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QUANTUM WORLDS

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Abstract. Because of the conceptual difficulties it faces, quantum mechanics provides a salient example of how alternative metaphysical commitments may clarify our understanding of a physical theory and the explanations it provides. Here we will consider how postulating alternative quantum worlds in the context of Hugh Everett III's pure wave mechanics may serve to explain determinate measurement records and the standard quantum statistics. We will focus on the properties of such worlds, then briefly consider other metaphysical options available for interpreting pure wave mechanics. These reflections will serve to illustrate both the nature and the limits of naturalized metaphysics.

Keywords: Hugh Everett III; pure wave mechanics; many worlds interpretation; naturalized metaphysics; explanation.

1. Introduction

There is good reason to suppose that naturalized metaphysics should not involve trying to read a canonical metaphysics off our best physical theories. Since our theories are provisional, since different theories suggest different metaphysical commitments, and since even a particular theoretical framework may allow for radically different metaphysical interpretations, our best physics cannot be expected to provide anything like a canonical specification of one's proper metaphysical commitments.

Naturalized metaphysics, rather, involves balancing our pre-theoretic explanatory demands against the alternative understandings of the world suggested by our best theories. On this view, the metaphysician explores alternative ways of taking our best theories to be descriptive then evaluates the explanatory tradeoffs between these alternatives. The aim is to provide a clear and honest map of the options and a careful cost-benefit analysis. Of course, the metaphysical stories one tells along the way are at least as provisional as the theoretical frameworks themselves.

Metaphysics here is in the service of clarity and the careful evaluation of alternative explanatory options. It aims to provide a clearer understanding of our best theories and sharpen how we use them. Indeed, insofar as one individuates theories by the explanations they give, since a particular theoretical framework will typically provide different explanations in the context of different background metaphysical commitments, alternative metaphysical commitments yield alternative physical theories. One is only clear about the descriptive content of particular theory when one is clear about how it provides explanations, and one is only clear about that when one

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is clear about the role played by one's metaphysics in those explanations. By characterizing how it describes and explains, the metaphysics we associate with a physical theory becomes a part of the theory. Naturalized metaphysics is constructive. It is a piece with the clear specification and individuation of our theories.

Explanations that appeal to metaphysical commitments often take the form of descriptive stories. Such stories may say why an event occurs, or why it should be expected, or how it is physically possible. Richer explanatory stories may characterize mechanisms, describe how events are caused, or account for the existence of entities of a particular sort or some aspect of the structure of the world described by the theory. It is in this way that our metaphysical commitments are in service of our best understanding of the physical world and the explanations that go with it.

Quantum mechanics provides examples of how alternative metaphysical commitments may help to pin down quite different ways of describing the physical world. This case is of particular philosophical interest since the commitments involved in making sense of alternative formulations of quantum mechanics are often strongly counterintuitive and, hence, instructive concerning both the nature of the world and the limits of philosophical intuition.

The task of interpreting Everett's (1955, 1956, 1957) pure wave mechanics provides an example of how metaphysical commitments may serve in our understanding of quantum mechanics. This example will also illustrate how metaphysical commitments contribute to the descriptive content of a theory. There is a sense in which the standard von Neumann-Dirac formulation of quantum mechanics, Everett's pure wave mechanics, his relative-state formulation of quantum mechanics, the many-worlds interpretation, Bohm's theory, and GRW are all just formulations of quantum mechanics.[1] But insofar as they provide radically different explanations for our experience, they are well-understood as different physical theories individuated, in part, by the metaphysics one finds appropriate to associate with each.[2] Here we will briefly consider the relationships between the standard collapse theory, pure wave mechanics, many worlds, and relative states.

2. Quantum mechanics

A compelling case can be made that our two best physical theories are quantum mechanics and special relativity. Indeed, in many ways they are the most successful empirical theories we have ever had. They not only correctly predict a broad range of counterintuitive phenomena, but they do so with remarkable precision. In some cases the two theories, working together, make the right empirical predictions to better than twelve significant figures. It is remarkable that we can make measurements that precisely. That we have theories that make the right empirical predictions to that precision is almost unbelievable, especially when we know that at least one of the two theories, quantum mechanics, cannot be true.

