Everettian Interpretations of Quantum Mechanics

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Key points:

- The Everett or Many Worlds interpretation is claimed to be the only realist interpretation that can recover the empirical success of quantum theory in its relativistic and non-relativistic variants, its advocates suggest that it does so without any additions to the physics.
- The modern (or Oxford) version of the theory depends on a functionalist or patterns-based ontology that, while defended in other contexts in the philosophy of science, remains philosophically controversial.
- This version identifies branching events and selection of the branching basis with the physical processes of decoherence, and is thus dependent on developments of physical models for decoherence.
- Probability within Everettian theories is strongly contested and it's unclear whether the many distinct resolutions in the literature are mutually incompatible and thus undermine one another or should provide succour to the theory's advocates on the grounds that at least one of them may be right.

1 Introduction

The state-of-play in foundations of quantum mechanics in the mid-20th century suggested that the quantum measurement problem was solved and the way forward was via some kind of Copenhagen approach. However, that changed with the suggestion of new, radical interpretations, including Everettian Quantum Mechanics (EQM); these held the hope of providing a detailed understanding of the process of measurement and the relations between the quantum and the classical. In 1957, Hugh Everett III published his dissertation, supervised by

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John Wheeler, putting forward the relative-state approach to quantum mechanics (Everett (1957)). Everett's proposal did not treat measurement as a special process and instead argued that in some way, all possible outcomes occur. This interpretation eliminates the need for a projection postulate or any other changes to the quantum formalism. However, its modern version comes with a commitment to a branching multiverse, something that has been accused of being an extravagant cost (Marchildon (2011)). Indeed, on this view there really are countless alternative realities, or parallel worlds, some of which mirror our own with only the slightest variations, while others are entirely alien. Nevertheless, EQM is not a fringe view and has received much attention from physicists and philosophers alike. In fact, it is by a significant margin the most popular of the realist interpretations of quantum physics among surveyed physicists, see Shmahal (2025).

Modern EQM begins with the core physical thesis that quantum theory is universal, describing the evolution of a universal wavefunction purely through unitary dynamics, i.e. without any collapse. Measurement is understood not as a special process but as an ordinary physical interaction that correlates systems and observers. In essence, this actually gives the bare theory, first discussed by Albert and Loewer (1988) and analysed by J. A. Barrett (1999), which can be the seen as the basis of any no-collapse approach. EQM starts from this bare theory and then takes seriously the multiplicity that comes from unitary evolution of quantum superpositions and entangled states. This multiplicity points us towards a branching structure, whereby measurement outcomes are no longer unique (Marchildon (2015)). Instead, the evolving universal wavefunction includes different entangled parts, which can be understood as effectively isolated, quasi-classical branches or worlds. Philosophically, EQM is realist and deterministic. It takes seriously the world described by quantum theory and does not include fundamental probabilities. At its core, EQM can be understood under the banner of just taking quantum theory as is, with no additions to the physics.

EQM is taken to face two major problems: the preferred basis problem and the probability problem. The preferred basis problem concerns how the universal wavefunction is decomposed, leading to different classical-like branches. In principle, the wavefunction can be decomposed into infinitely many mathematically equivalent bases, all leading to a different branching structure. So, the question is, if we are going to give ontological weight to the wavefunction, how is one decomposition privileged over all the others? This question matters especially to the EQM advocate because the decomposition is meant to support a division into 'many worlds'. The second major problem is the probability problem, which asks how probability can make sense in a deterministic theory where all possible outcomes occur. In everyday quantum mechanics, probabilities reflect the chances of different outcomes, governed by the Born rule. In EQM however, every outcome happens in some branch, so it is not immediately clear what probability refers to. If nothing is genuinely uncertain, why should an observer assign probabilities to future outcomes? These two problems have received extensive attention within the literature and often distinguish between different versions of EQM.

Thus far, this EQM is still quite bare. In part, this is because there is not a consensus between Everettians on how to then understand next steps. Nevertheless, there are broad agreements. Most Everettians, Vaidman (1998, 2019) being the key exception, take the process of environment decoherence to explain the emergent branching structure in which different components evolve approximately independently. These decohered components behave like separate classical histories, but these worlds are not fundamental. Instead, they are higher-level, dynamically robust patterns within the wavefunction. Observers, as physical subsystems within the universal state, likewise branch during measurement-like interactions, producing multiple successor observers who each register definite outcomes. The classical world we experience is simply one such dynamically isolated branch. Decoherence also has the advantage of arguably solving the preferred basis problem as it is taken to select an effective basis with respect to which between-branch interference is overwhelmingly suppressed.

The probability problem divides more Everettians. A large group, stemming from seminal work by Deutsch (1999), Saunders (1993, 2010), and Wallace (2012), often called ‘Oxonian Everettianism’, uses decision theory to solve the problem. However, there are also alternative views focusing on self-locating uncertainty, envariance and metaphysics (McQueen and Vaidman (2019), Sebens and Carroll (2018), and Zurek (2003, 2005)). Some major areas of contention are how to understand the branches or worlds, and whether EQM is dynamically local or not (Ney (2024) and A. Wilson (2020)).

Taken altogether, modern EQM is physically unified but philosophically pluralistic. It offers a clean and mathematically conservative account of quantum theory, but introduces a rich metaphysical landscape involving multiplicity, emergent classicality, and indexical probability. What divides Everettians is not the physics but the philosophical interpretation of these features: what counts as a world, how probability should be understood, and how to conceptualize identity and uncertainty within a richly branching multiverse.

2 History

To understand the core of EQM, it is worth looking at the original work by Everett and others in the 1950s, 60s and 70s. In submitting his thesis in the 1950s, Everett identified key problems with the orthodox view of the time. In particular, that it included two distinct but incompatible processes: probabilistic collapse (process 1) and unitary evolution via the Schrödinger equation (process 2). Everett (1956)’s unpublished long thesis, titled ”The Theory of the Universal Wavefunction”, outlined even more problems with the accepted view such as the status of observers and various paradoxes. Importantly, Everett noted that quantum theory could not be applied to closed systems or to the universe as a whole, since these lacked the external observer required for process 1.

Everett's revolutionary step was to construct a theory based solely on process 2, leading to a pure wave mechanics based on unitary evolution. He proposed treating state functions themselves as fundamental entities, allowing for a universal wavefunction that described the entire universe. Crucially, he omitted all postulates relating to observation and collapse. Instead, he defined observers and measuring devices as physical systems, which themselves were subject to the quantum dynamics. Thus, measurement is a correlation-inducing interaction between subsystems. When an observer measures a quantum system, the composite observer-system evolves into an entanglement where each term contains a definite observer state correlated with a definite measurement outcome. Everett interpreted this literally, such that each element describes an observer who perceives a distinct result. This interpretation gave rise to the famous branching structure, though in the published thesis, Everett instead emphasised the relative-state aspect. He also argued that the different relative states were non-interacting, preventing an observer in one branch from learning about outcomes in others. Thus, he described memory as "not a linear sequence of memory configurations, but a branching tree, with all possible outcomes existing simultaneously in a final superposition with various coefficients in the mathematical model" (Everett (1957, p. 460)).

On probability, Everett (1957) claimed to derive the Born rule as subjective appearances to observers. He defined a measure based on the square amplitude of different relative-state components and argued that the ordinary probabilistic assertions hold true for almost all observers in the superposition (relative to that measure). However, his derivation remained somewhat unclear and would become a major point of interest. The difference between Everett's unpublished long thesis (1956) and his published relative-state paper (1957) was largely due to the influence of his supervisor, John Wheeler. The unpublished version focused heavily on the inconsistencies and problems with the orthodox view and included more philosophical analysis of pure wave mechanics. However, Wheeler was concerned about the reception such a critique would receive and thus pushed Everett to focus on the advantages of relative-states in applying to cosmology and the universe. Wheeler (1957, p. 464) himself took an even more cautious stance, stating that "it does not seek to supplant the conventional eternal observer formulation, but to give a new and independent foundation for that formulation" . See J. A. Barrett (2023) for more on Everett's views and related references.

