



THE UNDETERMINED WORLD

Struck by the way sunlight glancing off granite can seem to set a mountain on fire, Río Arriba's Spanish occupiers named the *Sangre de Cristo* Mountains after their sanguine glow, a light so pure and uniform that a nineteenth-century physicist might have been tempted to think of black body radiation, as though the rocks themselves were hot and radiating from within. Albuquerque's mountains, the *Sandias*, were named for the Spanish word for watermelon, again because of the way they redden as the night falls.

Photons from the sun scattered by electrons in granite. For all the talk about the menagerie of particles locked inside the nuclei of atoms, the universe we directly experience is generated almost entirely through the play of electrons and photons, a dance whose steps are laid out in one of the supreme accomplishments of twentieth-century science, a theory called quantum electrodynamics, or QED. The theory ignores gravity and stops short of the nuclear frontier, but it is stunning how much is still encompassed within its grasp. We are electromagnetic creatures in an electromagnetic world, existing at the intersection between light and electricity.

Moonlight reflecting off a lake becomes, in the language of QED, solar photons bounced by the electron shells of silicon and oxygen atoms in lunar rock and bounced again by the electrons in the hydrogen and oxygen atoms that clasp together to make water. And the photons ricochet from the water interact with electrons again—the charged haze surrounding the carboniferous chains of protein molecules in our retinas. Almost everything we experience comes to us as reflected light, and so QED gives us a theory of how we know the world.

But electromagnetism is more than a carrier of signals, or a beacon to illuminate matter. Even for creatures that have no eyes, light and the way it plays with electrons is as fundamental as anything can be; it is the very reason atoms stick together to form matter. And they do so according to the rulebook of QED. In the way twentieth-century physics has carved up the world, quantum electrodynamics lies at the foundation of chemistry. Whenever two atoms pull together or push apart, the force arises from photons bouncing back and forth between their electron shells. Most of these interactions are invisible, but sometimes a chemical reaction will shed such an excess of photons that they light up the night: oxygen rapidly binds with carbon to make a forest fire; a firefly phosphoresces with a dull green glow. But even when the light is too weak or vibrates at frequencies our nerves cannot register, it is there providing the medium through which electrons communicate, through which atoms become objects and objects disintegrate into atoms again. With every step we take, it is electrons exchanging photons that generates the repulsive force that stops our feet from going through the sidewalk, that creates the illusion of solidity in a world that, we have come to believe, is mostly the empty space inside electron shells.

There is another, parallel science, quantum chromodynamics, that explains how colored gluons play with colored quarks to generate the stuff inside the nucleus. But that dance takes place on a hidden realm. Atoms and all that is made from atoms "know" one another through their electron shells, the charged facades they present to the world. To them, the nucleus is a black box, obeying rules they need not fathom. In the world where we find ourselves, it is QED that provides the rules of the game.

We live in a world orderly enough that it pays to measure. And we make our measurements using electrons and light. We feel the tug of gravity as we walk the earth, but once we train our sights beyond the planet we measure gravitational forces indirectly, by the effect they have on celestial objects: the pull of one planet on another, the centripetal ef-

fect of dark matter on a rotating galaxy. And how does news of these effects reach us? From signals of light that are registered only when their photons scatter off the electron shells of the atoms that make up our instruments and our eyes. The same is true when we try to see within the nuclei of atoms. The hypothesized chain reactions of particles creating particles creating particles ultimately must end with photons scattering off electrons, leaving their mark on our brains. The maps we make, the patterns we find, are rooted in this most basic interaction.

Explorations of Maxwell's demon showed the complications that arise when we contemplate the subtleties of how we find order in the world. There is no such thing as an immaculate perception; we are inevitably part of the world we are trying to measure. And everywhere we look, we come face-to-face with randomness. We build our orders, but only at the expense of creating randomness elsewhere.