The problem is not that the standard von Neumann-Dirac formulation quantum mechanics is counterintuitive. It is, but it must be to make the right empirical predictions. The problem, rather, is that the theory is logically inconsistent on a strict reading and empirically incomplete on even the most charitable reading.

Further, the standard formulation of quantum mechanics is incompatible with relativistic constraints in two fundamental ways. Both the essential use of $3N$-dimensional configuration space to represent the states of spacelike separated systems and the dynamical laws of the standard collapse formulation presuppose an absolute standard of simultaneity, which is incompatible with the constraints of relativity, at least as Einstein himself understood it.[3] Addressing the quantum measurement problem, then, involves coming up with a formulation of quantum mechanics that can be understood as providing a complete and consistent description of quantum systems while at the same time finding some sort of reconciliation between quantum mechanics and special relativity.

Hugh Everett III proposed a solution to the measurement problem that he called pure wave mechanics. The theoretical framework he described is manifestly logically consistent and is arguably compatible with relativistic constraints. The problem is that it is unclear how it explains our experience. It is not that the theory makes the wrong empirical predictions; rather, it is unclear that it predicts anything at all for the sort of experiments we routinely perform, and, if it does, it is unclear precisely what. Explaining our quantum experience involves explaining why observers end up with determinate measurement records at the end of their measurement interactions and explaining why such records should be expected to exhibit the characteristic quantum statistics. And pure wave mechanics alone accomplishes neither of these explanatory tasks.

That said, one can get a start on accounting for determinate measurement records and their statistical properties by adding appropriate metaphysical assumptions to pure wave mechanics. Of course, the explanations one gets depend on the metaphysics one adds.

On his earliest formulation of the theory, Everett appealed to *cross-sections* and *branches* to explain determinate measurement records and their properties.[4] Given the explanatory role he seemed to have in mind for them, one might understand the branches represented in a cross-section of the total state as alternative *quantum worlds*.[5] But if one does understand branches as worlds, then they are not much like the sort of alternative possible worlds that philosophers typically consider.[6]

In particular, to mesh with Everett's explanations, alternative quantum worlds have the following properties: (*i*) they explain our having determinate measurement records and why these records exhibit the standard quantum statistics, (*ii*) they are all equally actual, (*iii*) they may always, at least in principle, interact with each other and, hence, may be detectable, (*iv*) they are physically emergent in the sense that what quantum worlds there are at a time depends on the total quantum state of the physical world, and (*v*) they are conventional in the sense that the precise set of alternative quantum worlds that there are depends on what cross-section of the total state one chooses to consider.

Here we will consider how Everett understood these properties and why. We will start by considering the quantum measurement problem and Everett's proposal for solving it in more detail, paying particular attention to the explanatory role that branches, or quantum worlds, might play. We will then briefly consider the corresponding story in the context of an alternative metaphysical option suggested by his relative-state formulation of pure wave mechanics.

3. The standard theory and the measurement problem

Everett proposed pure wave mechanics as a graduate student at Princeton in the years just prior to 1957. At this time, there were two standard options for formulating quantum mechanics, the von Neumann-Dirac collapse formulation and Bohr's Copenhagen interpretation, and a small handful of non-standard alternatives, like Bohmian mechanics, that were taken seriously then by very few. Everett used the von Neumann-Dirac collapse formulation of quantum mechanics to set up the measurement problem because he considered it to be the "more common" form of quantum theory, at least in the U.S.[7]

Importantly, Everett took both the standard von Neumann-Dirac collapse formulation of quantum mechanics and Bohr's Copenhagen interpretation to encounter a similar, fatal conceptual problem. Neither could satisfactorily address *nested* measurements of the sort one finds in the Wigner's Friend Story. Everett used the von Neumann-Dirac collapse theory to tell his version of the Wigner's Friend Story, to explain how he understood the measurement problem, and to characterize his solution to the problem.

