Prolegomena for a Quantum Reformation

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A program for the reformation of quantum mechanics is offered. The philosophical implications of current interpretations of quantum mechanics produce severe inconsistencies. Principles are offered for a new approach including a return to robust realism. New lines of inquiry are suggested aimed at developing a successor theory without the current defects.

1. Introduction

Since the 1920's, quantum mechanics (QM) has formed the theoretical cornerstone of physics. During the past century, the formalism of QM has yielded a body of predictive success unprecedented in the history of science. Yet QM has been beset with conceptual problems since its inception. Albert Einstein spent much of his career in a dramatically unsuccessful campaign to highlight the issues, for which he was universally and unfairly disparaged.

Proponents of the current formulation of QM are of two types. On the one hand are the practitioners who employ the formalism to great success. So long as the formalism works, they are content. They don't worry about the conceptual problems. On the other hand are the quantum philosophers. They revel in the inconsistencies of the standard interpretations with a priestly confidence. They believe the inconsistencies should be accepted or even embraced as representing the deepest nature of the world. Neils Bohr was the first and most influential of the quantum philosophers.

And then there are the skeptics. Einstein and Erwin Schrödinger were among the first, followed by David Bohm and John Bell. The skeptics saw a deep inconsistency, an illogic, in quantum philosophy, despite the success of the formalism. Count me in this group.

In this paper I propose a program to address the problems of quantum mechanics. In Section 2, I provide a brief overview of the orthodox interpretation of QM. I discuss the uncertainty principle in Section 3. This principle has often been touted as the essence of quantum mechanics, but is merely a result of the extended nature of quantum entities.

In Section 4, I describe the real mystery of quantum mechanics, wave particle duality, which may be an important clue to our ultimate understanding. Section 5 addresses quantum measurement. Here I address the first of the two fundamental problems with the orthodox interpretation, the bifurcation of reality. I discuss the second problem in Section 6, the probability problem. The orthodox interpretation of QM requires an objective notion of probability knitted into the very fabric of reality. I believe this concept is incoherent. In Section 7, I discuss Bell's theorem which purports to place very restrictive constraints on any potential alternative formulations of quantum mechanics. Then with a clear view of the problems of the current quantum interpretations, I lay out a set of guiding principles for a new approach in Section 8. Finally, in Section 9, I offer some suggestions for the direction of a possible solution. These are somewhat speculative but nevertheless offer a clear picture of the direction a solution should take. Section 10 gives my concluding thoughts.

2. Background

In the 1930's, John Von Neumann wrote down the formal mathematical theory of non-relativistic quantum mechanics [Von Neumann, 1932]. It is Von Neumann's formal theory that is taught to physics graduate students under the guise of the Copenhagen or orthodox interpretation. When physicists solve problems in quantum mechanics, they follow the prescriptions of Von Neumann, employing the mathematical machinery he set forth. Here I lay out the formalism of quantum mechanics in sufficient detail to highlight the conceptual issues while omitting most of the mathematical technicalities.

1) The state of a quantum mechanical system is represented by a vector $\left|\Psi\right\rangle$ in a suitable Hilbert space. These state vectors all have magnitude 1; that is, $\left\langle\Psi\middle|\Psi\right\rangle = 1$. Two state vectors that differ only by a phase factor (a complex number of magnitude 1) represent the same physical state.
2) A physically observable quantity like the position or momentum of a particle is represented by a Hermitian operator on the Hilbert space of states.

3) The evolution of a quantum mechanical system in time is provided by the Schrödinger (or wave) equation given by

$$i\hbar \frac{d}{dt}|\Psi\rangle = H(t)|\Psi\rangle,$$

where $|\Psi\rangle$ is the state vector, $i = \sqrt{-1}$, $\hbar$ is Planck's constant divided by 2π and $\frac{d}{dt}|\Psi\rangle$ is the time derivative (time rate of change) of $|\Psi\rangle$. H is a Hermitian operator called the Hamiltonian of the system. The eigenvalues of H are the allowable energies of the system.

4) Since an observable quantity is a Hermitian operator, we can write any state vector in terms of the eigenvectors of that observable. Thus, if A is an observable, then the state vector $|\Psi\rangle$ can be written $|\Psi\rangle = \sum_{i=1}^{N} a_i |A_i\rangle$.

5) If a measurement of an observable is made, the result of the measurement will be one of the eigenvalues of the corresponding operator. The eigenvalues of Hermitian operators are real numbers. The probability that the result of the measurement will be a particular eigenvalue λ_i, corresponding to the eigenvector $|A_i\rangle$ is given by $|a_i|^2$, the square of the expansion coefficient of $|\Psi\rangle$ with respect to that same eigenvector.

6) At the time of the measurement where λ_i is the result, the state of the system changes to a state represented by $|A_i\rangle$. This is called the collapse of the wave function.

The problems with QM come from items 5 and 6. It is here that the formalism makes connection with the real world through the process of measurement. It is here that the concepts measurement and probability enter the theory at a fundamental level. And as I will show below, these two concepts give rise to issues that must be solved if QM or its successor can be viewed as truly fundamental.

