The British Journal for the Philosophy of Science Advance Access published June 10, 2011

Brit. J. Phil. Sci. **0** (2011), 1–17

On the Faithful Interpretation of Pure Wave Mechanics

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ABSTRACT

Given Hugh Everett III's understanding of the proper cognitive status of physical theories, his relative-state formulation of pure wave mechanics arguably qualifies as an empirically acceptable physical theory. The argument turns on the precise nature of the relationship that Everett requires between the empirical substructure of an empirically faithful physical theory and experience. On this view, Everett provides a weak resolution to both the determinate record and the probability problems encountered by pure wave mechanics, and does so in a way that avoids unnecessary metaphysical complications. Taking Everett's goal to be showing the empirical faithfulness of the relative-state formulation agrees well with his characterization of his project as one of seeking a model for observation in the correlation structure described by pure wave mechanics and seeking a measure of typicality over this empirical substructure that covaries with our empirically warranted expectations.

1 Pure Wave Mechanics and Relative States

Hugh Everett III took both the standard von Neumann-Dirac and the Copenhagen formulations of quantum mechanics to encounter different, but related, problems. The standard collapse theory led to a straightforward contradiction if one supposed that measuring devices are physical systems like any other, and the Copenhagen interpretation simply stipulated that measurement interactions could only be understood by supposing a classical measuring apparatus. Neither theory allowed for a coherent quantum mechanical

doi:10.1093/bjps/axr004

understanding of measurement. This, in brief, was Everett's characterization of the quantum measurement problem.[1]

Everett's proposed resolution was to take pure wave mechanics, the standard collapse theory without the collapse dynamics, to be a complete physical theory for all interactions, then deduce the appearance of collapse and the usual quantum statistics for observers who were themselves treated within the theory. The goal was to 'deduce the probabilistic assertions of Process 1 [the collapse of the state on measurement] as *subjective* appearances [...] thus placing the theory in correspondence with experience. We are then led to the novel situation in which the formal theory is objectively continuous and causal, while subjectively discontinuous and probabilistic' (Everett [1973], p. 9).

His model for treating observers within the theory was simple. An ideal observer was a physical system with memory registers whose states might become strongly correlated to the states of object systems over the course of measurement interactions. More specifically, given the linearity of the dynamics of pure wave mechanics, if such an observer M begins in a ready-to-make-a-measurement state and measures the observable O of system S, with eigenstates ϕ_S^i, then M's memory becomes correlated to S's state as follows:

$$|\text{ready}\rangle_M \sum_i a_i \phi_S^i \longrightarrow \sum_i a_i |a_i\rangle_M \phi_S^i. \quad (1)$$

Repeated measurements simply lead to more complicated entangled superpositions, each term of which, when written in the determinate-record basis as above, describes M as having recorded a particular sequence of measurement results. The next step, as Everett ([1973], p. 68) put it, was to 'seek the *interpretation* of such final total states'.

To this end, Everett ([1973], p. 38) introduces the notion of relative states, which he reports 'will play a central role in our interpretation of pure wave mechanics'. They play this role by providing Everett with an expression of his principle of the fundamental relativity of states:

> There does not, in general, exist anything like a single state for one subsystem of a composite system. Subsystems do not possess states that are independent of the states of the remainder of the system, so that the subsystem states are generally *correlated* with one another. One can arbitrarily choose a state for one subsystem, and be led to the relative state for the remainder. Thus we are faced with a fundamental *relativity*

[1] See (Barrett [1999], [2008]) for further details on how Everett understood the measurement problem. (Barrett [2010]) provides preliminary reflections on his notion of empirical faithfulness, and (Barrett [forthcoming]) provides a discussion of the many-worlds and emergent-worlds interpretations of pure wave mechanics and Everett's attitude toward the metaphysics of pure wave mechanics.

> *of states*, which is implied by the formalism of composite systems. It is meaningless to ask the absolute state of a subsystem—one can only ask the state relative to a given state of the remainder of the subsystem. ([1957b], p. 456)

