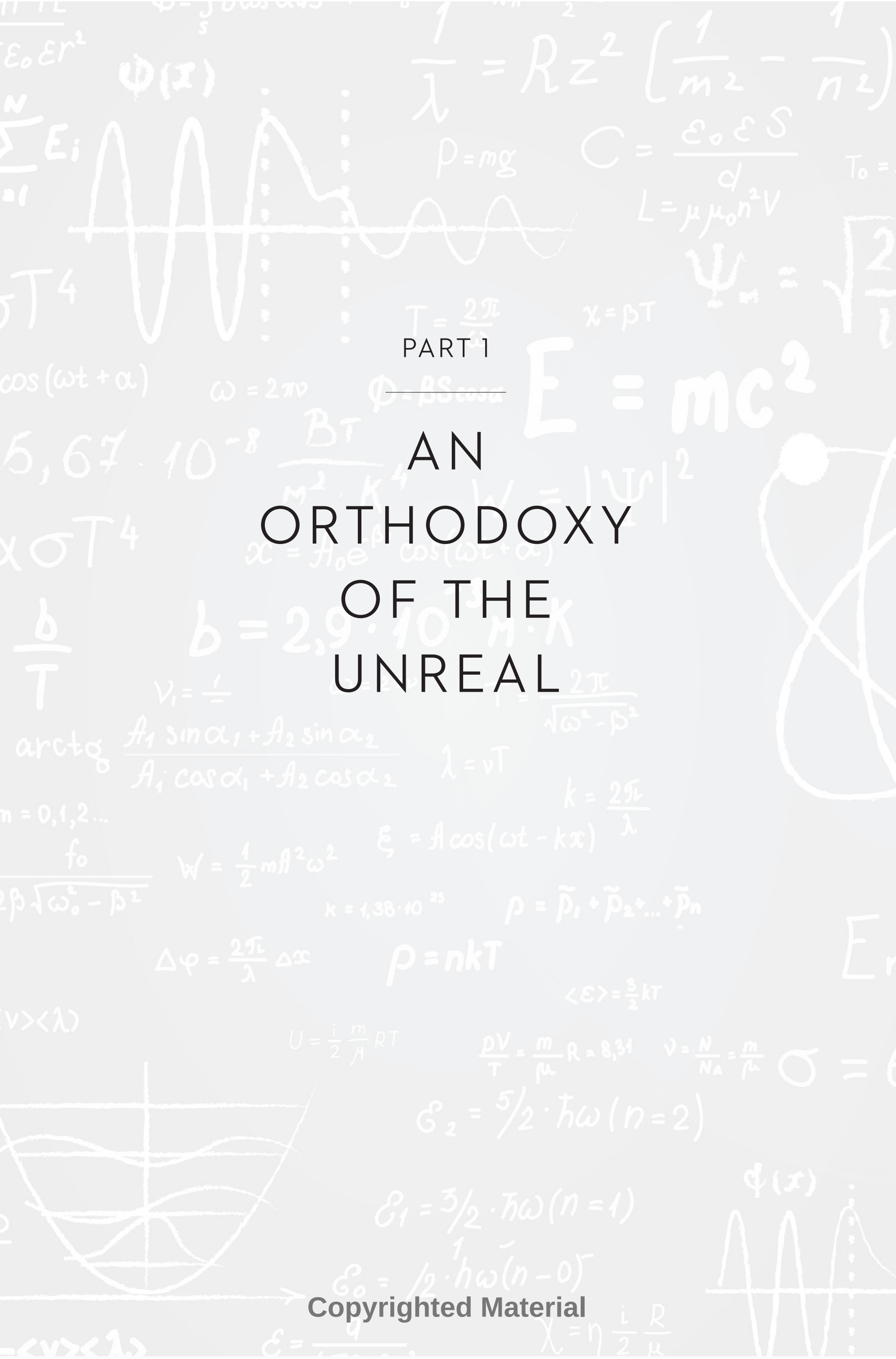
Einstein's Unfinished Revolution

The Search for What Lies Beyond the Quantum

Lee Smolin

'A masterful exposition on the state of quantum physics ... spellbinding'
Financial Times



PART 1

AN ORTHODOXY OF THE UNREAL

ONE

Nature Loves to Hide

Reality is the business of physics.

—ALBERT EINSTEIN

Quantum mechanics has been the core of our understanding of nature for nine decades. It is ubiquitous, but it is also deeply mysterious. Little of modern science would make sense without it. But experts have a hard time agreeing what it asserts about nature.

Quantum mechanics explains why there are atoms, and why those atoms are stable and have distinct chemical properties. Quantum mechanics also explains how atoms combine into diverse molecules. As a result, it is the basis for how we understand the shapes and interactions of those molecules. Life would be incomprehensible without the quantum. From the behavior of water to the shapes of proteins to the fidelity and transmittal of information by DNA and RNA, everything in biology depends on the quantum.