3. The Uncertainty Principle

In classical Newtonian mechanics a particle is characterized by its position and momentum. *That* a particle could be said to have a position and a momentum is part of the classical mindset. A curious and seemingly shocking feature of the quantum world is that the position and momentum of a particle cannot be simultaneously defined or measured. This fact is the famous Heisenberg uncertainty principle. It is often claimed to be the essence of QM, and the critical junction where QM parted ways with classical physics [Lindley, 2007]. It this section, I show that the uncertainty principle is a rather ordinary consequence of the extended nature of quantum mechanical entities.

In its simplest form the Heisenberg uncertainty principle is written as $\Delta x \Delta p \geq \hbar / 2$, where Δx is the uncertainty in the position of the particle and Δp is the uncertainty in the momentum. From the formalism, an observable such as position or momentum is represented by an operator on the Hilbert space of states. An arbitrary state can be expressed as a sum of eigenvectors (also called eigenstates) of that operator. To explain the uncertainty principle in these terms we note the mathematical fact that no state can be simultaneously an eigenstate of position and momentum, that the eigenstates of these particular operators are incompatible. In fact, if a system is in an eigenstate of position (the uncertainty in position is zero) then its expansion in terms of eigenstates of momentum includes a contribution from all possible momentum eigenstates (the uncertainty in momentum is maximized—infinite in the case of a free particle) and vice versa.

In the early days of quantum mechanics Einstein rebelled against the limitations of the uncertainty principle. He devised ingenious schemes in an attempt to circumvent and avoid the restriction imposed by Heisenberg, but to no avail. Each time his arguments were refuted by Bohr, using ingenious reasoning of his own. And each time Bohr used arguments hinging around the measurability of position and momentum in the quantum system. It seemed, and was argued, that in the course of measuring the position of an electron, for example, the electron would be disturbed by the measurement so that its momentum became subsequently changed or ill defined.

That the process of measurement disturbs the physical system being measured is a common sense conclusion that applies to all physics, quantum or otherwise. Consider a free system, a system isolated from the rest of the world, evolving in time according to a set of physical laws. How should we obtain information about that system? By measurement, of course. But the act of measurement implies a physical interaction with the system in question, in which case the system is no longer isolated. We have changed it. This phenomenon is not unique to physics but is fundamental to all of science: psychologists can never be quite sure if a subject is responding for the psychologist's benefit—acting—or relating deep features of their inner selves. Field biologists go to great lengths, erecting blinds, wearing disguises, to minimize their interactions with animal subjects. It's just that in dealing with the incredibly tiny objects of the quantum realm the problem becomes even more acute.

Fundamentally, the uncertainty principle is not about disturbing the system, it is about the extended nature of matter. Although not obvious, Schrödinger's equation, when equipped with a standard form for the Hamiltonian operator, describes the behavior of a wave-like entity. And as can easily be shown, even classical waves obey an uncertainty principle. This elementary property of waves is derived in most texts on classical wave theory. It is a consequence of the Schwarz inequality and Parseval's theorem. Parseval's theorem is a relationship between a parameter like position x, or time t, and its Fourier twin, in this case the wave number k or the frequency ω. The key mathematical point is that to calculate the wave number distribution of a wave packet, you need to do a spatial integral, i.e., average the wave packet over a spatial region. Then, if you equate the wave number to the momentum, you recover the Heisenberg relation.

Waves are distributed entities; it is only possible to determine global properties of waves (like their direction of travel) by looking at them globally. Think of a cork bobbing in the ocean. If you look at its motion, all you can tell is that it's going up and down. Although you know its position precisely, you know nothing about the direction of the underlying wave. If you start adding more corks at different locations, you begin to get some information about direction, but you can only get a really accurate estimate of the direction from a large array of corks—and now you've lost a precise position. The uncertainty principle is a classical consequence of the global, extended nature of fundamental entities.

4. Wave Particle Duality

A better candidate for the essence of quantum mechanics is the dual wave-particle nature of matter. This feature, highlighted by Bohr with his principle of complementarity, can be described by the fact that sometimes a fundamental entity behaves like a point particle possessing mass and momentum (like a marble), but at other times seems to behave like a wave, exhibiting typical wavelike phenomena like diffraction and interference. Yet clever nature conspires to insure that these apparently contradictory features are not simultaneously displayed.

Bohr's principle of complementarity is perhaps the heart of quantum mechanics as he saw it. Both the particle view and the wave view are necessary for a complete description of nature yet they are mutually exclusive with respect to any particular experimental situation. In Bohr's own words, quantum mechanics

> forces us to adopt a new mode of description as complementary in the sense that any given application of classical concepts precludes the simultaneous use of other classical concepts which in a different connection are equally necessary for the elucidation of the phenomena. [Bohr, 1934, p. 10]

The key concepts in complementarity are joint completion and mutual exclusiveness. Joint completion means we need both the wave and particle nature of matter to completely characterize it. Mutual exclusiveness means that either the wave nature or the particle nature, but not both, will manifest itself in a given experimental situation.