Following the publication of the relative-state formulation, little attention was paid to it until the late 1960s and early 70s with the work of Neill Graham and Bryce DeWitt. Graham (1970) wrote his thesis on EQM, focusing more on the details of branching and probability. For Graham, it was the apparently classical nature of each relative-state that allowed it to be real in its own right. He explicitly used the terminology of 'parallel worlds' defining them as, "worlds [that] develop independently of each other according to the same physical laws" (Graham (1970, p. 19)). DeWitt, Graham's supervisor, showed particular interest in Everett's approach for cosmological applications. He outlined what he called the Everett-Wheeler-Graham (EWG) interpretation, identifying its key principles (DeWitt (1970, 1971)):

1. The formalism of quantum mechanics is sufficient; no metaphysics needs to be added
2. It is unnecessary to introduce external observers or a classical realm
3. It makes sense to talk about the state vector of the entire universe
4. The state vector never collapses, so the universe is deterministic
5. Measuring instruments are inessential to the foundations of quantum mechanics
6. The statistical interpretation need not be imposed a priori

Both Graham and DeWitt took different approaches to probability from Everett, utilizing relative frequency as their basis. DeWitt defined measures based on sequences of measurements yielding apparently chance-based results matching Born weights. Graham developed a more detailed two-step frequency method, first having apparatus measure relative frequencies in collections of identically prepared systems, then having these apparatus read by observers. He argued this approach avoided problems with Everett's measure, which he claimed lacked a clear physical meaning. It is through DeWitt (and Graham) that EQM became also known as the 'Many Worlds Interpretation' and received more attention. In fact, DeWitt (1971, p. 168) concludes "the mathematical formalism of [Everett's] quantum theory is capable of yielding its own interpretation" , a claim that is now central to modern EQM.

It is worth noting that Cooper and Van Vechten (1969) independently published a similar approach to EQM, retaining all branches of the wavefunction. They focused particularly on quantum mechanical consequences for the mind and argued that cognition itself is governed by the Schrödinger equation, with nothing special about consciousness. They did acknowledge differences between their view and Everett's. And in some ways, this is an early concept of the Many Minds Interpretation (Albert and Loewer (1988)).

In some ways, EQM adopts what might be called a naïve realism about quantum mechanics, since it takes a direct correspondence between the mathematical formalism and reality. The wavefunction is not merely a calculational tool or representation of knowledge but a real physical object. EQM solves the measurement problem by giving up the assumption that measurements have unique outcomes and embracing the multiplicity within quantum theory. This allows it to remove the projection or collapse postulate and thus have a unique, unitary dynamics. A consequence of this, is that EQM is deterministic. This deterministic character particularly attracted DeWitt, who thought it resolved any concerns surrounding indeterminism in quantum theory. The theory's commitment to pure wave mechanics leads to profound philosophical implications, especially by abandoning the uniqueness of the observer. Since accepting multiple outcomes is required to solve the measurement problem, Everettians take seriously each part of the full entangled state.

2.1 Alternatives

Following Everett, Graham, and DeWitt's work, there have been a number of Everett-type interpretations posited. One is of course modern EQM, but there are also other spin-offs.

In the late 1980s, the many-minds interpretation became briefly popular, following work by Albert and Loewer (1988) and Lockwood (1989). This view aimed to solve issues with probability and also provide a clear understanding of identity and minds within the Everett framework. On this view, there is a single, non-branching physical world described by a universal wavefunction, but each observer's mind splits into multiple minds that experience different outcomes. This moves the strangeness from physical reality to consciousness but faces its own challenges about the nature and individuation of minds, the mechanism of mental splitting, and how mind-body correlations are maintained.

A more popular approach is the consistent histories, or decoherent histories, view, developed by Gell-Mann and Hartle (1990), Griffiths (1984), and Omnès (1988). It identifies consistent families of histories, sets of sequences of events whose probabilities can be consistently defined. The approach treats quantum systems by assigning probabilities to entire histories rather than focusing primarily on measurement outcomes. Measurements do not play a fundamental role. Instead, the formalism treats measurement as just another physical interaction. One selects a consistent framework and within that framework assigns probabilities. The flexibility arises because there are many possible incompatible frameworks (families of histories), and the interpretation requires one to choose a single framework when doing probabilistic reasoning. While sharing EQM's rejection of collapse and commitment to unitary evolution, consistent histories differs by not necessarily committing to the reality of all histories. Instead, it emphasizes that different consistent frameworks can be used for different purposes, with no single framework being the true description; see Wallace (2008) for a detailed critique of this approach from the EQM perspective.

While consistent histories and modern EQM, depart from Everett's (1957) published theory, Rovelli (1996) returns to the notion of relative states. Relational Quantum Mechanics (RQM) holds that the quantum state of a system is never absolute but always relative to another physical system. According to RQM, properties like position, momentum, or spin are not intrinsic features possessed independently, but instead exist only relationally between interacting systems. What one system takes to be an event or a definite value may not be definite relative to another system that has not interacted with it. This relational ontology dissolves the traditional measurement problem by denying that there is a single, observer-independent state that collapses. Instead, the quantum formalism describes how physical systems store and update information about each other through interaction. Different observers (or systems) may assign different states to the same system without contradiction, because state assignments encode relational information rather than universal facts. RQM therefore emphasizes a sparse, information-based ontology and rejects the idea of a privileged observer or absolute quantum state.

RQM differs from modern EQM in both ontology and explanatory strategy. Whereas EQM treats the universal wavefunction as a real, physical object, RQM rejects the idea of a single, observer-independent quantum state altogether. For RQM, it is only the values of physical variables that we should include in our ontology and the quantum state is at best a useful theoretical construct. EQM therefore offers an abundant ontology, while RQM offers a perspectivalist ontology, which purports to be far sparser. Probability is also treated differently in the two interpretations: at least prima facie RQM has a less troublesome conception of probability than EQM because only one outcome becomes definite relative to a given observer, the Born rule is applied just as in standard quantum mechanics, without the need for special derivations. Similarly, the preferred basis problem does not arise in RQM. In RQM, the relevant basis is held to be fixed by the specific physical interaction between systems, not by decoherence across a universal state. Thus, RQM seemingly avoids both the major problems facing EQM. However, RQM comes with disadvantages. Its denial of observer-independent facts is a radical departure from the realist leanings of EQM. Here, two systems can legitimately disagree about the state of a third system, and there is no global perspective that reconciles their descriptions; see Rovelli (2025) for further details and references.

3 Physics

The physics of EQM is taken by its advocates just to involve the physics of the bare theory. While quantum physics is a huge subject, only a small portion is required to get to grips with the insights of EQM. For this purpose it's helpful to divide quantum measurement into two components, following Wallace (2008): the quantum algorithm is the process that physicists use to predict the outcomes of experiments; and the unitary quantum evolution explains, or purports to explain, why that algorithm is successful.

As mentioned above, it used to be thought that quantum mechanics' evolution should be divided into process 1 and process 2 – wavefunction collapse and unitary evolution (i.e. evolution that conserves probability e.g. the Schrödinger equation) respectively. The insight of talking in terms of the quantum algorithm is that only process 2 corresponds to the dynamics, and process 1 is rather to be understood as a methodology for extracting predictions at any particular time.

There are many sources of the technical details (see e.g. Binney and Skinner (2013) and Sakurai and Napolitano (2020)), so it suffices here to note that process 1 involves projecting the quantum state on to a subspace associated with a quantity of interest. The output is a probability for a range of values each of which might be discovered in measurement. What is important is that there is a clear and unique algorithm for evolving the quantum state according to process 2, and for the Everettian this applies at all times. Further, it is deterministic, and thus does not involve probabilities. The measurement problem may then be located as the question of why the probabilistic algorithm is so successful notwithstanding the universal applicability of process 2.

In other words, how does EQM get away without depicting process 1 as a real physical process. In particular, what legitimates excising the so-called 'observer effect' – the well-known claim that observing a quantum system changes it? And how does EQM dispel the claim that quantum physics requires reference to measurement in its formulation?

3.1 Decoherence

The answer to these questions, in the modern (or Oxonian) formulation of EQM requires reference to decoherence theory. 'Decoherence' is the name for the set of physical effects that follow from the unitary evolution of a quantum system where interference between parts of that system is radically suppressed. This matters because interference phenomena are our empirical evidence for the existence of superposition states, and where interference between them is suppressed each part of the superposition evolves independently.

