Pure Wave Mechanics and the Very Idea of Empirical Adequacy

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Abstract

Hugh Everett III proposed his relative-state formulation of pure wave mechanics as a solution to the quantum measurement problem. He sought to address the theory's determinate record and probability problems by showing that, while counterintuitive, pure wave mechanics was nevertheless empirically faithful and hence empirical acceptable. We will consider what Everett meant by empirical faithfulness. The suggestion will be that empirical faithfulness is well understood as a weak variety of empirical adequacy. The thought is that the very idea of empirical adequacy might be renegotiated in the context of a new physical theory given the theory's other virtues. Everett's argument for pure wave mechanics provides a concrete example of such a renegotiation.

1 Introduction

Hugh Everett III proposed his relative-state formulation of pure wave mechanics as a solution to the quantum measurement problem, and there is indeed a sense in which it clearly solves the problem. But there is also a sense in which it predicts that most every measurement yields most every physically possible measurement result, which, at least on the face of it, is incompatible with experience.

In order to argue that pure wave mechanics is empirically acceptable, one must recover determinate measurement records and show that they will in some relevant sense exhibit the standard statistical predictions of quantum mechanics. In pure wave mechanics, these two tasks involve addressing the *determinate record problem* and the *probability problem*. For his part, Everett believed that he could fully address both of these problems in the context of pure wave mechanics by showing, without appeal to any special metaphysical assumptions, that the theory was *empirical faithful*. We will consider what he meant by empirical faithfulness, a sense in which he was certainly right to claim that pure wave mechanics was empirically faithful, and the relationship between his notion of empirical faithfulness and empirical adequacy.[1]

A companion to the present paper, Barrett (2014) provides a general introduction to Everett's formulation of quantum mechanics and briefly summarizes some of arguments originally developed here. In addition to providing more argumentative, textual, and historical detail, the present paper treats a number of topics that would be inappropriate in an introduction to the theory. In particular, the central concern here is how one's explanatory demands, and particularly those related to empirical explanation, guide one's understanding and evaluation pure wave mechanics. Getting clear on this involves tracking the auxiliary assumptions that must be added to the formalism of pure wave mechanics for Everett's account of quantum experience. To that end, the present paper provides an extended discussion of the determinate record and probability problems, attends to philosophical issues like the individuation of physical theories and theory selection, provides detailed description of the steps in Everett's overall argument, including his account of quasiclassical experience, and contrasts his explanations and

[1]See Barrett (2009), (2010), (2011a), (2011b), and (2014) and Barrett and Byrne (eds) (2012) for recent discussions of Everett's understanding of physical theories in general and pure wave mechanics in particular. Much of this work is based on documents that can now be found in Barrett and Byrne (eds) (2012) and at the UCIspace Hugh Everett III Manuscript Archive permanent url: http://hdl.handle.net/10575/1060.

the auxiliary assumptions required against those presented by current many-worlds proponents. We also consider how the empirical faithfulness of pure wave mechanics might be tested, the problem of relevance for faithfulness as a standard for empirical explanation, his argument against other no-collapse theories like Bohmian mechanics, and the explanatory sacrifices involved in accepting his conclusion.

The suggestion will be that empirically adequacy, along with other standards for evaluating theories, may be renegotiated in the context of theory selection and that the evaluation of pure wave mechanics against its competitors provides an ongoing example of just such a renegotiation.

2 From Orthodox Quantum Mechanics to Pure Wave Mechanics

Everett used the standard von Neumann-Dirac collapse formulation of quantum mechanics to explain the measurement problem and to characterize pure wave mechanics. His discussion of the measurement problem in the long and short versions of his Ph.D. thesis indicates that Everett took the standard collapse theory to involve at least the following principles:[2]

1. **Representation of states**: The state of a physical system S is represented by a vector ψ_S of unit length in a Hilbert space $\mathcal{H}$.

2. **Representation of observables**: Every physical observable O is represented by a Hermitian operator $\hat{O}$ on $\mathcal{H}$, and every Hermitian operator on $\mathcal{H}$ corresponds to some observable.

3. **Interpretation of states**: A system S has a determinate value for observable O if and only if $\hat{O}\psi_S = \lambda\psi_S$.

[2]See Everett's discussions of the "external observation formulation of quantum mechanics" beginning (1956, 73) and (1957, 175) in the long and short versions of his thesis respectively.

4. **Dynamical laws**:

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

b. **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 with the standard collapse theory, Everett argued, was that it was logically inconsistent and hence untenable. The inconsistency was apparent when one tried to describe nested measurements in the theory. He illustrated the problem in the context of an "amusing, but *extremely hypothetical* drama," a story that was a few years later retold by Eugene Wigner.[3]

Everett's version of the Wigner's Friend story involved an observer A who knows the state function of some system S, that is not in an eigenstate of the measurement he is about to perform on it, and an observer B who is in possession of the state function of the composite system $A + S$. Observer A believes that the outcome of his measurement on S will be randomly determined by rule 4b, hence A attributes to $A + S$ a separable state describing A as having a determinate measurement result and S as having collapse to the corresponding state. Observer B, however, attributes the state function of the room after A's measurement according to the deterministic rule 4a,

[3]See Everett (1956, 74–8) and Wigner (1961) for the two versions of the story. Wigner was a member of the physics faculty at Princeton while Everett was a graduate student in the department. The stories are remarkably similar, but there is a salient difference in presentation. While Everett used his story to argue that the standard collapse theory was inconsistent, Wigner used his to argue that in order for the standard theory to be consistent and for observers get determinate measurement results, observers, unlike ordinary physical systems, must cause collapses. Wigner thought that a sort of mind-body dualism was required to provide a complete, consistent, and principled formulation of the standard theory. In particular, he took the nonlinear dynamics to apply if and only if a conscious entity apprehends the state of a physical system.

hence B attributes to $A + S$ and entangled state where, on rule 3, neither A nor S even has a determinate quantum mechanical state of its own. Everett argues that since A and B make incompatible state attributions to $A + S$, the standard collapse theory yields a straightforward contradiction.

While it might, in practice, be extraordinarily difficult for B to make a measurement that would determine the state of a composite system like $A+S$, hence the "extremely hypothetical" nature of the drama, Everett was careful to explain why this was entirely irrelevant to the conceptual problem at hand. Indeed, among the options that he explicitly rejected as solutions to the measurement problem was the proposal that one "deny the possibility that B could ever be in possession of the state function of $A + S$." Everett had two objections to this move that reveal how he understood the problem. He first argued that "no matter what the state of $A+S$ is, there is in principle a complete set of commuting operators for which it is an eigenstate, so that, at least, the determination of *these* quantities will not affect the state nor in any way disrupt the operation of A," nor, he added, are there "fundamental restrictions in the usual theory about the knowability of *any* state functions." He further argued that

> [I]t is not particularly relevant whether or not B actually *knows* the precise state function of $A + S$. If he merely *believes* that the system is described by a state function, which he does not presume to know, then the difficulty still exists. He must then believe that this state function changed deterministically, and hence that there was nothing probabilistic in A's determination. (1956, 76)

And, Everett argued, B is precisely right in so believing.

Everett's version of the Wigner's Friend story illustrates an essential point in his understanding of the measurement problem and its solution. That he took a thought experiment that would be virtually impossible to perform to pose the central, and ultimately fatal, threat to the standard collapse formulation of quantum mechanics indicates that he considered the measurement problem to be a conceptual, not a practical, problem. Here and in his criticisms of alternative interpretations of quantum mechanics, Everett made it clear that he had no interest whatsoever in a for-all-practical-purposes solution to the quantum measurement; rather, he wanted, and ultimately believed he had found in pure wave mechanics, a theory that could be taken as providing a complete and consistent model of all physical interactions whatsoever.

His discussion here also indicates that Everett believed that there was nothing preventing observer B from at least in principle knowing the entangled state of system $A+S$ after A's measurement and, as Wigner would also argue, that Everett believed that it was in principle possible for the observer B to determine the entangled state of $A+S$ that is predicted by the linear dynamics rule 4a by measuring a quality that would not affect the state of $A+S$. An example of such a quantity would be an observable O that has the entangled post-measurement state predicted by pure wave mechanics for the composite system $A+S$, $\sum_i a_i \psi[\text{``}i\text{''}]_A \phi^i_S$, as an eigenstate of $\hat{O}$ corresponding to eigenvalue $+1$ and a state orthogonal to this as an eigenstate of $\hat{O}$ corresponding to eigenvalue -1.[4] It immediately follows from the fact that the linear dynamics always allows one at least in principle to detect interference between branches that Everett would have ruled out any interpretation of pure wave mechanics where different branches were causally isolated from each other. Indeed, he explicitly and repeatedly argued that it was always in principle possible to observe interference effects between branches. And, as we will see, it was for precisely this reason that he regarded all branches

[4]Wigner believed that O-type measurements would allow one to tell whether A caused a collapse of S. If the result was always $+1$, then it did not cause collapses; if the result was ever -1, then it did. For his part, Everett held that there were no collapses and, hence, a measurement of O would always reveal that $A+S$ was in the entangled superposition predicted by pure wave mechanics.

to be equally real.

To understand Everett's solution to the measurement problem, one must first understand what he took a solution to require. He held that one only has a solution to the quantum measurement problem if one can provide a satisfactory account of nested measurement, which requires that *one must at least be able to tell the Wigner's Friend story completely and consistently.* He believed that pure wave mechanics could do precisely this, and in doing so explained the sense in which both A's and B's state attributions are correct.[5]

Everett characterized *pure wave mechanics* as the standard von Neumann-Dirac collapse theory but with the "complete abandonment" of the collapse process described by rule 4b (1956, 77). Pure wave mechanics is consistent since, with only the linear dynamics, there can be no conflict between incompatible dynamical laws as illustrated in the hypothetical drama. In this sense, pure wave mechanics immediately solves the consistency problem. The question then is how to understand the theory as empirically acceptable.