The paradigmatic example of complementarity in quantum mechanics is the famous double slit experiment. Consider a light source (laser) shining on a blank screen. Cut in the screen are two narrow vertical slits spaced very close together. Several feet behind the screen is another screen upon which one can view the light after having passed through the slits. What appears on this screen is the classic interference pattern we expect to see from a wave-like phenomenon. We see a series of strips of alternating light and dark parallel to the slits with the brightest strip directly between the slits, and decreasing in brightness to either side. This pattern is explained by the interference between the two sets of waves, one emanating from each slit. The bright areas represent constructive interference, where the crests of the two waves add together; the dark areas represent destructive interference, where the crest of one wave meets the trough of the other and cancel each other out.

If our light source is a 10 Watt bulb of green light (wavelength = 5000 angstroms) and our exposure was for 1 second, then the interference pattern we see is composed of approximately 25 billion-billion individual photons. But what if we could turn down the intensity of our source? Experiment shows that the interference will remain. Suppose we turn the source way, way down, so that only one photon is emitted every minute? We will have to replace our screen with a series of photo-multipliers (photon detectors). Each minute will register the receipt of a photon at one of the detectors. The amazing thing is if we put a dot where each photon is detected and let the data accumulate over time, we will begin to fill in the original interference pattern!

How do we understand this result? When there are trillions of photons going through the slits we have no trouble imagining how they interfere with each other, but when there is just one? Does the photon interfere with itself? Does it go through both slits at once? Either of these views seems inconsistent with the view of a photon as an indivisible particle of light. What if we attempt to determine if the photon went through one or the other of the slits? Experiment shows that the interference pattern disappears, leaving a pattern consistent with two single, non-interfering slits. This phenomenon of the double slit is not restricted to light (photons). We can get similar results with electrons and even heavier particles like protons or neutrons though the technical difficulties are magnified. There is even evidence showing double slit behavior for buckeyballs (C_{60}), an aggregate structure made up of carbon atoms arranged in a spherical shape, with a mass some 720 times that of a proton [Arndt et. al., 1999].

5. The Measurement Problem

The measurement problem in QM has been perplexing physicists since the formative days of the theory. The intractability of this problem greatly discouraged many of the early developers of the theory, most notably Schrödinger and de Broglie. Schrödinger elegantly and pointedly characterized the measurement dilemma with his famous Schrödinger's cat thought experiment [Schrödinger, 1935]. De Broglie became one of the first to propose an alternative formulation to QM in the hopes of avoiding some of the difficulties of the orthodox interpretation [de Broglie, 1956].

The crux of the measurement problem lies in the bifurcation of the world into a quantum system and a classical measurement apparatus. Why do we need this division? Experience tells us that when we perform an experiment, we obtain a definite result, without exception. There is a fact-of-the-matter as to the outcome. But in the orthodox formalism of QM, quantum states are represented by vectors in a Hilbert space whose connection with the reality of everyday experience is through the additional notion of probability. Thus a mechanism is required to make the transition from quantum states to definite measurement results.

The problems with the bifurcation are many. First is that nothing in the formalism tells how or where to draw the line. That in and of itself might be acceptable if the predictions were insensitive to the distinction. In other words, if the theory were invariant with respect to the choice of the dividing line, then having a dividing line would not be a problem. This is the principle of representational invariance at work. We demand that our theories depend not at all on our representational choices. We would desire a situation like general relativity with respect to coordinate systems on spacetime. The theory of general relativity does not prescribe any particular coordinate system for the solution of its equation of motion. Yet any concrete solution requires such a specification. It is one of the deepest principles of the theory that this choice is moot; the results are invariant and we can choose based on mathematical convenience.

The point of the Schrödinger's cat thought experiment is that the results of QM do indeed seem dependent on the choice of the dividing line and that for many choices the results are insensible. Consider a small chunk of radioactive material whose half-life is such that it has a fifty percent probability of emitting one particle within the next hour. The material is attached to a detector and a mechanism that will break a vial of cyanide poison if and only if the decay is detected. This apparatus is placed in a sealed box with a live cat (Schrödinger's cat).

Now how can we describe this situation? The orthodox formalism asserts that after an hour has passed the radioactive atom will be in a quantum state which represents a superposition of decayed and non-decayed states. If we draw the quantum-classical boundary around the atom, then we would say that the detector is described classically and that it is in either the detected state or the non-detected state, but not a superposition. Similarly, the cat will be either dead or alive. Now let's draw the quantum-classical boundary around the box. The orthodox formalism will insist that the atom/detector/cat system is in a superposition of the decayed/detected/dead state and the not-decayed/not-detected/alive state. Clearly this is a very different description of the situation than the previous one. In the first case we insist that the cat is either dead or alive, but not both. In the second case we are forbidden from making any statement about the health of the cat. In fact, for the subsequent evolution of the system, we must be careful to preserve both branches of the wave function just in case there is some interference. The double slit experiment taught us that lesson well—that there is more than a semantic distinction between the two cases—that the difference is physical.

