Bohm's Alternative to Quantum Mechanics

This theory, ignored for most of the past four decades, challenges the probabilistic, subjectivist picture of reality implicit in the standard formulation of quantum mechanics

by David Z Albert

The study of the behavior of subatomic particles in this century is supposed to have established at least three exceedingly curious facts about the physical world. First, pure chance governs the innermost workings of nature. Second, although material objects always occupy space, situations exist in which they occupy no particular region of space. Third and perhaps most surprising, the fundamental laws that govern the behaviors of "ordinary" physical objects somehow radically fail to apply to objects that happen to be functioning as "measuring instruments" or "observers." That at any rate is what the founders of quantum mechanics decided; that is what has since become the more or less official dogma of theoretical physics; and that is what it says, to this day, in all the standard textbooks on that subject.

But it is now emerging that those conclusions were settled on somewhat too quickly. As a matter of fact, a radically different, fully worked-out theory exists that accounts for all known behaviors of subatomic particles. In this theory, chance plays no role at all, and every material object invariably does occupy some particular region of space. Moreover, this theory takes the form of a single set of basic physical laws that apply in exactly the same way to every physical object that exists.

That theory is principally the work of the late David J. Bohm of Birkbeck College, London. Although his formulation has existed in the scientific literature for more than 40 years, it has until quite recently been mostly ignored. Throughout that period, the thinking about such matters has been dominated by the standard dogma, usually referred to as the Copenhagen interpretation of quantum mechanics because it can more or less be traced back to the Danish physicist Niels Bohr and his circle.

I will begin this article with an outline of the main arguments for the standard dogma. I will then indicate briefly how Bohm's theory manages to get around some of those arguments. Finally, I will say a little about how and where Bohm's theory fits into contemporary speculation about the foundations of quantum mechanics.

DAVID Z ALBERT has done scientific and philosophical work on various aspects of the foundations of quantum mechanics, with special emphasis on the quantum measurement problem. Recently he has also been thinking about the relation between that problem and the direction of time. In 1981 he received his Ph.D. in theoretical physics from the Rockefeller University. Before taking his current position as professor of philosophy at Columbia University, he served on the faculty of the physics department at the University of South Carolina at Columbia and was a postdoctoral fellow at Tel Aviv University. His book *Quantum Mechanics and Experience* was published last year by Harvard University Press.

Perhaps the simplest way of formulating the arguments for the standard dogma is in the context of certain experiments with electrons. The experiments all involve measurements of two components of what are usually called the spins of electrons. For simplicity's sake, I will refer to them as the horizontal spin and the vertical spin.

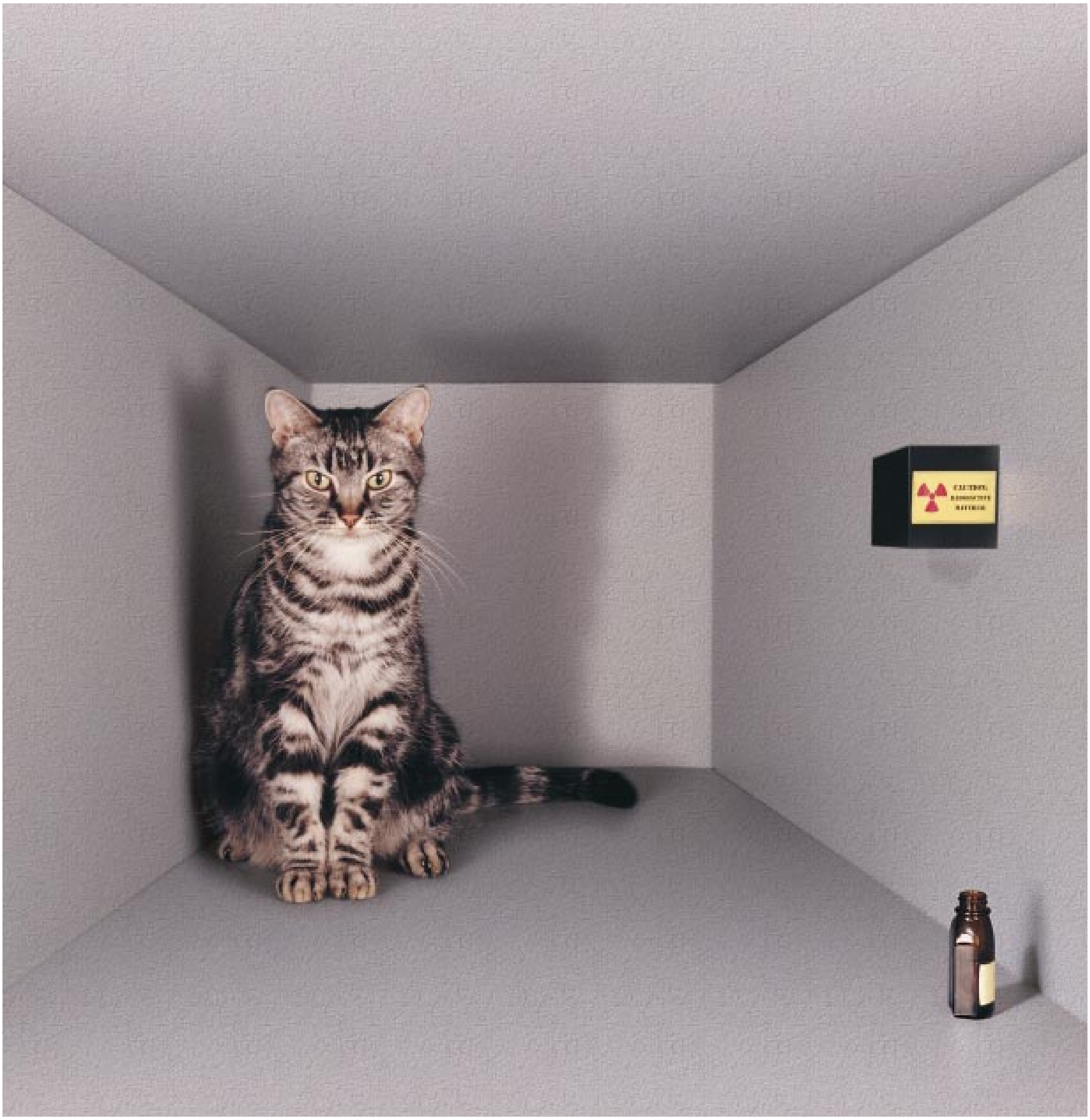
It happens to be an empirical fact (as far as we know) that the horizontal spins of electrons can assume only one of two possible values. The same applies for vertical spins. I will call the values of the horizontal spin right and left and those of the vertical spin up and down.

