QUANTUM THEORY WITHOUT OBSERVERS—PART ONE

Despite the claims of most of the founding fathers, the appeal at a fundamental level to observers and measurement, so prominent in orthodox quantum theory, is not needed to account for quantum phenomena.

Sheldon Goldstein

The concept of "measurement" becomes so fuzzy on reflection that it is quite surprising to have it appearing in physical theory at the most fundamental level. *[D]oes not any* analysis *of measurement require concepts more* fundamental *than measurement? And should not the fundamental theory be about these more fundamental concepts?*

—J. S. Bell[1]

Since its inception some 70 years ago and despite its extraordinary predictive successes, quantum mechanics has been plagued by conceptual difficulties. Plainly put, the basic problem is this: It is not at all clear what quantum mechanics is about. What, in fact, does quantum mechanics describe?

Since it is widely agreed that the state of any quantum mechanical system is completely specified by its wavefunction, it might seem that quantum mechanics is fundamentally about the behavior of wavefunctions. Quite naturally, no physicist wanted this to be true more than did Erwin Schrödinger, the father of the wavefunction. Nonetheless, Schrödinger ultimately found this impossible to believe. His difficulty was not so much with the novelty of the wavefunction: "That it is an abstract, unintuitive mathematical construct is a scruple that almost always surfaces against new aids to thought and that carries no great message." Rather, his difficulty was that the "blurring" suggested by the spread-out character of the wavefunction "affects macroscopically tangible and visible things, for which the term 'blurring' seems simply wrong."[2]

For example, Schrödinger noted that it may happen in radioactive decay that "the emerging particle is described . . . as a spherical wave . . . that impinges continuously on a surrounding luminescent screen over its full expanse. The screen however does not show a more or less constant uniform surface glow, but rather lights up at *one* instant at *one* spot [emphasis in original]. . . ."[2] And he observed that one can easily arrange—for example, by including a cat in the system—"quite ridiculous cases" with "the ψ-function of the entire system having in it the living and the dead cat (pardon the expression) mixed or smeared out in equal parts."

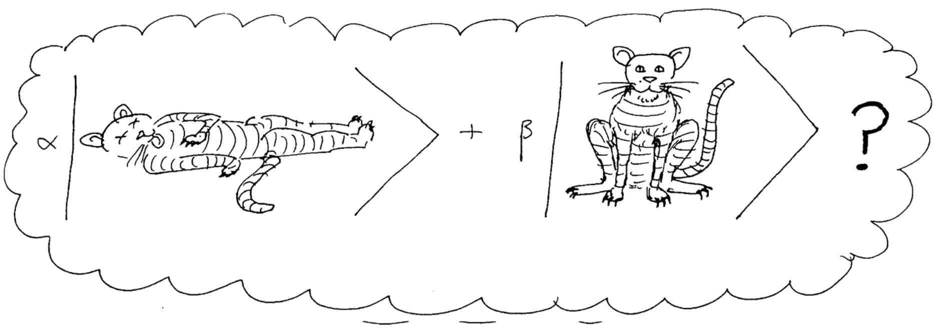
It is thus because of the "measurement problem," of macroscopic superpositions, that Schrödinger found it difficult to regard the wavefunction as "representing reality." But then, what does? With evident disapproval, Schrödinger described how "the reigning doctrine rescues itself or us by having recourse to epistemology. We are told that no distinction is to be made between the state of a natural object and what I know about it, or perhaps better, what I can know about it if I go to some trouble. Actually—so they say—there is intrinsically only awareness, observation, measurement."

Schrödinger's portrayal of the views of his contemporaries was quite accurate. Niels Bohr, the founder of the "Copenhagen interpretation," insisted upon the "*impossibility of any sharp separation between the behavior of atomic objects and the interaction with the measuring instruments which serve to define the conditions under which the phenomena appear*" and claimed that "in quantum mechanics, we are not dealing with an arbitrary renunciation of a more detailed analysis of atomic phenomena, but with a recognition that such an analysis is *in principle* excluded [emphasis in original]."[3] Werner Heisenberg claimed that "the idea of an objective real world whose smallest parts exist objectively in the same sense as stones or trees exist, independently of whether or not we observe them . . . is impossible . . ."[4] and that "We can no longer speak of the behavior of the particle independently of the process of observation. As a final consequence, the natural laws formulated mathematically in quantum theory no longer deal with the elementary particles themselves but with our knowledge of them. Nor is it any longer possible to ask whether or not these particles exist in space and time objectively."[5]

Many physicists pay lip service to the Copenhagen interpretation, and in particular to the notion that quantum mechanics is about observation or results of measurement. But hardly anybody truly believes this anymore—and it is hard for me to believe that anyone really ever did. It seems clear that quantum mechanics is fundamentally about atoms and electrons, quarks and strings, and not primarily about those particular macroscopic regularities associated with what we call measurements of the properties of these things. But this, of course, does not really provide an answer to the question with which I began. After all, if these entities are not to be somehow identified with the wavefunction itself—and if talk of them is not merely shorthand for elaborate statements about measurements—then where are they to be found in the quantum description?