How does decoherence suppress interference? See chapter 30 by Barandes for details – this is a subject of contemporary and ongoing physics research, both experimentally and theoretically [see Schlosshauer (2019)]. But the short story is that there are internal and external processes that lead to the decoupling of variables, and consequently to the loss of local phase information and the effective independence of parts of the wavefunction.

As in Joos's contribution to Joos et al. (2013, pp. 63–64): "since scattering depends in an essential way on the position of the object, as in a microscope. Interference terms between different positions in the density matrix of the scattering centre are destroyed . . . ['Destroyed'] means that certain interference terms are unobservable for "local" observations – so interference/phase information and superpositions between positions have very low amplitude/information is locally inaccessible". [1]

There are two aspects of this story that are crucial for the Everettian. First, there is no extra physics in decoherence beyond that which follows from unitary evolution. And second, that this seems to be sufficient to explain the success of the quantum algorithm: take a system and divide it, without loss of generality, into two parts that may represent a target system and environment or fast-

[1] Textbooks on decoherence are Joos et al. (2013) and Schlosshauer (2004) and the Everettian perspective is discussed by Wallace (2012) in detail. See also Crull (2021) for an overview and Halliwell (2010) for work on internal decoherence.

and slow-evolving variables; run the unitary evolution on the combined system; discover that within a very short time interference will be suppressed to lead to emergent and robust degrees of freedom that are effectively well-localised and classical. One can then interpret the superposition in the decohered basis as asssigning probabilities to each branch.

What about the dynamics of this decoherent-branching process? There is a recent debate about whether branching occurs locally or globally in EQM (Ney (forthcoming[b])). It is often stated as an advantage of Everettian approaches that it has no action-at-a-distance and so is local, unlike other rival interpretations (Wallace (2012)). Blackshaw, Huggett, and Ladyman (2024) present a simple argument and model demonstrating that the process of entanglement, decoherence, and consequent branching unfolds locally. They go on to show that the propagation remains local and all residual non-locality stems from the non-separability of the initial system. However, some have claimed that branching is best understood as global and in fact that global branching does not resurrect action-at-a-distance worries (Ney (forthcoming[a]) and Sebens and Carroll (2018)). Nevertheless, on all views decoherence is just a consequence of unitary evolution and this is crucial for establishing the compatibility of EQM with special relativity.

The principal idea of these versions of EQM is that the quantum state has no preferred basis and thus, no preferred branching structure or splitting while interference between branches in any given basis is dynamically significant. Insofar as there is no basis with respect to which individual branches evolve effectively independently from one another, there is only one world. Interference between putative branches guarantees the absence of such effectively independent dynamics. Non-constant phase relations are associated with spreading in configuration space (loss of overlap), and this leads to interference being strongly suppressed. Given the numbers of particles involved in interaction with generic environments, this loss of local constant phase relations happens extremely quickly.

3.2 Preferred Basis

There are two further steps to be described to understand the modern EQM programme. Given that decoherence establishes approximate dynamical independence of parts or branches of the superposition described by the quantum state, how does this give rise to many worlds?

First, the problem of the preferred basis – how does the quantum state or wavefunction decompose into worlds or branches, and is that decomposition unique? Second, in the next section we'll return to the ontological issue: what licenses the claim that these parts of the wavefunction do in fact represent multiple worlds?

Quantum physics represents the physical state of a system with a vector (or ray) in Hilbert space. This object is basis independent, so, for example $|\uparrow_x\rangle =$

$\frac{1}{\sqrt{2}}(|\uparrow_z\rangle + |\downarrow_z\rangle)$ may represent either one or two worlds if one were na ively to take superposed branches to represent distinct worlds.

Approaches to EQM without decoherence are forced to stipulate a set of branches, but this is taken to be unattractive due to the Everettian claim that they take the physics at face value with no additions. Decoherence theory is claimed to provide an *emergent* preferred basis that grounds the division into worlds with the physics of quantum mechanics alone.

Questions still remain about whether this is done uniquely, and one might wonder if a unique decomposition into worlds is required given the patterns-based ontology discussed in the next section. The claim is that there is an (or perhaps multiple) effective bases with respect to which the interference between branches is overwhelmingly suppressed by the processes of decoherence. It's that basis in which the branches of the superposition of the quantum state are effectively non-interacting, dynamically independent, and therefore may represent distinct emergent worlds. In which basis does this take place? It's supposed to be close to the position basis, and that can be justified in part by the following heuristic account.

Consider a modern take on Schrödinger's cat: some x-spin measurement device is connected up with a vial of poison that when triggered will kill an innocent cat. In principle this whole set-up can be described by a quantum state, and, given the basis independence of a quantum state, there is no preferred decomposition. Thus one might think of this set-up as corresponding to a superposition of massively interfering parts, each representing an overwhelmingly complex admixture of dead and alive cat, broken and unbroken poison vial, and up and down z-spin. However, taking decoherence into account, it's claimed (though the actual physics can only be approached heuristically and concrete calculations are well beyond the state of the art) we'll find after very little time a basis with respect to which there are multiple alive and dead cats each correlated with an eigenstate of x-spin and any interference terms between the superposition branches in that preferred basis will be overwhelmingly suppressed. Why this basis? Well, the claim is that interactions in physics are local, roughly, in position: localised photons arrive from the sun, localised particles travel through space, and this basis is thus dynamically preferred for all but coherent systems.

This may then be seen as leading to an effective collapse, where for all practical purposes the branches with any cat other than the one we directly observe should be discarded, and we can carry on our calculations, observations, and all other descriptive and representational accounts with a massively truncated quantum state, corresponding only to the branch of the superposition to which we have local access.

3.3 The Space of the Theory

One further question concerns how to conceive of the space in which the dynamics and physics described above unfolds. Albert (1996, 2013) and Ney (2021), and others have argued that there's a sense in which the wavefunction (the quantum state projected onto the position basis) is the more natural or intuitive vehicle for understanding and describing quantum physics. If that's so, they claim we should think of the primary space of quantum physics (and the fundamental space of the world) as configuration space, which has three dimensions for each particle in any given system. Thus, for a universe with N particles, configuration space has $3N$ dimensions.

This is taken to be a natural space for the evolution of the wavefunction because within that space such evolution is local. On the other hand, the wavefunction or quantum state understood as representing goings-on in our familiar 3 dimensional space (or 4D spacetime) is highly non-local: given quantum entanglement one cannot provide the most detailed or accurate predictions for any region of the world without taking into account states of affairs in all regions with which it's entangled, no matter how far away they are; in other words the state of any region does not supervene on the states of its subregions, this is 'non-separability'.

What exactly is the advantage of locality in configuration space? It's somewhat hard to say; while in some sense this is the most natural space in which to depict the evolution of the wavefunction, should that have any implications for what we take to be the fundamental space of the world? In addition, one might be concerned by the fixed particle number presupposed by the $3N$-dimensional space, given that in quantum field theory particle number can change.

An alternative conception of the space of quantum mechanics, one that's more specifically tailored to EQM is given by Wallace and Timpson (2010). The Wallace-Timpson framework is called 'Spacetime State Realism': the claim is that, if the universe is divided into spatial subsystems, one can assign a density operator to each subsystem. The subsystems are the bearers of properties and the density operators represent "the intrinsic properties that each subsystem instantiates, just as the field value assigned to each spacetime point in electromagnetism, or the complex number assigned to each point in wave-function realism, represented intrinsic properties" (Wallace and Timpson (2010, p. 709)).

The fact of non-separability is encoded in Spacetime State realism via the observation (ibid. p. 713): "if the state $\hat{\rho}_{A \cup B}$ is known, then via the partial trace operation we can learn the states of A and B, but of course the converse is not so".

Given some macroscopic systems in different regions, the quantum state for the combined region can be divided by partial trace into states for each subregion. Different quasi-classical states in some region A will, in general, be non-trivially entangled with states in a different region B. This entanglement may be understood in terms of the joint density matrix. This means that while one can perform measurements and predict quasi-classical evolutions in one region, there are correlations between regions which cannot be determined from each region alone.

