Metaphysical Indeterminacy in the Multiverse

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Introduction

One might suppose that Everettian quantum mechanics (EQM) is inhospitable to indeterminacy (MI), given that, as A. Wilson (2020) puts it, "the central idea of EQM is to replace indeterminacy with multiplicity" (77). But as Wilson goes on to suggest, the popular decoherence-based understanding of EQM (henceforth: DEQM) appears to admit of indeterminacy in both world number and world nature, where the latter indeterminacy—our focus here—is plausibly metaphysical. After a brief presentation of DEQM (§1), we bolster the case for there being MI in world nature in DEQM (§2). The remainder of the paper is devoted to a comparative assessment of the two main approaches to MI for purposes of accommodating this MI—namely, a metaphysical supervaluationist approach (as per Barnes and Williams 2011) and a determinable-based approach (as per Wilson 2013 and Calosi and Wilson 2018 and forthcoming). We briefly describe each approach (§3), then offer five arguments in favour of a determinable-based approach to world nature MI in DEQM (§4).

1 Decoherence-based EQM (DEQM)

We start with a brief overview of DEQM. Here and in the next section we periodically excerpt from Wilson's (2020) presentation, for continuity with the discussion of indeterminacy in DEQM later in this paper.

Consider a simple superposition state such as that at issue in the case of Schrödinger's cat:

$$|\psi\rangle = c_1|Live\ Cat\rangle + c_2|Dead\ Cat\rangle \tag{1}$$

On the face of it, such a superposition state represents a system as being in a single indefinite or indeterminate state. But what does this come to, exactly? On a common understanding (see Wallace 2008, 40; Wilson 2020, 77), the crucial insight at the core of the EQM approach is that a superposition state such as (1) may be taken to represent a multiplicity of systems, each in a familiar definite or determinate state, rather than a single system in an unfamiliar indeterminate state. As Wilson puts it, "the central idea of EQM is to replace indeterminacy with multiplicity" (77).

To be sure, the supposition that the multiplicity at issue involves multiple systems represents a development of Everett's own take on his (1957) theory (the 'Relative State Interpretation'), as involving multiple states of a single system. Everett's take was driven largely by concern with the measurement problem—in brief, the question of how to bridge the gap between the world as Schrödinger's equation (deterministically but indeterminately, via superpositions) expresses it as being, and the world as we (indeterministically but determinately, via components of superpositions output from individual measurements) experience it as being. Rather than bridge this gap in ad hoc fashion via a supposed 'collapse' of the wave function upon measurement, Everett suggested that measurements (e.g., opening the box) result in entanglements generating relative states, so that, e.g., a single cat is dead relative to one substate (or class of substates) and alive relative to another substate (or class of substates).[1]

The central idea was developed in influential fashion in DeWitt 1968 and 1970, with the multiplicity at issue involving multiple individual systems, and indeed multiple *worlds*. There are many variations on the so-called 'Many Worlds' interpretation of quantum mechanics (see Saunders *et al.* 2010), aiming to address stated concerns with, e.g., the reintroduction of something like collapse in talk of 'splitting' of worlds upon measurement, or with the seeming need to stipulate a preferred basis (reflecting that different bases for characterizing the universal quantum state generate different worlds), or with the introduction of profligate fundamental ontology.[2] Among these variants, the approach to EQM found most promising of late has been that developed by Saunders (1993, 1994) and Wallace (2008, 2012), along with other 'Oxford Everettians', according to which the multiplicity of worlds is understood in terms of the branching structure induced by decoherence. As Wilson (2020) puts it:

> The most significant step towards a plausible version of EQM came when, in the early 1990s, progress in technical work on decoherence was applied to the preferred basis problem in EQM by Saunders (1993, 1994, 1995). Decoherence theory can be used to model the quantum-mechanical interactions between a system and its environment [...]. The essence of decoherence is that a broad range of quantum systems evolve in such a way as to suppress to a negligible level the interference terms representing interactions between components of the state of the system corresponding to distinct macroscopic properties. (80)

DEQM's popularity reflects its neat handling of each of the aforementioned concerns. First, the approach provides a principled and plausible answer to the measurement problem.[3] Decoherence suppresses interference—not entirely, but to a degree sufficient to prise apart the components of a given superposition state—in a way consonant with ordinary experience, without requiring, e.g., conscious observers to make a collapse-inducing 'measurement'.[4] Second, decoherence phenomena fix the preferred basis, in an approximate but non-stipulative way which is fine for all practical purposes (for short: FAPP):

> Although decoherence suppresses interference between macroscopic superpositions, it does not eliminate this interference altogether. The idea behind decoherence-based EQM is that a preferred basis is approximately picked out by decoherence, to a degree of

[1]Our own view is that Everett's relative-state interpretation has a lot going for it—and moreover, is appropriately seen as accommodating metaphysical indeterminacy of a specifically 'glutty' variety, along lines of the multiple relativized determination discussed in Wilson 2013 and Calosi and Wilson 2018 and 2020. Development of this suggested reading, and its connection to Rovelli's 'Relational Quantum Mechanics' (as in, e.g., Rovelli 1996), must await another occasion.

[2]As on Deutsch's (1985) proposal, according to which infinitely many worlds correspond to each individual physically possible history.

[3]The measurement problem can be phrased as the joint inconsistency of the following three statements: (i) the quantum state provides a complete description of a quantum system; (ii) the quantum state always evolves according to the Schrödinger equation, and (iii) measurement results are unique. Everettian Quantum Mechanics in general solves the problem by rejecting (iii). Correspondingly, it is worth noting that decoherence per se does not provide a solution to the measurement problem. Thanks to a referee here.

