

# PROBABILITIES DON'T MATTER \*

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(1994 Nov. 25)

## Abstract

It is suggested that probabilities need not apply at all to matter in the physical world, which may be entirely described by the amplitudes given by the quantum mechanical state. Instead, probabilities may apply only to conscious perceptions in the mental world. Such perceptions may not form unique sequences that one could call individual minds.

## 1 Probabilities in Quantum Mechanics

One of the most mysterious aspects of quantum mechanics is its usual probabilistic interpretation. There is first the uncertainty of which amplitudes should be squared to get probabilities. Then there is the even deeper puzzle of what the resulting probabilities mean.

For example, one viewpoint on the first question is that whenever a measurement is made, the amplitude for each macroscopically-distinct outcome should be squared to get a probability. (More precisely, one takes a complete set of orthogonal projection operators, each representing one of the macroscopically-distinct outcomes. One projects the wavefunction by one of these projection operators to get a reduced wavefunction. Then one takes the inner product of this reduced wavefunction with itself—i.e., “squares the amplitude”—to get the probability of the corresponding outcome. This probability is the same as the expectation value of the projection operator in the quantum state given by the original wavefunction.)

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\*Alberta-Thy-28-94, gr-qc/9411004, to be published in *Proceedings of the 7th Marcel Grossmann Meeting on General Relativity*, eds. M. Keiser and R.T. Jantzen (World Scientific, Singapore 1995).

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A broader viewpoint is that the expectation value of any projection operator is a probability for the corresponding “event.” An even broader viewpoint is that one can square the amplitude given by projecting the wavefunction not just by one, but by a whole sequence of (possibly noncommuting) projection operators representing a “history” or sequence of “events.” (For the resulting probabilities to obey the sum rules under a coarse-graining of the projection operators, the sequences must obey certain consistency conditions [1, 2].) One can extend this viewpoint, of assigning probabilities to “consistent histories,” yet further to the viewpoint that one can project the wavefunction by sums of sequences of projection operators that represent coarser-grained histories. (Then one needs “decoherence” conditions for the resulting probabilities to obey the sum rules for “decohering histories” [3, 4, 5].) An even further extension is the viewpoint that probabilities are the real parts of the expectation values of sums of sequences of projection operators, whenever these obey a “linear positivity” condition of being nonnegative, giving probabilities for “linearly positive histories” that automatically obey the sum rules [6].

Besides this sample of the wide variety of viewpoints of what quantities should be assigned probabilities in quantum mechanics, there is the enigma of how to interpret the resulting probabilities. One attitude is that a unique one of the possible “events” or “histories” actually occurs, with the probability assigned by quantum mechanics, and that the other possibilities do not. This attitude still leaves open the question of whether the “probability” is a “frequency” in an ensemble of actual worlds, or whether it is a “propensity” in a single world and what that could mean. If the latter, what is it that actually makes the choice of the actual “event” or “history” from those potentially possible?

Another attitude is that all of the possible “events” or “histories” with nonzero probabilities actually occur, but with measures proportional to the probabilities. This “many-worlds” interpretation [7] is very similar to the frequency interpretation in an ensemble of actual worlds mentioned above, but it need not have the implication that our present world is a single member of the ensemble that has a definite (albeit unpredictable) future.

In any of these approaches in which one or all of the possibilities are actualized, there is the further question of which set of possibilities is singled out. In general, there are many different allowed sets of possibilities (e.g., different sets of orthogonal projection operators, or of sequences of projection operators, that each add up to the identity operator). If only one “event” or only one “history” actually occurs, there must be mysterious choices both of the set of possibilities and of the single actual element within that chosen set. If, on the other hand, all of the possible “events” or “histories” with nonzero probabilities in a given set of possibilities actually occur, there must apparently still be a mysterious choice of this set of possibilities out of the family of all such sets of possibilities.

One conceivable answer is that all possibilities in all sets of possibilities actually occur, with measures given by the probabilities deduced from quantum mechanics

in one of the ways discussed above. Since, for a normalized quantum state, these probabilities are designed to add up to unity for a single set of possibilities, the measures will sum to more than unity when one adds up all the sets. In fact, typically the number of allowed sets of possibilities is infinite (e.g., even for a two-state spin-half system, there is a rank-one projection operator for each direction in space and hence an infinite number of such projection operators). This means that the sum of the measures for all possibilities typically is unnormalizable, which may lead to problems. (These problems may be avoidable. For example, in the spin-half system, the sum of the quantum probabilities for all of the infinite number of possibilities for the spin direction is infinite, but instead of simply adding these quantum probabilities, one can divide by the total solid angle of the unit sphere of spin directions to get a probability density which can then be integrated over a nonzero solid angle to get a normalized second-order probability that the spin is in a direction within that solid angle.)

## 2 Sensible Quantum Mechanics

Here I shall propose instead that probabilities not be applied at all to the physical world (the “matter” of the title), which is instead to be described entirely by the quantum amplitudes of its wavefunction (or by the elements of its density matrix, or possibly by a more general description, such as a  $C^*$ -algebra state). I suggest instead that probabilities apply only to the mental world of conscious perceptions. In this viewpoint, and in a certain loose manner of speaking in which “mind” is this whole mental world rather than a sequence of perceptions, probabilities are only in the mind.

Consider the set of all possible perceptions  $p$ , which I shall call the mental world  $M$ . By a perception, I mean all that one is consciously aware or consciously experiencing at one moment. This is what Lockwood, in a book expressing what seems to be ideas mostly concordant with mine [8], calls a “phenomenal perspective” or “maximal experience.” In another way of putting it, my  $p$  denotes a total “raw feel” that one has at once. It can include components such as a visual sensation, an auditory sensation, a pain, a conscious memory, a conscious impression of a thought or belief, etc., but it does not include a sequence of more than one immediate perception that in other proposals might be considered to be strung together to form a stream of consciousness of an individual mind.