The dilemma becomes even more acute if we push the boundary out a little farther. We could maintain that the cat is indeed in a superposition up until the time someone looks in the box. At that time the wave function collapses to one or the other of the two possibilities. But if we move the boundary to encompass the human observer, we will have to say that the system is in a superposition of the decayed/detected/dead/observed-to-be-dead state and the not-decayed/not-detected/alive/observed-to-be-alive state. At this point we have lost all connection with reality for we are unable to explain the fact that the person observing will perceive a definite outcome, and that the outcome can be communicated to others who will agree.

Along with the bifurcation of reality, the orthodox interpretation includes the collapse of the wave function as a postulate. This is the mechanism for transitioning from the quantum world to the classical world. As a postulate for a fundamental theory, the collapse postulate (item 6 above) is flawed in that it explicitly includes the term measurement, a term notoriously difficult to define precisely.

6. The Probability Problem

The second great philosophical problem with the orthodox interpretation of QM is what I call the probability problem. Philosophically, the concept of probability is a measure of uncertainty—an epistemic quantity. This is the Bayesian interpretation of probability. The mathematics of probability then becomes an extension of deductive reasoning to situations of incomplete knowledge or ignorance. As such, the concept is inextricably tied to the notion of minds and belief. Probability *is* degree of belief. The related idea of chance addresses our lack of knowledge of the detail of a system within a class of systems. And yet even in that case, where the measure is ostensibly assigned to a property of a system, it connects back philosophically (and physically) to the concept of epistemic probability. In other words, the frequentist interpretation of probability can be derived from the Bayesian interpretation.

Now within the orthodox interpretation of QM we have apparently changed the philosophic concept of probability entirely. In this case, probability is an objective feature of the world, not a measure of our subjective beliefs about the world. It is my claim that an objective concept of probability is impossible to make cogent, and furthermore, the way in which probability arises in the theory of QM strongly suggests that the standard epistemic notion of probability ought to be applied instead. Shifting the interpretational sense of probability from objective to subjective has profound implications for the way we view QM and provides some strong clues for how we should construct its replacement.

The great champion of Bayesian logic, Edwin Jaynes, was one of the first to recognize the severity of the probability problem and believed it to be at the root of the conceptual problems of QM. That we take a limitation of ourselves, our own uncertainty, our own lack of knowledge, and project that lack onto Nature herself, Jaynes called the Mind Projection Fallacy:

> We routinely commit the Mind Projection Fallacy: supposing that the creations of our own imagination are real properties of Nature, or that our own ignorance signifies some indecision on the part of Nature. It is then impossible to agree on the proper place of information in physics. This muddying up of the distinction between reality and our knowledge of reality is carried to the point where we find some otherwise rational physicists, on the basis of the Bell inequality experiments, asserting the objective reality of probabilities, while denying the objective reality of atoms! These sloppy habits of language have tricked us into the mystical, pre-scientific standards of logic, and leave the meaning of any QM result ambiguous. Yet from decades of trial-and-error we have managed to learn how to calculate with enough art and tact so that we come out with the right numbers! [Jaynes, 1989]

Can we make sense at all of an objective notion of probability? My claim is that we can't, a conclusion based on a simple argument sketched as follows: What do we mean when we say that the probability of *S* is *p*? Here *S* is a statement and *p* is a real number. Let's focus on the statement *S*. In the standard interpretation of probability, *S* is a statement made by an agent, an entity with a mind and an internal representation of objective reality. The real number *p* represents the agent's certainty as to the truth of *S*—his degree of belief in *S*. It is a judgment not about the state of the world, but about the state of the agent. Logically, probability is a predicate on beliefs.

In order to make probability objective, we would need to redirect the predicate to apply to some object within the world itself or more precisely, to some attribute of the state of the world. What is it that we wish to attribute to the state of the world with such a predicate? Perhaps, following the thinking of the orthodox school, we want to say that there *is* no definite state, that the state of the world is such that it has no state—that the state of the world is indeterminate. This particular claim is certainly false with respect to the past. It is clear that for events that have occurred, there is a fact of the matter, a definiteness, as to what has transpired, including those related to quantum systems. Consider a sequence of QM measurements made one per second starting at time t_{start} and ending at time t_{end}. From the perspective of the experimenter, at time *t*, $t_{\text{start}} \le t \le t_{\text{end}}$, there is a fact of the matter as to the outcome of the string of measurements from t_{start} to *t*. It is only the future measurements that remain of uncertain outcome. So if probability is a predicate on the state of the world, it only applies to the future state!

Furthermore, since the division of the world into future and past parts is a subjective division, depending on a particular perspective, so must the concept of objective probability. Recall that special relativity eliminates the notion of absolute simultaneity: past, future and present are relative notions only, dependent upon the perspective of the observer. This implies that the dividing line between fact and probability, definiteness and indefiniteness, is inconsistent between different observers, those with a relative velocity, to be precise. In my mind, this inconsistency rules out a coherent concept of objective probability. We are left with probability as uncertainty—an epistemic quantity—a concept quite consistent with these future directed, subjective considerations.

