SOMETHING DEEPLY HIDDEN

Quantum Worlds and the Emergence of Spacetime

SEAN CARROLL

New York Times bestselling author of *The Big Picture*

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SOMETHING DEEPLY HIDDEN

PROLOGUE

Don't Be Afraid

You don't need a PhD in theoretical physics to be afraid of quantum mechanics. But it doesn't hurt.

That might seem strange. Quantum mechanics is our best theory of the microscopic world. It describes how atoms and particles interact through the forces of nature, and makes incredibly precise experimental predictions. To be sure, quantum mechanics has something of a reputation for being difficult, mysterious, just this side of magic. But professional physicists, of all people, should be relatively comfortable with a theory like that. They are constantly doing intricate calculations involving quantum phenomena, and building giant machines dedicated to testing the resulting predictions. Surely we're not suggesting that physicists have been faking it all this time?

They haven't been faking, but they haven't exactly been honest with themselves either. On the one hand, quantum mechanics is the heart and soul of modern physics. Astrophysicists, particle physicists, atomic physicists, laser physicists—everyone uses quantum mechanics all the time, and they're very good at it. It's not just a matter of esoteric research. Quantum mechanics is ubiquitous in modern technology.

Semiconductors, transistors, microchips, lasers, and computer memory all rely on quantum mechanics to function. For that matter, quantum mechanics is necessary to make sense of the most basic features of the world around us. Essentially all of chemistry is a matter of applied quantum mechanics. To understand how the sun shines, or why tables are solid, you need quantum mechanics.

Imagine closing your eyes. Hopefully things look pretty dark. You might think that makes sense, because no light is coming in. But that's not quite right; infrared light, with a slightly longer wavelength than visible light, is being emitted all the time by any warm object, and that includes your own body. If our eyes were as sensitive to infrared light as they are to visible light, we would be blinded even when our lids were closed, from all the light emitted by our eyeballs themselves. But the rods and cones that act as light receptors in our eyes are cleverly sensitive to visible light, not infrared. How do they manage that? Ultimately, the answer comes down to quantum mechanics.

Quantum mechanics isn't magic. It is the deepest, most comprehensive view of reality we have. As far as we currently know, quantum mechanics isn't just an approximation of the truth; it is the truth. That's subject to change in the face of unexpected experimental results, but we've seen no hints of any such surprises thus far. The development of quantum mechanics in the early years of the twentieth century, involving names like Planck, Einstein, Bohr, Heisenberg, Schrödinger, and Dirac, left us by 1927 with a mature understanding that is surely one of the greatest intellectual accomplishments in human history. We have every reason to be proud.

On the other hand, in the memorable words of Richard Feynman, "I think I can safely say that nobody understands quantum mechanics." We *use* quantum mechanics to design new technologies and predict the outcomes of experiments. But honest physicists admit that we don't truly *understand* quantum mechanics. We have a recipe that we can safely apply in certain prescribed situations, and which returns mindbogglingly precise predictions that have been triumphantly vindicated by the data. But if you want to dig deeper and ask what is really going on, we simply don't know. Physicists tend to treat quantum mechanics like a mindless robot they rely on to perform certain tasks, not as a beloved friend they care about on a personal level.

This attitude among the professionals seeps into how quantum mechanics gets explained to the wider world. What we would like to do is to present a fully formed picture of Nature, but we can't quite do that, since physicists don't agree about what quantum mechanics actually says. Instead, popular treatments tend to emphasize that quantum mechanics is mysterious, baffling, impossible to understand. That message goes against the basic principles that science stands for, which include the idea that the world is fundamentally intelligible. We have something of a mental block when it comes to quantum mechanics, and we need a bit of quantum therapy to help get past it.

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When we teach quantum mechanics to students, they are taught a list of rules. Some of the rules are of a familiar type: there's a mathematical description of quantum systems, plus an explanation of how such systems evolve over time. But then there are a bunch of extra rules that have no analogue in any other theory of physics. These extra rules tell us what happens when we *observe* a quantum system, and that behavior is completely different from how the system behaves when we're not observing it. What in the world is going on with that?

There are basically two options. One is that the story we've been telling our students is woefully incomplete, and in order for quantum mechanics to qualify as a sensible theory we need to understand what a "measurement" or "observation" is, and why it seems so different from what the system does otherwise. The other option is that quantum mechanics represents a violent break from the way we have always thought about physics before, shifting from a view where the world exists objectively and independently of how we perceive it, to one where the act of observation is somehow fundamental to the nature of reality.

In either case, the textbooks should by all rights spend time exploring these options, and admit that even though quantum mechanics is extremely successful, we can't claim to be finished developing it just yet. They don't. For the most part, they pass over this issue in silence, preferring to stay in the physicist's comfort zone of writing down equations and challenging students to solve them.

That's embarrassing. And it gets worse.

You might think, given this situation, that the quest to understand quantum mechanics would be the single biggest goal in all of physics. Millions of dollars of grant money would flow to researchers in quantum foundations, the brightest minds would flock to the problem, and the most important insights would be rewarded with prizes and prestige. Universities would compete to hire the leading figures in the area, dangling superstar salaries to lure them away from rival institutions.

Sadly, no. Not only is the quest to make sense of quantum mechanics not considered a high-status specialty within modern physics; in many quarters it's considered barely respectable at all, if not actively disparaged. Most physics departments have nobody working on the problem, and those who choose to do so are looked upon with suspicion. (Recently while writing a grant proposal, I was advised to concentrate on describing my work in gravitation and cosmology, which is considered legitimate, and remain silent about my work on the foundations of quantum mechanics, as that would make me appear less serious.) There have been important steps forward over the last ninety years, but they have typically been made by headstrong individuals who thought the problems were important despite what all of their colleagues told them, or by young students who didn't know any better and later left the field entirely.

In one of Aesop's fables, a fox sees a juicy bunch of grapes and leaps to reach it, but can't quite jump high enough. In frustration he declares that the grapes were probably sour, and he never really wanted them anyway. The fox represents "physicists," and the grapes are "understanding quantum mechanics." Many researchers have decided that understanding how nature really works was never really important; all that matters is the ability to make particular predictions.

Scientists are trained to value tangible results, whether they are exciting experimental findings or quantitative theoretical models. The idea of working to understand a theory we already have, even if that effort might not lead to any specific new technologies or predictions, can be a tough sell. The underlying tension was illustrated in the TV show *The Wire*, where a group of hardworking detectives labored for months to meticulously gather evidence that would build a case against a powerful drug ring. Their bosses, meanwhile, had no patience for such incremental frivolity. They just wanted to see drugs on the table for their next press conference, and encouraged the police to bang heads and make splashy arrests. Funding agencies and hiring committees are like those bosses. In a world where all the incentives push us toward concrete, quantifiable outcomes, less pressing big-picture concerns can be pushed aside as we race toward the next immediate goal.

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This book has three main messages. The first is that quantum mechanics should be understandable—even if we're not there yet—and achieving such understanding should be a high-priority goal of modern science. Quantum mechanics is unique among physical theories in drawing an apparent distinction between *what we see* and *what really is*. That poses a special challenge to the minds of scientists (and everyone else), who are used to thinking about what we see as unproblematically "real," and working to explain things accordingly. But this challenge isn't insuperable, and if we free our minds from certain old-fashioned and intuitive ways of thinking, we find that quantum mechanics isn't hopelessly mystical or inexplicable. It's just physics.

The second message is that we have made real progress toward understanding. I will focus on the approach I feel is clearly the most promising route, the Everett or Many-Worlds formulation of quantum mechanics. Many-Worlds has been enthusiastically embraced by many physicists, but it has a sketchy reputation among people who are put off by a proliferation of other realities containing copies of themselves. If you are one of those people, I want to at least convince you that Many-Worlds is the *purest* way of making sense of quantum mechanics—it's where we end up if we just follow the path of least resistance in taking quantum phenomena seriously. In particular, the multiple worlds are predictions of the formalism that is already in place, not something added in by hand. But Many-Worlds isn't the only respectable approach, and we will mention some of its main competitors. (I will endeavor to be fair, if not necessarily balanced.) The important thing is that the various approaches are all well-constructed scientific theories, with potentially different experimental ramifications, not just woolly-headed "interpretations" to be debated over cognac and cigars after we're finished doing real work.