Suppose that there is a basic measure on the mental world which weights each perception equally, which I shall denote by  $dp$  without implying a choice between the conceptual possibilities that the space of perceptions is discrete (in which case  $dp$  simply counts the number of perceptions) or continuous (in which case  $dp$  might represent some basic multi-dimensional integration measure or volume element). Now I shall postulate that our actual world does not have all possible perceptions occurring equally, but instead that there is a nontrivial measure  $m(p)dp$ , the non-

negative real scalar function or measure density  $m(p)$  times the basic measure, for the perceptions in our actual world. Thus I get the following basic assumption:

**Measure Axiom for Perceptions:** There is a nontrivial measure on the space of (maximal) perceptions  $p$ , namely  $m(p)$  times the basic measure  $dp$  that weights each perception equally.

Because of the fact that our perceptions seem to be more simply explained by assuming that they are related to a physical world, I shall assume a principle of psycho-physical parallelism, that the nontrivial part  $m(p)$  of the measure for perceptions is a functional of the properties of the physical world.

For example, if the physical world were represented by a single classical trajectory in some phase space, it might be natural to assume that  $m(p)$  has a form of a sum of Kronecker deltas or an integral of a discrete set of Dirac delta function distributions over sequences of perceptions that a set of conscious beings has as the point moves along the trajectory in phase space. In other words, each point in phase space might naturally be assigned a discrete set of conscious perceptions, one for each conscious being whose point in its phase space is derived from the point in the phase space of the entire system (e.g., the universe). Even in this classical model, there can be many perceptions at one time, but each is ascribed to a different conscious being.

If the physical world is represented by a quantum state that has no preferred classical trajectories (such as do occur in Bohm's version of quantum mechanics [9], but which I shall not further consider here), then it seems unnatural to assume that  $m(p)$  is completely concentrated on a discrete sequence of trajectories, one for each conscious observer. Instead, in view of the linearity of quantum mechanics, I propose the following basic assumption for interpreting quantum mechanics 'sensibly,' i.e., in terms of sensations or perceptions:

**Sensible Quantum Axiom:** Each  $m(p)$  is given by the expectation value of a corresponding positive perception or "maximal experience" operator  $E(p)$  in the quantum state of the universe. As a formula,

$$m(p) = \langle E(p) \rangle = \langle \psi | E(p) | \psi \rangle = \text{Tr}(E(p)\rho), \quad (1)$$

where the third expression applies if the quantum state is represented by the wavefunction or pure state  $|\psi\rangle$ , and the fourth expression applies if the quantum state is represented by the statistical operator or density matrix  $\rho$ . (The second expression can apply in more general situations, such as in  $C^*$ -algebra.)

In this framework, which I shall call Sensible Quantum Mechanics, the quantum state of the universe is fixed, in the Heisenberg picture I am using, and never collapses or changes to another state, so the von Neumann intervention  $\mathbf{1}$  [10] is assumed never to occur. Neither is there assumed to be any nonlinearity in quantum mechanics when consciousness is involved, as Wigner proposed [11]. If the quantum state and all the perception operators  $E(p)$  are known, one can in principle calculate from Eq. (1) the measure density  $m(p)$  for all perceptions. (Of course, I am not competent to give these essential elements, so the present proposal is a framework,

on the level of other frameworks or interpretations of quantum mechanics, rather than a complete theory.) Since all maximal perceptions  $p$  with  $m(p) > 0$  really occur in this framework, it is completely deterministic if the quantum state and the  $E(p)$  are determined: there are no random or truly probabilistic elements in this framework of Sensible Quantum Mechanics.

Thus Sensible Quantum Mechanics has no need for any axiom of what is typically called “measurement” [10], or what Unruh calls “determination” [12] to distinguish this hypothetical process from the physical measurement interactions that are encoded in the quantum state and the structure of the operators. In particular, there are no probabilistic results of such “determinations.”

Nevertheless, because the framework has measures for perceptions, one can readily use them to calculate quantities that can be interpreted as conditional probabilities. One can consider sets of perceptions  $A$ ,  $B$ , etc., defined in terms of properties of the perceptions. For example,  $A$  might be the set of perceptions in which there is a feeling that the universe is approximately described by a Friedman-Robertson-Walker model, and  $B$  might be the set of perceptions in which there is a feeling that the universe is approximately described by a Friedman-Robertson-Walker model with an age (at the perceived time) between ten and twenty billion years. By summing or integrating  $m(p)dp$  over the sets  $A$ ,  $B$ ,  $A \cap B$  ( $= B$  in the example here), etc., one can get corresponding measures  $m(A)$ ,  $m(B)$ ,  $m(A \cap B)$ , etc. Then one can interpret

$$P(B|A) \equiv m(A \cap B)/m(A) \tag{2}$$

as the conditional probability that the perception is in the set  $B$ , given that it is in the set  $A$ . In our example, this would be the conditional probability that a perception including the feeling that the universe is approximately described by a Friedman-Robertson-Walker model, also has the feeling that at the time of the perception the age is between ten and twenty billion years.

An analogue of this conditional “probability” is the conditional probability that a person in 1994 is the Queen of England. If we consider a model of all the five to six billion people, including the Queen, that we agree to consider as our contemporary humans on Earth in 1994, then at the basic level of this model the Queen certainly exists in it; there is nothing random or probabilistic about her existence. But if the model weights each of the five to six billion people equally, then one can in a manner of speaking say that the conditional probability that one of these persons is the Queen is somewhat less than  $2 \times 10^{-10}$ . I am proposing that it is in the same manner of speaking that one can assign conditional probabilities to sets of perceptions, even though there is nothing truly random about them at the basic level.

When one’s perceptions include feelings of belief about what is ascribed to be external events or histories (e.g., results of experiments in the physical world rather than in the mind), and when it is believed that these beliefs are an accurate representation of some aspects of those ascribed-to-be-external events or histories, it is

tempting to the theorist to interpret the conditional probabilities of the perceptions as giving conditional probabilities for those aspects of the ascribed-to-be-external events or histories. One may even go further and develop formalisms for directly calculating probabilities of such events or histories. With this viewpoint one can say that the historical development of quantum mechanics has been fruitful (or more strictly, I have a feeling that what I perceive to have been its historical development was fruitful), but it has left unexplained which events or histories are to be assigned probabilities and what those probabilities mean.

Thus I am proposing that at the basic level, probabilities (or, more strictly, measures) have meaning only for perceptions in the mental world and should not be assigned to anything (e.g., to events or histories) in the physical world of matter. In this sense “probabilities don’t matter.”