3 Determinate Records and Probability

Everett's project was to take pure wave mechanics to be a complete physical theory that provides a faithful model of all physical interactions whatsoever, then show that when observers are themselves modeled as physical systems, it makes the same empirical predictions for their subjective experience as the standard collapse theory. He drew conclusions regarding subjective experience by way of his model of an ideal physical observer.[6] His strategy was to show that the state of an ideal observer, as described by the theory, was associated with determinate relative measurement records that were typically distributed according to the standard quantum statistics. Care is required even just to say what he meant by this.

[5]On his account, as we will see, B is describing the absolute state of $A + S$ and A is describing relative states of A and S.

[6]See, for example, Everett (1956, 119) and the *Deductions* section following that page.

Everett took an ideal observer to be a physical system with memory registers whose states become perfectly correlated to the physical quantity being measured. If such an observer F begins in a ready-to-make-a-measurement state $\psi[\text{“ready”}]_F$ and measures the observable P of system S, with eigenstates ϕ^i_S, then the composite system $F+S$ evolves from F being ready to make a measurement on the left to the entangled state on the right

$$\psi[\text{“ready”}]_F \sum_i a_i \phi^i_S \longrightarrow \sum_i a_i \psi[\text{“}i\text{”}]_F \phi^i_S \tag{3.1}$$

And repeated measurements simply lead to more complicated entangled superpositions, each term of which, when written in the determinate-record basis as above, describes F as having recorded a different sequence of measurement results.

Everett knew that there were two related problems with how pure wave mechanics describes such a measurement interaction.

The first is the *determinate record problem*. On the standard eigenvalue-eigenstate link, rule 3 above, which Everett adopted from the standard theory as the interpretation of the *absolute state* of a system in pure wave mechanics, F has no determinate measurement record. Regarding state 3.1, he explained:

> Thus in general after a measurement has been performed there will be no definite system state nor any definite apparatus state, even though there is a correlation. It seems as though nothing can ever be settled by such a measurement. Furthermore this result is independent of the *size* of the apparatus, and remains true for apparatus of quite macroscopic dimensions. . . . This behavior seems to be quite at variance with our observations, since macroscopic objects always appear to us to have definite positions. Can we reconcile this prediction of the purely wave mechanical theory with experience, or must we abandon it as untenable? (1956,

117)

It will turn out, however, that while the absolute state of the $F + S$ fails to describe F with a determinate measurement record, each of F's relative states do.

The second is the *probability problem*. Since the evolution of the state is deterministic and there is no epistemic uncertainty, it is unclear how to understand the standard quantum probabilities. As Everett explained it:

> In order to establish quantitative results, we must put some sort of measure (weighting) on the elements of a final superposition. This is necessary to be able to make assertions which will hold for almost all of the observers described by elements of a superposition. In order to make quantitative statements about the relative frequencies of the different possible results of observation which are recorded in the memory of a typical observer we must have a method of selecting a *typical* observer. (1956, 123–4)

The problem then is to find a suitable measure of typicality associated with the relative states of F, one that covaries with standard quantum expectations.

Everett took the key to the solution of both problems to be *the 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 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.[7]

His distinction between absolute and relative states then works as follows. The *absolute state* of a physical system S is represented by a vector ψ_S of unit length in a Hilbert space $\mathcal{H}$. If the absolute state of system E is $\sum a_i \psi_S^i \chi_{S'}^i$, the *relative state* of subsystem S to its complement S' in relative state $\chi_{S'}^k$ is ψ_S^k. And the system E has an *absolute value* λ for an observable O if and only if the absolute state of E is an eigenstate of $\hat{O}$ with eigenvalue λ. If the absolute state of system E is $\sum a_i \psi_S^i \chi_{S'}^i$, subsystem S has a *relative value* λ_S for an observable O, relative to its complement S' being in relative state $\chi_{S'}^k$, if and only if ψ_S^k is an eigenstate of $\hat{O}$ with eigenvalue λ_S.

The principle of the fundamental relativity of states supplements pure wave mechanics with an interpretive distinction between absolute and relative states. Absolute states provide absolute properties for composite systems by way of the standard eigenvalue-eigenstate link. Relative states provide relative properties for subsystems of a composite system. And this distinction between the two different types of states plays an essential explanatory role in Everett's account of the empirical faithfulness of pure wave mechanics. In particular, measurement outcomes are associated with the relative memory states of idealized observers modeled within the theory

While he continues to use the standard eigenvalue-eigenstate link to understand absolute states and properties, it is, then, relative states and properties that Everett takes to explain our having determinate measurement records. That F has no determinate absolute record above does not mean that F has no determinate record; rather, each relative F has a fully determinate relative record that explains the content of her subjective experience. While there are no absolute measurement records in state 3.1 above, F has record "1" *relative to* S being in state ϕ_S^1, F has record "2" *relative to* S

[7] Everett presents this as the central interpretational principle with just slightly different words and italics in both the long and short versions of his thesis (1956, 103) and (1957, 180). The quotation here follows the latter.

being in state ϕ_S^2, etc. for each possible measurement record i. Each relative record is also associated with an amplitude. Relative record "1" is associated with a_1, record "2" is associated with a_2, etc. And, as we will see, the amplitudes associated relative records play the key role in Everett's account of the appearance of the standard quantum statistics.

In trying to make sense of Everett's various explanations, there is a recurring issue of what should count as part of the theory and what must be added for the theory to explain our experience. This issue is particular salient as there is a long tradition of claiming that nothing whatsoever needs to be added to pure wave mechanics to get all the standard predictions of quantum mechanics.[8] Everett is at least in part to blame for this attitude since he firmly believed that pure wave mechanics was complete, whatever that should mean. It seems to me, however, that, for the sake of clarity, it is useful to try to be as clear as possible about what is being used in the explanations one takes the theory to provide. While this may take some of the magic out of the theory and its explanations, the thought is that one gains enough in clear understanding to compensate for the loss.

Insofar as it is the content a physical theory that provides its explanations, since the distinction between relative and absolute states is essential to Everett's resolution of the determinate record and probability problems, one might properly consider it to be addition to the theory of pure wave mechanics. Further, since pure wave mechanics itself says nothing whatsoever regarding probability, rational expectation, typicality, or anything else related to statistical inference, one should expect to need further additions to the theory in order to get anything like the standard quantum statistical predictions. In particular, Everett's strategy will be to define a typical-

[8]This sometimes appears as the curious claim that the mathematical formalism of pure wave mechanics somehow interprets itself. This was DeWitt's (1970) explicit view when he came to accept the theory and serve as its principle apologist. See Saunders et al. (2010) for more recent expressions of this view. Wallace (2010a, 69–70) provides a particularly salient example.

ity measure for relative sequences of measurement records as a function of the amplitudes associated with the relative sequences. This will require the distinction between absolute and relation states, a notion of typicality that appears nowhere in the most basic statement of pure wave mechanics, and an account of how this measure is to be understood in the model of the theory.

The theory that results from adding the explanatory distinction between absolute and relative states and related explanatory assumptions might, following Everett, be referred to as *the relative-state formulation of pure wave mechanics*. The suggestion is that this theory is more than just pure wave mechanics precisely insofar as it is the distinction between relative and absolute states that explains the sense in which a modeled observer has determinate measurement records and that yet further explanatory resources must be added to understand the relationship between relative amplitudes and quantum statistics in the theory.

That said, it may not be immediately clear that adding the distinction between absolute and relative states does anything to resolve the determinate record and probability problems. Indeed, there is a sense in which the two problems are simply transformed. The determinate record problem is now a *surplus-structure problem*. It is not that there is no determinate record; rather, it is that there are *too many* determinate relative records. And the probability problem is now a *sure-thing problem*. It is not that there are no probabilities; rather, it is that the theory provides the *wrong* probabilities insofar as every physically possible relative measurement record is predicted to occur with probability one.

When Bryce DeWitt first heard of Everett's theory, he objected to it because its surplus structure made the theory too rich in content. In his 7 May 1957 letter to John Wheeler, Everett's Ph.D. advisor, DeWitt wrote:

> I do agree that the scheme which Everett sets up is beautifully consistent; that any single one of the [relative memory states of an observer] . . . gives an excellent representation of a typical

> memory configuration, with no causal or logical contradictions, and with "built-in" statistical features. The whole state vector ..., however, is simply too rich in content, by vast orders of magnitude, to serve as a representation of the physical world. It contains all possible branches in it at the same time. In the real physical world we must be content with just one branch. Everett's world and the real physical world are therefore not isomorphic. Barrett and Byrne (eds) (2012, 246–7)

For DeWitt, the richness of pure wave mechanics indicated an empirical flaw in the theory because we do not notice alternative branches or the process of branching on measurement. As he put the objection:

> The trajectory of the memory configuration of a real observer ... does *not* branch. I can testify to this from personal introspection, as can you. I simply do *not* branch. Barrett and Byrne (eds) (2012, 246)

But, as we will see, the richness to which DeWitt objected also makes the theory too strong since one might use it to explain virtually any sequence of experience.[9]

Everett explained how his relative-state formulation of pure wave mechanics worked in his 31 May 1957 letter to DeWitt replying to the worry over surplus structure. Everett began by summarizing his understanding of the proper 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

[9] One needs something like a notion of typicality here to defend the theory against explaining too much, but we do not have this yet. It is in this sense that solving the surplus structure problem requires one to also solve the probability problem.

> 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. Barrett and Byrne (eds) (2012, 253)

In the final long version of his thesis, Everett explained in a footnote that "[t]he word *homomorphism* would be technically more correct, since there may not be a one-one correspondence between the model and the external world" (1956, 169). And in his letter to DeWitt, Everett described how he understood the aim of physical inquiry: "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" Barrett and Byrne (eds) (2012, 253).

For Everett, a theory was *empirically faithful*, and hence empirically acceptable, if there was a homomorphism between its model and the world as experienced. The task then was to find our experience appropriately associated with modeled observers in the model of pure wave mechanics. Specifically, he argued that pure wave mechanics is empirically faithful because one can find our experience in the model of the theory as relative sequences of memory records associated with idealized relative observers. Precisely how this was to work requires some explanation.