Physicists can measure the horizontal and vertical spins of electrons easily and accurately with currently available technologies. Spin-measuring devices typically work by altering the direction of motion of the electron fed into the device based on the value of its measured spin component. In this way, the value of that spin component can be determined later by a simple measurement of the electron's position. I will refer to these measuring devices as horizontal and vertical boxes [*see illustration on page 60*].

Another empirical fact about electrons is that as a rule there are no correlations between their horizontal spin values and their vertical spin values. For example, of any large collection of right-spinning electrons fed into the entry aperture of a vertical box, precisely half (statistically speaking) will emerge through the "up" aperture and half through the "down" aperture. The same applies for left-spinning electrons fed into the entry aperture of a vertical box and for up- and down-spinning electrons fed into horizontal boxes.

Another experimental truth about electrons, and an extremely important one for our purposes, is that a measurement of the horizontal spin of an electron can disrupt the value of its vertical spin, and vice versa, in what appears to be a completely uncontrollable way. If, for example, one carries out measurements of the vertical spins of any large collection of electrons in-between two measurements of their horizontal spins [*see top illustration on page 61*], what always happens is that the vertical spin measurement changes the horizontal spin values of half of the electrons that pass through it, leaving those of the other half unchanged.

No one has ever been able to design a measurement of vertical spin that avoids such disruptions. Moreover, no

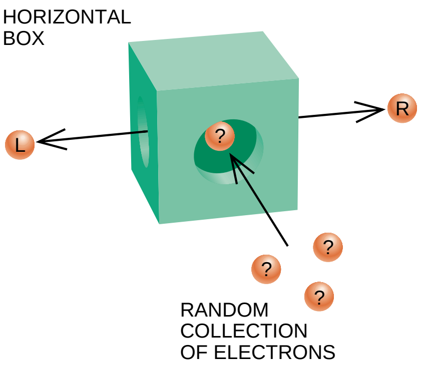


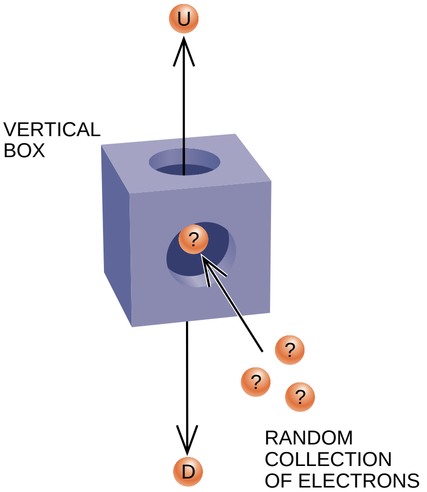
LIVE QUANTUM CAT is one possible outcome of Schrödinger's famous thought experiment, in which a radioactive substance, on emitting a particle, would trigger the release of lethal poison. The problem posed by the experiment is to reconcile the two following facts. The first is that, empirically, cats invariably appear to us either alive or dead. The second is that the linear quantum-mechanical equations of motion seem to predict that cats can be in an almost unimaginably bizarre state in which they are neither alive nor dead. In the standard formulation, sometimes called the Copenhagen interpretation, the approach to this problem involves assigning a unique and indispensable role to observers or measuring devices in bringing about a determinate outcome. Bohm's theory rejects this subjectivist picture: one of the important achievements of this theory is that it solves the problem without recourse to any special role for observers.

one has ever been able to identify any physical properties of the individual electrons in such collections that determine which of them get their horizontal spins changed in the course of having their vertical spins measured and which do not.

What the official doctrine has to say about these matters is that in principle there can be no such thing as a vertical spin measurement that has anything other than precisely that effect on horizontal spin values. Furthermore, the standard doctrine dictates that it is a matter of absolutely pure chance which electrons get their horizontal spins changed by measurements of their vertical spins and which do not; the laws governing those changes simply fail to be deterministic. And these conclusions certainly seem innocent and reasonable given the experimental data.

