Centering the Everett Interpretation

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Abstract

I propose an account of probability in the Everett interpretation of quantum mechanics. According to the account, probabilities are objective chances of centered propositions. As I show, the account solves a number of problems concerning the role of probability in the Everett interpretation. It also challenges an implicit assumption, concerning the aim and scope of fundamental physical theories, that is made throughout the philosophy of physics literature.

1 Introduction

A quantum mechanical principle—called the 'Born rule'—uses probabilities to account for the observed outcomes of experiments. For example, take any electron in the 'z-spin up' state. Suppose that its x-spin is measured. Thousands of experiments have confirmed the following: the probability that the electron is in the 'x-spin up' state, after measurement, is $\frac{1}{2}$. The Born rule implies probabilistic statements like this.

The Born rule poses a problem for one of the most prominent interpretations of quantum mechanics: the Everett interpretation. According to the Everett interpretation, the complete physical state of the universe is aptly represented by a wavefunction that evolves, deterministically, in the manner described by the Schrödinger equation. In other words, according to the Everett interpretation, the evolution of the universe is deterministic. So what should be made of the Born rule, with its probabilistic posits? Where does it come from, and why is it so helpful in accounting for the observed outcomes of experiments?

In this paper, I propose an account of Born rule probabilities that answers these questions. According to my account, Born rule probabilities are *centered chances*, where a centered chance is a chance of a centered proposition. Nevertheless, the Born rule itself is still a physical law, just as the Schrödinger equation is. So the Born rule, despite invoking centered propositions, is not a normative principle of rationality.[1] It is an objective physical law of the universe.

For example, consider the following statement: the probability that a 'z-spin up' electron will be in the 'x-spin up' state, after a measurement of its x-spin, is $\frac{1}{2}$. Roughly put, according to my account, this probabilistic statement should be interpreted as assigning a physical chance of $\frac{1}{2}$ to the centered proposition 'I will see the electron in the "x-spin up" state.' So according to my account, as a matter of physical law, centered propositions can be objectively chancy. And those centered chances are what the Born rule describes.[2]

In Section 2, I formulate a complete theory of probability in the Everett interpretation: I introduce the specific version of that interpretation on which I will focus, I propose an account of the Born rule that invokes centered chances, and I analyze centered chances by using the best system account of laws. In Section 3, I show that this theory of probability solves four problems for the Everett interpretation that the Born rule poses. In Section 4, I compare my account with other Everettian accounts of the Born rule.

Before beginning, it is worth pointing out an interesting upshot of the discussion to come. This paper challenges an implicit but pervasive assumption, made throughout the philosophy of physics literature. I discuss it in more detail in Section 2, but for now—very roughly put—the basic idea of the assumption is this: in order to completely account for our experiences, all we need from our fundamental physical theory is an account of

[1]For this reason, as I discuss later, my account differs from accounts that identify Born rule probabilities with certain sorts of rational credences (Deutsch 1999; Greaves 2007a; Wallace 2007).

[2]As I discuss later, my account is somewhat similar to—though ultimately quite different from—the 'many-minds' account (Albert & Loewer 1988) and the 'many-threads' account (Barrett 1999).

various uncentered facts. Fundamental physical laws, according to this assumption, do not invoke centered propositions of the form 'I am thus-and-so.' This paper questions that. For according to my approach to probability in the Everett interpretation, we need our fundamental physical theory to account for various centered facts as well as various uncentered facts. Fundamental physical laws, in other words, can invoke centered propositions. So this paper should interest even those who are skeptical of the account of probability that I will ultimately formulate. For this paper raises a series of interesting questions about what the purview of the complete, fundamental physical theory of the world ought to be.

2 The Centered Everett Interpretation

In this section, I formulate my account of Born rule probabilities in terms of centered chances. In Section 2.1, I describe the specific version of the Everett interpretation on which I will focus. In Section 2.2, I use that version—along with centered chances—to propose an account of the Born rule. In Section 2.3, I analyze centered chances using the best system account of laws. In Section 2.4, I briefly summarize the key components of my proposal. Finally, in Section 2.5, I discuss some general issues—concerning the purview of fundamental physics—that my proposal raises.

2.1 Branches and Worms

Roughly put, according to the particular version of the Everett interpretation which will be relevant here, the classical world of our experience is just one of many different worlds. Individual people are temporally extended parts of these worlds. Since these worlds split apart from each other, individual people do too. And as in all standard versions of the Everett interpretation, after a measurement is performed, each possible outcome of that measurement obtains in a different world.[3]

Here are the details. According to this version of Everett, there is a multiplicity of approximately classical, approximately non-interacting regions of the wavefunction which can be described as classical worlds (Wallace 2012: 38). These regions are called 'branches', and together they comprise the Everettian universe.

For present purposes, three features of branches are particularly important. First, as on most other accounts, branches are four-dimensional. A branch is a temporally extended region of the wavefunction.

Second, and relatedly, branches can split apart from each other. A split occurs whenever, roughly, a measurement is performed.[4] For example, consider an electron in the 'z-spin up' state. Suppose someone measures its x-spin. Then after measurement, the wavefunction splits into two branches: one contains an electron in the 'x-spin up' state, and the other contains an electron in the 'x-spin down' state. So both outcomes of the experiment actually occur. Both electrons—the one in the 'x-spin up' state, and the one in the 'x-spin down' state—exist. They are just on different branches.

Third, branches are infinitely extended both towards the past and towards the future. Branches do not come into existence when a split occurs. Rather, a split separates two branches which had always existed. Those branches were just exact physical duplicates of one another, before the split.

Individual people are parts of these branches. In particular, each person is temporally extended along the branch to which they belong. In other words, just like branches, people are four-dimensional. They are 'spacetime worms': they extend through time as well as through space.[5]

[3]The metaphysical view presented here, concerning worlds and individuals, is akin to one of the views presented in (Saunders & Wallace 2008; Wallace 2012). Wallace calls it the 'Lewisian view' (2012: 281).