Quantum mechanics explains the properties of materials, such as what makes a metal a conductor of electricity, while another is an insulator. It explains light and radioactivity, and is the basis of nuclear physics. Without it we wouldn't understand how the stars shine. Nor could we have invented the chips or the lasers on which so much of our technology is based. Quantum mechanics is the language that we use to write the standard model of particle physics, which contains all we know about the elementary particles and the fundamental forces by which they interact.

According to our best theory of the early universe, all matter, along with the patterns that eventually coalesced into the galaxies, was yanked into existence from the quantum randomness of the vacuum of empty space by the rapid expansion of the universe. I don't expect the reader to understand precisely what this means, but perhaps the words evoke an image. In any case, if this is right, then without quantum physics there would literally be nothing except empty spacetime.

Yet for all its success, there is a stubborn puzzle at the heart of quantum mechanics. The quantum world behaves in ways that challenge our intuition. It is often said that in quantum physics an atom can be in two places at once, but that is only the start; the full story is far weirder than that. If an atom can be here or there, we must speak of states in which it is, somehow, simultaneously both here and there. This is called a *superposition*.

If you are new to the quantum world, you are undoubtedly wondering what it means for an atom to be somehow both here and there. Don't be discouraged if you find this confusing. You are absolutely right to wonder what it means. This is one of the central mysteries of quantum mechanics. It is enough, for now, if you just accept this as a mystery, to which we attach the term "superposition." Later we will be able to demystify it.

Here is a first step. When we say that a quantum particle is in a "superposition of being here and there," this is related to the wavelike nature of matter, for a wave is a disturbance that is spread out, and so it can be both here and there.

We speak of elementary particles, but everything quantum, including atoms and molecules, is both a particle and a wave. Here is a taste of what that means. If we do an experiment that asks where an atom is, the result will be that it is somewhere definite. But between measurements, when we are not looking for it, it turns out to be impossible to project where it might be. It is as if the likelihood or propensity of finding the particle spreads as a wave when we are not looking. But as soon as we look again, it is always somewhere.

Imagine playing a game of hide-and-seek with an atom. We open our eyes, or turn on a detector, and we see it somewhere. But when we close our eyes it dissolves into a wave of potentiality. Open our eyes again and it is always somewhere.

Another feature unique to the quantum world is called *entanglement*. If two particles interact, and then move apart, they remain intertwined in the sense that they seem to share properties which cannot be broken down to properties each enjoys individually.

We can stretch our imagination to apply these new concepts to atoms and molecules which are too small to see directly. We must study them indirectly, and to do that we employ large and complex measurement devices.

Those measurement devices are part of the everyday, familiar world of large objects. One thing we can be sure of is that big everyday things display none of the bizarre behavior quantum mechanics describes. A chair is here or it is there, never in a combination of such states. When we wake up in the middle of the night in a strange hotel room, we may be unsure where the chair is, but we can be sure it is somewhere. And after we collide with it in the dark, our future does not become entangled with its future.

In the world as we experience it, cats are either alive or dead, even if they are locked in a box. When we open the box, the cat does not suddenly resolve from a combination of dead and alive to dead. If we find it dead it will likely have been so for some time, as we will instantly smell.

Ordinary objects appear to share none of the quantum weirdnesses of the atoms of which they are made. This seems obvious, but it raises a mystery. Quantum mechanics is the core theory of nature. As such it must be universal. If it applies to an atom it must apply to two atoms, or ten or ninety. And we have excellent experimental evidence that it does. Delicate experiments, in which large molecules are put in quantum superpositions, show us that they are just as quantum weird as electrons. For one thing, they diffract and interfere as waves.

But then quantum mechanics must apply to the vast collections of atoms that make up you or me or our cat or the chair on which she is perched. But it doesn't seem to. Nor does quantum mechanics appear to apply to any of the instruments and machines we employ to image the atoms and reveal their quantum weirdnesses.

How can this be?

In particular, when we measure a property of an atom, we employ big devices. The atoms may be in superpositions of states and so be several places at once, but the measuring instrument always indicates just one out of the possible answers to the questions we pose. Why is that? Why does quantum mechanics not apply to the very devices we use to measure quantum systems?

This is called the *measurement problem*. It has been controversial and unresolved since the 1920s. The fact that, after all this time, we have found no agreement among experts means there is something basic about nature we have yet to understand.

So there is somewhere a transition between the quantum world, in which an atom can be several places at once, and the ordinary world, in which everything is always somewhere. If a molecule made from ten or ninety atoms can be described by quantum mechanics, but a cat cannot, then somewhere between the two there is a line delineating where the quantum world stops. An answer to the measurement problem would tell us where that line is and explain the transition.

There are people who are sure they know the answer to the measurement problem. We will meet some of them and their ideas later on. We will want to look out for what price we have to pay to expunge this quantum insanity from our understanding of the world.

BROADLY SPEAKING, the people who aim to address the mysteries of quantum mechanics fall into two classes.

The first group assumes that the theory as it was formulated in the 1920s is essentially correct. They believe the problem is not with quantum theory; it is instead with how we understand it or speak about it. This strategy to mitigate the strangeness of quantum mechanics goes back to some of the founders, beginning with Niels Bohr.