[4]The worlds generated by decomposition are sometimes described as 'semi-classical', in being (and notwithstanding that decoherence does not entirely eliminate interference between components of macroscopic superpositions) compatible with the world as we ordinarily experience it.

approximation easily high enough to explain the fact that superpositions of macroscopic states are unobserved and effectively unobservable. (Wilson 2020, 80)

Third, in DEQM the generation of 'Everett worlds' requires no new fundamental ontology. At the fundamental level there is just one highly structured object: the universal quantum state (the 'universe'). Decoherence produces dynamically robust patterns in the universal state; these patterns represent a multiplicity of different worlds and objects within those worlds—the 'multiverse'.[5] Correspondingly, Everettian worlds are *derivative* entities, 'grounded' (to speak schematically) in the fundamental quantum state.

DEQM is naturally embedded in decoherent histories interpretations of quantum theory. These interpretations use what is sometimes called the Heisenberg picture, where operators representing measurable quantities change over time, while the quantum state remains constant. This is in contrast with the intertranslatable Schrödinger's picture, where operators remain constant while the quantum state evolves. As applied to DEQM, observables corresponding to the whole state of a world at each time t are represented by a projection operator. Different possible observable possibilities are represented by orthogonal projections $\hat{P}_i$ summing up to unity, as per (2) and (3) below:

$$\hat{P}_i \hat{P}_j = \delta_{ij} \hat{P}_i \tag{2}$$

$$\sum_i \hat{P}_i = 1 \tag{3}$$

Equation (2) says that any two distinct projection operators are orthogonal, whereas equation (3) says that such projection operators sum up to unity. These equations are intended to encode that any two observational possibilities describing the state of the whole world are mutually exclusive (2), and the collection of such possibilities is—so to speak—exhaustive (3).

A partition of projection operators meeting the conditions in (2) and (3) provides a 'coarse graining' of the universal state; a coarse graining in turn generates histories H_i—time-ordered sequences of time-dependent projection operators:

$$H_i = \hat{P_{i_n}}(t_n) \hat{P_{i_{n-1}}}(t_{n-1}) ... \hat{P_{i_0}}(t_0) \tag{4}$$

A history is a sequence of operators describing the whole state of the world, with one operator describing the entire observable state of the world for each time. Correspondingly, a history provides a maximal description of the world at each time.

According to DEQM, individual such histories are potentially suited to represent individual worlds, and sets of such histories are potentially suited to represent complete multiverses. For this promise to be fulfilled, however, the histories must be sufficiently causally isolated—sufficiently well-decohered—that they can provide a basis for accommodating our experience of macroscopic phenomena as comparatively determinate. Effectively, what is required here is that the histories be well-decohered enough to be dynamically independent (i.e., such that independent probabilities can be assigned to those histories). This requirement is usually cashed out in terms of the 'medium decoherence condition' (see Gell-Mann and Hartle 1993), where ρ is a density operator for the initial state of the universe, and Tr is the trace:

$$Tr(H_i \rho H_j^\dagger) \approx Tr(H_i \rho H_i^\dagger) \delta_{ij} \tag{5}$$

[5]Here and elsewhere we use 'multiverse' to refer to the multiplicity of Everettian worlds, following Wallace (2012) and Wilson (2020).

On DEQM, histories meeting condition (5) are taken to represent a multiplicity of Everettian worlds—the (or a) multiverse.[6] Decoherence is here thought of as involving the suppression of quantum interference as a result either of internal interaction within a system, or of external interaction with the environment, and in cases of decoherence the component terms in the superposition behave semi-classically (see note 4) in that we observe no interaction between them. It is in this sense that decoherence produces a multiplicity of comparatively independent, causally isolated systems and worlds—worlds which are independent and causally isolated 'FAPP'—a process referred to as *branching*. As Wilson (2020) describes it:

> Branching occurs whenever decoherence becomes sufficient to render different histories effectively causally isolated, for example when a dust particle becomes entangled with a radiation bath environment so that the components of the particle's state corresponding to superposition of macroscopic properties become negligible compared to the components corresponding to reasonably precise macroscopic properties. Branching may be thought of as a transition from a particle not yet correlated with its environment and with a relatively indeterminate location, to multiple particles correlated with their environments, each with a relatively determinate location. (84)

Situating DEQM in the decoherent histories formalism also provides a basis for capturing the aforementioned approximate nature of decoherence, since different coarse-grainings may satisfy the conditions. Decoherence results in fewer candidate coarse-grainings and associated bases—again, sufficient to capture failures to experience macro-superpositions—but does not narrow these down to one.

2 MI in world nature

We are now in position to see how, notwithstanding the usual gloss on EQM as replacing indeterminacy with multiplicity, there remains room for indeterminacy on DEQM. Indeed, Wilson maintains that two sources of indeterminacy remain on this view:

> First, in contemporary decoherence-based EQM the space of Everett worlds is indeterminate with respect to the *number* of worlds it includes. Different coarse-grainings may each give rise to decoherent history spaces satisfying the decoherence conditions, and nothing in the theory picks out one over the other as the uniquely correct space of Everett worlds. Second, Everett worlds are indeterminate in *nature*: a world for example may fail to determine which of the two slits an electron travels through, if the electron wavefunction does not decohere in the process. (172)

Each form of lingering indeterminacy can be seen as reflecting that, as above, decoherence as a mechanism for suppression of interference "does not eliminate this interference altogether". That decoherence is only approximate entails that different coarse-grainings generate different and differently numbered multiverses of Everett worlds. No coarse-graining is (meta)physically privileged. As Wallace (2012) puts is, there is no "natural grain". Wilson suggests that one can make sense of this by claiming that there is indeterminacy in world number. Here we are primarily interested in indeterminacy in world nature, so at this point leave aside indeterminacy in world number.

