A physicist spends part of his time with the rest of us in the [illegible] world where things make sense.

But he also lives in a very different place, where nothing behaves the way that it is supposed to.

By James Trefil

Quantum physics' world: now you see it, now you don't

If you have to cope with atomic particles that can read your mind even when they don't exist, it can be hard to explain what you do all day

Some people have it easy. When their kids ask them what they do at work, they can give a simple, direct answer: "I put out fires" or "I fix sick people" or "I do arbitrage." As a theoretical physicist, I never had this luxury. Society has come to expect many things from physicists. It used to be that we only had to discover the basic laws that govern the world and supply the technical breakthroughs that would fuel the next Silicon Valley. With these expectations we were fairly comfortable: they involve the sorts of things we think we know how to do. What bothers us—and what makes it hard for us to tell our kids what we're up to—is that in this century we have become, albeit unwillingly, gurus on philosophical questions such as "What is the nature of Reality?"

We now deal with a whole new class of problems. We ask how the Universe began and what is the ultimate nature of matter. The answers we are coming up with just do not lend themselves to simple explanations.

In the good old days we could explain Sir Isaac Newton's clockwork Universe by making analogies with things familiar to everyone. And if the math got a little complicated, that was all right: it gave a certain panache to the whole enterprise. But those days are gone forever. How is a physicist supposed to find a simple way of explaining that some of his colleagues think our familiar world is actually embedded in an 11-dimensional Universe? Or that space itself is curved and expanding? The math is still there; the theories are as coherent as they ever were. What's missing is the link between those theories and things that "make sense"—things the average person can picture. This leads to a situation where it's easy for anyone to ask questions that can't be answered without recourse to mathematics, such as my all-time least favorite: "Well, if the Universe is really expanding, what is it expanding *into*?"

There's no place where this problem is worse than in the theory that underlies things like digital watches and personal computers. This theory, called quantum mechanics, describes the behavior of atoms and their constituents. It tells us that the world of the physicist is not at all like the world we are used to. When physicists get out of their cars in the morning, have a cup of coffee and sit down in front of computer terminals, they leave a familiar, cozy environment and enter a place where things act in strange, virtually inexplicable ways.

Let me give you an example of what I mean. When you run into a wall, you expect to bounce off. If you were an electron, however, our theories say there is some chance that you would simply appear on the other side of the wall without leaving a hole behind you. In fact, if electrons didn't behave this way, your transistor radio wouldn't work. How do you explain something like *that* to your kids? And what does it tell you about whether the electron is "real" or not?

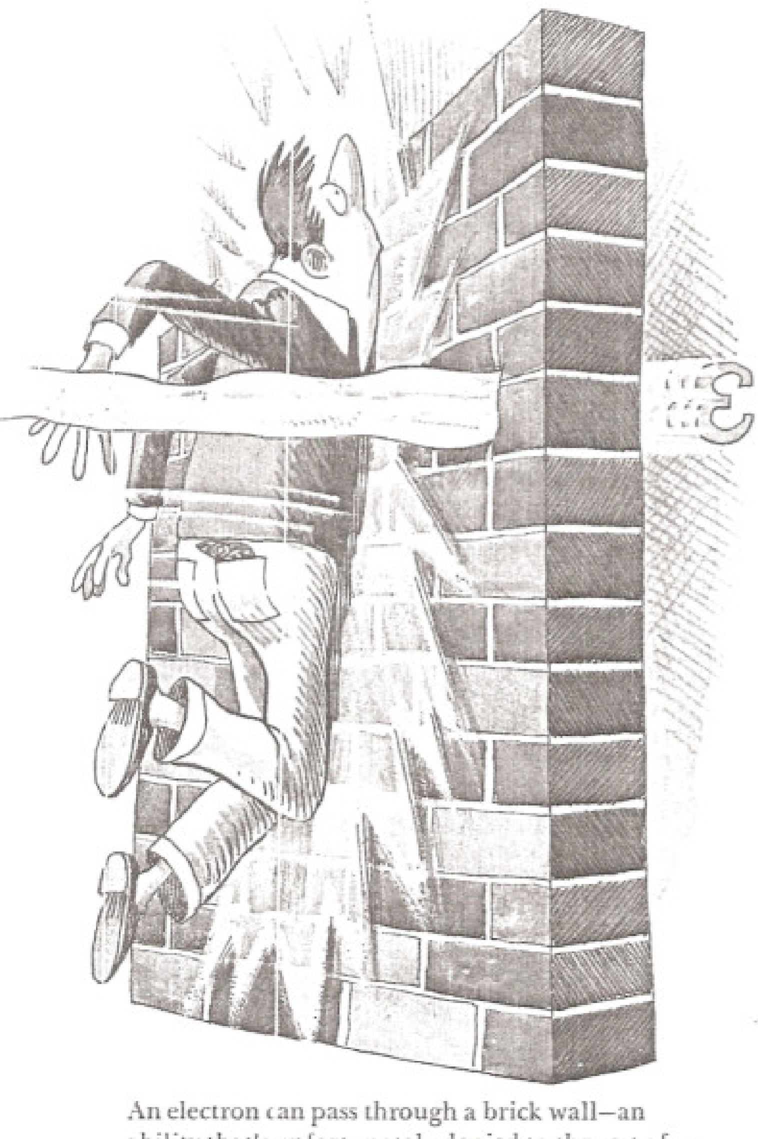
Don't get me wrong. I don't think that people—even physicists—go around with these sorts of questions on their minds all the time. But as one friend put it to me, "It's not so much that I want to know the answers myself, it's just that I want to know that they're in good hands." It is this obligation to provide the good hands that in this century has been thrust on me and my colleagues.

