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The (Non)World (Non)View of Quantum Mechanics*

N. David Mermin

I was strongly reminded of the importance of utmost caution in all questions of terminology and dialectics.

Niels Bohr

One of the broad lessons of quantum mechanics is that one has to be extremely careful in thinking about the world. One must exercise “utmost caution” and be suspicious of any attempts, no matter how apparently harmless, to populate the world with conceptual entities. Even in those cases where it is permissible to say this is such-and-such and that is so-and-so, one should be wary of any attempts to develop a picture beyond the narrowest possible formulation of such-and-such-ness and so-and-so-ness.

If you think I exaggerate, consider how the views of Niels Bohr were described by a colleague: “When asked whether the algorithm of quantum mechanics could be considered as somehow mirroring an underlying quantum world, Bohr would answer, ‘There is no quantum world. There is only an abstract quantum physical description. It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature.’”

A (non)world (non)view, if ever there was one.

Bohr himself was unquestionably the highest authority in all matters of quantum metaphysics, a position he earned by virtue of being the second greatest physicist of the twentieth century. He never said anything nearly this dramatic in print for he was extraordinarily cautious in his writings. The closest to it I can find is “physics is to be regarded not so much as the study of something

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a priori given, but rather as the development of methods for ordering and surveying human experience."

If you have to rely on Bohr’s writings to convey the drama of his intellectual position, you rapidly succumb to despair. Heisenberg, on the other hand, offers sensational specimens of the (non)world (non)view: “The conception of the objective reality of the elementary particles has thus evaporated in a curious way, not into the fog of some new, obscure, or not yet understood reality concept, but into the transparent clarity of a mathematics that represents no longer the behavior of the elementary particles but rather our knowledge of this behavior”; or “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.”

Abraham Pais reports in his biography of Einstein that once when they were walking together “Einstein suddenly stopped, turned to me and asked whether I really believed that the moon exists only when I look at it.” It appears that all of them except Einstein were afflicted with an intellectual disease that I will call terminal positivism.

What led them there was the discovery that at the atomic level you cannot determine the properties of something without disturbing it. There thus are inherent limits to how much information one can acquire about an individual physical system. In prequantum (“classical”) physics, for example, you can learn both the position and the velocity of a particle with arbitrary precision. At the atomic level, you cannot. Any experiment giving information about the position of a particle necessarily alters its velocity in an uncontrollable way; the more accurately you determine the position, the more you disrupt the velocity. Conversely, the more precisely you measure the velocity, the more you will mess up the position.

The reason Bohr and Heisenberg always gave for these unavoidable disruptions is basically this: Even if all you do to learn about a particle is look at it, you must still shine light at it to see it, and light exerts a delicate pressure on whatever it illuminates. As you get down to the atomic level the particle becomes tinier and tinier—more easy to disturb—and you have to make your experimental probe more and more gentle. If your probe is light you have to make it dimmer and dimmer. Eventually, however, you run up against the fact that your probe itself has an atomic structure—in the case of light, it comes in discrete packages called photons—and therefore you cannot continue refining your probe to eliminate significant disturbance of the particle all the way down to the atomic level. You can’t make the light dimmer than a single photon without
turning it off altogether, and even a single photon is gross enough to inflict major disruptions on something as delicate as an atomic particle. (There are elaborations of this based on how the energy of a photon is related to the wavelength of the associated light, but at the heart of all such arguments is this unavoidable, uncontrollable, bumping around.)

These facts lie behind the famous Heisenberg “uncertainty” or “indeterminacy” principle. They certainly limit what we can learn from experiments, but what do they really tell us about the world—about what exists out there, independent of the experimental questions we choose to ask? Any physicist would strenuously object to this question: How can I talk about what is out there independent of our experiments? This is a good example of our terminal positivism.