Niels Bohr was a Danish physicist who, while still in his twenties, was the first to apply quantum theory to atoms. As he grew older he became the de facto leader of the quantum revolution, partly due to the attractiveness of his ideas and partly because he educated and mentored many of the young quantum revolutionaries.

The second group has concluded that the theory is incomplete. It can't be made sense of because it is not the whole story. They seek a completion of the theory that will tell us the rest of the story and, by doing so, resolve the mysteries of quantum mechanics. This strategy goes back to Albert Einstein.

More than anyone else, Einstein was responsible for initiating the quantum revolution. He was the first to articulate the dual nature of light as a particle and a wave. He is by now better known for his theory of relativity, but his Nobel Prize was for his work on quantum theory, and he himself admitted that he spent much more time on quantum theory than on relativity. Yet, even if he initiated the quantum revolution, Einstein did not become one of its leaders, because his realism required that he reject the theory as it was developed in the late 1920s.

In the language introduced in the preface, those in the first group are mostly anti-realists or magical realists. Realists find themselves in the second group.

Those who argue for the incompleteness of quantum mechanics point to the fact that in most cases it can only make statistical predictions for the results of experiments. Rather than saying what will happen, it gives probabilities for what might happen. In a letter to his friend Max Born in 1926, Einstein wrote:

> Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing. The theory says a lot, but does not really bring us any closer to the secret of the 'old one'. I, at any rate, am convinced that *He* is not playing at dice.[1]

Einstein was also friends with Niels Bohr, and their divergent responses to quantum mechanics fueled a passionate debate between them that lasted more than forty years, till Einstein's death. It continues between their intellectual descendants to this day. Einstein was the first person to clearly articulate the need for a revolutionary new theory of atoms and radiation, but he was unable to accept that quantum mechanics was that theory. His first response to quantum mechanics was to argue that it was inconsistent. When that failed, he argued instead that quantum mechanics gives an incomplete description of nature, which leaves out an essential part of the picture.

I believe that Einstein was unable to accept quantum mechanics as a definitive theory because he had exceedingly high aspirations for science. He was driven by the hope of transcending subjective opinion and discovering a true mirror of nature that exhibits the essence of reality in a few timeless mathematical laws. For him, science aimed to capture the true essence of the world, and that essence is independent of us and can have nothing to do with what we believe or know about it.

Einstein, of all people, must have felt he had the right to demand this because he had achieved it in his discoveries of special and general relativity. Having laid the groundwork for quantum physics, he sought to capture the essence of the atomic world in a complete description of atoms, electrons, and light.

Bohr replied that atomic physics required a revolutionary revision in how we understand what science is, as well as in our conception of the relationship between reality and our knowledge of it. This stemmed from the fact that we are a part of the world, so we must interact with the atoms we seek to describe.

Bohr asserted that once we absorbed this revolutionary change in our thinking, the completeness of quantum mechanics would be unavoidable, because it was built into our being participants in the world we seek to describe. From Bohr's perspective, quantum theory is complete in the sense that there is no more-complete description of the world to be had.

If we refuse these philosophical revolutions and insist on maintaining an old-fashioned, commonsense view of reality and its relation to our observations and knowledge, we have to pay a different kind of price. We have to contemplate that we are wrong about some aspect of nature. We have to find out which common assumption is wrong and replace it with a radically new physical hypothesis that opens the way to a new theory that will complete quantum mechanics.

Thanks to a combination of theory and experiment, starting with a paper by Einstein and two collaborators in 1935, we know one aspect of this completion. The new theory must violate the commonplace assumption that things interact only with other things that are near them in space.

This assumption is called locality. A big part of the story I will be telling in later chapters is how this commonsense idea must be transcended in the theory which will replace quantum mechanics.

THIS BOOK HAS THREE PURPOSES. First, I want to explain to laypeople just what the puzzles at the heart of quantum mechanics are. After more than a century of studying quantum physics, it is remarkable that there continues to this day to be no agreement on the solution of these puzzles.

But having explained the reasons for the debate in a way that is fair to both sides, I will not stay impartial. In the great debate about whether quantum mechanics is the last word or not, I side with Einstein. I believe that there is a layer of reality deeper than that described by Bohr, which can be understood without compromising old-fashioned notions of reality and our ability to comprehend and describe it.

Thus, my second purpose is to advocate a point of view about the puzzles of quantum mechanics. This is that the problems can be resolved only by progress in science which will uncover a world beyond quantum mechanics. Where quantum mechanics is mysterious and confusing, this deeper theory will be entirely comprehensible.

I can make this claim because we have known since the invention of quantum mechanics how to present the theory in a way that dissolves the mysteries and resolves the puzzles. In this approach, there is no challenge to our usual beliefs in an objective reality, a reality unaffected by what we know or do about it, and about which it is possible to have complete knowledge. In this reality, there is just one universe, and when we observe something about it, it is because it is true. This can justly be called a realist approach to the quantum world.