Confused chitchat at cocktail parties

Physicists get involved in trying to explain these kinds of things because two of our 20th-century theories—relativity and quantum mechanics—have dealt major blows to accepted ideas about what is real in the world. The shock of relativity pretty well played itself out in the 1920s, mainly in cocktail party chitchat that confused relativity (a well-defined theory in physics) with philosophical and moral relativism, with which it has nothing in common except the name. It now looks as if quantum mechanics is about to suffer through its own period of popular misunderstanding, making physicists even more uncomfortable with their role as philosophical arbiters.

Physics has gone from studying familiar things in our everyday lives like tides and baseballs to strange things like atoms and the particles from which they are made: things we do not (indeed, cannot) ever

Illustrations by John Huehnergarth



An electron can pass through a brick wall—an ability that's unfortunately denied to the rest of us.

know directly. Inside the atom we find everything in little bundles called quanta. On the subatomic level, both matter and energy always come in quanta—discrete quantities. An electron can be at one energy level or another as it orbits a nucleus, for example, but never anything in between. Or, that characteristic of the electron known as spin will always be in certain quantities and never anything else. (The singular form of the word, quantum, is combined with mechanics, an old term for the study of motion, to give us quantum mechanics.) The first great difference between the familiar world and the quantum world—the world of the atom—is that we do not "see" things in the same way in the two worlds. This difference leads to results that defy our understanding, such as the electron going through the wall without leaving a hole behind it. The electron, in effect, disappears from one side of the wall and reappears on the other. Nothing in our everyday life prepares us for this.

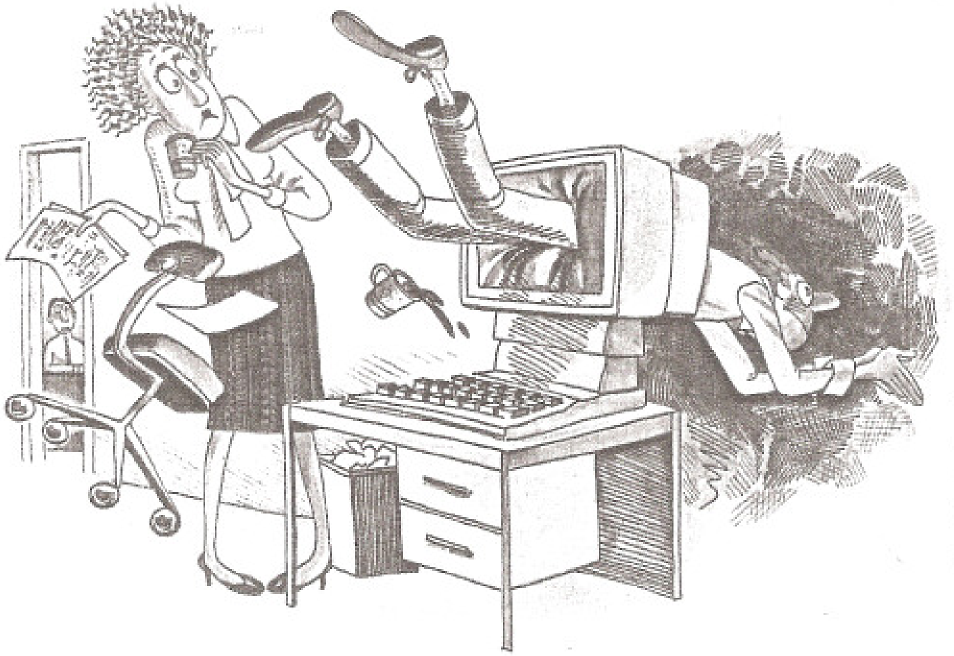
You probably never thought about it, but when you look at something (this magazine, for example), you're detecting light that has come from some source, bounced off the object and then come to your eye. The reason we normally don't think about seeing in this way is that in our everyday world we can safely assume that bouncing light off a magazine doesn't change the magazine in any way that matters. The light from a lamp does not push the magazine away.