If one were not afflicted with terminal positivism, a natural interpretation of the uncertainty principle would be that atoms or subatomic particles really do have both a position and a velocity, but there is simply no way to design an experiment that measures both with arbitrary precision. This, however, is too innocent a view. The correct attitude is that the concepts of position and velocity cease to have meaning at the atomic level. Matter on that tiny scale is simply a different kind of stuff. We devise experiments at the atomic level which, if we performed them with baseballs rather than protons, we would interpret as measuring the ball’s position, and we can devise other experiments that we would interpret as measuring the ball’s velocity, and it is therefore convenient to describe these experiments as “position measurements” and “velocity measurements.” But the naive concepts of position and velocity simply do not apply to the atomic particles we subject to such measurements. Atomic particles require a new description, and should be characterized by entirely new entities such as “wave-function” or “quantized field”—some of the ingredients of Heisenberg’s transparently clear mathematics.

This is certainly a radical break with old ideas, but hardly mind-boggling. Why did it lead Bohr to say “there is no quantum world” or at least “physics is not the study of something a priori given”? Why didn’t he just say in the quantum world there is no such thing as position or velocity or, more cautiously, what is a priori given is not what we used to think was a priori given? Why did Heisenberg say “the conception of the objective reality of the elementary particles has thus evaporated,” instead of the properties we customarily associate with particles have thus to be refined when applied to elementary particles?
It is tempting to conclude that they were just overwhelmed by the audacity of their overthrow of classical physics. After all, it had been with us as a scientific discipline since Galileo, and its fundamental concepts go all the way back to the origins of language. Who could blame them for going wildly overboard in characterizing the revolutionary character of their achievement? Is this refusal of quantum mechanics to assign properties to physical systems really as peculiar as Bohr and Heisenberg made it out to be? Many contemporary physicists, who grew up with quantum mechanics and are not at all shocked by the inadequacy of classical concepts would say no, it really isn't that peculiar. But they would be wrong. It really is. And that is the subject of this essay.

While these sensational statements were being issued Einstein was there, determined to demonstrate that physical systems did have properties. He kept inventing examples to demonstrate that all the usual properties were really there, and Bohr kept demonstrating that he was wrong—that there was no way you could find out all of those properties at once. In the course of these exchanges it was Einstein himself who, by refusing to accept Bohr's terminally positivistic view of the world, bit by bit refined these arguments to a point where, some forty years after they started their dispute (and a few years after both their deaths), it became possible to confirm unambiguously that Bohr's position, in its most extreme form, was correct.

By far the most dramatic of Einstein's challenges to the quantum theory, and the one that ultimately led to the unraveling of his attack, is embodied in the Einstein-Podolsky-Rosen experiment, a thought experiment Einstein wrote about in 1935 with Boris Podolsky and Nathan Rosen.7 Just a few years ago Daniel Greenberger, Michael Horne, and Anton Zeilinger invented a version of the EPR experiment that contains in a very compact form both the argument on behalf of objective reality that Einstein found so compelling and the seeds of its destruction.8 The GHZ argument, which I shall describe below in some detail, provides an exceptionally vivid illustration of these issues. (Before GHZ, one required a remarkable theorem of John Bell9—the famous "Bell's theorem"—to dispose of EPR. And before Bell's 1964 theorem there simply were no compelling grounds for rejecting the EPR argument, though most physicists did anyway.) I shall build up to EPR-GHZ by asking a series of simple questions that suggest other simple questions.

First of all, how can you tell whether something has a certain physical property? We want to answer this question in the most cautious way, isolating the bare bones of how you acquire infor-
**Fig. 1.** A particle is shown heading toward a box. Some time later it emerges from the box heading either toward the left (L) or right (R) bin. In this case it heads toward L.

Information. What follows will therefore sound tedious and banal: the sort of thing you are exposed to in the mandatory lecture on scientific method in a psychology course that convinces you to abandon the study of psychology. The only incentive I can offer for paying attention is that, at the end, all these incredibly cautious, overly fussy statements will lead directly to a contradiction. Somewhere along the line either one of these platitudes has to be wrong, or certain laboratory procedures I describe (not all of which have actually been carried out) cannot come out the way I confidently assert that they will. The reason I can assert with assurance that the laboratory procedures must work as advertised is that they are based on some of the most fundamental, well established, and well known elementary textbook quantum phenomena. We are just going to put them together in a way that leads to a new and rather surprising conclusion.

You may nevertheless want to conclude at the end of my argument that when I specify the results of those laboratory procedures I am either lying or deluded. To reassure you, I can only say that if anybody set up those procedures and they did not work as I described, then this would start a revolution in physics even more momentous than the quantum revolution that shook science to its roots in the first quarter of the twentieth century.