Everett held, in agreement with the standard interpretation of quantum-mechanical states, that subsystems of entangled composite systems, systems like M and S above, do not possess absolute physical properties or even absolute states to call their own. But he added to the standard interpretation that M and S, and every other subsystem one might specify, possess relative states that are determined by the correlation structure, which is in turn characterized by the universal state. If one *arbitrarily chooses*, as Everett put it, to assign the state ϕ_S^j to S, then the correlation structure assigns the relative state $|a_j\rangle_M$ to M. If, however, one chooses to assign a different state ϕ_S^k, $k \neq j$ to S, then the correlation structure assigns the relative state $|a_k\rangle_M$ to M. Or if one chooses another way of individuating the subsystems, one involving three subsystems, for example, where one subsystem contains parts of both S and M, then chooses to assign a state to one of these subsystems, one will likely end up with quite different relative states. Just as no particular relative state for an observer has the special status of being the state that is in fact realized, there is no preferred decomposition of the composite state into a preferred set of relative states.[2] The upshot is that correlation structure determined by the universal state, the complex-valued correlations that obtain between the properties of all physical systems at each time, characterizes a rich collection of relative states, some of which are recognizable as states describing systems with relative classical properties, some of these might even be taken as describing observers with determinate measurement records, but most of which have

[2] Everett was explicit that the specification of relative states did not involve stipulating a preferred basis. He also did not appeal to decoherence considerations to choose a physically preferred basis. Rather, like experience more generally, as argued below, all Everett required to explain classical appearances was that it be possible to find observer records corresponding to the quasi-classical behavior of macroscopic systems somewhere in the correlation structure. His more detailed argument went as follows: 'any general state can at any instant be analyzed into a superposition of states each of which [...] represent[s] the bodies with fairly well defined positions and momenta. Each of these states then propagates approximately according to classical laws, so that the general state can be viewed as a superposition of quasi classical states propagating according to nearly classical trajectories. In other words, if the masses are large or the time short, there will be strong correlations between the initial (approximate) positions and momenta and those at a later time, with the dependence being given approximately by classical mechanics' ([1973], p. 89). That said, finding classical appearances in the correlation structure would have been easier had Everett appealed to decoherence considerations. See (Wallace [2010]) for a well-reasoned example of how this might work if one reified the correlation structure. The point is that decoherence considerations would have only served to help Everett in his project of showing that pure wave mechanics is empirically faithful by showing that one can find classical appearances in the correlation structure. Part of the argument below is that Everett would not, however, have wanted to reify the correlation structure as in a robust metaphysics of emergent worlds as Saunders and Wallace, for example, would suggest. See (Barrett [2011]) for an extended discussion of the Saunders–Wallace version of the emergent-worlds interpretation and Everett's attitude toward metaphysics.

no classical analogue. In short, relative states gave Everett a convenient way of talking about the correlation structure determined by the universal state in the context of pure wave mechanics.

Pure wave mechanics with the descriptive extension afforded by the principle of the fundamental relativity of states was Everett's formulation of quantum mechanics of record. The two main problems it must address are (i) the determinate record problem, explaining how observers get determinate measurement outcomes, and (ii) the probability problem, explaining how quantum probabilities are to be understood in a deterministic theory where there there need be no uncertainty concerning one's postmeasurement absolute state. Everett's goal then was to explain both determinate measurement results and the statistical distribution of these results by appeal only to the correlation structure. It turns out that the extent to which this is possible depends on how rich an explanation one requires. For his part, Everett took the problem to be simply one of finding an appropriate map between the correlation structure and experience that allowed one to understand the theory as empirically faithful. On this description, his project was arguably successful.[3] The first step is to get clear on the sort of relationship between theory and experience that Everett required.[4]

2 Everett and Frank

In a letter to Philipp Frank at Harvard University dated 31 May 1957, Everett reported:

> As a result of membership in the 'Library of Science' book club, I have received several of your works on the philosophy of science. I have found them extremely stimulating and valuable. I find that you have expressed a viewpoint which is very nearly identical with the one which I have developed independently in the last few years, concerning the nature of physical theory. (Everett [1957c])

[3] Moreover, if this is right, Everett's project was more straightforward than many have supposed. There has been significant recent research on Everett and his formulation of quantum mechanics. Peter Byrne's ([2010]) biography and the Saunders *et al.* ([2010]) anthology are representative. The papers in (Saunders *et al.* [2010]) illustrate the current state of research on many-worlds formulations of quantum mechanics. For his part, insofar as Everett's primary consideration was the empirical faithfulness of pure wave mechanics, he would have simply dismissed many of the disputes regarding how one is to interpret his theory as unnecessarily metaphysical. Of course, if one requires more from a satisfactory physical theory than consistency, empirical faithfulness, comprehensiveness, and simplicity, then such metaphysical disputes might be rekindled. Everett also wanted pictorability in an ideal theory. While this condition clearly involves more than the theory's empirical virtues, there is good reason, as argued below, to suppose that this in no way involved metaphysical considerations for Everett.

