Introduction*

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While the standard theory of quantum mechanics has proven itself remarkably useful, it is a puzzling physical theory.[1] What makes it puzzling is that *measurement* occurs as a primitive term. The theory tells us that a physical system evolves one way unless it is being measured; in which case, it evolves another way, a way that is mathematically incompatible with the first. Consequently, one needs to know what constitutes a measurement in order to know how a system will evolve. But since *measurement* is a primitive term, this is just what the standard theory fails to tell us. When we supplement the theory with our intuitions concerning what events ought to count as measurements, we get very good empirical predictions for the sort of experiments we have performed so far. But there is a point where our intuitions become too vague to be useful, and when this happens we cannot rely on the standard theory for help since it says nothing about what constitutes a measurement.

The problem of finding a coherent quantum-mechanical account of measurement is known as the *measurement problem*. Each of the papers in this collection is concerned with some aspect of the measurement problem. As an introduction to these papers, I will very briefly say something here about how we ended up with a physical theory where *measurement* occurs as a primitive term, the sense in which the measurement problem is a serious problem for quantum mechanics, and some of the current options for solving it.

The standard theory of quantum mechanics was largely developed in the years 1923 to 1932.[2] In 1923 de Broglie suggested that Einstein's association of photons (light-quanta) with electromagnetic wave phenomena ought to be generalized to include all material particles. He suggested that $E = h\nu$ (energy equals Planck's constant times wave-length) holds for a "fictitious" wave associated with electrons as well as photons (de Broglie, 1923). He proposed that one might consequently expect electrons, like photons, to exhibit diffraction phenomena, which eventually turned out to be right.

In 1925 Heisenberg published a paper where he argued that "it is better . . . to admit that the partial agreement of the quantum rules [of the old quantum theory] with experiment is more or less accidental, and to try to develop a quantum theoretical mechanics, analogous to the classical mechanics in which only relations between observable quantities appear" (Heisenberg, 1925, translated and quoted in Pais, 1988, p. 253). He then set out on just such a project by sketching the basic principles of what would eventually become his matrix mechanics.

In January 1926 Schrödinger (1926a) picked up on de Broglie's idea that all matter has wave-like properties, and he published the first in a series of papers that presented the mathematical foundations of wave mechanics. Using his new theory he was able to derive both the discrete and the continuous spectra of hydrogen. In June of the same year Schrödinger's paper (1926b) containing his famous wave equation was received for publication. He believed that the wave equation provided the basis for a deterministic quantum theory where the waves represented something like classical charge-matter distributions, which he thought would properly replace particles as the stuff the physical world is made of.[3] As Born later remembered:

> [Schrödinger] believed . . . that he had accomplished a return to classical thinking; he regarded the electron not as a particle but as a density distribution given by the square of his wave-function $|\psi|^2$. He argued that the idea of particles and of quantum jumps be given up altogether; he never faltered in this conviction. . . . I, however, was witnessing the fertility of the particle concept every day . . . and was convinced that particles could not simply be abolished. A way had to be found for

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reconciling particles and waves. I saw the connecting link in the idea of probability (Born, 1968, p. 35).

It was Born who formulated the standard interpretation of Schrödinger's waves.

Born suggested that quantum mechanics keep Schrödinger's mathematical formalism but drop his classical interpretation. Rather than replacing particles as the fundamental objects that constitute the world, Born took Schrödinger's waves to be *descriptive* of particles, which were then taken to be fundamental. After briefly taking Schrödinger's wave-function ψ to be a measure of probability,[4] Born finally concluded that it was actually the norm squared of the wave-function $|\psi|^2$ that determined the probability for the presence of a particle. Born immediately realized that on his interpretation quantum mechanics does not tell one in what state a system will be found; rather, it tells one what the *probabilities* are for finding the system in various mutually incompatible states. Still later, Born stated that "the motion of particles follows probability laws but the probability itself propagates according to the law of causality" (Born, 1926, translated and quoted in Pais, 1988, p. 258). Here was the first explicit statement that quantum theory needed two dynamics; one probabilistic, and the other deterministic. When Schrödinger saw the interpretation that Born had in mind for his wave mechanics, he said that he regretted publishing anything on the subject (Pais, 1988, p. 261). Schrödinger thus became an opponent of what was soon the almost universally accepted interpretation of his wave mechanics.[5]