To tell whether or not an object has a physical property you must measure it. You must subject the object to some kind of apparatus that registers the property. Let us take as an example of this procedure a particle that enters a box through a window in the
front and emerges through one of two rear doors, heading toward a bin on the left or a bin on the right, as shown in figure 1. Exercising utmost caution, we won’t hazard a guess about what kind of property we might be sorting out in this way. But can we at least say that before entering the box there are two kinds of particles: the kind that the box sends to the right—R particles—and the kind that the box sends to the left—L particles?

No, of course we can’t. The particles might all be exactly the same, but the box might contain a mechanism that doesn’t respond to any feature of the particle at all, sending each particle to the left or right for reasons of its own, or just randomly. This is the quintessential quantum situation: How can you tell whether your experiment is giving you information about the object of study (particle), the apparatus (box), or some combination of the two?

Figure 2 shows a way to tell. Suppose you can test particles before they get to the box, and on the basis of the results of the test you can predict in advance which bin each particle ends up in. Clearly that rules out the possibility that the box disposes randomly of the particle. Indeed, if you can specify in which bin the particle ends up before it even reaches the box, then, if words have any meaning at all, we can say that two kinds of particles enter the box: those that always get put into the left bin, and those that always get put into the right bin. We can call them particles of type L and particles of type R. There are indeed two kinds of particle, and the box is sorting them out.

Note that in acquiring this information we must subject the particle to a test which may disturb the particle. In fact in the course of telling us that a particle is type L the test might actually change that particle from type R into type L. Indeed it might even convert a particle that is neither type R nor type L into a particle that is of a definite type.

But we don’t object to that. We don’t care if the process that tells us whether a particle is type L or type R is itself responsible for converting it into one type or the other. All we care is whether the box is responding to some property carried by the particle. If the test itself makes the particle type L or R, that doesn’t matter. What does matter is that we’re able, by whatever method, to produce particles of two types, for each of which we can certify in advance what will happen at the box. So exercising utmost caution we will only say that a particle the test identifies as type L is type L after passing the test, without committing ourselves to what, if anything, it might have been before.

Now on to the next level of complexity: Can a particle carry a
Fig. 2. The particle of figure 1 passes through a testing device on the way to the box at the top of the figure. The particle is shown, a little later, emerging at the other end of the testing device, and, still later, emerging from the box itself, heading toward bin L. Because the testing device invariably flashes the behavior (L or R) that the particle subsequently exhibits at the box at the top, we can say that after a particle has been tested but before it enters the box at the top, a particle is either of type L (which the box sends to the left bin) or type R (which the box sends to the right bin).

second property as well? (There is a close analogy here to the question of whether a particle can have both a position and a velocity.) Suppose there are two different boxes we can send the particle to. Each looks externally the same, but very different things could go on inside them. Call them box 1 and box 2. To make the figures simpler, I will represent in figure 3 the two boxes—box 1 and box 2—with a single box, having a switch that can convert it to one type or the other, depending on how the switch is set. We shall say that if we can predict whether a particle will go L or R when sent to a type 1 box, then that particle has the property of 1-ness. We shall also say that the 1-ness (or the value of the 1-ness) of a particle is 1L if our prediction is that it will go left, and 1R if we predict it will go right. In the same way if we have particles whose behavior at a type 2 box we can predict in advance, we'll say they have the property of 2-ness. Particles with 2-ness also come in two varieties: 2L particles and 2R particles.
Of course a particle taken off the shelf, so to speak, needn't have 1-ness or 2-ness at all. It could well be that a particle had no property to determine what it was going to do at box 1 until we did the test. Now the big question: Suppose we have a test that reveals the 1-ness of a particle (or endows it with 1-ness—it doesn't matter which) and another test that does the same for 2-ness. Can a particle have both 1-ness and 2-ness at the same time? The answer would clearly be yes if you could put the particle through a single test that told you what it would do at either box, so that after the particle emerged from that test it always did what you predicted, whether you sent it to a type 1 or a type 2 box. Such a particle would certainly have both 1-ness and 2-ness.
But there are cases where you simply can’t do this. For some properties (position and velocity are such a pair) it is built into the nature of the 2-ness and 1-ness tests that both cannot be performed at once. You can test for 1-ness or you can test for 2-ness but there is no test you can devise that will tell you both at the same time. You might think that if you have a 1-ness and a 2-ness test, then you could test for both at once by applying the 1-ness test and then following it by the 2-ness test. But this is to forget that the 2-ness test might easily mess up the 1-ness. It is, in fact, quite easy to explore this possibility. Test for 1-ness. Suppose you find that the particle is 1R. Now, instead of sending the particle directly to a type 1 box to confirm that it emerges on the right, test that particle for 2-ness. Only then—after the 2-ness test—send the particle to the type 1 box. If the particle does not always go into the bin the 1-ness test predicts, then you have confirmed that the 2-ness test can mess up the particle’s 1-ness. In fact in the case we are about to discuss the 2-ness test totally obliterates 1-ness; particles emerging from a 2-ness test behave absolutely randomly at a type 1 box (and vice versa) even if those particles possessed 1-ness before the test. When you give a particle 2-ness, you take away its 1-ness. And vice versa.

