Pure Wave Mechanics and the Very Idea of Empirical Adequacy
DRAFT

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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]

The suggestion will be that empirical faithfulness is well understood as a weak variety of empirical adequacy. To take this seriously, is to allow that the very idea of empirical adequacy might be renegotiated in the context of a new physical theory given the theory's other salient virtues. Everett's argument for pure wave mechanics provides a concrete example of 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

[1]See Barrett (2009), (2010), (2011a), and (2011b) 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.

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 $\hat{O}\psi_S = \lambda\psi_S$.

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]

[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.

[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

Everett's version of the Wigner's Friend story involved an observer A who knows the state function of some system S that it is not 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, 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."

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.

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 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.

[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.

[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.

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.

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

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

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 $\sum a_i \psi^i_S \chi^i_{S'}$, the *relative state* of subsystem S to its complement S' in relative state $\chi^k_{S'}$ is ψ^k_S. 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 $\sum a_i \psi^i_S \chi^i_{S'}$, subsystem S has a *relative value* λ_S for an observable O, relative to its complement S' being in relative state $\chi^k_{S'}$, if and only if ψ^k_S 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

[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.

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 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

[8]This sometimes appears as the curious claim that the mathematical formalism of pure wave mechanics interprets itself. See Saunders et al. (2011) for various recent expressions of this and similar views.

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 typicality 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 on 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 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

[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.

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 relatively 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]

[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 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.

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 correlations 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 cor-

[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.

relation 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]

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.

[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.

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

> [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

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

> 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 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

[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).

[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).

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 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

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

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 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

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

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]

[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

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 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

to DeWitt.

> 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]

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

[23]While proponents of the decohering-worlds interpretation are often tempted to argue that decoherence effects prevent macroscopic branches from ever even in principle interacting with each other in any detectable way, Everett himself 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.

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 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

[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.

[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).

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 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 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

[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.

[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.

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 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 describ-

[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.

ing 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 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

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

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]

5 The argument so far

Gathering the two main threads of the argument, pure wave mechanics is empirical 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

[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.

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 with those offered in more recent many-world interpretations of Everett.

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 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 question of what it is precisely that they emerge from.

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

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 of this idea, one would, of 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.

On this account the *quantum state* is supposed to be metaphysically basic. Indeed, as Wallace explains elsewhere, the quantum state 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 the quantum state completely specifies one's ontology does not in fact do much to specify one's ontology. One further needs to know how to interpret the quantum state. And, in particular, if the quantum state is the state of something, one only pins down one's ontology, and indeed the quantum state itself, by knowing what it is a state of.

There are a number of options that one might pursue to clarify matters. One might, for example, take the quantum state itself to be one's most basic physical entity, and it sometimes seems as if Wallace has something like this in mind. Such a view is suggested when he says 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).[33]

More often and more recently, however, Wallace seems to understand the quantum state, more conventionally, as the state of something (2012, 298–302).[34] But if the quantum state is the state of something, then it is clearly not all there is since there is also the something that is described by the quantum state. And this matters since 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.

When Wallace takes the quantum state to be descriptive, what he takes it to describe varies and depends on auxiliary ontological commitments that fall outside of what he identifies as quantum mechanics. In the context of one being committed to a particle theory and the corresponding ontology, Wallace takes the quantum state to be descriptive of particles; and, in the context of one being committed to a field theory and the corresponding ontology, he takes the quantum state to be descriptive of the properties of

[33] Note, however, that this would not mesh well with Everett's view that quantum states to be states of physical systems. More specifically, he took the absolute quantum state to be descriptive of a composite system and relative states to be descriptive of its parts. Indeed, this sort of compositional description is simply presupposed by his account of relative states.

[34] In correspondence Wallace has explained that this is the view he prefers. More specifically, he takes the quantum state to be descriptive of the "microreality" and he takes what the microreality actually is to be theory-dependent.

spacetime regions (2012, 298–302). And insofar as one is committed to providing a clear characterization of emergent worlds, the difference matters. 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, one should expect to be very different from a story about how emergent worlds and their states supervene on the properties of spacetime regions. Further, whatever one chooses as the basic entities to tell the story of emergent entities cannot themselves be among the emergent entities—insofar as one takes spacetime regions to be the basic entities on which emergent worlds supervene one precludes the possibility of those spacetime regions themselves being emergent from the quantum state.

