Quantum Mechanics Without Indeterminacy[*]

David Glick[†]

Abstract

Metaphysical indeterminacy in the context of quantum mechanics is often motivated by the eigenstate-eigenvalue link. However, the *sparse view* of Glick (2017) illustrates why it has no such implications. Other links connecting quantum states and property ascriptions—such as those associated with the GRW theory—may introduce indeterminacy, but such indeterminacy may be viewed as merely representational and is susceptible to familiar treatments of vagueness. Thus, I contend that such links fail to provide a compelling motivation for quantum metaphysical indeterminacy.

1 Quantum Metaphysical Indeterminacy

1.1 Metaphysical Indeterminacy

Quantum mechanics has often been associated with indeterminacy. In contrast to familiar cases of vagueness, the indeterminacy involved has seemed to some to be *worldly* as opposed to merely *representational*. There are several possible explications of this notion of worldly or metaphysical indeterminacy. First, there is the metaphysical supervaluationist approach developed by Barnes and Williams (2011).[1] According to the supervaluationist, a proposition is vague just in case it admits of multiple precisifications, each of which assign it a truth value, but some of which disagree about its value. Such vagueness is typically attributed to our epistemic or representational limitations. According to Barnes and Williams, metaphysical indeterminacy occurs when actuality admits of multiple precisifications, each of which is represented by an ersatz possible world. On this view, reality is indeterminate just in case there are propositions about actuality that are true at some but not all candidate ersatz worlds.

An alternative account of metaphysical indeterminacy is provided by the determinable-based approach of Wilson (2013, 2017). This view eschews the precisifications of the supervaluationist and instead allows for indeterminate states of affairs. The guiding idea is that a state of affairs is indeterminate

---

[*] To appear in V. Allori (ed.) *Quantum Mechanics and Fundamentality: Naturalizing Quantum Theory between Scientific Realism and Ontological Indeterminacy*, Springer Nature.

[†] Department of Philosophy, University of California Davis. Contact: daglick@ucdavis.edu

[1] See also Akiba (2004); Barnes (2010).

just in case it involves the instantiation of a *determinable* property without a unique *determinate*.[2] There are two ways this could occur: either a determinable property could have more than one determinate ("glutty" indeterminacy) or no determinates ("gappy" indeterminacy). Glutty indeterminacy involves the possessions of multiple determinates of a single determinable in a relativized or degree-theoretic fashion. Wilson (2013) gives the example of an iridescent feather that is both red (from one perspective) and blue (from another) as a case of glutty indeterminacy. Below we will see some potential examples of gappy indeterminacy in the context of quantum mechanics.

In the discussion of quantum indeterminacy that follows, I'll focus on Wilson's determinable-based understanding of metaphysical indeterminacy. There are two reasons for this. First, there is a concern that the metaphysical supervaluationist approach cannot be applied to the case of quantum indeterminacy. Several authors have noticed that no-go results such as the Kochen-Specker theorem seem to rule out the possibility of maximal and precise ersatz possible worlds that the approach seems to require (Darby, 2010; Skow, 2010). This is an open area of debate and tangential to my primary concerns.[3] Second, much of the articulation and defense of quantum indeterminacy occurs in the context of the determinable-based approach (Bokulich, 2014; Calosi and Wilson, 2019, 2021; Lewis, 2016).

This chapter proceeds as follows. In the remainder of this section, I briefly introduce quantum indeterminacy in the context of so-called "orthodox" quantum mechanics and the alternative offered by Glick (2017). In section 2, I turn to the GRW theory and the case for indeterminacy there. I argue that, while the GRW theory does introduce vagueness via the links between quantum states and properties, this indeterminacy may be viewed as representational. Finally, I conclude in section 3 by highlighting two remaining issues: alternative interpretations and emergent indeterminacy.

1.2 Quantum Indeterminacy

Assuming the determinable-based understanding, quantum mechanics is alleged to involve metaphysical indeterminacy in so far as it describes systems that lack unique determinate values of physical quantities. For instance, consider a particle characterized by a quantum state of spin that is a superposition of up and down in the x direction, $\psi = c_1|\uparrow_x\rangle + c_2|\downarrow_x\rangle$. In order to move beyond the quantum state description, we need a principle linking it to certain properties ("observables"). The best known of these is a tenet of orthodox quantum mechanics:[4]

---

[2] A familiar example of the determinable-determinate relationship is *red* and *scarlet*. Scarlet is a particular way of being red, hence it is a determinate of the determinable *red*. Note that a property may be a determinate at one level of analysis, but a determinable at a "deeper" level—Venetian scarlet is a determinate of the scarlet determinable.

[3] See Darby and Pickup (2019) for an attempt to resolve this challenge facing the metaphysical supervaluationist and Corti (2021) for criticism of their attempt.

[4] It's not entirely clear what constitutes "orthodox" quantum mechanics. For my purposes here, I assume that it involves the eigenstate-eigenvalue link, the collapse postulate, and Born's

Eigenstate-Eigenvalue Link (EEL): A system A has a value v of property P iff the quantum state of A is in an eigenstate of the associated operator $\hat{O}$ with eigenvalue v.

