universal acceptance. In this section, we summarize the key points of contrast and the remaining open issues.

A. Comparative Summary of Interpretations

Let us briefly compare how each major interpretation reviewed tackles the measurement problem: • Copenhagen (Standard): Postulates a collapse rule but does not explain it. Solves the problem pragmatically by dividing the world into quantum system vs. classical apparatus. Advantages: operationally easy to use, historically successful. Disadvantages: conceptually unsatisfying, relies on an ambiguous "cut" and treats measurement as special and outside the unitary framework. It leaves open "when/where does collapse occur" and indeed whether the wavefunction is anything more than a calculational device. • Many-Worlds (Everett): Eliminates collapse entirely. The universal wavefunction's unitary evolution is all that ever happens. Measurement results in branching of worlds via decoherence. Advantages: solves definite outcomes by having all outcomes occur (so no randomness at fundamental level), and is a local, deterministic theory (except that one must interpret probability in a self-locating sense). No ambiguity about when collapse occurs (never). Disadvantages: the ontological extravagance of innumerable unseen worlds; the difficulty of deriving the Born rule and why an observer should internalize the $|c_i|^2$ weighting as probability (though much work addresses this); and an apparent lack of falsifiability (since other branches are inaccessible). Some also question how to incorporate true contradictions like a "dead and alive cat" when each branch sees only one – many-worlds says both states exist but segregated. While decoherence explains the segregation, the existential status of other branches remains a philosophical point of contention (are they "equally real"? etc.). Nevertheless, many-worlds has grown in popularity among physicists comfortable with a realist but non-collapsing view, especially in cosmology where no external observer exists to collapse the wavefunction of the universe. • Bohmian (Pilot-Wave): Augments quantum mechanics with particle positions to ensure one definite outcome path occurs. Measurement is explained by particles following one branch of the wavefunction (the one that ends up with apparatus pointer moved, etc.), while other branch waves become empty. Advantages: provides a clear concept of reality – particles are always somewhere; no fundamental randomness (apparent randomness from unknown initial conditions); conceptually continuous transition from quantum to classical (in the classical limit, Bohmian trajectories obey Newtonian mechanics under certain conditions). It is explicitly a solution to the measurement problem as emphasized by Maudlin and others . Disadvantages: must be nonlocal (which sits fine with Bell's theorem, but is conceptually jarring and in tension with relativity); not easily extensible to all of quantum field theory in a Lorentz-covariant way (though specific advances for particular cases exist); and like many-worlds, it is empirically equivalent to standard QM in its domain, making it hard to test (although some claim possible nonequilibrium distributions could show up as deviations in cosmology , those are speculative). Some find it inelegant to have a dynamics where the wavefunction evolves in configuration space and pushes particles, but particles don't push back. Yet, Bohmian mechanics stands as a consistent and appealing picture for those who want determinism and clarity at the cost of introducing additional structure. • Ob jective Collapse (GRW/CSL): Modifies the dynamics to include collapse as a physical process. Advantages: in principle, solves measurement problem by providing a unified dynamics – a

