Getting real about quantum underdetermination

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In this essay, I argue that competing interpretations are empirically equivalent if and only if they are underdetermined by evidence, as the definition of each depends on the property of indistinguishable-ness—that competing interpretations are indistinguishable from each other. Then, I will argue that this link does not pose a problem for us to be realists about quantum mechanics, as we expect our physical theories to be universally applicable. Thus, by appealing to our expectation of universal applicability, and the fact that the competing interpretations are not underdetermined outside the domain of nonrelativistic quantum mechanics, we are justified in favouring an interpretation with a larger domain, despite the theoretical virtues of other competing interpretations that our choice interpretation lacks. First, I will outline what the competing interpretations of quantum mechanics are. Second, I will discuss the key terms involved and establish a link between empirical equivalence and underdetermination. Third, I will discuss the domains and theoretical virtues of each interpretation and provide motivating reasons for why we are able to choose one interpretation over the others. Finally, I will close by responding to one objection: Hoefer's abstention, a consequence of his tautological scientific realism thesis.

There are three competing interpretations of nonrelativistic quantum mechanics: Bohmian mechanics, GRW, and Everett's many worlds interpretation. Each aims to address the measurement problem. To understand the measurement problem, consider the following:

1. The wave function is the complete description of the physical system.
2. The wave function always obeys the Schrödinger equation.
3. Every experiment has a unique outcome.

(1.), (2.), and (3.) together are mutually inconsistent (Maudlin, 1995, p. 7). This is the measurement problem. Bohmian mechanics rejects (1.), arguing that there exists particles with precise locations along a determinate path (Chen, 2019, p. 6). Specifically, "the wave function also determines the velocity of the particles according to the guidance equation" (p. 6), where the guidance equation is posited by Bohmian mechanics to be $\gamma'(t)$, a function dependent on several variables, including the particle's velocity, given by the Schrödinger Equation, and its spatial derivative, &c (Skow, 2010, p. 4). Thus, Bohmian mechanics reduces the measurement problem to a question of where and how these particles evolve over time. This question is addressed by the guidance equation. GRW rejects (2.), arguing that the wave function sometimes collapses spontaneously, at a fixed rate per particle per unit time (p. 7). GRW collapses are characterised by Guassians in a fixed configuration space, while the collapse itself is centred at a point in physical space. The probability of collapse is given by $\tau = 1/\lambda$, where $\lambda_{micro} \simeq 10^{-16}$ sec^{-1} is a posited constant probability occurrence rate for the collapse of a single particle (Ghirardi et al., 1986, p. 480). The Everettian interpretation rejects (3.), arguing that there exists branches of worlds, corresponding to the possible outcomes of measurements (Chen, 2019, p. 7). That is, if there are two possible outcomes of a measurement, e.g. spin up and spin down, there are two worlds after the measurement: a world where the measuring device reads spin up, and another where it reads spin down. We simply occupy one of these worlds. Some argue that because of decoherence, i.e. when two worlds no longer interfere with each other (inference has a mathematical definition and a physical meaning; Maudlin, 2019, p. 176), we are unable to know of, or interact with these other worlds.

It should be noted that GRW has several variations. The specifics of these variations are not relevant to the discussion. Thus, I will outline two. GRW posits two ontologies: mass-density (GRWm) and flash ontology (GRWf) (Maudlin, 2019, p. 111). Goldstein et al.

(2012) notes that GRWm and GRWf is known to be empirically equivalent (p. 4). They define empirical equivalence as the fact that both variations "make exactly and always the same empirical predictions" (p. 4). I argue that empirical equivalence has a secondary, subtle aspect: that e.g. each variation of GRW is generated from the same set of observations. That is, the basis on which each GRW variation is derived from is the same. This secondary aspect highlights the domain of each interpretation. Thus, while the competing interpretations are not the same (i.e. not isomorphic to each other) because there are no Bohm particles in GRW, and there are no spontaneous collapses in Bohmian mechanics, &c (Callender, 2020, p. 8), all three interpretations arise from the same observations, and make the same predictions in the domain of nonrelativistic quantum mechanics. Despite their empirical equivalences, each interpretation is meaningfully distinct. Callender notes that GRW and Bohmian mechanics posits beables (i.e. "items that exist according to a theory", e.g. Bohm particles; Maudlin, 2019, p. 111) in addition to physical laws which govern said beables (e.g. mathematical equations that explains the observed behaviours of electrons and photons; Callender, 2020, p. 7). Thus, these kinds of additions (i.e. beables) preserve the empirical equivalence of each interpretation, as each makes no new (or differing) claims about the observations of fundamental particles.