Applied to the particle, EEL implies that it lacks both the value "up" and "down" of x-spin. Thus, one may be inclined to regard it as instantiating the determinable of x-spin without a unique determinate of it.[5] There are two ways this could go: either it lacks any determinate of x-spin (gappy) or it possesses more than one determinate (glutty). Initial applications of determinable-based metaphysical indeterminacy to quantum mechanics focused on the gappy understanding (Bokulich, 2014; Wolff, 2015), but more recently, some authors have advocated for the glutty view. For instance, the particle could be said to possess value "up" to a certain degree (given by its modulus-squared coefficient) and value "down" to a certain degree (Calosi and Wilson, 2019, 2021).

However, EEL alone doesn't imply indeterminacy of either form. It has the form of a biconditional between a quantum state description and the attribution of a specific value of an observable. The situations alleged to give rise to indeterminacy are those where the quantum state isn't in an eigenstate of the observable under consideration. It follows that we cannot attribute a specific value of that observable. But, as Glick (2017) observes, there is a clear distinction between (determinately) lacking a property and possessing an indeterminate value of that property.[6] So, EEL is compatible with a view that eschews indeterminacy: the *sparse view* according to which systems don't possess properties—determinate or determinable—for which they aren't in an eigenstate. On the sparse view, a particle in a superposition of x-spin up and down simply lacks x-spin.

While the sparse view may illustrate that the EEL is strictly compatible with metaphysical determinacy, if the sparse view is sufficiently implausible it may be alleged that any *reasonable* understanding of orthodox quantum mechanics will involve genuine metaphysical indeterminacy. Indeed, some allege that the sparse view has the implausible consequence that particles are not located in spacetime and that measuring a particle will cause it to pop into existence (Calosi and Wilson, 2021). In order to see why such worries are misplaced, let's briefly reconsider location on the sparse view of orthrodox quantum mechanics.

1.3 Quantum Location

To simplify matters, consider a particle that's confined to a region X, which is divided into 2 subregions A and B. We can write its position state as a

---

rule. See Wallace (2019) for a criticism of this view and Gilton (2016) for a defence of the role of the eigenstate-eigenvalue link in "orthodox" or "textbook" quantum mechanics.

[5] I will be challenging this inclination below. For now, a motivating idea might be that we can measure the particle's x-spin, and when we do so, it will be found either up or down. So, the particle in question is the kind of thing that can possess a precise value of x-spin even if it doesn't have one at the moment. This might incline one to regard it as possessing the x-spin determinable without a unique determinate of it (until it's measured).

[6] Consider, for instance, category mistakes. The number two lacks a determinate mass, but this does not imply that its mass is indeterminate because it lacks the determinable as well.

superposition $c_1|A\rangle + c_2|B\rangle$, where $|A\rangle$ is the quantum state associated with being in region A and likewise for $|B\rangle$ and B. From the Born rule we know that the probability of finding the particle in region A is given by $||c_1||^2$, and $||c_2||^2$ for region B. Moreover, we know that the probability of finding the particle in the region $X = A \cup B$ is 1. Given this, what should we say about the particle's position?

EEL implies that the system is (determinately) located in the region X, as it is in an eigenstate of the associated operator with eigenvalue 1. With respect to the regions A and B, EEL precludes attributing to the system a (determinate) location in either region. Thus, the sparse view (indeed, any version of orthodox QM) is committed to saying that the particle has a location—namely, it is located in X. But, despite being located in X, the particle isn't located in either of the subregions that X comprises, A and B. This may require a revision of our concept of position in light of quantum mechanics. In particular, it motivates denying *Precise Location.*

Precise Location: *being located in a region* X is a determinable with *being located in* $x_i \in X$ as determinates.

According to Precise Location, *being located in a region* X admits of further specificity in terms of a proper subregion of X. Perhaps, as one moves to even greater levels of specificity, the location of a system will bottom out in regions that are exactly the same size as the object they contain.[7] But Precise Location doesn't require this. All that is required is that the property associated with being in a region X is, at the relevant level of specificity, a determinable property with its only determinates corresponding to being located in proper subregions of X.

Precise Location leads to position indeterminacy when applied to the case described above. The particle will possess the maximally-unspecific position determinable with the determinate *being located in* X. At a deeper level of specificity, it will possess the determinable *being located in* X. However, it will lack a unique determinate of that determinable. Either it will possess no determinate or it will possess multiple determinates (e.g., each to a degree less than one). One reaction to this is to embrace position indeterminacy in quantum theory, another is to challenge the assumption of Precise Location.

Imprecise Location: *being located in a region* X can serve as an absolute determinate.

On Precise Location, *being located in* X is both a determinate of a more general location determinable and also a determinable with more precise location properties as determinates. Imprecise Location, by contrast, allows for regions that are intuitively larger than the physical system to serve as absolute determinates—i.e., determinates that are not themselves determinables. How

---

[7] Of course, it's often unclear what the "size" of a quantum system is. So, the relevant notion of a maximally precise location might be the smallest region to which the system can in principle be confined.

does this differ from indeterminacy about position? After all, Wilson (2013) refers to states of affairs involving determinables lacking unique determinates as both "indeterminate" and "imprecise." But absolute determinates are not bare determinables—only the latter implies that an object has an indeterminate position. On Imprecise Location, if asked where a particle confined to a region $X(> {x_p}^8)$ is located, the answer is simply "in region X." If asked *where* in region X the particle is located, the proper response is not that it is indeterminate, but rather, that the question rests on a mistaken assumption, namely, Precise Location. According to Imprecise Location, there is nothing indeterminate about having a location given by a region that is intuitively larger than the object in question.

