Why does quantum physics need an interpretation? Why doesn't it simply tell us what the world is like? Why was there any dispute between Einstein and Bohr at all? Einstein and Bohr certainly agreed that quantum physics worked. If they both believed the theory, how could they disagree about what the theory said?

Quantum physics needs an interpretation because it's not immediately clear what the theory is saying about the world. The mathematics of quantum physics is unfamiliar and abstruse, and the connection between that mathematics and the world we live in is hard to see. This is in stark contrast with the theory quantum physics replaced, the physics of Isaac Newton. Newton's physics describes a familiar and simple world with three dimensions, filled with solid objects that move in straight lines until something knocks them off their paths. The math of Newtonian physics specifies the location of an object using a set of three numbers, one for each dimension, known as a vector. If I'm on a ladder, two meters off the ground, and that ladder is three meters in front of you, then I could describe my position as (zero, three, two). The zero says that I'm not off to one side or the other, the three says I'm three meters in front of you, and the two says I'm two meters above you. It's fairly straightforward—nobody runs around deeply worried about how to interpret Newtonian physics.

But quantum physics is significantly stranger than Newtonian physics, and its math is stranger too. If you want to know where an electron is, you need more than three numbers—you need an infinity of them. Quantum physics uses infinite collections of numbers called *wave functions* to describe the world. These numbers are assigned to different locations: a number for every point in space. If you had an app on your phone that measured a single electron's wave function, the screen would just display a single number, the number assigned to the spot where your phone is. Where you're sitting right now, the Wave-Function-O-Meter™ might display the number 5. Half a block down the street, it'd display 0.02. That's what a wave function is, at its simplest: a set of numbers, fixed at different places.

Everything has a wave function in quantum physics: this book, the chair you're sitting in, even you. So do the atoms in the air around you, and the electrons and other particles inside those atoms. An object's wave function determines its behavior, and the behavior of an object's wave function is determined in turn by the Schrödinger equation, the central equation of quantum physics, discovered in 1925 by the Austrian physicist Erwin Schrödinger. The Schrödinger equation ensures that wave functions always change smoothly—the number that a wave function assigns to a particular location never hops instantly from 5 to 500. Instead, the numbers flow perfectly predictably: 5.1, 5.2, 5.3, and so on. A wave function's numbers can go up and down again, like a wave—hence the name—but they'll always undulate smoothly like waves too, never jerking around too crazily.

Wave functions aren't too complicated, but it's a little weird that quantum physics needs them. Newton could give you the location of any object using just three numbers. Apparently, quantum physics needs an infinity of numbers, scattered across the universe, just to describe the location of a single electron. But maybe electrons are weird—maybe they don't behave the way that rocks or chairs or people do. Maybe they're smeared out, and the wave function describes how much of the electron is in a particular place.

But, as it turns out, that can't be right. Nobody's ever seen half of an electron, or anything less than a whole electron in one well-defined place. The wave function doesn't tell you how much of the electron is in one place—it tells you the *probability* that the electron is in that place. The predictions of quantum physics are generally in terms of probabilities, not certainties. And that's strange, because the Schrödinger equation is totally deterministic—probability doesn't enter into it at all. You can use the Schrödinger equation to predict with perfect accuracy how any wave function will behave, forever.

Except that's not quite true either. Once you do find that electron, a funny thing happens to its wave function. Rather than following the Schrödinger equation like a good wave function, it collapses—it instantly becomes zero everywhere except in the place where you found the electron. Somehow, the laws of physics seem to behave differently when you make a measurement: the Schrödinger equation holds all the time, except when you make a measurement, at which point the

