# Metaphysical Indeterminacy in the Multiverse*

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One might suppose that Everettian quantum mechanics (EQM) is inhospitable to metaphysical 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 MI in world nature. After a brief presentation of DEQM (§1), we bolster the case for taking 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 (Barnes and Williams 2011) and a determinable-based approach (Wilson (2013) and Calosi and Wilson (2018 and forthcoming) (§3). We briefly describe each approach, then offer four arguments supporting a determinable-based approach to world nature MI in DEQM.

## 1 Decoherence-based EQM (DEQM)

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, (1) represents a system as being in a single indefinite or indeterminate state. But as Wilson (2020) and many others see it, the crucial insight at the core of the EQM approach is that superpositions such as (1) may rather represent a multiplicity of definite or determinate states:

> The quantum dynamics generically evolves quantum states into superpositions; where the orthodox interpretation took superposed quantum states to represent single systems with unfamiliar indeterminate properties, Everett proposed taking superposed states to represent multiple systems each with familiar determinate properties. In other words, the central idea of EQM is to replace indeterminacy with multiplicity. (77)

Everett's own (1957) gloss (the 'Relative State Interpretation') was driven by concerns about the measurement problem—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 measurements) experience it as being. Rather than bridge this gap via a supposed 'collapse' of the wave function, Everett suggested that measurements result in entanglements generating relative states: a single cat is dead relative to one substate and alive relative to another substate.

An alternative understanding of EQM's central idea, developed by DeWitt (1968, 1970), takes the multiplicity at issue to reflect multiple individual systems, and indeed multiple *worlds*. Among the

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variants on the many worlds theme, the most deemed most promising has been that developed by Saunders (1993, 1994) and Wallace (2008, 2012), according to which the multiplicity of worlds is understood in terms of the branching structure induced by decoherence:

> 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. (Wilson, 80)

Though decoherence does not entirely suppress interference, it does so to a degree sufficient to prise apart the components of a given superposition state in a way consonant with ordinary experience:

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

Metaphysically speaking: on DEQM, 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 (non-fundamental, derivative) worlds (the 'multiverse'):

> Everett worlds, as represented by decoherent histories, are to be understood as non-fundamental. The universal quantum state is the fundamental entity of EQM, and individual Everett worlds are emergent or derivative entities, grounded in the universal state. (Wilson, 80–1)

Formally speaking: DEQM is naturally situated in the 'decoherent histories' formalism, which presupposes the 'Heisenberg picture', according to which the universal quantum state remains fixed, and operators (associated with observable quantities) change with time. As applied to DEQM, the entire state of the world at each time $t$ is represented by a projection operator. Different possible states are represented by orthogonal projections $\hat{P}_i$ summing to unity, as per (2) and (3) below:

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

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

Partitions of projection operators satisfying (2) and (3) provide 'coarse grainings' of the universal state, which generate histories $H_i$—time-ordered sequences of time-dependent projection operators:

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

According to DEQM, such histories are potentially suited to represent individual worlds, and sets of such histories are potentially suited to represent complete multiverses. But 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.[1] This

[1] Effectively, what is required here is that the histories be well-decohered enough to be dynamically independent, such that independent probabilities can be assigned to those histories.

requirement is usually cashed out in terms of the 'medium decoherence condition' (Gell-Mann and Hartle 1993), where $\rho$ is a density operator for the initial state of the universe, and $Tr$ is the trace:

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

On DEQM, histories meeting condition (5) are taken to represent a multiplicity of Everettian worlds—the (or a) multiverse. Decoherence is here thought of as involving the suppression of quantum interference as a result of internal or external interactions; in cases of decoherence the component terms in the superposition behave semi-classically 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—a process referred to as *branching*:

> 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. (84)

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

## 2 MI in world nature

We are now in position to see how there remains room for MI on DEQM. To start, Wilson suggests that there are two sources of indeterminacy on DEQM:

> First, [...] the space of Everett worlds is indeterminate with respect to the *number* of worlds [...]. Different coarse-grainings may each give rise to decoherent history spaces satisfying the decoherence conditions, and nothing in the theory picks out one [...] 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". Relatedly, the two indeterminacies are tightly 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)

Wilson (2020) suggests that indeterminacy in world number can be handled in semantic supervaluationist terms, but that indeterminacy in world nature is also 'worldly':

> 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)

Wilson suggests that either a metaphysical supervaluationist (or 'precisificationist') 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 certain difficulties with a supervaluationist approach and suggests that a determinable-based approach "seems a more natural fit" with DEQM.

We agree that indeterminacy in world nature is metaphysical, and that a determinable-based approach to provide a more natural way of accommodating such QMI. We start by offering three arguments for there being indeterminacy in world nature:[2]

1. EQM aims to "replace indeterminacy with multiplicity" in superposition states such as (1). And on DEQM multiplicity is *only* a matter of decoherence—not a matter of conscious observers, new fundamentality ontology, etc. Hence in the absence of decoherence, a superposition state cannot be given a multiplicity reading, but must rather be given an indeterminacy reading. But as Wilson (2020) observes, decoherence generating branching is compatible with resulting Everett worlds containing undecohered superposition states, 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). Such worlds will contain superposition states which cannot be given a multiplicity reading, and so must rather be given an indeterminacy reading.[3]

2. Wallace observes:

   > [E]ven in a theory with linear equations [...] 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 quantum theory, the technical term for this "cancelling out" is the same: interference (62).