An anti-realist approach ascribes the mysteries of quantum mechanics to subtleties having to do with how we gain knowledge about nature. Such approaches have radical proposals to make about *epistemology,* which is the branch of philosophy concerned with how we know things. Realist approaches assume we are able to arrive sooner or later at a true representation of the world and so are deliberately naive about epistemology. Instead, realists are interested in *ontology,* which is the study of what exists. By contrast, anti-realists believe we cannot know what really exists, apart from our representation of the knowledge we have of the world, which is gained only through interacting with it.

So I will endeavor to reassure readers that quantum mechanics can be understood completely within a realist perspective in which the external world can be completely comprehended as independent from us. There is no mysterious effect of the observer on the observed. Reality is out there, recalcitrant to our will and the choices we make. That reality is fully comprehensible. And that reality consists of a single world.

The existence of these realist approaches to quantum mechanics does not by itself mean that the philosophically more extravagant proposals are wrong. But it does mean that there is no strong scientific reason to believe in them, because realism is always to be preferred in science, when it can be achieved.

Why, then, is so much of the talk about quantum theory inspired by the weirder ideas in which reality depends on our knowledge of it or there are multiple realities? This is a problem for historians of ideas. One such historian, Paul Forman, has tied the dominance of Bohr and Heisenberg's anti-realist philosophy within the scientific community in the 1920s and 1930s to the embrace of chaos and irrationality advocated by Spengler and others in the wake of the First World War.

That history is fascinating, but it is for scholars to do justice to it. I am not a scholar, I am a scientist, and this brings me to my third purpose in writing this book.

I have been on Einstein's side in the search for a deeper but simpler reality behind quantum mechanics since first reading him on the subject as a high school dropout. My journey in physics began with reading Einstein's autobiographical notes, where, in the last few years of his life, in the 1950s, he reflected on the two main tasks he felt were left incomplete in physics. These were to make sense of quantum physics and, after that, to unify the new understanding of the quantum with gravity, by which he meant his general theory of relativity. I recall thinking that maybe I could try to help. I was unlikely to succeed, but perhaps here was something worth striving for.

After, as it were, getting my mission from reading Einstein's autobiographical notes, I found that book by de Broglie, talked my way into a good college, found great teachers, and got lucky several times in my applications for graduate school and beyond. I'm having a wonderful life, and as a scientist on the frontier, I've had many chances to take a shot on goal, aimed at solving Einstein's two big questions.

I haven't succeeded, at least so far. Very unfortunately, neither has anyone else. At the same time, over the past several decades there has at least been progress toward understanding the problem. That is not nearly as good as it would be to solve the problem, but neither is it nothing. We know much better than Einstein did the obstacles that a theory that transcends the limits of quantum mechanics must overcome. And because of that, some very interesting proposals and hypotheses have been put forward, which may frame the deeper theory for which we search.*

I have been thinking about the question of how to go beyond quantum mechanics since the mid-1970s, and I've never been more excited and optimistic about the prospects for success. So this is my third reason for writing this book, which is to bring to a wider audience a report from the front in our search for the world beyond the quantum.

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* A note to my expert readers: Quantum foundations is presently a very lively subject, with many exciting developments both experimental and theoretical. Many proposals compete to resolve the puzzles we will meet here. I should warn the reader that our path through these frontiers will be a narrow one, and there are many exciting ideas and results that I do not mention here. Had I tried to review the whole field, or include all the latest supremely clever advances, the result would have been a less accessible book. My first aim is to introduce the world of quantum phenomena, not the full spectrum of competing interpretations of those phenomena. I apologize in advance to those experts who don't find their preferred version of quantum physics here, and encourage them to write their own books. I also apologize to the historians. I am not a scholar, and the stories I tell are creation myths, handed down from teacher to student, originating, in some cases, with the founders themselves.

TWO

Quanta

If we break quantum mechanics down to its most essential principle, it is this:

> ***We can only know half of what we would need to know if we wanted to completely control, or precisely predict, the future.***

This disrupts the basic ambition of physics, which is to be able to predict the future. It was hoped that this power would follow if only we could give the physical world a complete description. By describing fully the motion of every particle and the action of every force, we would be able to work out exactly what would happen in the future. Before quantum mechanics was formulated in the 1920s, we physicists were confident that if we could learn the laws that govern the fundamental particles, we would be able to predict and explain everything that happened in the world.

The hypothesis that the future is completely determined by the laws of physics acting on the present configuration of the world is called determinism. This is an extraordinarily powerful idea, whose influence can be seen in diverse fields. If you appreciate the extent to which determinism dominated thought in the nineteenth century, you can begin to understand the revolutionary impact of quantum mechanics across all fields, because quantum mechanics precludes determinism.

To emphasize this point, I like to quote from Tom Stoppard's play *Arcadia*, in which his precocious heroine, Thomasina, explains to her tutor:

> If you could stop every atom in its position and direction, and if your mind could comprehend all the actions thus suspended, then if you were really, *really* good at algebra you could write the formula for all the future; and although nobody can be so clever as to do it, the formula must exist just as if one could.[1]

A complete description of nature, at a given time, is called a *state*. For example, if we think of the world as composed of particles whizzing around, the state tells us where each of them is, and how fast and in what direction each is moving, at that moment.