On the other hand, I am not saying that it is forbidden to assign conditional “probabilities” to events and/or histories in the physical world. They can be much simpler to calculate than those in the mental world given by Eqs. (1) and (2), since we don’t know what the perception operators  $E(p)$  are, and these physical “probabilities” may often give good approximations for the mental probabilities. Indeed, I have been happy to help play the game of broadening the scope of histories to which one can assign mathematically-consistent probabilities [6]. However, I am now proposing that these probabilities are not fundamental and need not be added to complicate the basic ontology of a measurable set of perceptions (which I have been calling the mental world) and a quantum state of the universe (which I have been calling the physical world), with the measure and interpretation given entirely by the Measure Axiom for Perceptions and the Sensible Quantum Axiom above.

Goldstein has pointed out [14] that one can simplify the ontology and avoid the assumption of a basic measure  $dp$  on the mental world by replacing the measure density  $m(p)$  for single perceptions  $p$  with a measure  $\mu(S)$  on sets  $S$  of perceptions and by replacing the perception operators  $E(p)$  with a positive-operator-valued measure, say  $A(S)$ . This alternative formulation is given in [15, 16]. Another way to minimize the number of independent entities is to postulate that the basic measure  $dp$  is the volume element of a Riemannian metric

$$g_{ij}dp^i dp^j = Tr\{[E(p^i + dp^i) - E(p^i)][E(p^j + dp^j) - E(p^j)]\}, \quad (3)$$

if this is finite and nondegenerate, so that the basic measure is determined by the perception operators themselves.

### 3 Perceptions rather than Minds

Another point I should emphasize is that in Sensible Quantum Mechanics, the set of all perceptions is basic, but not any higher power of this set. In other words, perceptions and the measure  $m(p)dp$  on them are basic, but not  $n$ -tuples of perceptions, or measures on  $n$ -tuples of perceptions. Thus, for example, there is no

fundamental notion of a correlation between individual complete perceptions given by any measure. (On the other hand, if a perception can be broken up into component parts, say  $A$  and  $B$ , there can be a correlation between the parts, in the sense that the measure  $m(A \cap B)$  for all perceptions containing the part  $A$  and the part  $B$  need not be the same as  $m(A)m(B)$ , the measure for all perceptions containing  $A$  times the measure for all perceptions containing  $B$ . The enormous structure in a single perception seems to suggest that such correlations within perceptions are highly nontrivial, but I see no evidence for a nontrivial correlation between maximal perceptions, since no two different maximal perceptions can be perceived together.)

Furthermore, Sensible Quantum Mechanics postulates no fundamental equivalence relation on the set of perceptions. For example, the measure gives no way of classifying different perceptions as to whether they belong to the same conscious being (e.g., at different times) or to different conscious beings. The only such classification would be by the content (including the *qualia*) of the perceptions themselves, which distinguish the perceptions, so that no two different perceptions,  $p \neq p'$ , have the same content. Based upon my own present perception, I find it natural to suppose that perceptions that could be put into the classification of being alert human perceptions have such enormous structure that they could easily distinguish between all of the  $10^{11}$  or so persons that are typically assigned to our history of the human race. However, I doubt that in a fundamental sense there is any absolute classification that uniquely distinguishes each person in all circumstances. Therefore, in the present framework perceptions are fundamental, but persons (or individual minds) are not, although they certainly do seem to be very good approximate entities that I do not wish to deny. The concept of persons and minds certainly occurs in some sense as part of the *content* of my present perception, even if there is no absolute definition of it in the framework of Sensible Quantum Mechanics itself.

In this way the framework of Sensible Quantum Mechanics proposed here is a particular manifestation of Hume's ideas [13], that "what we call a *mind*, is nothing but a heap or collection of different perceptions, united together by certain relations, and suppos'd, tho' falsely, to be endow'd with a perfect simplicity and identity" (p. 207), and that the self is "nothing but a bundle or collection of different perceptions" (p. 252). As he explains in the Appendix (p. 634), "When I turn my reflexion on *myself*, I never can perceive this *self* without some one or more perceptions; nor can I ever perceive any thing but the perceptions. 'Tis the composition of these, therefore, which forms the self." (Here I should note that what Hume calls a perception may be only one component of the "phenomenal perspective" or "maximal experience" [8] that I have been calling a perception  $p$ , so one  $p$  can include "one or more perceptions" in Hume's sense.)

Furthermore, each perception operator need not have any precise location in either space or time associated with it, so there need be no fundamental place or time connected with each perception. Indeed, Sensible Quantum Mechanics can easily survive a replacement of spacetime with some other structure (e.g., superstrings) as

more basic in the physical world. Of course, the contents of a perception can include a sense or impression of the time of the perception, just as my present perception at the perceived time of writing this includes a feeling that it is now 1994 A.D., so the set of perceptions  $p$  must include perceptions with such beliefs, but there need not be any precise time in the physical world associated with a perception. That is, perceptions are ‘outside’ physical spacetime (even if spacetime is a fundamental element of the physical world, which I doubt).

As a consequence of these considerations, there are no unique time-sequences of perceptions to form an individual mind or self in Sensible Quantum Mechanics. In this way the present framework appears to differ from those proposed by Squires [17], Albert and Loewer [18], and Stapp [19]. (Stapp’s also differs in having the wavefunction collapse at each “Heisenberg actual event,” whereas the other two agree with mine in having a fixed quantum state, in the Heisenberg picture, which never collapses.) Lockwood’s proposal [8] seems to be more similar to mine, though he also proposes (p. 232) “a continuous infinity of parallel such streams” of consciousness, “*differentiating* over time,” whereas Sensible Quantum Mechanics has no such stream as fundamental. On the other hand, later Lockwood [20] does explicitly repudiate the Albert-Loewer many-minds interpretation, so there seems to me to be little disagreement between Lockwood’s view and Sensible Quantum Mechanics except for the detailed formalism and manner of presentation. Thus one might label Sensible Quantum Mechanics as the Hume-Everett-Lockwood-Page (HELP) interpretation, though I do not wish to imply that these other three scholars, on whose work my proposal is heavily based, would necessarily agree with my present formulation.

