Once settled in Texas, I began to think more and more about quantum theory. Relativity, despite all its drama and challenge, does not stretch human understanding—or human credulity—in the way that quantum theory does. It’s clear that if we are to understand our world more deeply in the twenty-first century, those two great theories of twentieth-century physics, relativity and quantum mechanics, must be harmoniously joined. Right now there exists at best an uneasy peace between them.

Planck’s quantum principle—that nature is granular—dates from 1900. Five years later, Einstein solidified the principle by applying it to corpuscles of radiation—photons. These events occurred before I was born, before my parents had met. In 1913 (when I was a toddler), Niels Bohr extended quantum theory to the structure of an atom, and introduced more strange ideas—the “quantum jump” (which has made its way into common speech), the unpredictability of a particular quantum event, the existence of a “ground state” in which particles move at high speed but can lose no more energy, and the emission of radiation with a frequency of vibration different from the frequency of revolution of the electron that caused the radiation.

In the mid-1920s (when I was in high school), these “strangenesses” of quantum theory were welded into the theoretical structure we call quantum mechanics by Werner Heisenberg, Erwin Schrödinger, Niels Bohr, and others. Nothing that came out of that synthesis was more startling than Heisenberg’s uncertainty principle, which denied the possibility of simultaneously measuring certain properties of motion. The uncertainty principle introduced us to quantum fluctuations, revealing empty space to be in fact a cauldron of activity, bubbling ever more vigorously as one looks at ever smaller bits of space and intervals of time. From quantum fluctuations come measurable properties of particles and atoms (as I discussed in Chapter 10), and not-yet-measurable properties of spacetime itself—wormholes, quantum foam, and uncertain geometry.

Since that grand synthesis in the 1920s, quantum mechanics has been largely a finished theory, applied in a myriad of ways but not altered at its core. It has fascinated me throughout my professional career. When I made the Center for Theoretical Physics on the ninth floor of the RLM Building in Austin my new home, I couldn’t resist coming back to the quantum. Einstein, by inventing the photon and by laying the theoretical base for lasers, had contributed as much as anyone to quantum theory. Yet he died not believing in it. Bohr died its champion, but recognized that it was unfinished business. “Whoever talks about Planck’s constant and does not feel at least a little giddy,” said Bohr, “obviously doesn’t appreciate what he’s talking about.” Well, it made me giddy in 1933 and it still does.

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Relativity has done some amazing things, showing the way to the expanding universe, black holes, gravitational radiation, dynamic geometry, and the origin of inertia. But without quantum mechanics, relativity, too, is unfinished business. If I wanted to tackle the largest questions, I told myself in Texas, I had better think harder about the quantum as well as about relativity.

Quantum mechanics is often described as the theory of the very small. A true statement, as far as it goes. Quantum mechanics is an absolute necessity, and an everyday tool, in explaining how molecules, atoms, photons, electrons, and other particles behave. It is of no consequence in explaining the motion of spacecraft, planets, comets, and whole galaxies. So what does the quantum have to do with the universe? Perhaps everything, because in any fundamental theory of existence, the large and the small cannot be separated. A Big Bang, with everything squeezed to infinite density, gave rise to our universe. The Big Bang was the original high-energy particle laboratory. A Big Crunch, with everything again infinitely squeezed, may end the universe. In between that beginning and that potential end, there seems to be no lack of infinitely squeezed matter and energy, in black holes of all sizes. A gravitational wave rolling across the cosmos can have its origin in a piece of mailer as heavy as many suns and as small as a single particle. Whatever quantum fluctuations contort the tiniest dimensions can influence the fabric of space and time in the large. In short, there is no hope of comprehending the “big picture” unless one takes account of both relativity and quantum mechanics.

I have spoken already of quantum fluctuations that can stir up space and time with wormholes and quantum foam in the realm of the incredibly small. The very geometry of spacetime fluctuates, too. Saying that geometry fluctuates is the same as saying that gravity fluctuates. Over small-enough distances and short-enough times, the uncertainty principle rules. The smooth, predictable behavior of classical physics is replaced by random fluctuations. As Yakov Zel’dovich guessed and Stephen Hawking proved, such fluctuations even permit a black hole to evaporate (albeit slowly), thus evading the rule that nothing escapes from a black hole. The uncertainty principle with its implication of limitless fluctuations is one of the great messages of quantum mechanics.