QED tells us that this thing we call measuring is even stranger and subtler than thermodynamics suggests. The Q at the beginning of the name is a sign that the mathematical choreography of our subatomic messengers will be nothing like that which reigns up here in the macroscopic world. Like all subatomic particles, photons and electrons obey quantum logic. In building a theory of the most ordinary phenomena, we are led into abstract realms as remote as anything in the scientific imagination, into mathematics that defines our mental imagery. Electrons and photons do not ricochet off one another like billiard balls, we are told. When we say that electrons repel one another by bouncing photons back and forth, what we really mean is this: the first electron creates a photon, which is absorbed by the second electron rapidly enough to avoid violating conservation of energy. (Once again, Heisenberg's uncertainty principle provides the loophole that allows energy to be seemingly created out of thin air.) But the process is even more counterintuitive than that. The path that a single electron or a single photon follows is said to be random. This is not the randomness of human ignorance, which we find with thermodynamics; it cannot be reduced by gathering more information. Since this is quantum mechanics, we must deal with *inherent* uncertainty, even when calculating something as seemingly straightforward as the route a photon takes when it is reflected from the face of a meter and into our eyes.

At Santa Fe, Los Alamos, and elsewhere, the scientists exploring the physics of information are trying to understand the implications that this inherent randomness holds for our attempts to measure and find struc-

ture in the world. In trying to cast quantum theory in a new light, they have been led again to a bedrock in which information seems irreducible and fundamental. But before turning, in the next chapter, to these attempts to recast quantum theory, we will consider anew the strange map bequeathed to us by twentieth-century physics in its attempts to chart the subatomic world.

We are used to thinking of quantum randomness as something hidden away on a realm too small to see. But through the theoretical lenses of QED, quantum effects become magnified until they seem to manifest themselves as a familiar part of our world. As you look out the window at a streetlight illuminating the snow, you might be momentarily startled to catch an image of flames from the fireplace behind you hovering in the nighttime air, or a ghost of your own reflection. A fraction of the photons passing through the window is bouncing back into your eyes. Why do most of the photons emanating from the room go right through the glass, unimpeded, while some are reflected? It seems that a single photon arriving at the surface of the glass must be faced with two possibilities, sail through or bounce back. How does it "decide" the trajectory it will take?

In the real world, of course, not all photons are the same. They come in different colors—frequencies—and arrive at different angles. But we can take steps to reduce the complications caused by these variables. We find in the laboratory that even if we illuminate a piece of glass with a uniform source of monochromatic light, a beam in which all photons are as similar as we can make them, we still get this phenomenon called partial reflection. Using a photoelectric cell, which counts individual photons, experimenters find that a certain percentage of these particles of light pass through the glass, while a certain percentage are reflected. If the device produced a stream of bits, 1 for a photon that passed through the glass, 0 for a photon that reflected, we would find a fixed ratio of 1s and 0s. Each time we ran the experiment, however, we would get a different arrangement of these bits. We might find that time after time we get eight 1s for every 0, but one time the pattern might look like this: 101111111, and another time like this: 111111011. We can no more predict the identity of an individual bit than we can the roll of a die. While we can measure the average behavior of swarms of photons, a single photon's "decision" to go through the mirror or bounce back seems to be random.

What determines the ratio of 1s and 0s? By tinkering further, we find

that we can change the percentage of reflected photons by varying the thickness of the glass. As we increase its thickness, the fraction of reflected photons rises from 0 percent to a maximum of 16 percent. But before we conclude that thicker glass means more reflection, we make the glass still thicker, and find that the number drops back toward 0 again. If we could rig a dial to adjust the glass's thickness, we would find that as we turned it higher and higher, the percentage of light reflected would rise and fall, rise and fall, in smooth sinusoidal undulations.

If we are content to think of light as waves instead of photons, partial reflection is not quite so mysterious. In the classical view, a wave passing through a piece of glass divides in two: part of it passes through, part of it is reflected. But if we carve up the world so that light is entirely wave-like, then we are hard-pressed to explain why our photodetector seems to register the beam as photons; if we hooked it to an amplifier and a loudspeaker we would hear a steady stream of clicks. And, more telling still, if we raise the brightness of the light the clicks remain just as loud, but they come at a faster pace. (If we want louder clicks—more energetic electrons dislodged from the photoelectric cell—we will have to increase the frequency of the beam. This is none other than Einstein's photoelectric effect.) In a lucid series of lectures, published as *QED: The Strange Theory of Light and Matter*, Richard Feynman, one of the principal architects of quantum electrodynamics, estimated that it takes five or six photons to fire the receptors in our retinas. If our eyes could be made only a bit more sensitive, he declared, we would be startled to see very dim monochromatic light as pulses.