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microscopic system has very infrequent collapses, but a macroscopic system (many particles entangled) collapses essentially immediately, thus measurements always yield one outcome. No separate postulate or observer effect needed. Can be experimentally distinguished from standard QM given sensitive enough apparatus or large enough superpositions, hence it's scientific in the Popperian sense. Disadvantages: Introduces new parameters (collapse rate, localization scale) that are not yet observed – so far only upper bounds exist, thus it's not confirmed; generally violates conservation laws or Lorentz invariance unless more complex formulations added; plus, one might question if it truly "explains" collapse or just shifts the mystery into a new stochastic mechanism (why those collapse rates? why that noise field?). If collapse is fundamentally random, one might ask about underlying causes (some models connect to gravity, as Penrose suggested). So objective collapse theories are semi-phenomenological at this stage. They face the challenge of potential conflict with observed physical laws (energy increase, etc.), but careful model building (colored noise, relativistic "flash" collapse models) attempts to mitigate that . • Decoherence-based (No-collapse interpretations): Not an interpretation alone, but an ingredient. If one embraces an interpretation like consistent histories or many-worlds, decoherence nearly solves the issue by itself. Even Copenhagen users can say: "Collapse occurs effectively due to decoherence at the apparatus, so we don't need to worry about the microscopic superposition." The open problem, as stated, is that decoherence doesn't select one branch – it gives an improper mixture. So one must supplement decoherence either with "each branch is a world" (Everett) or "the system actually is in one branch (and only ignorance makes it a mixture)" which is fine if one implicitly accepts a Copenhagen stance that somehow the system did pick a branch (perhaps via environmental entanglement one can use collapse out of system-of-interest into environment). The environment effectively plays the role of observer in modern descriptions. • QBism / Epistemic: Reinterprets the meaning of the quantum state and collapse. Advantages: logically avoids any paradox because it refuses to treat the wavefunction as a literal physical entity. Thus, there is no weird physical process, just Bayesian updating. The emphasis on personal probabilities is consistent and avoids issues like Wigner's friend paradox: for the friend, the collapse happened (because her knowledge updated); for Wigner, the friend+system is still in a superposition relative to him. No contradiction because they are talking about different quantum-state assignments (their own). It brings quantum mechanics conceptually closer to other fields of science where updating predictions on new data is normal. Disadvantages: many physicists are uneasy with the strongly subjectivist angle – it seems to defy the idea of an objective reality that physics seeks to describe. There is also the challenge of how to interpret what the formalism implies about the world if one insists it's only about experience. Does QBism imply a kind of solipsism or idealism? QBists say no, each of us is a physical system to others, but the theory doesn't provide a God's-eye view, only each agent's view. This softens the measurement problem but shifts to a philosophical position about the role of observers. Another issue: if quantum theory is "just a tool," one might feel unsatisfied about not understanding what is really happening in measurement (like is Schrodinger's cat both states until we open the box? QBism would say the quantum state "dead+alive" reflects your knowledge; the cat might have experienced one outcome long before you opened the box, and the cat itself updated its subjective state while you remained ignorant). • Relational: Similar to QBism in outcome (no single absolute state), but tries to be realist by saying reality is relations. That notion leads to potential questions: can one formulate it clearly and does it solve all paradoxes? It solves Wigner's friend by saying Wigner's description and friend's description are both true, but relative to different systems. An open problem here is whether one can find a way that all observers' accounts can be merged or is there a constraint that prevents inconsistency (Rovelli argues consistency is maintained because if observers exchange information, that is an interaction that brings about new relations where they agree). • Superdeterminism: Although not requested, a comment: one way to avoid the randomness is superdeterminism (the idea that initial conditions of the universe might be correlated with choices of measurements in Bell tests, thus circumventing Bell's assumption of measurement setting independence). This is very speculative and controversial because it undermines the ability to do free experiments, but some (e.g. 't Hooft, and more recently Sabine Hossenfelder and Tim Palmer) have entertained it. If everything including our "free will" to choose settings is pre-determined and correlated with particle states, local hidden variables could be possible. However, this line is generally not mainstream and remains hypothetical. It's relevant to measurement problem only insofar as it tries to restore a deterministic local reality at the expense of a huge conspiracy in initial conditions. Experiments cannot test "free will" assumption easily except by random setting choices from cosmological sources (as done by Zeilinger's group using distant quasars' light to pick settings, which found violation of Bell still , pushing any conspiracy to early universe).

B. Quantum Measurement in Quantum Field Theory and Gravity

Another layer of open problems: extending these interpretation debates to quantum field theory (QFT) and quantum gravity. Measurement in QFT (especially with relativistic causality) raises challenges like the Unruh effect and whether a clear Heisenberg cut can be defined in curved spacetime. Some recent work like by Fewster and Verch (2023) examines measurement in algebraic QFT , where they try to define local measurement operators that don't break causality. The conclusion tends to be that exactly localized projective measurements are tricky in relativistic contexts – you can't simply collapse a field in one location without causing issues, leading to discussions of "impossible measurements" in QFT . These are more technical aspects, but any resolution of measurement problem should ideally be compatible with relativity and QFT.