That the suppression of interference in decoherence is approximate also means that branching results in worlds with relatively determinate as opposed to absolutely determinate values of the

[6] See note 5.

observables at issue (e.g., position)—hence, there is indeterminacy in world nature. As Wilson observes, the two indeterminacies are deeply linked:

> The more fine-grained our partition of a consistent history space, the more histories there are and the more determinate each history is——up to the point at which the decoherence condition is not satisfied. It is a vague matter where this point is located. However coarsely or finely we grain a decoherent history space, events within individual Everett worlds will exhibit some (indeterminate) degree of indeterminacy in their properties. It is determinate that there is qualitative indeterminacy in the worlds, but it is indeterminate exactly how much indeterminacy there is. (180–1)

Importantly, this lingering indeterminacy is insuperable: "there is no way of coarse-graining the history space as to make the actual Everett world fully determinate" (181).

How should these forms of MI in DEQM be handled? Wilson (2020) says, somewhat confusingly, that "both indeterminacies ought to be regarded as epistemic or semantic in origin; however, indeterminacy of world nature [. . .] may usefully be understood as a novel example of emergent ontic indeterminacy" (173). Key here is that both forms of indeterminacy are associated with the 'semi-arbitrary' status of coarse-grainings (or the choice of a specific such coarse-graining), where the arbitrariness at issue is taken (by Wilson) to reflect semantic or (less plausibly) epistemic underdetermination. As he sees it, indeterminacy in world number is just a matter of semi-arbitrary coarse-graining; however, indeterminacy in world nature has an additional metaphysical component:

> The indeterminacy of the actual world is representational, in the sense that it depends on a semi-arbitrary choice of coarse-graining; but it is also worldly, in the sense that a complete description of the actual world fails to eliminate this indeterminacy. (182)

So Wilson is friendly to the idea that MI in world nature in DEQM is properly metaphysical; and in considering how such MI should be treated, he suggests that either a metaphysical supervaluationist (or 'precisificationist')[7] account of the sort endorsed by Barnes and Williams (2011) or a determinable-based account of the sort endorsed by Wilson (2013) might do the trick—though he registers that a supervaluationist approach faces difficulties of the sort highlighted by Darby (2010), Skow (2010), and others, and that a determinable-based approach has several advantages, and "seems a more natural fit" with DEQM in various respects.

We are also friendly to taking MI in world nature in DEQM to be properly metaphysical, and also see a determinable-based approach as more naturally accommodating such MI—more naturally than supervaluationism, in particular—and in the remainder of the paper will develop these lines of thought. We think there is more to say about the status and proper treatment of indeterminacy in world number in DEQM, but due to considerations of space leave this for another occasion.[8]

[7] The notion of precisification here is modeled on that associated with a supervaluationist theory of vagueness (see, e.g., Fine 1975), on which a precisification is a complete and maximal set of sentences, each having a determinate truth value.

[8] In lieu of a fuller treatment: we are inclined to think that indeterminacy in world number is also aptly treated as properly metaphysical indeterminacy, and moreover is best treated in determinable-based terms. Wilson (2020) suggests that indeterminacy in world number can be given a semantic supervaluationist treatment in line with classical logic and semantics, along lines of the non-standard supervaluationist approach proposed by McGee and McLaughlin (1995). However, first, it would be more systematic to treat indeterminacy in world number and in world nature similarly; but it is not plausible to treat the lingering indeterminacy in world nature as semantic. And second, a semantic supervaluationist treatment of indeterminacy in world number along lines of the 'preferred precisification' approach of McGee and McLaughlin is subject to the same difficulties that Wilson highlights with an epistemic approach to indeterminacy—namely, that it presupposes, implausibly, that there is a single preferred precisification/basis/decoherent history space/multiverse.

We start by filling in the case, first, for there being indeterminacy in world nature, and second, for this indeterminacy being reasonably taken to be 'worldly' or metaphysical.

We offer three arguments for there being indeterminacy in world nature.[9]

The first argument pertains to the fact that even in cases of decoherence of the sort giving rise to branching and associated Everett worlds, there may remain undecohered states. As above, the central idea of EQM is to "replace indeterminacy with multiplicity", such that superposition states such as (1) can be taken to represent not single systems with unfamiliar indeterminate properties—that is, as involving indeterminacy—but rather multiple systems, each with familiar determinate properties. And as above, on DEQM, multiplicity is *only* a matter of decoherence—it is not a matter of conscious observers, new fundamentality ontology, or anything else. It follows that in the absence of decoherence as applying to a superposition state such as (1), the state cannot be given a multiplicity reading, but must rather be given an indeterminacy reading.[10] But as Wilson (2020) observes, decoherence sufficient unto branching and the associated generation of Everett worlds is compatible with any given Everett world containing superposition states that are not decohered, as when "the world fails to determine which of the two slits an electron travels through, if the electron wavefunction does not decohere in the process", 172). So DEQM is compatible with there being Everett worlds containing superposition states which cannot be given a multiplicity reading, but which must rather be given an indeterminacy reading. And in practice this will often (always?) be the case.