Is there a relationship between empirical equivalence and underdetermination by evidence? I argue that such a link exists. I argue that competing interpretations are empirically equivalent if and only if they are underdetermined by evidence. This follows from the definitions of the relevant terms, specifically from the fact that each interpretation is indistinguishable from each other. Wallace (2023) defines underdetermination by evidence as "the failure of any realistically-obtainable evidence to distinguish between multiple scientifically-serious rival theories." (p. 2). Thus, if a set of interpretations are indistinguishable from each other, it immediately follows that they are empirically equivalent, and that there is a problem of underdetermination of interpretation by evidence. That is, for competing interpretations to be empirically equivalent, they need to be (empirically) indistinguishable from each other. For competing interpretations to be underdetermined by evidence, they need to be (empirically) indistinguishable from each other. While the latter may capture our metaphysical worries (i.e. that no amount of evidence can empirically distinguish between competing interpretations), in the domain of quantum mechanics, this relationship holds. One might argue that this relationship is incidental—that within a domain, there seems to be a relationship between empirical equivalence and underdetermination by evidence. One might argue that if one examines the metaphysical causes of the two, one would find no metaphysical cause. Thus, one might argue that empirical equivalence points towards knowledge-that—the status of competing theories. One might argue that underdetermination by evidence really is the metaphysical worry that we will never have the ability to distinguish between empirically equivalent interpretations, regardless of our efforts and attempts. Thus, if one is about the state of things, while the other is a metaphysical concern, there is no necessary relationship between the two, hence the incidental-ness claim. I admit that I have not established a metaphysical, causal link between the two terms across all domains. I do not intend to show such a link. Instead, I have shown that given the definitions of the two terms, a relationship establishes itself naturally, via the property of indistinguishable-ness (within the domain of quantum mechanics). Nevertheless, I disagree with the claim that underdetermination should only be about metaphysical worries, as despite people's beliefs for quantum underdetermination, competing interpretations are in actuality not underdetermined by evidence (hence, not a metaphysical underdetermination).

Are the competing interpretations underdetermined by evidence? One could argue that quantum mechanics is underdetermined by evidence because we are unable to distinguish each interpretation, empirically. Specifically, a lemma Wallace (2023) uses is that the competing interpretations are underdetermined by evidence because each makes no novel, testable predictions, thus each fails to generate distinguishing, novel results (p. 24). Wallace uses this lemma to argue that the three interpretations are not underdetermined by evidence, despite them being empirically equivalent in a specific domain. When we expand our domain from nonrelativistic quantum mechanics (domain A) to e.g. relativised quantum field theory, or experiments involving photons, we see that Bohmian mechanics, and GRW, says nothing in this new domain (domain B), as the interpretations themselves have not been extended to the new domain. He argues for a stronger claim, arguing that GRW and Bohmian mechanics cannot say anything about the spectral lines experiment, nor anything about the two-slit experiment, because of the physical measurement process involved in these experiments (p. 21). Specifically, he says that "[e]lectrons are standardly detected by one or other process that causes the electron to scatter a number of photons: in Maudlin's own presentation, for instance, a phosphor screen is used, and a flash of light marks the detection of each electron. Once again, this is well understood as a phenomenon in QED, but it cannot be modelled inside NRQM." (p. 20). Thus, while the experiment itself can be modelled in nonrelativistic quantum mechanics (domain A), the physical process of measuring where the electrons are lies outside domain A. Since e.g. Bohmian mechanics is currently confined to domain A, and the experiment it endeavours to explain is not entirely confined to domain A, can Bohmian mechanics really claim to have fully explained the experiment? I do not believe that it can. Furthermore, experiments outside the scope of nonrelativistic quantum mechanics, e.g. random decay times, the photoelectric effect, &c, are all examples of the current limits of GRW and Bohmian mechanics' domains (p. 22). Thus, Wallace argues that there is no underdetermination by evidence because the interpretations themselves are not "even remotely comparable" with each other (p. 24). Thus, those who argue that the competing interpretations are underdetermined are only focusing on a specific, narrow domain where there is an underdetermination. Since this underdetermination is contained within domain A $\subsetneq$ B, and that in domain B, we have reason to favour one interpretation above all else, the underdetermination within domain A itself is resolved by our choice of an interpretation (our choice is justified because there is no underdetermination in domain B).