In quantum gravity or cosmology, if no external classical world exists (the universe as a whole), the meaning of measurement is subtle. Decoherence via the environment is often invoked in cosmology (e.g. to explain the emergence of classical perturbations in inflation: the environment is the quantum state of other modes or a bath). But ultimately, in a closed universe, one may need to lean on interpretations like many-worlds or histories (Hartle- Gell-Mann consistent histories for cosmology). The Wheeler-DeWitt equation $H|\Psi\rangle = 0$ for the universe has no time; understanding "measurements" in that context is an ongoing conceptual struggle. Some approaches like the "quantum Darwinism" in cosmology or observers as part of the wavefunction (the "universe's density matrix") are being explored.

Another frontier: if gravity is fundamentally quantum, can it cause or assist collapse? Penrose's suggestion is one way. Experiments to entangle two masses via gravity (e.g. Bose et al.'s proposed test of entanglement mediation) might indicate whether gravity acts as a quantum channel or causes decoherence. If such experiments show gravity can entangle quantum objects (which people hope to test in the coming decade), it would support the idea that gravity itself doesn't cause collapse at least at that scale, thus pushing the need either to include gravity in quantum framework or look for collapse at higher mass scales. Conversely, if we saw an unexpected loss of entanglement when gravitational interaction is involved, that could hint at a fundamentally decohering role of gravity.

C. Open Conceptual Questions

Some of the enduring open questions and debates include: • Is the wavefunction ontic (a real physical thing) or epistemic? The PBR theorem gives conditions under which it must be ontic if one believes in objective reality of measurement outcomes and independence of state preparations . Epistemic interpretations have to find loopholes in PBR assumptions (like not allowing independent state preparations). • Can we have an entirely consistent story of measurement within quantum theory that doesn't separate classical and quantum? Many-worlds claims yes (but you must accept many worlds), Bohm claims yes (with extra variables), objective collapse claims yes (with modified equations). Copenhagen historically said no need, but most physicists would prefer a yes. • The role of consciousness : While not scientifically popular (and explicitly the user said not to mention QWD theory which might relate to a consciousness-caused collapse theory), historically people like Wigner and Stapp considered whether consciousness plays a

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fundamental role in collapse. Modern neuroscience-informed views mostly dismiss that (and objective collapse models have essentially taken the place of that idea by attributing collapse to complexity or gravity, not conscious- ness). Still, philosophically, the "problem of the observer" intersects with philosophy of mind if one wonders what constitutes an observer in quantum mechanics. Most interpretations nowadays try to avoid invoking consciousness as a special factor, treating observers as physical systems. • Can quantum mechanics be emergent from a deeper theory without a measurement problem? E.g., 't Hooft's ideas of deterministic hidden variables at Planck scale (which are superdeterministic) or proposals that quantum state arises from entanglement with environment via some principle. These remain speculative. If someone found a deeper theory (like a cellular automaton underpinning quantum am- plitudes) which at macro level yields apparent wavefunction collapse or branching, that could be revolutionary – but so far nothing compelling has been found.

From a pragmatic standpoint, many physicists adopt a kind of minimal stance: "Shut up and calculate" (as Mermin phrased it). With the advent of quantum information science, some focus changed: instead of "what is the meaning of the wavefunction?" the question became "what information processing power does quantum superposition give us?" That doesn't solve the measurement problem, but it shifts interest towards operational tasks (e.g. designing a quantum measurement that extracts maximal info without disturbing state too much, as in quantum tomography or weak measurement or quantum error correction that reverses "partial collapse" from decoherence). This has yielded practical advances (quantum cryptography uses the measurement disturbance principle for security, for instance). But the foundational question of "what actually happens in a measurement" remains for those who care about a coherent worldview.

D. Possibility of New Physics

It is worth noting that historically, many great physicists thought quantum mechanics might be replaced or expanded by a future theory that removes the measurement postulate as fundamental. For example, Einstein sought a more complete theory (hidden variables or other) because he was unhappy with indeterminism and wavefunction collapse. To date, we haven't found such a theory (except hidden-variable theories which remain one of the interpretations rather than new predictions, and objective collapse which is new physics but still awaiting confirmation). It's conceivable that a theory of quantum gravity might change our perspective on measurement (some have speculated that gravity could induce a nonlinearity in quantum mechanics that effectively acts like collapse). Or perhaps extended objects (string theory) smear out interactions enough to avoid hard projective measurements, though that seems unlikely to affect atomic physics scale.