In the long version of his thesis, Everett appealed to each of the following principles of the von Neumann (1955) formulation of quantum mechanics to set up the problem of nested measurements:

- **Representation of States**: The state of a physical system S is represented by a vector ψ_S of unit length in a Hilbert space $\mathscr{H}$.
- **Representation of Observables**: A physical observable O is represented by a set of orthogonal vectors $\mathscr{O}$. These vectors represent the eigenstates of the observable, each corresponding to a different value.

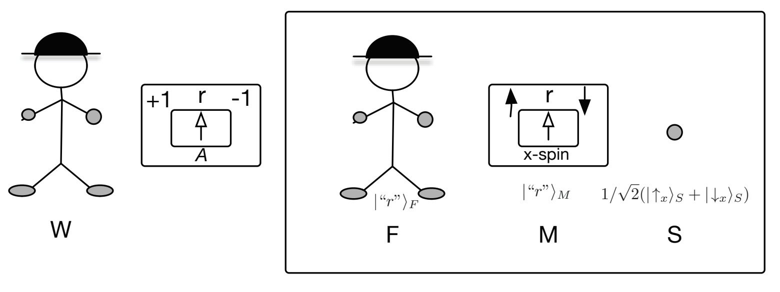
- **Interpretation of States**: A system S has a determinate value for observable O if and only if $\psi_S \in \mathscr{O}$.

- **Dynamical Laws**:

  I. **Linear dynamics**: If *no measurement* is made, the system S evolves in a deterministic linear way: $\psi(t_1)_S = \hat{U}(t_0, t_1)\psi(t_0)_S$.

  II. **Nonlinear collapse dynamics**: If a *measurement* is made, the system S randomly, instantaneously, and nonlinearly jumps to an eigenstate of the observable being measured: the probability of jumping to ϕ_S when O is measured is $|\psi^*\phi|^2$.

The problem, Everett argued, is that this theory is logically inconsistent and hence untenable. He examined what he called *the question of the consistency* of the standard theory in the context of an "amusing, but *extremely hypothetical* drama" (1956, 74–5). The story he told was Everett's original version of what has come to be known as the Wigner's Friend story after Eugene Wigner (1961) famously told it again some years later to support a formulation of quantum mechanics very different from Everett's.[8] For his part, Everett appealed to the story to argue that there is a contradiction between the two dynamical laws presented in the standard collapse formation of quantum mechanics.



Using Wigner's terminology, Everett's story involved a friend F in a state $|``r"\rangle_F$ ready to observe his measuring device and a measuring device $M$ in a state $|``\mathrm{r}"\rangle_M$ ready to to measure a property of a system S. We will suppose that S is spin-1/2 system, that the property being measured is x-spin, and that the system S begins in the state

$$(1) \qquad 1/\sqrt{2}(|\uparrow_x\rangle_S + |\downarrow_x\rangle_S).$$

Assuming ideal correlating interactions between the systems, the linear dynamics (I) predicts that the composite system $F + M + S$ will be in the state

$$1/\sqrt{2}(|\text{“}\uparrow_x\text{”}\rangle_F |\text{“}\uparrow_x\text{”}\rangle_M |\uparrow_x\rangle_S + |\text{“}\downarrow_x\text{”}\rangle_F |\text{“}\downarrow_x\text{”}\rangle_M |\downarrow_x\rangle_S). \tag{2}$$

after the measuring device M interacts with the object system S and after the friend F interacts with the pointer on the M. The standard interpretation of states, however, tells us that this is a state where the friend has no determinate measurement record at all. Indeed, he is in an entangled state with M and S here and hence does not even have a proper quantum-mechanical state of his own.

In contrast, if we use the nonlinear collapse dynamics (II) for the interaction between M and S or for the interaction between M and F, the composite system $F + M + S$ will either be in the state

$$|\text{“}\uparrow_x\text{”}\rangle_F |\text{“}\uparrow_x\text{”}\rangle_M |\uparrow_x\rangle_S \tag{3}$$

or in the state

$$|\text{“}\downarrow_x\text{”}\rangle_F |\text{“}\downarrow_x\text{”}\rangle_M |\downarrow_x\rangle_S, \tag{4}$$

each, in this case, with equal probability 1/2. Unlike state (2), each of these states describes the friend F as having a perfectly determinate measurement record on the standard interpretation of states. Specifically, in the first F determinately records the result “$\uparrow_x$” and in the second he determinately records the result “$\downarrow_x$.”