The second argument—a variation on the first, from a different direction—pertains to the connection between component interference and state indeterminacy. As Wallace (2012, 61) notes, the state

$$|\psi\rangle_L = |Live\ Cat\rangle \tag{6}$$

instantiates a structure that represents a live cat, and the state

$$|\psi\rangle_D = |Dead\ Cat\rangle \tag{7}$$

instantiates a structure that represents a dead cat. Again, according to DEQM, there is a reading of state (1) (the superposition of states 6 and 7) on which it represents not one cat in an indeterminate state, but two cats—one in state (6), the other in state (7). Yet as Wallace goes on to observe:

> In general, even in a theory with linear equations, like electromagnetism or quantum theory, adding together two states with certain structures might cause those structures to overlap and cancel out, so that the structure of the resultant state cannot just be read off from the structures of the components. Indeed, in both electromagnetism and

[9] Quantum indeterminacy is commonly motivated by attention to the Eigenstate-Eigenvalue link (EEL), according to which a quantum system has a definite value v for an observable O iff it is in an eigenstate of O having eigenvalue v. However, some proponents of DEQM (e.g., Wallace, ms.) are skeptical about the link, and Wilson (2020) never mentions it in his discussion. So in what follows we offer arguments that do not rely on EEL (or any variants thereof). See Calosi and Mariani 2021 for discussion of how EEL has been taken to motivate quantum indeterminacy, and see Calosi and Wilson 2018 for an argument that, that given EEL, the phenomenon of incompatible observables entails residual indeterminacy in Everett worlds.

[10] The line of thought here presupposes a disjunctive premise to the effect that superposition states must be interpreted either as indeterminacy states (involving a single system having an indeterminate property) or as multiplicity states (involving multiple systems having determinate properties). In general, this disjunctive premise might not available, for there might be other readings of superposition states. However, here we are concerned not with all available interpretations of superposition states, but just what interpretations are available given DEQM as standardly motivated; and here the disjunctive premise is in place.

quantum theory, the technical term for this "cancelling out" is the same: interference (62).

Here Wallace connects multiplicity to the absence of canceling out of the structures associated with the components—in other words, to the absence of interference. More precisely, on DEQM it is required not that there be *no* interference, but rather that any interference be *negligible*, as per the medium decoherence condition. When interference between components of a superposition state is negligible, then the multiplicity reading is available. It remains, however, that branching is compatible with there being some superposition states for which the interference is not negligible. For any such states, the multiplicity reading of states like (1) is not available, and the states must rather be given an indeterminacy reading (see note 10). And again, in practice this will often (always?) be the case. Hence it is, for example, that the double-slit experiments have the empirical interference results that they do.

The third argument pertains to the fact that even in cases of decohered states, the decoherence is approximate, rendering the values of the associated observables comparatively or relatively determinate, not absolutely determinate. For purposes of generating an Everett world, all that is required is that decoherence renders certain states determinate FAPP—determinate enough, in particular, to accommodate ordinary experience in response to the measurement problem. Even so, decoherence does not eliminate *all* interference between components of the associated components of a given superposition, and hence the values of the associated observables in the state components are rendered only comparatively or relatively determinate—that is, to some small extent indeterminate. Hence there is lingering indeterminacy even in cases of decohered superposition states.[11]

The upshot of the previous arguments is that there is indeterminacy in world nature in DEQM, associated with both cohered and decohered states. Is this indeterminacy moreover metaphysical in nature? Wilson thinks so: "indeterminacy in world nature may be thought of as a naturalistic form of *metaphysical indeterminacy*" (182).[12] We agree, but it is worth saying a bit more by way of substantiating the claim.

We might start with the presumed core insight of EQM. Here the choice presented is as between a reading of superposition states as involving 'unfamiliar indeterminate properties' and one involving multiplicity along with determinate properties; but indeterminacy in properties is metaphysical indeterminacy. And as we have just argued (and as Wilson agrees), the EQM strategy as cashed via DEQM does not, after all, result in elimination of the 'unfamiliar indeterminate properties'; at best, it renders some of them more determinate. That may be good enough to resolve the measurement problem that was Everett's main focus, but there remains some portion of the seeming MI originally at issue—namely, that associated with there being indeterminate quantum properties associated with not-completely-decohered superposition states.

It is also worth noting that standard motivations for or presuppositions required for treating a given case of indeterminacy as semantic or epistemic are not in place for MI in world nature. To start, semantic or epistemic treatments are most often directed at cases of vagueness involving with borderline cases and associated Sorites-susceptibility;[13] but indeterminacy in world nature does not obviously involve borderline cases. Moreover, semantic accounts also typically proceed on

[11] That there is indeterminacy even in cases of decohered states would appear to undercut the claim that (with exceptions for cases where micro-superpositions are magnified to a larger scale) "determinacy will tend to be associated with macroscopic states of affairs, with extensive indeterminacy restricted to microscopic states of affairs" (Wilson 2020, 181). On the contrary, decohered macroscopic states will still be a locus of indeterminacy.

[12] See also Lewis 2016.

[13] See Calosi and Mariani 2021.

the assumption that relevant expressions in the relevant language(s) are vague; but the mathematical language of the decoherent histories formalism is not vague. To be sure, Wilson thinks that indeterminacy in world number can be handled in semantic or epistemic terms, on grounds that coarse-grainings' being 'semi-arbitrary' provides a basis for treating indeterminacy in world number as reflecting a kind of ambiguity or ignorance in which representation correctly describes the actual world. But as he observes, these strategies don't carry over to the case of indeterminacy in world nature, for having resolved any representational indeterminacy, indeterminacy in world nature will remain. Finally, an epistemic approach to indeterminacy in world nature presupposes that each Everett world is maximally precise, such that any indeterminacy reflects just our ignorance about which precise way a given Everett world is. But in DEQM there is no way to make Everettian worlds maximally precise; for (as noted above) at a certain point, the medium decoherence condition (5) will fail to be satisfied, and the precise worlds in question will fail to be members of the set of decoherent histories. We will return to this line of thought in §3.3.1.

There thus appears to be good reason to take there to be indeterminacy in world nature in DEQM which is moreover properly metaphysical. At least this seem reasonable contingent on there being an adequate account of MI making sense of MI on DEQM—as we will argue there is, below.