4 The solution to the surplus structure and probability problems

Everett's solution to the surplus structure and probability problems involved four closely related steps. Together they show the sense in which he took pure wave mechanics to be empirically faithful. Further, since each step provides interpretive guidance that Everett took to be essential to his explanation of experience, insofar as one takes it to be the theory that explains our experience, they also provide his most complete description of the relative-state formulation of pure wave mechanics. We will consider each step in turn.

4.1 Experience is found in the relative memory records of observers

Everett held that one can find one's actual experience in the model of pure wave mechanics as a relative sequence of measurement records. In state 3.1 F has a different relative measurement record in each term of the superposition written in the determinate record basis. On modest assumptions concerning the absolute state, such relative records can typically be expected to span the space of quantum-mechanically possible outcomes of a measurement. Hence, regardless of what result one actually takes oneself to have, one will be able to find oneself as a relative observer and one's experience as an associated relative record in the model of the interaction provided by pure wave mechanics. Moreover, if one performs a sequence of measurements on identically prepared systems, it follows from the linearity of the dynamics and the model of an ideal observer that every quantum-mechanically possible sequence of determinate measurement results will be represented in the entangled post-measurement state as a relative sequence of determinate measurement records.[10] On modest assumptions concerning the absolute state, then, it is indeed possible to find one's actual experience as a relative sequence of measurements records in the model of pure wave mechanics.

Note that Everett does not require any physically preferred basis to solve the determinate record problem.[11] The principle of the fundamental rela-

[10]This is also true for approximate measurements (as Everett points out) or if one only relatively, rather than absolutely, makes the sequence of observations.

[11]Indeed, given what it means for a physical theory to be empirically faithful, there is a sense in which the preferred-basis problem is simply irrelevant to his project. Or put another way, Everett solves the preferred basis problem not by choosing a preferred basis but

tively of states explicitly allows for arbitrarily specified decompositions of the absolute universal state into relative states. Given his understanding of empirical faithfulness, all he needs to explain the existence of a determinate measurement record is that there be *some* decomposition of the state that represents the modeled observer with that determinate relative record. And he has that in pure wave mechanics under modest assumptions concerning the absolute quantum mechanical state.

That all relative states have precisely the same physical status is essential for understanding Everett's interpretation of pure wave mechanics. He took every relative state under every possible decomposition of the state of a composite system to be real in the only sense of real he understood: every relative state of a subsystem, every branch under any decomposition of the state of a composite system, is real precisely insofar as it might always, in principle, be detected by way of interference effects exhibited by the composite system.[12]

Everett held that a relative observer having a relative sequences of records was sufficient to explain an ideal observer's *subjective appearances* because, on the linear dynamics, every relative observer would have and would relatively report and relatively act as if she had, fully determinate, repeatable measurement records that agree with the records of other ideal observers. This together with his argument that a typical sequence of relative records will exhibit the standard quantum statistics was his promised deduction of subjective appearances for idealized observers (1956, 129–30).[13]

Everett's account of determinate records then involved only the correla-

by showing that no choice of preferred basis is required for empirical faithfulness. Rather, all one needs is to find an appropriate sequence of relative records appropriately associated with the modeled observer. That there are also relative states where the observer does not have any determinate relative records at all, indeed, where there is not even a determinate relative observer, doesn't matter for the empirical faithfulness of the theory.

[12]We will return to this point later.

[13]See Everett's discussions of this point (1955, 67), (1956 121–3 and 130–1), and (1957, 186–8 and 194–5). See also Albert (1992) and Barrett (1999) for discussions of these and other suggestive properties of pure wave mechanics (the bare theory). We will discuss Everett's *deductions* further below.

tions between an observer and her object system induced by measurement. One consequence of this is that decoherence effects involving subsequent interactions between the composite observer-object system and its environment are not required to explain the observer's measurement experience. The point is not that there is no explanatory role for decoherence considerations to play in the theory; rather, it is that the ideal observer has determinate relative records regardless of environmental decoherence, and it is ultimately the very having of such records that explains the determinateness of the observer's experience.

While decoherence considerations do not explain how an observer gets determinate relative measurement records, one might appeal to such considerations to explain the stability of relative records and the difficulty in observing macroscopic interference effects. Everett understood that the more degrees of freedom that become correlated with the value of a relative measurement record the more stable the relative record should be expected to be since to erase it one would have to undo each of the correlations. And his discussion of the Wigner's Friend story clearly indicates that he understood the difficulty in observing macroscopic interference effects. So while it is the correlation between the observer and her object system that explains her having determinate relative records, the physical degrees of freedom involved in the recording system and the correlations between the recording system and its environment help to explain why one should expect such relative records to persist.[14]

[14]Ultimately, the explanation of the expected stability of relative measurement records depends on implicit thermodynamic assumptions. In particular, to argue that a particular relative record is likely to persist, one must suppose that it is unlikely that the physical state is such that the relative records will interfere in just such a way as to undo the correlation between the recording and object systems. The argument might go something like this. If a particular measurement record involves many degrees of freedom, then states where an erasing re-interference would occur are relatively rare in Hilbert space the Lebesgue measure induced by the inner product. So if one assumes that the absolute state of the world is typical in this measure, then one should expect that relative records involving many degrees of freedom are typically stable.

The notion of relative states also played the central role in how Everett found macroscopic objects and their apparent classical behavior in the model of pure wave mechanics. He understood a composite physical object to be constituted by the correlations between the relative states of its parts. In a draft paper he wrote for Wheeler, Everett explained his picture of how composite physical objects might be naturally formed under the linear dynamics.

> Consider a large number of interacting particles. If we suppose them to be initially independent, then throughout the course of time the position amplitude of any single particle spreads out farther and farther, approaching uniformity over the whole universe, while at the same time, due to interactions, strong correlations will be built up, so that we might say that the particles have coalesced to form a solid object. (1955, 68)

He further explained that while it is the correlations between the parts of a macroscopic object that constitutes the object, it is the the correlations between our senses and the macroscopic objects in our environment that explain why they appear to have definite positions, for example, when they are in fact typically in complex entangled superpositions of different positions.

As Wheeler suggested in his marginal notes on the draft paper,[15] Everett later presented a more detailed description of his understanding of macroscopic objects and their apparent classical behavior in the long version of his thesis. In pure wave mechanics, what it means to say that a hydrogen atom has formed from a proton and an electron is just that a particular correlation has taken place between the two particles "a correlation which insures that the *relative* configuration for the electron, for a definite proton position, conforms to the customary ground state configuration." The center of mass of the hydrogen atom may hence be in a superposition of quite different positions, but still be the center of mass of a perfectly definite hydrogen atom. While the hydrogen atom does not have a determinate position

[15] See Barrett and Byrne (eds) (2011, 68).

> [t]he *relative* configuration (described by the *relative coordinate* state function) has . . . a permanent nature, since it represents a bound state, and it is this relative configuration which we usually think of as the object called the hydrogen atom. . . . no matter how indefinite the positions of the individual particles become in the total state function . . . , this state can be regarded as giving . . . an amplitude distribution over a comparatively definite object, the tightly bound electron-proton system" (1956, 135).

Similarly Everett explained that a macroscopic object, more specifically a cannonball, is constituted by the correlations between its parts in precisely the same way as the hydrogen atom. Just as with the hydrogen atom, "more complex objects can be built up through strong correlations which bind together the constituent particles." While these constituent particles will typically be in entangled superpositions of being at different positions, insofar as those positions are correlated

> we can speak of the existence of a relatively definite object, since the specification of a single position for a particle . . . leads to the case where the relative position densities of the remaining particles are distributed closely about the specified one, in a manner forming the comparatively definite object.

Even as the relative states of the individual particles spread in position, the fact that they are bound to each other restricts the final state "to a superposition of 'cannonball' states. . . . It is thus in this sense of correlations between constituent particles that definite macroscopic objects can exist within the framework of pure wave mechanics" (1956, 135-136).

Note that on this view environmental decoherence is not even required to characterize classical macroscopic objects. The macroscopic cannonball, just like the hydrogen atom, is constituted by the correlations between its parts, and it is the correlation between the observer and the macroscopic object that explains her determinate experience of the object and hence "allows us to give an adequate interpretation of the theory" (1955, 66).

While this was not Everett's strategy, one might appeal to decoherence considerations here, just as in the case of relative measurement records above, to explain the expected stability of relative macroscopic objects. But, for his part, Everett sought to explain the apparent classical behavior of relative macroscopic objects by the low dispersion in position and momentum of their relative states over appropriate short times:

> 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. (1956, 134–137)

It is in this sense that he believed that one could find relative quasi-classical macroscopic objects that approximately obey the laws of classical mechanics in the model of pure wave mechanics.

Regardless of his own view, appealing to environmental decoherence to explain classical experience has been a persistent theme in how people have understood Everett.[16] While he did not believe that he needed decoherence considerations to select a preferred basis or to explain determinate

[16] An early example is Zeh (1970). A more recent example is the Saunders-Wallace-Deutsch many-worlds interpretation of Everett, which appeals to decoherence considerations to characterize of the diachronic identity of worlds and the classical appearance of macroscopic objects in those worlds. See Deutsch (1997), Saunders et al. (eds) (2010), and Wallace (2012).

measurement outcomes[17] and while there is good reason to believe that he would not have liked the strong metaphysical commitments involved in recent decohering-worlds interpretations,[18] there is also good reason to believe that Everett would not have objected to such considerations playing a role in one's understanding of the theory insofar as they were employed with the metaphysically modest aim of finding quasi-classical experience in the model of pure wave mechanics. The thought is that since the relative properties of an object are determined by correlations, the persistence of its relative properties depends upon the persistence of correlations, so correlations between a macroscopic object and its environment by way of environmental decoherence would typically serve to provide relatively stable relative quasi-classical properties. So while Everett considered his own account of subjective appearances to be complete and to demonstrate the empirical acceptability of pure wave mechanics, decoherence considerations are at least compatible with this account. Further, while he might not have liked this way of putting it, by taking into account decoherence considerations, one might describe a richer sort of structural homomorphism between one's experience and the model than what Everett himself provided. We will return to compare Everett's explanations against those offered in recent many-worlds interpretations after we have considered Everett's line of argument.