[4]More accurately, a split occurs whenever the wavefunction evolves in a particular sort of way. For more discussion of the details of splitting, see (Greaves 2007b; Wallace 2012).

[5]For more on this account of people—and macro-objects, and worlds more generally—in the Everett interpretation, see (Greaves 2007b; Saunders & Wallace 2008; Wallace 2012). For more on this account of personal identity, see (Lewis 1983).

The picture below provides a helpful illustration of this version of the Everett interpretation. It depicts what happens, according to this version, when a series of measurements are performed.

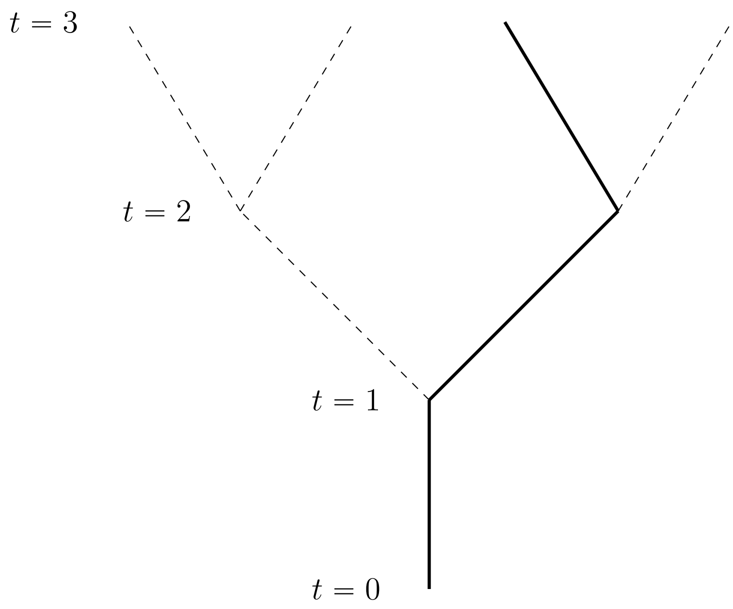

Figure 1: Branching Worlds

In this picture, there are four branches: three are represented by dotted lines, and one is represented by a solid line. The significance of the solid line will be explained in Section 2.2: for now, think of it as a branch like the other three. From time $t = 0$ to time $t = 1$, all four branches are exact physical duplicates of one another: in the picture, this is represented by the four lines overlapping throughout the bottom-most segment. At time $t = 1$, measurement occurs, and so there is a split: two branches go left, and two go right. At time $t = 2$, measurement occurs again, and so there are more splits: the two left-most branches split apart from each other, and the two right-most branches split apart from each other.

On each branch, there is a distinct individual: the experimenter who performs the relevant measurements. Those individuals are distinct because their four-dimensional, spacetime worms are distinct. But over certain periods of time, those individuals are exact physical duplicates of one another. For instance, this is the case from time $t = 0$ to time $t = 1$.[6] When the four branches split into two groups of two, the four individuals split into two groups of two as well. So from time $t = 1$ to time $t = 2$, it is no longer the case that all four individuals are exact physical duplicates. Instead, in that period of time, the two individuals on the left two branches are exact physical duplicates, and the two individuals on the right two branches are exact physical duplicates. When the left two branches split, the two individuals on those branches split. Similarly, when the right two branches split, the two individuals on those branches split as well. As a result, from time $t = 2$ to time $t = 3$, none of these individuals are exact physical duplicates. They were at $t = 0$, but because of splitting branches, they are not at $t = 3$.

In short, according to this version of the Everett interpretation, there are many copies of physical things. There are lots of worlds, there are lots of individual experimenters, there are lots of experiments, and there are lots of electrons. For periods of time, the copies are duplicates: the worlds are, the experimenters are, the experiments are, and the electrons are. But sometimes, the wavefunction evolves in certain special ways. And when that happens, the copies come apart. Call this version of the Everett interpretation the 'worm view'.[7]

2.2 The Centered Born Rule

In this section, I use the worm view to formulate a version of the Born rule. Roughly put, according to this version, Born rule probabilities are objective chances of centered propositions like 'I am on thus-and-so branches' or 'We are on such-and-such branches.' So Born rule probabilities are inherently agent-relative. They tell us what sorts of branches we are likely to

[6] In this paper, I describe various situations in terms of *discrete* numbers of worlds and *discrete* numbers of individuals. It would be somewhat more accurate to describe those situations in terms of *densities* of worlds and *densities* of individuals. But that would make the paper more complicated, and the complications would be largely irrelevant to the ideas explored here. So I will stick with the simpler descriptions.

[7] I will not defend the worm view, or its use of duplicate worlds, here. The aim of this paper is different: I seek to show that the worm view, along with a few other interesting posits, can be used to provide a complete theory of probability in the Everett interpretation. For discussion of advantages and disadvantages of the worm view in general, see (Wallace 2012; Wilson 2013).

be on, by telling us the chances that we ourselves—rather than duplicates of ourselves—will observe certain experimental outcomes.

Here are the details. Let E be an experimenter who performs a measurement. Let $|\psi\rangle$ be the wavefunction before the measurement is performed. Let $Ch_{E,\psi}$ be a chance function; think of $Ch_{E,\psi}$ as describing the chances of certain propositions relativized to E, given that the wavefunction is $|\psi\rangle$. After measurement, the wavefunction splits into branches. Let $|a\rangle$ be a branch—or more accurately, a collection of branches—into which the wavefunction splits.[8] Suppose that E is unsure of which branch is theirs. And let O_a be the centered proposition 'I am in one of the $|a\rangle$ branches.' Then

$$Ch_{E,\psi}(O_a) = |\langle a|\psi\rangle|^2 \tag{1}$$

In other words, the centered chance of E being in an $|a\rangle$ branch—relative to E, and given that the wavefunction was $|\psi\rangle$ before measurement—equals the relevant Born rule probability. Call this the 'centered Born rule'.