If measuring one type of spin indeed always uncontrollably disrupts the val-





SPIN-MEASURING BOXES change the direction of motion of electrons based on the particles' spin values. A "horizontal box" sends left-spinning electrons to the left; right-spinning electrons go to the right (*left*). A "vertical box" sends up-spinning electrons up and down-spinning ones down (*right*).

ue of the other, then there can be no way of ascertaining the values of both the horizontal and vertical spins of any particular electron at any particular moment. This phenomenon is an example of the uncertainty principle: certain pairs of measurable physical properties, such as position and momentum or, in our case, horizontal and vertical spin, are said to be incompatible with each other. Measurements of one will always uncontrollably disrupt the other. Many other known examples of incompatible pairs of physical properties exist as well.

So much for indeterminism. But there are still more puzzling features of subatomic particles. Displaying them will require a more complicated experiment. Imagine a box that measures the vertical spins of electrons [*see bottom illustration on opposite page*]. Up-spinning electrons emerge from the box along a route labeled up; down-spinning electrons exit along a route labeled down. We can then arrange a pair of "reflecting walls" to make the two paths cross at some other point. These surfaces can be designed so as not to alter the spin properties of electrons in any way. At the point where the two paths intersect, we place a "black box" that merges the paths back into one, again without altering spin values.

Suppose we feed a large collection of right-spinning electrons, one at a time, into the vertical box. The electrons travel along the paths to the black box. Then as they emerge from the exit of the black box, we measure their horizontal spins. What sorts of results should we expect? Our previous experience informs us that statistically half of such electrons will turn out to be up-spinning and will take the up route through the apparatus. The other half will turn out to be down-spinning and take the down route. Consider the first half. Nothing along the paths between the vertical box and the exit point can have any effect on the vertical spin values of the electrons. Therefore, they will all emerge from the apparatus as up-spinning electrons. In accord with our earlier data, 50 percent of them will turn out to be right-spinning and 50 percent left-spinning. The down-spinning half will have precisely the same horizontal spin statistics. Putting all these expectations together, it follows that for any large set of right-spinning electrons fed into this apparatus, half should be found at the end to be right-spinning and half to be left-spinning.

These conclusions seem absolutely cut-and-dried. But a funny thing happens when you actually try this experiment. Exactly 100 percent of the right-spinning electrons initially fed into this apparatus (one at a time, mind you) come out right-spinning at the end.

It is no exaggeration to describe this result as one of the strangest in modern physics. Perhaps modifying the experiment somewhat will clarify matters. Suppose that we rig up a small, movable, electron-stopping wall that can be slid at will in and out of, say, the up route [*see bottom illustration on opposite page*]. When the wall is out, we have precisely our earlier apparatus. But when the wall is in, all electrons moving along the up route are stopped, and only those moving along the down route get through to the black box.

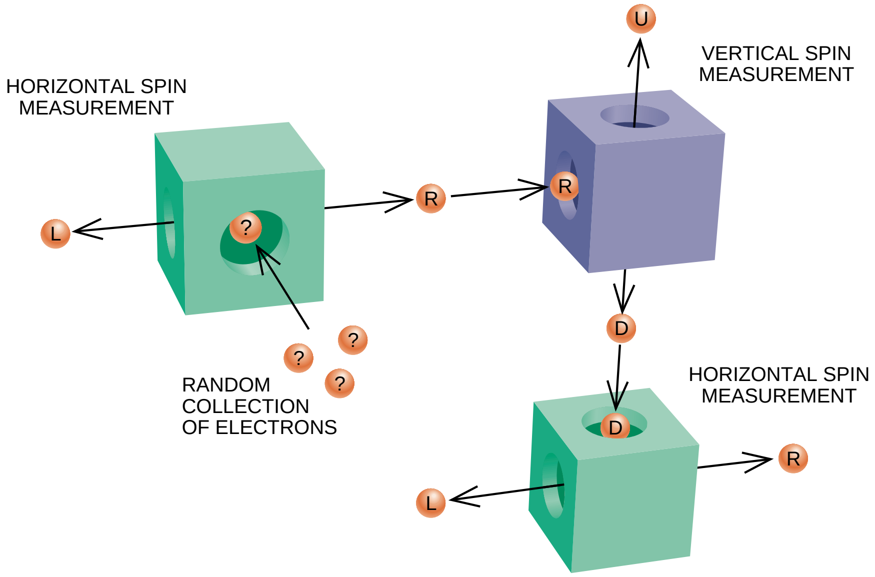
What should we expect to happen when we slide the wall in? To begin with, the overall output of electrons at the exit of the black box ought to drop by 50 percent, because one path is blocked. What about the horizontal spin statistics of the remaining 50 percent? When the wall was out, 100 percent of the right-spinning electrons initially fed in ended up as right-spinning electrons. That is, all those electrons ended up as right-spinning whether they took the up or the down route. Thus, because the presence or absence of the wall on the up route cannot affect electrons on the down route, the remaining 50 percent should all be right-spinning.

As you may have guessed, what actually happens in the experiment runs contrary to our expectations. The output is down by 50 percent, as predicted. But the remaining 50 percent are not all right-spinning. Half are right-spinning, and half are left-spinning. And the same thing happens if we insert a wall in the down path instead. (Readers familiar with quantum mechanics may recognize that this experiment is a logically streamlined version of the famous double-slit experiment.)