This understanding of position is consistent with the standard formalism of ordinary non-relativistic quantum mechanics. If we assume that observables are associated with self-adjoint operators on Hilbert space, then there is a problem with applying EEL to a position observable that incorporates Precise Location. The corresponding operator will have a continuous spectrum rather than discrete eigenstates. In order to apply EEL, we need to consider operators that project onto the subspace corresponding to being in some finite region of space X. So, if we take this seriously as a guide to thinking about position in quantum mechanics, position should always be understood in terms of questions of the form: "Is the particle confined to region X?" Moreover, there will always be some smallest region X beyond which the answer is always "no." If the system isn't in an eigenstate of any operator corresponding to being located in a proper subregion $x_i \in X$, then EEL precludes attributing to it a location more precise than X.[9]

Imprecise Location allows us to see why the sparse view doesn't imply that particles aren't located in spacetime and don't pop into existence upon measurement. In realistic scenarios, it may be impossible to ascribe a position more specific than the entirety of space. Even after measurement, particles will never be perfectly localized for any finite period of time. This may be unsatisfying, but such is orthodox quantum mechanics. Notice that the fan of indeterminacy will be compelled to adopt a parallel position: that position is almost always indeterminate. For instance, realistic position measurements cannot be understood as removing indeterminacy given that the particle isn't precisely localized after a measurement either (at least not for any finite period of time). The sparse view allows for a non-zero probability of finding a particle in a region in which it isn't located, but the implausibility of this claim rests on an understanding of measurement as revealing preexisting properties, which is rejected by orthodox quantum mechanics.

A more significant problem with Imprecise Location is that intuitively quantum theory provides a number of different ways in which a system can be located

---

[8] Let x_p denote a subregion of X that would be regarded as a maximally precise location for the particle. See previous footnote.

[9] Notice that there is nothing wrong with asking whether we will find the particle in the region $x_i \in X$ if we were to measure its position. To answer this question we use Born's rule, not EEL.

in X. There are any number of quantum states that are eigenstates of a projector onto the subspace associated with being located in X, for instance: the equally-weighted superposition $\frac{1}{\sqrt{2}}(|A\rangle + |B\rangle)$; non-equally-weighted superpositions $c_1|A\rangle + c_2|B\rangle$ (where $c_1 \neq c_2$); a more precise location x_i within X ($|x_i\rangle$). Each of these imply that an ideal measurement will find the particle in X with probability 1. Thus, Imprecise Location may be unsatisfying as an explication of the location of the system as it's unable to make important distinctions between the various states which seem to correspond to different ways the system may be located in X. A natural way to correct this is to allow for determinates associated with each such quantum state.

Quantum Location: *being located in the region X* is a determinable with *being in the quantum state* ψ_i among its determinates, where $P(\text{being located in } X|\psi_i) = 1$.

Quantum Location allows for many different ways of being located in the region X. For instance, being in a particular superposition of $|A\rangle$ and $|B\rangle$ is one such way. EEL doesn't license the attribution of any precise position observables in such a state, but so long as there is some self-adjoint operator associated with the quantum state, then it will be in an eigenstate of that operator. Thus, EEL will license the attribution of properties such as *being in an equally-weighted superposition of being located in A and being located in B*.[10] One might complain that such a property isn't a candidate for a physical property, but it has a clear connection to measurement outcomes (via Born's rule) and enters into causal/nomic relations with other physical properties. If one allows specific superpositions to represent novel determinates of position, then one gains additional resources that may allow the sparse view to explain phenomena seen as challenging for the view, such as interference phenomena.[11]

The case of position generalizes. If a system is described by a quantum state that is a superposition of x-spin—$\psi = c_1|\uparrow_x\rangle + c_2|\downarrow_x\rangle$—what is the indeterminate property? Suppose the system in question is an electron. Then we know it has a spin of $\frac{\hbar}{2}$, and we can use a two-dimensional Hilbert space to characterize its spin. So, *having a spin value* is a determinable with a unique determinate. EEL provides no basis for attributing the determinable *having an x-spin*. Indeed, it is often said that (in orthodox quantum mechanics) having a spin in one direction precludes having a spin in an orthogonal one. As in the position case, it seems better to limit our ontological commitments to those properties which are determinate: either (a) only attribute x-spin when the system is in

---

[10] The quantum state will not be in a superposition of the operator invoked in EEL, but we may wish to describe the state in terms of a distinct operator with clear physical significance—in this case, an operator with $|A\rangle$ and $|B\rangle$ as eigenstates.

[11] Of course, critics of the sparse view may allege that the quantum state must be given *some* metaphysical analysis, and it's here that metaphysical indeterminacy arises. Quantum Location is a denial of this demand. The property possessed by a system in a particular superposition of more precise position states is just that. Superpositions are novel kinds of determinates, not to be further analyzed in terms of the observables that appear in their arguments.

an eigenstate of x-spin or (b) allow for superpositions of x-spin to count as determinates of x-spin. On either approach, we never find determinables without unique determinates. On the first approach, a particle in a superposition of x-spin simply lacks x-spin (until measured). On the second approach, such a particle has the property of being in a particular superposition of x-spin, where such a property is a unique determinate of x-spin.