What I am describing corresponds precisely to an experiment that people actually do, complete to the pairs of properties and the particles coming out of the far end moving to one side or the other. The actual details of the process—the names given to the properties and the contents of the box—are of great interest to physicists, but not to many others, and they are of no interest for my conceptual point. Indeed, giving their names for the benefit of physicists might make those physicists think they understood what is going on so well that they would stop paying attention and fail utterly to see what makes it so interesting. Therefore I will not say what 1-ness and 2-ness actually are, not because I don’t want want to give physicists an unfair advantage over nonphysicists, but to remove the disadvantage they have of understanding these things too well for their own good!

So we must examine situations where you have the choice of learning what each particle will do at a type 1 or a type 2 box, but you cannot learn enough to predict what it will do no matter which box it goes to. Since we have defined the possession of 1-ness or 2-ness as that condition in which, without any further testing, you can predict with certainty what a particle will do at either a type 1 or a type 2 box, that’s the end of it: a particle cannot have both 1-ness and 2-ness.
Somebody not afflicted with terminal positivism might nevertheless be tempted to wonder whether a particle couldn't continue to be the kind that goes to the right (or to the left) at a type 2 box, even after a 1-ness test has messed up its 2-ness. Perhaps the 1-ness test simply gave the particle a new (but unfortunately unknown) 2-ness? To be sure, the only meaning we have given to the statement that a particle has definite 1-ness or 2-ness is that we are able to make a prediction about the particle, but what can the particle possibly care about whether or not we make predictions? Surely it's at least within the realm of possibility that the particle could have both 1-ness and 2-ness, even though there was no way we could know what both of them were.

Now the positivistic answer to this is simple: since 1-ness and 2-ness are only defined by the ability to perform a test which the behavior at a type 1 or type 2 box then confirms, and since there is no single test you can perform after which you can make either kind of prediction, the question is meaningless. Don't waste your time with it. But in 1935, in a paper with Boris Podolsky and Nathan Rosen, Einstein came up with a remarkably simple way of determining either the 1-ness or the 2-ness of a particle (but not both at once) by a test performed so far away from the particle that it could not possibly disturb it, unless there were what Einstein was later to refer to as "spooky actions at a distance" (spukhafte fernwirkungen).10

Einstein, Podolsky, and Rosen argued that since you could determine either the 1-ness or the 2-ness of the particle without disturbing it at all, it clearly possessed both properties. Stating it in a painfully obvious way, if you chose to determine the 1-ness, then you could predict with assurance whether the particle would go L or R at a type 1 box, and therefore the particle had 1-ness. But since you determined the 1-ness in a way that did not disturb the particle, it must have had 1-ness all along, whether or not you chose to determine it. The same, of course, applies to 2-ness. Therefore the particle has both 1-ness and 2-ness. QED.

According to Leon Rosenfeld, one of Bohr's closest friends and collaborators, when he saw the EPR article Bohr dropped everything to formulate a reply. "This onslaught came down upon us as a bolt from the blue."11 Bohr's reply, on which Rosenfeld says he labored mightily, was basically this: No, the particle doesn't have both 1-ness and 2-ness, because you still can find out only one of them. You have to remember that 1-ness is only defined by the ability to predict behavior at a type 1 box after a 1-ness test. Since you can still perform only a 1-ness or a 2-ness test but not both, you have
failed to meet the conditions for a particle having both 1-ness and 2-ness. Therefore it doesn’t.