One radical idea: maybe quantum mechanics needs slight modification to solve measurement problem. Objective collapse is one such, but there are also nonlinear quantum mechanics proposals (which typically conflict with experi- ment strongly, as Weinberg pointed out in 1989 and others tested in atomic systems). All tests so far confirm linearity to high precision, leaving little room for modifications except at very large scales or extremes.

Thus, an open problem is: do we accept the measurement postulate as fundamental (making quantum theory a two-tier theory for dynamics), or do we expect a future theory (or interpretation that becomes widely accepted) to unify it? Right now, it remains an open philosophical (and perhaps scientific, if collapse models get confirmed or ruled out) question.

XI. Conclusions

The quantum measurement problem has stimulated intense scrutiny since the inception of quantum mechanics. In this review, we have surveyed its essence – the apparent incompatibility between continuous unitary evolution and discontinuous collapse – and the manifold approaches

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developed to resolve it. Each interpretation or theory we discussed provides a different lens on quantum reality:

- The Copenhagen interpretation teaches us humility in assigning reality to the wavefunction and pragmatism in using the theory.
- The many-worlds interpretation offers a bold, expansive view where the mathematical formalism is taken as literally true, at the expense of a multiplicity of universes.
- Bohmian mechanics restores determinism and realism at the cost of explicit nonlocality and an extra level of description.
- Objective collapse models modify quantum dynamics to enforce single outcomes, introducing testable new physics that straddles the line between quantum and classical.
- Decoherence shows that much of the appearance of collapse can emerge from quantum entanglement with an environment – explaining why measurements have stable outcomes in practice (a crucial piece of any ultimate resolution).
- QBism and relational interpretations remind us that the theories we construct are, at the end of the day, about the information and experiences of observers – a provocative shift that potentially sidesteps the metaphysical quandaries by redefining their terms.

Despite their differences, all these approaches agree on the empirical core of quantum mechanics and thus are hard to distinguish experimentally (with the notable exception of objective collapse proposals). The choice between them often comes down to one's philosophical preferences: continuity vs. discreteness, realism vs. instrumentalism, determinism vs. indeterminism, parsimony vs. completeness. It may be that several of these interpretations are just rephrasing of one another at some deep level (e.g., decoherence within many-worlds yields a view not unlike Copenhagen for any single branch).

Experiments have thus far upheld standard quantum theory to every tested degree. Bell tests have eliminated broad classes of hidden-variable theories, reinforcing that any completed picture of quantum measurement must contain nonlocal or nonclassical elements. Tests of macroscopic superpositions and collapse effects are rapidly advancing, and the next decade might finally provide evidence for or against objective collapse ideas or at least push their viable parameter space to a corner. Wigner's-friend-type experiments are beginning to probe the observer's role more directly, perhaps pushing us to accept relational perspectives if their results hold in more elaborate settings.

As of today (2025), there is no consensus solution to the measurement problem among physicists. A plurality likely subscribe to a decoherence-informed Copenhagen view in practice, while acknowledging that foundational questions persist. Many-worlds has a strong following in the quantum foundations community and in cosmology. Bohmian mechanics has a dedicated group of researchers developing it further and applying it in quantum chemistry and other fields (where the notion of trajectories can be computationally useful) . Objective collapse is being actively tested by experimentalists working at the quantum-classical boundary. QBism and related approaches are influential in quantum information circles for providing an alternative mindset to think about quantum probabilities .

In closing, we emphasize that the quantum measurement problem is not merely an academic curiosity; it strikes at the heart of how we conceive reality through the lens of our best physical theory. Whether the solution comes from a new theoretical framework or a shift in interpretation, its resolution will profoundly shape our understanding of the quantum world. Until then, as experiments push further and theories are refined, the measurement problem remains a vibrant topic that continuously inspires both caution and wonder in equal measure. The story of Schrodinger's cat, in limbo between life and death, continues to captivate us – compelling us to examine what we truly mean by "observation" and "reality" in a quantum universe.

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