Of course, the perceptions themselves can include components that seem to be memories of past perceptions or events. In this way it can be a very good approximation to give an approximate order for perceptions whose content include memories that are correlated with the contents of other perceptions. It might indeed be that the measure (or measure density)  $m(p)$  for perceptions including detailed memories is rather heavily peaked around approximate sequences constructed in this way. But I would doubt that either the content of the perceptions or the measure on the set of perceptions would give unique sequences of perceptions that one could rigorously identify with individual minds.

Because the physical state of our universe seems to obey the second law of thermodynamics, with growing correlations in some sense, I suspect that the measure density  $m(p)$  may have rather a smeared peak (or better, ridge) along approximately tree-like structures of branching sequences of perceptions, with perceptions further out along the branches having contents that includes memories that are correlated with the present-sensation components of perceptions further back toward the trunks of the trees. This is different from what one might expect from a classical model with a discrete number of conscious beings, each of which might be expected to have a unique sharp sequence or non-branching trajectory of perceptions. In the

quantum case, I would expect that what are crudely viewed as quantum choices would cause smeared-out trajectories to branch into larger numbers of smeared-out trajectories with the progression of what we call time. If each smeared-out trajectory is viewed as a different individual mind, we do get roughly a “many-minds” picture that is analogous to the “many-worlds” interpretation [7], but in my framework of Sensible Quantum Mechanics, the “many minds” are only approximate and are not fundamental as they are in the proposal of Albert and Loewer [18]. Instead, Sensible Quantum Mechanics is a “many-perceptions” or “many-sensations” interpretation. One might label it philosophically as Mindless Sensationalism.

Even in a classical model, if there is one perception for each conscious being at each moment of time in which the being is conscious, the fact that there may be many conscious beings, and many conscious moments, can be said to lead to a “many-perceptions” interpretation. However, in Sensible Quantum Mechanics, there may be vastly more perceptions, since they are not limited to a discrete set of one-parameter sharp sequences of perceptions, but occur for all perceptions  $p$  for which  $m(p)$  is positive. In this way a quantum model may be said to be even “more sensible” than a classical model.

One might fear that the present attack on the assumption of any definite notion of a precise identity for persons or minds as sequences of perceptions would threaten human dignity. Although I would not deny that I feel that it might, I can point out that on the other hand, the acceptance of the viewpoint of Sensible Quantum Mechanics might increase one’s sense of identity with all other humans and other conscious beings. Furthermore, it might tend to undercut the motivations toward selfishness that I perceive in myself if I could realize in a deeply psychological way that what I normally anticipate as my own future perceptions are in no fundamental way picked out from the set of all perceptions. (Of course, what I normally think of as my own future perceptions are presumably those that contain memory components that are correlated with the content of my present perception, but I do not see logically why I should be any more concerned about trying to make such perceptions happy than about trying to make perceptions happy that do not have such memories: better to do unto others as I would wish they would do unto me.) Lockwood [21] informs me that Parfit [22] has drawn similar conclusions from a Humean view.

## 4 Properties of Perception Operators

Although no one is competent to give the complete set of perception operators  $E(p)$ , one can speculate about some of their properties. In this speculation, a theoretical physicist such as myself would like to be guided by the principles of simplicity and of agreement with observations. Both are difficult, the former because we do not know all that is logically possible and have a measure of the simplicity of the different possibilities, and the latter because we do not have direct access to more than one perception at once.

On the former principle, it is because of simplicity that I do not stop at the Measure Axiom for Perceptions but also postulate a physical quantum state and a set of perception operators  $E(p)$  which give the measure density  $m(p)$  by the Sensible Quantum Axiom. If one has the correct  $m(p)$  (as well as the basic measure  $dp$ , which is a separate element from the set of perceptions if they are not discrete), the Measure Axiom for Perceptions is logically sufficient for describing a measured set of perceptions. It might seem to be complicating the theory to add a physical quantum state and a set of perception operators  $E(p)$ , but I believe that this structure of a postulated physical world can give a simpler explanation of  $m(p)$  than just giving it directly without this explanation in terms of a postulated physical world. In this way the whole of the mental world and the physical world can be simpler than just the mental world considered by itself. (One might also raise the reverse question of whether the whole is simpler than the physical world alone, by which I mean an alternative logically possible world in which all  $E(p)$  are zero, so that in it the quantum state is the same as in ours, but no conscious perceptions occur.)

On the latter principle, the only agreement with observations that one can impose is the assumption that one's perception be not too atypical, i.e., that it have not too low a measure density  $m(p)$ . For example, if both the basic measure  $dp$  and the quantum measure  $m(p)dp$  were integrable, over the set of all perceptions  $p$ , to finite numbers, say  $b$  and  $q$  respectively, then one can ask that one's particular perception not have  $m(p) \ll q/b$ , the latter being the average of  $m(p)$  over all perceptions. Unfortunately, I see no reason why a simple theory should make either of these integrals finite, since almost any finite number is more complex than infinity. (Perhaps the fact that my present perception seems to have a large but not infinite amount of information in it is evidence that the simplest complete theory is not extremely simple, since I would expect an extremely simple theory to make typical perceptions have either an extremely small or an infinite amount of information.)

Perhaps a more realistic approach one can make toward agreement with observations is to assume that the measure density  $m(p)$  for one's perception is not much lower than the measure density for slightly different perceptions. For example, if one has a perception  $p$  of having made a certain quantum measurement  $n$  times and having gotten  $m$  positive results, one can imagine another perception  $p'$  which is similar except for perceiving  $m'$  positive results. Then one would like  $m(p)$  to be not much lower than  $m(p')$ . If the measures (or measure densities)  $m(p)$  and  $m(p')$  of the perceptions  $p$  and  $p'$  can to a good approximation be replaced by the quantum-derived measures  $\tilde{m}(r)$  and  $\tilde{m}(r')$  for the respective perceived results  $r$  and  $r'$  in the physical world, one can check whether  $\tilde{m}(r)$  is not much lower than  $\tilde{m}(r')$ . In such cases there is considerable experimental evidence that the ordinary quantum predictions are consistent with observations if  $\tilde{m}(r)$  is the expectation value of a projection operator  $P(r)$  for the physical result  $r$ .