When we get to the quantum world, however, this comfortable assumption no longer works. If you want to see that bundle of matter we call an electron, you have to bounce another bundle off it. In the process, the electron is bound to be changed.

Limited by the Uncertainty Principle

A simple analogy can help with this point. Suppose you wanted to find out if there was a car in a long tunnel, and suppose that the only way you could do this was to send another car into the tunnel and listen for a crash. It's obvious that you could detect the original car in this way, but it's also obvious that after your detection experiment that car wouldn't be the same as it was before. In the quantum world this is the *only* sort of experiment you can do. Therefore the first great rule of quantum mechanics is: *You cannot observe something without changing it in the process.* This is the basis of what is called the Uncertainty Principle: When you choose to observe one thing (e.g., the location of the car in the tunnel) you must forever be uncertain about something else (e.g., how fast the car was moving before the collision).

We usually associate the act of making a measurement with the presence of a conscious experimenter who wants the measurement made. Thus you some-



When he sits down at his computer in the morning, a physicist leaves the rest of us behind. When he comes back, he cannot explain where he has been, or what it is that he has been doing.

times run across the comment that quantum mechanics implies that nothing could exist without the presence of consciousness. From the example of the car in the tunnel, though, it's obvious that this is the modern-day analogue to the old confusion of relativity and relativism. It's the nature of the measurement, not the one who designs the experiment, that introduces the problem.

The inability to observe things in the subatomic world without at the same time disturbing them has some surprising consequences when you start to think about the way that particles move from one point to another. Let's use another automotive analogy. Suppose I asked you to tell me where a particular car will be tomorrow. Ordinarily, you would look to see where the car is, look again to see which way it is going and look again to see how fast. After a moment with your calculator, you would come back with a definite answer. If the car is like an electron, however, you can't look at it more than once—the first look changes everything. You cannot know with precision both where it is and how fast it is going; the best you can do is to play off the uncertainties. You might, for example, be able to say that the car is somewhere in the Chicago area and heading in a generally eastward direction at roughly 40 to 60 miles per hour. You can't be more precise than that without more measurements, and more measurements would only change the car's location or velocity and therefore increase your uncertainty.

James Trefil is now Clarence Robinson Professor of Physics at George Mason University. Meditations at Sunset, *his latest book, was published in June.*

If you want to talk about where the car will be tomorrow, then, you have to speak in probabilities—it might be in Cleveland, it might be in Detroit, it might even be in New York. The chances are, though, that it would not be in Miami or London. You could make your prediction, in other words, by giving me the odds of the car being in Detroit, Cleveland or New York after 24 hours. This collection of probabilities is what physicists call a wave function, and it's exactly the way we describe the motion of things like electrons.

Up to this point, you've probably been following along pretty easily, perhaps thinking that you might as well humor this guy as he makes all these obvious statements. Well, hold on, because things are about to become curious. The reason you aren't bothered by having to describe the car in terms of probabilities is that deep in your heart, you *know* that the car is really somewhere all the time, and if you could just peek, you could see it merrily tooling along any time you wanted to. Of course, if you did you'd change it and mess up the experiment, but you have the easy feeling that somehow the car is really there, even if you don't see it. You might even imagine the whole country as an underground parking lot in which you can see the car only at the exits. You may not be able to see the car between exits, but you know it's always somewhere in the garage.

The problem is that physicists don't envision electrons this way. Their view is that until you look at a particle, you have to treat it only as a set of proba-

Using one car to find out if there is another in a tunnel is messy; similar problems arise inside atoms.

bilities. In terms of our analogy, they say that the car isn't really at any particular place unless it's being measured. In between, it's just a set of probabilities that describe what would happen if a measurement occurred—a wave function.