To be clear, on Everett's own account, an observer has a determinate measurement record if and only if she has a determinate relative record, and it is sufficient for this that her physical record be correlated with the physical property being measured. And since one should expect to find relative records that agree with one's actual experience under relatively modest assumptions

[17]Since all Everett needed to explain determinate measurement outcomes was to find the outcomes as relative records in the model of pure wave mechanics, he did not need any mechanism to choose a physically preferred basis, so he did not need decoherence considerations for that purpose. He also required that a satisfactory formulation of quantum mechanics allow one to tell the Wigner's Friend story coherently, a story where decoherence considerations by stipulation do not obtain.

[18]See Barrett (2011b).

concerning the universal absolute quantum state, pure wave mechanics is empirically faithful over our actual measurement records.

But put that way, empirical faithfulness might feel like a hollow victory. Since every physically possible sequence of measurement records can be found in the model in the model of pure wave mechanics, even sequences of measurement records that are very unlikely on the standard quantum mechanical probabilities, part of the surplus structure problem is that its surplus structure makes it *too easy* to find one's experience in the model of the pure wave mechanics.

Consider a physical theory that simply stipulates that every physically possible sequence of measurement records is actual. Since, by stipulation, one can find any sequence of measurement records in the model, even that theory in some sense counts as empirically faithful. But this sort of empirical faithfulness is clearly too weak to count as a serious variety of empirical adequacy. If empirical faithfulness consists in nothing more than being able to find representations of one's measurement records in the model described by the theory, then it is not a significant empirical virtue.

Everett took pure wave mechanics to do more than just provide a representation of one's measurement records. In particular, he believed that it explained why one would not ordinarily notice other relative records, why alternative relative states do not represent surplus structure, and a sense in which the theory allows one to recapture the statistical predictions of the standard collapse formulation of quantum mechanics. Each of these points is part of what it means to say that pure wave mechanics is empirically faithful.

4.2 Pure wave mechanics predicts that one would not ordinarily notice surplus structure

It was important to Everett to explain why one would not ordinarily notice alternative relative measurement records. In his reply to DeWitt's letter, he argued that pure wave 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" Barrett and Byrne (eds) (2012, 254).

There are two distinct arguments that Everett seems to have had in mind. Each requires one to add a few details to complete. The second was clearly his main argument.

First, one would only notice macroscopic branching if one had access to records of macroscopic branching events, but one should expect such records to be rare. Measurements that would show that there are branches where macroscopic measurement apparata have different measurement records for the same measurement would require one to perform something akin to a Wigner's Friend measurement on a macroscopic system. And as Everett indicated in his characterization the story as "extremely hypothetical," this would be extremely difficult. So, one should not expect to find reliable relative measurement records of branches corresponding to alternative macroscopic measurement records.[19]

But again, while Everett implicitly assumes the noninterference of relative measurement records in the idealized examples of repeated measurement he considers,[20] this does not mean that his model of measurement in anyway depends upon decoherence considerations or even the de facto noninterference of measurement records. As characterized, an ideal observer need be neither macroscopic nor well-coupled to her environment generally; rather, an ideal observer need only be such that her memory records become well-correlated with the property being measured of her object system. Consequently, he never describes his idealized observers as being subject to environmental decoherence. Rather, just as in his version of the Wigner's Friend story, an idealized observer only becomes correlated to the system she measures, and

[19]See Albert (1986) and Albert and Barrett (1995) for further discussion of what it would take to detect a macroscopically distinct Everett branch.

[20]See, for example, Everett (1957, 186–9).

hence, would exhibit interference effects in a Wigner's Friend experiment that show that she is in fact in the entangled superposition predicted by the linear dynamics if one were ever able to perform such an experiment. And Everett consistently held that there was nothing in principle preventing one from doing so.

Second, as Everett explained in the first of his *deductions* of subjective appearances for idealized observers, it follows directly from the linearity of the dynamics of pure wave mechanics that it would appear to an ideal agent that she had fully determinate measurement results. A dispositional version of the argument goes as follows. If we ask an ideal observer F in a post-measurement state $\psi[\text{“}k\text{”}]_F\phi_S^k$ whether she has a determinate measurement record for her measurement of system S she will say “Yes” because she in fact has the determinate record k. So, it follows from the linearity of the dynamics, if we ask F whether she has a determinate measurement result in state

$$\sum_i a_i \psi[\text{“}i\text{”}]_F\phi_S^i \tag{4.1}$$

she will also say “Yes”. While this is an entangled superposition of F having recorded incompatible results, she would report that she had a determinate measurement record in every element of the superposition, so she will be in an eigenstate of saying “Yes” in the superposed state and hence have both the relative and the absolute property of reporting that she has a determinate outcome even when she is in fact in an entangled superposition of having recorded incompatible results. So, if F believes what she reports, she will believe that he has a determinate and otherwise perfectly ordinary measurement outcome, which, in turn, is incompatible with her noticing any surplus branch structure.

This is a more subtle explanation for why one would not notice surplus structure than the first. One way to put the point is that pure wave mechanics predicts that an observer, when herself treated as a quantum mechanical system, would be subject to the *illusion* that she is correctly described by the state of a single branch. As Everett argues, it similarly follows from the linear dynamics and the properties of an idealized observer that his measurement result will be repeatable and that it will agree with the results of other idealized observers.[21]

Everett's deductions of subjective appearances turn on the linearity of the wave equation. Following his exchange with DeWitt, Everett added a footnote to the proof of the published version of the short thesis that echoes part of his reply to DeWitt:

> It is unnecessary to suppose that all but one [element of the post-measurement superposition] are somehow destroyed, since all the separate elements of a superposition individually obey the wave equation with complete indifference to the presence or absence . . . of any other elements. This total lack of effect of one branch on another also implies that no observer will ever be aware of any "splitting" process. (1957, 189)[22]

The thought here is that together the deductions provide a rich explanation for why the linearity of the wave equation implies that an ideal observer will not be aware of alternative relative records. Since the dynamics is linear, one can think of each element of the superposition as independently obeying the wave equation with the resultant absolute state of the composite system determined by the superposition of the individual evolutions.

Note that Everett's main argument for the lack of effect of one branch on another had nothing whatsoever to do with decoherence considerations nor was he somehow insisting that there can be no interference effects between post-measurement branches. As he explained at the Xavier University conference in October 1962, "Yes, it is a consequence of the superposition

[21]These are three of what Albert calls the suggestive properties of the bare theory. Albert's bare theory is pure wave mechanics without an interpretational distinction between absolute and relative states. See Albert (1992) and Barrett (1999).

[22]See Everett's letter in Barrett and Byrne (eds) (2011, 254–5) for this part of his reply to DeWitt.

principle that each separate element of the superposition will obey the same laws independent of the presence or absence of one another. Hence, why insist on having a certain selection of one of the elements as being real and all the others somehow mysteriously vanishing?" Barrett and Byrne (eds) (2011, 274). And it was essential to his understanding of these elements being real that there was always the possibility of observing interference effects between them.

4.3 The surplus structure of pure wave mechanics isn't surplus.

While sometimes difficult to detect, Everett insisted that the surplus structure of pure wave mechanics is in principle detectable and hence is not surplus structure at all. Further, since all branches, in any basis, are in principle detectable, all branches in any decomposition of the state of a composite system are real in Everett's operational sense of real. As he put the point in the long thesis:

> 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)

While one should not typically expect to find a relative record of the relative macroscopic properties of a system on another branch, the operational existence of the other branch is required by the fact that it is in principle possible to detect by way of a Wigner's Friend type interference measurement. And since it is in principle possible to detect, such alternative branches do not represent surplus structure.[23]

[23]For proponents of the decohering-worlds interpretation, decoherence is a process by which branches on a decohering decomposition of the quantum state come to evolve in-

Pure wave mechanics then allows one, at least in principle, to have empirical evidence for the existence of the alternative sequences of measurement records on other branches. Indeed, since every orthogonal basis determines a set of branches, from the perspective of pure wave mechanics, any experiment that illustrates quantum interference provides empirical evidence for the existence of alternative branches.

From the beginning, Everett sought a formulation of quantum mechanics that would resolve the measurement problem by allowing one to tell the Wigner's Friend story completely and consistently, something that he believed neither the standard collapse theory nor the Copenhagen formulation could do. Since he was able to explain the sense in which B's absolute state attribution to $A+S$ is correct and the sense in which A nevertheless has fully determinate relative records in his version of the Wigner Friend story without any appeal to decoherence, decoherence considerations are not required to solve the measurement problem as Everett understood it.

4.4 One can find the standard quantum statistics in typical relative sequences of measurement records

Everett did not solve the probability problem by finding probabilities in pure wave mechanics. Indeed, he took it to be fundamental to his approach that there were no probabilities in the theory and he repeatedly insisted as much.[24] Rather, what it means for pure wave mechanics to be empirically faithful

dependently of each other. And it is this independence, at some level of description, that justifies treating each component as a real, emergent physical world. See, for example, Wallace (2010a, 62–5). Everett himself, however, argued the other direction. Since the linear dynamics requires that all branches are at least in principle detectable, pure wave mechanics requires that all branches are equal real. And again, this does not mean that only branches in some physically preferred basis are real. There is no preferred basis. Rather, it means that every branch in every decomposition of a composite system is real in the only sense of real that he understood.

[24] See, for example, Everett's discussions of the typicality measure (1956, 127) and (1957, 193). The title of the April 1956 draft of his long thesis was "Wave Mechanics Without Probability." See Barrett and Byrne (2011, 4) for the evolution of titles.

with respect to our statistical experience is that a typical relative sequence of measurement records will exhibit the standard quantum statistics, where the measure of typicality is determined by the norm squared of the amplitude associated with each relative state.[25] This means that while the probability of each occurrent relative state is one, if an observer supposes that her experience is faithfully represented by a *typical* relative sequence of measurements records, then she will expect to observe the standard statistical predictions of quantum mechanics.