Similarly, it might be natural to assume that each perception measure density  $m(p)$  is given by the expectation value of a projection operator, say one that projects

onto the brain states that cause the perception, if indeed the perception is caused by various brain states. However, before making this specific assumption, let me make some weaker postulates that one could add to Sensible Quantum Mechanics to make it more restrictive and yet have a more specific content:

**Hypothesis A:** The expectation value of each  $E(p)$  has a constant maximum value, say unity, in the set of all normalized quantum states.

Assuming that the quantum state is normalizable (perhaps an overly restrictive assumption), Hypothesis A and the resulting Sensible Quantum Mechanics A would have  $0 \leq m(p) \leq 1$  for all  $p$ , and there would exist a normalizable quantum state for each  $p$  such that the corresponding  $m(p)$  would be unity in that state.

Without some such restriction like that, one could leave all the explanation of  $m(p)$  in the operators  $E(p)$  rather than in the quantum state. For example, one could get  $m(p)$  to be any positive function whatsoever simply by choosing  $E(p)$  to be that function times the identity operator, which would make  $m(p)$  independent of the state (so long as the state is normalized so that the expectation of the identity operator is unity; other normalizations would change the scale of the measure but would leave the conditional probabilities of Eq. (2) unchanged). We would like to assume that instead the  $E(p)$  are restricted so the explanation for the  $m(p)$  lies largely in the quantum state.

Now Hypothesis A is still not highly restrictive, so one may wish to look for more restrictions on the operators  $E(p)$ . For example, one may be motivated by the consistent or decohering histories approaches [1, 2, 3, 4, 5] to assume that perceptions are connected with histories and so perhaps make the following assumption:

**Hypothesis B:** Each  $E(p)$  has the form  $E(p) = C^\dagger C / \max(C^\dagger C)$ , where  $C = P^{(n)}P^{(n-1)} \dots P^{(2)}P^{(1)}$  with the integer  $n$  and the projection operators  $P^{(i)}$  all depending on the perception  $p$ , and where  $\max(C^\dagger C)$  is the maximum expectation value of  $C^\dagger C$  in any normalized quantum state.

The denominator in the expression for  $E(p)$  in Hypothesis B is chosen so that Hypothesis B is a special case of Hypothesis A, but one could also consider an alternative Hypothesis B' in which the denominator is omitted. One could also consider generalizing Hypothesis B or B' to B\* or B\*' respectively, in which  $C$  is a sum of sequences of projection operators, as is allowed in decohering histories [3].

It is certainly logically possible that perceptions might depend on histories rather than events that one could consider localized on hypersurfaces of constant time if the physical world has such a time. However, as a previous advocate of the 'marvelous moment' approach to quantum mechanics in which only quantities on one such hypersurface can be tested [23], I find it more believable to assume that perceptions are caused by brain states which could be at one moment of time if there are such things in the physical world. The generalization of this hypothesis to the case in which there may not be a well-defined physical time leads me to make the following restriction of Hypothesis B or B' to the case in which the integer  $n$  is always 1:

**Hypothesis C:**  $E(p) = P(p)$ , a projection operator that depends on the per-

ception  $p$ .

Hypothesis C appears to be a specific mathematical realization of part of Lockwood’s proposal [8] (p. 215), that “a phenomenal perspective [what I have here been calling simply a perception  $p$ ] may be equated with a shared eigenstate of some preferred (by consciousness) set of compatible brain observables.” Here I have expressed the “equating” by Eq. (1), and presumably the “shared eigenstate” can be expressed by a corresponding projection operator  $P(p)$ .

I should also emphasize that if the same conscious perception is produced by several different orthogonal “eigenstates of consciousness” (e.g., different states of a brain and surroundings that give rise to the same perception  $p$ ), then in Hypothesis C the projection operator  $P(p)$  would be a sum of the corresponding rank-one projection operators and so would be a projection operator of rank higher than unity (perhaps even infinite), which is what I would expect. On the other hand, if  $E(p)$  were a sum of noncommuting projection operators corresponding to nonorthogonal states, or a weighted sum of projection operators with weights different from unity, then generically  $E(p)$  would not have the form of a projection operator  $P(p)$ .

If one has a constrained system, such as a closed universe in general relativity, the quantum state may obey certain constraint equations, such as the Wheeler-DeWitt equations. The projection operators  $P(p)$  of perception in Hypothesis C may not commute with these constraints, in which case they may give technically ‘unphysical’ states when applied to the quantum state. But so long as their expectation values can be calculated, that is sufficient for giving the perception measure density  $m(p)$ . What it means is that in Hypothesis C, the perception operators should be considered as projection operators in the space of unconstrained states, even though the actual physical state does obey the constraints.

Alternatively, if one wishes to write the perception operators  $E(p)$  as operators within the space of constrained states, Hypothesis C could be modified to the following assumption to give perception operators  $E(p)$  that commute with the constraints and so keep the state ‘physical’:

**Hypothesis  $\tilde{C}$ :**  $E(p) = P_C P(p) P_C$ , where  $P_C$  is the projection operator within the space of unconstrained states that takes any state to the corresponding constrained state, and  $P(p)$  is a projection operator in the space of unconstrained states that depends on the perception  $p$ .

One could obviously alternatively insert the projection operator  $P_C$  before and after the perception operators of Hypothesis B,  $B'$ ,  $B^*$ , or  $B^{**}$  to get Hypothesis  $\tilde{B}$ ,  $\tilde{B}'$ ,  $\tilde{B}^*$ , or  $\tilde{B}^{**}$  respectively.

One can also get something like Hypothesis  $\tilde{C}$ , say Hypothesis  $\hat{C}$ , even for unconstrained systems if they have symmetries (e.g., the Poincaré symmetries of quantum field theory in a classical Minkowski spacetime, though one would not expect these symmetries to survive when one includes gravity), since one might then expect that  $E(p)$  should be invariant under the symmetry group with elements  $g$ . Then if one starts with a projection operator  $P(p)$  that is not invariant under the action of each

group element, say  $P(p) \neq gP(p)g^{-1}$ , then one might expect  $E(p)$  to be proportional to the sum or integral of  $gP(p)g^{-1}$  over the group elements  $g$ . Unless all these different  $gP(p)g^{-1}$ 's are orthogonal (which does not appear possible for a continuous symmetry group), the resulting  $E(p)$  will generically not be a projection operator, but it can be said to have arisen from one, which is what I would propose as the translation of the marvelous moment assumption to Sensible Quantum Mechanics.