The power of physics comes from its laws, which dictate how nature changes in time. They do this by transforming the state of the world as it is now to the state at any future time. A law of physics functions in some ways like a computer program: it reads in input and puts out output. The input is the state at a given time; the output is the state at some future time.*

Along with the computation comes an explanation of how the

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* The metaphor of the universe as a computer is helpful for illustrating determinism, but is on the whole misleading, as I will argue below.

world changes in time. The law acting on the present state *causes* the future states. A successful prediction of the future state is taken as a validation of that explanation. The prediction is deterministic, in that a precise input leads to a precise output. This confirms a belief that the information that went into describing the state is in fact a complete description of the world at one moment of time.

This concept of a law is basic to a realist conception of nature and, as such, transcends any one theory. Newtonian mechanics and Einstein's two theories of relativity all work the same way. One applies the law to the state at an initial time, and it transforms that state to the state at some future time. This schema for explaining nature was invented by Newton, so we call it the Newtonian paradigm.

It is also worth mentioning that in almost all cases so far known, the laws are reversible. One can input the state at some future time and run the law backward to output the state at an earlier time. (The issue of the reversibility of time and of the fundamental laws is a central concern of chapters 14 and 15.)

It is often the case that the information needed to completely describe the state of a physical system comes in pairs. Position and momentum.* Volume and pressure. Electric field and magnetic field. We need both to predict the future. Quantum mechanics says we can know only one.

This means we can't precisely predict the future. That is just the first of the blows to our comfortable intuitions that we will have to absorb from quantum theory.

Which member of each pair is the one that can be known? Quantum mechanics says you choose! This is the basis of its challenge to realism.

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* Momentum will be defined shortly, but roughly, a body's momentum is proportional to both its speed and mass.

There is more to say about the impossibility of predicting the future. To get there, let's take advantage of the great generality quantum mechanics claims, and speak a bit abstractly. We want to describe some physical system in terms of a pair of variables—we will call them A and B. Quantum physics asserts a two-part principle.

1. If we knew both A and B at a given time, we could precisely predict the future of the system.
2. We can choose to measure A or we can choose to measure B; and in each case we will succeed. But we can't do better. We cannot choose to simultaneously measure both A and B.

As I have stated it, this is a prohibition of what we can measure; but, if we prefer, we can express it as a prohibition of what we can know about the system.

But wait, why can't you measure A and then, at a later time, measure B? You can. But your measurement of B will render irrelevant (for the purpose of predicting the future) your past knowledge of A. One way this can happen is that after the measurement of B, the value of A is randomized. We cannot measure B without disrupting the value of A, and vice versa. Thus, if we measure A, then B, then A again, the value of A we get the second time will be random, and hence unrelated to the value we got the first time we measured A.

1. and 2. together are called the *principle of non-commutativity.* Two actions are said to *commute* if it doesn't matter in what order we do them. If the action that is done first matters, we say they are non-commutative. It doesn't matter (except to a few fanatics) in what order you put milk and sugar into coffee; they commute.

Getting dressed involves non-commutative operations; the order in which you put on your underwear and pants matters. But it doesn't matter which sock you put on first, or whether you put your socks on first, partway through the process, or last. So putting on socks commutes with everything except putting on shoes. (The mathematically minded will understand this as an application of algebra to topology.)

What if we allow there to be some specified amount of uncertainty in the measurement of A? Then we can measure B, but only up to some accuracy. These uncertainties are reciprocal—the better we know A, the worse we can know B, and vice versa.

For example, let's suppose that A is the position of a particle. Then B is its momentum. Suppose we do a measurement that tells its location to within a meter. Then we can measure the momentum to a corresponding uncertainty. If we increase the uncertainty in A, then we can make the measurement of B more precise and vice versa. This gives us a principle called, not surprisingly, the *uncertainty principle*.*

(Uncertainty in A) × (Uncertainty in B) > a constant

Applied to position and momentum, it reads

(Uncertainty in position) × (Uncertainty
in momentum) > a constant

Physics is like a college campus where every building is named after someone. The constant is named after Max Planck, and the uncertainty principle is named after Werner Heisenberg.

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* > means "is larger than."

The uncertainty principle is quite powerful, as is shown by this important consequence. Let's go back to the scenario in which you measure A, then you measure B, then you measure A again. As I said above, once you know the result of measuring B, the second measurement of A is randomized; it is no longer equal to the original value of A. But suppose that, just before you remeasure A, you do something to forget what the value of B was. Then the system remembers—yes, that word is the one we use to describe this situation—the original value of A.

This is called *interference*. It is allowed by the uncertainty principle because once you forget the measurement of B, B's uncertainty is very large, so A's uncertainty can be small.

But how can we undo a measurement? Let me give a fanciful example. There are many simple cases in which A and B each have two possible values. Let the systems we study be people, and let A be political identity, which we will simplify to be a binary choice: either left-wing or right. I will let B be pet preference, cat lovers versus dog lovers. We now play a game in which a person can't have both a definite pet preference and a political identity. We go to a party where everyone has left-wing views and ask each whether they are a cat person or a dog person. We put the cat lovers in the living room and the dog lovers in the kitchen. If we go into either room and inquire about their political views, then half will now be right-wingers. That is what must happen if political identity and pet preference don't commute.