[4] Everett's notion of empirical faithfulness is perhaps best understood as a proposal for what it should take for a theory to be considered empirically adequate. As such, it is arguably weaker than standard notions of empirical adequacy in that the relationship between the theory and particular experience is much looser than one might expect.

Everett enclosed a copy of his paper ([1957b]) and the companion paper by John Wheeler ([1957]) that were scheduled to be published in the the July issue of *Reviews of Modern Physics*.[5]

That Everett described his view of the nature of physical theories as being very nearly identical with Frank's situates Everett's understanding in a relatively clear historical context. Frank was a founding member of the Vienna Circle and served as the Director of the Institute for Theoretical Physics at Prague University from 1912 to 1938 as Einstein's successor, at Einstein's own recommendation. Just before the Second World War, Frank emigrated to the USA and joined the faculty at Harvard University.[6] At this time, Frank characterized his philosophical position as positivist, pragmatic, and operational, and held that 'the spirit of of all these schools of thought is one and the same' (Frank [1946], p. 3). Frank found significant philosophical agreement with Carnap's recent work and with the pragmatic tradition represented by C. S. Peirce, William James, and P. W. Bridgman. For his part, Everett was most likely familiar with at least the basic arguments of Frank's ([1946], [1950], [1955]) and Frank's ([1954]) essay on reasons for the acceptance of scientific theories.[7]

While Frank's understanding of theories had evolved in detail and to better fit with the practice of science, his views remained broadly positivistic. Frank took every physical theory to have three essential parts: the equations of the theory, the logical rules for how one might manipulate the equations, and the semantic rules that tied the language of the formal theory (with terms like 'force', 'mass', and 'time') to the experiential language of everyday life (with terms like 'wooden', 'warm', and 'one inch long'). Frank understood the semantic rules as providing operational definitions of the formal theoretic language that are cashed out in experience. Given the formal theory and the operational meanings of its terms, one could check whether the theory was confirmed by experiment. If there was no disagreement, then the system as a whole was empirically confirmed in an operational sense. The three-part

[5] The short version of Everett's thesis ([1957a]) was essentially the same as the published paper by Everett ([1957b]). Frank replied to Everett's letter by apologizing for the long delay in responding and reporting that at first glance Everett's theory seemed rather attractive since he had always disliked the traditional treatment of measurement in quantum theory where measurements are treated as different from all other physical facts. Frank said that he would, however, reserve his final judgment until he had actually studied Everett's paper (Frank [1957]). Byrne discusses this exchange between Everett and Frank ([2010], pp. 173–5), but reaches a very different conclusion from what is argued below.

[6] See (Holton [2006]) for biographical details, especially of Frank's time at Harvard.

[7] While it is unclear what Everett received from his book club, in part since very little of his personal library was preserved, the works listed here exhibit substantial overlap in argument and were both readily accessible and widely read.

system, then, gets its empirical confirmation and operational significance by how it makes contact with experience together ([1946], pp. 3–4).[8]

Frank held that '[t]he general principles we set up have no significance other than the observable facts that may be deduced from them' ([1950], p. 112). Indeed, he believed that one could even make a good case for 'the assertion that the "experimental" theory of meaning, which has been advocated by pragmatists and logical empiricists, is the very basis of twentieth-century physics. Not only does it provide the method of presenting this physics systematically, but one can also point out that the authors of this new physics made explicit use of the this theory of meaning.' Frank cited Einstein's use of positivistic principles in the formulation of special relativity in particular ([1955], pp. 291–2). While there need not be direct empirical meaning for every statement of a theory, Frank endorsed the 'positivistic requirement' for scientific meaning that there be at least 'some consequences [...] which can be translated into statements about sense observations' ([1955], p. 294). While such checks are often holistic and indirect, 'the criterion of truth [for physical theories] remains ultimately with the checking by sense observations, as the older "positivists" claimed' ([1955], p. 295).