Again one might wonder how Quantum Location (and its generalization) differs from indeterminacy. Perhaps saying the system is in a particular superposition of x-spin ($\psi = c_1|\uparrow_x\rangle + c_2|\downarrow_x\rangle$) could be understood as possessing the "up" and "down" determinates to degrees given by the squared modulus of their coefficients. There are at least two problems with this proposal. First, EEL provides no basis for this claim. The state is not an eigenstate of x-spin with multiple eigenvalues, so another principle would need to be invoked.[12] Second, and more significantly, distinct quantum states lead to the same expectation values for x-spin values, for instance: the mixed state representing a system as x-spin "up" or x-spin "down" with equal probability; a system in an eigenstate of y-spin orthogonal to x; a system in an eigenstate of z-spin orthogonal to x and y. Thus, the property associated with being in a particular superposition of x-spin cannot be identified with the weighted possession of x-spin determinates.[13]

In sum, the argument for metaphysical indeterminacy in orthodox quantum mechanics rests on two assumptions. First, that particles possess determinables corresponding to operators of which they are not in eigenstates. Second, that these determinables have only the eigenstates of the corresponding operators as their determinates. Each of these assumptions may be challenged, leading to two versions of orthodox QM without indeterminacy. Rejecting the first assumption leads to the sparse view on which one can only attribute properties to particles in special circumstances, or when the properties in question are very general. This meager ontology may be unsatisfying, but represents a natural way of thinking about orthodox QM and doesn't require denying that particles have locations or pop into existence. Quantum location (and its generalization) rejects the second assumption by expanding the determinates of determinables associated with operators to include superpositions of their eigenstates. This view has the benefit of attributing properties corresponding to superpositions while retaining the one-to-one correspondence of determinables and determinates.

---

[12] Calosi and Wilson (2019) propose to replace EEL with DEEL, a principle that posits degrees of possession proportional to the coefficients of the arguments of a superposition. However, unlike EEL, DEEL is not part of the standard formulation of orthodox QM. Moreover, it goes beyond what is needed for orthodox QM to solve the measurement problem. See section 3.

[13] This means that Quantum Location (and its generalization) is distinct from the glutty indeterminacy view of Calosi and Wilson (2019). The former takes a particular superposition to be a novel kind of determinate of the determinable associated with the operator that defines the basis. The latter takes a particular superposition to correspond to a plurality of determinates (each corresponding to eigenstates) each possessed to a degree less than 1. The present point is that the views are inequivalent because the quantum state contains more information than a weighted collection of determinates.

2 Indeterminacy in GRW?

The sparse view shows that EEL fails to establish quantum metaphysical indeterminacy. But many regard orthodox quantum mechanics (and EEL) as problematic. Other interpretations may provide a more compelling basis for quantum indeterminacy. In particular, discussion of the problem of tails in the GRW theory has given rise to modifications of EEL which may be thought to provide a basis for metaphysical indeterminacy.

2.1 The GRW Theory

The measurement problem results from the conflict between the linear, unitary evolution of the quantum state according to Schrödinger's equation and the apparent fact that measurements have unique determinate results. The GRW theory attempts to solve the problem by replacing deterministic linear Schrödinger dynamics with a stochastic non-linear dynamics.[14] In particular, GRW dynamics involve spontaneous localization events ("hits") centered on a random point c and occurring randomly with an average frequency λ. The crucial points for our discussion are the following:

- Localizations (hits) are very unlikely for individual particles, but amplify rapidly with entanglement making it extremely likely for a hit to occur immediately for macroscopic systems.
- Hits have the effect of applying a Gaussian distribution of width σ centered on a random point c.
- The probability of a given point being the center of localization is given by the squared modulus of the amplitude of the wavefunction in accordance with Born's rule.

Like orthodox quantum mechanics, GRW is an indeterministic theory, but it differs in precisely specifying the dynamics that lead to wavefunction collapse.[15] With suitable values for the frequency of hits λ and the width of the Gaussian σ, GRW may be regarded as consistent with the current empirical evidence for quantum mechanics.

2.2 The Problem of Tails

In orthodox quantum mechanics, EEL acts as a principle linking quantum states and observables. In GRW, however, EEL must be replaced by a more forgiving

---

[14] The GRW theory is due to Ghirardi et al. (1986). It's the simplest and best known of a family of collapse interpretations. For more, see Ghirardi and Bassi (2020).

[15] It may be thought that indeterminism alone implies indeterminacy, and indeed, some motivate metaphysical indeterminacy by consideration of the "open future" (Barnes and Cameron, 2009). However, the metaphysical status of the future is largely independent of whether there are stochastic laws of nature. The path from indeterminism to indeterminacy is not at all straightforward and inevitable.

linking principle. The reason is that hits fail to localize the wavefunction precisely to a point. Indeed, while localizations cause the majority of wavefunction amplitude to be concentrated near c, the tails of the wavefunction will extend arbitrarily far away from c. Even after measurement, a particle will not be in an eigenstate of the operator associated with being located in the neighborhood of c, so EEL does not allow the attribution of a localized position to the particle. This is a problem as the GRW theory aims to solve the measurement problem by changing the dynamics of quantum mechanics so as to deliver determinate measurement outcomes.[16]

To solve this problem, several proposals for a revised link have been offered. In conjunction with reasonable assumptions, these principles allow the GRW theory to yield determinate outcomes for many kinds of quantum measurements. However, they also introduce a certain degree of indeterminacy. First, consider Albert and Loewer's *fuzzy link*.