So the dilemma remains: If light consists of these starbursts called photons, then how does a single particle "make up its mind," as Feynman put it, whether to bounce off the glass or go on through? And how does it adjust its behavior for different thicknesses of glass? Arriving at the front surface, it seems, the photon would have to somehow send out feelers and gauge how thick the glass was, then calculate the odds so it could decide which path to take. But even if a photon could sound the vitreous depths by sending out some kind of probe, we would be left with an insurmountable problem: for the signal to travel through the glass and back to the photon in time for it to adjust its course, it would have to move faster than the photon, faster than light.

Since superluminal signaling is supposed to be against the law, violating special relativity, our only recourse for explaining why seemingly identical photons are not treated identically by a windowpane is to blame

the phenomenon on randomness—a randomness that, so far as we can tell, is inherent, not based on our ignorance of some of the facts. QED makes no attempt to offer a mechanism for how partial reflection, or any other optical phenomenon, works. It describes but it does not explain. The photon, apparently for no reason whatsoever, just goes one way or the other, and the best we can do is calculate the odds.

For us, the information gatherers, this is a curious situation. In trying to describe the one phenomenon most fundamental to our world, electromagnetism, science gives us powerful tools to make statistical predictions, but it is incapable of offering an explanation we can picture in our heads. Since Planck's experiments forced the quantum on the world, physicists have honed the mathematics diamond-sharp. But the possibility of describing some kind of machinery behind the equations becomes more and more remote. Those whose intuition tells them that events in all worlds, invisible or not, should be linked in a tightly drawn web of cause and effect are left in the same state of confusion as Professor Jakob, the subject of Russell McCormack's novel *Night Thoughts of a Classical Physicist*. "Physicists used to seek picturable mechanisms for understanding the world," he lamented, "but now many of them had pretty well given it up." They had retreated into a "cold, gray cave of abstraction."

But it is hard not to be beguiled by how the utterly counterintuitive mathematics of quantum electrodynamics so neatly predicts the ways electrons and photons interact. We learn in high school physics that the angle at which light strikes a mirror (the angle of incidence) is equal to the angle at which it is reflected because of the "least time principle" put forth by Fermat in the seventeenth century: light takes the fastest path from A to B. But forget what we see in the macroscopic world—a beam of light reflecting off an area in the center of the mirror. In QED, Feynman shows that to reconcile the least time principle with quantum theory, we must assume that, behind the scenes, photons are behaving in ways that seem impossible, that they are bouncing off every single spot of the mirror, trying out even the unlikely of paths. Using the rules of QED, we assign an "amplitude" to each of the paths (the square root of the probability that a photon will go that way). When we add the amplitudes of these multiple routes, or "histories," we find that almost all of them cancel one another out, leaving the path in which angle of incidence equals angle of reflection, the one that takes the least time to traverse.

Feynman's "sum over histories" method can also be used to explain partial reflection or mirages on a desert highway or why your leg seems

to bend when you step into a pool of water. In each case we are asked to imagine every possible way the photons can travel, then add them together. To be as precise as possible, we can even allow for hypothetical trajectories in which the photon is moving slower or faster than light. Some possibilities reinforce one another, others cancel out, and we are left with the trajectory that we see in the classical, macroscopic world.

Feynman's method does not simply apply to photons traveling en masse. We can almost imagine one photon from a light beam bouncing here, another one bouncing there. But to address the original question—how a single photon “knows” where to go—we must assume that *each single particle* tries out every possible path simultaneously, and that they cancel one another out, leaving the classical trajectory.

What is true for photons also applies to electrons. If we want to consider the seemingly simple case of an electron moving from point A to point B, we must consider every conceivable route and entertain the possibility that along the way the electron might emit and absorb any number of photons. According to the rules of subatomic physics, when an electron collides with a positron, the two self-annihilate in a flash of light; conversely, a flash of light—a photon—can give birth to an electron-positron pair. And so we must also allow for the possibility that every photon emitted by a traveling electron becomes an electron and a positron, which might collide to form a photon again. Making matters weirder still, in Feynman's formulation of QED, a positron is equivalent to an electron moving backward in time.