The contradiction between dynamical laws (I) and (II) is represented in the fact that they predict incompatible states when applied to the same interaction. If one knew precisely when to apply each law, one might avoid the contradiction, but since *measurement* is a primitive term in the theory, the standard formulation of quantum mechanics provides no guidance for when to use dynamical law (I) and when to use dynamical law (II). Everett, consequently, took the theory to be inconsistent and hence untenable. A more charitable assessment would have been that the theory is at best incomplete since it does not clearly indicate which law to use, and it is logically inconsistent if one insists that measuring devices are physical systems like any other. But, then again, why shouldn't they be given that they are composed of ordinary physical systems interacting linearly.

For his part, Everett believed that sentient observers and measuring devices were indeed properly modeled as physical systems like any other. Hence, he believed that, were such an experiment ever performed, the composite system system $F + M + S$ would end up, as required by the linear dynamics, in a state like (2). Further, he believed that an external observer W might, in principle, measure an observable of the composite system $F + M + S$ that has (2) as an eigenstate with eigenvalue $+1$, say, and every state orthogonal to (2) as an eigenstate with eigenvalue -1 and that one would with certainty get the result $+1$, which would indicate that $F+M+S$ was in fact in state (2).

What makes the drama "extremely hypothetical" is that, in practice, quantum decoherence effects would make it extremely difficult for W to make such a measurement on a macroscopic system like $F+M+S$. Nevertheless, Everett held (1) that one only has a satisfactory formulation of quantum mechanics if one can provide a consistent account of such nested measurements like the one described in the Wigner's Friend story and (2) that, if such a measurement were ever made, one would find that there was no collapse of F's state, M's state, or the state of the object system S when they interacted with each other.

So to solve the quantum measurement problem as Everett himself understood it, one must be able to tell the Wigner's Friend story consistently. And Everett repeatedly described how the story must go on his view. His proposal for solving the measurement problem was to take pure wave mechanics, the von Neumann-Dirac theory but without the collapse dynamics (II), to provide a complete and accurate description of all physical interactions whatsoever. And his goal was to show that when observers are themselves modeled as physical systems, pure wave mechanics *can be understood as making the same empirical predictions as the standard collapse theory* (whenever the latter makes coherent empirical predictions).

In some sense pure wave mechanics does indeed immediately solve the measurement problem. With only one dynamical law, there is no threat of inconsistent state predictions nor any puzzle about what dynamics to apply and when. But pure wave mechanics also leads to two new problems: the *determinate record problem* involves explaining how measurements generate determinate measurement records and the *probability problem* involves explaining why measurement outcomes should be expected to exhibit the standard quantum probabilities. Postulating branches, or quantum worlds, is meant to explain both determinate records and quantum probabilities.

4. Elements, branches, and quantum worlds

Let's start by considering how pure wave mechanics models an observer in the context of a measurement interaction. Consider the Wigner's Friend experiment just discussed, but with a more general initial state

(5) $$\alpha|\uparrow_x\rangle_S + \beta|\downarrow_x\rangle_S.$$

Assuming perfect correlating interactions, by the linear dynamics, the resultant state will then be

$$\alpha|\text{“}\!\uparrow_x\!\text{”}\rangle_F|\text{“}\!\uparrow_x\!\text{”}\rangle_M|\uparrow_x\rangle_S + \beta|\text{“}\!\downarrow_x\!\text{”}\rangle_F|\text{“}\!\downarrow_x\!\text{”}\rangle_M|\downarrow_x\rangle_S. \tag{6}$$

When an experiment like this is in fact performed, the observer gets either the result “$\uparrow_x$” or the result “$\downarrow_x$” with probabilities $|\alpha|^2$ and $|\beta|^2$ respectively. But the state (6) does not describe an observer with any particular measurement result. And since the evolution of the state is deterministic and since there is no epistemic uncertainty in its evolution, it is unclear how to understand the standard quantum probabilities. Everett recognized both of these problems.