Fuzzy link: Particle x is in region R if and only if the proportion of the total squared amplitude of x's wave function which is associated with points in R is greater than or equal to $1 - p$. (Albert and Loewer, 1996, p.87)

Generalizing somewhat, the fuzzy link allows one to attribute a property to a system when its quantum state is sufficiently close to an eigenstate of the associated operator. "Sufficiently close" is captured by the $1 - p$ term, which acts as a cutoff below which a determinate property cannot be ascribed. Combined with GRW's non-linear stochastic dynamics and assumptions about the measurement process, the fuzzy link allows for determinate outcomes. A position measurement induces a hit to the wavefunction of a particle, after which it is sufficiently close to an eigenstate of the operator $\hat{P}_c$ with eigenvalue 1 for the fuzzy link to ascribe the determinate property of being located near c.[17] This determinate position property accounts for the measurement outcome, namely a detection near c.

The fuzzy link introduces indeterminacy into the ascription of observables in GRW. While EEL is unambiguous about the conditions under which observables are to be attributed, the fuzzy link requires imposing a threshold of "sufficiently close to an eigenstate." This threshold has features characteristic of vagueness: whatever threshold is chosen will be arbitrary, subject to disagreement and context-dependence, and will admit of borderline cases. Such vagueness is not unproblematic, but is familiar from ordinary cases involving the boundaries of mountains and clouds, baldness, etc. This would suggest that the strategies for dealing with familiar vagueness will apply here as well. In particular, approaches such as supervaluationism and epistemicism could be used to avoid the

---

[16] Armed with only EEL, the GRW theory is unable to secure determinate measurement outcomes because it precludes the assignment of precise positions to macroscopic systems like pointers that constitute such results. Again, the only position properties licensed by EEL are those that attribute a location in the region to which a system is strictly confined. Often this region will be no less than the entirety of space.

[17] $\hat{P}_c$ is a projector onto the subspace of Hilbert space associated with being located in some region C including c.

implication of metaphysical indeterminacy. A supervaluationist could identify a number of precisifications of "sufficiently close," each free from indeterminacy, but which disagree about the precise threshold. An epistemicist could claim that there is a precise threshold that lies beyond our ken. Both approaches relegate the resultant indeterminacy to the representational domain—the indeterminacy is the result of our language or epistemic limits, not the world itself.

More recently, Peter Lewis has proposed another linking principle with a more direct connection to metaphysical indeterminacy, the *vague link*.

Vague link: A system has a determinate value for a given determinable property to the extent that the squared projection of its state onto an eigenstate of the corresponding operator is close to 1, where the determinate value is the eigenvalue for that eigenstate. (Lewis, 2016, p.90)

The vague link allows for properties to be attributed in degrees. For a system sufficiently close to an eigenstate, the vague link says that the system possesses the property *to an extent* close to 1. Crucially, it also allows that such a system possesses other properties to a minimal extent. For example, a particle localized around c would possess the property of being in the neighborhood of c to a very high degree, but would also possess the property of being *outside* the neighborhood of c to a very low degree. On its own, the vague link fails to serve the required function for the GRW theory: it will not deliver (unique) determinate outcomes for quantum measurements. One possible response would be to reject the demand for determinate measurement outcomes, but such a stance removes much of the appeal of dynamical collapse theories like GRW. At any rate, this isn't the approach taken by Lewis when presenting the vague link.

> According to the vague link, my coffee mug almost entirely possesses the determinate property of being on top of my desk, but it also very slightly possesses the determinate property of being inside the drawer. Because the degree of possession of competing properties is so slight, for all practical purposes I can say that the coffee mug is on the desk. (Lewis, 2016, pp.90–91)

This suggests that the vague link is to be supplemented with a further principle that allows one to ascribe observables *for all practical purposes* when the degree of possession is sufficiently high. This allows the GRW theorist to say that measurements have determinate outcomes (for all practical purposes). But, again it does so at the cost of introducing indeterminacy into the ascription of observables. What counts as a sufficiently high degree of possession will exhibit the same familiar characteristics of vagueness as the fuzzy link—arbitrariness, disagreement, borderline cases, context dependence, etc. Moreover, these features will be susceptible to the same representational analysis. What counts as a sufficiently high degree may be subject to further precisification or may be beyond our ken. Of course, the phrase "for all practical purposes" suggests that Lewis may be happy to grant that such indeterminacy in the ascription of observables is merely representational.

So, the vague link is similar to the fuzzy link FAPP (for all practical purposes) but it differs in that, strictly speaking, it is naturally understood as positing glutty indeterminacy. The opponent of metaphysical indeterminacy must deny this aspect of the link, but there is very little cost in doing so. Quantum indeterminacy is typically thought to reside outside of measurement contexts, but on the fuzzy link indeterminacy is pervasive even after a maximally precise measurement. This is why it's unable to solve the measurement problem in the context of the GRW theory without ascending to the FAPP level of description. Compare a view that posits degrees of possession for the property of baldness, where a very bald person possesses baldness to a degree close to 1 and a very not bald person possesses baldness to a degree close to 0. This does nothing to resolve or clarify the vagueness of our application of the predicate "bald." We have just pushed the problem back to what degree of possession is sufficient to apply the predicate (FAPP). Similarly here, positing degrees of possession leaves unchanged the question of when we should ascribe a determinate value of some observable. The only remaining motivation for this aspect of the fuzzy link is the thought that non-eigenstates must involve metaphysical indeterminacy, but the considerations here are unchanged from the discussion of orthodox quantum mechanics above.[18]

Thus, both links allow for the attribution of determinate properties (at least FAPP) after measurement on the GRW theory, but in so doing introduce a certain degree of indeterminacy. Such indeterminacy shares many of the features of familiar cases of vagueness outside of quantum mechanics, but Lewis (2016) alleges that it's unique in at least two respects: (1) there is no continuum of property values in which a vague boundary occurs and (2) it isn't the result of composition.[19] I will address each point in turn.