The third message is that all this matters, and not just for the integrity of science. The success to date of the existing adequate-but-not-perfectly-coherent framework of quantum mechanics shouldn't blind us to the fact that there are circumstances under which such an approach simply isn't up to the task. In particular, when we turn to understanding the nature of spacetime itself, and the origin and ultimate fate of the entire universe, the foundations of quantum mechanics are absolutely crucial. I'll introduce some new, exciting, and admittedly tentative proposals that draw provocative connections between quantum entanglement and how spacetime bends and curves—the phenomenon you and I know as "gravity." For many years now, the search for a complete and compelling quantum theory of gravity has been recognized as an important scientific goal (prestige, prizes, stealing away faculty, and all that). It may be that the secret is not to start with gravity and "quantize" it, but to dig deeply into quantum mechanics itself, and find that gravity was lurking there all along.

We don't know for sure. That's the excitement and anxiety of cutting-edge research. But the time has come to take the fundamental nature of reality seriously, and that means confronting quantum mechanics head-on.

Part One

SPOOKY

1

What's Going On

Looking at the Quantum World

Albert Einstein, who had a way with words as well as with equations, was the one who stuck quantum mechanics with the label it has been unable to shake ever since: *spukhaft*, usually translated from German to English as "spooky." If nothing else, that's the impression we get from most public discussions of quantum mechanics. We're told that it's a part of physics that is unavoidably mystifying, weird, bizarre, unknowable, strange, baffling. Spooky.

Inscrutability can be alluring. Like a mysterious, sexy stranger, quantum mechanics tempts us into projecting all sorts of qualities and capacities onto it, whether they are there or not. A brief search for books with "quantum" in the title reveals the following list of purported applications:

Quantum Success
Quantum Leadership
Quantum Consciousness
Quantum Touch

Quantum Yoga
Quantum Eating
Quantum Psychology
Quantum Mind
Quantum Glory
Quantum Forgiveness
Quantum Theology
Quantum Happiness
Quantum Poetry
Quantum Teaching
Quantum Faith
Quantum Love

For a branch of physics that is often described as only being relevant to microscopic processes involving subatomic particles, that's a pretty impressive résumé.

To be fair, quantum mechanics—or "quantum physics," or "quantum theory," the labels are all interchangeable—is not only relevant to microscopic processes. It describes the whole world, from you and me to stars and galaxies, from the centers of black holes to the beginning of the universe. But it is only when we look at the world in extreme close-up that the apparent weirdness of quantum phenomena becomes unavoidable.

One of the themes in this book is that quantum mechanics doesn't deserve the connotation of spookiness, in the sense of some ineffable mystery that it is beyond the human mind to comprehend. Quantum mechanics is *amazing*; it is novel, profound, mind-stretching, and a very different view of reality from what we're used to. Science is like that sometimes. But if the subject seems difficult or puzzling, the scientific response is to solve the puzzle, not to pretend it's not there. There's every reason to think we can do that for quantum mechanics just like any other physical theory.

Many presentations of quantum mechanics follow a typical pattern. First, they point to some counterintuitive quantum phenomenon. Next, they express bafflement that the world can possibly be that way, and despair of it making sense. Finally (if you're lucky), they attempt some sort of explanation.

Our theme is prizing clarity over mystery, so I don't want to adopt that strategy. I want to present quantum mechanics in a way that will make it maximally understandable right from the start. It will still seem strange, but that's the nature of the beast. What it won't seem, hopefully, is inexplicable or unintelligible.

We will make no effort to follow historical order. In this chapter we'll look at the basic experimental facts that force quantum mechanics upon us, and in the next we'll quickly sketch the Many-Worlds approach to making sense of those observations. Only in the chapter after that will we offer a semi-historical account of the discoveries that led people to contemplate such a dramatically new kind of physics in the first place. Then we'll hammer home exactly how dramatic some of the implications of quantum mechanics really are.

With all that in place, over the rest of the book we can set about the fun task of seeing where all this leads, demystifying the most striking features of quantum reality.

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Physics is one of the most basic sciences, indeed one of the most basic human endeavors. We look around the world, we see it is full of stuff. What is that stuff, and how does it behave?

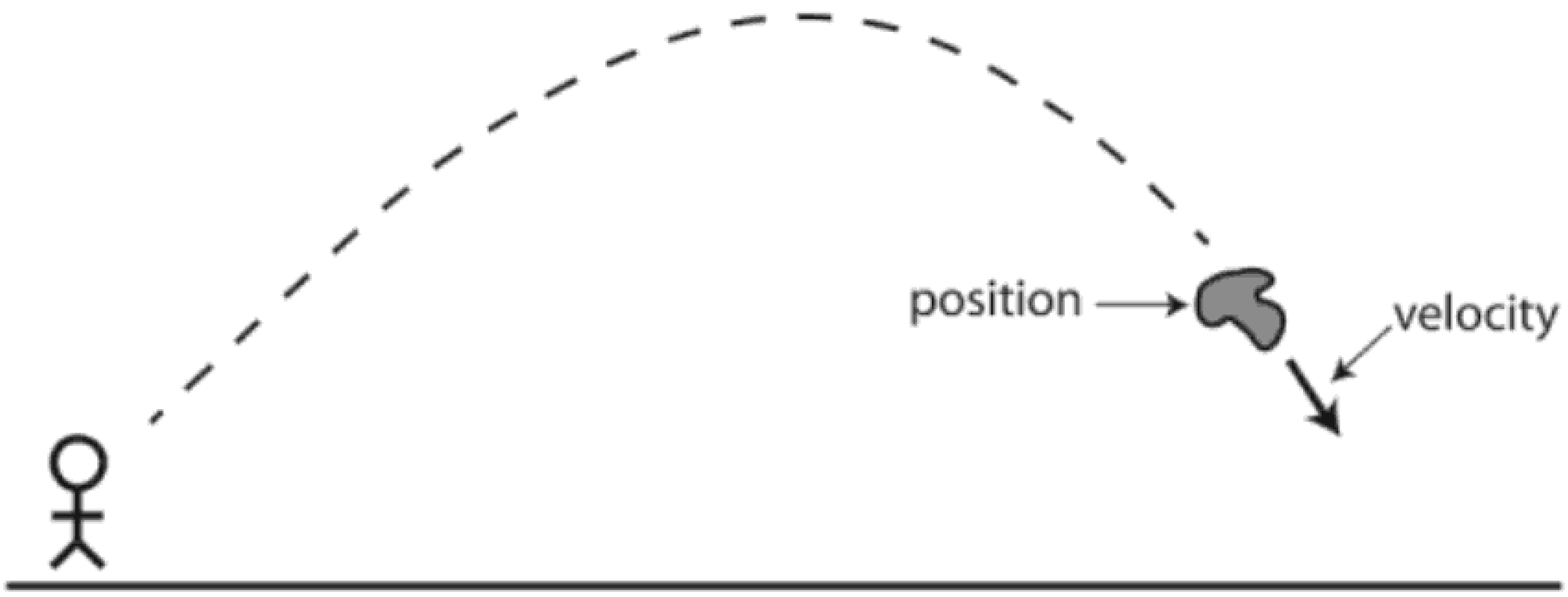
These are questions that have been asked ever since people started asking questions. In ancient Greece, physics was thought of as the general study of change and motion, of both living and nonliving matter. Aristotle spoke a vocabulary of tendencies, purposes, and causes. How an entity moves and changes can be explained by reference to its inner nature and to external powers acting upon it. Typical objects, for example, might by nature be at rest; in order for them to move, it is necessary that something be causing that motion.

All of this changed thanks to a clever chap named Isaac Newton. In 1687 he published *Principia Mathematica*, the most important work in the history of physics. It was there that he laid the groundwork for what we now call "classical" or simply "Newtonian" mechanics. Newton blew away any dusty talk of natures and purposes, revealing what lay underneath: a crisp, rigorous mathematical formalism with which teachers continue to torment students to this very day.