Locality in 3-dimensional as opposed to $3N$-dimensional space is a subject of controversy in the interpretation of quantum physics, as different interpretations bear different degrees of locality. It's claimed by (e.g.) Blackshaw, Huggett, and Ladyman (2024) and Wallace and Timpson (2010) that EQM does far better with respect to locality and compatibility with relativity than many rival interpretations, while Maudlin (2011) argues that violation of the Bell inequalities should reconcile us to the radical non-locality of quantum physics that one finds in the de Broglie-Bohm interpretation.

A final approach is offered by Carroll (2022) and Carroll and Singh (2019) which restricts the fundamental ontology to: "a Hilbert space $\mathcal{H}$, a vector $|\psi\rangle$ within it, and a Hamiltonian $\hat{H}$ governing the evolution of that vector over time" (Carroll and Singh (2019, p. 2)). The difference from rival approaches is that there are no preferred observables or basis – the approach is explicitly designed not to import classical or spacetime concepts and looks towards a quantum theory of gravity. While this project is certainly intriguing, it's fair to say (and its proponents concede) that the claim that all remaining structure is emergent from these sparse components has not yet been established.

4 Ontology

There are two principal schools of thoughts represented in the philosophy of physics literature regarding how to read an ontology off a theory. For the purposes of this article we'll briefly set out the primitive ontologist view, for this captures assumptions commonplace in parts of the philosophical community concerning the right way to work out what in the world a scientific theory is about. We will then go on to set out the functionalist/emergentist approach favoured by Everettians. The disagreement between these two positions is, at root, metaphysical, however it has deep consequences for how one should understand the theory.

The primitive ontologist position holds that it is essential to physics practice that one specifies an ontology prior to the theory that describes the dynamics for that ontology. As Maudlin (2019) makes clear on the opening page: physics is "the science of matter in motion" and quantum theory in particular answers the question "What is matter?" This view is defended by Allori (2013) by appealing to a set of claims about classical physics, invoking the view that classical physics specifies e.g. a set of particles or fields and then provides a dynamics afterwards. This idea does indeed have an intuitive appeal and may accord with the approach in other scientific areas – perhaps in ecology one specifies what there is and then describes how all the parts of the system interact. Although, see M. Wilson (2013) for a critique of the idea that classical physics has a straightforwardly comprehensible ontology.

The primitive ontologists develop this view about the right way to understand physical ontology to claim that there is no way to make sense of the Everettian view. For Everettians takes themselves to be interpreting the bare theory, and the bare theory doesn't offer a primitive ontology in the sense required. Of course there are particles, fields etc. described by quantum physics but these are not the entities of the fundamental theory in the standard view; see Wallace (2020) for the claim that quantum theory is a framework. Rather, the Everettian focusses on the quantum state, or as with Wallace and Timpson (2010), density matrices assigned to spacetime regions. The functionalist ideas offer an alternative to the primitive ontologist way of thinking and are taken by Everettians to counter positions of Hawthorne (2010) and Maudlin (2010).

4.1 Functionalist Everettians

We will talk of 'functionalist Everettians' without specifying who defends the view. This view has been developed significantly by Wallace (2012), but aspects have been further discussed by Franklin (2024), Knox and Wallace (2023), and Saunders (2022b).

How ought we to understand ontology in physics? The functionalist claims that the positing of ontology and the specification of dynamics cannot be straightforwardly distinguished. In fact, they suggest, it's standard in science for these to come together. This functionalist position is closely associated with the real patterns framework developed by Dennett (1991), Ladyman and Ross (2007), and Ross (2000). The suggestion is that we identify the ontology of science by what it does. There's clearly something to this: we do not know what a thing is unless we interact with it, and so understanding what it does is in some sense prior to a characterisation of what it is.

Wallace (2003a, p. 93) makes use of what he terms 'Dennett's criterion': "Dennett's criterion: A macro-object is a pattern, and the existence of a pattern as a real thing depends on the usefulness—in particular, the explanatory power and predictive reliability—of theories which admit that pattern in their ontology." And thus claims "A tiger is any pattern which behaves as a tiger."

What is it to be a pattern? This is something that worries many. But the basic claim is somewhat less controversial – namely that we get to know about scientific ontology by understanding its functions and relationships, and what it does. The functionalist asks 'how else could we get to know about the subject matter of any science?' We don't have some direct unmediated access, surely the positing of ontology involves inferences from the scientific relationships that we do observe. The claim made by functionalist Everettians is that the quantum state, evolving under linear Schrödinger dynamics, exhibits structures and patterns that correspond to a multiplicity of effectively causally independent emergent worlds. Thus, the claim is that bare realist quantum mechanics – i.e. the picture of the world provided by taking the quantum state to represent reality – can be interpreted as providing an emergent multiverse without any additions or ad hoc add-ons.

Let's spell that out in a little more detail. The Everettian claims that:

Functionalism + Decoherence ⇒ Branching Worlds

How does that work? The thought is that decoherence, on very short timescales, leads to effective independence of parts of a superposition in some basis. Consider the quantum state of a system in a superposition with respect to some spin axis. Following the quantum formalism, on interaction this becomes entangled with some external degrees of freedom and interference is very quickly suppressed in some basis that is closely related to the position basis. Once non-local interference terms are dynamically inaccessible, they make negligible difference to the dynamical evolution of our system.

Now the key step is to note that a set of degrees of freedom that interact with one another and evolve independently from another set of degrees of freedom is functionally equivalent to a local world. If this step is accepted, (and there are arguments in favour of functionalism across the sciences), and it's accepted that decoherence does have the consequence of leading to an effective selection of a preferred basis with respect to which what can be viewed as branches of the superposition evolve effectively independently, then quantum theory can be seen as giving rise to branching worlds. And what's more, branching will be happening more or less continuously more or less everywhere.

That's the argument in a nutshell. Worlds, functionally defined, emerge from the underlying quantum physics due to the suppression of interference that's studied as part of decoherence theory.

The story just outlined does not make much explicit mention of emergence – how crucial is that step? If 'emergence' is just the name for when certain degrees of freedom are screened off, then the label itself isn't essential. What's crucial for the functionalist or Wallacean Everettian is that the branching is not present at the fundamental level. Fundamentally, they claim, all there is is the unitary evolution of the quantum state. At more macrosopic and emergent scales we can find within the quantum state structures that are functionally equivalent to effectively independent worlds.

The details provided thus far give us an account that can, according to this school of Everettians, justify and make sense of the collapse postulate without this needing to be included in the dynamics or as an additional postulate. The claim is that what decoherence provides, with its account of effective dynamical independence of branches of superposition relative to an effectively preferred basis, is a justification for abstraction away from other branches. So if measurement is sufficient for decoherence, then after measurement the single outcome that's observed in any branch is all that's relevant to evolution in that branch. One may then collapse the wavefunction by tracing out or excluding other degrees of freedom corresponding to other branches. All that's left is the system of interest and its dynamical evolution. This all shows how the preferred basis is supposed to be solved according to the Everettians.

We can thus see how EQM solves the measurement problem. The question is 'what goes on in quantum measurement?' or 'how is it that a superposition can be interpreted in some circumstances as a physical state, and in other circumstances as a probabilistic mixture?'. The Everettian answers such questions by showing that in the presence of interference (pre-decoherence) superpositions must be interpreted as physical states (for this is the only way to explain interference phenomena) and may not be interpreted probabilistically (for this would lead to the wrong empirical predictions). On the other hand, any measurement scenario is one in which decoherence has already suppressed interference, the world has split into multiple copies and for each post-measurement, post-splitting observer, only one observation can be made and a probabilistic interpretation of the superposition is warranted.

Of course, much of this is controversial. In §5 we discuss issues surrounding probabilities and the Everettians' responses. In the remainder of this section we discuss the substantive critiques raised against this programme, followed by alternative Everettian approaches to the mainstream account in this section.

4.2 Critiques

Maudlin (2010) develops the interesting worry that the Everettian approach is inadequate because it does not provide a primitive ontology – the suggestion is that in the absence of any additional stuff that can be arranged in, say, the configurations to which the wavefunction assigns amplitudes in configuration space, the theory lacks empirical content:

> any theory whose physical ontology is a complete wavefunction monism automatically inherits a severe interpretational problem: if all there is the wavefunction, an extremely high-dimensional object evolving in some specified way, *how does that account for the low-dimensional world of objects that we start off believing in, whose apparent behaviour constitutes the explanandum of physics in the first place?* ... the obvious way for a physical theory to accomplish this task is to postulate that there *are* localized objects in a low-dimensional spacetime [ibid. 132-3, original emphasis]

Many take this to be a compelling argument against EQM. Those who wish to defend EQM have three paths available to them. First, the functionalist/emergence strategy laid out above, in combination with decoherence, is taken by many to provide a satisfactory account of how the world is found in the wave function and the claim is that this package allows the empirical success of textbook quantum theory to vindicate EQM.