Here again we face the question of what should properly count as part of the theory itself. On a strict reading, even supplemented with the distinction between absolute and relative states, pure wave mechanics theory says nothing whatsoever about the norm-squared-amplitude measure of typicality nor about how of why it should guide one's statistical expectations. Rather, the most basic statement of pure wave mechanics just provides a complex-valued function over relative states for the various constituent subsystems for each decomposition of the absolute state of the composite system. One must assume that one's actual experience will be represented by the sequence of records in a typical branch, in the norm-squared-amplitude sense of typical, in order to get the standard quantum expectations. An assumption that, if made, would clearly constitute a significant explanatory addition to the relative state formulation of pure wave mechanics.

For his part, Everett never explicitly makes this assumption. Rather, he explicitly looks for and finds a well-behaved measure of typicality over relative states whose value is fully determined by the model of pure wave mechanics. Then he argues that most relative sequences of measurement records, in the sense of *most* given by this measure, will exhibit the standard quantum statistics. And it is left to the reader to notice that if one assumes that one's relative sequence of records is typical in this sense, then it should

[25]See Everett (1956, 124–30) for his most detailed discussion of this point. See also the discussion of the limiting suggestive properties of the bare theory in Albert (1992) and Barrett (1999).

be expected to exhibit the standard quantum statistics.

Everett explained how he intended to get the standard quantum expectations for idealized observers:

> [w]e shall deduce the probabilistic assertions of Process 1 [the standard random collapse dynamics] as *subjective* appearances to such observers, thus placing the theory in correspondence with experience. (1956, 77)

His deduction in this case amounted to arguing that most relative sequences of measurement records, which he took to represent the subjective experiences of observers, exhibit the standard quantum statistics. Since every physically possible sequence of measurement results is represented by some relative sequence of records in the final absolute state, he needed a measure of typicality over relative sequences of records in order to say what he meant by most.

As Everett put it:

> In order to establish quantitative results, we must put some sort of measure (weighting) on the elements of a final superposition. This is necessary to be able to make assertions which will hold for almost all of the observers described by elements of a superposition. In order to make quantitative statements about the relative frequencies of the different possible results of observation which are recorded in the memory of a typical observer we must have a method of selecting a *typical* observer. . . . Let us therefore consider the search for a general scheme for assigning a measure to the elements of a superposition of orthogonal states $\sum a_i \phi_i$. (1956, 123–4)

And he imposed three constraints on the search. First, the measure must be a positive function over the elements of the superposition for each possible orthogonal expansion of the state. While he was clear that his typicality measure was not a probability, he wanted it to satisfy the properties of a probability measure over the orthogonal elements. Second, the measure must depend only on the magnitude, not the phase, of the coefficients associated with the terms describing the elements on the particular expansion. There are two parts to this condition. That the measure must be a function of the coefficients on the elements is natural enough insofar as one might argue that it is only the coefficients that provide a quantitative difference between the elements of the superposition. But that it should not involve the phase of the coefficients is less clear. What Everett reported as his motivation was that since one can only determine the values the coefficients up to an arbitrary phase factor, in order to avoid ambiguities, the measure must be a function of the magnitudes of the coefficients alone. That said, since he was well aware that the relative phases of the coefficients on different elements of a superposition may have direct empirical consequences, this part of the condition is at least a bit ad hoc. He knows what measure he wants, and he knows it has nothing to do with the phase of the coefficients. Third, and finally, he stipulated that the measures associated with different expansions of the absolute state must be related in such a way that the measure assigned to a term in a coarser-grained expansion that represents a linear combination of individual terms in a finer-grained expansion be equal to the sum of the measures assigned to the individual terms by the finer-grained measure. This last condition represents a constraint on how the measures associated with different expansions of the state are related.[26]

In the version of his long thesis that he edited for inclusion in the 1973 DeWitt and Graham anthology, Everett concluded that

> we have shown that the only choice of measure consistent with

[26]Note that Everett assumes that the decomposition of the absolute state is in terms of *orthogonal* elements. Note further that the third condition only makes sense if there is *no canonical decomposition* of the absolute state of the composite system. The general scheme then allows one to assign a measure over any orthogonal decomposition of the state whatsoever, not just a scheme for assigning a measure to the relative states of macroscopic systems or to decohering relative states or to the relative states of a rational observer.

> our additivity requirement is the square amplitude measure, apart from an arbitrary multiplicative constant which may be fixed, if desired, by normalization requirements. (The requirement that the total measure be unity implies that this constant is 1.) ... The situation here is fully analogous to that of classical statistical mechanics, where one puts a measure on trajectories of systems in the phase space by placing a measure on the phase space itself, and then making assertions which hold for "almost all" trajectories (such as ergodicity, quasi-ergodicity, etc). (1956, 125)

And he continued, "Having deduced that there is a unique measure which will satisfy our requirements, the square-amplitude measure, we continue our deduction" (1956, 126).[27]

There is reason to believe that Everett himself took the next step in his deduction to be his most significant contribution to understanding quantum mechanics.[28] It was this step that Everett took to provide the deduction of the standard quantum statistical predictions as the subjective experience of an idealized observer in pure wave mechanics. In particular, he argued that, in the limit as an infinite number of measurement are performed, most relative sequences measurement records *in the norm-squared-amplitude measure of most* are randomly distributed with the standard quantum relative frequencies.

Filling in a few details in the description, the following is the argument for a particular concrete case.[29] Consider a system T consisting of an observer F and an infinite set of systems $S_1, S_2, S_3, \ldots, S_n, \ldots$, each of which is initially

[27]The original version of the long version of Everett's thesis reads more modestly "We choose for this measure the square amplitude of the coefficients of the superposition, a choice which we shall subsequently see is not as arbitrary as it appears". Of course, this is enough, since all he needs for the faithfulness of the theory is to find a suitable measure of typicality that is determined by the model of pure wave mechanics.

[28]See, for example, the 1962 exchange between Everett and Podolski at the Xavier conference (Barrett and Byrne (eds) 2011, 274–5).

[29]See Barrett (1999) for a full reconstruction of the argument.

in the state $\alpha|\uparrow\rangle_{S_n} + \beta|\downarrow\rangle_{S_n}$, where $|\uparrow\rangle_{S_n}$ and $|\downarrow\rangle_{S_n}$ are x-spin eigenstates and α and β are non-zero. Suppose F makes an x-spin measurement on each S_n in turn. The state of F and the first system before the first measurement is

$$|r\rangle_F(\alpha|\uparrow\rangle_{S_1} + \beta|\downarrow\rangle_{S_1}), \tag{4.2}$$

After the first measurement, the composite system is in the entangled state

$$\alpha|\uparrow\rangle_F|\uparrow\rangle_{S_1} + \beta|\downarrow\rangle_F|\downarrow\rangle_{S_1}. \tag{4.3}$$

And after the second measurement, F and the first two object systems are in the entangled state

$$\begin{aligned} \alpha^2|\uparrow,\uparrow\rangle_F|\uparrow\rangle_{S_1}|\uparrow\rangle_{S_2} \quad &+ \quad \alpha\beta|\uparrow,\downarrow\rangle_F|\uparrow\rangle_{S_1}|\downarrow\rangle_{S_2} \\ &+ \quad \beta\alpha|\downarrow,\uparrow\rangle_F|\downarrow\rangle_{S_1}|\uparrow\rangle_{S_2} \\ &+ \quad \beta^2|\downarrow,\downarrow\rangle_F|\downarrow\rangle_{S_1}|\downarrow\rangle_{S_2} \end{aligned} \tag{4.4}$$

And after the first n measurements the entangled state of F and the first n object systems in the determinate record basis is has 2^n terms, each describing one of the possible sequences of outcomes for the first n measurement results and each associated with an amplitude. While it is not true that most sequences of records in such states will exhibit the standard quantum statistics in a simple counting sense of most, one can show that in the limit most sequences will exhibit the standard quantum statistics in the norm-squared-amplitude measure of most. Further, one can show that most sequences of records with appear to be random on standard criteria.[30]

As Everett put the point:

> Thus, in particular, if we consider the sequences to become longer and longer (more and more observations performed) *each* memory

[30] See Barrett (1999) for a discussion of the range of criteria of randomness for which this is true.

> sequence of the final superposition will satisfy any given criterion for a randomly generated sequence, generated by the independent probabilities [$|\alpha|^2$ and $|\beta|^2$], except for a set of total measure which tends toward zero as the number of observations becomes unlimited. Hence all averages of functions over *any* memory sequence, including the special case of frequencies, can be computed from the probabilities [$|\alpha|^2$ and $|\beta|^2$], except for a set of memory sequences of measure zero. We have therefore shown that the statistical assertions of [the collapse process] will appear to be valid to *almost all* observers described by separate elements of the superposition ... in the limit as the number of observations goes to infinity. (1956, 127)

And that completes the deduction of the standard quantum statistical predictions as the subjective experiences of idealized observers in pure wave mechanics.

Everett argued that the relative state formulation of pure wave mechanics is empirically faithful over the standard quantum statistics not by finding probabilities in the theory but by finding a measure in the model of pure wave mechanics such that most relative sequences of records exhibit the standard quantum statistics. Then it is left to the reader to notice that if a relative observer were to believe that her relative records were typical in the norm-squared-amplitude sense, she should expect her relative records to exhibit the standard quantum statistics.[31]

[31] As discussed below, Everett's strategy for finding the standard quantum statistics in the theory was quite different from the one employed by the Saunders-Wallace-Deutsch many-worlds interpretation. Following a suggestion by David Deutsch (1999), probabilities on the Saunders-Wallace-Deutsch many-worlds view are taken to be recovered by arguing that in a universe described by pure wave mechanics a rational agent would act as if the Born rule (rule 4b) obtained. See Saunders et al. (eds) (2010) and Wallace (2012). While Everett was always looking for applications of game theory and decision theory, a lifelong passion, he never argued for this.