For an example application, consider Figure 1 from Section 2.1. Let E be the individual on the bolded branch. At $t = 1$, E—along with the three duplicates of E—measures the x-spin of an electron in state 'z-spin up'. Recall that according to the worm view, from time $t = 0$ to time $t = 1$, there are four duplicate branches. When the measurement is performed, the four branches split into two groups of two. On two of those branches—the ones that go right, say—the corresponding electrons have x-spin up. On the other two branches—the ones that go left—the corresponding electrons have x-spin down. Suppose that E is unsure of whether they are in an 'x-spin up' branch or an 'x-spin down' branch.[9] Then the centered

[8] In the case where the wavefunction continues to split into the future, $|a\rangle$ does not represent just one branch. Rather, $|a\rangle$ represents a collection of branches: one for each branch into which the corresponding region of the wavefunction will eventually split.

[9] Strictly speaking, this way of putting things—in terms of E being *unsure* of something—is unideal. For centered chances are, in various ways, independent of what agents do or do not know. A better description would invoke the analysis of centered chance provided in Section 2.3, and would go like this: suppose that the best summary of E's branch assigns chances to that branch being one way rather than another. For now, however, the unideal way of putting things will suffice.

Born rule implies that relative to E, and given the initial wavefunction, the proposition 'I am in one of the "x-spin up" branches' has chance $\frac{1}{2}$.

In other words, according to the centered Born rule, the Born rule probabilities are chances that we are on certain branches. Before branches split apart, they are exact physical duplicates of each other. There is no telling which, of the many duplicate branches, is ours. So the centered Born rule assigns a chance to *our* branch being one of these—one of the branches that is thus-and-so, after the split—rather than one of those.[10]

Note that the chances of centered propositions can differ from the chances of related, yet uncentered, propositions. For instance, the chance of the centered proposition 'I am in one of the "x-spin up" branches' (relative to E and ψ) can differ from the chance of the uncentered proposition 'E is in one of the "x-spin up" branches.' The chance of the latter proposition, of course, is 1. For recall that E is the individual on the bolded branch in Figure 1. The 'x-spin up' branches are the branches that go right. So with chance 1, E is in an 'x-spin up' branch. But 'I am in one of the "x-spin up" branches' and 'E is in one of the "x-spin up" branches' are different propositions.[11] So they can be assigned different chances. In particular, even though the latter has chance 1, the former can have chance $\frac{1}{2}$ (relative to E and ψ), as the centered Born rule implies.

There are at least two significant differences between the centered Born rule and the sorts of principles proposed by Sebens and Carroll (2018), Srednicki and Hartle (2010), and Wallace (2007; 2012). One of those differences concerns some subtle features, of the centered Born rule, which I only present later; so I postpone the discussion of that difference until

[10] One might wonder what counts as 'our' branch: how, one might ask, is that branch defined? That question, however, makes a false presupposition. Indexical expressions like 'our' make certain semantic contributions to the meanings of sentences in which they appear: 'our', for example, contributes us. Those contributions do not need to be defined in terms of something further—something non-indexical, say—in order for sentences which feature indexicals like 'our' to be coherent, meaningful, or fit for use in a philosophical theory. That is just how the semantics for sentences with indexical expressions works. And similarly for the case of indexicals involving branches. An indexical expression like 'our branch' makes a certain semantic contribution to the meaning of a sentence like 'Our branch is thus-and-so': 'our branch' contributes our branch. That contribution does not need to be defined in terms of something further, in order for the sentences in which it appears to be coherent, meaningful, or fit for use in a philosophical theory.

[11] For accounts of centered and uncentered propositions that imply this, see (Ninan 2013).

Section 4.1. The other difference, though, can be presented here: the centered Born rule is a physical law, not a principle of rationality. The sorts of principles discussed by Sebens and Carroll, Srednicki and Hartle, and Wallace, concern the credences of rational agents. Those principles connect Born rule probabilities to what agents' credences should be. The centered Born rule, however, is not about the credences of rational agents. The centered Born rule is a fundamental law of the universe, just like the Schrödinger equation. It connects Born rule probabilities to the objective chances of centered propositions; that is, to centered chances.

Centered chances are relativized to agents. In (1), Ch is defined relative to the individual E. Because of that, the centered chance of a proposition like O_a can differ from one individual to the next. That might seem odd, but it is not. Centered propositions have different semantic values for different individuals. The 'I' in O_a has a different semantic value, for instance, depending on who utters it. So it makes sense to think that the chance assigned to a proposition like O_a can vary, depending on the individual in question. Besides, the relativity of centered chance to individuals is akin to the relativity of chance—centered or uncentered—to times. The chance of a proposition can differ from one time to another. Times, of course, can be centers of centered propositions. Therefore, chances can vary along one kind of center: namely, the kind corresponding to times. The relativity of centered chance to individuals is just variation along another kind of center: namely, the kind corresponding to individuals. So the fact that centered chances can vary from individual to individual is quite similar to the fact that chances can vary from time to time.

Because centered chances are defined relative to agents, one might think that centered chances are just *centered credences*, where a centered credence is a credence in a centered proposition. But they are not. Centered chances are objective; centered credences are subjective. Centered chances are worldly states; centered credences are mental states.

Centered chances and centered credences are related, of course: as argued in (Wilhelm 2021), they both obey a centered version of Lewis's Principal Principle.[12] The precise details

[12]In that paper, I formulate several modified versions of the Principal Principle: these principles describe the ways in which centered chances constrain rational centered credences.

of that relationship will not matter here, but roughly put, the basic idea is this: centered chances are those objective, worldly states which constrain rational centered credences. Centered chances explain why some centered credences are rational while other centered credences are not.