Supposing that we (and Wilson) are correct that there is MI in world nature in DEQM, this is of significance to the metaphysics of MI, not just as a naturalistically motivated general case study, but also because the indeterminacy at issue in DEQM is distinctively derivative, on the assumption (which we are here granting) that the fundamental ontology of the theory—given solely by the universal quantum state—is maximally determinate.[14] Some have argued that any metaphysical indeterminacy there might be must be fundamental (Barnes) or that any derivative metaphysical indeterminacy there might be is eliminable (Glick 2017). As we discuss further below, Barnes's argument applies only to a certain approach to metaphysical indeterminacy, different from that we endorse; and in our (forthcoming) we argue that Glick's argument doesn't go through. In any case, the case of derivative MI in DEQM stands as a challenge to both arguments.

3 Two approaches to MI

Given that DEQM involves MI in world nature, the question remains of how to account for this indeterminacy. In this and the following section, we offer an answer to this question. We start with brief summaries of the two main approaches to MI: first, metaphysical supervaluationism; second, a determinable-based approach.

3.1 Metaphysical supervaluationism

A metaphysical supervaluationist account of MI takes a 'meta-level' approach to MI, according to which MI involves its being indeterminate which state of affairs, of some range of determinate/precise states of affairs, obtains. As Barnes (2010) expresses the general idea:

[14]We grant that the sole fundamental entity in DEQM—the universal wavefunction/quantum state—is maximally determinate in that its properties are maximally determined (as, e.g., the property of having such and such amplitude and phase at such and such point). The further metaphysical picture behind DEQM is not perfectly clear. To start, there are several, incompatible ways to interpret the universal wavefunction. Moreover, there remains controversy over how to recover derivative entities out of the universal wavefunction. Just to mention a few options, Wallace (2012) takes derivative entities to be *patterns* in the universal wavefunction, whereas Ney (2021) takes them to be *parts*.

> It's perfectly determinate that everything is precise, but [...] it's indeterminate which precise way things are. (622)

Somewhat more specifically, Barnes and Williams (2011) say:

> When p is metaphysically indeterminate, there are two possible (exhaustive, exclusive) states of affairs—–the state of affairs that p and the state of affairs that not-p—–and it is simply unsettled which in fact obtains.

Here the sense of a 'possible' state of affairs—where states of affairs may be local or global (i.e., entire worlds)—is one restricted to 'admissible' possibilities: possibilities that are compatible with what is actually the case, in that they do not determinately misrepresent reality.[15] This leads (see Barnes and Williams 2011, 113–14) to the following characterization:

> *Metaphysical Supervaluationism*: It is metaphysically indeterminate whether P iff there are two possibly admissible, exhaustive and exclusive states of affairs (SOAs): the SOA that p and the SOA that $\neg p$, and it is indeterminate which of these SOAs obtains.

On the face of it, such a view might seem well-suited to accommodating the sort of quantum metaphysical indeterminacy that is our concern here:

> [There is] a suggestive parallel between the terms in the superposition and the idea [. . .] of precisifications. One of the terms in the superposition [. . .] is a term where the cat is alive, the other is not; that is reminiscent of multiple ways of drawing the extension of 'alive', on some of which 'the cat is alive' comes out true, on some, false. (Darby 2010, 235)

Crucially, the precisifications that are identified with superposition terms are maximal—or complete—and classical, hence indeterminacy-free:

> Importantly, given our picture of indeterminacy, all the worlds in the space of precisifications are themselves maximal and classical (Barnes & Williams, 2011: 116).

3.2 Determinable-based MI

A determinable-based approach to MI was initially proposed in Wilson 2013, and defended in Wilson 2016; it has been applied to the case of QMI in Bokulich 2014, Calosi and Wilson 2018 and forthcoming, and elsewhere. A determinable-based account takes an 'object-level' approach to MI, according to which indeterminacy is located in indeterminate states of affairs themselves, and where what it is for a state of affairs to be indeterminate is more specifically cashed in terms of a certain pattern of instantiation of determinable and determinate features:

> **Determinable-based MI**: What it is for an SOA to be MI in a given respect R at a time t is for the SOA to constitutively involve an object (more generally, entity) O such that (i) O has a determinable property P at t, and (ii) for some level L of determination of P, O does not have a unique level-L determinate of P at t (Wilson 2013: 366).

There are two ways in which an object (system) can have a determinable but no unique determinate: either it has no determinate ('gappy MI'), or it has more than one determinate ('glutty MI'). There are, moreover, two variants on the 'glutty' theme:

[15] Otherwise it would be settled that such an (incompatible) state of affairs (possibility) does not obtain.

1. multiple determinates are instantiated, albeit in relativized fashion
2. multiple determinates are instantiated, each to degree less than one.

As discussed in Wilson 2013 and 2016, a determinable-based approach to MI differs from a supervaluationist approach in various important ways, including that a determinable-based account reduces MI to a pattern of instantiations of determinable and determinate properties, and so (unlike a supervaluationist account) does not take MI to be primitive (a point to which we return below); a determinable-based account does not introduce propositional indeterminacy, and so (unlike a supervaluationist account) does not require introducing an indeterminacy operator into one's semantics or logic; and a determinable-based account is more generally thoroughly compatible with classical logic and semantics, and so (unlike a supervaluationist account) requires no revision in these classical theories.

4 Supervaluationist vs. determinable-based treatments of MI in world nature in DEQM

We now offer five arguments aimed at establishing that a determinable-based approach has a clear comparative advantage, so far as accommodating MI in DEQM is concerned.