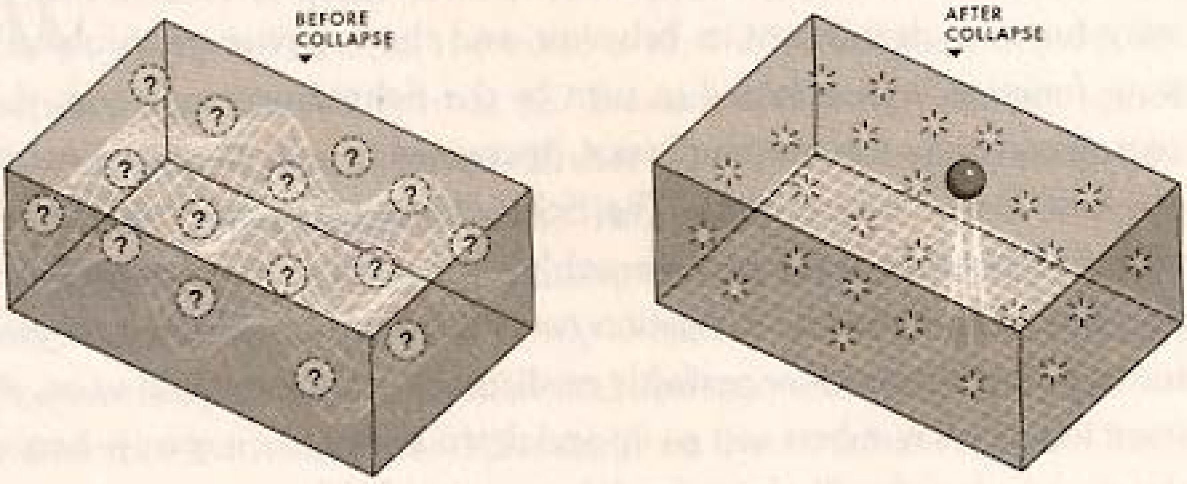

Figure 1.1. The measurement problem.

Left: The wave function of a ball in a box undulates smoothly, like ripples on the surface of a pond, governed by the Schrödinger equation. The ball could be anywhere in the box.

Right: The ball's location is measured and found in a particular spot. The wave function immediately and violently collapses, radically disobeying the Schrödinger equation. Why does the Schrödinger equation—a law of nature—apply only when measurements are not occurring? And what counts as a "measurement" anyhow?

Schrödinger equation is temporarily suspended and the wave function collapses everywhere except a random point. This is so weird that it gets a special name: the *measurement problem* (Figure 1.1).

Why does the Schrödinger equation only apply when measurements aren't happening? That doesn't seem to be how laws of nature work—we think of laws of nature as applying all the time, no matter what we're doing. If a leaf detaches from a maple tree, it will fall whether or not anyone is there to see it happen. Gravity doesn't care whether anyone is around to watch.

But maybe quantum physics really is different. Maybe measurements do change the laws that govern the quantum world. That's certainly strange, but it doesn't seem impossible. But even if that's true, it still doesn't solve the measurement problem, because now we have a new challenge: what is a "measurement," anyhow? Does a measurement require a measurer? Does the quantum world depend on whether it has an audience? Can anyone at all collapse a wave function? Do you need to be awake and conscious for it, or can a comatose person do it? What about a newborn baby? Is it limited to humans, or can chimps do it too? "When a mouse observes, does that change the [quantum] state of the universe?" Einstein once asked. Bell asked, "Was the world wavefunction waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer for some more highly qualified measurer—with a Ph.D.?" If measurement has nothing to do with living observers, then what does it involve? Does it just mean that a small object, governed by quantum physics, has interacted with a big one, which is somehow exempt from quantum physics? In that case, doesn't that mean that measurements are happening basically all of the time, and the Schrödinger equation should almost never apply? But then why does the Schrödinger equation work at all? And where's the divide between the quantum world of the small and the Newtonian world of the large?

Finding this Pandora's box of weird questions lying at the heart of fundamental physics is disturbing, to say the least. Yet despite all this weirdness, quantum physics is wildly successful at describing the world—much more so than simple old Newtonian physics (which was already pretty good). Without quantum physics, we wouldn't have any understanding of why diamonds are so hard, what atoms are made of, or how to build electronics. So wave functions, with their numbers scattered across the universe, must somehow be related to the everyday stuff we see around us in the world, otherwise quantum physics wouldn't be any good at making predictions. But this makes the measurement problem even more urgent—it means there's something about the nature of reality that we don't understand.

So how should we interpret this strange and wonderful theory? What story is quantum physics telling us about the world?

Rather than answering that question—which seems like it would be difficult—we could deny that it's a legitimate question at all. We can claim that making predictions about the outcomes of measurements is all that matters in quantum physics. Now we don't have to worry about what's happening when we're not making measurements, and all these difficult questions melt away. What is the wave function? How is it connected to the objects in the world around us? Easy, comforting solutions are at hand: the wave function is merely a mathematical device, a bookkeeping tool to allow us to make predictions about measurements. And it has no connection to the world around us at all—it's merely a useful piece of mathematics. It doesn't matter that wave functions behave differently when we're not looking, because between measurements, nothing matters. Even talking about the existence of things between measurements is unscientific. This, strangely enough, is the orthodox view of quantum physics—the "soft pillow" of the Copenhagen interpretation.

These suspiciously easy answers raise another question, one without an obvious solution. Physics is the science of the material world. And quantum theory purports to be the physics governing the most fundamental constituents of that world. Yet the Copenhagen interpretation says that it's meaningless to ask about what's actually going on in quantum physics. So what is real? Copenhagen's reply is silence—and a look of stern disapproval for having the temerity to ask the question in the first place.

This is, at best, a profoundly unsatisfying answer. But this is also the standard answer. The physicists who pursued the question anyhow—physicists like Einstein, and later on, Bell and Bohm—did so in open defiance of Copenhagen. So the quest for reality is also the story of that rebellion, a rebellion as old as quantum physics itself.