First, it's not obvious that there isn't a continuum of properties in which the boundary occurs. Recall that according to Quantum Location, each quantum state is taken to describe a specific determinate property. In the context of a position measurement, different quantum states could be arranged in a continuum with respect to the degree of localization to which they correspond. Even if one rejects this association of quantum states with determinates, there is nevertheless an underlying continuum of quantum states (and corresponding probabilities) in which the threshold for possession of a given observable is located according to the fuzzy link. And again, where to locate this threshold within the continuum of quantum states (or probabilities) exhibits the characteristic features of familiar cases of vagueness. On the vague link, there is an

---

[18] Of course the GRW theory is a more "realist" interpretation than orthodox quantum mechanics, so one might think that we are owed more of a story about non-eigenstates. However, rejecting metaphysical indeterminacy doesn't require silence about non-eigenstates. In addition to providing probabilities for various measurement outcomes, such states can also provide a basis for the attribution of novel properties along the lines of Quantum Location as outlined in section 1.3.

[19] Lewis takes the GRW theory to involve indeterminacy that is both metaphysical and distinct from familiar non-quantum cases of indeterminacy. Here I treat the distinctness claim independently with the aim to rebut the claim that there is anything distinctively "quantum" about the indeterminacy introduced by the GRW links.

additional level of properties possessed to varying degrees, which may also be ordered in a continuum. Along this continuum of degrees of possession, one must establish some threshold that allows for ascription of the relevant observable for all practical purposes. As with that of the fuzzy link, this threshold shares the characteristics of familiar cases of vagueness and is susceptible to the usual representational treatments.

Second, the indeterminacy here isn't the result of composition, but composition is not the only source of indeterminacy familiar from cases outside of quantum mechanics. The indeterminacy of a mountain, or a cloud, or some other medium-sized object may be understood in compositional terms. For instance, the indeterminacy of a mountain can be taken to concern which molecules are part of the mountain and which are not. The case of observables in GRW is not like this. As best we know, electrons aren't composed of anything, and so any indeterminacy associated with them cannot be the result of their composition. However, there are other instances of indeterminacy involving familiar ("non-quantum") objects that are independent of their material composition. The indeterminacy exhibited by these cases admits of representational analyses that make no appeal to composition.

Consider an ordinary doorstop. Whether a given object counts as a doorstop is a matter of it performing a certain function, namely, holding open a door. Clearly it can be vague whether a given object satisfies this functional role. For instance, one may count a rock as a doorstop, but only if it is sufficiently large or heavy to hold open the door, a matter that admits of degrees. Now, while it may be true that a rock is composed of material parts, this fact is irrelevant to the indeterminacy surrounding whether it is a doorstop or not. A representational view locates the indeterminacy in our representation of the object *as a doorstop*, and hence, denies that it is an instance of metaphysical indeterminacy. The representational approach is compatible with either supervaluationism or epistemicism as applied to the specification of the functional role characterizing the entity rather than its composition—the indeterminacy dissolves if the function of *holding open a door* is specified or known with sufficient precision.

Observables in GRW may be viewed as functional entities. Each property has an associated probability of resulting in a certain measurement result. Indeed, it is this connection that gives observables (and quantum mechanics more generally) empirical significance. This suggests that the indeterminacy introduced by the GRW theory can be understood in terms of whether the system satisfies a given functional role. Consider again the case of location near c. If the probability of being found near c is sufficiently high, then it is natural to regard the particle as possessing the determinate property, *being located near c*. But the probabilities form a continuum corresponding to the extent to which the particle plays the functional role associated with being located near c. Both the fuzzy and vague links may be seen as attempts to ascribe observables to systems when they are almost certain to deliver the corresponding measurement result. This is simply another way of representing the nature of the functional role of observables in quantum mechanics.

Thus, even if some quantum systems are not composed of smaller parts, the indeterminacy of property attribution in the GRW theory needn't be seen as *novel* or *metaphysical*. It can be seen as an instance of the familiar vagueness concerning whether an entity satisfies a certain functional role. Such vagueness can be readily understood as representational indeterminacy.

3 Remaining Issues

In this chapter I have argued that two approaches to quantum mechanics can be understood without invoking metaphysical indeterminacy. In the case of orthodox quantum mechanics, the sparse view demonstrates that EEL does not require metaphysical indeterminacy. In the case of the GRW theory, the problem of tails requires modifying EEL in a way that introduces some indeterminacy. However, such indeterminacy may be regarded as merely representational.

3.1 Other Interpretations

Several issues remain. First, there are other interpretations of quantum mechanics beyond those considered here, and nothing I've said rules out that they may involve metaphysical indeterminacy. Indeed, there are variants of orthodox quantum mechanics and the GRW theory that posit indeterminacy. For example, Calosi and Wilson (2021) propose replacing EEL with a degree-theoretic variant:

DEEL: A quantum system S has a definite value v for an observable O to a degree y iff $\sqrt{y}$ is the absolute value of the coefficient of the associated eigenvector having eigenvalue v in the quantum state of S (Calosi and Wilson, 2019, p.2621).