Whatever memory you may have of high-school or college homework assignments dealing with pendulums and inclined planes, the basic ideas of classical mechanics are pretty simple. Consider an object such as a rock. Ignore everything about the rock that a geologist might consider interesting, such as its color and composition. Put aside the possibility that the basic structure of the rock might change, for example, if you smashed it to pieces with a hammer. Reduce your mental image of the rock down to its most abstract form: the rock is an object, and that object has a *location in space*, and that location *changes with time*.

Classical mechanics tells us precisely how the position of the rock changes with time. We're very used to that by now, so it's worth reflecting on how impressive this is. Newton doesn't hand us some vague platitudes about the general tendency of rocks to move more or less in this or that fashion. He gives us exact, unbreakable rules for how everything in the universe moves in response to everything else—rules that can be used to catch baseballs or land rovers on Mars.

Here's how it works. At any one moment, the rock will have a position and also a velocity, a rate at which it's moving. According to Newton, if no forces act on the rock, it will continue to move in a straight line at constant velocity, for all time. (Already this is a major departure from Aristotle, who would have told you that objects need to be constantly pushed if they are to be kept in motion.) If a force does act on the rock, it will cause acceleration—some change in the velocity of the rock, which might make it go faster, or slower, or merely alter its direction—in direct proportion to how much force is applied.



That's basically it. To figure out the entire trajectory of the rock, you need to tell me its position, its velocity, and what forces are acting on it. Newton's equations tell you the rest. Forces might include the force of gravity, or the force of your hand if you pick up the rock and throw it, or the force from the ground when the rock comes to land. The idea works just as well for billiard balls or rocket ships or planets. The project of physics, within this classical paradigm, consists essentially of figuring out what makes up the stuff of the universe (rocks and so forth) and what forces act on them.

Classical physics provides a straightforward picture of the world, but a number of crucial moves were made along the way to setting it up. Notice that we had to be very specific about what information we required to figure out what would happen to the rock: its position, its velocity, and the forces acting on it. We can think of those forces as being part of the outside world, and the important information about the rock itself as consisting of just its position and velocity. The acceleration of the rock at any moment in time, by contrast, is not something we need to specify; that's exactly what Newton's laws allow us to calculate from the position and the velocity.

Together, the position and velocity make up the *state* of any object in classical mechanics. If we have a system with multiple moving parts, the classical state of that entire system is just a list of the states of each of the individual parts. The air in a normal-sized room will have perhaps 10^{27} molecules of different types, and the state of that air would be a list of the position and velocity of every one of them. (Strictly speaking, physicists like to use the momentum of each particle, rather than its velocity, but as far as Newtonian mechanics is concerned the momentum is simply the particle's mass times its velocity.) The set of all possible states that a system could have is known as the *phase space* of the system.

The French mathematician Pierre-Simon Laplace pointed out a profound implication of the classical mechanics way of thinking. In principle, a vast intellect could know the state of literally every object in the universe, from which it could deduce everything that would happen in the future, as well as everything that had happened in the past. *Laplace's demon* is a thought experiment, not a realistic project for an ambitious computer scientist, but the implications of the thought experiment are profound. Newtonian mechanics describes a deterministic, clockwork universe.

The machinery of classical physics is so beautiful and compelling that it seems almost inescapable once you grasp it. Many great minds who came after Newton were convinced that the basic superstructure of physics had been solved, and future progress lay in figuring out exactly what realization of classical physics (which particles, which forces) was the right one to describe the universe as a whole. Even relativity, which was world-transforming in its own way, is a variety of classical mechanics rather than a replacement for it.

Then along came quantum mechanics, and everything changed.

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Alongside Newton's formulation of classical mechanics, the invention of quantum mechanics represents the other great revolution in the history of physics. Unlike anything that had come before, quantum theory didn't propose a particular physical model within the basic classical framework; it discarded that framework entirely, replacing it with something profoundly different.

The fundamental new element of quantum mechanics, the thing that makes it unequivocally distinct from its classical predecessor, centers on the question of what it means to *measure* something about a quantum system. What exactly a measurement is, and what happens when we measure something, and what this all tells us about what's really happening behind the scenes: together, these questions constitute what's called the *measurement problem* of quantum mechanics. There is absolutely no consensus within physics or philosophy on how to solve the measurement problem, although there are a number of promising ideas.

Attempts to address the measurement problem have led to the emergence of a field known as *the interpretation of quantum mechanics*, although the label isn't very accurate. "Interpretations" are things that we might apply to a work of literature or art, where people might have different ways of thinking about the same basic object. What's going on in quantum mechanics is something else: a competition between truly distinct scientific theories, incompatible ways of making sense of the physical world. For this reason, modern workers in this field prefer to call it "foundations of quantum mechanics." The subject of quantum foundations is part of science, not literary criticism.

Nobody ever felt the need to talk about "interpretations of classical mechanics"—classical mechanics is perfectly transparent. There is a mathematical formalism that speaks of positions and velocities and trajectories, and oh, look: there is a rock whose actual motion in the world obeys the predictions of that formalism. There is, in particular, no such thing as a measurement problem in classical mechanics. The state of the system is given by its position and its velocity, and if we want to measure those quantities, we simply do so. Of course, we can measure the system sloppily or crudely, thereby obtaining imprecise results or altering the system itself. But we don't have to; just by being careful, we can precisely measure everything there is to know about the system without altering it in any noticeable way. Classical mechanics offers a clear and unambiguous relationship between what we see and what the theory describes.

Quantum mechanics, for all its successes, offers no such thing. The enigma at the heart of quantum reality can be summed up in a simple motto: what we *see* when we look at the world seems to be fundamentally different from what actually *is*.

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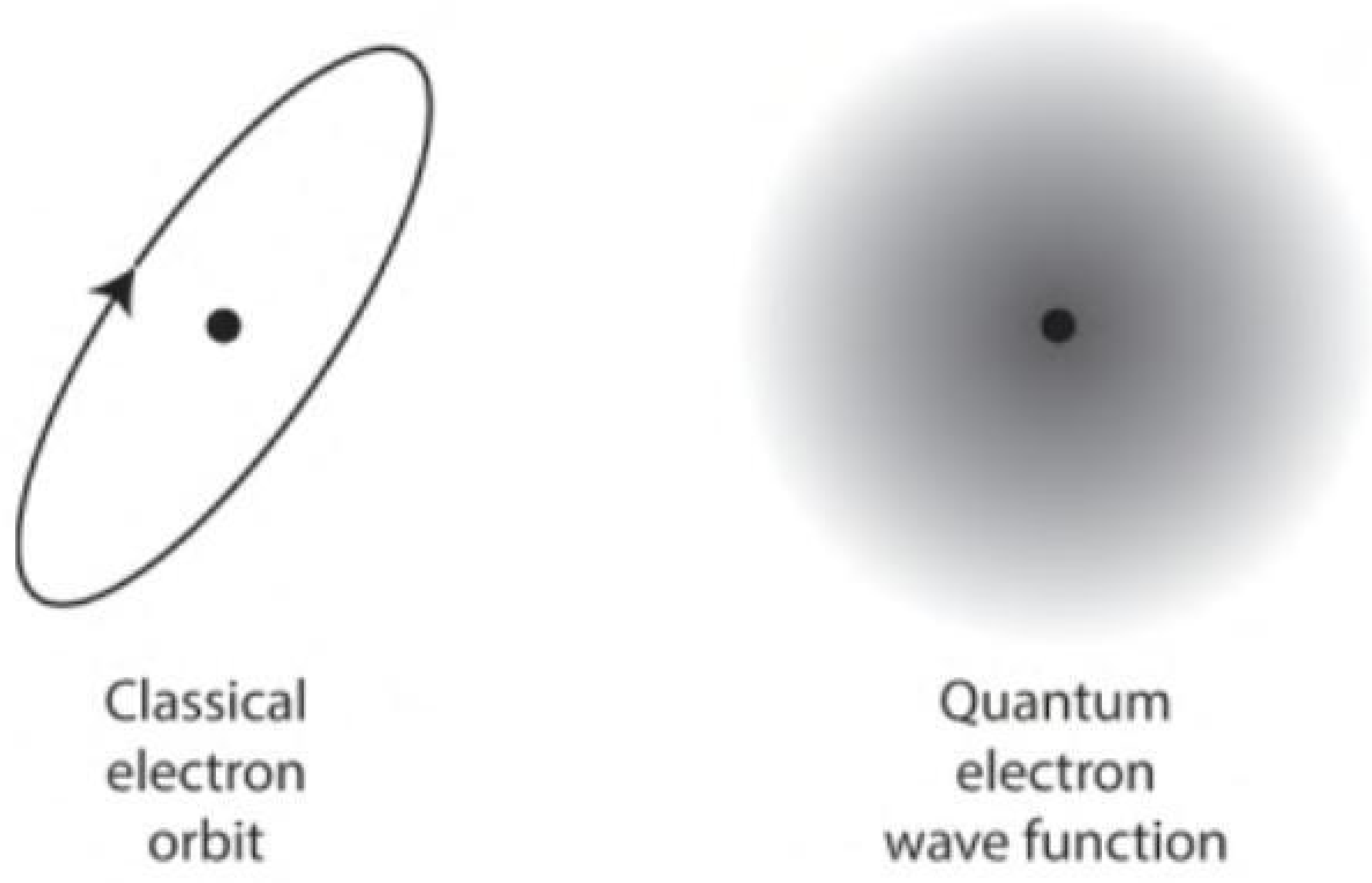
Think about electrons, the elementary particles orbiting atomic nuclei, whose interactions are responsible for all of chemistry and hence almost everything interesting around you right now. As we did with the rock, we can ignore some of the electron's specific properties, like its spin and the fact that it has an electric field. (Really we could just stick with the rock as our example—rocks are quantum systems just as much as electrons are—but switching to a subatomic particle helps us remember that the features distinguishing quantum mechanics only become evident when we consider very tiny objects indeed.)