Frank further held that 'twentieth-century science [...] has no use for metaphysics' ([1955], p. 289). He took metaphysics, which involved imposing pre-theoretical commonsense and philosophical intuitions on the construction and interpretation of scientific theories, to be 'meaningless from the scientific viewpoint' ([1955], p. 290). Since such intuitions represent older systems of science 'which were dropped because new discoveries demanded a new conceptual scheme,' any attempt to interpret our current theories by appeal to metaphysical intuitions is at best 'an attempt to formulate our actual science by the conceptual scheme that was adequate for a older age of science, now abandoned' ([1955], p. 301). Frank summarized his understanding of the mistake of using metaphysics in modern science:

> To believe that some 'metaphysical interpretation' may tell us the 'truth' about the 'real world' means in practice to believe that the conceptual

[8] Frank took himself to be following Carnap and Bridgman in this characterization of confirmation and meaning. Frank's position is also, of course, reminiscent of Quine's ([1951]) empirical holism, who was also at Harvard at the time. Frank argued that 'a single word or even a single proposition cannot have factual meaning' since '[o]nly if we have a system of propositions, a coherent group of statements, can we investigate whether we can deduce from this system individual statements that tell us what experiences we should have if the original system of principles were true' ([1950], p. 30). While Frank identified agreement with observations as the primary virtue of physical theories, he also allowed for secondary virtues such as simplicity. Even so, Frank argued, since one never has perfect agreement with observations nor perfect simplicity, a physical theory will be, at best, only in fair agreement with observations and of sufficient simplicity to be useable. Frank thus concluded that 'it is obvious that such a theory cannot be "the truth" '; rather, it is 'an instrument that serves toward some definite purpose [...] a tool that produces other tools according to a practical scheme' ([1954], p. 14).

> scheme of some older stage of science is necessarily the scheme to be used for all the future. ([1955], p. 301)

While such a belief can be stimulating insofar as it encourages the unification of theories, it also represents a methodological mistake insofar as scientific advance requires giving up on the notion that there is any single, canonical metaphysical interpretation of our best physical theories ([1955], p. 302).

With respect to the cognitive status of theories generally, Frank reported that '[i]n practice we encounter only experiences, never an object; hence nothing can be compared with an object. Actually, the physicist compares only experiences with other experiences. He tests the truth of the theory through what one is accustomed to call "agreements"' ([1955], p. 102). With respect to quantum mechanics, in particular, Frank held that we can 'ascribe "physical reality" to the objects of our new mechanics, provided we mean "reality" in the operational and not the metaphysical sense' ([1946], p. 53). More specifically, to say that a quantum object, property, or state is 'real' is to assert that a particular set of operational consequences in fact obtains, and these ultimately get their significance in terms of our experience.

3 Everett on the Nature of Physical Theories

Everett's discussion of the nature of physical theories and the proper goals of theoretical physics meshed well with Frank's pragmatic empiricism. The position that Everett formulated allows for an explanation of both determinate measurement records and quantum statistics. While the sort of explanation provided is weaker than standard notions of empirical adequacy, the sense in which pure wave mechanics is empirically faithful can be made perfectly clear. Moreover, the sort of empirical faithfulness exhibited by pure wave mechanics is arguably enough to make it empirically acceptable in the absence of better options.

In the second appendix to his long thesis, Everett explains that an essential goal of theoretical physics is to produce empirically faithful physical theories; that is, theories that can be put into a close structural correspondence with the elements of the world of experience.[9] While Frank divided theories into three parts, Everett put the equations with the logical rules and called it the formal part, then sought to provide a sharper understanding of the interpretive part.

> Every theory can be divided into two separate parts, the formal part, and the interpretive part. The formal part consists of a purely logico-mathematical structure, i.e., a collection of symbols together with rules for their manipulations, while the interpretive part consists of a set of 'associations,' which are rules which put some of the elements of the

[9] Everett's long thesis was written in 1955–56 before the redacted short thesis ([1957a]) that he defended for his PhD. The long thesis was later published ([1973]), with some modifications.

> formal part into correspondence with the perceived world. The essential point of a theory, then, is that it is a *mathematical model*, together with an *isomorphism* between the model and the world of experience (i.e., the sense perceptions of the individual, or the 'real world'—depending upon one's choice of epistemology). ([1973], p. 133)

In an associated footnote, Everett further explained that:

> By isomorphism we mean a mapping of some elements of the model into elements of the perceived world which has the property that the model is faithful, that is, if in the model a symbol A implies a symbol B, and A corresponds to the happening of an event in the perceived world, then the event corresponding to B must also obtain. The word homomorphism would be technically more correct, since there may not be a one-one correspondence between the model and the external world. ([1973], p. 133)

The map is a homomorphism both because there may be elements of the theory that do not directly correspond to experience and because a particular theory may not seek to explain all of experience.