Terminal positivism! I can only imagine how disappointed Einstein, Podolsky, and Rosen must have been by this answer, particularly when everybody else agreed that Bohr had once again put Einstein in his place. After all, the point of EPR was to go beyond this terminal positivism, by finding a novel situation in which it was absolutely clear that the determination of the property could not possibly disturb the particle. Until the EPR argument was published, no such example was known. Bohr and Heisenberg’s extremely cautious way of attributing properties emerged from the belief that there was no way to determine certain properties that did not disturb the particle. Yet when EPR called attention to such a way, Bohr’s considered response was simply to continue to adhere to this overly cautious approach, even when he had been presented with a case that made it unnecessary.

Remarkably—amazingly—Bohr was right to do so. But this did not become clear for nearly thirty years. Since the overwhelming majority of physicists believed that Bohr had refuted Einstein in 1935, the remarkable 1964 paper by John Bell showing that Bohr was right to keep his head in the sand, had negligible impact on practicing physicists. Within the last decade, however, there has been a revival of interest in the foundations of quantum mechanics, primarily because experimental techniques are now available that reveal a far greater variety of exotic quantum phenomena than were available to the founders of the theory sixty-five years ago. In 1988 Greenberger, Horne, and Zeilinger came up with a spectacular refinement of the EPR argument and its refutation by Bell, that I shall now describe.

The ingenious trick EPR came up with is this: They found a situation in which the particle leaves something behind when it sets off for the box, and the information needed to determine whether the particle will go L or R at a type 1 or type 2 box is determined by tests performed only on the stuff that is left behind. It is most important to note that you can use the stuff left behind to test only for 1-ness or 2-ness but not both—doing a 1-ness test messes up the stuff left behind, making it impossible to do a 2-ness test on it, and vice versa. But since whichever test you choose to perform is guaranteed to work, it is hard to believe that the particle, which left for the box long before the test is performed, does not have both 1-ness and 2-ness. After all, the particle has to behave in a way that confirms our prediction, whether we chose to predict its behavior at a type 1 or type 2 box. And we don’t need to choose
Fig. 4. The Einstein-Podolsky-Rosen experiment. This is a clever variation of what happened in figure 3. There are two particles. Particle A plays the role of the particle in figures 1-3, going directly to the box at the top of the figure. At the start of its journey A leaves behind a second particle, B, which goes to another box at the bottom of the figure. If both boxes are of the same type, then whenever particle B goes L at its box, so does particle A, and similarly for R. Particle B and its box therefore perform the same function as the testing device of figure 3, with the important difference that now the test does not interfere with particle A in any way.

until the particle is well on its way to the box, far away from where we perform the test that makes the prediction possible.

Figure 4 shows an EPR experiment. It has a pleasing symmetry. What the particle, now called A, leaves behind is a second particle, called B; and the test we perform on B to determine what A will do, consists of letting B enter a box just like the box that A goes to. We set B's box to type 1 or type 2, depending on whether we wish to test for the 1-ness or 2-ness of particle A. The ingenuity of EPR consisted in realizing that quantum mechanics allowed you to set things up\textsuperscript{12} so that if you choose to test B for 1-ness, then if it comes out 1R a 1-ness test for A will also give 1R, and if B is 1L so will be A. And similarly for the 2-ness tests. The 1-ness or 2-ness test on particle B, therefore served as a 1-ness or 2-ness test on the particle A, performed so far away from particle A that it could not possibly disturb it.
The quantum theory says unambiguously that a situation like this can be arranged. It is not easy actually to build such an apparatus, but during the past two decades some have been constructed, and except for a tiny minority of extremely stubborn people, everybody else agrees that they perform just as the quantum theory says they should. But even if to this day the experiment were too difficult to perform, the mere fact that the quantum theory says it would in principle work the way I have described, would seem to be a sure sign within the theory itself that it is indeed possible for a particle to possess two properties, even when it is inherently impossible to ascertain the values of both at once.