As a calculating tool, QED is as good as they come, yielding numbers that agree so closely with those measured by experiment that, as Feynman put it, it is as though one could gauge the distance from New York to Los Angeles to within the width of a human hair. But is QED just a mathematical device, like the cumbersome algorithms once taught in high school for extracting square roots and cube roots by hand? Or does it really describe an underlying reality? In *QED*, Feynman insists that many optical phenomena such as diffraction (the cause of the rainbow you see when you hold a phonograph record or a compact disc to the light) can only be understood if we assume that each photon glancing off a surface really is taking every possible path. It is not reality's fault that our brains are incapable of imagining this. It seems that this level beneath the classical, Newtonian world operates according to different principles. And from these quantum rules arise the familiar rules of our realm. In the old days, scientists would study a system and imagine a mecha-

nism that could explain how it worked, then they would discover or invent some mathematics to make it precise. With quantum theory we have the mathematics but we don't know what it means. In contemplating this strange situation, we might sympathize with the fictional Professor Jakob, left out in the cold by the new quantum theory:

“Over his lifetime,” McCormack wrote, “physics had taken a turn toward increasingly advanced mathematical conceptions of nature. Fifty years had not proved long enough for him to see into the depths of the equations of classical physics, certainly not into the final revelations of Maxwell's equations, which Hertz correctly saw were wiser than their creator and his followers. And it was unrealistic of him to expect to see into the depths of the equations of physics that came after Maxwell, if they had depths and were not a mathematical trick in the end. (For weeks he had been struggling with a paper on atoms by Sommerfeld, only to conclude that he was not doing physics but conjuring with numbers.)”

Feynman's “sum over histories” method is only one of the formalisms used to solve problems in quantum mechanics. Quantum phenomena can also be described using mathematical devices called Heisenberg matrices, Dirac state vectors, and, the most familiar, Schrödinger waves. All are mathematically equivalent and equally strange. The surprising predictions of quantum theory have become such a staple of popular culture that, by now, we all know the drill. While in transit a particle cannot be said to have a definite position or momentum. Until we measure it, it hovers in a limbo in which all of its possible positions or all of its possible momenta somehow exist simultaneously, represented by the Schrödinger wave function. Only when the particle collides with a detector, when we make a measurement, does it assume an actual value. The wave describes the likelihood that it will end up in one state or another, but the outcome is uncertain until it occurs. Whichever formalism we use, the mathematics dictates that the more precisely we know one of these values, position or momentum, the less precisely we can know the other. Once we determine precisely where a particle is, we can know nothing about how fast it is moving. This, of course, is the Heisenberg uncertainty principle, which also holds that time and energy and other pairs of attributes are complementary. We the observers must decide which to measure. Likewise, light can seem like particles or waves, depending on our experimental point of view.

How can the world we live in be so different from the world that lies underneath? Up here in the classical world, things look different from different perspectives, but like the blind men investigating the elephant we can reconcile our differences and agree on the shape of what is before us. But quantum theory takes this subjectivity to a strange extreme: There is no elephant, only blind men.

To the pueblo Indians, Sandia Crest is known as Turtle Mountain, a name that seems inappropriate to anyone who grew up in Albuquerque. From that vantage point, at the foot of the eastern escarpment, the mountain looks nothing like a turtle. But head north, up the Rio Grande, and it becomes stretched and distorted until by the time you get to Santo Domingo pueblo and look back, its animal form has snapped into view. Most people know the mountain from its Albuquerque angle. But just as there is no privileged reference frame in the universe where we can step outside the system and see it whole, neither is there a canonical view of Sandia. Settlers coming in wagons from the east would have seen a long gentle slope rising toward the granite knife edge where the ground suddenly gives way. Still, all observers will agree that there is a mountain there and that if we all got together and rose directly above it in a hot air balloon we would see the same geography.

With quantum theory there is no mountain, only the views. If Sandia obeyed the rules that each of its particles does, it would be wrong to grant it an independent existence. Until observed, it would hang in a quantum limbo, as a superposition of all the possible ways it could be.

How do we get from this level of quantum mushiness to our world of objects that have definite positions, not superpositions, that have both positions and momenta at the same time? Built atop the quantum rules, it seems, is a higher level called Newtonian mechanics. How do we make the jump? That is what QED does not even attempt to explain: why objects in our world do not seem to obey the same rules as the stuff they are made of.