Does the subjective view of probability fit the quantum mechanical situation? It seems clear that for the moment we are stuck with probability in the theory: quantum mechanics makes few definite predictions. But, the evidence seems to point quite directly that the concept of probability we need for QM can be—indeed, must be—subjective. But most importantly, a subjective interpretation of QM probabilities can go a long way towards exorcising some of the demons plaguing the orthodox interpretation. First, let us look at how probability arises in the postulates of the theory. Item 5 states that the probability a measurement will produce a given outcome is the square of the amplitude of the corresponding component of the wavefunction. It is in the act of measurement that we invoke probability. Philosophically, there are two alternative ways at looking at measurement in QM. First, a measurement can be viewed as a physical process consisting of an apparatus and the quantum system. Second, it can be viewed as a means to gain information, knowledge about the system—a bridge across the mind-world gulf. If we are looking at a measurement in the first sense, as a physical process, then we become mired in the problems of the collapse of the wave function and its relatives. However, if we look at measurement in the second sense then it becomes natural to associate probability with a measure of knowledge about the quantum system in the standard Bayesian sense, and much of the confusion—much of the quantum philosophy—melts away.

Once we make the shift from measurement as a physical process to measurement as a means to knowledge, many of the mysterious features of orthodox QM become moot. For example, the collapse of the wave function becomes simply the acquisition of information about the system at hand. Instead of the world being indeterminate, we shift the focus to uncertainty in our beliefs. Whatever the state of the quantum system, the result of a particular measurement is predictable only in terms of probabilities—our knowledge of the system is incomplete. Once the measurement has occurred, we gain some knowledge of the system, namely the result of the measurement, and some of our uncertainty is eliminated. Hence the mysterious collapse of the wave function is replaced with the reduction of uncertainty accompanied by the acquisition of knowledge.

This latter situation could not be more familiar, more aligned with common sense. If we flip a fair coin, we do not say that before flipping, the coin is in a superposition of the heads state and the tails state, and that when it lands, the state function "collapses" into one or the other states. That would be absurd. We readily acknowledge that it is not the coin that is indeterminate, but rather the state of our knowledge that is uncertain.

Besides Jaynes, there have been other physicists in pursuit of the Bayesian interpretation of probability in QM. Recent activity in the field of quantum information theory, spurred by the prospects of quantum computing, has led to the emergence of a group of informational interpretations of QM. These approaches generally embrace the Bayesian interpretation of probability and view the wave function as embodying nothing more than information about the quantum system as known by a rational agent. Led by Chris Fuchs, this school has achieved some important results, having derived many strong parallels between classical Bayesian probability theory, information theory and QM. For example, a quantum analogue of de Finiti's theorem relating subjective probabilities to long run frequencies has been proved [Caves et. al., 2001]. I expect that many of these results will be important to the ultimate solution of the quantum dilemma.

7. EPR and Bell's Theorem

I will argue below that the eventual replacement of QM will be a local deterministic theory. This was Einstein's conviction and is mine as well. Yet the brilliant Irish physicist John Bell proved a theorem in the 1960's that purports to prove the futility of such a conviction. At this point, a short digression on Bell's theorem is appropriate. It begins with the famous EPR thought experiment.

Arguably the most famous challenge to the quantum orthodoxy came from Einstein and his collaborators, Boris Podolsky and Nathan Rosen. In a paper published in 1935 titled "Can Quantum-Mechanical Description of Reality be Considered Complete?" [Einstein, et. al., 1935], they introduced a thought experiment claiming to show that quantum mechanics offered an incomplete description of reality or else violated other cherished principles like locality, implying action at a distance or a violation of special relativity. The EPR thought experiment and its later refinements involve a construction of two systems, A and B, which are known to have interacted in the past, but are now separated. The gist of the EPR argument is a measurement on system A which would then precipitate a collapse of the joint wave function affecting system B. This collapse could leave system B in an eigenstate of an observable in which case we could know with certainty that system B possessed the exact property associated with that observable. But if we chose to measure something different at A, then we would know with certainty a different property at B. Since the measurement of A by assumption cannot affect the physical reality extant within B, and since the measurement of A could be either of a pair of non-commuting observables, we conclude that we could know either of two non-commuting properties at B, in contradiction to the postulates of the orthodox view. The EPR conclusion is that the wave function does not provide a complete description of reality.