In his earliest account of determinate records, Everett appealed to *cross sections* (1955, 66–8) and *branches* (1955, 68–9). He argued that, while the observer does not have any particular determinate record, there are “cross sections of the total wave function” in which each term or element in the superposition describes the observer with a definite measurement record that is correlated with a definite state of the object system. Everett used the term *cross section* to refer to a particular decomposition of the total state in terms of a selected orthonormal basis. Here (6) provides one cross section of the total state. Writing the same state in another basis would provide a different cross section.

Everett held that the existence of such cross sections explains both determinate measurement outcomes and the standard quantum statistics. In particular, one can *find* the determinate measurement records one gets in a branch represented by the terms in a cross section like that provided by (6). In this case, the first term represents a branch where F records the result “$\uparrow_x$” and in the second term represents a branch where F records the result “$\downarrow_x$.” If one thinks of each of these branches as representing a quantum world, then F gets perfectly determinate, but different records, in each world. The addition of this bit of metaphysics, then, explains why it will appear to a particular F that he gets a determinate measurement result. As Everett put it in conversation with Abner Shimony in 1962, “Each individual branch looks like a perfectly respectable world where definite things have happened” (Barrett and Byrne 2012, 275–6).

Concerning the standard quantum statistics, Everett proceeded to argue that if an observer like F were to perform a series of measurements, the records of the results in a typical branch would exhibit the standard quantum statistics, in a special sense of *typical* that Everett specified. It is important to note that, while the typicality measure that Everett specified satisfies the axioms of a probability measure, he explicitly denied that it in any way represented probabilities. This point was sufficiently central to his project that he originally titled his thesis “Wave Mechanics without Probability” (Barrett and Byrne 2012, 72). Everett's strategy, then, was to use his notion of typicality to explain the standard *quantum statistics* but without an appeal to probabilities.

In brief, this worked as follows.[9] Everett argued that if one performs a sequence of measurements, the sequence of records in a typical branch (or quantum world), in the *norm-squared amplitude measure* sense of typical, will exhibit the standard quantum statistics. It is not that *most* determinate-record branches, in the counting sense of most, will exhibit the standard quantum statistics. Rather, it is that the *greatest weight* of branches will exhibit the standard quantum statistics when one weights each branch by the square of the coefficient associated with it.[10]

It is in this way that Everett found the standard quantum statistics in a *typical* quantum world without there being any quantum probabilities. As a consequence, if one supposes that one's own world is typical in the sense that Everett described, this stipulation would explain why one's experimental results exhibit the standard quantum statistics. But for the theory to predict that one should *expect* that one's world is likely typical in this sense would require one to add something else to the theory that ties Everett's typicality measure to one's expectations. Everett never did that. He seems to have thought it was unnecessary given his modest explanatory goals.

Not only did Everett never explain why one should expect that the branch representing one's experience should be typical, it is unclear how such expectations might be made compatible with his insistence that there were no probabilities in the theory.[11] That said, he did show how one can find the experiences of an observer as typical, in his specified sense, in the model of pure wave mechanics. And he explicitly took that to be enough.

Everett held that his theory was empirically faithful.[12] Empirical faithfulness might be thought of as a weak sort of empirical adequacy. In some ways, it is akin to empirical adequacy on Bas van Fraassen's (1980) constructive empiricism as it consists in finding an observer's experience associated with the observer as represented in the model of the theory. Inasmuch it was empirically faithful, Everett took pure wave mechanics to be empirically acceptable. And since it was also logically consistent and simple, indeed, arguably the simplest possible formulation of quantum mechanics, he took pure wave mechanics to be clearly better than other options for addressing the quantum measurement problem.

5. The properties of quantum worlds

We are now in a position to discuss the properties of branches, or quantum worlds, as Everett understood them. To begin, the point of postulating quantum worlds is to explain why we get a determinate measurement records and why such records exhibit the standard quantum statistics.