Born's position eventually led to what might be called the standard interpretation of states. On the standard interpretation of states a system determinately has a property if and only if it is in an eigenstate of having that property. A particle fails to have a determinate position, for example, if it is not in an eigenstate of having a particular position. It is not that we do not *know* what its position is. Rather, the particle simply fails to have a determinate position – it is in a *superposition* of mutually incompatible positions, and according to Born's rule for assigning probabilities, and our experience, this state has empirical properties that distinguish it from any state where the particle has a determinate position (that is, any particular eigenstate of position).

It is often said that the *theory* of quantum mechanics is fine, that it is the *interpretation* that has problems. But here we see that the two are not so easy to separate. Born's interpretation of quantum-mechanical states required him to introduce a new dynamical law, which is presumably to be counted as a part of the formal theory of quantum mechanics (what justification could one have for including the linear dynamics as a part of the theory but excluding the nonlinear dynamics?). If a system only has a determinate physical property when it is in an eigenstate of having that property, then the process of measurement cannot be linear – if it was, then, given the standard interpretation of states, we would presumably have no way to account for how observers end up with determinate results to their measurements.

After Schrödinger's 1926 papers, it soon became evident that his wave mechanics and Heisenberg's matrix mechanics were essentially equivalent. By 1932 there was enough of a consensus on both the formalism and the interpretation of quantum mechanics that von Neumann (1955) was able to write down a more or less axiomatized version of the theory. We will refer to von Neumann's careful formulation of quantum mechanics as the standard theory.

Following Born, von Neumann described "two fundamentally different types of interventions which can occur in system *S*" (von Neumann, 1955, p. 351). The first of these are "the arbitrary changes by measurements" when, by what von Neumann referred to as *process 1*, the state of a system instantaneously evolves to one of the eigenstates of the observable being measured. This is Born's probabilistic, nonlinear dynamics. The second was "the automatic changes that occur with the passage of time," which are characterized by a set of unitary operators on the state space $\mathcal{H}$ that represent the smooth time evolution of quantum-mechanical states in the absence of measurement; von Neumann referred to this as *process 2*. This is Schrödinger's deterministic, linear dynamics.

According to von Neumann, then, a measurement has the consequence of causing the physical system measured to depart from its usual linear evolution and to jump into an eigenstate of the observable being measured a state where the system has a determinate value for the observable. Specifically, the probability P_n of a system in the state represented by ψ jumping into the state represented by ϕ_n, where ϕ_n is an eigenvector of the operator corresponding to the observable being measured, is given by

(1) $P_n = |(\psi, \phi_n)|^2$

which is simply an expression of Born's statistical interpretation of the wave-function.

Filling in some of the details, von Neumann's formulation of quantum mechanics is based on the following principles:

1. Every physical state is represented by an element of unit length in a Hilbert space.
2. Every complete physical observable is represented by a Hermitian operator on the Hilbert space, and every Hermitian operator on the Hilbert space corresponds to some physical observable.
3. A system S has a determinate value for some observable if and only if it is in an eigenstate of that observable: if the state of S is represented by an eigenvector of a Hermitian operator corresponding to eigenvalue λ, one will get the result λ when one makes the observation corresponding to the particular Hermitian operator.
4. The dynamics has two parts:
   I. The linear dynamics: if no measurement is made of a physical system, it will evolve in a deterministic, linear way that depends only on its energy properties.
   II. The nonlinear collapse dynamics: if a measurement is made of the system, it will instantaneously, and nonlinearly, jump (or collapse) to an eigenstate of the observable being measured (a state where the system has a determinate value for the physical quantity being measured). The probability of collapsing to a particular eigenstate is equal to the norm squared of the amplitude of the projection of the system's premeasurement state onto the eigenstate.