Before moving on, it is worth making a final clarification about the centered Born rule. In the formulation of (1), I stipulated that E is an individual. But E could be an entire world instead. So the chance function invoked in the centered Born rule can be relativized to either individuals or worlds.

2.3 The Best System Analysis of Centered Chance

In this section, I analyze centered chances using the best system account of lawhood. Roughly put, centered chances are propositions which the best deductive systems imply. Centered chances help deductive systems strike the best balance between various theoretical virtues: simplicity, informativeness, fit, tractability, and so on.

Before introducing the analysis of centered chance, it is worth reviewing the best system account of uncentered chance. And to do that, we must first review the best system account of lawhood. Laws, according to the best system account, are theorems of those deductive systems that best balance theoretical virtues like simplicity, strength, and fit.[13] In short, laws help summarize: to be a law is to be part of the best overall summary of the world. Uncentered chances, according to the best system account, help with that summary. In particular, an uncentered chance is a proposition which (i) assigns a probability to an uncentered proposition, and (ii) follows from the best deductive systems (Lewis 1994: 480; Loewer 2004: 1118–9).

Centered chances, I propose, are the same sorts of things. A centered chance is a proposition which (i) assigns a probability to a centered proposition, and (ii) follows from

[13] Loewer (2004: 1119) describes these theoretical virtues in some detail.

the best deductive systems. In other words, centered chances help provide the best overall summary of the world. Call this the ‘best system analysis’ of centered chance.

Centered chances and uncentered chances summarize different sorts of facts. Centered chances help summarize *centered* facts: they help summarize facts about where we are in the Everettian universe. Uncentered chances, in contrast, help summarize *uncentered* facts: they help summarize facts about the universe that are, in a sense, independent of where we find ourselves in it.[14]

Note that the centered chances, in the centered Born rule, summarize the frequencies with which experimental outcomes obtain on *our* branch. For example, on our branch, the relative frequency with which we find that ‘z-spin up’ electrons have x-spin up—after certain kinds of measurements—is $\frac{1}{2}$; and the relevant Born rule probability matches that. In other words, on *our* branch, the centered chances in the centered Born rule correctly capture the frequency facts. For us, the Born rule probabilities get the frequency facts right.

On other branches, however, the Born rule probabilities get the frequency facts wrong. For example, let b be a branch where every ‘z-spin up’ electron, after a measurement of its x-spin, is found to have x-spin up. In other words, relative to the agents on b, the chance of the centered proposition ‘I am in one of the “x-spin up” branches’ is 1. Then on b, the centered Born rule is false.

This might seem problematic. How can the centered Born rule be a law, if it is false on branches like b? Grant that the best system summarizes centered facts concerning our particular branch, since it summarizes facts about where we find ourselves in the deterministic Everettian universe. What, then, does the best system say about other branches? Does it get the centered facts concerning those other branches wrong? If so, then is it really the best system?

[14]One might object by claiming that the best system does not summarize centered facts; the best system, one might claim, summarizes uncentered facts only. In (Wilhelm 2021), I respond to this objection in detail. Very briefly, the basic idea of that response is as follows. Many of the theoretical virtues which the best deductive systems balance—the testability of a system, for instance, or a system’s ability to support explanations of observations—concern us. So the best deductive system should summarize facts about where we find ourselves in the universe.

My answer: it is indeed the best system – for our branch. In other words, I propose the following: different branches have different best systems, and so different branches have different laws. Lawhood, in short, is sometimes branch-relative. For example, the best system for our branch is different from the best system for b. The centered Born rule is in the former best system, but not the latter. So on our branch, but not on b, the centered Born rule is nomological.

The branch-relativity of lawhood might seem strange. But given the guiding idea behind the best system account of laws, it is quite well-motivated. For according to that guiding idea, laws are summaries that serve us well. And it makes perfect sense that in order to serve us well, laws should summarize centered facts—about us in particular—as well as uncentered facts. So in an Everettian universe, it makes perfect sense that in order to serve us well, laws should summarize the centered frequency facts on our branch. And it makes perfect sense that other agents, on other branches, are best served by summaries of their own centered frequency facts. So unsurprisingly, the best summarizes of those other branches—that is, the laws for those other branches—are different. And so given the best system account of lawhood, the branch-relativity of lawhood is not strange at all. It is to be expected.

For example, consider branch b once more. The best system for b does not include the centered Born rule, since on b, the centered Born rule is false. Instead, the best system for b includes a formal version of the following: 'Electrons with z-spin up, when passed through thus-and-so magnetic fields,[15] end up having x-spin up.' On branch b, this sentence—call it 'S'—does a better job of concisely and informatively summarizing the facts about z-spin and x-spin than the centered Born rule. Indeed, S does a better job of summarizing those facts on b than any other sentence does. So on b, the best system includes S. That is, on b, S is a law.[16]

To summarize: the same statement may be a law relative to one branch, but not relative

[15] These would be the sorts of magnetic fields created by Stern-Gerlach devices.

[16] Of course, there are many other ways that branches could evolve. Some branches start out obeying the centered Born rule, but ultimately deviate from it. Other branches initially deviate from the Born rule, but end up conforming to it.

to another. In particular, the centered Born rule is a law on our branch, because it gets the centered frequency facts on our branch right. But on other branches, the centered Born rule is not a law, since it does not correctly summarize those other branches' centered frequency facts.

Advocates of the best system account of lawhood often explain their view in terms of a conversation with God (Albert 2015: 23). So in closing, let me do likewise for the best system analysis of centered chance. You ask God to tell you about the universe. God begins to recite a long litany of facts: this particle is over here, that one is over there, and so on. Pressed for time, you ask God if there is some simple yet highly informative summary of what the universe is like. In granting your request, God gives you a law: in particular, God gives you the deterministic component of the Everett interpretation of quantum mechanics. For that component—namely, the Schrödinger equation—is a simple yet highly informative summary of the universe's goings-on.