5 The argument so far

Gathering the two main threads of the argument, pure wave mechanics is empirically faithful since (1) one can find an observer's determinate measurement records as the relative records of an idealized observer in the model of the theory and (2) can find a typicality measure over relative states corresponding in the model of pure wave mechanics such that a typical relative sequence of measurement records in that measure will exhibit the standard quantum statistics. The first point is Everett's resolution of the determinate record problem, and the second his resolution of the probability problem. If one associates one's experience with relative records and if one expects one's relative sequence of records to be typical in the norm-squared-amplitude sense, then one should expect one's experience that agrees with the standard statistical predictions of quantum mechanics where it makes coherent predictions. And where it doesn't, as in the Wigner's Friend story, one should expect to see evidence that the linear dynamics always correctly describes the evolution of every physical system whatsoever.

On this view, pure wave mechanics explains why one would not typically observe other branches. But it also predicts that other branches are in principle observable, and hence do not represent surplus structure. Regarding the sure thing problem, Everett simply agreed that every relative state under every decomposition of the absolute state does in fact obtain. He explicitly held that there are no probabilities in the model of pure wave mechanics. Rather, one can find a typicality measure associated with relative states such that a typical relative sequence of measurement records in the measure will exhibit the standard quantum statistics. Insofar as one can find both determinate records and the standard quantum statistics in pure wave mechanics, it is fair to say that Everett provided perfectly clear solutions to both the determinate record and probability problems as he understood them.

6 Contrasting explanations

Having reviewed his main line of argument, we are now in a position to compare Everett's explanations against those offered by recent many-world proponents.

The central idea in a many-worlds interpretation is to designate some set, or sets, of branches of the global absolute state as corresponding to real physical worlds then to explain one's experience in terms of the properties of such privileged branches The physically privileged branches might be stipulated to be those where measurement records are determinate or where a specified decoherence condition is satisfied or that exhibit an appropriate quasiclassical sort of stable diachronic identity. Whatever the condition, these branches are then taken to represent the worlds, or emergent worlds, or approximate emergent worlds, or elements that observers inhabit and hence explain their experience.

For his part, Everett individuated branches on the basis of relative states, and he did not designate any particular set, or sets, of branches to be in any way physically privileged. Indeed, as we have seen, rather than take *some* branches to be somehow physically privileged, he took *all* branches to be operationally real since, regardless of how they might be individuated, all branches are in principle physically detectable. And since all branches in all decompositions are real in the only sense of real that Everett understood, he did not require a preferred basis or decoherence considerations to single out any particular decomposition as somehow physically preferred at the expense of others. It was enough, rather, that he be able to find the experiences of modeled observers within the full set of operationally real branches.

While Everett himself did not do so, one might add a condition to the theory designed to identify which branches correspond to basic or emergent worlds. One motivation for doing so would be if one is unsatisfied with Everett's account of an observer's experience and requires something stronger. One might, for example, insist that one only has a satisfactory account of an observer's determinate experience if the real physical world that one in fact inhabits can be expected to be quasiclassical. In any case, if one does choose to take a particular set of branches as somehow physically privileged, then one should be clear concerning why one is doing so and precisely how one's auxiliary metaphysical commitments accomplish one's explanatory aims.

DeWitt took worlds to be the basic physical entities described by Everett's theory. And he took what worlds there are and the states of those worlds to be determined by a privileged decomposition of the global absolute state that makes all measurement records, whatever they may be, determinate in each world. In exchange for such an ad hoc specification of what branches correspond to physically real worlds, one directly explains why all observers experience determinate measurement records.[32]

David Wallace, in contrast, takes worlds to be physically real but emergent, rather than basic, entities. But if worlds are emergent entities, one immediately faces the puzzle of what it is precisely that they emerge from and how. The thought is that one is clear concerning the nature of emergent entities only insofar as one is clear about what the more basic entities are and how the emergent entities and their properties supervene on the properties of the more basic entities.

The guiding analogy in Wallace's argument is that just as one might understand tigers as emergent patterns, or structures, "*within* the states of a microphysical theory" like classical mechanics, one should understand worlds as emergent patterns, or structures, *within* the quantum state (2010a, 56). More specifically, worlds are to be understood as physically real, local, contingently emergent entities that are identified with approximate substructures of the quantum state, or as Wallace puts it, "mutually dynamically isolated structures instantiated within the quantum state, which are structurally and dynamically 'quasiclassical' " (2010a, 70). As a slight tuning, one would, of

[32]See the discussions of DeWitt's splitting worlds formulation of quantum mechanics in Barrett (1999) and (2014).

course, expect emergent worlds so characterized to be more or less isolated, and hence better or worse individuated, depending on the properties one seeks to describe of the systems and the degree of decoherence they in fact exhibit.

Along these lines, one might simply stipulate the quantum state to be metaphysically basic. Such a move is suggested by Wallace's instance on the completeness of Everettian quantum mechanics. It is also suggested by his expressed view that the quantum state alone fully determines one's ontological commitments:

> Everettian quantum mechanics reads the quantum state literally, as itself standing *directly* for a part of the ontology of the theory. To every quantum state corresponds a different concrete way the world is, and the quantum state *completely* specifies the ontology. (2012, 295)

But saying that one should take the quantum state literally and explaining that this means that it completely specifies one's ontology does not in fact do much to specify one's ontology. One still needs to know how to understand the quantum state.

There are a number of ways one might seek to clarify matters. One might take the quantum state to directly describe a basic physical entity on which worlds and their properties supervene. While this is ultimately not Wallace's considered view, something like this seems to be suggested when he explains that, according to the Everett interpretation, "[a]t the most fundamental level, the quantum state is all there is" and that, in consequence, it is a theory "about the structure and evolution of the quantum state in the same way as classical field theory is about the structure and evolution of the fields" (2010a, 69). Alternatively, and this is Wallace's considered view, one might take the quantum state to be descriptive of the state of a physical system, then take what the physical system consists in to be determined by metaphysical commitments associated with one's choice of an auxiliary physical theory. [33]

On this view, there is a clear sense in which Everettian quantum mechanics alone *completely fails* to specify the basic physical ontology. But, more importantly, if one does not know what the quantum state describes, the properties and degrees of freedom exhibited by those entities, and how they interact with each other, then neither the quantum state nor how it evolves nor the physical conditions under which one should expect the emergence of decohering worlds are well-defined.

Consider two relatively simple ways that one's auxiliary theoretical commitments might specify one's basic physical ontology. In the context of a particle theory and its corresponding ontology, Wallace takes the quantum state to describe particles; and, in the context of a field theory and its corresponding ontology, he takes the quantum state to describe the field properties of spacetime regions (2012, 298–302). If one wants a clear characterization of emergent worlds, this difference matters. Specifically, if one opts for particles as one's fundamental entities, then one is committed to tell a story about how emergent worlds and their states supervene on the properties of particles, which, given the difference in the possessed properties of the basic entities involved and the dynamical laws governing them, one might expect to differ significantly from a story about how emergent worlds and their states supervene on the field properties of spacetime regions.

Indeed, whether one can understand there being emergent worlds at all on decoherence considerations depends on one's choice of auxiliary theory or other basic auxiliary assumptions. In some cases, an auxiliary theory may not provide suitable interactions between its basic entities for decoherence to produce emergent entities with world-like features; in others, the basic entities described by the theory may themselves be unsuitable for telling an emergent-worlds story.

[33] More specifically, Wallace has explained in correspondence that he takes the quantum state to be descriptive of the "microreality" and that he takes what the microreality actually is, physically, to be "very theory-dependent."

Given its impressive track-record of empirical and explanatory success, one might take general relativity to be a good candidate for an auxiliary physical theory that characterizes at least some of one's basic ontological commitments. On the understanding of spacetime provided by general relativity, emergent worlds that correspond to different matter distributions, as alternative emergent worlds typically would, would also correspond to different spacetime structures. But if spacetime structure is itself co-emergent with worlds, then one clearly cannot specify the basic ontology on which emergent worlds supervene by appealing to the location of particles or to the field properties of spacetime regions. Rather, one would need to find something else on which emergent worlds might supervene, then one would need to find a decoherence story to tell for their emergence in terms of that something else.

While Wallace recognizes that we do not have a satisfactory theory of quantum gravity, he nevertheless believes that there will be no special problem making sense of such a theory in the context of a many-worlds formulation of quantum mechanics and he applies his decoherence account of emergent quasiclassical worlds to a number of examples drawn from general relativity.[34] Further, Wallace expects that "the true quantum state is a superposition of geometries, but that matter and geometry as fairly entangled, so that with respect to a macroscopically definite geometry, facts about the matter distribution are fairly definite too (2012, 312). But without an appropriate auxiliary theory, it is entirely unclear whether it will in fact be possible to tell a story like that, and, if it is possible, how it might go.[35]

While it is unclear how one might even begin to tell such a story, that's

[34]Consider, for example, his application of his formulation of quantum mechanics to field theories that he characterizes as including general relativity as a special case (2012, 298), to black-hole dynamics (2012, 400–01), and to closed timeline worlds trajectories in spacetimes with nontrivial global topologies (2012, 401–19).

[35]One of the reasons that Wallace's hunch is particularly puzzling is that alternative geometries, at least as represented by alternative spacetime manifolds, do not form a linear space where one might represent linear superpositions.

not the important point. The important point is that pure wave mechanics fails to provide any account for the emergence of quasiclassical worlds by way of decoherence considerations whatsoever without one first adopting an auxiliary theory that specifies the basic entities and precisely how they interact with each other. Then whether one can tell the decoherence story depends on the details of the auxiliary theory. So whether one can tell an emergent-worlds story at all, one's basic ontological commitments and how one tells the story if one can, the role decoherence considerations play in the story, one's understanding of what it means to have alternative emergent worlds, and the explanatory role that they might arguably play in accounting for quantum experience all depend on one's choice of the auxiliary theory and how one understands it. When one chooses what entities to take as the basic things described by the quantum state, one is making a choice concerning what entities might be understood as emergent and how they might be understood as emergent. Without a specific choice, one simply has no story to tell.