The nonlinear collapse of the quantum-mechanical state on measurement is curious. As von Neumann put it:

> one should expect that [the linear dynamics] would suffice to describe the intervention caused by a measurement: Indeed, a physical intervention can be nothing else than the temporary insertion of a certain energy coupling into the observed system . . . [in which case, the linear dynamics would describe the time-evolution of the composite system] (von Neumann, 1955, p. 352).

So what exactly causes the nonlinear collapse when there is a measurement? Here we get the first glimmer of the measurement problem. Von Neumann said that "we have answered the question as to what happens in the measurement of a quantity. To be sure, the 'how' remains as unexplained as before" (von Neumann, 1955, p. 217).

While von Neumann lacked an explanation for the linear dynamics's failure to correctly describe measurement interactions, he nonetheless believed that the standard theory of quantum mechanics was perfectly coherent. It was probably Bohr, however, who did the most to convince physicists that there were no foundational problems in quantum mechanics. Or, as Gell-Mann once put it, "The fact that an adequate philosophical presentation [of quantum mechanics] has been so long delayed is no doubt caused by the fact that Niels Bohr brainwashed a whole generation of theorists into thinking that the job was done fifty years ago" (quoted in Sudbery, 1986, p. 178).

Lets consider the process of measurement in more detail. A particularly simple quantum mechanical observable is called x-spin. There are only two possible results of an x-spin measurement: *up* and *down*. A system S in the *up* eigenstate will be represented by $|\uparrow\rangle_S$ and a system in the *down* eigenstate will be represented by $|\downarrow\rangle_S$.[6] Suppose that M is an ideal x-spin measuring device – that is, M's pointer becomes perfectly correlated with the x-spin of its object system S without disturbing S's state. If M begins in a state where it is ready to make a measurement $|r\rangle_M$ and S begins in an *up* eigenstate of x-spin $|\uparrow\rangle_S$, then the composite system $M + S$ will end up in a state were M reports that its result was x-spin *up* and S is left in an *up* state $|\uparrow\rangle_M\,|\uparrow\rangle_S$. And if M begins in a state where it is ready to make a measurement $|r\rangle_M$ and S is in a *down* eigenstate $|\downarrow\rangle_S$, then $M + S$ will end up in the state $|\downarrow\rangle_M\,|\downarrow\rangle_S$. This is what it means to say that M is an ideal measuring device here.

What happens when M measures the x-spin of a system S that is *not* initially in an eigenstate of x-spin? Suppose, for example, that S is initially in the state

$$(2)\quad \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_S + |\downarrow\rangle_S\right)$$

The standard theory tells us that S will instantaneously jump to either $|\uparrow\rangle_S$ or $|\downarrow\rangle_S$ when it is measured. The probability of the final state being $|\uparrow\rangle_M\,|\uparrow\rangle_S$ is 1/2 and the probability of the final state being $|\downarrow\rangle_M\,|\downarrow\rangle_S$ is also 1/2, which is just what we find empirically. In either case, since S ends up in an eigenstate of x-spin, the standard theory predicts that M will get the same result if it *remeasures* the

x-spin of S without disturbing it between measurements.

While the linear dynamics accounts for the wave-like properties of matter, the collapse dynamics plays an important role in the standard theory. If there were no collapse of the wave-function, it follows from the linear dynamics that the final state would be

$$(3) \quad \frac{1}{\sqrt{2}}(|\uparrow\rangle_M |\uparrow\rangle_S + |\downarrow\rangle_M |\downarrow\rangle_S)$$

Note that on the standard interpretation of states this is not a state where M makes a determinate report one way or the other: it is not a state where M reports *up*, it is not a state where M reports *down*, and it is not a state where M reports both or says it doesn't know either indeed, strictly speaking M does not even have a state of its own here since it is entangled with S. So not only does the collapse dynamics provide a prescription for calculating probabilities but it also accounts for the fact that measuring devices make determinate x-spin reports and the fact that an observer will get the same x-spin result on a subsequent measurement if the object system is undisturbed between measurements.