4.1 The argument from imprecise histories

Histories cannot be maximally precise: after a certain point, they fail to meet the medium decoherence condition (5). Roughly (see Gell-Mann and Hartle 1990 for technical details), if the medium decoherence condition fails to be met, the histories (could) interfere. And if they interfere, it is impossible to assign them independent probabilities—as it is required by the formalism, if histories are to represent somewhat semi-classical worlds. As Gell-Mann and Hartle (1990) note:

> [C]ompletely fine-grained histories [...] cannot be assigned probabilities; only suitable coarse-grained histories can (433).

Completely fine-grained histories are those histories in which every value of every projection operator is specified. It follows that it is not possible to assign a precise value to every projection operator, if a history is going to qualify as a decoherent history. Decoherent histories represent Everett worlds. So, Everett worlds cannot be maximally precise.[16]

Now, a determinable-based approach to MI can take the failure of decoherent histories—Everett worlds—at face value, as representing (for a given system) the system's having a given determinable property—say, *having a certain life status*, in the case of Shrödinger's cat, or *having traveled between the emittor and the detector*, in the case of the double-slit experiment—without the system's having a unique determinate of the determinable.

Not so for metaphysical supervaluationism. An application of this approach would most naturally be seen as identifying precisifications with decoherent histories. But precisifications are supposed to be classical: maximally precise and indeterminacy-free. Since decoherent histories are not maximally precise/determinacy-free, supervaluationist precisifications cannot be identified with decoherent histories. Equivalently: decoherent histories do not qualify as admissible precisifications.

One might try to identify precisifications with suitable *fine-graining* of decoherent histories, as Wilson (2020) suggests:

[16] Gell-Mann and Hartle (1990) consider different ways of coarse-graining completely fine-grained histories; one approach proceeds by specifying ranges of values rather than precise values to associated observables (434).

> Can we nonetheless find suitable candidates for [ontic precisificiations] within EQM? One prospect is that they might be identified with quantum consistent histories [...]. In order to play the role of ontic precisifications, the consistent history space in question would need to be maximally fine-grained. The decoherence conditions fail for these fine-grained consistent histories, so they are not dynamically decoupled from one another and quantum modal realists ought not to regard them as representing genuine alternative possibilities. Still, these consistent histories may be apt to play a different role in the metaphysics of quantum modal realism: the role of ontic precisifications in a Barnes–Williams-style model of metaphysical indeterminacy. (182)

But this strategy won't work—and not just because the the decoherence conditions fail for such fine-grained histories, rendering them unsuitable for being genuine possibilities by lights of Wilson's quantum modal realism. The more general problem is that the failure of the decoherence conditions means that there is no reason to expect that interference effects will be negligible. And as discussed previously, with interference comes indeterminacy—contra the supervaluationist supposition that precisifications are indeterminacy-free.

Nor does it make sense to simply stipulate that (to some extent indeterminate) Everett worlds have multiple classical precisifications; for (in addition to such precisifications not being admissible, on the usual understanding of admissibility as requiring compatibility with the actual world) this would undercut the core contention of DEQM, according to which the multiplicity of Everett worlds is generated by decoherence alone.

The upshot is that a determinable-based approach can, while a metaphysical supervaluationist approach cannot, accommodate MI in DEQM.

4.2 The argument from interference

In §2, we argued that MI in world nature in DEQM is strictly related to interference—such MI is present on DEQM when and only when there are residual interference effects.[17]

As we argue in our (forthcoming), a determinable-based approach to MI can accommodate, and indeed provides the basis for, an intelligible explanation of quantum interference. There, and here, we use the case of quantum self-interference in the double-slit experiment as our case-in-point.[18] Simplifying a bit, we can ascribe to each particle traveling from the source to the screen detector in the double-slit experiment the following superposition state:

$$|\psi\rangle = c_1 |A\rangle + c_2 |B\rangle \tag{8}$$

Here $|A\rangle$ represents the state of the particle's traveling from emitter to detector through slit A but not slit B, and $|B\rangle$ represents the state of the particle's traveling from emitter to detector through slit B but not slit A. On a determinable-based account, the MI associated with double-slit indeterminacy is understood as follows:

> [T]he associated QMI reflects that, on any given pass of the experiment, the emitted particle has the determinable property *having traversed the region between source and*

[17]Recall the argument in §2. There we observed that DEQM can resort to the multiplicity reading of superposition states—the reading that eliminates indeterminacy—iff interference effects are negligible. In what follows we are going to discuss an experimental setting in which such effects are not negligible—namely, the double-slit experiment. In such cases, we contend, we are left with the indeterminacy reading.

[18]The discussion to follow is abbreviated, for considerations of space. See Calosi and Wilson (forthcoming) for further details.

> *detector* (which property is itself a determinate of *position* or of *being spatiotemporally located*), but does not have a unique determinate of that determinable, due to too many of the determinates of the determinable, associated in particular with the states $|A\rangle$ and $|B\rangle$, being instantiated, in glutty fashion (Calosi and Wilson, forthcoming).

As above, glutty MI can be cashed out in at least two ways: one in which the relevant object (system) has different determinates relative to different perspectives, and one in which its has the different determinates at a degree less than 1. On the relativization variant of glutty MI as applied to the case at hand, while superposition prevents attributing a unique trajectory to the particle, there remains a sense in which the particle can, in relativized fashion, consistently travel through both slits at a time. The claim is then that these relativized instantiations can interact, consonant with self-interference. On the degree-theoretic variant of glutty MI the particle has both determinates associated with states $|A\rangle$ and $|B\rangle$, to degrees $|c_1|^2$ and $|c_2|^2$ respectively. The claim is then that these degreed instantiations can interact, consonant with self interference. (Again, see our forthcoming for further details about these implementations of glutty MI.) Either way, interference is the result of the relevant particle's having——either in relativized fashion, or to a degree less than one—each of the causally efficacious determinate properties associated with $|A\rangle$ and $|B\rangle$.