   Here Wallace connects multiplicity to absence of cancelling out of component structures—that is, to absence of interference. Now, on DEQM it is required only that any interference be *negligible*, as per the medium decoherence condition. When interference between components of a superposition state is negligible, the multiplicity reading is available. But branching is compatible with superposition states for which interference is non-negligible. The multiplicity reading is not available for such states; they must rather be given an indeterminacy reading.

3. Even in cases of decohered states, there is lingering indeterminacy. For purposes of generating an Everett world, all that is required is that decoherence renders certain states determinate enough to accommodate ordinary experience. 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, not absolutely, determinate—that is, to some small extent indeterminate.

[2] Reflecting that some proponents of DEQM (e.g., Wallace) are skeptical about the link, the arguments to follow do not rely on 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 $v$.

[3] This line of thought, and the next, involve a disjunctive premise to the effect that superposition states must be interpreted as either indeterminacy states or multiplicity states. To be sure, there might be other readings of superposition states. However, here we are concerned not with all available readings, but just with the readings available given the suppositions driving DEQM; and here the disjunctive premise is in place.

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

- The key contribution of EQM is presented as offering a choice between a reading of superposition states as involving 'unfamiliar indeterminate properties'—that is, as involving MI—and one involving multiplicity along with determinate properties. But DEQM does not, after all, result in complete 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 of the MI originally at issue.
- 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:
  - Semantic or epistemic treatments are typically directed at vagueness, indicated by borderline cases or Sorites-susceptibility; but indeterminacy in world nature has nothing to do with such phenomena (see Calosi and Mariani 2021). Nor is the mathematical language of the decoherent histories formalism is not vague.
  - Wilson thinks that indeterminacy in world number can be handled in semantic or epistemic terms, on grounds that coarse-grainings' being 'semi-arbitrary' allows a treatment in terms of ambiguity or ignorance in which representation correctly describes the actual world. But as he notes, these strategies don't carry over to the case of indeterminacy in world nature, for having settled the representational issue, 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 would reflect just our ignorance about which precise way the Everett world was, in fact. But in DEQM there is no way to make Everettian worlds maximally precise; for 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. Hence Wilson notes, "[T]here is no way of coarse-graining the history space as to make the actual Everett world fully determinate" (181).

So, it seems reasonable to take indeterminacy in world nature on DEQM to be metaphysical, contingent on there being an adequate account of MI making sense of MI on DEQM.

# 3 How is MI in world nature in DEQM best accommodated?

## 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:

> 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.[4] 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 and 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 (more specifically) what it is for a state of affairs to be indeterminate is 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 two variants on the 'glutty' theme:

1. multiple determinates are instantiated, albeit in relativized fashion

2. multiple determinates are instantiated, each to degree less than one.

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

As discussed in Wilson 2013 and 2016, *Determinable-based MI* has certain general advantages, including that such an account ...

1. ... reduces MI to a pattern of instantiations of properties of the sort with which we are already familiar, and so (unlike a supervaluationist account), does not take MI to be primitive.
2. ... does not introduce propositional indeterminacy, and so (unlike a supervaluationist account) does not require introducing an indeterminacy operator into one's semantics or logic.
3. ... is thoroughly compatible with classical logic and semantics, and so (unlike a supervaluationist account) requires no revision in these classical theories.

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

We now offer three arguments in support of a determinable-based over a metaphysical supervaluationist treatment of MI on DEQM.

### 3.3.1 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 no condition is imposed upon different histories, they (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 Everettian worlds. So, Everettian worlds cannot be maximally precise.

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 maximally fine-grained decoherent histories:

> Can we [...] find suitable candidates for multiple actualities 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. (Wilson, 182)

But this strategy won't work, for the failure of the decoherence conditions means that interference effects will be non-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 admissible (to some extent indeterminate) Everett worlds have multiple classical precisifications; for this would undercut the core contention of DEQM, according to which the multiplicity of Everett worlds is generated by decoherence alone.

### 3.3.2 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.

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. Simplifying a bit, we can ascribe to each particle travelling from the source to the screen detector in the double-slit experiment the following superposition state:

$$|\psi\rangle = c_1 |A\rangle + c_2 |B\rangle \tag{6}$$

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 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).

Glutty MI can be cashed in terms either of the relevant object (system) having different determinates relative to different perspectives, or in its having the different determinates at a degree less than 1. Focusing on the relativization variant: 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.

By way of contrast, a metaphysical supervaluationist account of MI does not have the resources to explain double-slit interference patterns:

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, metaphysical supervaluationism is unable to 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.[5]

### 3.3.3 The Argument from Nonfundamental MI

As above, the MI in DEQM is derivative, attaching to nonfundamental, not fundamental, ontology.

- A determinable-based approach to MI can accommodate derivative MI. On this approach, MI involves indeterminacy in a given state of affairs itself, where this is cashed in terms of the holding of a certain pattern of determinable and determinate features. This pattern may be instantiated by either fundamental or derivative states of affairs: if the state of affairs instantiating the pattern is fundamental, then so will be the associated MI; if derivative, then so will be the associated MI. Correspondingly, 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, Barnes (2014) argues that metaphysical supervaluationism is incompatible with MI's being derivative. More specifically, she argues that any MI there may be must be fundamental, on pain of contradiction.

  As we observe in our (forthcoming), Barnes's argument presupposes that MI involves (as per a 'meta-level' approach) its being indeterminate which of some range of determinate options obtains. Barnes's argument 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 (e.g., determinable-based) approach to MI. Hence 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 shows that metaphysical supervaluationism cannot accommodate the MI at issue in DEQM.

[5] 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.

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