There is, perhaps, a very simple reason why there has been so much difficulty discerning in the quantum description the objects we believe quantum mechanics

SHELDON GOLDSTEIN *is a professor of mathematics at Rutgers University in New Brunswick, New Jersey. Part two of this article will appear in next month's issue.*



SCHRÖDINGER'S CAT should be either dead or alive, depending upon whether or not a radioactive decay has released the poison. But according to orthodox quantum theory, the cat is somehow both dead and alive until an observer checks to see. Quantum theories without observers avoid such paradoxes. (Drawing by Gregory Eyink.)

should be describing. Perhaps the quantum mechanical description is not the whole story, a possibility most prominently associated with Albert Einstein.

On the basis of more or less the same considerations as those of Schrödinger quoted above, Einstein concluded that the wavefunction does not provide an exhaustive description of individual systems, while noting that "there exists . . . a simple psychological reason for the fact that this most nearly obvious interpretation is being shunned. For if the statistical quantum theory does not pretend to describe the individual system . . . completely, it appears unavoidable to look elsewhere for a complete description of the individual system."[3] In relation to this more complete theory, he declared, "the statistical quantum theory would . . . take an approximately analogous position to the statistical mechanics within the framework of classical mechanics." Earlier, Einstein, Boris Podolsky and Nathan Rosen had concluded their famous EPR paper as follows: "While we have thus shown that the wave function does not provide a complete description of the physical reality, we left open the question of whether or not such a description exists. We believe, however, that such a theory is possible."[6]

Regarded as a response to the measurement problem, the position of Bohr and Heisenberg seems excessive in comparison with that of Einstein. After all, Einstein denied merely that the wavefunction is a complete description of an observer-independent physical reality, whereas Bohr and Heisenberg seemed to deny that there is any such reality, at least insofar as atomic phenomena are concerned. And as regards the plausibility of their conclusions, Einstein's insistence on the possibility of a more complete description seems rather modest when contrasted with Bohr's categorical assertions of "impossibility" and "in principle" exclusion. Nonetheless, it is generally believed in the physics community that Bohr vanquished Einstein in their great, decades-long, debate. At the same time, it is also widely believed that their debate was merely philosophical and hence not susceptible to any clear-cut resolution.

However, the Bohr–Einstein debate has already been resolved, and in favor of Einstein: What Einstein desired and Bohr deemed impossible—an observer-free formulation of quantum mechanics, in which the process of measurement can be analyzed in terms of more fundamental concepts—does, in fact, exist. Moreover, there are many such formulations, the most promising of which belong to three basic categories or approaches: decoherent histories, spontaneous localization and pilot-wave theories. In fact, the simplest pilot-wave theory, Bohmian mechanics, has existed almost since the inception of quantum theory itself. These approaches can be regarded, each in its own way, as minimal responses to the problem of formulating a quantum theory without observers. Each of these, I argue, can also be regarded as realizations of Einstein's insight that the wavefunction does not provide us with a complete description of physical reality, and of his belief that a more complete theory is possible.

Below, I discuss the most popular of these approaches to a quantum theory without observers—decoherent histories. Then, in part two of this article, which will appear in next month's PHYSICS TODAY, I will focus on spontaneous localization and on Bohmian mechanics, which are versions of quantum theory that are less popular but, arguably, far simpler.

Decoherent histories

The decoherent histories (DH) approach was initiated in 1984 by Robert Griffiths[7] (who spoke, however, of consis-

ULLSTEIN BILDERDIENST

ERWIN SCHRÖDINGER. Although he formulated its fundamental equation, Schrödinger was one of quantum theory's most acerbic critics.

tent histories) and was independently proposed by Roland Omnès[8] a little later; it was subsequently rediscovered by Murray Gell-Mann and James Hartle,[9] who made crucial contributions to its development.

(DH should not be confused with the environment-induced superselection approach of Wojciech Zurek,[10] in which decoherence also plays a crucial role, but one that differs significantly from its role in DH. In Zurek's approach the environment is fundamental, acting in effect as an observer, so that it is difficult to regard this proposal as genuinely providing a quantum theory without observers.)