The EPR thought experiment was later modified by David Bohm to represent two systems with correlated spin or angular momentum [Bohm and Aharonov, 1957]. This formulation was then used by the Bell to derive his famous theorem which purports to prove the inherent futility of any local deterministic alternative to QM [Bell, 1964]. Bell's theorem states that it is impossible for a *local* hidden variable theory to recreate the results of quantum mechanics. In addition, Bell derived a series of inequalities which must be satisfied by a class of physical experiments as a test of the relative truth of quantum mechanics versus local hidden variables. Several of these experiments have now been performed and can be regarded as critical tests of QM, having yielded essential agreement with QM in each instance. How definitive are Bell's results? For most physicists, the issue has been settled. Even an iconoclast like Fuchs believes things are hopeless:

> The last seventeen years have given confirmation after confirmation that the Bell inequality (and several variations of it) is indeed violated by the physical world. … Incompleteness, it seems, is here to stay: The theory prescribes that no matter how much we know about a quantum system—there will always be a statistical residue. There will always be questions that we can ask of a system for which we cannot predict the outcomes. In quantum theory, maximal information is simply not complete information. As Wolfgang Pauli once wrote to Markus Fierz, "The well-known 'incompleteness' of quantum mechanics (Einstein) is certainly an existent fact somehow-somewhere, but certainly cannot be removed by reverting to classical field physics." Nor, I would add, will the mystery of that "existent fact" be removed by attempting to give the quantum state anything resembling an ontological status. [Fuchs, 2002]

Yet, I think there is still some wiggle room left.

The crux of the matter is the definition of locality and the nature of the Bell thought experiment. It involves two particles having interacted so that their properties are correlated as dictated by a conservation law. The original EPR experiment took the system to have zero total linear momentum; Bell's version focused on spin or angular momentum again with a zero value for the total system. We then allow the particles to develop a spatial separation and consider measurements on both particle subsystems. At this point, I will mention two possible sources for non-locality (as examples) which do not violate the philosophical commitments of a local realist theory. Relative to the original EPR situation dealing with linear momentum, we saw that by its very nature, momentum is not a local concept except for point particles, that the definition of momentum involves an integral over a (large) spatial region. The supposition, then, is that non-locality inherent in a hidden variable account of QM is provided by the non-local nature of fundamental entities themselves and is not in violation of the principles espoused above.

In Bell's version of the thought experiment, we have created two particles in the so-called singlet state, a state with zero angular momentum. Hence the two particles must have equal and opposite spins. The particles are allowed to separate and then measurements are performed on the spin directions of each. Conservation of momentum requires that the spins be found in the opposite directions. What Bell showed was that the measurement result of the particle at one location depended on the direction of the particle at the other location, no matter how far apart the measurements were. In the mathematics used to derive Bell's result, we end up comparing directions, angles if you will, from one point in spacetime to directions at another point in spacetime. Yet we know from differential geometry that to relate a vector at one spacetime point to a vector at another spacetime point requires the notion of parallel transport which, in turn, requires the structure of the connection as well as the definition of a path between the points. This introduces an inherent dependence between the vector specified at one point and the vector specified at another point. Again we have smuggled in non-locality without violating the principles of a local, deterministic theory. Another way of stating this point is that Bell's formulation of his thought experiment is non-covariant. It assumes the existence of a preferred global coordinate system by which one can compare vectors at spatially distinct points.

It would be rash of me to claim on this basis that Bell's theorem is obviated—my arguments are far too undeveloped for that. Yet I do wish to plant the seed of suggestion that sources of non-locality abound, consistent with the broader principles of a local, deterministic worldview—and on that basis, perhaps the philosophical consequences of Bell's theorem can be avoided.

8. Principles for a Solution

The first sections of this paper have described the current situation in QM and its fundamental problems. What are the principles that should guide us in seeking a successor theory to QM that solves the problems? This section provides a suggested list, many of which are currently violated by one or more of the competing interpretations of QM.

The successor theory should be based on a foundation of robust realism. First and foremost, the ultimate solution to the QM dilemma has to make ontological commitments about the world. There is an underlying reality that gives rise to our perceptions, that produces measurement outcomes. This reality is unified and of a single nature. It exists independent of the thoughts and actions of human agents though human agents are part of the world and manifestations of its single nature. This principle banishes the muddled thinking of quantum philosophy that has cluttered bookshelves with exhortations to the mysterious quantum.

The successor theory should be local. Having exorcised action at a distance with general relativity, we should be very reluctant to reinstate it. This principle is merely a commitment to the strictures of special relativity and rules out the instantaneous collapse of the wave function as a physical phenomenon.

The successor theory should be deterministic. As I have discussed above, the place for uncertainty is in the minds of agents, not in the workings of the world.

The successor theory should adhere to the principle of representational invariance. This principle is an explicit avoidance of one consequence of the "Mind Projection Fallacy" of Jaynes. It follows from a commitment to robust realism, to wit, the physical content of the theory, the reality it describes, must be invariant to the representational choices we make. One familiar example of this principle is the coordinate invariance (covariance) of General Relativity. The challenge is recognizing when a particular attribute of the theory is faithful to the world versus when it is simply a vagary of the representation itself—or an effect of our own limitations as physical beings interacting with a physical world.

Finally, the successor theory must explain the success of the quantum recipes while resolving the various problems with the existing interpretations. The successes of QM are clear and impressive. That is why it is so important to resolve the foundational issues.

9. Visions of the Solution

A theory that adheres to these principles probably requires a revolutionary new understanding of the nature of matter and reality. Again without having the solution in hand, let me offer a few suggestions for the directions in which the solution might lie. I think there are enough clues in the results obtained so far to begin the attempt. Each of my suggestions is phrased in terms of a conjecture followed by a few justificatory statements. I'll start with the easy ones.