But let's afterward call everyone together into the dining room. We let them mingle for a while, then we go in and pick a random person. They could have come from either the living room or the kitchen, we don't know which, so we've lost track of their pet preference. Then, when we ask them about politics, we find they are all left-wingers again.

These principles are entirely general. A and B are often the answers to yes/no questions. But in the original case, A was the position of an elementary particle, say an electron, and B was the momentum of the particle.

Momentum is one of those words that functions as a barrier to comprehension, so let's take a moment to define it.

In physics we often have to refer to the speed and the direction of motion of a particle. We combine these into one quantity which we call the *velocity*. You can think of a particle's velocity as an arrow that points in the direction of its motion. The faster the speed, the longer the arrow.

To survive a collision you want to experience as little force as possible. The force a truck will impart on a car is proportional to the truck's change of speed. But it's also proportional to the mass of the truck. You'd rather collide with a Ping-Pong ball than a truck, even if they are traveling toward you at the same speed. To express this, physicists define momentum as the product of the mass times the velocity. This is also an arrow pointing in the direction of motion, only now the length is proportional to both the speed and the mass.

Momentum is a central concept in physics because it is conserved. That means that in any processes at all, we can add up the momenta of the various particles involved at the beginning, and, no matter what happens, the resulting total momentum won't change in time. Before, during, and after a collision, the total momentum will be the same. What happens in a collision is that momentum is exchanged from one body to another. This change of momentum is experienced as a force.

Energy is another conserved quantity. The total energy of a system of particles never changes in time. When particles interact, one may gain energy while the rest lose energy. But the total energy remains the same; none is created or destroyed.

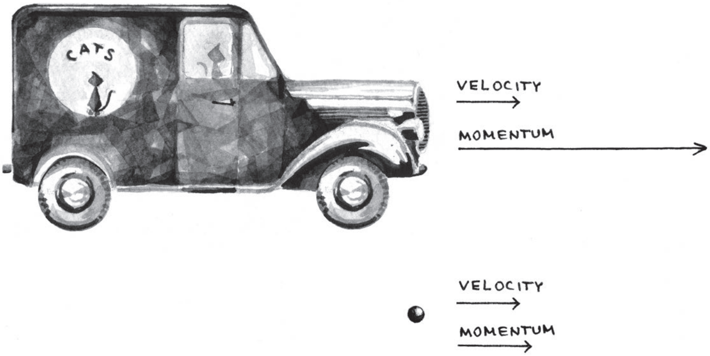

FIGURE 1. A truck carries much more momentum than a Ping-Pong ball going the same velocity, because its mass is so much greater, and the momentum is the product of the mass and the velocity.

Energy and momentum are related. We won't need the exact relation, but we need to know that a particle that is moving freely, and has an exact value of momentum, also has an exact energy.

The uncertainty principle then says that we can't know both the position and momentum of a body at the same time. This means we can't make a precise prediction of its future, because to do so we would need to know both where something is and how fast and in what direction it is moving, with complete accuracy.

If we want to develop an intuition about how quantum particles behave, we will need to be able to visualize a particle with a definite position, but, because of the uncertainty principle, no definite momentum or velocity. This is not hard: visualize the particle being somewhere momentarily. In the next moment it will also be somewhere definite, just somewhere else. Because its momentum is indefinite, it jumps around randomly.

But how do we visualize a particle with a definite momentum, but a completely indefinite position? This seems more challenging. If you look for it, you have an equal chance of finding it anywhere.

So it is completely spread out. But how do we visualize its definite momentum?

The answer is that a particle with a definite momentum, but a completely indefinite position, can be visualized as a wave. And not just any wave, but a pure wave, one which vibrates at a single frequency.

A wave can be characterized by two numbers. One is its frequency; this is the number of times per second that it oscillates. The other is the distance between the peaks, which is known as the wavelength. These are related in the following way: if you multiply these two numbers together, you get the speed at which the wave is traveling. Thus a wave which oscillates with a single frequency will also have a definite wavelength.

Quantum mechanics asserts that the momentum of the particle and the wavelength of the wave that represents it are related in a simple way, which is that they are inversely proportional. That is,

$$\text{wavelength} = h/\text{momentum}$$

h is the same Planck's constant that came into the uncertainty relations.

Let us assume for a moment that no force acts on our particle, perhaps because it is very far from everything else. In the absence of forces, a particle with a definite momentum also has a definite energy. That energy is in turn related to the frequency of the wave, in that they vary proportionately.

$$\text{Energy} = h \times \text{frequency}$$

These relations and correspondences are universal. Everything in the quantum world can be viewed as both a wave and a particle.

This is a direct consequence of the basic principle that we can measure the particle's position or measure its momentum, but we cannot measure both at the same time.

When we wish to measure its position, we visualize it as a particle, localized, but just momentarily, at a point in space. The momentum is completely uncertain, so the next moment, if we look again, we will find it has randomly jumped somewhere else. It can't remain in one place because, if it did, it would have a definite value of momentum, namely zero.