The idea that there had to be some sort of underlying reality beneath the wave functions and probabilities that physicists use was probably what led Albert Einstein to his famous comment that "God does not play dice" with the Universe. This is a well-known statement, and I only wish that the reply of Niels Bohr, Nobel laureate and longtime friend and colleague of Einstein's, was as well known. "Albert," he is supposed to have said one day, "stop telling God what to do."

Einstein, being Einstein, put his objection into concrete form in 1935 when, along with Boris Podolsky and Nathan Rosen, he published what has come to be known as the Einstein-Podolsky-Rosen (EPR) paradox. This paradox was intended to show the inherent ridiculousness of treating the particle as a set of probabilities between measurements, and hence to imply that the whole probabilistic view of the world was wrong. The argument goes like this: There are some common reactions that result in two particles (like electrons) being emitted back-to-back from the same atom; electrons spin around their axes, and general laws of physics tell us that in this sort of reaction the electrons have to spin in opposite directions—if one is spinning clockwise, the other must be counterclockwise and vice versa.

Einstein applies some common sense

Einstein argued as follows. You tell me that the electrons don't really have a spin, just as they don't have a position, unless they're being measured, but I could let those two electrons travel until they were light-years apart, and then measure only one of them. For example, if you measured the right-hand electron and found it spinning clockwise, you'd know instantly that the left-hand electron was spinning counterclockwise—*without ever measuring it.* The left-hand electron, therefore, must have had that spin all along and you must be wrong about it not being anywhere or having any spin between measurements.

Well, that sounds pretty convincing, but quantum mechanics worked so well and explained so much that most physicists tacitly ignored Einstein and kept on using it. The practical payoffs—from microelectronics to lasers—have been tremendous. But the old problem of reality still rankled. Then in 1964, the Scottish physicist John Bell discovered something that has come to be known as Bell's Theorem. What he found was that in the kind of back-to-back reactions that Einstein talked about, there were certain quantities that were predicted to be different if the electrons were described as being "really there" than they would be if the electrons were described in terms of wave function. What these quantities are is not important (they have to do with the way the axes of rotation of the electrons point in space with respect to the direction in which the particles move). What is important is that with Bell's Theorem we have, for the first time, an experimental way of resolving the problem of what that electron is doing between measurements, the problem of whether it's really there or not. All we have to do is measure some of the quantities Bell talked about and see if they match up with quantum mechanics or with the common sense approach Einstein advocated.

In the 1960s, no one thought the experiments suggested by Bell's Theorem could ever be done; they had something of the status of that old sophomore problem of whether a million monkeys at typewriters could ever create *Hamlet*. It was interesting in an intellectual sort of way, but totally outside the realm of practical possibility.

Well, it never pays to underestimate experimental physicists. By the mid-1980s, a large number of EPR-type experiments had been done, and in all cases the results were unequivocal. The standard theory, the one that says that the electron has to be described by a wave function between measurements, is right. The predictions of the theories that say that the electron really has a well-defined spin before it is measured are wrong. Period. The results mean as well that the electron really is not any place between measurements. When you are not looking, it is not there.

How can we understand this? If you try to make a mental picture of what the electrons are doing, you have to say that the left-hand electron somehow knows what experiment will eventually be done—that it changes itself depending on what happens to its right-hand partner before it can ever "know" what happened. No matter how transmitted, information—like everything else in the Universe—cannot travel faster than light. Thus in an experiment in which a pair of electrons is produced and they fly away from each other until they are light-years apart, it would take years for the results of measuring the right-hand electron to reach the left-hand electron. But the latter knows instantly.

This result is the crux of the problem in understanding quantum mechanics, and it certainly makes it tough for physicists to explain what they do to their kids. How do you talk about things in simple everyday terms when the particles you're trying to describe insist on acting as if they could read your mind? There is just no way of picturing electrons in any way that makes sense or squares with our intuition.

Having made this point, though, I have to remind you that all of the conceptual problems with figuring out what the electrons are up to have to do with what happens *between* measurements. We can never actually answer this question because the Uncertainty Principle tells us that if we try, we will change everything. Quantum mechanics succeeds beautifully in describing the result of any experiment that you can actually do.

The new wave of quantum mechanical experi-

When Einstein said that God does not "play dice," Bohr cautioned him against telling God what to do.