In his letter to Frank, Everett explained how the homomorphism works in the relative-state formulation of pure wave mechanics:

> I think that you may be interested in [the relative-state formulation of pure wave mechanics], as I am, as an example of a certain type of theory—a completely abstract mathematical model which is ultimately put into correspondence with experience. It has the interesting feature, however, that this correspondence can be made only by invoking the theory itself to predict our experience—the world picture presented by the basic mathematical theory being entirely alien to our usual conception of 'reality.' The treatment of observation itself in the theory is absolutely necessary. If one will only swallow the world picture implied by the theory, one has, I believe, the simplest, most complete framework for the interpretation of quantum mechanics available today. ([1957c])

The theory provides a world picture insofar as it allows one to model physical systems and processes. Of particular importance to Everett was that one can model observation within the theory since this was something that he believed the Copenhagen interpretation could not do. This is the special feature of pure wave mechanics to which Everett wanted to draw Frank's attention. This was what allowed for a connection between pure wave mechanics and experience at all on Everett's view. Pure wave mechanics is empirically faithful if and only if an appropriate aspect of the empirical substructure of the theory, determined by how the theory models observers and the measurement process, is isomorphic to quantum mechanical experience.[10]

[10] The result of Everett's considerations is a view that is strikingly similar to van Fraassen's constructive empiricism, but arguably with a slightly more lenient notion of empirical adequacy. While pictorability is not a requirement for an acceptable theory, it is a good thing to have when

Before turning to the detailed requirements for empirical faithfulness, one should be clear regarding how Everett understood physical theories and their models. Most significantly, he argued that since the theoretical constructs of physical theories are fictional, it is a methodological mistake to understand physical theories as being descriptive of the metaphysical structure of the world.

> [W]hen a theory is highly successful and becomes firmly established, the model tends to become identified with 'reality' itself, and the model nature of the theory becomes obscured. The rise of classical physics offers an excellent example of this process. The constructs of classical physics are just as much fictions of our own minds as those of any other theory, we simply have a great deal more confidence in them. It must be deemed a mistake, therefore, to attribute any more 'reality' here than elsewhere ([1973], p. 134).

The confidence we have in classical mechanics, or any other physical theory, is operational confidence gained through the successful empirical use of the theory. In agreement with Frank, Everett held that the methodological error of mistaking operational success for metaphysical truth stands in the way of empirical progress. Indeed, Everett felt that both commonsense metaphysical intuitions and the metaphysical prejudices of his colleagues who favored something like the Copenhagen interpretation were responsible for pure wave mechanics not being taken as seriously as it deserved. It would have been to commit the same methodological mistake to imagine that the elements of his own model were any less fictional. The moral for Everett was that

> Once we have granted that any physical theory is essentially only a model for the world of experience, we must renounce all hope of finding anything like '*the* correct theory.' There is nothing which prevents any number of quite distinct models from being in correspondence with experience (i.e., all 'correct'), and furthermore no way of ever verifying that any model is completely correct, simply because the totality of all experience is never accessible to us ([1973], p. 134).

Pure wave mechanics, then, is a contender if and only if it is logically consistent and can be put into an appropriate correspondence with experience.

one can get it and hence enters into the cost-benefit analysis involved in selecting a theory on Everett's view. Not allowing for such considerations is one reason that Everett takes the old positivist view that prohibits theories from containing elements that do not directly correspond to observables to be too restrictive. Another is that Everett thought that unobservable elements of the model, while not descriptive of the metaphysics of the world, might play a role in constructing new physical theories and hence have future operational consequences. In the handwritten notes that he used as the basis for the second appendix to the long thesis Everett refers to the position that there should be no elements in a theory which do not correspond directly to observables as the 'extreme positivist view.' See (Everett [1957d], [1973], p. 136) and the handwritten draft (forthcoming online at UCIspace @ the Libraries <ucispace.lib.uci.edu>).

Moreover, the full expectation is that the theory will be temporary. As Everett explained in the long thesis, 'the primary purpose of theoretical physics is [...] to make useful models which serve for a time and are replaced as they are outworn' ([1973], p. 111).[11]

4 Conditions for Empirical Faithfulness

Everett described what it meant to judge that pure wave mechanics was empirically faithful in his early correspondence with Bryce DeWitt. John Wheeler, Everett's thesis advisor at Princeton University, had asked his friend DeWitt to look at Everett's paper ([1957b]).[12] DeWitt replied to Wheeler with detailed comments.