Then you notice that this law allows for situations in which many physical subsystems, all duplicates of one another, look a whole lot like you. You notice, in other words, that the Everett interpretation allow for situations in which you could be this physical system over here, or that physical system over there, or that other one, and so on. This is what happens, of course, when multiple branches are duplicates of one another.

So you say to God: 'I want to be able to check this law. I want to run experiments on it, to see whether or not it is true. But to do that, I need to know which physical subsystem of the universe is me. Or at least, I need to know something about where I am in the universe. Otherwise, I won't know whether the data I collect is from this branch, or that branch, or elsewhere. And so I won't be able to empirically confirm the law.'

God says: 'Okay. But since you're in a rush, I won't bother specifying exactly which subsystem you are at each moment in time. Instead, I'll just give you some chancy rules to help guide your guesses as to where you might be.'

That, according to the view presented in this section, is what centered chances are.

Centered chances are the things that God would give you, to help you determine your location. And in particular, that chancy rule—which God would give you—is the centered Born rule.

Note that in this story, God gives the centered Born rule to *you*. God would not give the centered Born rule to individuals who (i) temporarily look exactly like you, but (ii) belong to branches where the centered frequency facts deviate from the Born rule probabilities. To help guide those individuals' guesses as to where they might be, God would give them different chancy rules. Hence the branch-relativity of lawhood.

2.4 Summary

Taken together, the worm view, the centered Born rule, and the best system analysis of centered chance, provide a complete theory of probability in the Everett interpretation of quantum mechanics; call it the 'centered Everett interpretation'. Here is a summary of the centered Everett interpretation's three parts.

1. The worm view
    - The complete physical state of the universe is aptly represented by a wavefunction that evolves in accord with the Schrödinger equation.
    - Certain regions of the wavefunction form 'branches'. These branches are approximately isolated, approximately classical worlds. Branches are four-dimensional, and they have infinite temporal extent.
    - Individuals are parts of branches. And individuals are four-dimensional, spacetime worms: like branches, they are temporally extended.
2. The centered Born rule
    - Equation (1): the centered chance of being in a particular branch—relative to an individual, and given a particular wavefunction—is equal to the Born rule probability of that particular branch obtaining.

3. The best system analysis of centered chance
    - Centered chances are propositions which the best deductive systems imply. They help deductive systems summarize centered facts, such as facts about where we are in the universe.
    - Lawhood is relative to branches: different branches may have different best systems, and so different branches may have different laws. The centered Born rule is a law on our branch, but there are other branches—with different frequency facts—where the centered Born rule is not a law.

2.5 Against the Orthodox Assumption

In this section, I describe an interesting upshot of the above discussion. Basically, that discussion raises some questions concerning the purview of fundamental physical theories. The centered Everett interpretation suggests that fundamental physics can account for more phenomena than has been appreciated.

In particular, the following assumption is implicit throughout the philosophy of physics literature: in order to completely explain our experiences using fundamental physics, all we need from our fundamental physical theory is a complete account of various uncentered facts about the world. Of course, we might need *a priori* principles of rationality, or metaphysical principles linking the fundamental to the non-fundamental, or some other such posits, in order to completely explain all aspects of our experiences. But all physics needs to contribute, to those explanations, is a complete, fundamental physical theory of various uncentered facts. In short, fundamental physics is only in the business of discovering laws about various uncentered facts in the world. Call this the 'orthodox assumption'.[17]

[17] Here is another way to describe what the orthodox assumption says: in order to explain various centered facts about non-fundamental phenomena, we need not posit fundamental physical laws for centered propositions. Centered phenomena, in other words, do not occur at the fundamental level. Centered phenomena occur at higher levels only. And all higher-level centered phenomena can be completely explained by a combination of (i) fundamental physical laws that describe only uncentered facts, and (ii) principles of rationality,

The orthodox assumption is extremely common in the philosophy of physics literature: there have been few proposals, if any, of fundamental physical laws for centered facts. The orthodox assumption is so common, in fact, that it often goes unarticulated. It is simply, implicitly, always taken for granted.

The centered Everett interpretation implies that the orthodox assumption is false. For according to the centered Everett interpretation, the fundamental physical laws include the centered Born rule. And the centered Born rule provides an account of centered facts, such as facts about what our branch is like. So the centered Everett interpretation represents a new sort of fundamental physical theory. It takes fundamental physics to be in the business of providing theories of both centered and uncentered facts. It allows for fundamental physical laws which describe centered phenomena.[18]

This raises a host of interesting questions. Is this a problematic feature of the centered Everett interpretation? In other words, does this feature of the centered Everett interpretation—that it implies the falsity of the orthodox assumption—count against it? If so, why, and if not, why not? More generally, should we accept the orthodox assumption? Should fundamental physics only be in the business of providing theories of various uncentered facts? If so, why? Why should fundamental physics be restricted in that way? If not, are there any restrictions on the sorts of facts which fundamental physical theories can, or should, account for? What sorts of centered facts, if any, are off limits?

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or metaphysics, or some such things, which connect fundamental uncentered facts to centered phenomena at higher levels.

[18]It is worth comparing (i) the conflict between the orthodox assumption and the centered Everett interpretation, to (ii) the debate over temporal asymmetry and fundamental physical laws (Albert 2015; Maudlin 2007). According to some, temporally asymmetric phenomena at higher levels can be explained by a combination of (i) fundamental dynamical laws which are temporally symmetric, and (ii) some other principles which can be used to recover the asymmetry of time at the scale of medium-sized dry goods. According to others, that is not so: some temporally asymmetric phenomena, at higher levels, can only be explained by fundamental dynamical laws which are temporally asymmetric themselves. Analogously for the conflict between the orthodox assumption and the centered Everett interpretation. According to the orthodox assumption, centered phenomena at higher levels can be explained by a combination of (i) fundamental dynamical laws which describe uncentered facts only, and (ii) some other principles which can be used to recover centered phenomena at the scale of medium-sized dry goods. According to the centered Everett interpretation, that is not so: some centered phenomena, at higher levels, can only be explained by fundamental laws which describe centered facts themselves.