If, on the other hand, we choose to measure the particle's momentum, we will discover it has some definite value. It is nowhere in particular, so we visualize it as a wave, but one with a definite wavelength and frequency, according to the relations just mentioned.

What is so crazily fabulous about this is that waves and particles are quite different. A particle always has a definite position, localized somewhere in space. Its motion traces out a path through space, what we call its trajectory. Moreover, according to Newtonian physics, at each moment a particle also has a definite velocity and, consequently, a definite momentum. A wave is almost the opposite. It is delocalized; it spreads out as it travels, occupying all the space available to it.

But now we are learning that waves and particles are different sides of a duality, that is, different ways of visualizing one reality. A single reality with a dual nature: a duality of waves and particles.

A quantum particle can have a position. We ask where it is, and we will find it somewhere. But a quantum particle never has a trajectory, because, if we know where it is, where it will be next is completely uncertain. We must get used to thinking of particles at definite positions which are not points on trajectories. Similarly, if we measure a momentum we will always find a value. But then it's a wave, spread out everywhere. Where we will find the particle, if we next measure its position, is completely uncertain.

This scheme, it must be admitted, has an incredible elegance. But what is most compelling is its universality. It applies to light, it applies to electrons, and it applies to all the other elementary particles known. It applies to combinations of those particles, such as atoms and molecules. It has worked successfully to describe the motions of large molecules, such as buckyballs and proteins. There is no case of an experiment that was sensitive enough to reveal the quantum nature of an object, but failed to do so. At least so far, size and complexity provide no limit. We do not yet know if the wave-particle duality applies to people or cats or planets or stars, but there is no reason known why it definitely can't.

In all these cases the effect is the same: we can only know half of what we would need to know to precisely predict the future.

THREE

How Quanta Change

In the first lecture of his course on quantum mechanics, my teacher Herbert Bernstein asserted that physics is the science of everything. Our goal in physics is to find the most general laws of nature, from which the multitude of phenomena exhibited by nature may all be explained.

Quantum mechanics explains the widest variety of phenomena of any theory so far. At the same time, it greatly restricts the questions that can be asked of any particular phenomenon. We have already encountered one kind of limitation: that we can know only half what we would need to know about a system to make precise predictions for its future. As a result, we must give up describing exactly what goes on in individual atoms in favor of statistical predictions, which apply only to averages taken over many cases. Hence, to believe in quantum theory we must give up the ambition to precisely predict the future.

Most physicists have given up those ambitions in the face of the success of quantum mechanics. But I believe that this is shortsighted and there is a deeper level of reality to be discovered, the mastery of which will restore our ambitions for a complete understanding of nature.

Another restriction limits the range of quantum theory. We can express this in a principle I call the *subsystem principle*:

Any system quantum mechanics applies to must be a subsystem of a larger system.

One reason for this is that quantum mechanics refers only to physical quantities which are measured by measuring instruments, and these must be outside the system being studied. Further, the results of these measurements are perceived and recorded by observers, who are also not part of the system being studied.

Most of us approach science with the naive expectation that it will tell us what is real. We can follow John Bell and call a real property of a system a *beable*: it is part of what is. Bell coined the word as a contrast to the term *observables*, which is what anti-realists want out of a theory.

"Observables" and "beables" are loaded terms, whose use can signify allegiance to a side of the debate between realism and anti-realism. An observable is a quantity produced by an experiment or an observation. There is no commitment to believe it corresponded to something that exists apart from the measurement or had a value before the measurement. Anti-realists use this term to emphasize that the quantities quantum physicists measure need have no existence apart from, or prior to, our observation of them. Realists use John Bell's term "beable" to refer to the reality that they believe exists whether we measure something or not.

Most scientific explanations, whether of the flights of cannonballs or of birds and bees, speak in terms of beables.

But not quantum mechanics! As Heisenberg and Bohr insisted, quantum mechanics speaks not in terms of what is, but only of what has been observed. There is, according to them, no useful talk about beables in the atomic domain; instead, quantum mechanics deals only in observables.

To measure an atom's observables, we impose on it a large, macroscopic instrument. By definition, that device is not part of the system whose observables we are studying. Nor is the observer.

Therefore, to be described in the language of quantum mechanics, a system must be part of a larger system that includes the observer and her measuring instruments. Hence our subsystem principle.

Most applications of quantum theory are to atoms and molecules or other tiny systems; in these cases the restriction is irrelevant. But some of us have the ambition to describe the whole universe. We feel that is the ultimate goal of science. However, the universe as a whole is not, by definition, part of a larger system. The subsystem principle frustrates our hope to have a theory of the whole universe.

There is a subtle but key difference between the idea that quantum mechanics is the theory of everything, and the hope of extending quantum theory to include the whole universe. What Professor Bernstein meant by his claim is that physics is the root of the correct description of everything—each considered as a subsystem of the whole. It is very different to imagine applying quantum theory to the entire universe, which would mean including us observers inside the system being studied, and our measuring instruments.

Over the last century several attempts were made to extend quantum mechanics to a theory of the whole universe. We will meet one of these later on; a part of our overall argument is that these attempts fail.