Can we choose one interpretation over another, given an underdetermination in domain A, and the lack of an underdetermination in domain B? I argue that we can, since physics aims to describe all of reality. All of our physical theories and interpretations should be universally applicable (i.e. able to explain all current and future physical observations). Does this give us reason to favour an interpretation with a larger domain? As it stands, I argue that we have reason to favour the Everettian interpretation, because it is extendable outside nonrelativistic quantum mechanics, and not necessarily because it has a larger domain. I argue that this choice is justified in spite of the theoretical virtues each competing interpretation has. For example, Brichmont argues that Bohmian mechanics is unrivaled in its "level of clarity" and "explanatory power" (Callender, 2020, p. 19). This is in contrast with the Everettian interpretation being "minimalist" (p. 20), as it does not posit any new beables or equations such as the guidance equation, nor does it introduce any fundamental constants, such as τ with some choice of λ. It should be noted that GRW may possess the virtue of being falsifiable, if GRW interpretations are committed to some parameter pairs (p. 4). Alternatively, if the constant τ in GRW is empirically verifiable, that would make GRW falsifiable in another way. Thus, if one values specific virtues, e.g. falsifiability, explanatory power, or the domains of interpretations, one could choose which interpretation to favour. However, my choice is not based on theoretical virtues. Instead, it appeals to the expectation of a grand, unified theory. As we live in one, objective reality, we expect our physical theories to be about the same reference, that there exists a successful theory (i.e. a theory which can explain all quantum phenomena), that the theory itself is unique (i.e. there exists no competing empirically equivalent interpretations), and the theory is knowable (i.e. we will arrive at this theory given sufficient time and effort, and not at some approximation of it). For the sake of argument, suppose that such a theory exists. It need not be unique. As it stands, two of the three interpretations are unable to describe a significant subset of observations we have made about the quantum realm, e.g. the photoelectric effect. Bohmian mechanics' and GRW's current inability to discuss the photoelectric effect gives us a strong reason to disfavour it, and favour an interpretation which is currently compatible with such experiments. Thus, by appealing to the status of each interpretation in domain B, and given our expectation of universal applicability, we have reason to favour an interpretation which is extended to domain B, thereby resolving our debate within domain A. Afterall, if Bohmian mechanics is the correct interpretation, why would it fail to explain the photoelectric effect?

An objection to the act of choosing is made by Hoefer (2020), who argues for his tautological scientific realism thesis (p. 22). In essence, he argues that there are many scientific facts and theories that have been established beyond reasonable doubt, and thus we should be scientific realists about these theories and facts (p. 24). This is in contrast with foundational physics, of which we have reasonable doubt about the status of such interpretations. For instance, the measurement problem gives us reason to doubt that quantum formalism is true (as it is). The fact that quantum mechanics is not compatible with general relativity gives us reason to doubt both (I note that this commonly held claim appeals to the expectation of universal applicability). Thus, how can we choose one interpretation over the other, if we have reason to doubt all three? I accept that we have reason to believe that quantum mechanics (more specifically, quantum field theory) is incomplete. However, this does not detract from its empirical success. Thus, in response to Hoefer's thesis, I argue that this empirical success forces us to be realists about something. This something need not be an interpretation of quantum mechanics. Instead, it can be about the observations themselves, and that quantum mechanics is approximately true. After all, the basis of Hoefer's approach is our inability to doubt that which is so successful. We have overwhelming reason to believe in other successful theories. Why not quantum theories as well, as it also is empirically successful? Perhaps, Hoefer would argue that we should be realists about specific equations, e.g. $hf = \Phi + KE_{max}$, the equation characterising the photoelectric effect. Thus, one could argue for a distinction between laws and theories, where laws are standalone equations with narrow, specific domains, while theories are complete physical descriptions of a beable or a phenomena (it need not be this distinction, any rigorous one will suffice).

In conclusion, I have shown that we should be realists despite the link between empirical equivalence and underdetermination, as we can resolve the underdetermination of competing interpretations by discussing larger domains, and appealing to our expectation of universal applicability. The discussion we should be having is what quantum realism entails (i.e. what we should be realists about in quantum mechanics).

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