> In the first place, it seems to me that the professional philosopher will have a greater appreciation of Everett's work than will the average physicist, at least for the present. [...] On the other hand, since the days of Boltzmann and Poincaré it has become increasingly clear that physicists themselves are obliged to be their own epistemologists, since no other persons have the necessary competence. Therefore Everett's effort is to be praised. (DeWitt [1957])

DeWitt's praise on this methodological point, however, was accompanied by his criticism of the theory on empirical grounds. Since the standard collapse theory made the right empirical predictions for every experiment that had been performed so far, there is no good empirical reason for a new formulation of quantum mechanics. Further, DeWitt argued that Everett's theory, in some sense, made the wrong empirical predictions.

> What I am *not* prepared to accept [...] however, is that the temporal behavior of the *superposition* of relative observer states $\psi^O[\alpha_i^1, \alpha_i^2, \ldots]$ is isomorphic to the 'trajectory' of the memory configuration of a real physical observer, whether human or inanimate. As Everett quite explicitly says: 'With each succeeding observation [...] the observer state "branches" into a number of different states.' The trajectory of the memory configuration of a real physical observer, on the other hand, does *not* branch. I can testify to this from personal introspection, as can you. I simply do *not* branch. (DeWitt [1957])

[11] From the beginning, Everett understood his project as an hypothetical investigation concerning how one might model what people said about quantum mechanics. In an informal 1977 recorded conversation, Charles Misner asked Everett how he got started on his formulation of quantum mechanics. Everett replied: 'Oh, it was because of you and Aage Petersen, one night at the Graduate College [at Princeton University] after a slosh or two of sherry, as you might recall. You and Aage were starting to say some ridiculous things about the implications of Quantum Mechanics and I was having a little fun joshing you and telling you some of the outrageous implications of what you said.' (Misner and Everett [1977], taped conversation).

[12] This is essentially identical to Everett's ([1957a]) short thesis.

Wheeler shared DeWitt's comments with Everett, who replied to DeWitt the same day he wrote to Frank.

Everett began his reply by summarizing his understanding of the cognitive status of physical theories.

> First, I must say a few words to clarify my conception of the nature and purpose of physical theories in general. To me, any physical theory is a logical construct (model), consisting of symbols and rules for *their* manipulation, *some* of whose elements are associated with elements of the perceived world. If this association is an isomorphism (or at least a homomorphism) we can speak of the theory as correct, or as faithful. The fundamental requirements of any theory are logical consistency and correctness in this sense.
>
> However, there is no reason why there cannot be any number of different theories satisfying these requirements, and further (somewhat arbitrary) criteria such as usefulness, simplicity, comprehensiveness, pictorability, etc., must be resorted to in such cases. There can be no question of which theory is 'true' or 'real'—the best that one can do is reject those theories which are *not* isomorphic to sense experience. ([1957d])

Since pure wave mechanics was clearly consistent, Everett just needed to argue for empirical faithfulness.

> A crucial point in deciding on a theory is that one does *not* accept or reject the theory on the basis of whether the basic world picture it presents is compatible with everyday experience. Rather, one accepts or rejects on the basis of whether or not the *experience which is predicted by the theory* is in accord with actual experience. ([1957d])

And the relative state formulation of quantum mechanics

> is in full accord with our experience (at least insofar as ordinary quantum mechanics is) [...] just because it *is* possible to show that no observer would ever be aware of any 'branching,' which is alien to our experience as you point out. ([1957d])

While Everett did not explain how this was supposed to work in the letter, the argument is easy enough to reconstruct from how he treats observation. The relative state formulation models an observer's experience in terms of the relative observer's physical memory sequence, and such relative memory sequences simply do not contain records of branching events. Hence

> [t]he theory is isomorphic with experience when one takes the trouble to see what the theory itself says our experience will be. Little more can be asked of it without exposing a naked philosophic prejudice of one kind or another. ([1957d])

DeWitt believed that Everett would have an satisfactory explanation of experience if and only if his theory somehow singled out one branch, the branch that described our actual experience, as the only branch that was in fact actual. Pure wave mechanics, however, lacks any parameter that might select one relative state or branch as in any way special. Consequently, the theory cannot make the distinction that DeWitt required for empirical adequacy. Everett responded that

> [f]rom the viewpoint of the theory, all elements of a superposition (all 'branches') are 'actual,' none any more 'real' than another. It is completely unnecessary to suppose that after an observation somehow one element of the final superposition is selected to be awarded with a mysterious quality called 'reality' and the others condemned to oblivion. We can be more charitable and allow the others to coexist—they won't cause any trouble anyway because all the separate elements of the superposition ('branches') individually obey the wave equation with complete indifference to the presence or absence ('actuality' or not) of any other elements. (Everett [1957d]).[13]

The explanation of our determinate experience then is most directly that one can find a relative memory sequence of records that corresponds to our actual experience in the correlation structure characterized by the absolute state. The surplus empirical structure represented in other relative memory sequences need not correspond with one's experience. The presence of this surplus empirical structure does not undermine the empirical faithfulness of the theory because the surplus structure is not represented in the relative records that characterise our actual experience.