Second, some accept that decoherence theory remains somewhat underdeveloped: it currently provides idealised models for certain situations but it's still the subject of substantial scientific research, and bespoke models are required for many situations, where the precise details of the suppression of interference depend on the system-environment interactions. So many might be optimistic that decoherence can eventually fill in the details connecting a grand system-environment wavefunction to the outcomes of individual experiments, but believe that there is still work to be done. Third, the decoherence approach may be rejected, and one might seek to connect EQM to empirical results in different ways [see §4.4].

There are two related worries within Maudlin's claims. First, that the whole emergence framework presupposed by EQM cannot work. If this response is to be refuted a new way of thinking about emergence across science must be offered. Maudlin (2015, p. 356) suggests that the problem of defining the local characteristics of non-microscopic systems is "easily and transparently solved by simple aggregation of microscopic parts".

Maudlin's second worry is specific to quantum theory. Maudlin may draw the disanalogy with other sciences as follows: each really is about the fundamental description – e.g. even though it's difficult to tell, the subject matter of biology is arrangements of fundamental stuff, and the empirical grounding of biology happens via such arrangements. We know however, that EQM cannot be quite like that, because we know that its subject matter is not fundamentally local. But, in response to Maudlin, what reason is there to think that the fundamental stuff of quantum mechanics has to be localised?

A related set of concerns are raised by Monton (2013, p. 164) in response, especially, to analysis in Wallace and Timpson (2010): "It's simply not the case that one can have a $3N$-dimensional space with a field evolving in it, such that when the field has a configuration, three-dimensional objects come into existence . . . for them to come into existence emergently, without this happening in accordance with certain novel laws of physics, is not the way a world where quantum mechanics is true works."

There are two ways to interpret this claim: first that it requires novel fundamental (strongly emergent) laws – the Everettian will argue that these are not required; or, secondly, that weakly emergent laws are required for the existence of three-dimensional objects. The latter option is the view that Wallace's functionalism is designed to offer.

While many others have commented on the Everettian ontology these two critiques suffice to set out the general worry: that the functionalist/patterns-based ontology is just insufficient, either because it does not settle all metaphysical questions or because there isn't enough primitive stuff to act as a foundation for the many worlds. Responses to these worries are found in Franklin (2024), Ladyman (2010), and Wallace (2012) and references therein.

4.3 Splitting vs. Diverging

Once one has in place an ontology of branching worlds, a further (somewhat abstruse metaphysical) question that gets asked is whether the objects and/or persons in those worlds are three- or four-dimensional. If they are three-dimensional then one may think of branching as increasing the number of objects because the unitary dynamics lead to parts of the wavefunction that were previously interacting, now no longer interacting, and this functionally realises different worlds and thus more objects. This is the splitting view.

On the other hand, if objects are four-dimensional, and so they are spread out over time, one can use the distinct futures to disambiguate and effectively separate such objects. Pre-branching there are just as many objects as post-branching, it's just that pre-branching their three-dimensional temporal parts are co-located and, at that time, indistinguishable. Thus they diverge.

P. J. Lewis (2007b) sets out such metaphysical distinctions in the context of the debate over probability in EQM; see §5. In their response Saunders and Wallace (2008, p. 303) say "[w]e do not, in particular, accept that there is a *correct* semantics, whether or not consistent with ours, as determined by metaphysical principles. For we do not believe there *are* any metaphysical truths when it comes to the meanings of everyday words like 'person' and 'I', over and above those that are fixed by observable linguistic usage". A. Wilson (2020) rather uses this distinction to set out views on the nature of modality. One can thus take this question more metaphysically seriously. For example Wilhelm (2022) attempts to use this to ground approaches to probability, as does A. Wilson (2020); see Romagosa (forthcoming) for a response to Wilhelm.

But taking the view metaphysically seriously raises a number of difficult questions. Should we, for example, consider there to be a great number of intrinsic duplicates at any moment, we might wonder how many there are. Does this depend on how many splitting events in the history of the universe? And if these worlds are metaphysically distinct, what are the dynamics like? Are they unitary and deterministic for each world up until a certain time and then they stochastically diverge? If so, when do they diverge? Perhaps the dynamics are across such worlds but then why do they depend on each other?

One might worry that the simplicity of the Everettian approach to the measurement problem is somewhat undermined by the complexity of this metaphysics. This is certainly an area ripe for future work. And we take this to be a general theme: that in EQM the physics is relatively settled but the metaphysics remains a matter of tension among both advocates and dissenters.

4.4 Alternative Ontologies

Everett's original thesis suggested that the branching structure comes from the dynamics itself, and there are reasons to suppose that he had early notions of decoherence in mind, before the theory itself was formally developed, see Barandes (in this encyclopedia).

However, in response to the preferred basis and probability problems, David Deutsch developed an alternative version of EQM that involves infinitely many worlds from the outset, thus splitting doesn't happen and we should understand branching as a process of the infinitely many worlds' diverging. Thus Deutsch (1984) adds the axiom "The world consists of a continuously infinite-measured set of universes.” This not only underwrites his approach to probability but also allows him to justify the Everett interpretation with the claim that this is the best way to explain the relative efficiency of quantum computers on the view that the computations take place in parallel worlds. Note that on the view spelt out in the previous section, given that the computations in a quantum computer take place before decoherence (indeed the technological challenge in scaling up such computers is to prevent decoherence) these take place in a single world.

Vaidman’s version of EQM is different again: “Contrary to others, I do not consider decoherence with the environment as a definition of world-splitting.” (Vaidman (2024)). Instead Vaidman (2021) argues that we should understand the many worlds as a superposition of objects that are classically described and thus well localised: “Different worlds correspond to different classically described states of at least one object”. The choice of the preferred basis is due to the “nature of the observer and her concepts for describing the world”. Vaidman also introduces the concept of ‘measure of existence’, which “quantifies the ability of the world to interfere with other worlds” and underwrites his approach to probability.

Sebens and Carroll (2018) develop yet another slightly different approach to the Everett interpretation, with a view to articulating a novel account of probability within the interpretation. While they emphasise the importance of decoherence, they advocate an all-at-once account of branching: “When the universal wave function splits into multiple distinct and effectively non-interacting parts, the entire world splits—along with every object and agent in it.” (p. 34). One might worry about this approach because it may obscure the resolution to the measurement problem. If multiplicity emerges just to the extent that branches of a superposition decohere then the physics itself may be taken to be sufficient for an explanation of what’s observed. If, however, some other mechanism is responsible for branching – if it happens globally rather than locally following the local expansion of decohered states – then rather more needs to be said. A simple local branching model has been presented by Blackshaw, Huggett, and Ladyman (2024), following the dynamics of decoherence. It is therefore incumbent on the global-branching advocates to show how this picture aligns with the physics of quantum mechanical evolution.

A final alternative is developed in J. A. Barrett (2019), building on J. A. Barrett (1999), which he terms the ‘many threads approach’: “There is an infinite set of non-splitting worlds. The history of each world corresponds to a path through the branching structure determined by the evolution of the global quantum state written in the determinate-record basis” (p. 184). This is also partly motivated by the claim that “one can understand probabilities in a perfectly straightforward way as epistemic probabilities concerning self-location” (p. 186).

It’s worth noting that the disputes over the correct formulation of EQM among its advocates relate closely to questions of probability raised in the next section: there is a trade-off between the physics-first approach of the decoherentist/Oxonian school and dissatisfaction with their favoured approach to probability, which justifies the development of alternatives.