Only recently have experimentalists been able to find out if electrons spin in the ways theorists say.

Whether a bit of subatomic matter should be treated as a wave or a particle depends on how you look at it.

ments has produced other results that are even harder to deal with than the EPR outcome. For example, one of the old problems in quantum mechanics has to do with something called the "wave-particle duality." In essence, the problem arises because in some experiments an electron acts like a miniature baseball (a particle), but in others it seems to have the property of a wave. In classical physics, waves and particles were all there was, and everything was either one or the other. The ability of quantum particles to assume the character of either, depending on the experiment being done, constituted another of those seemingly inexplicable paradoxes of the quantum world.

Of course, you could argue that electrons were neither particle nor wave, but something different that exhibited the properties of both. Like the standard probabilistic view, however, this is a profoundly unsatisfying solution. It doesn't give a *picture* of what the particle is.

A few years ago several groups in Europe carried out experiments designed to "trick" the quantum particles into revealing their true identity. A particle would be directed toward an apparatus and then, while it was still in flight, the experiment would be changed so that either the wave or particle aspects of the moving particle would be tested. The point is that the particle, in flight, couldn't know what the experiment was to be.

For all the cleverness involved in this setup, the results were exactly as predicted by quantum mechanics: when the particle experiment was done, a particle was seen, and when a wave experiment was chosen, a wave was seen. If you insist on thinking of an electron as something analogous to a baseball or a ripple on water, this result is hard to comprehend. What *is* the electron, anyway, and how can it transform itself while it is in flight?

There are some things we will never know

The sense of frustration you are feeling right now arises because try as we may, we cannot find an intuitively pleasing way to describe what the electron is doing during those periods when we aren't actually looking at it. Does this remind you of the old college bull sessions about the tree in the forest? It should, because the quantum theory of the ultimate nature of matter seems to raise questions that simply cannot be resolved.

Some people, confronted by the sorts of paradoxical behavior we've been describing, have been driven to truly bizarre points of view. In discussing the EPR experiment, for example, some people have argued that the two particles communicate with each other by some unknown process of a kind that could also produce telepathy and extrasensory perception in humans. Others describe a Universe in which everything is connected to everything else. As the poet Francis Thompson put it, "Thou canst not stir a flower/ Without troubling of a star." All this may be going overboard, but it shows how disturbing the physics is.

Many people are surprised that supposedly tough-minded physicists agonize over questions like what the electron is doing when it's not being measured. But the fact is that most physicists think in pictures and have the same intuitive notions that you do. Anything that bothers you, therefore, is likely to bother them as well.

I often wonder if the real difficulty arises because there are limits to what we can know—what we can comfortably absorb. Perhaps we have moved to the limits of what our minds can picture and our intuitions can deal with. Perhaps the problems we have with 20th-century science are tokens of things to come, and in the future everything will be as strange to us as quantum mechanics. I hope things don't turn out this way, but they certainly could.

Over the years, I have talked to colleagues about their reactions to this state of affairs in our science. Some of the answers may be enlightening.

Go Away—Anonymous.

This is far and away the most common reaction. We have a theory (quantum mechanics) that allows us to make the next big technological advance, win the next Nobel Prize. Why bother about questions that can't be answered, anyway?

What's the problem?—Asher Peres, theoretical physicist.

Peres is a man who has thought deeply about the question and has come to the conclusion that the problems are all in the mind. After all, problems arise only when we try to think about the electrons as if they were baseballs. Obviously they're not, and there's no reason to expect that they will be. If we just stick to the rules of quantum mechanics and ignore the demands of intuition, no difficulties arise. The title of one of his articles, "Unperformed Experiments Have No Results," tells it all. I have to admit that I find this line of thought very attractive.

It only bothers me when I think about it—Mike Chanowitz, theoretical physicist.

A typical response of a thoughtful man. It *is* hard to stick with pure logic and give up a lifetime's worth of intuitive knowledge about the way the world really ought to be.

The mind demands more—Bernard d'Espagnat, experimental physicist.

It's not enough to have a theory that predicts what will happen in experiments; it has to give you a coherent and intuitively appealing view of the world as well. I suspect that most of you feel this way.

Anyone who isn't bothered by Bell's Theorem has rocks in his head—David Mermin, theoretical physicist, quoting a friend.

What can I say?

Today's physicists find themselves called upon to be philosophers who can deal with the ultimate question. But in the inexplicable world of quantum mechanics, comprehensible answers are few and far between.