It is beyond the scope of this paper to answer these questions. But they deserve investigation. And for that reason, the centered Everett interpretation should be interesting even to those who are skeptical of it. For the centered Everett interpretation raises a series of new questions about the aim and scope of fundamental physical theorizing. The centered Everett interpretation, that is, motivates exploring the extent to which fundamental physical theories ought to provide accounts of centered facts as well as uncentered facts.

3 Probability Problems

In this section, I show how the centered Everett interpretation can be used to solve four problems stemming from probabilities. The problems—discussed by Greaves (2007a: 121–2; 2007b: 110) and Wallace (2012: 40–1; 158)—concern the relationship between the Born rule and Everettian approaches to quantum mechanics. They are as follows.

1. The incoherence problem: given that all possible outcomes of experiments occur, in the deterministic Everettian universe, how can there be any non-trivial probabilities at all?
2. The quantitative problem: even if there are probabilities in the deterministic Everettian universe, why are they correctly given by the Born rule?
3. The practical problem: even if the probabilities in the deterministic Everettian universe are given by the Born rule, why should they guide our decision-making?
4. The epistemic problem: given that all possible outcomes of experiments occur on some branch or other, in the deterministic Everettian universe, how do the outcomes of experiments confirm quantum theory?

Call these the 'probability problems'. As I will show, the centered Everett interpretation can be used to solve them.

The solution to the incoherence problem is straightforward. There can indeed be non-trivial probabilities in the deterministic Everettian universe, according to the centered Everett interpretation: the non-trivial probabilities are chances of centered propositions, rather than chances of uncentered propositions. According to the centered Everett interpretation, the chances of uncentered propositions are always either 0 or 1: that follows from the fact that the wavefunction evolves deterministically. But other propositions—in particular, propositions that are centered—can still have non-zero, non-unit chances. Those centered chances are the quantum mechanical probabilities.

The solution to the quantitative problem is straightforward too, given the branch-relativity of lawhood. The probabilities are correctly given by the Born rule, according to the centered Everett interpretation, because the Born rule probabilities correctly describe the frequencies with which experimental outcomes obtain on our branch. So the Born rule probabilities are correct, but only for us. They are indeed the right probabilities for our branch, because they get the frequency facts on our branch right. But on other branches, the Born rule probabilities do not correctly summarize the relevant frequency facts. So on other branches, the Born rule probabilities do not feature in any of the laws.

The solution to the practical problem is pretty simple, given the solution to the quantitative problem. According to the centered Everett interpretation, the Born rule probabilities should guide our decision-making because on our branch, they are a good guide to the frequency facts. We are confined to our particular branch, so when we make decisions, we should use the frequencies on our branch as a guide. Those frequencies are summarized by the centered chances for our branch, and those centered chances are equal to the Born rule probabilities. So the Born rule probabilities should guide our decisions.

The solution to the epistemic problem is pretty simple too. According to the centered Everett interpretation, the outcomes of experiments confirm quantum theory because on our branch, the main ingredients of that theory—namely, the Schrödinger equation and the Born rule probabilities—can be used to make accurate predictions. The Born rule probabilities are centered chances, according to the centered Everett interpretation. So like all chances, they can help confirm or disconfirm theories. More precisely, the outcomes of experiments on our branch directly confirm the centered Born rule. Those outcomes also confirm the Schrödinger equation, since the Schrödinger equation describes the evolution of a crucial component of the centered Born rule: the wavefunction. So the outcomes of experiments on our branch confirm the centered Everett interpretation.

4 Other Accounts

In this section, I briefly compare the centered Everett interpretation to other accounts of probability in Everettian quantum mechanics. In Section 4.1, I discuss accounts that identify probability with rational credence. In Section 4.2, I discuss accounts based on posits—about branches and individuals—that are somewhat similar to the posits of the centered Everett interpretation.[19]

4.1 Rationality Accounts

In this section, I compare the centered Everett interpretation with accounts—call them 'rationality accounts'—that posit principles of rationality. As I show, there is reason to prefer

[19]The centered Everett interpretation is also quite different from the interpretations proposed by Saunders (2010), Wilson (2013), and Vaidman (1998). The main difference concerns the nature of Born rule probabilities. According to the centered Everett interpretation, Born rule probabilities are centered chances. According to those other interpretations, however, Born rule probabilities are centered credences instead. But there are other noteworthy differences too. For instance, according to Wilson, propositions are sets of Everettian worlds. That is, propositions are sets of branches, where the branches are drawn from an Everettian universe. These propositions are uncentered, and so they have all the standard properties that uncentered propositions have: the truth conditions of these propositions do not invoke centers; when probabilities are assigned to these propositions, the resulting propositions are uncentered chances; and so on. According to the centered Everett interpretation, however, propositions are sets of pairs consisting of (i) a center, and (ii) an Everettian universe. That is, propositions are built out of total wavefunction histories, not out of isolated branches. And these propositions are centered, so they have all the standard properties that centered propositions have: the truth conditions of these propositions invoke centers; when probabilities are assigned to these propositions, the resulting propositions are centered chances; and so on. Finally, according to Vaidman, an individual on a branch before splitting is identified with each of the individuals on the branches that exist after splitting. For this reason, according to Vaidman, diachronic identity—and even phrases like 'the individual'—are meaningless. According to the centered Everett interpretation, however, an individual on a branch before splitting is only identified with one of the individuals on one of the branches after splitting. As a result, diachronic identity—and phrases like 'the individual'—are perfectly meaningful; they are meaningful in the ways that all indexicals are. And it contradicts the empirical facts, studied in basic linguistics, to claim that such expressions are meaningless.

the centered Everett interpretation over rationality accounts. But in addition, when both sorts of accounts are properly understood, it becomes clear that they are compatible with one another. In fact, the centered Everett interpretation complements rationality accounts quite nicely. For the centered Everett interpretation provides helpful constraints on the normative principles that rationality accounts posit.