5 Probability

The probability problem stands as one of the most significant challenges facing EQM and has probably received the most attention in the literature Saunders, J. Barrett, et al. (2010). While ordinary quantum mechanics incorporates probability through the collapse postulate and the Born rule, EQM's commitment to pure unitary evolution creates a genuine puzzle about how probabilistic predictions can be understood or justified. The problem stems from two key features of EQM, its determinism and non-unique measurement outcomes. These two characteristics are often conflated in discussions of the probability problem, but understanding their distinct roles is essential for properly diagnosing the challenge. EQM is deterministic because the entire wavefunction of the universe evolves according to the Schrödinger equation. More critically, EQM denies unique outcomes so when a measurement occurs, the world branches such that all possible results actually occur in different branches of reality.

It is this second feature that creates the difficulty with probability. In ordinary probability theory, whether classical or quantum, we assign probabilities to possible outcomes with the understanding that exactly one will actually occur. When I roll a die, I can predict probabilistically which face will show, but after the roll, a single definite outcome obtains. EQM fundamentally alters this picture such that all outcomes occur, just in different branches. An Everettian observer facing a quantum experiment knows with certainty that every possible result will be realized somewhere in the branching structure, which seems to eliminate the very basis for probabilistic reasoning: if I know all outcomes occur, shouldn't I assign probability 1 to each?

In the EQM literature, the probability problem has been addressed in various sub-questions. The incoherence problem (Wallace (2003b)) asks, if every outcome occurs in EQM, does an agent have any uncertainty about future events? This is an overarching question about the connection between probability and uncertainty within a branching multiverse. Alongside the incoherence problem, the quantitative problem is also defined (Wallace (2003b)). This asks how probability can be quantified in EQM. This is a very important aspect of the probability problem as it focuses on trying to regain the very successful predictions and statistics given by the Born rule in ordinary quantum mechanics. The concern for Everettians is that if EQM does not include a notion of probability, how can we understand the success of predictions via the Born rule. A solution to the quantitative problem would alleviate this concern and put EQM back on par with standard quantum theory. This is why the quantitative project has been extensive over the last few decades.

A slightly different way to approach the probability problem is developed in Greaves (2004) and Greaves and Myrvold (2010). This defines a practical and epistemic problem. The former is essentially a version of the previous questions, but where a focus on agent action is taken as the starting point. The more interesting, and highly relevant epistemic question, is an extension that is worth outlining further. It concerns how EQM can be used to make predictions and whether it is empirically testable, based on the fact that all outcomes occur; this worry is developed in detail in Adlam (2014).

These problems are all deeply interconnected, though the quantitative problem has received the most attention. Without solving it, EQM appears to make no empirical predictions and loses its status as a physical theory. The overarching question might be better framed as: if all outcomes occur in EQM, how does our notion of uncertainty and probability transform to accommodate this radical metaphysics?

5.1 Calculating the Born Rule

In addressing the probability problem (and in particular the quantitative problem) Everettians have used various strategies. Here the most important are surveyed including decision theory, self-locating uncertainty, and typicality. What is interesting when analysing the different approaches, is that there are core commonalities between them. Most notably, symmetry considerations are often employed in the arguments to show that equal amplitudes imply equal probabilities. If two branches have identical squared amplitudes in a superposition, symmetry dictates they should be treated identically regarding probability assignments. This basic insight then needs to be extended to handle unequal amplitudes, typically by introducing additional systems or considerations that restore symmetry. The mathematical symmetries of entangled quantum states, particularly as expressed through Schmidt decompositions and unitary transformations, provide the technical machinery for these arguments.

Whether explicitly acknowledged or not, symmetry reasoning underlies the decision-theoretic approach, self-locating uncertainty methods, and the more physics-focused derivations. The differences lie in how symmetry is invoked, what additional structure is required, and what the symmetries are taken to mean for rational agents or physical systems.

The decision-theoretic approach, initially developed by Deutsch (1999) and refined extensively by Wallace (2012), has dominated discussion of the probability problem and become characteristic of Oxonian EQM. The core strategy is that rather than trying to define what probability is in a branching universe, it asks how rational agents should act when facing quantum measurements. Deutsch's original insight was that even though every outcome occurs and agents effectively receive every possible payoff across branches, rationality constraints on preferences can force agents to value outcomes in accordance with Born rule weightings. Using axioms like additivity, substitutability, and the zero-sum rule, he showed that agents must maximize expected utility calculated using squared amplitude weights.

Wallace's (2012) argument extended the decision theory framework, distinguishing richness axioms (concerning what acts are available to agents) and rationality axioms (constraining preference orderings). Key rationality axioms include branching indifference (agents don't care about branching irrelevant to rewards), state supervenience (preferences depend only on final states, not initial ones), and macrostate indifference (agents don't care about microstates, only macrostates). Through these axioms, Wallace derives that the Born rule is not merely one reasonable choice but the unique rational way for Everettian agents to structure their preferences. The approach has significant strengths. It avoids introducing probability as primitive, instead deriving Born rule probabilities from accepted rationality constraints. And it aims to do so in a mathematically rigorous way.

Wallace hopes that the decision-theoretic strategy can address both the quantitative problem and the incoherence problems. The claim is that this strategy demonstrates that rational observers ought to set their personal probabilities for each outcome to the modulus-squared amplitude for that outcome. D. Lewis (1986)'s Principal Principle claims that credences should be set according to any known chances. If one seeks a functionalist account of chance, then chances may be exactly what determine credences. So modulus-squared amplitudes satisfy the functional role of chance and, thus, are chances for the functionalist, resolving the incoherence problem, and they set the values of chances, resolving the quantitative problem.

However, the decision-theoretic program faces severe objections as well. Firstly, multiple critics have challenged specific axioms. Mandolesi (2018, 2019) argues that most of the axioms Wallace utilises are unjustified or lead to contradictions. Further, the ambiguity of terms like 'macrostate' and 'reward' are exploited to allow the derivation to carry through. Jansson (2016) focuses specifically on state supervenience, arguing it lacks adequate justification as a rationality axiom and may covertly depend on probabilistic assumptions, potentially making the derivation circular. Dizadji-Bahmani (2015) and P. J. Lewis (2010) challenge branching indifference as irrational, particularly when justified through subjective uncertainty.

Second, numerous counterexamples have been put forward, suggesting the Born rule is not uniquely justified in this framework. P. J. Lewis (2010) proposes average and sum rules as alternatives. Finkelstein (2009)'s stoic agent, whose preferences for rewards don't follow from preferences for games, apparently violates no axioms yet doesn't act according to the Born rule. Albert (2010) suggests a fatness rule, where one weight preferences by physical mass in branches, and Price (2010) puts forward a distributive justice rule, providing further challenges. While Wallace (2012) attempts to show these violate certain axioms and so are not valid alternative, the sheer number of them raises doubts about whether the proof truly singles out the Born rule uniquely.

Thirdly, more fundamental worries question whether decision theory is even the right strategy to address any part of the probability problem in EQM. Kent

(2010) argues that Wallace relies on Savage's approach, which is already problematic in single-world cases, and that precise decision theory cannot be applied to EQM's fuzzy ontology (since branches are emergent and only approximately defined through decoherence). More broadly, critics have highlighted the difference between the grounding of physics predictions in probabilities versus modelling rational action. As Gill (2005, p. 278) puts it, "we do not accept that the behaviour of a rational decision maker should play a role in modelling physical systems."

Moving beyond the connection to probability, one of the greatest problems faced by the decision theory view is a possible circularity (Baker (2007), Dawid and Thébault (2015), and Hemmo and Pitowsky (2007)). Certain axioms, such as branching indifference, already assume a decoherence-picture of branches. However, Dawid and Thébault along with others, have argued that using decoherence to in some way solve the preferred basis problem, or set branches, assumes an understanding of probability already. This issue connects deeply to questions about what branches are and when they exist, suggesting the probability and preferred basis problems cannot be cleanly separated.

5.2 Self-Locating Uncertainty

An alternative approach to probability that has received more attention in the last two decades, uses the idea of self-locating uncertainty. This clearly can help with the incoherence problem by understanding quantum probabilities in epistemic terms. Even if an observer knows all outcomes will occur, she can be uncertain about which branch she finds herself in after branching occurs. This strategy attempts to ground probability in a kind of indexical ignorance that persists even in a deterministic branching universe. Within this type of solution, there are different approaches.