So in this way EPR concluded, as any person not afflicted with terminal positivism would, that particle A had both a 1-ness and a 2-ness. Furthermore the situation is perfectly symmetric as concerns the two particles. The quantum theory simply says that both particles behave the same way (both L or both R) at boxes of the same type (both type 1 or both type 2), without regard to which particle is the first to go through a box. As a result, you could equally well regard the behavior of particle A at its box as a test for how particle B will behave at its box, so by the same reasoning particle B must also have had both a 1-ness and a 2-ness. The full situation of the EPR argument is displayed in figure 5, with both particles schematically displaying the 1-ness and 2-ness that the EPR argument requires them to have.

It was thirty years before John Bell pointed out that there were other aspects of the EPR situation (involving the behavior of the particles at additional types of boxes through which they might be sent) which, though not contradicting in any way the data on which EPR based their conclusion, were nevertheless inconsistent with each particle possessing both 1-ness and 2-ness. I shall not pursue Bell's argument, because I believe the argument found a few years ago by GHZ is even more dramatic and compelling.

GHZ considered three particles. The three particles head off for three different boxes, each of which can be a type 1 or type 2 box, as shown in figure 6. Quantum mechanics says it is possible to have a situation in which the particles behave at the boxes as follows: If all three boxes are type 1 then an odd number of particles (3 or 1) will go R; if only a single box is type 1 then an even number (2 or 0) will go R. (If two boxes or no boxes are of type 1, then the behavior of the particles is completely random and of no further interest.) This simple state of affairs (summarized in the table below) contains within it both the EPR argument, and a devastating refutation of that argument.
Fig. 5. Figure 4 is redrawn with each particle shown schematically displaying the value of its 1-ness and 2-ness that the EPR argument requires it to have. In this particular case we know that both particles must have 1-ness L, since both go L when they get to their respective boxes. We do not know the value of their 2-ness, but we know that whatever that value is, it must be the same for both, since if the boxes had been of type 2, the two particles would have behaved in the same way. (We could find out both values by letting one box be of type 1 and the other of type 2.)

<table>
<thead>
<tr>
<th>Box Types ABC</th>
<th>Behavior of Particles at boxes</th>
</tr>
</thead>
<tbody>
<tr>
<td>111</td>
<td>Odd number (3 or 1) go R</td>
</tr>
<tr>
<td>122</td>
<td>Even number (2 or 0) go R</td>
</tr>
<tr>
<td>212</td>
<td>Even number (2 or 0) go R</td>
</tr>
<tr>
<td>221</td>
<td>Even number (2 or 0) go R</td>
</tr>
<tr>
<td>(all others)</td>
<td>(completely random)</td>
</tr>
</tbody>
</table>

Call the three particles A, B, and C, and identify the box each goes to with the same letter. As in 2-particle EPR, the situation is completely symmetric as regards the three particles, so any conclusion we can draw about one of them must be equally valid for the other two. We can establish that particle A has 1-ness as follows. We make
Fig. 6. The Greenberger-Horne-Zeilinger experiment. The boxes are as before, but now there are three particles. The behavior of the particles at their boxes is summarized in the table.

Boxes B and C type 1 boxes, and take advantage of the fact that an odd number of particles must go R when all three boxes are of type 1. We then look to see what particles B and C do. If both go R (or if neither go R) then particle A must go R (to result in an odd number going R) but if just one of B and C go R, then A must go L. We have thus established what particle A will do at a type 1 box in the approved EPR manner, by measurements made so far away that they cannot possibly have disturbed it.

To establish in the same EPR style that particle A has 2-ness we can make box B type 1 and box C type 2, and exploit the fact that when the boxes A, B, and C are respectively of types 2, 1, and 2, then an even number of particles always go R. In this case if just one of B and C go R, then A must also go R (to result in an even number going R), but if both B and C or neither of them go R then A must go L.