If one can learn what the  $E(p)$ 's are, one can compare them with the forms given by these hypotheses and thereby distinguish between the consistent or decohering histories approaches and the marvelous moment approach as I here propose they be applied to conscious perceptions (if indeed any of them do). Of course, either of these approaches could be applied without inconsistency to mathematical probabilities that one might wish to define in the physical world, but in the present framework of Sensible Quantum Mechanics, such probabilities are an unnecessary addition to the ontology.

I should emphasize that in no case am I assuming that the  $E(p)$ 's commute for different perceptions, or that the sum or integral of the  $E(p)$ 's over all perceptions is the identity operator. Neither am I assuming that the resulting expectation values  $m(p)$  in the particular quantum state of the universe are normalized so that their sum or integral over all perceptions gives a finite number  $q$ , or that this number is unity, though in any case the conditional probabilities given by Eq. (2) are automatically normalized to give unity when summed over a complete set of disjoint sets  $B$  of perceptions. Of course, if  $q$  is finite, one can simply rescale  $E(p)$  to  $e(p) = E(p)/q$ , which rescales  $m(p)$  to  $m(p) = m(p)/q$  that is normalized to give unity when summed or integrated over all perceptions. This rescaling obviously leaves the conditional probabilities of Eq. (2) invariant when  $m(A \cap B)$  and  $m(A)$  there are replaced by  $m(A \cap B)$  and  $m(A)$  respectively. On the other hand, I am sceptical that the simplest consistent description of our universe will give a normalizable  $m(p)$  (finite  $q$ ).

If a perception operator  $E(p)$  is a projection operator, and the quantum state of the universe is represented by the pure state  $|\psi\rangle$ , one can ascribe to the perception  $p$  the pure Everett "relative state"

$$|p\rangle = \frac{E(p)|\psi\rangle}{\|E(p)|\psi\rangle\|} = \frac{E(p)|\psi\rangle}{\langle\psi|E(p)E(p)|\psi\rangle^{1/2}}. \quad (4)$$

Alternatively, if the quantum state of the universe is represented by the density matrix  $\rho$ , one can associate the perception with a relative density matrix

$$\rho_p = \frac{E(p)\rho E(p)}{\text{Tr}[E(p)\rho E(p)]}. \quad (5)$$

Either of these formulas can be applied when the perception operator is not a projection operator, but then the meaning is not necessarily so clear.

If one has two perceptions  $p$  and  $p'$ , one can calculate an overlap fraction between them as

$$f(p, p') = \frac{\langle E(p)E(p')\rangle\langle E(p')E(p)\rangle}{\langle E(p)E(p)\rangle\langle E(p')E(p')\rangle}. \quad (6)$$

If the quantum state of the universe is pure, this is the same as the overlap probability between the two Everett relative states corresponding to the perceptions:  $f(p, p') = |\langle p|p'\rangle|^2$ . Thus one might in some sense say that if  $f(p, p')$  is near unity, the two perceptions are in nearly the same one of the Everett “many worlds,” but if  $f(p, p')$  is near zero, the two perceptions are in nearly orthogonal different worlds. However, this is just a manner of speaking, since I do not wish to say that the quantum state of the universe is really divided up into many different worlds. Thus I do not wish to propose that  $f(p, p')$  be interpreted as a fundamental element of Sensible Quantum Mechanics. In any case, one can be conscious only of a single perception at once, so there is no way in principle that one can test any properties of joint perceptions such as  $f(p, p')$ .

## 5 Quantum Field Theory Model

Although Sensible Quantum Mechanics transcends quantum theories in which space and time are fundamental, and although I believe that such theories will need to be transcended to give a good theory of our universe, it might help to get a better feel for the spacetime properties of perceptions by considering the context of quantum field theory in an unquantized curved globally-hyperbolic background spacetime in which spacetime points are unambiguously distinguished by the spacetime geometry (so that the Poincaré symmetries are entirely broken and one need not worry about integrating over  $gP(p)g^{-1}$ 's to satisfy superselection rules for energy, momentum, and/or angular momentum [24]). This simplified model might in some sense be a good approximation for part of the entire quantum state of the universe in a correct theory if there is one that does fit into the framework of Sensible Quantum Mechanics and does give a suitable classical spacetime approximation.

In the Heisenberg picture used in this paper, the quantum state is independent of time (i.e., of a choice of Cauchy hypersurface in the spacetime), but the Heisenberg equations of evolution for the fundamental fields and their conjugate momenta can be used to express the operators  $E(p)$  in terms of the fields and momenta on any Cauchy hypersurface. The arbitrariness of the hypersurface means that even in this quantum field theory with a well-defined classical spacetime, and even with a definite foliation of the spacetime by a one-parameter (time) sequence of Cauchy hypersurfaces, there is no unique physical time that one can assign to any of the perceptions  $p$ ; they are ‘outside’ time as well as space.

Furthermore, the operators  $E(p)$  in this simplified model are all likely to be highly nonlocal in terms of local field operators on any Cauchy hypersurface, since quantum field theories that we presently know do not seem to have enough local operators to describe the complexities of an individual perception, unless one considers high spatial derivatives of the field and conjugate momentum operators. However, for a given one-parameter (time) sequence of Cauchy hypersurfaces, one might rather arbitrarily choose to define a preferred time for each perception  $p$  as the time giving

the Cauchy hypersurface on which the corresponding  $E(p)$ , if expressed in terms of fields and momenta on that hypersurface, has in some sense the smallest spatial spread at that time.