Vaidman (1998, 2020) draws on notions of self-locating uncertainty to define a post-measurement uncertainty that can be equivalent to an agent's ignorance of results in a single-world case. For instance, take some quantum agent Alice who sets up an automatic quantum experiment and falls asleep before the result comes in. Depending on the outcome (say, spin up or spin down), she'll wake in one of two identical rooms. When Alice wakes, she faces genuine indexical uncertainty about her location, even though she knew beforehand that both outcomes would occur. Vaidman argues this post-measurement uncertainty grounds an illusion of probability that can guide pre-measurement decisions (Vaidman (2021)). This scenario is very reminiscent of the Quantum Sleeping Beauty Problem, which has been connected to the Everettian approach (Groisman, Hallakoun, and Vaidman (2013) and A. Wilson (2014)). Debates on this topic centre around whether Everettian branching corresponds to a particular way of solving the classic Sleeping Beauty Problem. Further, it has been connected to how probability is understood in both cases (P. J. Lewis (2007a) and Papineau and Durà-Vilà (2009)). This is partly why Vaidman (2021) uses self-locating uncertainty as a means to understand probability within a branching structure.

McQueen and Vaidman (2019), in fully deriving this post-measurement uncertainty, require two axioms that push beyond the bare theory and even the simplest Everettian picture. These are the symmetry principle that equal amplitudes give equal probabilities and no superluminal signalling. While there are clear reasons that these are well-motivated (for the former, most other views also accept this assumption; for the latter, a quantum theory compatible with relativity will need to acknowledge this limitation), these are still additional principles over-and-above unitary dynamics that require clear justification. In much the same way that the axioms of decision theory must be motivated in EQM, these must face the same scrutiny.

While in its simplicity, using self-locating uncertainty seems to avoid many of the pitfalls of decision theory, there are problems. Albert (2010) and P. J. Lewis (2007b) argue that post-measurement uncertainty comes too late to ground pre-measurement probabilistic reasoning. Thus, the ignorance identified cannot be genuinely predictive. Vaidman (2012) attempts to avoid this issue by using a 'measure of existence' to provide the basis for pre-measurement action precisely because agents know their descendants will face this uncertainty. But this seems to require some principle connecting pre- and post-measurement agents, potentially smuggling in assumptions about personal identity or continuity.

Perhaps the biggest concern comes over how exactly self-locating uncertainty is motivated and what additions are actually required to solve the problem. One of the central claims of modern EQM is that it is just quantum mechanics, without any change to the physics. Whether the additional principles here amount to changes, needs to be justified. This is seen most clearly in a different approach to self-locating uncertainty from Sebens and Carroll (2018). They develop their view starting with the Epistemic Separability Principle (ESP), which states that probability assignments should not depend on the state of irrelevant parts of the universe: "[t]he credence one should assign to being any one of several observers having identical experiences is independent of the state of the environment" (p. 40). From there, they define a quantum version of the ESP. They claim to identify a post-measurement but pre-observation period where observers have branched but remain in identical quantum states, producing genuine self-locating uncertainty. With this set up and the quantum ESP, they claim to derive the Born rule. Again though, the ESP or quantum version, acts as an additional premise that needs to be compatible with EQM and justifiable.

Sebens and Carroll's view also faces criticism. Kent (2015) and Vaidman (2020) argue that two observers in identical quantum states are actually a single observer, and thus there is no genuine branching in this post-measurement but pre-observation phase, invalidating the claimed uncertainty; note that this relates to questions of splitting vs. diverging and global vs. local branching discussed above. McQueen and Vaidman (2019) further show that Sebens and Carroll's examples involve absent uncertainty rather than true self-locating uncertainty.

Dawid and Friederich (2022) also demonstrate that the quantum ESP is not actually a less general version of ESP and cannot be considered a general principle of reasoning, undermining its justificatory force.

5.3 Alternative Approaches

While the views just discussed prioritise the incoherence problem by developing ways of understanding quantum probabilities as fundamentally epistemic, alternative views prioritise quantitative approaches. Implicit here is that we should first consider how one can match the statistics observed in experiments with EQM, and that we may then understand the probabilities as we see fit.

J. A. Barrett (2023), following Everett, (for proof, see J. A. Barrett (1999, pp. 100–107)), demonstrates that a typical branch, as the number of measurements gets large, will be one that is both random and exhibits long term relative frequencies that match those predicted by standard quantum mechanics. Importantly, this is typicality relative to the Born rule measure. While this view may be accused of a kind of circularity, Saunders (2022a, p. 234) observes that "Denizens of anomalous branches, or of anomalous stretches of history in one-world theories, will be misled by the observed statistics of measuremens. They will conclude that quantum mechanics (or at least the Born rule) is false. But they will simply be unlucky." The argument is that probabilities are, by their very nature, undetermined by the observed facts and its perfectly consistent with any account of probability that many observers will be misled by their observations.

Saunders (2021) has recently developed an alternative account of probability in the Everett interpretation, which he terms 'branch counting'. Unlike the more naïve branch counting advocated by Dizadji-Bahmani (2015) and Khawaja (forthcoming) that disagree with the Born rule and therefore spell trouble for Everettians, this approach is designed to reproduce the probabilities of standard QM. The idea is that one can divide the quantum state into what are termed 'microstates' in just such a way that the coarse-grained union of similar microstates has a relative frequency in accordance with the Born rule.

Before moving on, there are few other notable approaches to solving the probability problem worth mentioning. Greaves (2004, 2007) and Greaves and Myrvold (2010) have developed a slightly different decision theory approach, in that they do not begin with the assumption that EQM is correct. This changes some of the mechanisms put forward, with a focus on Bayesian updating of credences. However, the view still is very similar to the Deutsch-Wallace approach, and thus faces many of the same criticisms. Read (2018) develops a view that combines these two decision-theoretic approaches.

Zurek (2003, 2005) takes a more physics-focused approach. He defines objective probabilities through physical symmetries of entangled quantum states, rather than any discussion of an agent. Through entanglement-assisted invariance (i.e. envariance), he claims to derive the Born rule based on set properties of composite quantum systems. When a system becomes entangled with an environment, certain quantum symmetries, specifically invariance under complementary unitary transformations, pick out the Born rule weights as the unique consistent probability measure. Zurek's approach has significant advantages: it is based on physical principles rather than facts about agents; it claims to derive objective rather than subjective probabilities; and it connects naturally to decoherence theory. However, it faces objections. Fine and Schlosshauer (2005) argue it implicitly assumes four key principles that require more explicit justification and might even smuggle probability in from the start. Barnum (2003) and Caves and Schack (2005) question whether Zurek adequately justifies his use of swapping operations and whether the approach extends properly to unequal amplitude cases. It's also noteable that Zurek does not regard himself as an Everettian, despite working within the unitary framework and developing insights regarding decoherence theory that are essential to many Everettian arguments.

Despite their differences, most solutions share the reliance on symmetry highlighted above. This commonality is insufficiently stressed in the literature but it might offer a lesson about non-collapse probability. Once symmetry is established, focus moves to the connection between equal amplitude and equal probability – an assumption that requires more analysis. While it follows from standard views in probability, including things like probability current, when the connection is to branches and possible branch weights, the principle holds more weight. It is also worth noting that all approaches in some ways supplement the bare theory. This addition might just be in terms of rationality principles rather than deeper physics, but it does show the limitations of the claims that EQM just is physics. While quantum theory without collapse might be taken at face value, at the very least interpretational and philosophical work must be added in order to solve the probability problem.

Overall, the question might be how we should understand these connected but distinct solutions. One view is encouraging, that the convergence suggests EQM naturally leads to Born rule structure through multiple pathways, and while no single derivation may be perfect, collectively they demonstrate EQM's viability. However, Kent (2010) raises a troubling alternative, that these apparently competing approaches may actually represent core conflicts in EQM itself. If the approaches genuinely conflict in their metaphysical commitments about branches, persons, or the nature of probability, we do not have multiple solutions to a single problem but rather incompatible variants of EQM that must be evaluated as separate theories.

However, there is an important and distinct lens through which to view the probability problem, argued for by Papineau (1996, 2010). The entire setup (as presented here even) begins from the premise that EQM faces a problem with probability, and that this is not the case for single-world, orthodox quantum mechanics. However, Papineau asks if this is truly the case. Instead, he shows how confused the understanding of probability is in philosophy quite generally, and he argues that it is orthodox quantum mechanics that faces a probability problem, since the collapse postulate and Born rule are assumed without derivation. In contrast, Everettians have made genuine progress toward deriving the Born rule from more fundamental principles, whether through decision theory, symmetry arguments, or physical considerations.