We can thus use the EPR trick to determine either the 1-ness or the 2-ness of particle A. Note that we can use this trick to determine either A's 1-ness or its 2-ness but not both. But our choice of which one to determine need not be made until A is far away from B and C, and it is only B and C that we must subject to tests to make
Fig. 7. An attempt to assign values of the 1-ness and 2-ness of each of the three particles, analogous to the assignment of values in figure 5. The particular choice depicted here gives values agreeing with the rules in the table when the switch settings encountered by A, B, and C are 111 (three R's—an odd number), 211 (two R's—an even number), and 121 (two R's—again an even number). But for 112 we have three R's—an odd number, which violates the rules.

the prediction. It therefore seems quite pig-headed to insist that A cannot have both 1-ness and 2-ness. Since the symmetry of the arrangement makes it possible to draw exactly the same conclusions about B and C, we seem unavoidably led to the conclusion that all three particles have both 1-ness and 2-ness. How foolish of Bohr to have clung to his terminal positivism when presented with a clearcut case demonstrating its inadequacy! And how irresponsible of the other physicists not to take off time from the enormous fun they were having, using the new quantum theory to solve one longstanding problem after another, in order to examine the dispute and rise to Einstein's defense.

Figure 7 is a picture of the three particles, all with their 1-ness and 2-ness on display. Note that when A, B, and C all go to type 1 boxes then we will indeed get three R's, an odd number. If A goes to a type 1 box and B and C go to type 2, we will get two R's, an even number; If B goes to type 1 and A and C to type 2, we have again two R's, an even number; and if C goes to type 1 and A and B type 2, we have—whoops—an odd number of R's.
Fig. 8. A template for an attempt to get systematic about what values of the 1-ness and 2-ness of each particle can be put into figure 7 to make it work in all four cases (111, 122, 212, and 221). Each of the three pairs of vertically separated squares labeled 1 and 2 has to contain either the letter L or the letter R, specifying the 1-ness and the 2-ness of the particle labeled by the letter directly above the two squares.

(just one), which contradicts the entry for 221 in the table. So let us try again to find an example, this time systematically.

Figure 8 is a template, containing empty squares in which we can write the values (R or L) to be assigned to the alleged 1-ness and 2-ness of the three particles A, B, and C. We must assign values that work for all four choices of the three boxes specified in the upper part of the table—namely all three boxes type 1 (which we will call choice 111), or one of the three boxes A, B, or C type 1 and the other two boxes type 2 (which we will call choices 122, 212, and 221). In figure 9, I have redrawn figure 8 with four balloons, surrounding the four groups of three blank squares associated with each of the four choices for the boxes. We must have an odd number of R's if the boxes are 111, and an even number in the other three cases. Suppose we make a list of letters, first writing down the three in the 111 balloon, then those in the balloons associated with 122, 212, and 221. The twelve letters on the list must have an odd number of R's, since the 111 balloon must contain an odd number of R's, and the other three, an even number.

But the letter in each of the six squares must appear on the list \textit{twice}, since each square is contained in two balloons. Therefore the
Fig. 9. The conditions specified in the table apply to the letters in the four groups of three squares surrounded by the four balloons. The three squares labeled 1 (surrounded by the horizontal balloon) must contain an odd number of R's, while the three squares surrounded by each of the other three balloons must contain an even number of R's. If you now imagine the list of twelve letters you get by writing down the four groups of three letters you get from each balloon, the rules require that list to contain an odd number of R's (since the horizontal balloon contributes an odd number and each of the other three contributes an even number). On the other hand every square belongs to exactly two balloons (see the figure) and therefore contributes to the list the letter it contains exactly twice. Since each of the six squares therefore contributes either 2 L's or 2 R's to the list, the list cannot possibly contain an odd number of R's, and therefore there is no way of filling the squares with L's and R's that satisfies the rules in the table.

number of R's on the list must be twice the number of R's appearing in the six squares—an even number.

So it was no accident that figure 7 failed to work: there is, in fact, no way to make it work. It is impossible for each particle to have both 1-ness and 2-ness and behave as required by the data in the table in each of the four cases 111, 122, 212, and 221. No matter what values (R or L) you tentatively assign to the 1-ness and 2-ness of each particle, those values must necessarily yield an unallowed result, for at least one of those four choices of boxes. Compelling as the EPR argument is, it is internally inconsistent when applied to the data in the GHZ experiment. Even though you can find out what a particle will do at either type of box without
disturbing it in any way, it cannot have both 1-ness and 2-ness. We are stuck with terminal positivism; a nonworld nonview!