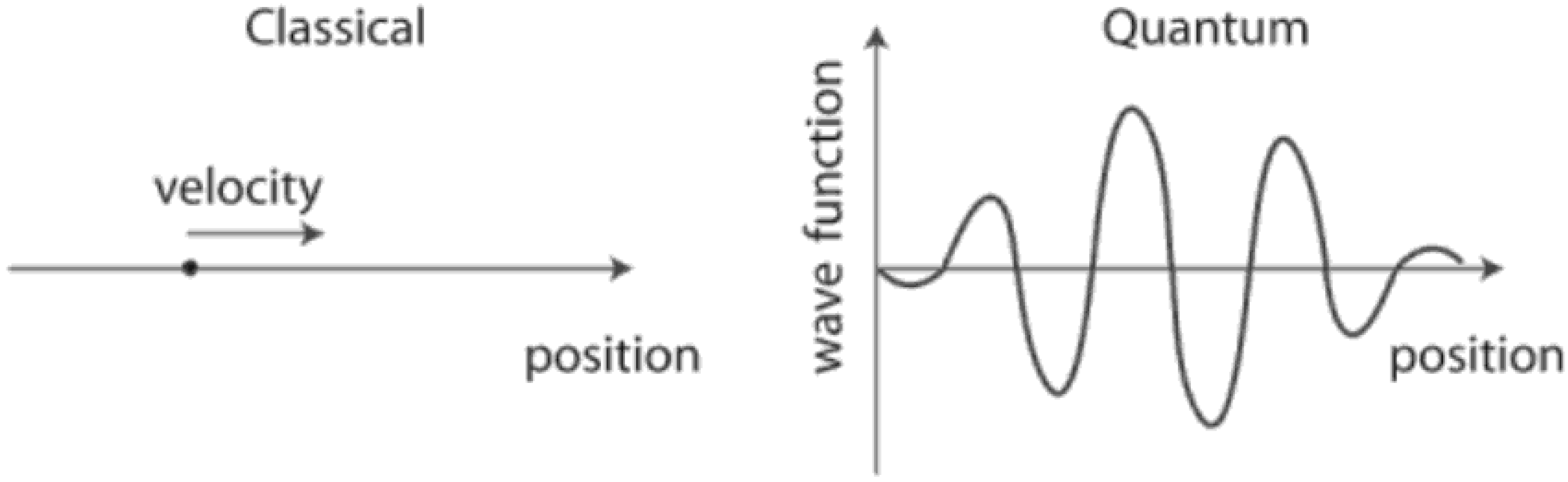
Unlike in classical mechanics, where the state of a system is described by its position and velocity, the nature of a quantum system is something a bit less concrete. Consider an electron in its natural habitat, orbiting the nucleus of an atom. You might think, from the word "orbit" as well as from the numerous cartoon depictions of atoms you have doubtless been exposed to over the years, that the orbit of an electron is more or less like the orbit of a planet in the solar system. The electron (so you might think) has a location, and a velocity, and as time passes it zips around the central nucleus in a circle or maybe an ellipse.

Quantum mechanics suggests something different. We can *measure* values of the location or velocity (though not at the same time), and if we are sufficiently careful and talented experimenters we will obtain some answer. But what we're seeing through such a measurement is not the actual, complete, unvarnished state of the electron. Indeed, the particular measurement outcome we will obtain cannot be predicted with perfect confidence, in a profound departure from the ideas of classical mechanics. The best we can do is to predict the *probability* of seeing the electron in any particular location or with any particular velocity.



The classical notion of the state of a particle, "its location and its velocity," is therefore replaced in quantum mechanics by something utterly alien to our everyday experience: a cloud of probability. For an electron in an atom, this cloud is more dense toward the center and thins out as we get farther away. Where the cloud is thickest, the probability of seeing the electron is highest; where it is diluted almost to imperceptibility, the probability of seeing the electron is vanishingly small.

This cloud is often called a *wave function*, because it can oscillate like a wave, as the most probable measurement outcome changes over time. We usually denote a wave function by Ψ, the Greek letter Psi. For every possible measurement outcome, such as the position of the particle, the wave function assigns a specific number, called the *amplitude* associated with that outcome. The amplitude that a particle is at some position x_0, for example, would be written $\Psi(x_0)$.



The probability of getting that outcome when we perform a measurement is given by the amplitude squared.

Probability of a particular outcome = |Amplitude for that outcome|^2

This simple relation is called the *Born rule*, after physicist Max Born.* Part of our task will be to figure out where in the world such a rule came from.

We're most definitely *not* saying that there is an electron with some position and velocity, and we just don't know what those are, so the wave function encapsulates our ignorance about those quantities. In this chapter we're not saying anything at all about what "is," only what we observe. In chapters to come, I will pound the table and insist that the wave function is the sum total of reality, and ideas such as the

* There's a slight technicality, which we'll mention here and then pretty much forget about: the amplitude for any given outcome is actually a complex number, not a real number. Real numbers are the ones that appear on the number line, any number between minus infinity and plus infinity. Anytime you take the square of a real number, you get another real number that is greater than or equal to zero, so as far as real numbers are concerned there's no such thing as the square root of a negative number. Mathematicians long ago realized that square roots of negative numbers would be really useful things to have, so they defined the "imaginary unit" *i* as the square root of -1. An imaginary number is just a real number, called "the imaginary part," times *i*. Then a complex number is just a combination of a real number and an imaginary one. The little bars in the notation |Amplitude|^2 in the Born rule mean that we actually add the squares of the real and the imaginary parts. All that is just for the sticklers out there; henceforth we'll be happy to say "the probability is the amplitude squared" and be done with it.

position or the velocity of the electron are merely things we can measure. But not everyone sees things that way, and for the moment we are choosing to don a mask of impartiality.

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Let's place the rules of classical and quantum mechanics side by side to compare them. The state of a classical system is given by the position and velocity of each of its moving parts. To follow its evolution, we imagine something like the following procedure:

Rules of Classical Mechanics

1. Set up the system by fixing a specific position and velocity for each part.
2. Evolve the system using Newton's laws of motion.

That's it. The devil is in the details, of course. Some classical systems can have a lot of moving pieces.

In contrast, the rules of standard textbook quantum mechanics come in two parts. In the first part, we have a structure that exactly parallels that of the classical case. Quantum systems are described by wave functions rather than by positions and velocities. Just as Newton's laws of motion govern the evolution of the state of a system in classical mechanics, there is an equation that governs how wave functions evolve, called *Schrödinger's equation*. We can express Schrödinger's equation in words as: "The rate of change of a wave function is proportional to the energy of the quantum system." Slightly more specifically, a wave function can represent a number of different possible energies, and the Schrödinger equation says that high-energy parts of the wave function evolve rapidly, while low-energy parts evolve very slowly. Which makes sense, when we think about it.