How can one understand the discrepancy between the results of these experiments and our expectations about them? Consider an electron that passes through the apparatus when the wall is out. Consider the possibilities as to which route it could have taken. Could it have taken the down route? Apparently not, because electrons taking that route (as the experiment with the wall in reveals) are known to have horizontal spin statistics of 50-50, whereas an electron passing through our apparatus without the wall is known with certainty to be right-spinning at the apparatus exit. Can it have taken the up path, then? No, for the same reasons.

Could it somehow have taken both routes? No: suppose that when a certain electron is passing through this apparatus, we stop the experiment and look to see where it is. It turns out that half the time we find it on the up path and locate nothing at all on the down path, and half the time we find it on the down path and see nothing at all on the up path. Could it have taken neither route? Certainly not. If we wall up both routes, nothing gets through at all.

Something breathtakingly deep, it would seem, has got to give. And indeed, something does—at least according to what has become one of the central tenets of theoretical physics over the past half-century (it is the second of the three official dogmas to which I alluded in the opening paragraph, the one about the indefiniteness of position). That doctrine stipulates that these experiments leave us no alternative but to deny that the very question of which route such an electron takes through



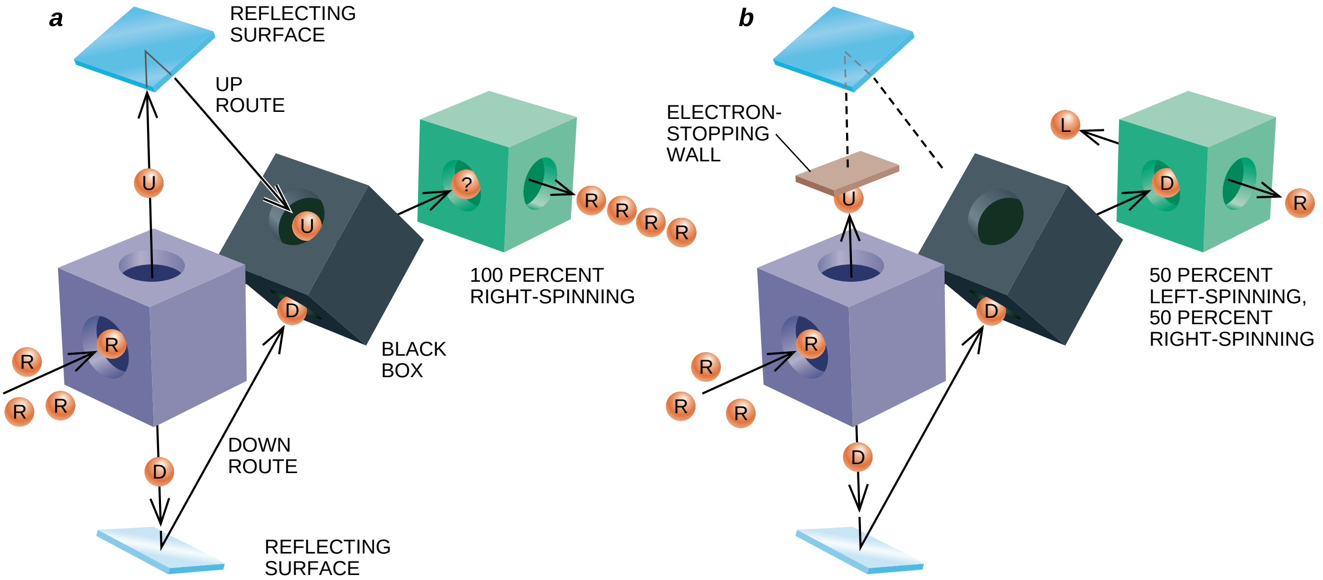
SPIN BEHAVIOR is disrupted in a sequence of three measurements. Electrons are measured one at a time for their horizontal spins (*left*), then for their vertical spins (*right*), and again for their horizontal spins (*bottom*). The vertical box disrupts the spins of half those electrons, so that half emerge from the second horizontal box with right spin, and half emerge with left spin.

such a contraption makes any sense. Asking what route such an electron takes is supposed to be like asking about, say, the political convictions of a tuna sandwich or about the marital status of the number 5. The idea is that asking such questions amounts to a misapplication of language, to what philosophers call a category mistake.

Hence, what physics textbooks typically declare about such electrons is emphatically not that the particles take either the up route or the down route or both routes or neither route through the apparatus. Rather there is simply not any fact about which route they take—not merely no known fact, but no fact at all. They are in what the textbooks term a superposition of taking the up route and the down route through the apparatus.

Notwithstanding the profound violence these ideas do to our intuitive picture of the world, to the very notion of what it is to be material, to be a particle, a compact set of rules has been cooked up that has proved extraordinarily successful at predicting all the observed behaviors of electrons under these circumstances. Moreover, these rules—known of course as quantum mechanics—have proved extraordinarily successful at predicting all the observed behaviors of all physical systems under all circumstances. Indeed, quantum mechanics has functioned for more than 70 years as the framework within which virtually the entirety of theoretical physics is carried out.