Let me summarize the dramatic history of this peculiar state of affairs:

1. Faced with the realization that at the atomic level we cannot gather information about things without disturbing them, Bohr and Heisenberg in 1925 took an exceedingly cautious view of what it means for something to have a property. When we say that an object has a property we only mean that we possess the information necessary to predict in advance the outcome of a measurement of that property.

2. Ten years later, in 1935, EPR discovered a situation in which one has a choice of which of two properties of an object one can predict in advance, and in which getting the information we need to make that prediction in no way disturbs the object. Therefore, they concluded, it is fair to say that the object has both properties.

3. Bohr said no, even though you have just called to our attention a novel case in which we can acquire the information on which the prediction is based without disturbing the object, we must nevertheless retain the view that the object does not have the property, unless we actually possess the information.

This seems to be a bizarre response; EPR would appear to have eliminated the need for such extreme conservatism.

4. The success of the quantum theory in the decade since its birth was so phenomenal, and the pace at which it was leading to new discoveries was so exhilarating, that nobody paid much attention. Everybody immediately said “Einstein’s an old fool; Bohr won the argument,” though few could have bothered to read Bohr’s reply to EPR, which seems to me even today, when we know for a fact that EPR were wrong, simply to beg the question.

5. In 1964 John Bell proved, by means of an argument that Bohr could not possibly have known at the time, that the EPR position is untenable; in 1988 Greenberger, Horne, and Zeilinger discovered the version of the argument I have given above.

The Einstein-Podolsky-Rosen paper was Einstein’s last attack on quantum mechanics. I learned about it when I was a graduate student in 1956. It was never mentioned in any quantum mechanics course—it was a kind of dirty little secret that students told each other about when they were sure no professors were listening. I immediately concluded that Einstein was right—that Bohr and Heisenberg had pulled the wool over everybody’s eyes—that there had to be a deeper level of description than quantum mechanics. I was
therefore astonished when I finally read John Bell’s 1964 paper in 1979 (when I stumbled on a reference to it in a 1979 Scientific American article). Bell himself seems to have been somewhat appalled by his discovery:

For me it is so reasonable to assume that the [particles] in those experiments carry with them programs . . . telling them how to behave. This is so rational that I think that when Einstein saw that, and the others refused to see it, he was the rational man. The other people, although history has justified them, were burying their heads in the sand. I feel that Einstein’s intellectual superiority over Bohr, in this instance, was enormous—a vast gulf between the man who saw clearly what was needed, and the obscurantist. So for me, it is a pity that Einstein’s idea doesn’t work. The reasonable thing just doesn’t work.13

It is one of the great misfortunes of intellectual history that Bell’s argument or the GHZ argument, which could have been constructed any time after David Bohm proposed a new version of the EPR experiment in 1952, was not discovered before Einstein died in 1955. Einstein would have understood it at once—he was after all, a deeply rational man, convinced that his colleagues had succumbed to a kind of mass delusion on the matter of physical reality. “The Heisenberg-Bohr tranquilizing philosophy—or religion?—is so delicately contrived that, for the time being, it provides a gentle pillow for the true believer,”14 he wrote to Schrödinger in 1928. Confronted with the argument I have just described, would he finally have given up his opposition to the (non)world (non)view of quantum mechanics? Or would he once again have come up with an entirely new way of looking at a problem that astonished us all?

**NOTES**


12 That quantum mechanics does allow things to be set up in this way (and in the way I describe below for the GHZ experiment) is not immediately obvious; indeed nobody had realized that this was allowed by the quantum theory until Einstein, Podolsky, and Rosen pointed it out ten years after the theory had assumed its final form. To the skeptical reader I can only offer the assurances mentioned above: that if the EPR (or GHZ) experiment did not behave as I have described it, then the foundations of physics would crumble and the science would have to be reconstructed from the ground up.

13 John Bell, conversation with Jeremy Bernstein, quoted in Jeremy Bernstein, Quantum Profiles (Princeton, 1991), p. 84. Bell was undoubtedly the most brilliant and profound of those who thought hard about the meaning of quantum mechanics in the post-Bohr period, and his sudden death in 1990 was a tragic loss. Although Bernstein’s anecdotes of Bell are vividly evocative of the man, his description of EPR and Bell’s theorem is so muddled as to be unintelligible.