What matters for our purposes is simply that there is such an equation, one that predicts how wave functions evolve smoothly through time. That evolution is as predictable and inevitable as the way objects move according to Newton's laws in classical mechanics. Nothing weird is happening yet.

The beginning of the quantum recipe reads something like this:

Rules of Quantum Mechanics (Part One)

1. Set up the system by fixing a specific wave function Ψ.
2. Evolve the system using Schrödinger's equation.

So far, so good—these parts of quantum mechanics exactly parallel their classical predecessors. But whereas the rules of classical mechanics stop there, the rules of quantum mechanics keep going.

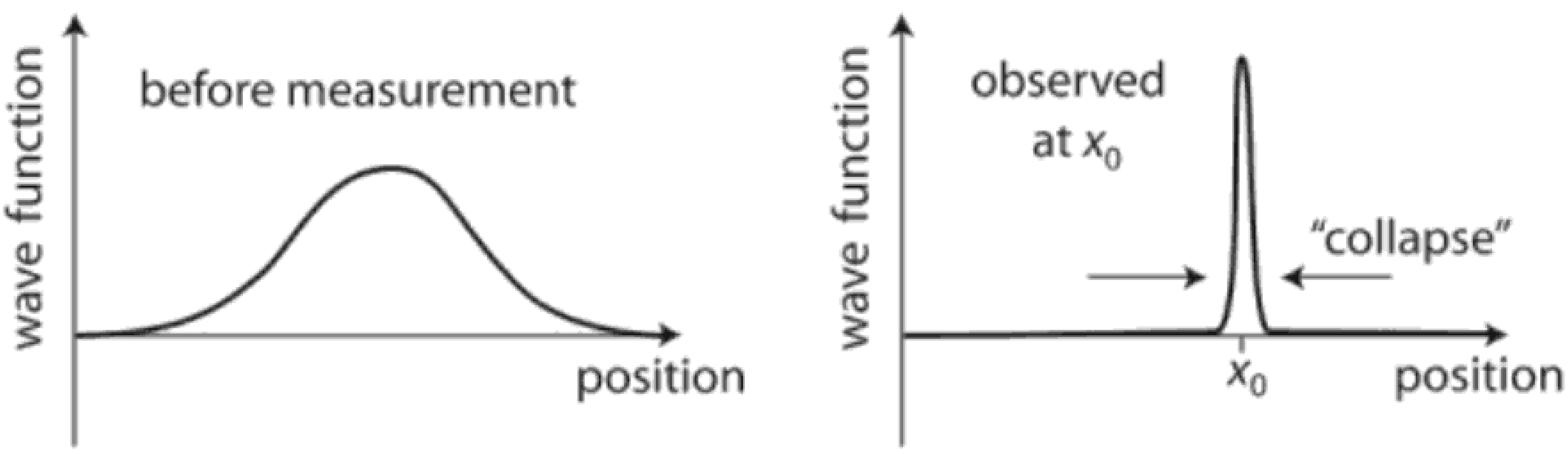
All the extra rules deal with measurement. When you perform a measurement, such as the position or spin of a particle, quantum mechanics says there are only certain possible results you will ever get. You can't predict which of the results it will be, but you can calculate the probability for each allowed outcome. And after your measurement is done, the wave function *collapses* to a completely different function, with all of the new probability concentrated on whatever result you just got. So if you measure a quantum system, in general the best you can do is predict probabilities for various outcomes, but if you were to immediately measure the same quantity again, you will always get the same answer—the wave function has collapsed onto that outcome.

Let's write this out in gory detail.

Rules of Quantum Mechanics (Part Two)

3. There are certain observable quantities we can choose to measure, such as position, and when we do measure them, we obtain definite results.

4. The probability of getting any one particular result can be calculated from the wave function. The wave function associates an amplitude with every possible measurement outcome; the probability for any outcome is the square of that amplitude.
5. Upon measurement, the wave function collapses. However spread out it may have been pre-measurement, afterward it is concentrated on the result we obtained.



In a modern university curriculum, when physics students are first exposed to quantum mechanics, they are taught some version of these five rules. The ideology associated with this presentation—treat measurements as fundamental, wave functions collapse when they are observed, don't ask questions about what's going on behind the scenes—is sometimes called the *Copenhagen interpretation* of quantum mechanics. But people, including the physicists from Copenhagen who purportedly invented this interpretation, disagree on precisely what that label should be taken to describe. We can just refer to it as "standard textbook quantum mechanics."

The idea that these rules represent how reality actually works is, needless to say, outrageous.

What precisely do you mean by a "measurement"? How quickly does it happen? What exactly constitutes a measuring apparatus? Does it need to be human, or have some amount of consciousness, or perhaps the ability to encode information? Or maybe it just has to be macroscopic, and if so how macroscopic does it have to be? When exactly does the measurement occur, and how quickly? How in the world does the wave function collapse so dramatically? If the wave function were very spread out, does the collapse happen faster than the speed of light? And what happens to all the possibilities that were seemingly allowed by the wave function but which we didn't observe? Were they never really there? Do they just vanish into nothingness?

To put things most pointedly: Why do quantum systems evolve smoothly and deterministically according to the Schrödinger equation *as long as we aren't looking at them*, but then dramatically collapse when we do look? How do they know, and why do they care? (Don't worry, we're going to answer all these questions.)

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Science, most people think, seeks to understand the natural world. We observe things happening, and science hopes to provide an explanation for what is going on.

In its current textbook formulation, quantum mechanics has failed in this ambition. We don't know what's really going on, or at least the community of professional physicists cannot agree on what it is. What we have instead is a *recipe* that we enshrine in textbooks and teach to our students. Isaac Newton could tell you, starting with the position and velocity of a rock that you have thrown into the air in the Earth's gravitational field, just what the subsequent trajectory of that rock was going to be. Analogously, starting with a quantum system prepared in some particular way, the rules of quantum mechanics can tell you how the wave function will change over time, and what the probability of various possible measurement outcomes will be should you choose to observe it.

The fact that the quantum recipe provides us with probabilities rather that certainties might be annoying, but we could learn to live

2

The Courageous Formulation

Austere Quantum Mechanics

The attitude inculcated into young students by modern quantum mechanics textbooks has been compactly summarized by physicist N. David Mermin as "Shut up and calculate!" Mermin himself wasn't advocating such a position, but others have. Every decent physicist spends a good deal of time calculating things, whatever their attitude toward quantum foundations might be. So really the admonition could be shortened to simply "Shut up!"*

It wasn't always thus. Quantum mechanics took decades to piece together, but rounded into its modern form around 1927. In that year, at the Fifth International Solvay Conference in Belgium, the world's

* If you look on the Internet, you will find numerous attributions of "Shut up and calculate!" to Richard Feynman, a physicist who was an all-time great at doing difficult calculations. But he never said any such thing, nor would he have found the sentiment congenial; Feynman thought carefully about quantum mechanics, and nobody ever accused him of shutting up. It's common for quotations to be reattributed to plausible speakers who are more famous than the actual source of the quote. Sociologist Robert Merton has dubbed this the Matthew Effect, after a line from the Gospel of Matthew: "For unto every one that hath shall be given, and he shall have abundance: but from him that hath not shall be taken away even that which he hath."

leading physicists came together to discuss the status and meaning of quantum theory. By that time the experimental evidence was clear, and physicists were at long last in possession of a quantitative formulation of the rules of quantum mechanics. It was time to roll up some sleeves and figure out what this crazy new worldview actually amounted to.

The discussions at this conference help set the stage, but our goal here isn't to get the history right. We want to understand the physics. So we'll sketch out a logical path by which we will be led to a full-blown scientific theory of quantum mechanics. No vague mysticism, no seemingly ad hoc rules. Just a simple set of assumptions leading to some remarkable conclusions. With this picture in mind, many things that might otherwise have seemed ominously mysterious will suddenly start to make perfect sense.