DH may be regarded as a minimalist approach to the conversion of the quantum measurement formalism to a theory governing sequences of objective events, including, but not limited to, those that we regard as directly associated with measurements. Where the Copenhagen interpretation talks about *finding* (and thereby typically disturbing) such and such observables with such and such values at such and such times, the DH approach speaks of such and such observables *having* such and such values at such and such times. To each such history h, DH assigns the same probability $\mathrm{P}(h)$ of *happening* that the quantum measurement formalism—the wavefunction reduction postulate for ideal measurements together with the Schrödinger evolution—would assign to the probability of *observing* that history in a sequence of ideal (coarse-grained, or approximate) measurements of the respective observables at the respective times: If the (initial) wavefunction of the system is ψ,

$$\mathrm{P}(h) = \langle E(h)\psi | E(h)\psi\rangle, \tag{1}$$

where $E(h) = E_n \cdots E_2 E_1$ with $E_1, E_2, \ldots, E_n$ being the Heisenberg projection operators corresponding to the time-ordered sequence of events defining the history h. For example, for a spin-½ particle initially (at $t = 0$) in the state $\psi = |\uparrow\rangle_z$ with z component of spin $\sigma_z = 1$, we could consider the history h for which $\sigma_x = 1$ at $t = 1$ and $\sigma_y = -1$ at $t = 2$. For Hamiltonian $H = 0$, equation 1 then yields $\mathrm{P}(h) = 1/4$.

DH can be regarded as describing a stochastic process, a process with intrinsic randomness. Think, for example, of a random walk, with histories corresponding to a sequence of jumps, and probabilities of histories generated by the probabilities for the individual jumps. The histories with which DH is concerned are histories of observables—of positions of particles, for example. Although Schrödinger's spherical wave impinges continuously on a screen over its full expanse, the screen lights up at one instant at one spot because it is precisely with such events that DH is concerned and to such events that DH assigns nonvanishing probability.

To understand DH, one must appreciate that the histories with which it is concerned are not histories of wavefunctions. For DH the wavefunction is by no means the complete description of a quantum system; it is not even the most important part of that description. DH is primarily concerned with histories of observables, not of wavefunctions; in DH, wavefunctions play only a secondary role, as a theoretical ingredient in the formulation of laws governing the evolution of quantum observables by way of the probabilities assigned to histories. Thus, DH avoids the measurement problem in exactly the manner suggested by Einstein.

It should come as no surprise that the consistent development of the DH idea, of assigning probabilities to objective histories, is not easy to achieve. After all, Bohr and Heisenberg surely would not have insisted that all is observation if such a radical conclusion were easily avoidable. It is only as a first approximation that DH can be regarded as merely describing a stochastic process. There are, in fact, some very significant differences. Perhaps the most crucial of these concerns the role of coarse graining. Because of quantum interference effects, coarse graining plays an essential role for DH—not just for the description of events of interest to us, but in the very formulation of the theory itself. A fine-grained history—given for a system of particles by, for example, the precise specification of the positions of all particles at all times in some time interval—will normally not be assigned any probability. In fact, most coarse-grained histories won't either.

For example, for the two-slit experiment, DH assigns no probability to the history in which the particle passes (unobserved) through, say, the upper slit and lands in a small neighborhood of a specific point on the scintillation screen. Nor, indeed, does it assign any probability to the spin history that differs from the one described after equation 1 only by the replacement of $\sigma_y = -1$ by $\sigma_z = -1$ at $t = 2$; this is because equation 1 yields the value $1/4$ also for this history, which is inconsistent with the value 0 for the corresponding coarse-grained history with $t = 1$ ignored. (These values involve no inconsistency for the usual quantum theory, in which they concern the results of measurements, since the *measurement* of σ_x at $t = 1$ would be expected to disturb σ_z.)

DH assigns probabilities, through the use of equation 1, only to histories belonging to special families $\mathcal{H}$, closed under coarse graining, that satisfy a certain decoherence condition:

$$\mathrm{Re}\langle E(h)\psi | E(h')\psi\rangle = 0$$

for all "elementary" histories $h, h' \in \mathcal{H}$ with $h \neq h'$. This condition guarantees that $\mathrm{P}(h)$ is additive on $\mathcal{H}$ and hence provides a consistent assignment of probabilities to elements of $\mathcal{H}$.