The moral is that showing how decoherence-induced emergent worlds are possible requires auxiliary assumptions that go well beyond a commitment to pure wave mechanics. Among the auxiliary assumptions required for a decoherence account of emergent worlds are assumptions concerning ones basic ontology. This might involve the many-world realist specifying a commitment to particles, fields, spacetime geometries, or something else. Then one needs to know how the basic entities, whatever they may be, behave. This might involve specifying a particular Hamiltonian or Lagrangian described in terms of the basic entities. It is only in the context of such assumptions that one can begin to tell a story in pure wave mechanics for the existence of quasiclassical worlds as emergent entities in terms of possible basic entities and their dynamical properties.

Such auxiliary assumptions might be given by one's commitment to an auxiliary physical theory, the theory to which one seeks to apply pure wave mechanics. If one actually believes the auxiliary theory and if it in fact yields a compelling account of decoherence-induced emergent quasiclassical worlds, then the many-worlds realist has an explanation for why he believes in such worlds. But if the many-worlds realist takes the auxiliary theory are merely provisional, he just has an account of how such worlds are possible on a particular choice of auxiliary theory.

In any case, if the many-worlds realist also wants theory that makes statistical predictions, he must make further auxiliary assumptions concerning how to get statistical predictions from the quantum-mechanical amplitudes pure wave mechanics would associate with alternative decohering worlds. Then one would want to make sure that one's full statistical account is compatible with the view that all of the emergent worlds, on every level of description, are equally actual.

One might imagine that the auxiliary assumptions a many-worlds realist needs in order to provide a decoherence account of experience in pure wave mechanics are no more objectionable than a Bohmian's auxiliary commitments to taking particles with always-determinate positions as basic entities and supplementing pure wave mechanics with a dynamics that describes their motion. This may well be right, but it is also a clear methodological virtue that the Bohmian does not pretend to take pure wave mechanics to be complete. insofar as she seeks to include the auxiliary assumptions required for her account of quantum experience in the specification of her physical theory, if the auxiliary assumptions are found wanting on physical grounds, the whole theory gets tuned. While there is no canonical way to individuate theories, including the auxiliary assumptions required for a theory's basic account of experience in the specification of the theory has the virtue of increased clarity and provides a more even playing field for the evaluation of competing theories resolutions to the quantum measurement problem.

Everett also needed an auxiliary theory to describe measurement interactions in the model of pure wave mechanics, but, on his account, any auxiliary theory that allows for a modeled observer's record to become correlated with a property of her object system provides fully determinate relative measurement records. In particular, he did not require an auxiliary theory that provided a decoherence-induced emergent-worlds story. Further, Everett's weaker explanatory demands made the probability problem easier for him to address.

While Everett was content just showing that one can find the standard quantum statistics associated with measure-typical relative sequences of records in the model of pure wave mechanics, a many-worlds proponent would almost certainly want more than this. In particular, if she could get it, a many-worlds realist would presumably want to explain why an observer in an emergent world should expect her measurement results to exhibit the standard quantum statistics. But, since the theory is fully deterministic and since it is difficult to make sense of the right sort of epistemic uncertainty and since there are always some emergent worlds that exhibit the standard quantum statistics and some that do not, it is difficult to provide such an explanation.[36] As a fallback strategy, many-worlds proponents have sought to explain why, if pure wave mechanics is in fact true, a rational physical agent would make decisions precisely as if the norm-squared of quantum amplitudes represented probabilities.[37] The difference between Everett's explanatory demands and the many-worlds proponents' is perhaps most clearly manifest in the difference in the difficulty in providing the relevant explanations. It requires significant subtlety, if it is possible at all, to provide a compelling explanation for why a rational agent should care to act one way rather than another when she knows that every physically possible outcome of her action will certainly be realized in at least some emergent worlds.[38]

[36]See Kent (2010) and Albert (2010).

[37]For examples, see Deutsch (1999), Greaves and Myrvold (2010), Wallace (2010b).

[38]See Wallace's (2010b) discussions of the many-worlds decision-theoretic account of quantum expectations and his replies to a number of objections and Kent's (2010) and Albert's (2010) arguments that there is no satisfactory decision-theoretic account of probability in Everett.

On the other hand, Everett in fact described a clear sense in which a typical relative observer, in his sense of typical, would be associated with relative records that exhibit the standard quantum statistics in the model of pure wave mechanics.

I take it to be uncontentious that if one cannot support Everett explanations, then, whatever else may be the case, one is not endorsing pure wave mechanics as he understood it. To reconcile a many-worlds interpretation with Everett's account, then, would require at least the following. Since Everett took being able to address the Wigner's friend story to be a requirement for solving the measurement problem and since he was clear concerning how the story should be told in the context of pure wave mechanics, one would need to explain how a many-worlds telling of the Wigner's friend story meshes with Everett's, which would involve explaining the sense in which all of the branches on all decompositions of the global state are operationally real. One would then need to show how the other explanations that Everett provided for the four steps described above mesh with one's favored many-worlds interpretation and one's account of probability in particular. And one would need to be clear along the way regarding the role played by one's auxiliary physical theory.

7 Empirical coherence and relevance

Given Everett's relatively weak account of experience, one might wonder whether it is even the sort of theory that one might have empirical evidence for accepting. There are, of course, preconditions for the possibility of empirical inquiry and, salient among these, one must be able to perform experiments and reliably record and access these records in order to assess the empirical adequacy of one's theory. If one takes one's theory to be descriptive of the physical world, then this means that it must describe a world that allows for such experiments and reliable access to their results. Along these lines, one might take a theory to be *empirically coherent* if and only if one can explain how one might have reliable empirical evidence for accepting it if it were in fact true.

I once argued that the bare theory, a version of pure wave mechanics, was not empirically coherent.[39] The argument, in short, was that if the bare theory were true, then one would typically not be able to distinguish between being in an entangled superposition of recording mutually incompatible results and a separable state with a determinate measurement record. I also argued that Bell's Everett(?) theory, a version of the many-worlds formulation of pure wave mechanics, was not empirically coherent since, if it were true, one would not have reliable epistemic access to one's past measurement records. Similar worries concerning the testability of more recent versions of the many-worlds interpretation are echoed in a number of discussions.[40]

While the bare theory interpretation of pure wave mechanics is not empirically coherent and while empirical coherence poses a serious problem for Bell's Everett(?) theory and many-worlds formulations of pure wave mechanics more generally, it is worth considering whether there is any clear sense in which one might have empirical evidence for accepting pure wave mechanics as Everett understood it. It seems to me that there are two very weak senses in which one might. First, one might have evidence for the *empirical faithfulness* of pure wave mechanics. This meshes well with his discussion of empirical faithfulness as the theories primary empirical virtue. Second, one might have evidence for the reliability of the predictions one gets if one uses Everett's typicality measure to set one's expectations. This might have appealed to some of his operational commitments. Note, however, that both of these senses in which the theory might be tested are much weaker than

[39]See Barrett (1996 and 1999) for discussions of empirical coherence and, more specifically, the empirical coherence the bare theory.

[40]See Saunders (2010, 17, 28–31) and Greaves and Myrvold (2010) for discussions of the worry, and for explanations concerning why it need not be a serious worry for the many-worlds proponent. See Kent (2010) for a discussion of why accounts like Greaves and Myrvold's (2010) are inadequate.

requiring that the theory be empirically coherent.

For his part, Everett clearly took there to be no special problem in evaluating the empirical virtues of pure wave mechanics. And there is, indeed, a direct sense in which one might have evidence for the empirical faithfulness of pure wave mechanics. Check to see whether the statistics of one's actual records are typical among relative sequences of measurement records in Everett's sense of typical. If they are, then one has evidence that pure wave mechanics is in fact empirically faithful.[41] But this is just to put an old argument in a new way. Pure wave mechanics is empirically faithful with respect to one's statistical experience if one can find a typicality measure in the model of the theory according to which our experience is typical. Since that is precisely what Everett found, it is unsurprising that our empirical evidence supports the empirical faithfulness of the theory.

The weakness of faithfulness as an empirical standard is exhibited by the fact that pure wave mechanics can be empirical faithful without telling us what it is about the physical world that makes it appropriate to expect one's relative sequence of records to be typical in the norm-squared-amplitude, or any other, sense. More strikingly, pure wave mechanics can be empirically faithful without making any statistical predictions whatsoever. These issues are closely related. We will briefly discuss each in turn.

If one tries to take pure wave mechanics as closely descriptive of the physical world, one immediately encounters a problem of relevance. The relevance problem concerns why an observer's expectations of relative sequences of records should be determined by Everett's norm-squared-amplitude measure of typicality. To call this a measure of *typicality* suggests that a sample

[41]In terms of Everett's model of pure wave mechanics, some relative observers, in particular those with typical measurement records, would have evidence for the empirical faithfulness of pure wave mechanics. Of course, a relative observer whose experience does not exhibit the standard quantum statistics would not have evidence for the empirical faithfulness of pure wave mechanics. And the model provides no good reason to imagine that the first sort of observer is in any standard sense more likely than the second among real physical observers.

relative state is somehow selected with respect to the measure. It might then appear a small thing to assume that one should expect one's relative sequence of measurement records to be typical. But it would follow from this that it is also *probable* that one's relative sequence of measurements records exhibit the standard quantum statistics, but that cannot be right since as every possible relative sequence is fully realized.