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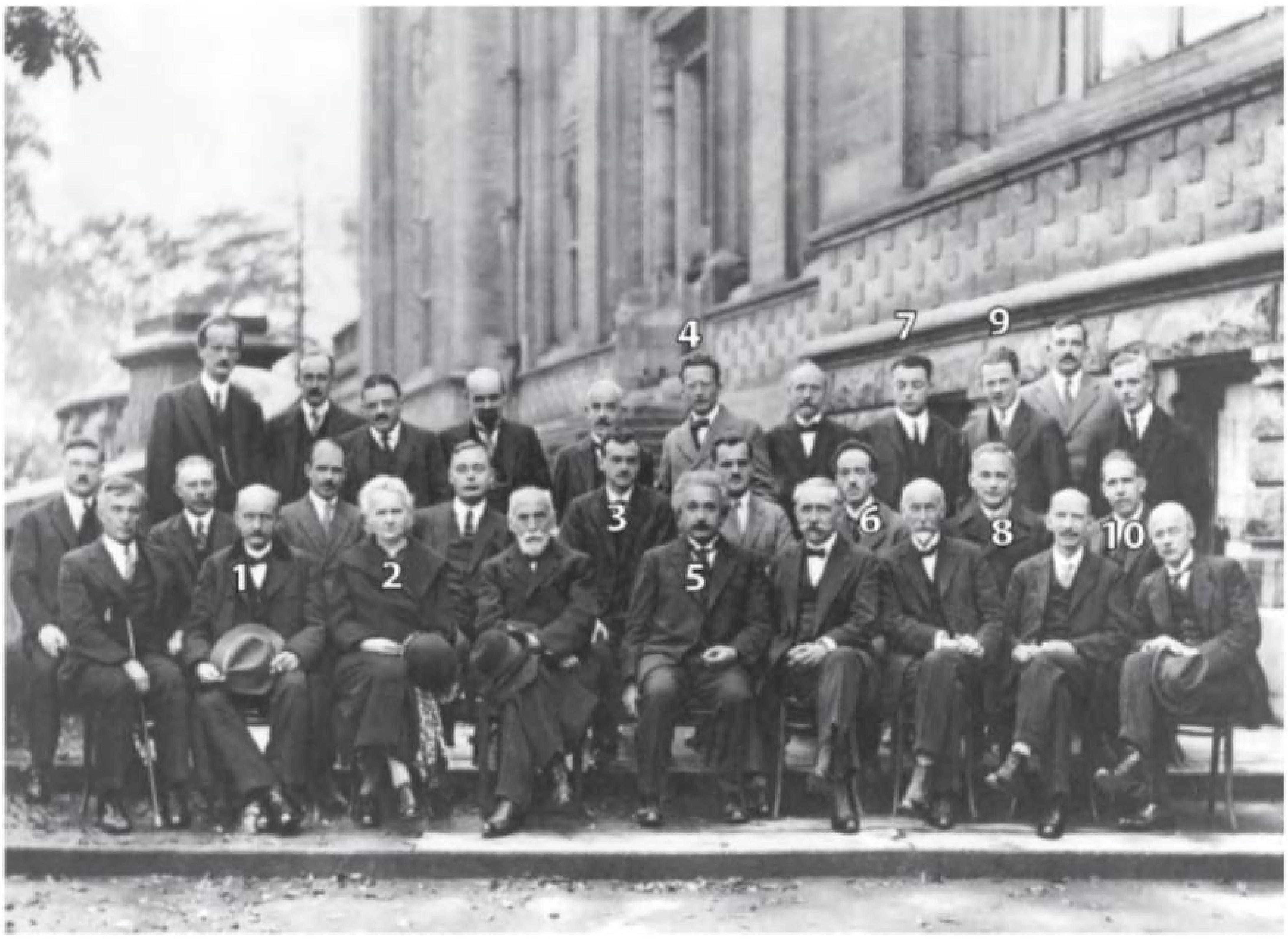
The Solvay Conference has gone down in history as the beginning of a famous series of debates between Albert Einstein and Niels Bohr over how to think about quantum mechanics. Bohr, a Danish physicist based in Copenhagen who is rightfully regarded as the godfather of quantum theory, advocated an approach similar to the textbook recipe we discussed in the last chapter: use quantum mechanics to calculate the probabilities for measurement outcomes, but don't ask of it anything more than that. Do not, in particular, worry too much about what is really happening behind the scenes. Supported by his younger colleagues Werner Heisenberg and Wolfgang Pauli, Bohr insisted that quantum mechanics was a perfectly fine theory as it was.

Einstein would have none of it. He was firmly convinced that the duty of physics was precisely to ask what was going on behind the scenes, and that the state of quantum mechanics in 1927 fell far short of providing a satisfactory account of nature. With his own sympathizers, such as Erwin Schrödinger and Louis de Broglie, Einstein advocated looking more deeply, and attempting to extend and generalize quantum mechanics into a satisfactory physical theory.



Participants in the 1927 Solvay Conference. Among the more well-known were: 1. Max Planck, 2. Marie Curie, 3. Paul Dirac, 4. Erwin Schrödinger, 5. Albert Einstein, 6. Louis de Broglie, 7. Wolfgang Pauli, 8. Max Born, 9. Werner Heisenberg, and 10. Niels Bohr. (Courtesy of Wikipedia)

Einstein and his compatriots had reason to be cautiously optimistic that such a new-and-improved theory was out there to be found. Just a few decades before, in the later years of the nineteenth century, physicists had developed the theory of statistical mechanics, which described the motion of large numbers of atoms and molecules. A key step in that development—which all took place under the rubric of classical mechanics, before quantum theory came on the scene—was the idea that we can talk profitably about the behavior of a large collection of particles even if we don't know precisely the position and velocity of each one of them. All we need to know is a *probability distribution* describing the likelihood that the particles might be behaving in various ways.

In statistical mechanics, in other words, we think that there actually is some particular classical state of all the particles, but we don't know it, all we have is a distribution of probabilities. Happily, such a distribution is all we need to do a great deal of useful physics, since it fixes properties such as the temperature and pressure of the system. But the distribution isn't a complete description of the system; it's simply a reflection of what we know (or don't) about it. To tag this distinction with philosophical buzzwords, in statistical mechanics the probability distribution is an *epistemic* notion—describing the state of our knowledge—rather than an *ontological* one—describing some objective feature of reality. Epistemology is the study of knowledge; ontology is the study of what is real.

It was natural, in 1927, to suspect that quantum mechanics should be thought of along similar lines. After all, by that time we had figured out that what we use wave functions for is to calculate the probability of any particular measurement outcome. Surely it makes sense to imagine that nature itself knows precisely what the outcome is going to be, but the formalism of quantum theory simply doesn't completely capture that knowledge, and thus needs to be improved. The wave function, in this view, isn't the whole story; there are additional "hidden variables" that fix what the actual measurement outcomes are going to be, even if we don't know (and perhaps can't ever determine ahead of the measurement) what their values are.

Maybe. But in subsequent years a number of results have been obtained, most notably by the physicist John Bell in the 1960s, implying that the most simple and straightforward attempts along these lines are doomed to failure. People tried—de Broglie actually put forward a specific theory, which was rediscovered and extended by David Bohm in the 1950s, and Einstein and Schrödinger both batted around ideas. But Bell's theorem implies that any such theory requires "action at a distance"—a measurement at one location can instantly affect the state of the universe arbitrarily far away. This seems to be in violation of the spirit if not the letter of the theory of relativity, which says that objects and influences cannot propagate faster than the speed of light. The hidden-variable approach is still being actively pursued, but all known attempts along these lines are ungainly and hard to reconcile with modern theories such as the Standard Model of particle physics, not to mention speculative ideas about quantum gravity, as we'll discuss later. Perhaps this is why Einstein, the pioneer of relativity, never found a satisfactory theory of his own.

In the popular imagination, Einstein lost the Bohr-Einstein debates. We are told that Einstein, a creative revolutionary in his youth, had grown old and conservative, and was unable to accept or even understand the dramatic implications of the new quantum theory. (At the time of the Solvay Conference Einstein was forty-eight years old.) Physics subsequently went on without him, as the great man retreated to pursue idiosyncratic attempts at finding a unified field theory.