(The decoherence condition actually has several versions, the differences between which I ignore here. There is also a perhaps simpler version of equation 1, with a linear dependence on $E(h)$, that involves a much more

ALBERT EINSTEIN AND NIELS BOHR, the leading figures of 20th-century physics. The two engaged in a decades-long debate about the meaning and interpretation of quantum mechanics. (Photo courtesy of AIP Emilio Segrè Visual Archives.)

robust decoherence condition than the one given above.[11])

Whether or not a family $\mathcal{H}$ satisfies the decoherence condition depends not only on a sequence of times and coarse-grained observables at those times, but also on the (initial) wavefunction ψ (or density matrix ρ) as well as the Hamiltonian H of the relevant system, so it is convenient to regard also these as part of the specification of $\mathcal{H}$. DH assigns probabilities P(h) to those histories h that belong to at least one decoherent family $\mathcal{H}$ (as I call those families satisfying the decoherence condition).

It turns out, naturally enough, that a family of histories describing the results of a sequence of measurements will normally be decoherent, regardless of whether or not we actually observe the measurement devices involved. Moreover, interaction with a measurement device is incidental; satisfaction of the decoherence condition may be induced by any suitable interaction—or by none at all.

In fact, families defined by conditions on (commuting) observables at a *single* time are always decoherent. After all, it is for precisely such families that textbook quantum mechanics supplies perfectly straightforward probability formulas—by means of spectral measures. It is important to bear in mind, however, that even for such standard families, the textbook probability formulas have an entirely different meaning for DH than for orthodox quantum theory. They describe the probability distribution of the actual value of the relevant observable at the time under consideration, and not merely the distribution of the value that would be found were the appropriate measurement performed. This difference is the source of a very serious difficulty for DH.

Inconsistency

The difficulty arises already for the standard families, involving observables at a single time. The problem is that the way that the probabilities P(h) are intended in the DH approach—as probabilities of what objectively happens and not merely of what would be observed upon measurement—is precisely what is precluded by the no-hidden-variables theorems of, for example, Andrew Gleason,[12–14] Simon Kochen and Ernst Specker[14,15] and John Bell.[13,14,16] It is a consequence of these theorems that the totality of quantum mechanical probabilities for the various sets of commuting observables is genuinely inconsistent: The ascription of these probabilities to actual simultaneous values, as relative frequencies of occurrence over an ensemble of systems (a single ensemble for the totality of probabilities, for the wavefunction under consideration) involves an inconsistency, albeit a hidden one. For example, the correlations between spin components for a pair of spin-½ particles in the singlet state, if consistent, would have to satisfy Bell's inequality. They don't.

A simple and dramatic example of the sort of inconsistency I have in mind was recently found by Lucien Hardy.[17] For almost all spin states of a pair of spin-½ particles (the exceptions are the product states and, perhaps surprisingly, maximally entangled states like the singlet state), there are spin components A, B, C and D such that the quantum probabilities for appropriate pairs would imply that in a large ensemble of such systems:

▷ It sometimes happens that $A = 1$ and also $B = 1$.
▷ Whenever $A = 1$, also $C = 1$.
▷ Whenever $B = 1$, also $D = 1$.
▷ It never happens that $C = 1 = D$.

The quantum probabilities are thus inconsistent: There clearly is no such ensemble. (The probability that $A = 1 = B$ is about 9% with optimal choices of state and observables.) The inconsistency implied by violation of Bell's inequality is of a similar nature.

Thus, as so far formulated, DH is not well defined. For a given system, with specified Hamiltonian and fixed initial wavefunction, the collection of numbers P(h), with h belonging to at least one decoherent family, cannot consistently be regarded as intended—as the probability for the occurrence of h. Too many histories have been assigned probabilities. To be well defined, DH must restrict, by some further condition or other, the class of decoherent families whose elements are to be assigned probabilities. It is not absolutely essential that there be only one such family. But if there be more than one, it is essential that the probabilities defined for them be mutually consistent.

Without directly addressing this problem of mutual inconsistency, Gell-Mann and Hartle have emphasized that for various reasons the decoherence condition alone allows far too many families.[9,18] They have therefore introduced additional conditions on families, such as "fullness" and "maximality," and have proposed distinguishing families according to certain tentative measures of "classicity." With such ingredients, they hope to define an optimization procedure—and hence what could be called an optimality condition—that will yield a possibly unique

JOE MUNROE (ORINDA, CALIF.)

MURRAY GELL-MANN AND RICHARD FEYNMAN in 1959. Over the past half century, Gell-Mann has been one of the most sensible critics of orthodox quantum theory while Feynman was one of its most sensible defenders. (Courtesy of the Archives, California Institute of Technology.)

