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Typical worlds

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ABSTRACT

Hugh Everett III presented pure wave mechanics, sometimes referred to as the many-worlds interpretation, as a solution to the quantum measurement problem. While pure wave mechanics is an objectively deterministic physical theory with no probabilities, Everett sought to show how the theory might be understood as making the standard quantum statistical predictions as appearances to observers who were themselves described by the theory. We will consider his argument and how it depends on a particular notion of branch typicality. We will also consider responses to Everett and the relationship between typicality and probability. The suggestion will be that pure wave mechanics requires a number of significant auxiliary assumptions in order to make anything like the standard quantum predictions.

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1. Introduction

It is tempting to claim that one can derive strong conclusions from weak assumptions, but there is a no-magic constraint. Since the conclusion of a valid deductive argument cannot be stronger than the premises required to get it, if one gets a strong conclusion, one must have made similarly strong assumptions somewhere along the way. In practice, however, it is often difficult to say where.

Hugh Everett III (1955a, 1955b, 1956, 1957) presented pure wave mechanics, also known as the many-worlds interpretation, as a solution to the quantum measurement problem.[1] While he believed that there was a sense in which one could derive the standard quantum statistics from pure wave mechanics alone, his approach was significantly less ambitious than deducing probabilistic predictions. That said, even Everett's relative weak account of quantum statistics requires significant additions to pure wave mechanics.

Here we are concerned with Everett's presentation of pure wave mechanics, his derivation of the quantum statistics, and DeWitt's and Graham's response. We will pay particular attention to the explanatory role played by alternative notions of branch typicality and the relationship between typicality and probability. The aim is to understand Everett's approach better and to get a sense of the strength of the auxiliary assumptions one would need to derive anything like the standard quantum probabilities from pure wave mechanics.[2]

The present paper seeks to get at what Everett thought about typicality and probability, including his reaction to DeWitt and Graham's criticisms. While there are methodological morals to this story that clearly apply more generally, other proposals for how to understand quantum typicality and probability require careful analysis on their own terms.[3] The present argument involves how one might best identify a physical theory for the purpose of probabilistic explanation. Since it is implausible that there are canonical criteria for how to individuate theories or for what constitutes a good explanation, the approach will be thoroughly pragmatic. How the methodological morals might be best applied beyond the story told here is largely left to the reader.

2. Pure wave mechanics

While pure wave mechanics is an objectively deterministic theory that says nothing whatsoever about probability, Everett

[1] Everett himself did not refer to branches as worlds in his written work. See Barrett (2011b, 2016a) for discussions of his metaphysical commitments and the role of metaphysics in interpreting pure wave mechanics more generally.

[2] See Barrett (2016b) for a preliminary discussion of typicality in pure wave mechanics.

[3] Questions concerning the relationship between typicality and probability arise in other formulations of quantum mechanics as well. For a recent discussion of typicality and probability in Bohmian mechanics see Goldstein (2012).

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sought to describe a sense in which it might be understood as making the same statistical predictions as the standard von Neumann–Dirac collapse theory.[4] The thought was to get the standard quantum predictions as subjective appearances to observers who were themselves described quantum-mechanically. What this meant for Everett was that the relative measurement records of a *typical* relative observer will exhibit the standard quantum statistics. In order to track the various auxiliary assumptions required, we will start with a specification of pure wave mechanics.

Everett presented pure wave mechanics as a modification of the standard collapse formulation of quantum mechanics. And, following von Neumann (1955), Everett took the standard collapse formulation of quantum mechanics to be characterized by the following principles:

1. Representation of States: The state of a physical system S is represented by a vector $|\psi\rangle_S$ of unit length in a Hilbert space $\mathcal{H}$.
2. Representation of Observables: A physical observable O is represented by a set of orthogonal vectors $\mathcal{O}$. These vectors represent the eigenstates of the observable, each corresponding to a different value.
3. Dynamical Laws:
   I. Linear dynamics: If *no measurement* is made, the system S evolves in a deterministic linear way: $|\psi(t_1)\rangle_S = \hat{U}(t_0, t_1)|\psi(t_0)\rangle_S$.
   II. Nonlinear collapse dynamics: If a *measurement* is made, the system S randomly, instantaneously, and nonlinearly jumps to an eigenstate of the observable being measured: the probability of jumping to $|\phi\rangle_S$ when O is measured is $|\langle\psi|\phi\rangle|^2$.

In addition to these principles, Everett appealed to the standard eigenvalue-eigenstate link to attribute *absolute* properties to a system. In particular, a system S has an *absolute* value for observable O if and only if $|\psi\rangle_S \in \mathcal{O}$, and the value is given by the eigenvalue corresponding to $|\psi\rangle_S$.

Everett believed, however, that its incompatible dynamical laws rendered the von Neumann-Dirac collapse theory logically inconsistent and hence untenable. He presented what he called the *question of the consistency* of the standard theory in the context of an "amusing, but *extremely hypothetical* drama" (1956, 74).[5] This would later become known as the Wigner's Friend story after Eugene Wigner (1961) retold it without attribution to Everett.