The notion of rules on one level giving rise to completely different rules on another level is not so mysterious in itself. Our world is a whole wedding cake of layers. Subatomic particles obeying laws of quantum electrodynamics and quantum chromodynamics give rise to atoms and molecules obeying the laws of chemistry, which give rise to cells obeying the laws of biology and creatures obeying, to some extent, laws of psychology, sociology, and economics. Without straying far from the classical world, we can find such emergent phenomena everywhere. Water

with all its properties emerges from hydrogen atoms joined to oxygen atoms, but a single molecule of H_2O cannot be said to be wet. In the brain, components called neurons, each obeying simple rules, send signals back and forth and properties we call perception, intelligence, and consciousness arise. Each of these levels is, in a sense, sealed off from the one below it. Gas molecules jostling about in a container give rise to emergent qualities called temperature and pressure. But it is meaningless to speak of a single particle having a temperature or pressure just as it would be meaningless to say that a neuron is conscious or a water molecule is wet; these are ensemble properties that exist only on a higher level.

Burrowing through the levels of a digital computer, we find a hierarchy of languages. At the bottom of the ladder, microprocessors and memory chips communicate in a binary tongue, in which everything—numbers, letters, images—consists of strings of 1s and 0s. The rules that reign are those of binary logic. Riding on top of this machine code is a higher-level, more abstract language whose tokens are not 1s and 0s but simple commands like ADD and MOVE. By harnessing these tokens, one can devise still higher-level languages like BASIC, FORTRAN, and C and use their more powerful commands to write word processors, painting programs, and video games. Between each of the levels is a program—called an assembler or a compiler—that translates from one set of rules to another. The rules in a video game bear no resemblance to those of FORTRAN, which bear no resemblance to the machine code dictating how the 1s and 0s must move. But if we had the patience, we could translate the succinct higher-level rules—“When you destroy an asteroid, you get 10 points”—into a long binary string.

The difficulties arise when we try to go one level deeper, to the murky bottom where the silicon and other atoms that make up the logic and memory chips are mired in the world of quantum mechanics. As different as the upper levels are from one another, they all obey the same deterministic logic; everything happens for a reason and is woven into a tight skein of cause and effect. On the quantum level, the language is indeterministic. We can only speak of the probability of an electron's moving this way or that. Yet somehow this garbled quantum bedrock, like the formless Precambrian gneiss at the bottom of the Grand Canyon, supports all the neatly arrayed layers above it. To return to our computer metaphor: What is the nature of the compiler that allows us to make this mysterious transition? How does classicality emerge? Why do we agree that there is one mountain?

One of the windows we are given to glimpse the hard truths of quantum theory is the infamous two-slit experiment. Shine a light beam at a photosensitive screen, and between the source and the screen place a barrier with two holes in it. The image cast is called an interference pattern, which is just what we would expect if light consisted of waves: light and dark bands indicate the regions where the waves, passing through the two holes, are in phase, reinforcing each other, or where they are out of phase, canceling each other out. But repeat the experiment using a beam of electrons and they too leave a striped interference pattern, the classic signature of a wave. We can turn down the intensity of the beam and see evidence of particles: individual flashes each time an electron or photon strikes the target. But if we wait long enough, the individual collisions will trace out, point by point, the same dark and light bands.

We expect a wave to leave an interference pattern: it passes through both holes simultaneously and is split into two waves that interfere with each other. But why would a steady stream of particles behave this way? We are faced with the same problem that arises with partial reflection. Explaining why some particles go through the first hole, while other particles, presumably emitted with the same initial conditions, go through the second hole, is difficult enough. The choice seems to be made at random. But why is the result of this strange behavior an interference pattern? How do the particles "know" to arrange themselves this way?

One recourse is to suppose that our particle source isn't as uniform as we believed, that the particles are actually emitted with slightly different trajectories, causing them to glance off the edges of the holes at different angles. Or perhaps they are affected in transit by other particles or waves. Then we might conclude that the wave pattern is an illusion, a statistical distribution of particles which land in different places because of randomness caused by ignorance—factors we did not account for. If we knew all the information we could predict exactly where each electron would land.