"quasiclassical domain of familiar experience," a family that should be thought of as describing familiar (coarse-grained) macroscopic variables—for example, hydrodynamical variables. When the probability formula P(h) is applied to this family, Gell-Mann and Hartle hope that the usual macroscopic laws, including those of phenomenological hydrodynamics, will emerge, together with quantum corrections permitting occasional random fluctuations on top of the deterministic macrolaws (and classical fluctuations).

Gell-Mann and Hartle do not seem to regard their additional conditions as fundamental, but rather merely as ingredients crucial to their analysis of a theory they believe to be already defined by the decoherence condition alone. While I've argued that there is no such theory, a physical theory could well be defined by the decoherence condition, together with suitable additional conditions, like those proposed by Gell-Mann and Hartle, that would also be regarded as fundamental. In this way, DH becomes a serious program for the construction of a quantum theory without observers.

It is true that much work remains to be done in the detailed construction of a theory along these lines, even insofar as nonrelativistic quantum mechanics is concerned. It is also true that many questions remain concerning exactly what is going on in a universe governed by DH, particularly with regard to the irreducible coarse graining. Nonetheless, it seems likely that the program of DH can be brought successfully to completion. It is, however, not at all clear that the theory thus achieved will possess the simplicity and clarity expected of a fundamental physical theory. The approaches to which I shall turn in part two of this article—spontaneous localization and Bohmian mechanics (a pilot-wave theory)—have already led to the construction of several precise and reasonably simple versions of quantum theory without observers.

I am grateful to Karin Berndl, Jean Bricmont, Martin Daumer, Detlef Dürr, Gregory Eyink, GianCarlo Ghirardi, Rebecca Goldstein, Michael Kiessling, Joel Lebowitz, Eugene Speer, Herbert Spohn, James Taylor and Nino Zanghì for their comments and suggestions—as well as for their patience. This work was supported in part by a grant from the National Science Foundation.

References

1. J. S. Bell, *Speakable and Unspeakable in Quantum Mechanics*, Cambridge U. P., Cambridge, England (1987).
2. E. Schrödinger, Naturwissenschaften 23, 807 (1935); English trans. by J. D. Trimmer, Proc. Am. Philos. Soc. **124**, 323 (1980); reprinted in J. A. Wheeler, W. H. Zurek, eds., *Quantum Theory and Measurement*, Princeton U. P., Princeton, N. J. (1983).
3. P. A. Schilpp, ed., *Albert Einstein, Philosopher-Scientist*, Library of Living Philosophers, Evanston, Ill. (1949).
4. W. Heisenberg, *Physics and Philosophy*, Harper and Row, New York (1958), p. 129.
5. W. Heisenberg, *The Physicist's Conception of Nature*, trans. by A. J. Pomerans, Harcourt Brace, New York (1958), p. 15.
6. A. Einstein, B. Podolsky, N. Rosen, Phys. Rev. **47**, 777 (1935).
7. R. B. Griffiths, J. Stat. Phys. **36**, 219 (1984).
8. R. Omnes, J. Stat. Phys. **53**, 893, 933, 957 (1988).
9. M. Gell-Mann, J. B. Hartle, in *Complexity, Entropy, and the Physics of Information*, W. Zurek, ed., Addison-Wesley, Reading, Mass. (1990), p. 425. M. Gell-Mann, J. B. Hartle, Phys. Rev. D **47**, 3345 (1993).
10. W. H. Zurek, Phys. Rev. D **26**, 1862 (1982). W. H. Zurek, PHYSICS TODAY, October 1991, p. 36 and April 1993, p. 84.
11. S. Goldstein, D. Page, Phys. Rev. Lett. **74**, 3715 (1995).
12. A. M. Gleason, J. Math. and Mech. **6**, 885 (1957).
13. J. S. Bell, Rev. Mod. Phys. **38**, 447 (1966); reprinted in ref. 1.
14. N. D. Mermin, Rev. Mod. Phys. **65**, 803 (1993).
15. S. Kochen, E. P. Specker, J. Math. and Mech. **17**, 59 (1967).
16. J. S. Bell, Physics **1**, 195 (1964); reprinted in ref. 1.
17. L. Hardy, Phys. Rev. Lett. **71**, 1665 (1993). S. Goldstein, Phys. Rev. Lett. **72**, 1951 (1994).
18. M. Gell-Mann, J. B. Hartle, in *Proceedings of the 25th International Conference on High Energy Physics*, K. K. Phua, Y. Yamaguchi, eds., World Scientific, Singapore (1990). ■