The theory delivers its other great message at a different level, the level of the human observer and the measurement laboratory. No matter what the uncertainties of the small-scale world, no matter how chaotic the fluctuations, our knowledge of nature rests ultimately on perfectly definite, unambiguous observations—what we see directly or what our measuring apparatus tells us. How can this be? If the world “out there” is writhing like a barrel of eels, why do we detect a barrel of concrete when we look? To put the question differently, where is the boundary between the random uncertainty of the quantum world, where particles spring into and out of existence, and the orderly certainty of the classical world, where we live, see, and measure? This question, related to the correspondence principle discussed in Chapter 13, is as deep as any in modern physics. It drove the years-long debate between Bohr and Einstein. It has motivated international conferences. Books could be written about the quantum theory of measurement—and have been (Wojciech Zurek and I assembled such a book in 1983).

The common way of dealing with the question of measurement in quantum theory is to say that the act of measurement “collapses” uncertainty into certainty. The idea can be illustrated with a famous experiment—originally a thought experiment, but now a real one. A weak source of light sends photons, one at a time, toward an opaque plate that contains a pair of closely spaced slits. Beyond the opaque plate is an array of small detectors that can record the arrival of photons. The detectors produce signals that inform a human observer where each photon arrived.

Classically, there are no puzzles. Each photon passes through one slit or the other, and strikes a detector that tells which slit it passed through. The results of an experiment with only the first slit open added to the results of an experiment with only the second slit open gives the same results as an experiment with both slits open.

Quantum mechanically, the situation is much more interesting. Each photon is governed by laws of probability and behaves like a cloud until it is detected. It passes through both slits, not one or the other,
and arrives *everywhere* at the detector array, with a large probability of arriving at certain detectors, a small probability of arriving at others, and zero probability of arriving at still others. Yet finally, if the detectors are sensitive enough to be triggered by single photons, each photon will be detected *somewhere*—somewhere quite specific. Where a particular photon will be detected is completely unpredictable. After many photons are detected, the calculated distribution of probability over the many detectors can be verified. The act of measurement is the transforming act that collapses uncertainty into certainty.

Interference of waves from two slits. Bohr’s colleague Harald Høffding: “Where can the photon be said to be?” Neils Bohr: “To be? To be? What does it mean to be?”

Watching this actual experiment in progress makes vivid the quantum behavior. One sees a flash at one point, then another, then another, then another. They seem random. At first no pattern is evident. Then, gradually, as the flashes accumulate—each one signaling a detection event—one sees places where many photons are detected, other places where none are detected, and a regular oscillation of intensity from strong to weak to strong to weak again. This oscillation precisely mirrors the original probability, a probability calculated on the assumption that each photon passes through both slits and that different parts of each photon cloud “interfere” with other parts. Moreover, unlike the classical situation, if the experiment is carried out first with only the first slit open, then with only the second slit open, the combined results do *not* mimic the results of the experiment with both slits open. Because the photons pass through both slits at once in the two-slit experiment, the result of this experiment is totally different from the summed results of two one-slit experiments.

I spoke above of classical behavior and quantum behavior. The quantum behavior is the one actually observed in experiments with photons or electrons. The classical behavior is only what *would* be observed if particles followed classical laws. They don’t. But what of baseballs? Why do they follow classical laws if photons and electrons do not? Imagine a large metal barrier mounted near home plate on a baseball diamond, a barrier containing two holes, each, say, a foot in diameter, with a few inches of separation between them. When a pitcher throws baseballs toward the barrier, some go through one hole, some through the other (and some through neither). A baseball can’t go through both holes at once. It seemingly has no cloud of probability, no interference, and no “collapse” of uncertainty to certainty. Well, in fact, it *does* have a cloud of probability, and there is collapse to certainty. But the baseball’s cloud is of less than microscopic dimension. It is as if the baseball had a tiny skin of uncertainty, vastly less than the thickness of its actual skin, less than the diameter of a single atom. Quantum fluctuations are large for small domains of space and time, and small for large domains of space and time. For the “huge” baseball, the quantum fluctuations are entirely below the threshold of observation.

Now, as to collapse of uncertainty to certainty. A photon goes entirely unobserved until it triggers a detector. From the moment of its emission until that moment of detection, one has no knowledge of its
location or direction of travel. It remains an ethereal cloud of probability precisely because it is unobserved. The baseball, by contrast, can be observed repeatedly all along its course from pitcher to barrier to catcher. By any number of means—high-speed camera, radar, sonic rangefinder, even the human eye—it is progressing can be monitored. So detection, the thing that collapses uncertainty to certainty, is occurring repeatedly, providing certain information about where the baseball is and how fast it is moving and in what direction all along its path, not just at some final observation point. The photon and the baseball differ only in scale, not in principle.