A version of the story goes as follows. Suppose that a spin-1/2 system S begins in the state

$$\alpha|\uparrow_x\rangle_S + \beta|\downarrow_x\rangle_S \tag{1}$$

and a friend F and his measuring device M begin ready to make a measurement of the x-spin of S. Assuming perfect correlating interactions, the linear dynamics (von Neumann's Process 2, rule 3II above) predicts that the resultant state will be:

$$\alpha|``\uparrow_x"\rangle_F|``\uparrow_x"\rangle_M|\uparrow_x\rangle_S + \beta|``\downarrow_x"\rangle_F|``\downarrow_x"\rangle_M|\downarrow_x\rangle_S. \tag{2}$$

In contrast, if one were to suppose, as suggested by the standard collapse theory, that there is something special about the friend or his measuring device that causes a collapse of the state of his object system on measurement, one would end up with one of the states predicted by the collapse dynamics (von Neumann's Process 1, rule 3I above):

$$|``\uparrow_x"\rangle_F|``\uparrow_x"\rangle_M|\uparrow_x\rangle_S \tag{3}$$

or

$$|``\downarrow_x"\rangle_F|``\downarrow_x"\rangle_M|\downarrow_x\rangle_S \tag{4}$$

with probabilities $|\alpha|^2$ and $|\beta|^2$ respectively.

The moral of the story is that the two dynamical laws of the standard von-Neumann-Dirac formulation of quantum mechanics predict incompatible states when applied to the same physical interaction. Further, as Everett explicitly recognized, state (2) is in principle empirically distinguishable from states (3) and (4) by an inference measurement on the composite system consisting of F, M, and S.[6]

Everett held that one only has a satisfactory formulation of quantum mechanics if one can provide a satisfactory account of such nested measurements. Hence, if one cannot tell the Wigner's Friend story consistently, then one does not have a satisfactory formulation of quantum mechanics.

Everett believed that the Wigner's Friend story could be told simply and consistently in the context of pure wave mechanics, the theory one gets by starting with the standard collapse theory and simply deleting the collapse dynamics (rule 3II). In particular, he believed that the final state after F's measurement interaction is simply given by state (2), thus removing the possibility of a contradiction. And, again, he believed that an external observer would in principle be able to show this empirically by an appropriate interference measurement on the composite system F, M, and S.[7] But he also believed that it will appear to F that she has a perfectly determinate measurement outcome, and, more generally, that one can recover the standard quantum statistics for such appearances from pure wave mechanics alone. He took pure wave mechanics thereby to provide a satisfactory resolution to the quantum measurement problem.

As Everett described his project, "we shall deduce the probabilistic assertions of [the collapse dynamics (3II)] as *subjective* appearances" to observers who are themselves treated as perfectly ordinary physical systems always subject to the linear dynamics (3I) "thus placing the theory in correspondence with experience." The upshot is that "We are then led to the novel situation in which the formal theory is objectively continuous and causal, while subjectively discontinuous and probabilistic." Everett took this to solve the nested measurement problem because "while this point of view thus shall ultimately justify our use of the statistical assertions of the orthodox view, it enables us to do so in a logically consistent manner, allowing for the existence of other observers" (1956, 77–8). Specifically, this amounted to describing a sense in which pure wave mechanics predicted the standard quantum statistics for the relative measurement records of a typical relative observer.[8]

[4] See Dirac (1930) and von Neumann (1955) for early descriptions of the standard collapse theory.

[5] Everett was arguably too critical here. The theory as it stands is just ambiguous inasmuch as one does not know precisely when to apply rules 3I and 3II. That is, one could remove the threat of inconsistency by specifying strictly disjoint conditions for when each rule obtains. This is what Wigner later sought to do. For his part, Everett assumed that a measuring device should evolve linearly like every other physical system. It is this auxiliary assumption that yields the inconsistency.

[6] This might be accomplished by measuring an observable that has state (2) and the orthogonal state one gets by subtracting the second term rather than adding it to the first as eigenstates corresponding to different eigenvalues.

[7] In other words, the linear dynamics entails that Everett worlds cannot be causally closed. This point is also discussed in Albert (1986) and Albert and Barrett (1995), and a point that we will return to later.

[8] There is a long tradition of physicists and philosophers who have sought as Everett did to deduce the standard quantum probabilities from pure wave mechanics. The list includes, among others, Hartle (1968), DeWitt (1971), Graham (1973), Farhi, Goldstone and Gutmann (1989), Deutsch (1999), Zurek (2005), Saunders (2010b), Wallace (2010b, 2012), and Sebens and Carroll (2016). While the details of the arguments and precisely what is meant by quantum probability varies significantly, each of these deductions relies on auxiliary assumptions that go beyond pure wave mechanics, at least as Everett understood the theory. See Saunders (2010) and Kent (2010) for discussions of this tradition.