By way of contrast, as we argue in our (forthcoming), a metaphysical supervaluationist account of MI does not have the resources to explain the existence of the interference patterns characteristic of the double-slit experiment:

> On [metaphysical supervaluationism], a superposition is a state whose precisifications are given by the terms of the superposition. Superposition QMI is then taken to reflect its being indeterminate which term (or associated property) of the superposition obtains.
>
> How does such an approach fare as an account of the double-slit experiment? Not well. For the supervaluationist, indeterminacy is unsettledness about which one of a range of maximally precise states of affairs obtains. On this view, it is determinate that only *one* such state of affairs obtains, notwithstanding that it is indeterminate *which* one obtains. Hence in the case of the double-slit experiment, the supervaluationist takes the superposition QMI at issue to reflect its being indeterminate which one of the states $|A\rangle$ or $|B\rangle$ obtains. On this account, there is no question of there being any sense in which *both* states obtain; again, it is determinate that only one of the states obtains. But if only one of the states obtains, then there's no physical basis for the interference characteristic of the double-slit pattern.

More generally, and for the same reason, metaphysical supervaluationism cannot accommodate quantum interference as associated with superpositions. But MI on DEQM precisely consists in the presence of interference. Hence metaphysical supervaluationism cannot accommodate MI on DEQM.[19]

4.3 The argument from nonfundamental MI

As previously noted, the MI in DEQM is derivative—attaches to nonfundamental ontology, not fundamental.

[19]One might wonder whether the supervaluationist might aim to provide a non-causal explanation of interference, as Wilson (2020)is himself inclined to do, as somehow reflecting patterns of variation across different worlds. However, Wilson's non-causal conception aims to accommodate interference across different branches, not within a branch. Interference within a branch would presumably remain a causal affair.

A determinable-based approach to MI can accommodate derivative MI, since this approach is compatible with MI's being either fundamental or derivative. As above, on the determinable-based approach, MI involves indeterminacy in a given state of affairs itself, where the status of a state of affairs as indeterminate is cashed in the holding of a certain pattern of determinable and determinate features.[20] This pattern—whereby an object (entity, system) has a determinable feature, but no unique determinate of that determinable feature—may be instantiated by states of affairs that are fundamental and by states of affairs that are derivative. If the state of affairs instantiating the pattern is fundamental, then so will be the associated MI; if the state of affairs instantiating the pattern is derivative, then so will be the associated MI. Reflecting this flexibility, past applications of a determinable-based account have sometimes pertained to fundamental cases of MI (involving certain readings of certain interpretations of QM) and sometimes pertained to derivative cases of MI (involving macro-object boundaries and the open future).

By way of contrast, one of the main proponents of a metaphysical supervaluationist approach—namely, Barnes—has argued that this approach is incompatible with MI's being derivative. More specifically, Barnes (2014) argues that if there is MI, it must exist at the fundamental level, on pain of contradiction.

As we observe in our (forthcoming), Barnes's argument presupposes (as per a meta-level metaphysical supervaluationist approach to MI) that MI involves its being indeterminate which of some range of perfectly determinate options obtains. In particular, Barnes's "simple argument that in order for there to be metaphysical indeterminacy at all there has to be indeterminacy in how things are fundamentally" (341) has as a premise that "For some complete description, D, of a way for things to be derivatively, it is indeterminate whether D is true". This claim is rejected on an object-level determinable-based approach to MI. Correspondingly, Barnes's argument shows, at best, that any MI of the meta-level, metaphysical supervaluationist variety must be fundamental.

So to the extent that Barnes's argument goes through, it serves also to show that metaphysical supervaluationism cannot accommodate the MI at issue in DEQM.

4.4 The argument from 'unfamiliar properties'

While the EQM strategy of 'replacing indeterminacy with multiplicity' was primarily motivated by the aim of providing a non-ad-hoc basis for reconciling Schödinger's equation with ordinary experience, a secondary motivation was no doubt to avoid commitment to the 'unfamiliar indeterminate properties' seemingly represented by superposition states. DEQM provides an attractive means of accomplishing the first aim, but commitment to indeterminate properties remains, on this view. As such, it would be an advantage of an account of MI if it could not only accommodate MI in world nature on DEQM, but do so in a way rendering this MI familiar or in any case intelligible.

A determinable-based account has an advantage over a metaphysical supervaluationist account, in appealing to pretheoretically and independently understood notions—a certain pattern of properties of the sort with which we are experientially and theoretically familiar—as opposed to a primitive feature of worldly 'unsettledness'. As even proponents of a supervaluationist account admit:

> The conceptual advantage [of a determinable-based account over a supervaluationist account] is this: nobody who understands the machinery of determinates and determinable can fail to understand Wilson when she says that the world is metaphysically

[20] Note that here there is no indeterminacy in 'which' states of affairs, precise or imprecise, do or do not obtain. Hence it is that, unlike a supervaluationist account of MI, a determinable-based account does not require or invoke propositional or sentential indeterminacy, or associated indeterminacy operators, and as such requires no departures from classical logic or semantics.