Insofar as a probability is a measure over possibilities where precisely one is realized and insofar as all possibilities are realized in pure wave mechanics, there can be no probabilities associated with alternative relative sequences of measurement records. Similarly, any understanding of typicality that somehow involves the selection of a typical relative sequence of records rather than an atypical sequence of records is incompatible with pure wave mechanics since the theory describes no such selection. Neither can the typicality measure represent an expectation of the standard quantum statistics obtaining for one's actual relative sequence of measurement records since all such sequences are equally actual in the model. Insofar as the theory describes anything happening, it describes everything happening, so there is no particular sequence of measurement records that might be taken as *probable*, *typical* or *expected* in any standard sense of the terms.[42]

This has immediate implications for the empirical confirmation of the theory. In particular, if one takes the empirical confirmation of pure wave mechanics to require one to have evidence that it assigns the right probabilities to relative measurement records, one cannot confirm the theory for the simple reason that it does not assign nontrivial probabilities to anything. This, of course, is closely related to the fact that pure wave mechanics does

[42]Note that contrary to what DeWitt and Graham once argued (see for example, DeWitt and Graham (eds) 1973), the problem is not that one would be better off with a notion of typical that involves counting up relative states. Everett himself took DeWitt and Graham's argument to be "bullshit." See Barrett and Byrne (2012, 364–6) for scans of Everett's handwritten marginal notes. The central problem with understanding Everett's measure as providing an expectation, rather, is that there is no sense whatsoever in which the theory selects a typical relative state, expected or not.

not make statistical predictions in any standard sense. There is nothing about pure wave mechanics that requires one to set one's expectations to accord with Everett's typicality measure. But, even if there were, it would be difficult to understand what such expectations might concern if one also took all relative measurement records to be somehow descriptive of actual measurement records.

The upshot is that if one insists on getting standard statistical predictions out of the theory, then one must add something to the theory that connects Everett's typicality measure to probabilities. And if one wants to understand these as probabilities of relative records in fact being realized, then one cannot interpret the theory as describing a world where all possible relative records are in fact realized.

One option would be simply to set one's credences according to Everett's typicality measure, then take the resulting theory to provide a predictive algorithm that one uses in conjunction with one's standard practice of assigning quantum-mechanical states. One might then seek to have empirical support for taking such an algorithm as providing reliable quantum expectations. But, again, one would need to be clear about what one is doing and what it yields. In order to get an algorithm that makes statistical predictions, one would need to add assumptions to pure wave mechanics regarding the relationship between the typicality measure and one's expectations and the role of one's beliefs concerning relative states. And, for the reasons just discussed, this yields a predictive algorithm, not a description of nature.

Augmenting pure wave mechanics to get a predictive algorithm might be taken to mesh well with at least some of Everett's operational commitments. In any case, if one were to set one's expectations as suggested, then one would expect that the linear dynamics would correctly predicts interference effects for all systems regardless of their size or complexity. Given Everett's explanatory goals, an interference measurement of Wigner's Friend that shows that the Friend is in an entangled superposition of having recorded mutually incompatible results is a particularly salient example. Getting the result that Everett expected would provide empirical evidence for the universal applicability of the linear dynamics and, hence, count as evidence for setting one's expectations to accord with Everett's typicality measure on relative measurement records. And, hence, might be taken as evidence in favor of the the predictive algorithm. But empirical evidence for the reliability of the predictions of this augmented version of pure wave mechanics would be equally strong evidence in favor of other no-collapse formulations of quantum mechanics, such as Bohmian mechanics.

Everett had explicit views regarding the relationship between pure wave mechanics and Bohm's theory. In particular, he argued that, while no experiment could rule out Bohmian mechanics in favor of pure wave mechanics, "[o]ur main criticism of this view is on the grounds of simplicity." He thought that adding particles with determinant positions was "superfluous since, as we have endeavored to illustrate, the pure wave theory is itself satisfactory" without the addition of any hidden variables whatsoever (1956, 154). More generally, since he took pure wave mechanics to be the simplest possible no-collapse theory, he would have taken any evidence in favor of the universal applicability of the linear dynamics to be evidence for accepting pure wave mechanics as the best operational account on grounds of its simplicity, one of his explicit criteria for theory selection.

That said, it matters that in return for adding particle positions, an auxiliary dynamics for how the particles move, and a statistical boundary condition to get the right epistemic probabilities, Bohmian mechanics provides much richer explanations than augmented pure wave mechanics understood as a predictive algorithm. Bohmian mechanics can be taken as simply descriptive of a quantum world where the standard quantum probabilities can be understood as subjective degrees of belief and where the observers, as described by the theory, may have good empirical evidence for accepting the theory as empirically adequate in a conventional sense. In short, it is both empirically coherent and empirically adequate in a perfectly straightforward sense over a significant domain of quantum phenomena.

While one cannot take pure wave mechanics to be descriptive of the quantum world in the same sense that one might take Bohmian mechanics to be, one might nevertheless regiment one's expectations as suggested to recapture the probabilistic assertions of the standard collapse dynamics by expecting typical measurement records in Everett's sense of typical, then simply accept that the theory does not seek to describe a physical world where such expectations might be understood as expectations concerning what will in fact occur. But, again, even this modest proposal would require one to add significant auxiliary assumptions to pure wave mechanics regarding how to use the typicality measure and one's beliefs regarding physical states to set expectations.

8 Methodological Morals

There is a tension between rejecting a counterintuitive theory on the grounds that it fails to satisfy our pre-theoretic explanatory demands and allowing it to inform those intuitive demands. If we take our pre-theoretic standards too seriously, then we run the risk of rejecting a theory that may correct our fallible intuition. But if we do not take them seriously enough, then we lack relevant extra-theoretic criteria for revising the theory or rejecting it for a competitor that is richer in empirical and other explanatory virtues. I take this to be the central methodological issue in evaluating pure wave mechanics, and it plays out in different ways on alternative understandings of the theory.[43]

[43] When many-worlds proponents argue that Everettian quantum mechanics requires one to modify one's notion of *probability* or to consider a *caring measure* or *quasicredences* associated with alternative branches, they are, on this view, suggesting that one give up or modify at least some of one's pre-theoretic assumptions for evaluating physical theories when on comes to evaluate this particular theory. See Saunders (2010) for a description of these particular proposals for modifying our basic evaluative notions. Of course, an

One might have thought that a satisfactory formulation of quantum mechanics would necessarily have characterized measurement outcomes as more or less probable and that one might, then, have judged the theory's empirical adequacy on whether it got the probabilities right. Everett sacrifices this pre-theoretic understanding of the theory and its confirmation when he opts for a description of measurement where every possible relative record is fully realized and repeatedly insists that there are no probabilities associated with the relative records. The methodological problem, then, is how to determine the empirical adequacy of a theory like that.

One option is simply to reject pure wave mechanics on the grounds that one's pre-theoretic standard of empirical adequacy cannot be satisfied by a theory where every possible outcome is realized and there are no probabilities, but this would be never to take the theory seriously at all. Another is to give up empirical adequacy as a requirement for a theory being acceptable, then simply to accept pure wave mechanics as a satisfactory formulation of quantum mechanics, but this would clearly be to give too much to the theory. Or one might argue for an alternative notion of empirical adequacy that is reverse-engineered to be compatible with the theory. This was Everett's strategy, and it is the story we have followed here.

Empirical faithfulness captures precisely those empirical virtues that Everett found he could get from pure wave mechanics. That it may best be understood as a reverse-engineered notion of empirical adequacy should serve as a reminder that it does not represent evaluative standards that are independent of the theory we wish to evaluate.[44]

While empirical faithfulness is a relatively weak, reverse-engineered criterion for empirical adequacy, it is stronger than just requiring an empirically adequate predictive algorithm. In addition to providing a procedure for get-

ardent proponent of a theory may very quick in suggesting that we give up evaluative assumptions that do not favor the theory.

[44]The same holds for other reverse-engineered proposals like those described in footnote 43.

ting the right predictions, Everett accounts for the subjective experience of an observer by finding her experience in a model of the theory appropriately associated with the modeled observer. In this sense, he took his formulation of pure wave mechanics to provide a consistent model of measurement that was descriptive of the subjective experiences of observers. The important case was his version of the Wigner's Friend story. Here pure wave mechanics provides a complete model for the evolution of the absolute state of the system, the relative states of observers A and B are fully descriptive of their relative subjective experience, and one can find a parameter associated with these relative states that covaries with the standard quantum expectations.

Regarding the empirical coherence of pure wave mechanics, there are at least two ways that one might seek to understand confirmation, and both depend on the weakness of Everett's explanatory aims. First, one might have evidence for the *empirical faithfulness* of pure wave mechanics. The weakness of this account of experience is manifest in the problem of relevance—the way that one's experience is found in the model of pure wave mechanics does nothing whatsoever to explain why one should expect to have that particular relative experience in a world described by pure wave mechanics. Or one might have evidence for the reliability of the predictions one gets if one uses Everett's typicality measure to set one's expectations. The explanatory weakness here is that one has settled for a predictive algorithm over a theory that can be taken as descriptive of the physical world, and there are such theories.

In contrast with pure wave mechanics, Bohmian mechanics includes its main auxiliary assumptions as a part of the statement of the theory, it allows one to represent quantum-mechanical probabilities, and it explains how an observer, as described by the theory, might have empirical evidence for accepting it as empirically adequate in a conventional way. Everett's reason for rejecting Bohmian mechanics in favor of pure wave mechanics was the simplicity of the latter. But even this requires special care given the requirement of auxiliary assumptions in order to account for one's experience at all in the context of pure wave mechanics. In order to maintain that pure wave mechanics is both simple and complete, there is a temptation to smuggle auxiliary assumptions into one's explanations without stating them as a part of the theory. Among these are assumptions regarding the interpretive distinction between absolute and relative states and the relationship between the typicality and expectation. We have also seen the role that methodological assumptions regarding what one should expect from a satisfactory physical theory play in his overall argument for pure wave mechanics. And why a many-worlds proponent requires yet further assumptions to tell a compelling emergent-worlds story by appeal to the basic ontology of an auxiliary physical theory and whatever decoherence considerations it may support.

Whatever its problems, pure wave mechanics has a number of compelling virtues. It eliminates the collapse dynamics and hence immediately resolves the potential conflict between the two dynamical laws of the standard collapse theory. It is consistent, applicable to all physical systems, and arguably as simple as a formulation of quantum mechanics can be. And it is empirically faithful in that one can find an observer's quantum experience as relative records in the model of pure wave mechanics and one can find a measure over relative sequences of records such that most such sequences exhibit the standard quantum statistics.

Whether this is enough depends on one's other theoretical options. But it also depends on our evaluative standards. And here, in particular, our understanding of empirical adequacy is subject to revision as we compare pure wave mechanics against more complicated formulations of quantum mechanics and their more conventional accounts of experience.[45]

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