This is an important point. Empirical faithfulness as Everett understood it did not require every element in the the theory's representation of an observer's experience to correspond to the observer's experience; rather, it was enough that there was an element of the empirical substructure associated with the observer that represented the observer's experience. Everett agreed with DeWitt that the surplus empirical structure was not necessary to explain our particular experience, but he also insisted that its presence did not undermine the theory's explanation since one can find our particular experience appropriately represented in the correlation structure.[14]

While other elements of the superposition are typically unobserved, Everett took them to have potential empirical consequences, and hence to be real in an

[13] Everett, like Frank, used scare quotes for metaphysical terms. While, as Everett indicates here, one can think of the linear dynamics as evolving each branch individually, he also realized that the linear dynamics also required that it always in principle be possible for there to be interference between branches. See, for example, (Everett [1973], p. 107) quoted below.

[14] In order to satisfy DeWitt's criterion for empirical adequacy here, one would need to choose a preferred basis and a parameter that selects one branch as actual in this basis. One gets a more conventional notion of empirical adequacy but only at the cost of adopting a hidden variable theory akin to Bohmian mechanics, which Everett ([1973], p. 112) took to be a contender but explicitly argued against. The other option is to require only that one be able to *find* one's experience in the theory in order for the theory to be empirically faithful then consider the surplus experiential structure as explanatorily harmless. Everett gets a simple and compelling theory but at the cost of an arguably nonstandard notion of empirical adequacy.

operational sense. The operational consequences of branches are clearest in the context of something like a Wigner's friend experiment where one considers interference effects between multiple branches.[15] Everett recognized that pure wave mechanics always allowed for such interference effects.

> It is therefore improper to attribute any less validity or 'reality' to any element of a superposition than any other element, due to [the] ever present possibility of obtaining interference effects between the elements. All elements of a superposition must be regarded as simultaneously existing. ([1973], p. 107)

The ever present possibility of obtaining such interference effects and the simplicity of a theory that did not select one basis or branch as somehow special were Everett's positive reasons for taking each element of the superposition to be equally actual or real in an operational sense.

5 The Empirical Faithfulness of Pure Wave Mechanics

On this understanding, Everett's solution to the determinate record problem consists in noting that the values of determinate measurement records for those measurements we take ourselves to have performed can be found in the correlation structure of pure wave mechanics as relative states, relative to there being a record of the measurements in fact being performed and relative to the properties we take the measured systems to have. Similarly, his solution to the probability problem was a matter of finding a measure of typicality over relative states that could be determined from the correlation structure alone and that covaried with our empirically warranted quantum mechanical expectations. As Everett put it: 'Let us therefore consider the search for a general scheme for assigning a measure to the elements of a superposition of orthogonal states $\sum_i a_i\phi_i$' ([1973], p. 71).

Everett first required that the typicality measure, m, over elements in a particular decomposition of the state be a positive function of the complex coefficients of the elements of the superposition.[16] He then required that m must be a function of the amplitudes of the coefficients alone.[17] Finally, he

[15] For discussions of the interactions between branches on the linear dynamics, see (Wigner [1961]; Albert [1992]; Barrett and Albert [1995]; or Barrett [1999]). Everett explicitly discussed Wigner-friend type experiments and the associated interactions between branches in the long thesis ([1957a]), a few years before Wigner's own discussion ([1961]).

[16] A simple count of the elements, while arguably a natural measure of branches, would not satisfy this condition.

[17] This is a further background assumption. The grounds for this constraint involve what Everett believes one might know regarding the renormalized coefficients of the relative state of a subsystem of a composite system. If one could only know the coefficients up to a phase factor, one might take only their squared amplitudes to be significant. There are, however, quantum-mechanical predictions, such as the Aharonov–Bohm effect, that depend on the precise relative phase of each element of the superposition. Everett would likely not have known of such effects since Aharonov and Bohm's paper was published in 1959.

required that if one regarded the subset of the elements of a superposition representing the absolute state, say $\sum_{i=1}^{n} a_i\phi_i$, as a single element $\alpha\phi'$, where

$$\alpha\phi' = \sum_{i=1}^{n} a_i\phi_i, \tag{2}$$

in a new expression representing the absolute state, then the measure assigned to ϕ' must be the sum of the measures assigned to the ϕ_i.[18] Given these constraints, the correlation structure determines the measure of typicality m to be the square amplitude of the coefficient up to a multiplicative constant ([1973], p. 71).