One is making a choice, then, concerning what entities might be understood as emergent and how they might be understood as emergent when one chooses precisely what entities to take as the basic things described by the quantum state. Returning to the tiger analogy, without clearly specifying the entities on which tigers and their states supervene, it is unhelpful to claim that one has completely specified the one's ontological commitments. And while one might affirm that the true micro-theory of the world is one where tigers and their properties supervene on patterns in the states of more basic physical entities, whatever they may be, if one does not know what they are, then one does not know how to characterize their states and hence cannot know how tiger and tiger properties supervene on those states. And this, it seems, would be to confess that one does not really know the sense in which tigers are emergent physical entities.

Everett avoids such metaphysical issues by settling for a weaker variety of explanation. On this view, then, what drives the difference between the explanations of the many-worlds proponent and Everett is the formers explanatory demands. This is perhaps particularly salient in the context of how Everett's account of the quantum statistics differs from recent attempts to derive the standard quantum probabilities in pure wave mechanics. Rather than take the finding of typical relative records that exhibit the quantum statistics to be sufficient, the at least some many-worlds proponents want to show that a rational agent who actually inhabited a world described by pure wave mechanics would make decisions precisely as if the norm-squared of quantum amplitudes represented probabilities,[35] The difference between the explanatory aims here is clearly manifest in the difference in the difficulty in providing the 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 the same set of branch outcomes may be fully realized regardless of the action taken.[36] In contrast, while one might wonder at how to interpret the accomplishment, there is a clear and precise sense in which Everett did in fact find the standard quantum statistics associated with measure-typical relative sequences of records in the model of pure wave mechanics.

As suggested earlier, there is a role for the notion of decoherence determined branches in pure wave mechanics in providing a richer sense in which quasiclassical experience may be found in the model of the theory than the sense that Everett described. Indeed, it may ultimately turn out that Everett's views and those of the sophisticated many-worlds proponent can be, at least to a large extent, reconciled. But, insofar as such a reconciliation is perceived to be a virtue, it would require some careful explanation.

I take it to be uncontentious that if one cannot support the Everett's 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 views, then, would require at least the following. Since Everett took being able to address the Wigner's friend story to be a require-

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

[36]See Wallace's (2010b) discussion of the many-worlds decision-theoretic account of quantum expectations and various objections and Kent's (2010) argument that there is no satisfactory decision theoretic account of probability in Everett.

ment 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.

7 Empirical coherence and relevance

Given the relatively weak account of experience provided by pure wave mechanics on this understanding of Everett, 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. But if one takes one's theory to be directly descriptive, 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 one can explain how one might have reliable empirical evidence for accepting it if it were in fact true. So is Everett's formulation of quantum mechanics empirically coherent?

I once argued that pure wave mechanics was not empirically coherent on the grounds that if it were true, one would typically not have epistemic access to measurement records that one might take to reliably indicated the physical state.[37] Similar worries concerning the the testability of the theory

[37]See Barrett (1996 and 1999) for discussions of empirical coherence and, more specifically, the empirical coherence of pure wave mechanics. The argument was that the bare theory predicts that if one were in an entangled superposition of recording mutually incompatible results, one would typically believe that one were in a separable state with a

if it were true are echoed in discussions of the many worlds interpretation.[38]

Insofar as Everett did not take his theory to be directly descriptive of the world, there is a sense in which the condition of empirical coherence is simply not applicable. Moreover, on this view, there is also a sense in which pure wave mechanics is empirically testable in a perfectly straightforward way. One just checks to see if the statistics of one's actual relative records are typical among relative sequences of measurement records in the appropriate sense of typical. If they are, then one's experience is appropriately findable in the model of the theory, and one, in consequence, has empirical evidence for accepting the theory.

But if one wants a strong account of experience and hence takes the theory to be directly descriptive of the physical world, then the condition of empirical coherence is applicable. If so, I do not believe that one could test the theory by appeal to statistical considerations. If pure wave mechanics is true, then some relative observers would have measurement records that agree with the standard quantum predictions and some would not. So if the theory is true, one may or may not have records that are compatible with the statistical properties exhibited by a typical relative sequence of records. A typical relative observer in Everett's sense would have relative records that are typical in Everett's sense, so such an observer would have empirical evidence that Everett's notion of typicality tracks the statistical properties of her de facto experience. But this clearly falls short of the observer having evidence that increases the probability of the theory being true insofar as Everett's notion of typicality cannot be understood as indicating the likeli-

determinate measurement record even when then is in fact no determinate measurement record that one has. I also argued that Bell's Everett(?) theory was not empirically coherent since, if it were true, one would not have reliable epistemic access to one's past measurement results.