Nothing could be further from the truth. While Einstein failed to put forward a complete and compelling generalization of quantum mechanics, his insistence that physics needs to do better than shut up and calculate was directly on point. It is wildly off base to think that he failed to understand quantum theory. Einstein understood it as well as anyone, and continued to make fundamental contributions to the subject, including demonstrating the importance of quantum entanglement, which plays a central role in our current best picture of how the universe really works. What he failed to do was to convince his fellow physicists of the inadequacy of the Copenhagen approach, and the importance of trying harder to understand the foundations of quantum theory.

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If we want to follow Einstein's ambition of a complete, unambiguous, realistic theory of the natural world, but we are discouraged by the conversation, even among grizzled veterans of quantum physics, people are always talking about concepts like "the position of the electron." But this wave-function-is-everything view implies that such talk is wrong-headed in an important way. There is no such thing as "the position of the electron." There is only the electron's wave function. Quantum mechanics implies a profound distinction between "what we can observe" and "what there really is." Our observations aren't revealing pre-existing facts of which we were previously ignorant; at best, they reveal a tiny slice of a much bigger, fundamentally elusive reality.

Consider an idea you will often hear: "Atoms are mostly empty space." Utterly wrong, according to the AQM way of thinking. It comes from a stubborn insistence on thinking of an electron as a tiny classical dot zipping around inside of the wave function, rather than the electron actually *being* the wave function. In AQM, there's nothing zipping around; there is only the quantum state. Atoms aren't mostly empty space; they are described by wave functions that stretch throughout the extent of the atom.

The way to break out of our classical intuition is to truly abandon the idea that the electron has some particular location. An electron is in a *superposition* of every possible position we could see it in, and it doesn't snap into any one specific location until we actually observe it to be there. "Superposition" is the word physicists use to emphasize that the electron exists in a combination of all positions, with a particular amplitude for each one. Quantum reality is a wave function; classical positions and velocities are merely what we are able to observe when we probe that wave function.

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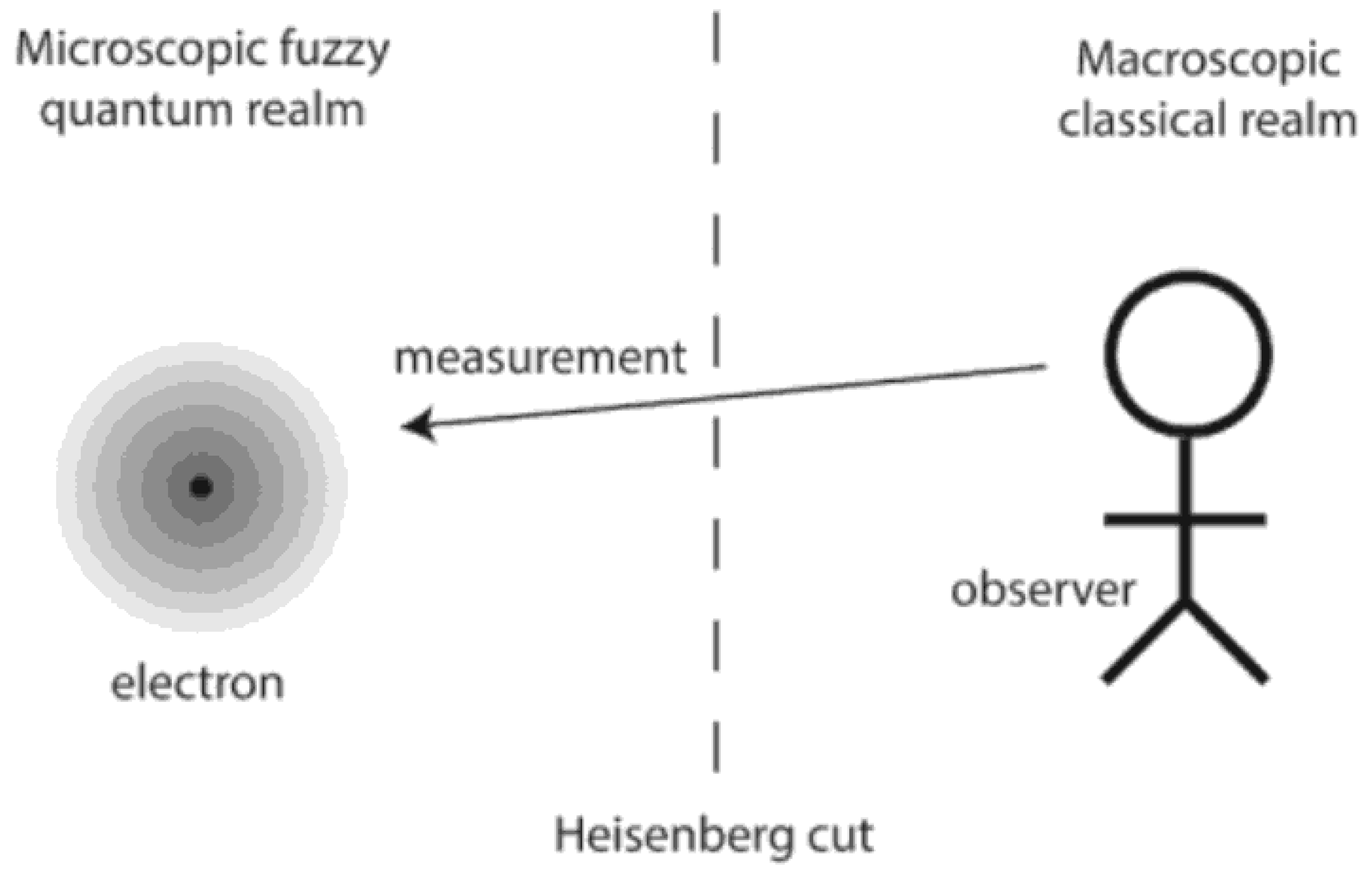
So the reality of a quantum system, according to austere quantum mechanics, is described by a wave function or quantum state, which can be thought of as a superposition of every possible outcome of some observation we might want to make. How do we get from there to the annoying reality that wave functions appear to collapse when we make such measurements?

Start by examining the statement "we measure the position of the electron" a little more carefully. What does this measurement process actually involve? Presumably some lab equipment and a bit of experimental dexterity, but we don't need to worry about specifics. All we need to know is that there is some measuring apparatus (a camera or whatever) that somehow interacts with the electron, and then lets us read off where the electron was seen.

In the textbook quantum recipe, that's as much insight as we would ever get. Some of the people who pioneered this approach, including Niels Bohr and Werner Heisenberg, would go a little bit further, making explicit the idea that the measuring apparatus should be thought of as a classical object, even if the electron it was observing was quantum-mechanical. This line of division between the parts of the world that should be treated using quantum versus classical descriptions is sometimes called the *Heisenberg cut*. Rather than accepting that quantum mechanics is fundamental and classical mechanics is just a good approximation to it in appropriate circumstances, textbook quantum mechanics puts the classical world at center stage, as the right way to talk



about people and cameras and other macroscopic things that interact with microscopic quantum systems.

This doesn't smell right. One's first guess should be that the quantum/classical divide is a matter of our personal convenience, not a fundamental aspect of nature. If atoms obey the rules of quantum mechanics and cameras are made of atoms, presumably cameras obey the rules of quantum mechanics too. For that matter, you and I presumably obey the rules of quantum mechanics. The fact that we are big, lumbering, macroscopic objects might make classical physics a good approximation to what we are, but our first guess should be that it's really quantum from top to bottom.

If that's true, it's not just the electron that has a wave function. The camera should have a wave function of its own. So should the experimenter. Everything is quantum.