The mathematical object with which quantum mechanics represents the states of physical systems is referred to as the wave function. In the simple case of a single-particle system of the kind I have been discussing, the quantum-mechanical wave function takes the form of a straightforward function of position. The wave function of a particle located in some region A, for example, will have the value zero everywhere in space except in A and will have a nonzero value in A. Similarly, the wave function of a particle located in some region B will have the value zero everywhere in space except in B and will have a nonzero value in B. And the wave function of a particle in a superposition of being in region A and in region B—the wave function, for example, of an initially right-spinning electron that has just passed through a vertical box—will have nonzero values



TWO-PATH CONTRAPTION depicts the unusual spin behavior of electrons. In panel *a*, right-spinning electrons fed into a vertical box are sent along the up route or the down route. Reflecting surfaces cause the two paths to converge at a "black box," after which all the electrons are found to be right-spinning. In panel *b*, a wall blocks one of the paths, so that only half the electrons make it to the end. Half these electrons are left-spinning, and half are right-spinning.

Creator of a Brave, New Quantum World

David Joseph Bohm was born in 1917 in Wilkes-Barre, Pa. After studying physics at Pennsylvania State College, he pursued graduate studies at the University of California at Berkeley. There, during World War II, he investigated the scattering of nuclear particles under the supervision of J. Robert Oppenheimer. After receiving his degree from Berkeley, Bohm became an assistant professor at Princeton University in 1946.

It was during those years that Bohm wrote his now classic defense of the Copenhagen interpretation, *Quantum Theory.* At the same time, however, Bohm's doubts about the adequacy of that interpretation were becoming more acute. His own alternative emerged in published form shortly thereafter, in 1952.

By then, Princeton had forced him from its faculty. During the McCarthy era, Bohm had been called before the House Un-American Activities Committee in connection with completely unsubstantiated allegations that he and some former colleagues at the radiation laboratory at Berkeley were communist sympathizers. (During World War II, Oppenheimer began turning in to the Federal Bureau of Investigation names of friends and acquaintances who he thought might be communist agents. Bohm apparently was one of the accused.) A passionate believer in liberty, Bohm refused to testify as a matter of principle. As a result, the committee found him to be in contempt of Congress.

The incident proved disastrous to Bohm's professional career in the U.S. Princeton refused to renew his contract and told him not to set foot on the campus. Unable to find employment at any other university, Bohm left the country in 1951 to take a position at the University of São Paulo in Brazil. There he was asked by U.S. officials to give up his passport, effectively stripping him of his American citizenship.

After teaching in Brazil, Bohm went to the Technion in Israel and to Bristol University in England. Although he was later cleared of the contempt charges and was eventually allowed to travel back to the U.S., Bohm settled permanently at Birkbeck College, London, in 1961.

In addition to his interpretation of quantum mechanics, he contributed to mainstream physics, working on plasmas, metals and liquid helium. In 1959 he and his student Yakir Aharonov discovered what is now known as the Aharonov-Bohm effect. They showed that quantum mechanics predicts that the motions of charged particles can be influenced by the presence of magnetic fields even if those particles never enter the regions to which those fields are confined. Subsequent experiments have amply confirmed the effect [see "Quantum Interference and the Aharonov-Bohm Effect," by Yoseph Imry and Richard A. Webb; SCIENTIFIC AMERICAN, April 1989].

Later in life Bohm became interested in broader philosophical questions. He developed a picture of the universe as an interconnectedness of all things, a notion he called "implicate order." He wrote several books on physics, philosophy and the nature of consciousness. He was in the middle of a collaborative effort on another quantum mechanics book when he died of a heart attack in October 1992. Friends and colleagues remember Bohm not only as brilliant and daring but also as extraordinarily honest, gentle and generous.

DAVID J. BOHM (*center*) is escorted to the House Un-American Activities Committee hearing room by Donald Appel, a staff investigator, on May 25, 1949.

in both of those regions and a zero value everywhere else.

And it is a cardinal rule of quantum mechanics (a rule that Bohm's theory will explicitly break) that representing physical objects by a wave function represents them completely. It states that absolutely everything there is to be said about any given physical system at any given instant can be read from its wave function.

What the laws of physics are about—indeed, all that the laws of physics could be about, all that there is for the laws of physics to be about, according to quantum mechanics—is how the wave functions of physical systems evolve in time. The textbook version of quantum mechanics refers to two categories of such laws. And what is particularly peculiar about this formulation is that one of those categories applies when the physical systems in question are not being directly observed, and the other applies when they are.