For example, to give a tediously explicit *ad hoc* prescription, on a Cauchy hypersurface labeled by the time  $t$  one might choose a point  $P$  and a ball that is the set of all points within a certain geodesic radius  $r$  of the point. Then one can define an operator  $E'(p; t, P, r)$  that is obtained from  $E(p)$  written in terms of the fields and conjugate momenta at points on the hypersurface by throwing away all contributions that have any fields or conjugate momenta at points outside the ball of radius  $r$  from the point  $P$ . Now define the overlap fraction

$$F(p; t, P, r) = \frac{\langle E(p)E'(p; t, P, r) \rangle \langle E'(p; t, P, r)E(p) \rangle}{\langle E(p)E(p) \rangle \langle E'(p; t, P, r)E'(p; t, P, r) \rangle}. \quad (7)$$

(If both  $E(p)$  and  $E'(p; t, P, r)$  were projection operators, and the actual quantum state were a pure state, then  $F$  would be the overlap probability between the states obtained by projecting the actual quantum state by these projectors and normalizing.) If  $E(p)$  is nonlocal, this fraction  $F$  will be small if the radius  $r$  is small but will be nearly unity if the radius  $r$  is large enough for the ball to encompass almost all of the Cauchy hypersurface. For each perception  $p$ , time  $t$ , and point  $P$ , one can find the smallest  $r$  that gives  $F = 1/2$ , say, and call that value of the radius  $r(p; t, P)$ . Then one can find the point  $P = P(p; t)$  on the hypersurface that gives the smallest  $r(p; t, P)$  on that hypersurface for the fixed perception  $p$  and call the resulting radius  $r(p; t)$ . Finally, define the preferred time  $t_p$  as the time  $t$  for which  $r(p; t)$  is the smallest, and label that smallest value of  $r(p; t)$  for the fixed perception  $p$  as  $r_p$ .

If the perception operator  $E(p)$  for some human conscious perception is not unduly nonlocal in the simplified model under present consideration, and if the quantum state of the fields in the spacetime has macroscopic structures that at the time  $t_p$  of the perception are fairly well localized (e.g., with quantum uncertainties less than a millimeter, say, which would certainly not be a generic state, even among states which give a significant  $m(p)$  for the perception in question), one might expect that at this time the ball within radius  $r_p$  of the point  $P(p; t_p)$  on the hypersurface labeled by  $t_p$  would be inside a human brain. It would be interesting if one could learn where the point  $P(p; t_p)$  is in a human brain, and what the radius  $r_p$  is, for various human perceptions, and how the location and size of this ball depends on the perception  $p$ .

## 6 Questions and Speculations

One can use the framework of Sensible Quantum Mechanics to ask questions and make speculations that would be difficult without such a framework. I shall here give some examples, without intending to imply that Sensible Quantum Mechanics

itself, even if true, would guarantee that these questions and speculations make sense, but it does seem to allow circumstances in which they might.

First, in the model of quantum field theory on a classical spacetime with no symmetries, and with a quantum state having well-localized human brains on some Cauchy hypersurface labeled by time  $t$ , one might ask whether it is possible to have two quite different perceptions, say  $p$  and  $p'$ , in nearly the same Everett world in the sense of having the  $f(p, p')$  of Eq. (6) near unity, and giving  $E(p)$  and  $E(p')$  both with the same preferred time  $t_p = t$  and both localized (by the rather *ad hoc* prescription above) in balls in the same brain. In other words, can one brain have two different (maximal) perceptions in the same world at the same time, each not aware of the other? Unless we are solipsists, we generally believe this is possible for two separate brains, but would one brain be sufficient? Furthermore, if it is possible, can the two balls (corresponding to  $p$  and  $p'$  respectively) be overlapping spatially, or need they be separate regions in the brain?

Second, one might ask whether and how the sum (or integral) of the measures (or measure densities)  $m(p)$  associated with an individual brain region at the time  $t$  depends on the brain characteristics. One might speculate that it might be greater for brains that are in some sense more intelligent, so that in a crude sense brighter brains have more perceptions. This could explain why you do not perceive yourself to be an insect, for example, even though there are far more insects than humans. To speculate even further, it might imply that your perception is not atypical even if you perceive yourself to be more intelligent than the average person, as I predict that most of my readers do. Of course, my prediction is based on an assumed selection effect of those who read physics papers, on my own sinful pride that leads me to assume that physicists are brighter than average, and on a psychologically-projected assumption that most people think they are more intelligent than most people. But if you really had good reasons for believing that you were brighter than average, even before reading this paper, you may not really be justified in any feeling of atypicality; it might simply be that your perceptions, like most perceptions in the measure  $m(p)dp$ , are associated with brighter-than-average people.

I should emphasize that even if this wild conjecture, which is not an inevitable consequence of Sensible Quantum Mechanics (but which can be considered under this framework in a way that might be difficult under other frameworks), could be shown to be true, I would not propose that a more intelligent person be assigned more value or be given more political rights or privileges. It would just say that, when weighted by the quantum-mechanical operators  $E(p)$  for perceptions, it is conceivable that more intelligent people would have the bulk of the weight rather than being unusual. But being in this newly-defined majority (if indeed it is the bulk of the weight) should not confer more individual political rights or privileges, just as with the weighting of numbers the majority of people who are economically poor are not given more individual political rights or privileges than the minority of people who are economically rich.

Third, one might conjecture that an appropriate measure on perceptions might give a possible explanation of why most of us perceive ourselves to be living on the same planet on which our species developed. This observation might seem surprising when one considers that we may be technologically near the point at which we could leave Earth and colonize large regions of the Galaxy, presumably greatly increasing the number of humans beyond the roughly  $10^{11}$  that are believed to have lived on Earth. If so, why don't we have the perceptions of one of the vast numbers of humans that may be born away from Earth? One answer is that some sort of doom is likely to prevent this vast colonization of the Galaxy from happening [25, 26, 27, 28], though these arguments are not conclusive [29]. Although I would not be surprised if such a doom were likely, I would naïvely expect it to be not so overwhelmingly probable that the probability of vast colonization would be as small as is the presumably very small ratio of the total number of humans who could ever live on Earth to those who could live throughout the Galaxy if the colonization occurs. Then, even though the colonization may be unlikely, it may still produce a higher measure for conscious perceptions of humans living off Earth than on it.