Since the linear dynamical describes all physical interactions in pure wave mechanics, the total quantum state does not typically describe an observer as getting any particular measurement record. But a particular measurement record can be found in each quantum world on an appropriately selected cross section of the total state. So, if one imagines that an observer inhabits a particular such quantum world, then one has an explanation for why the observer sees a particular measurement result. Similarly, the standard quantum statistics are descriptive of determinate sequences of measurement records if the quantum world is typical in Everett sense. So, if one identifies branches with quantum worlds and if one supposes that one's own world is typical in Everett's sense, then one has an explanation for one's determinate measurement records and their statistical properties.

Still identifying branches with worlds, each quantum world is equally actual. But, importantly, for Everett this was not a matter of metaphysical stipulation. Rather, it was true by dint of the empirical consequences of the linear dynamics. As he explained, "It is ... 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" (1956, 150). Each element, branch, or quantum world, then, is real because it might, in principle, be detected by a subtle enough interference experiment of the sort that Wigner W might do to detect that the friend F, his measuring device M, and object system S are in fact in the entangled superposition of determinate record states predicted by the linear dynamics.[13]

Note that this account of determinate measurement records does not rely on decoherence considerations. Not only did Everett not need decoherence effects to explain determinate measurement outcomes, he described the goal of his project as providing a clear and consistent account of nested measurement in the context of a story where where he stipulated that there were no decoherence effects. Indeed, he called the version of the Wigner's Friend nested-measurement story that he told "an extremely hypothetical drama" precisely because he was insisting on the implausible condition that there are no interactions with the environment that might prevent the external observer from determining the state of the internal $F + M + S$.[14]

The Wigner's Friend story was a litmus test for Everett for whether one had a satisfactorily account of nested measurement and hence could address the measurement problem. Not only did he insist that one be able to tell the Wigner's Friend story consistently, he was also clear regarding how it must go. An external observer would in principle be able to show empirically that the Friend recorded a superposition of different results. Alternative quantum worlds on this view are real not as causally separate worlds but as *potentially detectable features of our world*. Quantum worlds, hence, are always in principle detectable.

Further, quantum worlds are emergent in the sense that what worlds there are on a particular cross-section at a time depends on the evolution of the total quantum state of the physical world. Such worlds come and go as the elements in the superposition written in a particular basis or cross-section changes as the total state evolves in accord with the linear dynamics.[15]

Finally, quantum worlds are conventional in the sense that what worlds there are depends on what basis or cross-section of the global state one considers. If one wants an account of determinate measurement records, it is natural to choose a basis that makes measurement records determinate in each branch of the superposition. But one could choose a basis that does not do that, and Everett would still insist that each branch in the alternative corresponding decomposition of the full state was equally actual due to the ever present possibility of obtaining interference effects between different branches. Further, even if one does choose a basis that makes one's measurement records determinate, one must also choose a level of descriptive detail for the records, and different levels of descriptive detail will typically involve different bases and, hence, characterize different sets of alternative quantum worlds.[16]

6. Relative states, typicality, and expectations

For his part, Everett never referred to quantum worlds in any of his published work. Rather, he called his theory the *relative-state formulation of quantum mechanics*, appealing to relative states rather than worlds to explain determinate measurement outcomes and their statistics.

In both the long and short versions of his Ph.D. thesis, Everett appealed to the distinction between *absolute states* and *relative states* to explain experience.

> 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 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*. (1956, p.103; 1957, p.180)

It was by supplementing pure wave mechanics with this distinction between absolute and relative states that he got to his relative-state formulation.

On the relative state formulation of quantum mechanics, facts regarding the properties of a subsystem of a composite system are relative to specifications of a state for the compliment of that subsystem. The post-measurement observer F described by the absolute state (6) has no determinate absolute measurement record but does have determinate relative measurement records—relative to specifications of the state of his object system S. In particular, F has the determinate measurement record "$\uparrow_x$" *relative to S* being in state $|\uparrow_x\rangle_S$ and F has the determinate measurement record "$\downarrow_x$" *relative to S* being in state $|\downarrow_x\rangle_S$.