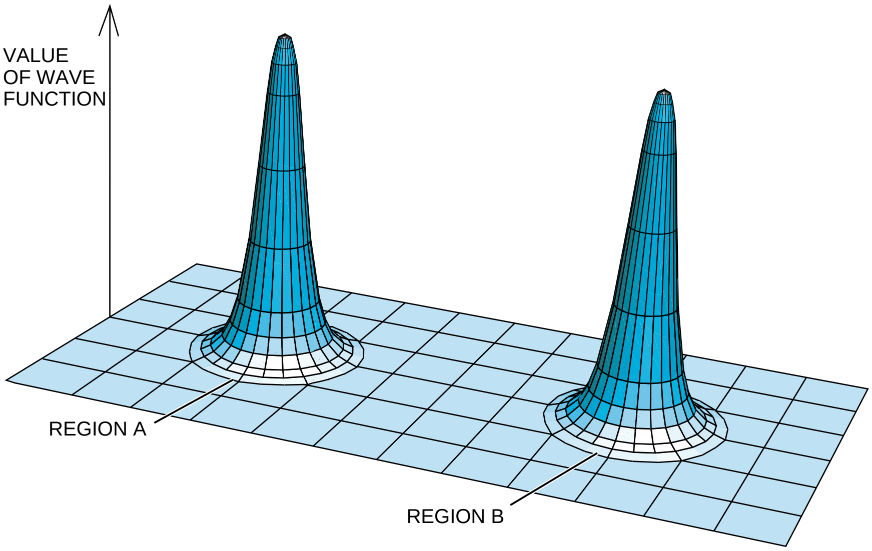
The laws in the first category are usually written down in the form of linear differential "equations of motion." They are designed to entail, for example, that an initially right-spinning electron fed into a vertical box will emerge from that box in a superposition of traveling along the up route and traveling along the down route. Moreover, all available experimental evidence suggests that those laws govern the evolutions of the wave functions of every single isolated microscopic physical system under all circumstances. So, because microscopic systems are the constituents of everything that exists, there would on the face of it seem to be good reason to suppose that those linear differential equations are the true equations of motion of the entire physical universe.

Yet that conclusion cannot possibly be quite right if wave functions are indeed complete descriptions of physical systems, as quantum mechanics maintains. To begin with, the laws expressed by those equations are completely deterministic, whereas an element of pure chance seems to play a role in the outcomes, for example, of experiments with the spin boxes.

Consider the outcome of a measurement of the position of an electron that is initially in a superposition of being in region A and being in region B. Straightforward calculations reveal that the linear differential equations of motion offer a definite prediction about the end of such a measuring process. Those equations, however, do not predict that the measuring device would either indicate that the electron was found in A or that the electron was found in B (which is what happens when you actually make measurements like that). Rather those equations say the measuring device would with certainty end up in a superposition of indicating that the electron was found in A and indicating that the electron was found in B. To put it slightly differently, those equations predict that the measuring device would end up in a physical state in which there is simply no fact about what it is indicating. It hardly needs mentioning that such superpositions (whatever they are, precisely) do not correctly describe how things end up when you actually make such a measurement.

As a result, according to the official reasoning, the first category of laws needs to be supplemented with a second, which will be explicitly probabilistic. It demands, for example, that if the position of an electron that is initially in a superposition of being in region A and region B were to be measured, there would be a 50 percent chance of finding that electron in region A and a 50 percent chance of finding it in region B. In other words, if the position of the electron were measured, there would be a 50 percent chance that the electron's wave function will be altered in the course of the measurement to one whose value is zero everywhere other than in region A and a 50 percent chance that its wave function will be altered to one whose value is zero everywhere except in region B. (This alteration is sometimes called a "collapse" of the wave function.)

How does one distinguish those conditions in which the first category of laws applies from those in which the second category does? All the founders of quantum mechanics had to say was that it has something to do with the distinction between a "measurement" and an "ordinary physical process," or between what observes and what is observed, or between subject and object.



PARTICLE WAVE FUNCTIONS have nonzero values in those areas of space in which a position measurement might ultimately find the particle. In the standard dogma, the observation "collapses" the wave function onto either region A or region B.

For some time, many physicists and philosophers have viewed this state of affairs as profoundly unsatisfactory. It has seemed absurd that the best existing formulation of the most fundamental laws of nature should depend on such imprecise and elusive distinctions. The challenge of either eliminating or repairing that imprecision has emerged over the past 30 years as the central task of the foundations of quantum mechanics. It has gone by a number of names: the problem of Schrödinger's cat, for example, or of Wigner's friend, or of quantum state-reduction. I will refer to it by its most common contemporary name: the measurement problem.

One particularly striking solution to the measurement problem was invented by the American-born physicist David J. Bohm. The French physicist Louis de Broglie had devised a related scheme some years earlier, but de Broglie's formulation was much less general and powerful than was Bohm's. More recently, the late physicist John Bell recast Bohm's original theory into a very simple and compelling form.

Notwithstanding all the evidence to the contrary presented above, Bohm's theory presumes that particles are the sorts of things that are invariably located in one or another particular place. In addition, Bohm's theory is a great deal clearer than is the Copenhagen interpretation about what the world is made of. In Bohm's account, wave functions are not merely mathematical objects but physical ones, physical things. Bohm treats them somewhat like classical force fields, such as gravitational and magnetic fields. What wave functions do in Bohm's theory (just as classical force fields do) is to in effect push the particles around, to guide them, as it were, along their proper courses.

The laws that govern the evolutions of those wave functions in time are stipulated to be precisely the standard linear differential quantum-mechanical equations of motion—but this time with no exceptions whatever. There are other laws in Bohm's theory as well that dictate how those wave functions push their respective particles around. All those laws are fully deterministic. Therefore, the positions of all the particles in the world at any time, and the world's complete quantum-mechanical wave function at that time, can be calculated with certainty from the positions of all the particles in the world and the world's complete quantum-mechanical wave function at any earlier time.