I want to pursue the double-slit experiment only a little further. Simple though it is in concept, it strikingly brings out the mind-bending strangeness of quantum theory. (It has been a touchstone for discourse about the implications of quantum theory for three-quarters of a century.) Imagine some object larger than a photon and smaller than a baseball—a large molecule, for instance. If fired at a barrier with slits, does it behave more like a photon or more like a baseball, more like a “pure” quantum object or more like a classical object? It could behave like either; it all depends on how we choose to examine it. If we subject it to no perturbing observations, its quantum properties can dominate. It can go through both slits at once, land at an unpredictable point, and reveal interference between one part of its cloud and another. Such behavior has been demonstrated for objects as large as whole atoms. If, however, we get overly curious, and follow it with observations along its path, it will respond by behaving classically. Then we cause its repeated “collapse” to certainty. By tracking it, we evaporate its cloud of uncertainty.

For twenty-eight years, in Europe and in America, Bohr and Einstein debated the meaning of quantum mechanics. These two giants, full of admiration for each other, never came to agreement. Einstein refused to believe that quantum mechanics provides an acceptable view of reality, yet he could never find an inconsistency in the theory. Bohr defended the theory, yet he could never escape being troubled by its strangeness. Reportedly, once when Einstein remarked, as he liked to do, that he could not believe that God played dice, Bohr said, “Einstein, stop telling God what to do.”

A thought experiment that I first discussed in 1978 gets at the core of what fueled the Bohr-Einstein debate. Beyond illuminating that famous debate, this experiment may have something to tell us about the very machinery of the universe. I call it the “delayed-choice experiment.” Here is how it works.

First, we borrow a baseball diamond. On home plate we install a half-silvered mirror. This is a piece of glass with a thin reflective layer on one side, a gossamer layer of metal that reflects half the light that strikes it and lets the other half through. We put a light source nearby and arrange the light source and the half-silvered mirror so that half the light from the source is sent toward third base and half is sent toward first base. In quantum language, any photon has a 50 percent chance of being sent toward third base and a 50 percent chance of being sent toward first base. On the average, after many photons have been emitted, half will have gone each way.

Next, we mount fully reflective mirrors on the first and third bases. The one on third base reflects the light that hits it toward second base and on out into right field. The one on first base reflects the light that hits it toward second base and on out into left field. If we mount detectors in left and right fields, they will tell us how many photons took each route. When the detector in right field clicks, signaling the arrival of a photon, we can conclude that a photon reached the detector via third base. When the detector in left field clicks, we can conclude that a photon has reached that detector via first base. Quantum mechanics predicts that the photons will arrive at random times at both detectors, but at the same average rate. Nothing strange yet. We have just arranged for photons to be sent randomly over two different routes, with equal probability, and whenever we detect a photon, we can determine what route it followed.

But wait. Quantum mechanics does more than say that photons may follow either route according to

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6 My apologies to readers not familiar with baseball. You may need to consult a baseball fan to help you visualize the placement of parts in this experiment.
some random sequence. It says that the cloud of probability that is the photon until it is detected can take both routes at once! This is just like the double-slit experiment, where interference between the two paths shows that single photons go through both slits. Uncertainty collapses to certainty only when the measurement is made.

Now, for our baseball-diamond experiment, we can demonstrate that every photon does take both the first-base route and the third-base route. On second base we install another half-silvered mirror. This one is arranged so that half of the light reaching it from third base is reflected into left field and half is transmitted straight ahead into right field; and half the light reaching it from first base is reflected into right field and half is transmitted straight ahead into left field. This half-silvered mirror works in such a way that the two beams headed for left field destructively interfere with each other; that is, the crest of one probability wave overlaps the trough of the other probability wave, canceling it out, so no light reaches left field. The two beams headed for right field constructively interfere (meaning the crests of the two probability waves overlap and reinforce each other); all the light reaches right field. (By this time, if your ability to visualize baseball diamonds is not well honed, you may feel “out in left field” yourself, where there is no light.)

If we watch our two detectors for some time, we will find that the one in left field never clicks and the one in right field clicks at about twice the rate it did in our first baseball-diamond experiment. All the photons are going to right field. Now we have learned something new, that every photon went by both routes simultaneously, for otherwise there is no explaining the action of the half-silvered mirror on second base that sends them all to right field.