However, unlike EEL, DEEL is not part of the standard formulation of orthodox quantum mechanics, nor is it needed for the orthodox solution to the measurement problem. In order to secure determinate measurement outcomes in the context of orthodox quantum mechanics, we only need EEL, not DEEL. In the context of the GRW theory, Lewis's vague link is naturally understood as positing glutty metaphysical indeterminacy. But, as noted above, the vague link alone is unable to solve the measurement problem in the context of the GRW theory as it fails to secure determinate measurement outcomes after a hit. Thus, neither link plays a role in the solutions to the measurement problem offered by these interpretations.

Of course, the availability of indeterminacy-free versions of these interpretations isn't an argument for them over their indeterminacy-involving counterparts. Ultimately, as with many metaphysical issues in the sciences, the question of metaphysical indeterminacy is underdetermined. However, there is *prima facie* reason to prefer avoiding metaphysical indeterminacy in physical theories when it is possible to do so. Other things being equal, we should avoid interpreting our physical theories in a way that commits us to controversial metaphysical theses.

3.2 Emergent Indeterminacy

A second outstanding issue concerns the possibility of emergent metaphysical indeterminacy.[20] Suppose that an interpretation deploys a link from the quantum state to observables that introduces some kind of indeterminacy. For example, the GRW links discussed above allow for situations where there can be indeterminacy surrounding the location of a particle after a position measurement. Any such indeterminacy will be *emergent* in that it is derived from the fundamental description provided by the quantum state of the system via the link in question. But just because something is emergent doesn't mean it's not real, so this fact alone fails to tell against quantum metaphysical indeterminacy. Indeed, this is once again a matter that is underdetermined by one's choice of interpretation qua solution to the measurement problem. However, there is more to say about the status of emergent metaphysical indeterminacy: whether one countenances it has more to do with one's attitude toward ordinary cases of non-fundamental indeterminacy than anything specific to quantum theory. This means that quantum theory is unlikely to make much of a difference to the debate—those who find metaphysical indeterminacy in the everyday world irrespective of quantum theory can maintain their beliefs and likewise for opponents of metaphysical indeterminacy.

First, consider the situation in the GRW theory. Suppose the position wavefunction of a particle has support within the region R but also outside of it. Is the particle located in R? Given that the system isn't in an eigenstate of the associated operator ($\hat{P_R}$), it will depend on the details of our link, which may (or may not) introduce indeterminacy concerning the position of the particle. Such indeterminacy can be given either a deflationary or inflationary reading. The former would say the indeterminacy concerns the attribution of the predicate *is located in R* and may rely on standard treatments of vagueness to resolve the indeterminacy. The latter approach would regard the system's location as genuinely metaphysically indeterminate—even though there is no indeterminacy in the quantum state, the link introduces indeterminacy in the location properties of the particle. It's worth noting that Barnes (2014) regards emergent metaphysical indeterminacy as impossible in principle. Barnes argues that if the fundamental level is fully determinate, and it determines the emergent level, then there is nowhere for indeterminacy to come from. However, Lewis's vague link provides a potential counterexample. For a system like the particle considered above, its quantum state description will give rise to multiple determinates of the location determinable (each possessed to an extent less than 1).[21] Alternatively, one can adopt Albert and Loewer's fuzzy link and only attribute

---

[20] For a defense of emergent quantum metaphysical indeterminacy, see Mariani (2021).

[21] Barnes doesn't share Wilson's determinable-based account of metaphysical indeterminacy, however, one may develop an understanding of the vague link that fits with the metaphysical supervaluationist account. In the present case of a position measurement in GRW, one could posit a candidate ersatz world corresponding to each location where the wavefunction has support. Then, the position of the system will be metaphysically indeterminate in that the truth of a proposition of the form *the system is located in region R* will differ between candidate ersatz worlds, hence it will be indeterminate whether the system is located in R.

determinate properties. There remains residual indeterminacy in the specific conditions under which we can attribute determinate properties, but this can be regarded as an ordinary case of representational vagueness.

Second, consider Wallace's (2012) version of the Everett interpretation. On this view, the fundamental ontology is described by the universal quantum state, which evolves unitarily according to the Schrödinger equation.[22] This fundamental ontology gives rise to a vast emergent ontology of many quasi-classical worlds, each populated by a full complement of macroscopic objects. As Wallace recognizes, "it is commonplace in emergence for there to be some indeterminacy" (Wallace, 2012, p.101). The number of worlds, the objects they contain, and even human minds can exhibit indeterminacy. One reason for this is the process of environmental decoherence that Wallace's account relies on, but equally important is the functionalist account of emergent ontology he adopts. As noted above, functionalist criteria often introduce a certain amount of indeterminacy. It follows that if one endows such criteria with metaphysical significance—i.e., regards them as existence criteria—then emergent metaphysical indeterminacy results. There is nothing incoherent about such a view, which would give rise to widespread metaphysical indeterminacy in the quantum world. There is, however, an alternative. One could take a more deflationary attitude toward the emergent multiverse as a way of representing the universal quantum state in terms that we can more readily understand. As Wallace (2002) argues, the many worlds of the Everett interpretation could be seen as analogous to global planes of simultaneity in relativity, indeterminacy in the properties of which is the result of our representational limitations, not the world itself.[23]

What these examples show is that emergent indeterminacy in quantum interpretations may be regarded as metaphysical or merely representational. Which version of the interpretation one prefers will depend on their general attitude toward indeterminacy in non-fundamental ontology. If one finds metaphysical indeterminacy in everyday properties like baldness and heaphood, they may find it in quantum observables as well. But, if one prefers to adopt a deflationary strategy in everyday contexts, they are free to do the same here. A link connecting the quantum state to observables may be taken to be part of our representation of the quantum world, in which case any indeterminacy such a link introduces will be representational as well.