The standard theory's two dynamical laws, however, are mathematically incompatible. This incompatibility can be seen by the fact that in the above measurement stories the two dynamics yield very different final states. The collapse dynamics tells us that the final state will be the statistical mixture: probability 1/2 that the state is $|\uparrow\rangle_M |\uparrow\rangle_S$ and probability 1/2 that the state is $|\downarrow\rangle_M |\downarrow\rangle_S$. The linear dynamics, however, tells us that the final state is the superposition represented by equation (3). This is more than just some abstract or formal incompatibility. The standard theory tells us that there is some physical observable, call it A, that has equation (3) as an eigenstate. Since neither $|\uparrow\rangle_M |\uparrow\rangle_S$ nor $|\downarrow\rangle_M |\downarrow\rangle_S$ could also be eigenstates of A (the eigenstates of an observable are always mutually orthogonal), there is, at least in principle, an experiment that would determine whether M had in fact caused a collapse of S's state: make a series of A-measurements. If you get the measurement result corresponding to the state represented by equation (3) every time, then there was no collapse; if you get this result only half of the time, then there was a collapse. This means that in the standard theory there are *empirical consequences* to which systems are measuring devices and which are not, and yet the theory is perfectly silent as to which is which.

Since the standard theory's dynamical laws constitute mutually incompatible descriptions of the time-evolution of physical systems, they threaten to render the theory inconsistent unless one can specify strictly disjoint conditions for when each applies. Since the standard theory does not provide these conditions, and our intuitions are too vague to provide precise conditions (Does a cat cause collapses? What about a mosquito? A large protein molecule?), we do not know when to apply the linear dynamics and when to apply the collapse dynamics. This means that the standard theory is *at best* incomplete in an empirically significant way since A-type measurements would distinguish between the two dynamics. This is made especially puzzling by the fact that whenever we have had the technological ability to perform A-type measurements on a system, we have found that the system always follows the *linear dynamics*.[7]

Von Neumann's question of *how* a collapse occurs also causes explanatory problems for the standard theory. Measuring devices are presumably built exclusively from fundamental particles, and our empirical evidence provides us with very good reasons to believe that fundamental particles obey the linear dynamics, so how could a measuring device behave in a grossly nonlinear way? Is the object system S somehow supposed to know when it is being measured? What does it take to be a measuring device anyway? The standard theory provides no answers.[8]

At this point one might argue that the measurement problem cannot be very serious – after all, most physicists have successfully used the standard theory for over seventy years barely noticing the problem. The reason is that if one takes the events that one would naturally call measurements to be the events referred to by the theoretical term *measurement*, then the standard theory makes the right empirical predictions for the sort of experiments we have performed so far. But in order to be satisfied with this, one would have to have very weak standards for physical theories indeed. In addition to giving up on any real understanding of the physical world, one would have to be content with the fact that there is a class of experiments (which would be extraordinarily difficult to perform but are at least in principle possible) for which the standard theory (even when supplemented with our intuitions concerning what constitutes a measurement) can make no empirical predictions whatsoever.

There have been several attempts

to resolve the measurement problem. Broadly speaking, these have followed one or the other of two general strategies. One strategy is to provide a criterion for when collapses occur. Along these lines, some, like Wigner (1961), have tried to find a satisfactory criterion for what constitutes a measurement – Wigner's proposal was that a system collapses to an eigenstate of the observable being measured when a conscious entity apprehends the state of the system. Ghirardi, Rimini, and Weber (GRW) (1986) have made a very different proposal. They have suggested replacing the linear dynamics with a dynamics where each elementary particle has a nonzero probability per unit time of collapsing to an eigenstate of position, which has the effect of keeping macroscopic pointers close to eigenstates of position.