All is going well with our experiment when a dog wanders onto the field and onto the baseline between second and third bases. He interrupts the light path from third to second base, and suddenly the detectors change their behavior. The detectors in left and right field start clicking at about the same rate, each one at a quarter the rate of the right-field detector before the dog appeared. Half of the light is hitting the dog. The other half, all going via first base, is being split at second base to go half to one detector and half to the other. There is no interference, constructive or destructive, for only one path is now open. The mirror on second base simply splits the beam. Now the dog wanders across the infield, no longer interrupting any photon beam. Once again, the left-field detector goes silent and the right-field detector picks back up to its previous rate of recording photons, showing that every photon is again following both paths at once, not just one or the other. You can guess what happens when the dog crosses the baseline between home plate amid first base. Both detectors are active at the same rate, as when the dog interrupted the other beam. Finally, the dog wanders off the field and we see again the result of each photon interfering with itself as it makes its way from home plate to right field.

The great lesson of quantum mechanics is that if we choose to measure one thing, we thereby prevent the measurement of something else. We can decide what we want to measure, but we can’t decide to measure all properties of a system at once. The most elementary example of this limitation is that the position amid speed of an electron cannot be measured at the same time. In our baseball-diamond experiment, we can choose to measure which path a photon followed (by having no half-silvered mirror at second base), but then we lose information about interference between different parts of the electron’s probability cloud. Or we can choose to reveal the interference (by placing the half-silvered mirror at second base), but then we lose information about the path followed by the photon. More exactly, we make the whole idea of following a single path meaningless.

This is already mind-stretching. To make it more so, we come now to delayed choice. We will turn on the light source near home plate for only 1 billionth of a second, during which time it emits, say, 1,000 photons. At the speed of light, a photon travels only about 1 foot in a billionth of a second. So we can wait a leisurely 10 or 20 billionths of a second after the light source is turned off before we decide which experiment we want to do—that is, what we want to measure. During the time we are thinking it over, the photons are long gone from home plate, but none can yet have reached second base. They are somewhere en route. If we want to find out which route each photon followed, we need only remove the half-silvered
mirror from second base and wait for the clicks of the detectors in left and right field to reveal the paths of each one. If we want to demonstrate that every photon followed both paths at once, we need only place our half-silvered mirror at second base (after all the photons have left home plate) and wait for the silence of the left-field detector and the increased rate of clicking of the right-field detector to tell us that every photon went by both paths at once.

As with some other thought experiments, the march of technology has caught up with and made it a real experiment. At the University of Maryland, Carroll Alley, Oleg Jakubowicz, and William Wickes—on a laboratory bench, not a baseball diamond—demonstrated delayed choice in 1984. The strangeness of the quantum world, from which Einstein incessantly sought escape and from which Bohr saw no escape, is real.

If delayed choice is real in the laboratory, it is surely real on a baseball diamond and real in the universe at large. We need only expand the dimension of the baseball diamond to a billion light-years, putting a quasar at home plate, galaxies at first and third bases, and Earth, with its telescopes amid counters, at second base. Galaxies 1 and 3, as we may choose to call them, are capable of bending the quasar light so that it will reach Earth by two different paths. (Such galaxies really exist. Gravity can bend light as surely as it bends moving material particles.) If we point a telescope at Galaxy 1, we see photons from the quasar that were deflected as they passed near Galaxy 1. If we point a telescope at Galaxy 3, we see photons from the quasar that were deflected as they passed near Galaxy 3. But if we put a half-silvered mirror (like the one we had at second base) at the place in our observatory where light from both Galaxies 1 and 3 is directed, we can—in principle—cause quasar light from these two directions to interfere so that all of it goes off in one direction, none in the other. Moreover, the rate of arrival of light from the quasar could be so low—again in principle—that only one photon at a time is detected, with a waiting time until the next one arrives. What interpretation is then possible but that each single photon on its billion-year trip from the quasar to Earth followed both paths via both galaxies in the form of ephemeral clouds of probability spreading through remote reaches of space until we pin down that photon with our measurement? Since we make our decision whether to measure the interference from the two paths or to determine which path was followed a billion or so years after the photon started its journey, we must conclude that our very act of measurement not only revealed the nature of the photon’s history on its way to us, but in some sense determined that history. The past history of the universe has no more validity than is assigned by the measurements we make—now!