> indeterminate. She has told you exactly what that means: it is for a certain kind of property to be instantiated without a certain [unique] other kind of property to be instantiated. If you understand what she means by such properties—if you grasp the determinate/determinable distinction—then there is simply no room for not understanding worldly indeterminacy. Our own account, by contrast, makes ineliminable appeal to the notion of indeterminacy when we tell you how the world is. When p is indeterminate, we tell you that either the demands for p's truth or the demands for p's falsity are met, it is simply indeterminate which. Someone who is sceptical about the very idea of worldly indeterminacy is of course not going to be helped by this. (Barnes and Cameron 2016, 127–8)

To be sure, proponents of metaphysical supervaluationism aim to fill in their primitive by modeling it along lines familiar from supervaluationist treatments of semantic indeterminacy, with metaphysical indeterminacy reflecting unsettledness not between linguistic precisifications, but between precisificationally possible worlds or states of affairs. Even so, the parallel doesn't extend so far as to render a primitivist account of MI intelligible. In particular, while it is clear enough how semantic indeterminacy might reflect our having not yet decided how to use our language, it is not as clear how MI might reflect the world's having not yet decided which actual way it is. In the non-quantum context: how could the world be settled (right now) about Mount Everest's having a determinate boundary, but be unsettled (right now) about which boundary that is? In the quantum context: how could the world be settled (right now) that the particle has gone through exactly one slit, but be unsettled (righ now) about which slit that was? Appeals to 'multiple actualities' and the like don't do much to render such claims intelligible, much less familiar.

That said, one might wonder if a determinable-based account really does accommodate MI in familiar terms, insofar as this account rejects a traditional assumption about determinables and determinates, according to which an object possessing a determinable property, one and only one—a unique—determinate of that property (at a given level of determination). As discussed in Wilson 2013, however, attention to cases such as that of an iridescent feather (which has the determinable *colour* but no unique determinate of that determinable) indicate that the uniqueness supposition is arguably too strong, and should be rejected as generally characterizing determinables and determinates.[21] In addition, as Wilson goes on to discuss (§III.iv), the slate of traditionally endorsed features of determinables and determinates can be imported without much ado into the more general (and more accurate) understanding of determinables and determinates.[22] Correspondingly, it remains that a determinable-based account as involving a certain pattern of instantiation of determinable and determinate properties accommodates MI in terms that are—unlike the primitivist terms of a supervaluationist account—experientially and theoretically familiar.

4.5 The argument from Quantum Modal Realism

Our fifth argument elaborates the first, in a way drawing on Wilson's suggestion that DEQM provides a basis for *Quantum Modal Realism* (QMR)—a streamlined, naturalistic heir to Lewis's

[21] For discussion of other sources of resistance to the uniqueness supposition, see Wilson 2017.

[22] For example, consider the 'core' feature of the determinable/determinate relation, according to which it is a relation of increased specificity different from the conjunct/conjunction and disjunction/disjunct relations. Even if a determinable instance may be multiply determined (in relativized or degree-theoretic fashion) or undetermined, this core feature would characterize each of the actual or counterfactual determinable/determinate relations at issue. It remains that instances of determinates are necessarily accompanied by instances of all associated determinables. The traditional supposition that the determinates associated with a given determinable may be ordered along one or more 'determination dimensions' remains intact. And so on.

classical modal realism. A core tenet of QMR is what Wilson calls *Alignment*:

> *Alignment*: to be a metaphysically possible world is to be an Everett world. (22)

On QMR, roughly speaking, "for an event to be metaphysically possible is for it to occur in some Everett world, for it to be metaphysically necessary is for it to occur in all Everett worlds, and for it to be actual is for it to occur in our own world" (29).

Given QMR, the first argument in this section can be precisified (no pun intended) as follows. Supervaluationist precisifications are maximally precise; hence they are not Everett worlds. It follows, given *Alignment*, that supervaluationist precisifications are not metaphysically possible worlds. In that case, however, a proponent of QMR cannot appeal to metaphysical supervaluationism as a means of accommodating MI in decoherence-based EQM, for not only will supervaluationist precisifications be inadmissible, they will be metaphysically impossible. To be sure, Wilson does consider impossible worlds as a means of making sense of *epistemic* and *conceptual* modalities; but such uses of impossible worlds do not clearly carry over to the explicitly metaphysical case of quantum MI. An additional difficulty is that precisifications are supposed to be admissable, in not determinately misrepresenting reality. As such, an appeal to impossible worlds in a supervaluationist treatment of MI in world nature in DEQM would need to argue that something impossible does not determinately misrepresent something possible (and indeed actual). That seems like a hard row to hoe, to put it mildly.

Conclusion

Let's sum up the main results of this paper and their significance. First and perhaps most importantly, on a widely endorsed realist interpretation of quantum mechanics—(Decoherence Only) Everettian Quantum Mechanics—there is metaphysical indeterminacy, and in particular, indeterminacy in world nature. This is significant, insofar as quantum indeterminacy has most frequently been located in the less popular orthodox interpretation (as in Darby's 2010 and Skow's 2010 discussions; but see Calosi and Wilson 2019). Second, indeterminacy in world nature in DEQM is derivative, a result which undercuts recent arguments according to which metaphysical indeterminacy must be fundamental. Third, indeterminacy in world nature in DEQM cannot be accounted in metaphysical supervaluationist terms, as yet another case-in-point of the failure of a supervaluationist approach to quantum indeterminacy. Fourth, and by way of contrast, a determinable-based account of metaphysical indeterminacy provides the basis for an illuminating explanation of indeterminacy in the multiverse, as yet another case-in-point of the success of a determinable-based approach to quantum indeterminacy. It is also worth noting that, reflecting that the eigenstate-eigenvalue link plays no role in DEQM, these results do not hinge on acceptance of that link; hence they sidestep concerns (as in Fletcher and Taylor forthcoming) about treatments of quantum indeterminacy relying on that link. All told, then, indeterminacy in world nature in DEQM represents a powerful case study of quantum metaphysical indeterminacy and of the aptitude of a determinable-based account to accommodate such indeterminacy.

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