The other general strategy is to deny that collapses ever occur, then try to find a satisfactory theory where the linear dynamics is taken to be an accurate description of the time-evolution of every physical system under all circumstances. Some, like Everett (1957), have taken the linear dynamics to be a *complete* as well as an accurate description of the time-evolution of every system. The problem then is to explain how measuring devices could make (or seem to make?) determinate reports when the linear dynamics tells us that they would generally be in complicated superpositions of making mutually incompatible results, of being broken, of never having been constructed, etc. Providing such an explanation seems to be the strategy of Gell-Mann and Hartle (1990), among many others, who advocate an interpretation of quantum mechanics where environmental decoherence is somehow supposed to account for an observer ending up with determinate measurement results. Others, like Bohm (1952) and Vink (1993), have taken the quantum-mechanical state to provide an *incomplete* physical description and have supplemented it with so-called hidden variables that then describe measuring devices as reporting determinate results. Still others, like Albert and Loewer (1988) have suggested supplementing the quantum-mechanical state with a *nonphysical* state, specifically the mental state of each observer, that always has a determinate value and explains how observers get determinate measurement results.

So far, no proposed resolution to the measurement problem has proven entirely satisfactory. What does seem increasingly clear is that whatever formulation of quantum mechanics we end up with will violate some cherished intuitions concerning what a satisfactory physical theory should look like.[9]

Notes

* This introduction and most of the papers in this volume assume some understanding of how the standard formulation of quantum mechanics works and of the basic mathematics involved. There are, of course, several very good, accessible introductions to quantum mechanics. Albert (1992) requires little mathematical background and is a clear introduction to quantum mechanics and some of the problems involved in formulating a satisfactory theory. Also worth mention are Shimony (1989), Hughes (1989), and van Fraassen (1991). As long as we are on the topic of literature, there are two collections of papers that are particularly good: Wheeler and Zurek (1983) and Bell (1987). The first is a general collection on the measurement problem and the interpretation of quantum mechanics and the second contains some of Bell's papers. For detailed descriptions of the standard formulation of quantum mechanics, its historical development, how it is used, and the mathematics involved, one might consult von Neumann (1955), Dirac (1958), Messiah (1965), Mackey (1963), and Baym (1969). These are all standard texts and each provides a slightly different perspective. Finally, some of the works that have been particularly influential in the development of quantum mechanics and its interpretation are mentioned in the following bibliography.

1 What I am calling the standard theory of quantum mechanics throughout this introduction is the formulation described by von Neumann (1955).

2 Much of this historical sketch follows Pais (1988, pp. 244–261).

3 See, for example, Schrödinger (1926c).

4 Pais (1988, p. 259) tries to reconstruct what might have led Born to make this curious mistake.

5 Schrödinger published his famous criticism of the standard theory of quantum mechanics in 1935. The paper, "Die gegenwärtige Situation in der Quantenmechanik," was published in three parts in *Naturwissenschaften* 23, 807–812, 823–828, and 844–849. It has since been translated and reprinted as "The present situation in quantum mechanics: a translation of Schrödinger's 'cat paradox' paper", in Wheeler and Zurek (1983, pp. 152–167).

6 These are unit-length vectors in a Hilbert space. There is almost a one-to-one correspondence between unit-length vectors and possible physical states. The exception is that $|v\rangle$ and $-|v\rangle$ are usually taken to specify the same physical state.

7 One might wonder why we don't perform the appropriate experiments and determine what systems cause collapses. It turns out to be very difficult, however, to control the environment of most macroscopic systems well enough to perform an *A*-type measurement. For a discussion of how *A*-type measurements are performed and the various technical difficulties involved see Leggett (1986) and Clark *et al.* (1991).

8 While the standard theory provides no explanation, there has been significant progress toward formulating a physical theory that would explain why measurements yield determinate results in just this way. On the GRW theory, the cumulative effect of very slight nonlinearities in the evolutions of fundamental particles ensures that macro-

scopic pointers will almost always be close to eigenstates of position.

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