One way to characterize a metaphysics that meshes well with how Everett described his theory would be to affirm that there is just one physical world but insist that the facts concerning physical systems and observers, including observers' records, are essentially relational. Along these lines, one might say that the observer F has a perfectly determinate outcome to his measurement—it is just that what it is is relative to a particular specification of the x-spin of system S. Branches on this view might be thought of as representing a new indexical akin to time. Following up on a suggestion that Simon Saunders (1995, 1996a, 1996b) made some years ago, Christina Conroy (2010, 2012, 2015) has described how the metaphysics of such a proposal might work in considerable detail.

The point for us here, however, is that, insofar as one individuates theories by the explanations they provide, Everett's relative-state formulation of pure wave mechanics, just like the many-worlds formulation described above, is *more than* pure wave mechanics. Specifically, insofar as the distinction between absolute and relative states is essential to Everett's explanation of experience, the distinction and the explanatory role it plays is a part of Everett's theory.

Moreover, explaining the standard quantum statistics, just as above, requires yet further additions to the relative-state theory. Specifically, Everett's particular notion of typicality must be added to the theory to get the conclusion that a typical relative sequence of measurement records will exhibit the standard quantum statistics as the number of measurements gets large. Whether one is talking about alternative quantum worlds or relative states, there are an infinite number of probability measures that one might consider using as a typicality measure. Hence, one must add *something* to pure wave mechanics to characterize both what one means by typical and how that particular notion of typical is supposed to provide explanations for what we observe. And, if one wants to explain why one should *expect* one's relative records to exhibit the standard quantum statistics, one must add something further still.

An upshot is that, whether one favors a many-worlds or a relative-state version of the theory, there remain a number of problems interpreting Everett's theory. Among these is the fact that on one hand he set out to explain how one might understand pure wave mechanics as making precisely the same empirical predictions as the standard collapse theory, which presumably involves making probabilistic predictions, while, on the other hand, he clearly insisted that there were no probabilities in his theory. So there is significant work remaining to do. But, as one reconstructs the theory, one has metaphysical options, and what one chooses will determine how one one's explanations go and hence how one ultimately understands the theory.

7. Conclusion

Pure wave mechanics provides a basic mathematical framework and a partial physical interpretation of the framework, but it does not, by itself, explain physical phenomena. To be sure, the framework constrains one's explanations, but it does not determine them. To get satisfactory explanations one must supplement the theory with metaphysical commitments that fit as neatly as possible both with the theoretical framework and one's explanatory demands. This involves negotiating between the framework and one's explanatory demands, and each side may well require tuning along the way. Consequently, the resulting metaphysical commitments are contingent on the details of the particular explanatory demands and how one sets about satisfying them.

In the present case, we have considered how quantum worlds and relative states may be used to clarify our understanding of pure wave mechanics and supplement the theoretical framework with what it needs to provide compelling explanations. Specifically, we have considered how quantum worlds and relative states might be characterized in a way that meshes well with Everett's talk of branches and how such worlds and states might help to provide explanations of determinate measurement records and the standard quantum statistics.

Starting with a theory as simple as pure wave mechanics, one would naturally like to claim that nothing at all needs to be added to get the standard quantum predictions. But such a claim cannot be honestly made. Insofar as one individuates theories by the explanations they provide, even Everett added a number of essential notions and assumptions to get the very modest sort of explanations he sought. This included adding distinctions like that between relative and absolute states and a typicality measure and providing concrete examples of how to appeal to such notions for explanations of quantum phenomena. And, if one wanted a theory that predicted the standard quantum *probabilities*, one would need to add yet more to pure wave mechanics, arguably assumptions that would be incompatible with Everett's project as he understood it.

Insofar as alternative quantum worlds are neither sharply individuated nor canonical, the explanations one gets for determinate records and quantum statistics by appealing to records in alternative worlds is correspondingly modest. Further, as we have seen, there are other metaphysical options for providing such explanations. Everett himself accounted for determinate records and how they are distributed by appealing to the relative records. Such explanations are no stronger than what one gets with the sort of quantum worlds we have characterized here, but they suggest a rather different set of metaphysical commitments.