There are many rationality accounts of probability in the Everett interpretation (Deutsch 1999; Greaves 2007a; 2007b; Sebens & Carroll 2018; Wallace 2007; 2012). Though different in various ways, they share a common core: Born rule probabilities, according to these accounts, are generally rational credences. The probabilities given by the Born rule are the credences which agents in an Everettian universe ought to have.

The main reason to prefer the centered Everett interpretation over rationality accounts concerns agents on other branches.[20] Let A be an agent on branch b: recall that on b, every 'z-spin up' electron is found—after passing through certain kinds of magnetic fields—to have x-spin up. Suppose that A has measured thousands of 'z-spin up' electrons. In each case, A sees that the electron has x-spin up; and so in each case, A sees that the electron does not have x-spin down.

According to the rationality principles posited by rationality accounts, A's credences ought to equal the Born rule probabilities. So suppose that A prepares to measure the x-spin of yet another 'z-spin up' electron. Then according to the rationality principles posited by rationality accounts, A ought to have credence $\frac{1}{2}$ that the 'z-spin up' electron will be found to have x-spin up. Any other credence in that result is irrational, according to the posited rationality principles. So if A has credence 1 in the 'z-spin up' electron being found to have x-spin up, then A is irrational.

But that is wrong. A is on a branch where every single 'z-spin up' electron is found, after passing through certain kinds of magnetic fields, to have x-spin up. And A has seen thousands of experiments in which exactly that occurs. So at the very least, it seems rationally

[20] For other criticisms of rationality accounts, see (Albert 2010; Baker 2007; Maudlin 2014; Price 2010).

permissible for A to have credence 1 in that result. A is not irrational if their credence—in the 'z-spin up' electron having x-spin up—is 1.

Unlike rationality accounts, the centered Everett interpretation respects that. There are two reasons why. First, the centered Everett interpretation does not posit any principles of rationality at all. So the centered Everett interpretation does not imply that A is rationally required to have a specific credence in the 'z-spin up' electron having x-spin up. And because of that, the centered Everett interpretation allows for the permissibility of being completely certain of that result. Second, as discussed in Section 2.3, the centered Everett interpretation only provides an account of the laws on our branch. On other branches, the laws may be different. On b, recall, the following statement is a law: 'Electrons with z-spin up, when passed through thus-and-so magnetic fields, end up having x-spin up.' And plausibly, once A knows that this statement is a law, A ought to use it when setting their credences. So once A knows that this statement is a law, A ought to be completely certain—A ought to have credence 1—that any given 'z-spin up' electron will enter an 'x-spin up' state, when passed through thus-and-so magnetic fields.[21]

So branches like b provide a reason for favoring the centered Everett interpretation over rationality accounts. Those rationality accounts subscribe to principles about Born rule probabilities that, ultimately, are based on uncentered facts about the distribution of weights across the universal wavefunction.[22] The centered Everett interpretation subscribes to principles about Born rule probabilities that, ultimately, are based on centered facts instead: in particular, the centered Born rule is based on facts about the frequencies of experimental outcomes on our branch. And as branches like b demonstrate, it is much more natural to adopt principles about Born rule probabilities which are based on centered facts than to

[21] In other words, A should not assign Born rule probabilities to the outcomes of experiments. For another proposal which denies that Born rule probabilities should be assigned to experimental outcomes, see (Brown & Porath 2020).

[22] For example, see the diachronic consistency principle endorsed by Wallace (2012: 167). Very roughly put, that principle says the following: for any agent on any branch, the preferences of that agent constrain the future preferences of agents with which they overlap. The details of those constraints are ultimately underwritten by uncentered facts about the wavefunction.

adopt principles about Born rule probabilities which are based on uncentered facts.[23]

Proponents of rationality accounts might respond as follows. Properly understood, they might claim, rationality accounts only imply the following: the rational credence for A to have in the 'z-spin up' electron being found to have x-spin up, *conditional on the truth of the uncentered Born rule*, is $\frac{1}{2}$.[24] In other words, rationality accounts only constrain A's conditional rational credences in propositions concerning the outcomes of experiments. And that, proponents of rationality accounts might claim, is perfectly compatible with it being rational for A to assign credence 1 to the proposition that this particular 'z-spin up' electron will be found to have x-spin up. All that follows, according to these proponents of rationality accounts, is that A is rationally required to reject—that is, assign credence 0 to—the uncentered Born rule. Call this the 'conditional response' to the issue mentioned above.

The conditional response has an unattractive consequence. Suppose that it is indeed rational for A to have credence 1 in the proposition that the 'z-spin up' electron will be found to have x-spin up – so long as it is also rational for A to reject the uncentered Born rule. Nevertheless, note that according to rationality accounts, the uncentered Born rule is true. So the conditional response is committed to the following: agents like A, on branches like b, are rationally required to have false beliefs about the fundamental laws of their universe. Such agents must reject the uncentered Born rule, in order to be rational; even though they are wrong to do so. And that is, of course, an unattractive consequence of this approach to rationality.

The centered Everett interpretation has no such consequence. For according to the centered Everett interpretation, the uncentered Born rule is false on branch b. Therefore, A is right to reject it. A is both rational, and also correct, to reject the uncentered Born rule.

[23]Thanks to an anonymous reviewer for this point.