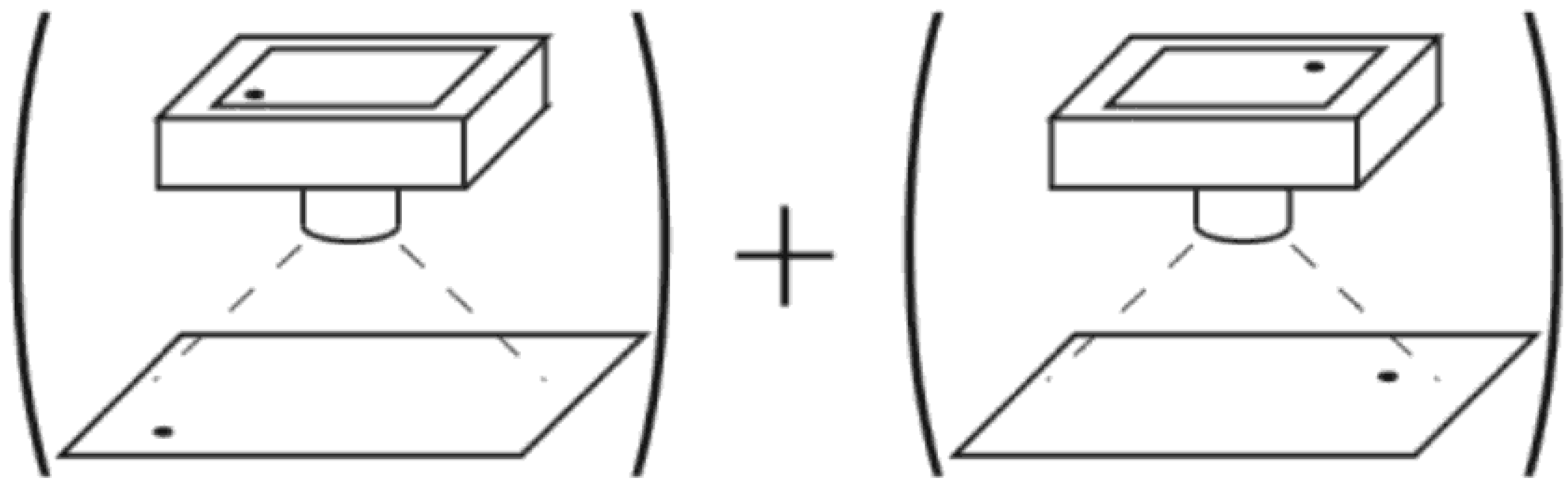
That simple shift of perspective suggests a new angle on the measurement problem. The AQM attitude is that we shouldn't treat the measurement process as anything mystical or even in need of its own set of rules; the camera and the electron simply interact with each other according to the laws of physics, just like a rock and the earth do.

A quantum state describes systems as superpositions of different measurement outcomes. The electron will, in general, start out in a superposition of various locations—all the places we could see it were we to look. The camera starts out in some wave function that might look complicated, but amounts to saying "This is a camera, and it hasn't yet looked at the electron." But then it does look at the electron, which is a physical interaction governed by the Schrödinger equation. And after that interaction, we might expect that the camera itself is now in a superposition of all the possible measurement outcomes it might have observed: the camera saw the electron in *this* location, or the camera saw the electron in *that* location, and so on.

If that were the whole story, AQM would be an untenable mess. Electrons in superpositions, cameras in superpositions, nothing much resembling the robust approximately classical world of our experience.

Fortunately we can appeal to another startling feature of quantum mechanics: given two different objects (like an electron and a camera), they are not described by separate, individual wave functions. There is *only one wave function*, which describes the entire system we care about, all the way up to the "wave function of the universe" if we're talking about the whole shebang. In the case under consideration, there is a wave function describing the combined electron+camera system. So what we really have is a superposition of all possible combinations of where the electron might have been located, and where the camera actually observed it to be.

Although such a superposition in principle includes every possibility, most of the possible outcomes are assigned zero weight in the quantum state. The cloud of probability vanishes into nothingness for most possible combinations of electron location and camera image. In particular, there is no probability that the electron was in one location but the camera saw it somewhere else (as long as you have a relatively functional camera).



This is the quantum phenomenon known as *entanglement*. There is a single wave function for the combined electron+camera system, consisting of a superposition of various possibilities of the form "the electron was at this location, and the camera observed it at the same location." Rather than the electron and the camera doing their own thing, there is a connection between the two systems.

Now let's take every appearance of "camera" in the above discussion and replace it with "you." Rather than taking a picture with a mechanical apparatus, we (fancifully) imagine that you have really good eyesight and can see where electrons are just by looking at them. Otherwise, nothing changes. According to the Schrödinger equation, an initially unentangled situation—the electron is in a superposition of various possible locations, and you haven't looked at the electron yet—evolves smoothly into an entangled one—a superposition of each location the electron could have been observed, and you having seen the electron in just that location.

That's what the rules of quantum mechanics would say, if we hadn't tacked on all of those extra annoying bits about the measurement process. Maybe all of those extra rules were just a waste of time. In AQM, the story we just told, about you and the electron entangling and evolving into a superposition, is the complete story. There isn't anything special about measurement; it's just something that happens when two systems interact in an appropriate way. And afterward, *you and the system you interacted with are in a superposition*, in each part of which you have seen the electron in a slightly different location.

The problem is, this story still doesn't match onto what you actually experience when you observe a quantum system. You never feel like you have evolved into a superposition of different possible measurement outcomes; you simply think you've seen some specific outcome, which can be predicted with a definite probability. That's why all of those extra measurement rules were added in the first place. Otherwise you seemingly have a very pretty and elegant formalism (quantum states, smooth evolution) that just doesn't match up to reality.

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Time to get a little philosophical. What exactly do we mean by "you" in the above paragraph? Constructing a scientific theory isn't simply a suffice to provide a complete, empirically adequate account of the world. ("Empirically adequate" is a fancy way that philosophers like to say "it fits the data.") Any other approach to quantum mechanics consists of adding something to that bare-bones formalism, or somehow modifying what is there.

The most immediately startling implication of pure Everettian quantum mechanics is the existence of many worlds, so it makes sense to call it Many-Worlds. But the essence of the theory is that reality is described by a smoothly evolving wave function and nothing else. There are extra challenges associated with this philosophy, especially when it comes to matching the extraordinary simplicity of the formalism to the rich diversity of the world we observe. But there are corresponding advantages of clarity and insight. As we'll see when we ultimately turn to quantum field theory and quantum gravity, taking wave functions as primary in their own right, free of any baggage inherited from our classical experience, is extraordinarily helpful when tackling the deep problems of modern physics.

Given the necessity of these two ingredients (wave functions and the Schrödinger equation), there are a few alternatives to Many-Worlds we might also consider. One is to imagine adding new physical entities over and above the wave function. This approach leads to hidden-variable models, which were in the back of the minds of people like Einstein from the start. These days the most popular such approach is called the *de Broglie–Bohm theory*, or simply *Bohmian mechanics*. Alternatively, we could leave the wave function by itself but imagine changing the Schrödinger equation, for example, to introduce real, random collapses. Finally, we might imagine that the wave function isn't a physical thing at all, but simply a way of characterizing what we know about reality. Such approaches are broadly known as epistemic models, and a currently popular version is *QBism*, or *quantum Bayesianism*.

All of these options—and there are many more not listed here—represent truly distinct physical theories, not simply "interpretations" of the same underlying idea. The existence of multiple incompatible theories that all lead (at least thus far) to the observable predictions of quantum mechanics creates a conundrum for anyone who wants to talk about what quantum theory really means. While the quantum recipe is agreed upon by working scientists and philosophers, the underlying reality—what any particular phenomenon actually *means*—is not.

I am defending one particular view of that reality, the Many-Worlds version of quantum mechanics, and for most of this book I will simply be explaining things in Many-Worlds terms. This shouldn't be taken to imply that the Everettian view is unquestionably right. I hope to explain what the theory says, and why it's reasonable to assign a high credence to it being the best view of reality we have; what you personally end up believing is up to you.

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Why Would Anybody Think This?

How Quantum Mechanics Came to Be

"Sometimes I've believed as many as six impossible things before breakfast," notes the White Queen to Alice in *Through the Looking Glass*. That can seem like a useful skill as one comes to grips with quantum mechanics in general, and Many-Worlds in particular. Fortunately, the impossible-seeming things we're asked to believe aren't whimsical inventions or logic-busting Zen koans; they are features of the world that we are nudged toward accepting because actual experiments have dragged us, kicking and screaming, in that direction. We don't choose quantum mechanics; we only choose to face up to it.

Physics aspires to figure out what kinds of stuff the world is made of, how that stuff naturally changes over time, and how various bits of stuff interact with one another. In my own environment, I can immediately see many different kinds of stuff: papers and books and a desk and a computer and a cup of coffee and a wastebasket and two cats (one of whom is extremely interested in what's inside the wastebasket), not to mention less solid things like air and light and sound.

By the end of the nineteenth century, scientists had managed to