Whatever option one ultimately favors in making sense of pure wave mechanics, there are other quantum-mechanical frameworks that suggest quite different metaphysical commitments. Examples can be seen in accounts like those provided by particular formulations of Bohmian mechanics and GRW. This, again, is why the naturalized metaphysician does not seek to infer a canonical metaphysics from quantum mechanics or any another physical theory. Rather, the aim is to make clear the trade-offs involved in alternative explanatory options.[17]

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Notes

[1] See Albert (1992) and Barrett (1999) for introductions to these and other formulations of quantum mechanics.

[2] As suggested earlier, a single theoretical framework may be associated with quite different sets of metaphysical commitments. Bohmian mechanics, for example, may be thought of as a theory about events in ordinary three-dimensional space (as David Bohm himself suggested), or as a theory about events in a high-dimensional configuration space (as John Bell and David Albert have suggested), or as a many-worlds theory (as characterized by something like the many-threads formulation of quantum mechanics). See Barrett (1999) for discussions of these and other options.

[3] Einstein expressed his view against the essential use of configuration space and he thought that the collapse of the state on measurement implied "a contradiction with the postulate of relativity" (*Instituts Solvay* 1928, p.256).

[4] As indicated in his notes and the short pre-dissertation papers he wrote for his advisor John Wheeler.

[5] See Barrett (2011b) for a discussion of Everett's reluctance to refer to quantum worlds in his presentation of this theory.

[6] As indicated by his being one of the first people to read Everett's deposited thesis, David Lewis was very much interested in Everett's formulation of quantum mechanics (Lewis checked the original thesis out from the Princeton library on 25 January 1966). But, as Lewis reported when he and I discussed this in the mid 1990's, he quickly concluded that Everett possible worlds were quite different from his own, and he did not see any immediate implication of one notion for the other. See Barrett and Byrne (2012, p.174) for a list of early readers of Everett's original thesis.

[7] See Everett's letter to Aage Petersen 31 May 1957 (Barrett and Byrne 2012, p.238–40).

[8] Everett's proposal for solving the problem was to drop dynamical law (II) from the theory. In contrast, Wigner's solution was to stipulate that law (II) kicked in when a conscious entity apprehended the physical state of the object system.

[9] See, for example, Everett 1957, p.188–94.
[10] In this measure, for example, the branches represented by the elements in the superposition (6) after a a single measurement get assigned weights $|\alpha|^2$ and $|\beta|^2$ respectively.
[11] Since there are quantum worlds where the quantum statistics are satisfied and others where they are not, one should only *expect* one's own world to exhibit the standard quantum statistics if one takes it to be *probable* for one to inhabit such a world, but Everett repeatedly denied that the theory involved probabilities.
[12] See Barrett (2011) for a discussion of Everett's notion of empirical faithfulness.
[13] See Albert (1986) for a short story of how Everett worlds might interact and Albert and Barrett (1995) for why this consequently involves a very weak notion of what it takes to be a world.
[14] Everett's position here is quite different for that of current Everettians who use decoherence considerations to roughly individuate quantum worlds and hence explain determinate measurement outcomes. See Saunders et al. (eds.) (2010) for a number of papers that take the decoherence line and Wallace (2012) for a particularly well-developed example. Of course, this does not mean that decoherence considerations can have no role at all in the theory. For one thing, they help to explain why macroscopic measurement records can be expected to be stable. The sort of interference interaction that would erase a macroscopic record would be as difficult to perform as the Wigner's Friend interference measurement.
[15] Here we are setting aside the problem of how to identify the same quantum world at different times.
[16] That there is no canonical way to individuate quantum worlds has led even Everettians who rely on decoherence to individuate worlds to insist that there is no matter of fact about how many quantum worlds there are at a time. See, for example, Wallace (2012).
[17] I would like to thank Christina Conroy for comments on an earlier draft of this paper.