However, another possibility is that colonization of the Galaxy is not too improbable, but that it is mostly done by self-replicating computers or machines who do not tolerate many humans going along. If the number of these dominate humans as “intelligent” beings, one might still have the question of why we perceive ourselves as being humans rather than as being one of the vastly greater numbers of such machines. But the explanation might simply be that the *weight* of conscious perceptions (the sum or integral of the  $m(p)$ 's corresponding to the type of perceptions under consideration) is dominated by human perceptions, even if the *number* of “intelligent” beings is not. In other words, human brains may be much more efficient in producing conscious perceptions than the kinds of self-replicating computers or machines which may be likely to dominate the colonization of the Galaxy. If such machines are more “intelligent” than humans in terms of information-processing capabilities and yet are less efficient in producing conscious perceptions, our perceptions of being human would suggest that the measure of perceptions is not merely correlated with intelligence.

It might be tempting to take the observations that these speculations might explain (your perception of yourself as human rather than as insect or even possibly as more intelligent than average humans, if my prediction of that is correct, and our perception of ourselves as humans on our home planet) as evidence tending to support the speculations. For example, if one assigns prior probabilities  $P(H_i)$  to an exhaustive set of hypotheses  $H_i$  (say each giving a quantum state of the universe and a set of operators  $E(p)$  in Sensible Quantum Mechanics), and then if the conditional probability of a perception  $p$ , given the hypothesis  $H_i$ , were  $P(p|H_i)$ , by Bayes' rule the posterior conditional probability of the speculation  $H_i$  would be

$$P(H_i|p) = \frac{P(p|H_i)P(H_i)}{\sum_j P(p|H_j)P(H_j)}. \quad (8)$$

Unfortunately, in Sensible Quantum Mechanics one has at most measure densities  $m(p)$  for individual perceptions, and so one cannot unambiguously give the probability  $P(p|H_i)$  without some specification of the normalization of  $m(p)$  in the hypothesis  $H_i$ . Possibly one can replace the probability for a perception with the ‘typicality’ of the perception [15, 16]. Without some such solution to this problem, I do not see how to use observations to turn prior probabilities (say given by some function of the simplicity of the quantum state and perception operators) into posterior probabilities for quantum states and perception operators. Otherwise it would appear that one could only start with a given quantum state and set of perception operators, and then can one calculate the measure for all perceptions by Eq. (1) and use Eq. (2) to calculate conditional probabilities for sets of perceptions.

## 7 Conclusions

In conclusion, I am proposing that Sensible Quantum Mechanics, with its Measure Axiom for Perceptions and its Sensible Quantum Axiom above, is the best framework we have at the present level for understanding conscious perceptions and the interpretation of quantum mechanics. Of course, the framework would only become a complete theory once one had the set of all perceptions  $p$ , the basic measure  $dp$  on it, the perception operators  $E(p)$ , and the quantum state of the universe.

Even such a complete theory of perceptions and the physical world need not be the ultimate simplest complete theory. There might be a simpler set of unifying principles from which one could in principle deduce the perceptions, basic measure, perception operators, and quantum state, or perhaps some simpler entities that replaced them. For example, although in the present framework of Sensible Quantum Mechanics, the physical world (i.e., the quantum state), along with the perception operators, determines the measure density for perceptions in the mental world, there might be a reverse effect of the mental world affecting the physical world to give a simpler explanation than we have at present of the correlation between will and action (why my desire to do something I feel am capable of doing is correlated with my perception of actually doing it, i.e., why I “do as I please”). If the quantum state is partially determined by an action functional, can desires in the mental world affect that functional (say in a coordinate-invariant way that therefore does not violate energy-momentum conservation)? Such considerations may call for a more unified framework than Sensible Quantum Mechanics, which one might call Sensational Quantum Mechanics. Such a more unified framework need not violate the limited assumptions of Sensible Quantum Mechanics, though it might do that as well and perhaps reduce to Sensible Quantum Mechanics only in a certain approximate sense.

To explain these frameworks in terms of an analogy, consider a classical model of spinless massive point charged particles and an electromagnetic field in Minkowski spacetime. Let the charged particles be analogous to the physical world (the quantum state of the universe), and the electromagnetic field be analogous to the mental

world (the set of perceptions with its measure  $m(p)dp$ ). At the level of a simplistic materialist mind-body philosophy, one might merely say that the electromagnetic field is part of, or perhaps a property of, the material particles. At the level of Sensible Quantum Mechanics, the charged particle worldlines are the analogue of the quantum state, the retarded electromagnetic field propagator (Coulomb's law in the nonrelativistic approximation) is the analogue of the perception operators, and the electromagnetic field determined by the worldlines of the charged particles and by the retarded propagator is the mental world. (Here you can see that this analogue of Sensible Quantum Mechanics is valid only if there are no free incoming electromagnetic waves.) At the level of Sensational Quantum Mechanics, at which the mental world may affect the physical world, the charged particle worldlines are partially determined by the electromagnetic field through the change in the action it causes. (This more unified framework better explains the previous level but does not violate its description, which simply had the particle worldlines given.) At a yet higher level, there is the possibility of incoming free electromagnetic waves, which would violate the previous frameworks that assumed the electromagnetic field was uniquely determined by the charged particle worldlines. Finally, at a still higher level, there might be an even more unifying framework in which both charged particles and the electromagnetic field are seen as modes of a single entity (e.g., to take a popular current speculation, a superstring).

Therefore, although it is doubtful that Sensible Quantum Mechanics is the correct framework for the final unifying theory (if one does indeed exist), it seems to me to be a move in that direction that is consistent with what we presently know about consciousness and the physical world.

## Acknowledgments

I consciously perceive a gratitude for having had fruitful discussions or correspondence on this general subject with David Albert, Andrei Barvinsky, Arvind Borde, David Boulware, Patrick Brady, Howard Brandt, Bruce Campbell, Brandon Carter, David Deutsch, Valeri Frolov, Murray Gell-Mann, Farhad Ghodoussi, Shelly Goldstein, Richard Gott, Jim Hartle, Geoff Hayward, Bei-Lok Hu, Viqar Husain, Rocky Kolb, Tomáš Kopf, Pavel Krtouš, Werner Israel, John Leslie, Andrei Linde, Michael Lockwood, Robb Mann, John Polkinghorne, David Salopek, Abner Shimony, Euan Squires, Lenny Susskind, Bill Unruh, Alex Vilenkin, John Wheeler, and various others whose names aren't in my immediate perception. I am especially grateful to my wife Cathy for helping me become more aware of my feelings. Finally, financial support has been provided by the Natural Sciences and Engineering Council of Canada.

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