Any incapacity to carry out those calculations, any uncertainty in the results of those calculations, is necessarily in this theory an epistemic uncertainty. It is a matter of ignorance and not a matter of the operations of any irreducible element of chance in the fundamental laws of the world. Nevertheless, this theory entails that some such ignorance exists for us, as a matter of principle. The laws of motion of Bohm's theory literally force this kind of ignorance on us. And this ignorance turns out to be precisely enough, and of precisely the right kind, to reproduce the familiar statistical predictions of quantum mechanics. That happens by means of a kind of averaging over what one does not know, which is exactly the kind of averaging that goes on in classical statistical mechanics.

The theory describes a real, concrete and deterministic physical process—a process that can be followed out in exact mathematical detail—whereby the act of measurement unavoidably gets in the way of what is being measured. In other words, Bohm's theory entails that this ignorance—although it is merely ignorance of perfectly definite facts about the world—cannot be eliminated without a violation of physical law (without, that is, a violation of one or the other of the two laws of motion described in the box on page 66, from which everything else about Bohm's theory follows).

Bohm's theory can fully account for

the outcomes of the experiments with the two-path contraption—the experiments that seemed to imply that electrons can be in states in which there fails to be any fact about where they are. In the case of an initially right-spinning electron fed into the apparatus, Bohm's theory entails that the electron will take either the up or the down route, period. Which of those two routes it takes will be fully determined by the particle's initial conditions, more specifically by its initial wave function and its initial position. Of course, certain details of those conditions will prove impossible, as a matter of law, to ascertain by measurement. But the crucial point here is that whichever route the electron happens to take, its wave function will split up and take both. It will do so in accordance with the linear differential equations of motion.

So, in the event that the electron in question takes, say, the up route, it will nonetheless be reunited at the black box with the part of its wave function that took the down route. How the down-route part of the wave function ends up pushing the electron around once the two are reunited will depend on the physical conditions encountered along the down path. To put it a bit more suggestively, once the two parts of the electron's wave function are reunited, the part that took the route that the electron itself did not take can "inform" the electron of what things were like along the way. For example, if a wall is inserted in the down route, the down component of the wave function will be missing at the exit of the black box. This absence in itself can constitute decisive information. Thus, the motion that such an electron executes, even if it took the up path through the apparatus, can depend quite dramatically on whether or not such a wall was inserted.

Moreover, Bohm's theory entails that the "empty" part of the wave function—the part that travels along the route the electron itself does not take—is completely undetectable. One of the consequences of the second equation in the box below is that only the part of any given particle's wave function that is currently occupied by the particle itself can have any effect on the motions of other particles. So the empty part of the wave function—notwithstanding the fact that it is really, physically, there—is completely incapable of leaving any observable trace of itself on detectors or anything else.

Hence, Bohm's theory accounts for all the unfathomable-looking behaviors of electrons discussed earlier every bit as well as the standard interpretation does. Moreover, and this point is important, it is free of any of the metaphysical perplexities associated with quantum-mechanical superposition.

As to the measurement problem, it can be persuasively argued that Bohm's theory can suffer from nothing of the kind. Bohm's theory holds that the linear differential equations of motion truly and completely describe the evolution of the wave function of the entire universe—measuring devices, observers and all. But it also stipulates that there are invariably definite matters of fact about the positions of particles and, consequently, about the positions of pointers on measuring devices and about the positions of ink molecules in laboratory notebooks and about the positions of ions in the brains of human observers and thus, presumably, about the outcomes of experiments.

Despite all the rather spectacular advantages of Bohm's theory, an almost universal refusal even to consider it, and an almost universal allegiance to the standard formulation of quantum mechanics, has persisted in physics, astonishingly, throughout most of the past 40 years. Many researchers have perennially dismissed Bohm's theory on the grounds that it granted a privileged mathematical role to the positions of particles. The complaint was that this assignment would ruin the symmetry between position and momentum, which had been implicit in the mathematics of quantum theory up until then—as if ruining that symmetry somehow amounted to a more serious affront to scientific reason than the radical undermining, in the Copenhagen formulation, of the very idea of an objective physical reality. Others dismissed Bohm's theory because it made no empirical predictions (no obvious ones, that is) that differed from those of the standard interpretation—as if the fact that those two formulations had much in common on that score some-

The Exact Mathematical Formulation of Bohm's Theory

Bohm's theory in its entirety consists of three elements. The first is a deterministic law (namely, Schrödinger's equation) that describes how the wave functions of physical systems evolve over time. It is:

$$i\frac{h}{2\pi}\frac{\partial}{\partial t}\psi(x_1\ldots x_{3N},t) = H\psi(x_1\ldots x_{3N},t)$$

where i is the imaginary number $\sqrt{-1}$, h is Planck's constant, ψ is the wave function, H is a mathematical object called the Hamiltonian operator, N is the number of particles in the system, $x_1\ldots x_{3N}$ represent the spatial coordinates of those particles, and t is the time. Loosely speaking, the Hamiltonian operator describes the energy in the system.

The second element is a deterministic law of the motions of the particles:

$$\frac{dX_i(t)}{dt} = \frac{j_i(X_1\ldots X_{3N},t)}{|\psi(X_1\ldots X_{3N},t)|^2}$$

where $X_1\ldots X_{3N}$ represent the actual coordinate values of the particles, $dX_i(t)/dt$ is the rate of change of X_i at time t, and j_i represents the components of the standard quantum-mechanical probability current. The subscript i ranges from 1 to $3N$.