On Papineau's view, probability is generally mysterious and requires explanation. Classical mechanics and deterministic theories generally don't give us probability for free. For instance, statistical mechanics requires additional work to recover thermodynamic probabilities. That orthodox quantum mechanics simply declares what the probabilities are, without any deeper meaning or mechanism, should strike us as more problematic than EQM's attempt to derive probabilistic predictions from unitary evolution. Moreover, Papineau questions whether linking probability to uncertainty is even necessary. Typical interpretations of probability exhibit similar puzzles and each (frequency interpretations, propensity interpretations, subjective interpretations etc.) face their own difficulties. Perhaps attempting to ground quantum probability in uncertainty of any kind is misguided, and we should instead accept that quantum probability in EQM is sui generis, neither reducible to classical ignorance nor requiring it for legitimacy.

This perspective reframes the debate. Rather than treating EQM's probability challenge as evidence against it, Papineau suggests it demonstrates EQM takes probability seriously enough to try explaining it rather than postulating it. The fact that multiple derivation attempts have been made, each illuminating different aspects of how probabilistic structure emerges in branching universes, represents theoretical progress orthodox approaches cannot match. However, how quickly should we dismiss the EQM probability problem following Papineau? Even if orthodox quantum mechanics also faces explanatory challenges regarding probability, EQM still needs to show how agents can coherently make probabilistic predictions when they know that all outcomes occur and some of their descendants *will* observe anomalous or maverick outcomes. The feeling persists that something requires explanation, whether we call it a problem or merely an "interpretive challenge", about how familiar probabilistic reasoning connects to Everettian metaphysics.

6 Conclusion

The interpretational landscape of quantum mechanics is often presented as a case of underdetermination, multiple incompatible pictures of reality that nevertheless make identical empirical predictions (Egg and Saatsi (2021)). In the philosophy of physics, what's regarded as the main contenders for realist interpretations are EQM, de Broglie-Bohm theory or Bohmian mechanics, and dynamical collapse theories (like GRW).[2] At first glance, this appears to ex-

[2]Note that many information-based and epistemic approaches are also developed in the literature, though their realism credentials are often called into question – see Healey (2023) for an overview of aspects of this programme.

emplify the problem of underdetermination that philosophers of science worry about. That is, we have competing theories explaining the same evidence, and the choice between them seems to rest on extra-empirical virtues like simplicity, elegance, or explanatory power rather than decisive empirical tests.

However, this picture of neat empirical equivalence becomes considerably more complicated upon closer examination. Both Bohmian mechanics and dynamical collapse theories don't merely interpret standard quantum mechanics, they revise it. This distinction matters for underdetermination. Collapse theories only approximately reproduce standard quantum mechanics, making them empirically distinguishable from unmodified quantum theory, though the effects are typically vanishingly small for systems we can currently test. Bohmian mechanics is more subtle as its modifications are designed precisely to ensure exact empirical equivalence with standard quantum mechanics in the quantum equilibrium regime. The hidden variables do no additional predictive work, they serve purely to provide a determinate ontology underlying the quantum statistics.

The dialectic within the literature reveals an odd tension. On the one hand, underdetermination is frequently invoked as a serious problem for quantum foundations. On the other hand, proponents of different interpretations regularly argue that rival approaches are fundamentally incoherent or inconsistent. Everettians are often told their interpretation faces an insurmountable probability problem that renders it incoherent. These cannot both be true. Either we have multiple consistent but underdetermined interpretations, or some interpretations are genuinely flawed and can be ruled out. The claim of underdetermination in quantum mechanics oversimplifies a complex situation. The competing approaches modify quantum mechanics to varying degrees, face different conceptual challenges, and may not even be genuinely distinct (if some are disguised versions of others – see e.g. Brown and Wallace (2005)). More fundamentally, restricting attention to non-relativistic quantum mechanics provides an artificially narrow view of the landscape.

A crucial development in recent philosophy of physics has been the recognition that focusing exclusively on non-relativistic quantum mechanics (NRQM) provides a distorted picture of quantum theory. NRQM deals only with N-particle systems (for fixed N) in a non-relativistic regime, excluding the vast domain of quantum field theories (QFTs) that describe particle creation and annihilation, relativistic phenomena, and essentially all of high-energy physics. Since QFT represents our actual best quantum physics (both in terms of fundamentality and empirical success), any interpretation claiming to explain quantum reality must ultimately address QFT, not merely NRQM.

When we expand our view to include relativistic QFT, the debate between interpretations changes dramatically. Neither Bohmian mechanics nor dynamical collapse theories have successfully (yet) extended to fully interacting relativistic QFT (Myrvold (2021)). Bohmian mechanics faces fundamental obstacles as the theory is not Lorentz invariant, relying on simultaneous particle positions defined by a guiding equation that involves strong non-locality. Various attempts have been made, but none provides a complete, satisfactory relativistic Bohmian theory. Additionally, QFT's treatment of particle creation and annihilation fits awkwardly with Bohmian mechanics' fundamental commitment to particles with definite positions. Collapse theories face different but equally serious challenges in the relativistic domain. The stochastic noise used in models like CSL to generate spontaneous localization often has a white noise character that creates normalization problems beyond those already present in QFT (Ghirardi (2018)). While some progress has been made, no complete collapse theory for interacting relativistic fields exists. The consensus among collapse theorists is cautiously optimistic but acknowledges that no actual working model has been achieved.

In contrast, Everettians claim EQM extends naturally to relativistic QFT. The core claim is simple: EQM just is quantum theory taken seriously, with universal unitary evolution and no additional postulates. Since QFT retains unitary dynamics, EQM should apply equally to QFT without modification. This seems to give Everettians a decisive advantage. Wallace (2022) has developed this point, arguing that the failure of modificatory interpretations to extend to QFT is not accidental. These approaches solve the measurement problem by enforcing a distinction between microphysical and macrophysical degrees of freedom. But QFT's structure does not support this kind of clean separation. Instead, the relationship between micro and macro scales in QFT is far more subtle and contextual, varying with energy scales and involving emergence through renormalization group flow. Trying to impose a fixed micro-macro distinction onto QFT misunderstands how the theory actually works.

However, we should be cautious about overstating EQM's advantage here. While EQM does extend to QFT more smoothly than rivals, this extension is largely a consequence of EQM's minimal modifications to the formalism. The question remains whether this minimalism is a virtue or a vice. Moreover, saying "EQM just is unitary QFT" risks making the interpretation vacuous. If EQM adds nothing to the physics, in what sense is it explaining quantum mechanics rather than merely relabelling it? Of course, this is where the philosophical additions to EQM need to be analysed within the wider framework of QFT, and much of that work remains to be done. Nevertheless, EQM's extendibility to QFT represents genuine progress. The interpretation can engage with cutting-edge physics in ways that Bohmian mechanics and collapse theories currently cannot. Whether this advantage is decisive depends on whether EQM can successfully address its own persistent challenges, particularly the probability problem, and whether alternative interpretations might yet overcome their QFT obstacles.

It's finally worth noting that other views, especially relational quantum mechanics and various neo-Copenhagenist positions (e.g. Schlosshauer and Camilleri (2008)) also assume the unitary framework and as such extend to QFT just as straightforwardly as Everettian approaches; however these approaches involve an explicit epistemic restriction, and the Everettian finds that as worrisome as Bell (1990) found the irreducible reference to 'measurement' in quantum theory.

7 Outstanding Questions

- What is required from the physics of decoherence to make sense of the environment/system split?
- How does internal decoherence work and which systems decohere in which circumstances?
- What is the pointer basis and in precisely which conditions is it selected?
- How exactly should we understand the fundamental ontology of EQM: wavefunction realism, spacetime state realism, density matrix realism, quantum state realism etc.?
- Is the functionalist account sufficient and how can it be further developed?
- What are the stakes in the splitting vs. divergence debate?
- Are the various approaches to probability complementary or inconsistent?
- Is EQM falsifiable?
- How does the probability problem carry over to the relativistic/QFT context?
- How does functionalism carry over to the relativistic/QFT context?

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