Everett then showed that most relative states, in the sense of most provided by the measure m, where there are determinate measurement records at all are states where the standard quantum statistics hold for the relative measurement records. He concluded that it will thus appear to the observer *as described by a typical element of the superposition* that the standard quantum statistical predictions hold ([1973], p. 74). His deduction of the standard quantitative statements concerning quantum probabilities then amounted to his showing that, subject to a small handful of background conditions, one can find a measure of typicality over branches that is determined by the correlation structure and that covaries with standard quantum expectations. Pure wave mechanics is hence empirically faithful in the sense that one can find both our particular experience and a closely associated measure that covaries with standard quantum expectations in the correlation structure described by pure wave mechanics.[19]

Everett finally argued that, in addition to being consistent and empirically faithful, pure wave mechanics fared better than the competition on nonessential, but desirable, theoretical virtues. In particular, he took it to be desirable to have a theory that was *comprehensive* and *simple*. While he allowed for yet other theoretical virtues, he took these to be important to inquiry ([1973], pp. 135–6). He concluded that 'it may be impossible to give a total ordering of [rival physical] theories according to "goodness," since different ones may rate highest according to the different criteria' ([1973], p. 136). Nevertheless, in the context of the sort of cost-benefit analysis of alternative formulations of

[18] This condition systematically connects the measures associated with different decompositions of the absolute state. Since his understanding of pure wave mechanics involved no physically preferred basis, Everett needed a typicality measure for each possible decomposition of the absolute state. He felt that it was most natural to require that the typicality measures associated with different decompositions of the absolute state were intertranslatable in this particular way. While perhaps not canonical, it is a simple constraint that allows translations between typicality measures to be determined by the decompositions and the correlation structure alone.

[19] It is important that Everett does more than just to find an image of one's particular experience in the correlation structure. Finding the associated notion of typicality shows that one can also find the image of our empirically justified empirical *expectations* in the model. It is this that warrants the use of the theory to make empirical predictions.

quantum mechanics that Everett took to be appropriate for the purpose of engineering future faithful theories, he took pure wave mechanics to be clearly the best option.

6 Conclusion

Given Everett's understanding of the proper cognitive status of physical theories and the associated notion of empirical faithfulness, one can explain both determinate measurement records and the standard quantum statistics while avoiding what he would have taken to be unnecessary metaphysical complications.[20]

The remaining question is whether pure wave mechanics being empirically faithful in the sense described by Everett is enough for it to be empirically acceptable.

While the notion of faithfulness is weaker than standard notions of empirical adequacy in that it allows for surplus empirical structure that does not correspond to one's experience, it is arguably a significant empirical virtue nevertheless. After all, in judging the empirical adequacy of a physical theory one always has some degree of freedom in choosing what aspect of the theory's model should correspond to empirical evidence, how it should correspond, and how the empirical evidence should itself be represented.[21] In this sense, Everett's notion of empirical faithfulness is simply a variety of empirical adequacy. Further, while one might indeed desire more from a satisfactory formulation of quantum mechanics, we have perhaps found nothing so far that is clearly preferable to pure wave mechanics understood as empirically faithful.

Acknowledgements

I would like to thank Brett Bevers, Peter Byrne, Samuel Fletcher, Brian Skyrms, Christian Wüthrich, and Jason Hoelscher-Obermaier for helpful discussions and Craig Callender, Thomas Barrett, and Jim Weatherall for comments on an earlier draft of this article. Bevers ([2011]) considers how one might understand Everett's project as a type of intertheoretic reduction between pure wave mechanics and the standard collapse theory. This captures,

[20] While a realist might be tempted to insist on somehow reifying the correlation structure in terms of worlds, minds, or histories, one would presumably want an argument that one gets increased richness in explanation that somehow justifies the fancy metaphysics. For his part, Everett would have understood such a move as at most providing another way, in addition to his language of relative states, of describing the correlation structure characterized by pure wave mechanics. Given his understanding of the epistemological limits of empirical science, he would not have welcomed a strong metaphysical reading of such language.

[21] See (van Fraassen [2008]) for a recent extended discussion of this point.

I believe, another useful way to understand his project that may be compatible with Everett's concern for empirical faithfulness.

Funding

The present work was funded in part by the National Science Foundation (SES-0924135).

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