The uncertainty principle is the result of the global nature of fundamental entities. The apparent mystery is the result of asking the wrong question, of having he wrong model in mind. It seems strange that we can't know the precise position of a particle at the same time we know its precise momentum, but it is only strange when we think of fundamental entities as point particles, small billiard balls. The fact that this principle obtains is telling us that the billiard ball model is incorrect, that fundamental entities have extent, and their properties must be found by averaging (integrating) over relatively large regions of spacetime.

Probability is interpreted in the Bayesian sense as reasonable degree of belief. Section 6 provides the justification for this statement. The subjective interpretation of probability is the only sensible interpretation possible. We must view probability as a measure of the uncertainty within the mind of an agent—not a property of the world. Determinism is the only acceptable answer for the workings of the real world. When describing real properties of the real world, we should eschew reference to probability; however, it can certainly enter the conversation when describing an agent's interaction with the world.

The collapse of the wave function is not a phenomenon of the real world but of an agent's interaction with the world. Collapse represents a sudden change in an agent's knowledge of the world, not a sudden shift in the state of the world itself. Mathematically, collapse represents a probability shift due to sudden conditioning on the information gained in the measurement interaction

Bell's theorem prohibiting local deterministic theories will be circumvented by either the non-local nature of fundamental entities themselves or in subtleties in the argument with respect to the nature of spacetime geometry. A brief sketch of this argument was given in Section 7.

Fundamental entities are neither particles nor waves but will be describable by a new model which exhibits particle-like properties as well as wave-like properties. The mystery of wave particle duality is due to the inadequacy of our current models of matter. A new model at the level of fundamental matter is, I believe, the key to cutting the quantum Gordian knot. It is my conviction that this model will be geometric and that matter will be describable as features of the spacetime manifold.

The phenomenology of 19th century physics includes two conceptually distinct models to describe fundamental entities in physics: the point particle and the wave. These two competing models have enjoyed a vigorous and sometimes rancorous competition going back to the days of Newton and the debates between the wave theory of light and the corpuscular theory of light. (Neither side won—presently, we have the quanta of light, the photon, which exhibits both wave and particle nature).

A point particle is an entity with no spatial extent; it is located at a precise point in the spacetime manifold. In modern physics, it typically has mass, charge and intrinsic spin. It also has a velocity so that it can be described by a point in phase space, at least classically. A point particle has a certain finite number of degrees of freedom; that is, the number of coordinates (and their time derivatives)—real or integer numbers—required to completely describe its state. A wave, on the other hand is a pattern in a continuous media or field. Waves are explicitly not localized or even localizable, but have amplitude defined at all points in spacetime. Typically, waves are described by the modes of vibration of the continuous media, each mode representing a single degree of freedom. A wave packet is a combination of modes of various amplitudes. Both these concepts have their origin in classical physics.

Consider an electron, the archetype quantum mechanical entity. It is notorious for exhibiting both a particle like nature and a wavelike nature. An electron can be localized through the measurement of its position. If we regard the wave function as a function of position, e.g., $\Psi(x)$, then the standard interpretation claims that $|\Psi(x)|^2$ is the probability of finding the electron at the point x. Experimentally, it has been found that an electron can be localized to an incredible degree of precision. Current estimates place an upper bound on its radius of 10^{-20} cm [Dehmelt, 1988]. Furthermore, we know that this electron carries a certain mass, electric charge and spin in well defined, quantized amounts. This is the particle-like aspect of the electron. On the other hand, we know from experiments like the double slit that electrons act like waves in that they can create diffraction patterns and interference patterns. In fact, as we said, a single electron (whatever that means) can apparently interfere with itself. This is the wave-like aspect of the electron.

Electrons are not unique in this schizophrenic behavior—it is exhibited by all fundamental entities, from α-particles to Z-bosons. To me, the key conclusion is not that the electron is schizophrenic, sometimes behaving like a particle, sometimes like a wave. The key question is why we have limited ourselves to only these two models. Cannot we find a model for the electron which can explain both its localizability *and* its self interference? Are we stuck with the models of the 19th century?

To introduce the final few conjectures, let me digress briefly into the world of modern physics. Three of the four fundamental forces are currently described by quantum field theories: electromagnetism, the weak nuclear interaction and the strong nuclear interaction. Gravity has so far resisted being brought into the quantum framework in large part because of its geometric quality. Much of the effort in theoretical physics over the last 50 years has been to seek a theory that unifies gravity with the other forces. It is my belief that the solutions to the problems of QM and the problem of unification lie in the same direction.

Instead of trying to quantize gravity, we should geometrize quantum field theory. Perhaps because most theoretical physicists have a quantum field theory background, and because quantum mechanics has taken on an almost religious significance, the approach to unification has been to try to force fit general relativity into a quantum field theory framework. To me, this is backwards. I view general relativity as the more beautiful theory, the more natural, the more intuitively correct. We should, instead, look for a way to cast the theories of quantum fields into a more geometric mode, following the lead of general relativity.