---

[22] In the case of quantum field theory, Wallace advocates for *spacetime state realism*, which understands the universal quantum state in terms of density operators assigned to regions of spacetime. On this view, the fundamental ontology includes spacetime (regions) and properties corresponding to density operators (see Wallace and Timpson (2010)).

[23] For example, whether two events are simultaneous is indeterminate in special relativity. Such indeterminacy is naturally regarded as representational given that instants—global planes of simultaneity—are artifacts of our representation of spacetime. Analogously, if the Everettian multiverse is "a more useful description of an entity whose perfect description as a physical system lies (at least for the moment) beyond our ability to comprehend directly"(Wallace, 2002, p.654), then any indeterminacy it engenders will be representational as well.

Acknowledgements

Many thanks to Claudio Calosi, Sam Fletcher, Dana Goswick, Peter Lewis, Cristian Mariani, Alyssa Ney, Paul Teller, Jessica Wilson, and audiences at the Dartmouth Workshop on Quantum Indeterminacy, the University of California Davis, the Society for the Metaphysics of Science, and the California Quantum Interpretation Network.

References

Akiba, K. (2004). Vagueness in the world. *Noûs*, 38(3):407–429.

Albert, D. Z. and Loewer, B. (1996). Tails of Schrödinger's cat. In *Perspectives on quantum reality*, pages 81–92. Springer.

Barnes, E. (2010). Ontic vagueness: A guide for the perplexed 1. *Noûs*, 44(4):601–627.

Barnes, E. (2014). Fundamental indeterminacy. *Analytic Philosophy*, 55(4):339–362.

Barnes, E. and Cameron, R. (2009). The open future: bivalence, determinism and ontology. *Philosophical Studies*, 146(2):291.

Barnes, E. and Williams, J. R. G. (2011). A theory of metaphysical indeterminacy. In Bennett, K. and Zimmerman, D. W., editors, *Oxford Studies in Metaphysics volume 6*, pages 103–148. Oxford University Press.

Bokulich, A. (2014). Metaphysical indeterminacy, properties, and quantum theory. *Res Philosophica*, 91(3):449–475.

Calosi, C. and Wilson, J. (2019). Quantum metaphysical indeterminacy. *Philosophical Studies*, 176(10):2599–2627.

Calosi, C. and Wilson, J. (2021). Quantum indeterminacy and the double-slit experiment. *Philosophical Studies*, page Forthcoming.

Corti, A. (2021). Yet again, quantum indeterminacy is not worldly indecision. *Synthese*.

Darby, G. (2010). Quantum mechanics and metaphysical indeterminacy. *Australasian Journal of Philosophy*, 88(2):227–245.

Darby, G. and Pickup, M. (2019). Modelling deep indeterminacy. *Synthese*, pages 1–26.

Ghirardi, G. and Bassi, A. (2020). Collapse Theories. In Zalta, E. N., editor, *The Stanford Encyclopedia of Philosophy*. Metaphysics Research Lab, Stanford University, Summer 2020 edition.

Ghirardi, G. C., Rimini, A., and Weber, T. (1986). Unified dynamics for microscopic and macroscopic systems. *Physical review D*, 34(2):470.

Gilton, M. J. (2016). Whence the eigenstate–eigenvalue link? *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics*, 55:92–100.

Glick, D. (2017). Against quantum indeterminacy. *Thought: A Journal of Philosophy*, 6(3):204–213.

Lewis, P. J. (2016). *Quantum Ontology: A Guide to the Metaphysics of Quantum Mechanics*. Oxford University Press.

Mariani, C. (2021). Emergent quantum indeterminacy. *Ratio*, 34(3):183–192.

Skow, B. (2010). Deep metaphysical indeterminacy. *The Philosophical Quarterly*, 60(241):851–858.

Wallace, D. (2002). Worlds in the everett interpretation. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics*, 33(4):637–661.

Wallace, D. (2012). *The emergent multiverse: Quantum theory according to the Everett interpretation*. Oxford University Press, Oxford.

Wallace, D. (2019). What is orthodox quantum mechanics? In Cordero, A., editor, *Philosophers Look at Quantum Mechanics*, pages 285–312. Springer International Publishing, Cham.

Wallace, D. and Timpson, C. G. (2010). Quantum mechanics on spacetime I: Spacetime state realism. *The British journal for the philosophy of science*, 61(4):697–727.

Wilson, J. M. (2013). A determinable-based account of metaphysical indeterminacy. *Inquiry*, 56(4):359–385.

Wilson, J. M. (2017). Are there indeterminate states of affairs? Yes. In Barnes, E., editor, *Current Controversies in Metaphysics*, chapter 7, pages 105–119. Routledge, New York.

Wolff, J. (2015). Spin as a determinable. *Topoi*, 34(2):379–386.