[38]See Saunders (2010, 28–31) and Greaves and Myrvold (2010) for discussions of this worry, and for explanations concerning why it should not be a real worry for the many-worlds proponent. See Kent (2010) for an explanation for why accounts like Greaves and Myrvold's (2010) are inadequate.

hood of any particular relative sequence of records. Put another way, since the theory does not predict that a typical branch is a more probable branch, conditioning on the fact that one's relative records are typical in Everett's sense does not increase the likelihood that the theory is true.

But this does not mean that one could not test the theory at all. What presumably would count as evidence for accepting pure wave mechanics would be relative records that indicate that the linear dynamics correctly predicts interference effects for all systems regardless of their size or complexity An interference measurement of Wigner's Friend that shows that the Friend is in a superposition of having recorded mutually incompatible results, for example, would provide strong evidence for the universal applicability of the linear dynamics, which would count as evidence against collapse theories and evidence for pure wave mechanics and other no-collapse theories. And records from such experiments would be something to which a relative observer would in principle have reliable epistemic assess.

There are other empirical problems if one wants to take theory as closely descriptive. Perhaps the most significant problem is one of relevance. It concerns why an observer's expectations of relative sequences of records should be determined by the norm-squared-amplitude measure of typicality at all. To call this a measure of *typicality* suggests that a sample 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 presumably follow from this that it is also *probable* that one's relative sequence of measurements records exhibit the standard quantum statistics, and, on the face of it, that cannot be right.

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.[39]

But again, this is not a problem for Everett insofar as one understands pure wave mechanics to be empirically faithful simply because one can find a measure in the model of the theory such that most relative sequences of measurement records in the measure exhibit the standard quantum statistics. But, on this view, the weakness of the notion of empirical faithfulness is exhibited in what it does not explain. In particular, it does not explain 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.

That said, even if one does not take the theory to be directly descriptive of the physical world, one might regiment one's expectations to recapture the probabilistic assertions of the standard collapse dynamics in one's subjective expectations. Indeed, part of the cost in so regimenting one's expectations is that the theory itself does not describe a physical world where such expectations might be understood as expectations concerning what will in fact occur. Rather, Everett's typicality measure might at most be taken to determine the subjective probability of a relative sequence of records being (relative) mine. And, of course, even this would require one to add auxiliary assumptions to

[39]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."[40] The 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.

the basic statement of pure wave mechanics.

8 Methodological Morals

Since one of the salient virtues of pure wave mechanics is taken to be its simplicity, there is perhaps a special temptation to smuggle significant assumptions into one's explanations so that one need not state them as a part of the theory. I have tried to identify some of the key assumptions that Everett took as essential to his argument for the empirical acceptability of pure wave mechanics. Among these, interestingly from a philosophical perspective, are methodological assumptions regarding what one should expect from a satisfactory physical theory.

Pure wave mechanics has a number of salient virtues. It eliminates the collapse dynamics and hence immediately resolves the potential conflict between the two dynamical laws. It is consistent, applicable to all physical systems, and perhaps 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.

Insofar as empirical adequacy involves finding one's actual experience in the model of a theory, one might take the empirical faithfulness of pure wave mechanics to be a variety of empirical adequacy. To be sure, it is a relatively weak variety since the way that one's experience is found in the model of pure wave mechanics does not explain why one should expect to have that particular experience in a world described by the physical theory. But empirical faithfulness also represents a nontrivial empirical virtue. While one might want a stronger sort of empirical adequacy, given its other virtues, there is a good argument, I believe, for taking pure wave mechanics to be an empirically adequate solution to the quantum measurement problem to be considered with other serious options.

Judging a theory to be empirically adequate when it tells us that there is a sense in which everything physically possible in fact happens clearly puts pressure on the very idea of empirical adequacy. The thought is that the very idea of empirical adequacy is something that might be carefully renegotiated as our best theories suggest alternatives in the context of trade-offs with other theoretical virtues. The argument here is that the empirical acceptability of pure wave mechanics in part depends on such a renegotiation.[41]

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