Einstein's equation offers a critical clue as to the nature of matter. In terms of making progress in fundamental physics, it seems to me that Einstein's equation provides a way. Recall the equation: $G_{ab} = 8\pi T_{ab}$, where G is Einstein's tensor and T is the stress-energy tensor of the matter fields. The left hand side is a function of the geometry of the spacetime manifold. The right hand side is a function of the matter and energy within the manifold. But if we think of the equality as more than just a numerical equality, but as a *conceptual* equality, then we reach the conclusion that matter *is* geometry, that particles are geometric objects. In this way it seems likely that the solution to the quantum problem and the solution of the problem of matter lie along the same general direction.

All fundamental forces are geometric connections on the spacetime manifold. The unification of fundamental forces must be based on a unifying principle—a principle that has been missing in attempts so far. This is a modification of the gauge principle that has been the guiding light of quantum field theory. Geometrically, the forces are not connections on a principal fiber bundle, where the fibers are group manifolds, but connections on the tangent bundle, where the fibers are the tangent space of the spacetime manifold. This approach requires extra dimensions like string theory. The beauty is that once extra dimensions are conceded, the principle of representational invariance then demands the kind of gauge invariance I'm looking for.

In a side note, while in graduate school, I once had a thought that extra dimensions could explain the weirdness of quantum mechanics, and I still have a slight affinity for that idea. The idea would be that the coordinates of the extra dimensions would provide the hidden variables that quantum statistics are averages over, and that the global nature of the connection field for those hidden dimensions would obviate Bell's theorem.

Particles are topological features of the spacetime manifold. Here we also need to carry over the notion of a manifold of higher dimensions. The model I have in mind is a kind of knot in higher dimensions. Different sorts of knots correspond to different sorts of particles. The unity this idea brings to the playing field is profound. First, it explains Einstein's equation. Matter and energy give rise to curvature because there is an irreducible amount of curvature inherent in any given knot. Second, it explains the quantum numbers of particles as topological/geometric invariants of the knots. Third, it explains wave/particle duality, the mystery of quantum mechanics, as an artifact of representational invariance. A knot can be loosened, spread over as much of the fabric as desired, by a simple coordinate transformation. Similarly, a knot can be tightened—localized—as much as desired by a similar transformation.

As an interesting aside, the mathematics of knots was originated by Lord Kelvin in the late 1800's as a means to explain the periodic table of the elements. Kelvin's idea was that atoms were knots in the ether. Here I am trying to explain matter as knots in spacetime.

10. Conclusions

For nearly 100 years, the theory of quantum mechanics has progressed yielding predictions of ever greater accuracy. Yet its foundations are fraught with inconsistencies and controversies. Much the same situation existed with Newtonian gravity before Einstein proposed his general relativity. Despite its predictive prowess, Newtonian gravity was saddled with the embarrassment of action at a distance. Eliminating that defect was one great accomplishment of general relativity

Much of Einstein's genius lay in his ability to perceive the physical principles that underlay the workings of the physical world. The principle of relativity, that the laws of physics are the same in all inertial reference frames, forms the basis for special relativity. The equivalence principle, that inertial and gravitational mass are the same, leads to general relativity's great insight that the apparent force of gravity is an artifact of the geometry of spacetime. But such foundational principles are lacking for quantum mechanics. Any program to place QM on firm footing must begin with a search for these principles.

In this paper, I have attempted to make a beginning. Any successor theory to Quantum Mechanics must be based on a foundation of robust realism. The ontological fuzziness of current interpretations of QM needs to be expunged. The theory should be local and deterministic. Probability must be returned to its proper place in the minds of observers and we must avoid the pitfalls of the mind projection fallacy keeping a firm grip as to what is true of the world versus what is an effect of our interaction with the world. Adhering to this last principle, by itself, goes far in removing much of what is disturbing about current interpretation of QM. The wave function no longer describes some kind of mysterious probability wave, but merely encodes our knowledge and the sudden (and perplexing) collapse of the wave function becomes merely a conditionalization based of gaining new knowledge.

On a more speculative note, I have made suggestions as to new directions to look for a solution. I believe our current models of fundamental matter are inadequate. We have been stuck with the classical models of wave or point particle, leading to the mystery of wave-particle duality. The more modern conception of matter fields is only a slight improvement. I believe we need a new model that describes matter as geometric-topological features of spacetime itself in four or higher dimensions. This sort of approach has several beneficial features. First, it eliminates the mystery of the uncertainty principle by giving matter extent which then yields the uncertainty principle as a classical result. Second, it obviates Bell's theorem as an obstacle to a local deterministic solution. Finally and most importantly, in my mind, it explains Einstein's equation as how matter on the one hand can cause (or be equivalent to) the curvature of spacetime on the other hand.

It is my great hope that those who have both more time and more math than I will take these suggestions and make progress. It is critically important that the foundational issues with QM be solved because of the fact that QM is so incredibly successful as a predictive tool. I am also certain that any attempts we make toward unified theories *without first solving QM* will fail because they are based on this quantum mechanical quicksand.

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