The third element is a statistical rule analogous to one used in classical statistical mechanics. It stipulates precisely how one goes about "averaging over" one's inevitable ignorance of the exact states of physical systems. It runs as follows. Assume one is given the wave function of a certain system but no information about the positions of its particles. To calculate the motions of those particles in the future, what one ought to suppose is that the probability that those particles are currently located at some position $(X_1\ldots X_{3N})$ is equal to $|\psi(X_1\ldots X_{3N})|^2$. If information about the positions of the particles becomes available (as during a measurement), the rule indicates that that information ought to be used to "update" the probabilities through a mathematical procedure called straightforward conditionalization.

That is literally all there is to Bohm's theory. Whatever else we know about it—everything presented in this article, for example—derives strictly from these three elements.

how transparently favored one of them over the other. Still others cited "proofs" in the literature—the most famous of which was devised by the American mathematician John von Neumann, and all of which were wrong—that no deterministic replacement for quantum mechanics of the kind that Bohm had already accomplished was even possible.

Fortunately, those discussions are mostly in the past now. Although the Copenhagen interpretation probably remains the guiding dogma of the average working physicist, serious students of the foundations of quantum mechanics rarely defend the standard formulation anymore. A number of interesting new proposals now exist for solving the measurement problem. (There are, for example, attempts at resuscitating in a more precise language the idea of a collapse of the wave function, which I mentioned earlier.) It is against those, against other proposals yet to be invented and, of course, against the experimental facts that Bohm's theory will ultimately have to be judged. The jury on all that is still very much out.

QUANTUM APOSTATE David J. Bohm, shown here three years before his death in 1992, formulated his interpretation of quantum mechanics in the 1950s.

Bohm's theory is the only serious proposal around just now that is fully deterministic. It is also the only one that denies there are any such things as superpositions, even for microscopic systems. But it is certainly not free of transgressions against what one might call common physical sense. Perhaps the most flagrant of those transgressions is nonlocality. The theory allows for the possibility that something that occurs in region A can have a physical effect in region B, instantaneously, no matter how far apart regions A and B may happen to be. The influence is also completely independent of the conditions existing in the space between A and B [see "Faster than Light?" by Raymond Y. Chiao, Paul G. Kwiat and Aephraim M. Steinberg; SCIENTIFIC AMERICAN, August 1993].

But nonlocality may be something we need to learn to live with, something that may simply turn out to be a fact of nature. The standard formulation of quantum mechanics is also nonlocal and so are most of the recently proposed solutions to the measurement problem. Indeed, according to a famous argument of Bell's, any theory that can reproduce those statistical predictions of quantum mechanics already known to be correct and that satisfies a few extremely reasonable assumptions about the physical nature of the world must necessarily be nonlocal. The only schemes that have been imagined for denying those assumptions and so avoid nonlocality are the "many worlds" and "many minds" interpretations of quantum mechanics. They suggest that in some sense all possible experimental outcomes, and not simply one or another of those outcomes, actually occur. And they are (maybe) too bizarre to be taken seriously.

Workers have raised various other concerns as well. What is the exact philosophical status of the probabilities in Bohm's theory? Does guaranteeing that every particle in the world invariably has a determinate position really amount to ensuring that every imaginable measurement has a determinate outcome and that everything that we intuitively take to be determinate is really determinate? Those questions continue to be the subject of active debate and investigation.

Finally, and most important, I must stress that all of what has been said in this article applies, at least for the moment, only to nonrelativistic physical systems. That is, it pertains just to systems whose energies are not very high, that are not moving close to the speed of light and that are not exposed to intense gravitational fields. The development of a Bohmian replacement for relativistic quantum field theory is still under way, and the ultimate success of that enterprise is by no means guaranteed. If such a replacement were somehow found to be impossible, then Bohm's theory would have to be abandoned, and that would be that.

But as it happens, most other proposals for solving the measurement problem are in a similar predicament. The exceptions, once again, are the many-worlds and many-minds interpretations, whose relativistic generalizations are quite straightforward but whose metaphysical claims are difficult to believe. Much of the future course of the foundations of quantum mechanics will hinge on how attempts at relativization come out.

In the meantime, the news is that a great deal more than has previously been acknowledged about the foundations of our picture of the physical world turns out to be radically unsettled. In particular, the possibilities that the laws of physics are fully deterministic and that what they describe are the motions of particles (or some analogue of those motions in relativistic quantum field theory) are both, finally and definitively, back on the table.

FURTHER READING

A SUGGESTED INTERPRETATION OF THE QUANTUM THEORY IN TERMS OF "HIDDEN" VARIABLES, I AND II. David Bohm in *Quantum Theory and Measurement.* Edited by J. A. Wheeler and W. H. Zurek. Princeton University Press, 1983.

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BOHM'S THEORY. In *Quantum Mechanics and Experience,* by David Z Albert. Harvard University Press, 1992.

QUANTUM EQUILIBRIUM AND THE ORIGIN OF ABSOLUTE UNCERTAINTY. Detlef Dürr, Sheldon Goldstein and Nino Zanghi in *Journal of Statistical Physics,* Vol. 67, Nos. 5/6, pages 843–908; June 1992.