[24]Strictly speaking, this response should be understood as claiming that rationality accounts imply something slightly more complicated. They imply that the rational credence for A to have in the 'z-spin up' electron being found to have x-spin up, conditional on the truth of the uncentered Born rule *and also* on the Schrödinger equation, *and also* on certain propositions about the preparation of the electron's initial state, is $\frac{1}{2}$. To keep this example simple, I set aside those other propositions on which to conditionalize.

So the centered Everett interpretation is not committed to agents like A, on branches like b, being rationally required to have false beliefs about the fundamental laws of their universe. And so the centered Everett interpretation does not have the unattractive consequence that the conditional response has.

Before moving on, it is worth making the following observation. Though there are reasons to prefer the centered Everett interpretation over rationality accounts, these approaches to quantum probabilities are not incompatible with one another. In fact, they complement each other quite nicely. For roughly put, rationality approaches have the right idea, but they go wrong in certain ways. The centered Everett interpretation provides the resources to keep rationality approaches on the right track.

In particular, I think that when appropriately limited, the rationality principles posited by rationality accounts are right. It seems right, for example, that on *certain kinds of branches*, agents ought to set their credences in *certain kinds of propositions* by using the Born rule probabilities. But which branches, exactly? And which propositions? The centered Everett interpretation provides the answer. The 'certain kinds of branches' are branches like ours, where the centered frequency facts conform to the centered Born rule. The 'certain kinds of propositions' are centered propositions of the form 'I am in one of the $|a\rangle$ branches.' So the rationality principles posited by rationality accounts are correct, so long as those principles are confined to those propositions and to those branches.

In this way, the centered Everett interpretation complements rationality accounts. The rationality principles posited by rationality accounts are, I think, vulnerable to problems like the one discussed above. But when appropriately limited, those principles seem right. The centered Everett interpretation can be used to specify what those limits are.

4.2 Duplicate Accounts

In this section, I compare the centered Everett interpretation with some other accounts—call them 'duplicate accounts'—that posit lots of duplicate entities. Because the centered Everett interpretation also posits duplicate entities—in particular, individuals and branches—it is somewhat similar to these accounts. But as will become clear, there are significant differences. And those differences, I think, favor the centered Everett interpretation.

To start, consider the 'many minds' account due to Albert and Loewer (1988). According to the many minds account, every observer is associated with an infinity of minds. The minds evolve probabilistically, in accord with the Born rule. That is, the proportion of minds associated with a particular quantum state equals the Born rule probability of that state obtaining (Albert & Loewer 1988: 206–7).

Like the centered Everett interpretation, the many minds account posits a collection of duplicate entities. In the case of the many minds account, those entities are non-physical minds. In the case of the centered Everett interpretation, however, those entities are physical spacetime worms.

For that reason, I prefer the centered Everett interpretation to the many minds account. The centered Everett interpretation does not posit any mentalistic entities, in order to account for quantum mechanical probability. The many minds account, however, does. So the many minds account is committed to dualism about the mental. The centered Everett interpretation is not, and that is a reason to prefer it.

Now consider the 'many-threads' account due to Barrett (1999). The many-threads account subscribes to something like the worm view. Worlds, according to the many-threads account, are four-dimensional entities (Barrett 1999: 179); and plausibly, individuals are four-dimensional entities too. Quantum mechanical probabilities are prior epistemic probabilities, and they evolve in accord with the Born rule.

So the many-threads account is somewhat similar to the centered Everett interpretation.

Both subscribe to the worm view, or something very much like it. That is, both posit the same sorts of duplicate entities.

There are two differences between the many-threads account and the centered Everett interpretation. First, the many-threads account takes quantum mechanical probabilities to be more like credences than chances. Epistemic probabilities seem more credal than chancy. The centered Everett interpretation, in contrast, takes quantum mechanical probabilities to be objective chances rather than subjective credences. Second, the many-threads account does not provide an account of those credence-like probabilities. That is, the many-threads account does not say where, exactly, those epistemic probabilities come from. The centered Everett interpretation, in contrast, provides an account of the objective chances that it posits: those chances come from the best summary of our branch.

The second difference is, I think, a reason to prefer the centered Everett interpretation over the many-threads account. The former, but not the latter, gives a complete account of probability in the Everett interpretation. Both accounts say what quantum mechanical probabilities are: centered chances, according to the centered Everett interpretation; epistemic probabilities, according to the many-threads account. But only the centered Everett interpretation provides a source for its probabilistic posit: the best system. The many-threads account does not. And that is a reason to prefer the centered Everett interpretation.[25]

5 Conclusion

According to the centered Everett interpretation, quantum mechanical probabilities are objective chances. But since the universe is deterministic, those chances are not chances of uncentered propositions like 'Hugh is in one of the $|a\rangle$ branches.' They are chances of

[25] Of course, there might be some way to supplement the many-threads account with an account of the source of epistemic probabilities. Any such supplemental account would have to be careful, however, to avoid the problems discussed in Section 4.1. Perhaps the most obvious supplemental account would take those epistemic probabilities to be rational credences. But if so, then the problems discussed in Section 4.1 arise for that supplemental account.

centered propositions like 'I am in one of the $|a\rangle$ branches.' And centered chances are not as strange as they initially seem to be. For centered chances can be analyzed: they are propositions—about where we are in the universe—which the best deductive system for our branch implies.

The centered Everett interpretation raises lots of interesting questions for future research. What is the relationship between centered chances and centered credences? What sorts of rationality principles provide the best complement to the centered chances posited by the centered Everett interpretation? Could centered chances be analyzed using other theories of chance, like propensity theories?

Perhaps the most interesting questions, however, concern the orthodox assumption. Why should we think that all we need from fundamental physics, in order to explain our experiences, is a complete, fundamental physical theory of various uncentered facts? Why not think that we need a complete, fundamental physical theory of some centered facts too?

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