For one thing, making the observer a part of the system being described raises tricky questions of self-reference. It is not even clear that an observer can give a complete self-description, because the act of observing or describing yourself changes you.

But there are deeper reasons why quantum mechanics cannot be extended to a theory of the whole universe.

In several of my books (namely *The Life of the Cosmos, Time Reborn,* and *The Singular Universe and the Reality of Time,* written with Roberto Mangabeira Unger), I investigate the question of how physics may be extended to give a theory of the whole universe. I conclude that a theory of the whole universe must differ in several crucial aspects from any of the physical theories so far developed, including quantum mechanics. All these theories only make sense when interpreted as descriptions of a portion of the universe.

Indeed, the fact that quantum mechanics only makes sense when read as a theory of a part of the universe is, by itself, a sufficient reason for regarding quantum mechanics as incomplete. One thing we may ask of a theory that completes quantum theory is that it makes sense when extended to a description of the universe as a whole.

However, this is not the only line of thought that leads to the conclusion that quantum mechanics is incomplete. Other concerns and difficulties had far more influence on how the subject has evolved historically. For the time being, I will ignore the cosmological issues and focus on more immediate challenges.

THE PROCESS OF APPLYING general laws to a specific physical system has three steps.

First, we specify the physical system we want to study.

The second step is to describe that system at a moment of time in terms of a list of properties. If the system is made of particles, the properties will include the positions and momenta of those particles. If it is made of waves, then we give their wavelengths and frequencies. And so on. These listed properties make up the state of the system.

The third step is to postulate a law to describe how the system changes in time.

Before quantum physics, physicists had a simple but powerful ambition for science. At the second step we would be able to describe a system in terms that were complete, in two senses. Complete means, first of all, that a more detailed description is neither needed nor possible. Any other property the system might have would be a consequence of those already included. Additionally, the list of properties should be exactly what is needed to give precise predictions of the future. This is done using the laws. The future can be determined precisely, given our complete knowledge of the present. This is the second meaning of the description being complete.

Between Newton, in the late seventeenth century, and the invention of quantum mechanics in the 1920s, it was believed that the properties making up that complete description were the positions of all the particles and their momenta.

It might, of course, happen that we don't know the precise positions and momenta of all the particles making up a system. The air in this room consists of around 10^{28} atoms and molecules, so a complete listing of their positions is impossible. We have to use a very approximate description in terms of density, pressure, and temperature. These refer to averages of the atoms' positions and motions. Our bulk description will have to employ probabilities, and the predictions it makes will then be to some degree uncertain.

But the use of probabilities is just for our convenience, and the resulting uncertainties just express our ignorance. Behind our bulk description of a gas in terms of density and temperature, we continue to believe there is a precise description, which includes listing where every last atom is and how it is moving. We share a faith that if we had access to that description we could use the laws to predict the future precisely. That faith is based on the belief in realism—that there is an objective reality, which it is possible for us to know.

Quantum mechanics blocks this complacent ambition, because its first principle asserts we can know, at most, only half the information that would be needed to realize it.

The complete information needed to precisely predict the future is called a *classical state*. "Classical" is how we refer to physics as it was between Newton and the discovery of the quantum. It is then natural to call a specification of half of that information a *quantum state*. The half is arbitrary; it can be chosen to be only the momentum, or only the position, or some mixture of these, as long as half the information needed to precisely predict the future is present, and half is missing.

The quantum state is a central notion in quantum theory. A realist will want to ask: Is it real? Does a particle's quantum state correspond precisely to the physical reality of that particle? Or is it just a convenient tool to make predictions? Perhaps the quantum state is a description, not of the particle, but only of the information we have about the particle?

We are not going to resolve these questions here. Experts disagree about them. We will soon enough have the chance to focus on these and other questions about the meaning and correctness of quantum mechanics. For now we take a pragmatic viewpoint and regard the quantum state as a tool for making predictions about the future.

A quantum state is a useful tool because it can do just that. This is our next principle:

> ***Given the quantum state of an isolated system at one time, there is a law that will predict the precise quantum state of that system at any other time.***

This law is called *Rule 1*. It is also sometimes called the Schrödinger equation. The principle that there is such a law is called *unitarity*.

Thus, while the relation between the quantum state and the behavior of an individual particle can be statistical, the theory is deterministic when it comes to how the quantum state changes in time.

As we said, quantum states with definite values of energy and momentum are represented by pure waves with exact frequency and wavelength. But these quantum states are very special. What about other quantum states, whose momenta are uncertain, so that they do not vibrate at a single frequency and with a single wavelength? More general quantum states are represented by waves with arbitrary profiles. These are sharp in neither position nor momentum, so if either of these quantities is measured, there will be uncertainties.*

There are also states of definite position and completely indefinite momentum; if we graph them, they look like spikes, which are zero everywhere except the single point where the particle is. Other states are peaked over a region of space and correspond to particles which are localized imprecisely, so we know only approximately where they are.

One way to make a general quantum state is by adding together pure waves, each with a different frequency and wavelength.

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* When a wave represents a quantum state, we sometimes call it a wave function.