If things were only so simple there would be no need for quantum theory; the two-slit experiment or partial reflection could be explained with Newtonian mechanics and ordinary statistics. But as we look closer, this interpretation breaks down. Close one hole and repeat the experiment with the electrons. We simply get a circular spot where the electrons or photons go through the open hole and hit the screen. They are acting like particles again. It is easy to think of this pattern as a probability distribution; slight fluctuations in the initial conditions cause the particles to

strike the target in various positions clustering around the open slit. Close that hole and open the other and we get a similar distribution. Put shutters on the holes and close one and then the other, alternating back and forth, and we get two of these blurs side by side. So far nothing has happened that our classical intuitions would find objectionable. But when we open both holes at once we get the wavelike interference pattern again—dark regions where most of the electrons strike the screen and light regions where few or no electrons land. But what is interfering with what? How can it be that simultaneously opening both holes prevents an electron from landing in places where it was previously free to go? As the physicist John Bell wrote in 1985, "It is as if the mere possibility of passing through the other hole influences its motion and prevents it going in certain directions."

Are we dealing with waves or particles? Suppose we zero in on the holes themselves, replacing the shutters with detectors. Now when an electron arrives at the barrier we can see if it acts like a wave, passing through both openings, or like a particle, passing through one or the other. What we find is this: when one detector clicks, the other is inevitably silent; they never go off at once. That seems to resolve the matter in favor of particles going through one hole or the other. But then we look at the target and see that the interference pattern has disappeared. We are back to two circular spots again. When we test for particles we get particles, when we test for waves we get waves. As with partial reflection, the demand for a mechanism reduces us to imagining that the particles must somehow sense the nature of the experimental apparatus by sending out superluminal probes, so they can adjust their behavior accordingly.

The compromise adopted by most physicists is to give up hope of a mechanical interpretation of quantum phenomena and think of each electron in the two-slit experiment as a mathematical abstraction, a wave that can be thought of as representing every possible path, or history, the particle can take on its way to the target. When the particle collides with the target, this wave function "collapses" or is "reduced" and the particle randomly assumes one of the possible positions. In this interpretation, the probability wave itself goes through both slits, splitting into two probability waves that interfere with each other, producing the striped pattern. When we put detectors at each of the slits, we are simply collapsing the mathematical wave sooner, before it has the opportunity to divide in two and create the interference bands.

Ever since Max Born proposed this odd view in the summer of 1926, physicists and philosophers have been arguing over what it could possibly mean. It is easy to think of probability waves involving many electrons, but how does one picture a single electron as a probability wave? On a day-to-day basis, most physicists content themselves with the fact that quantum theory yields such precise predictions. But when pressed for an interpretation, many will insist that the probability wave really does propagate through space. Forced to settle for mathematics without mechanism, they reify the mathematics, treating this abstraction as we would a wave of water, allowing it to engage in refraction, reflection, interference.

Some might argue that this elevation of mathematical devices to the status of real stuff is done all the time in classical physics; witness the electromagnetic field, an abstraction that we have little trouble granting substance to. But quantum wave functions seem far more ethereal than electromagnetic waves. For one thing, an electromagnetic field exists in physical space; we can walk about inside one, measuring its intensity from point to point. The wave function exists in a mathematical domain called configuration space. It does its waving in an imaginary region we can no more experience directly than we can the space in which a nucleon exhibits isospin.

And so, it is all the more amazing that these waves of probability can be manipulated as confidently as if they were musical waves. The French mathematician Joseph Fourier showed some two centuries ago that a wave of any shape—a flat-topped square wave, a jagged sawtooth wave—can be expressed as a sum of sine waves, those smooth, symmetrical undulations we associate with a pure musical tone. We have also learned how to express a sine wave as a sum of square waves, or sawtooth waves. In fact, any wave can be broken into a sum of any other kind of wave. These components can be manipulated and juxtaposed so that those in phase will reinforce each other, those out of phase will cancel out, leaving us with any waveform that we like. Some of these compositions are more natural than others. Sine waves and square waves are so similar that it takes relatively few of one to make the other. But other waves are complementary, occupying opposite corners in the space of waveforms. An impulse wave, the sharp spike you would get if you hit a stick suddenly on a piece of wood—all the amplitude concentrated in an infinitesimal time, a temporal point—is so different from the pure tone of a tuning fork that it takes a vast sum of impulse waves to make a sine

wave, and vice versa. In fact, to duplicate these tones with perfect precision would require an infinite number of complementary waves. Abstract as this seems, these wave conversions are done all the time in digital recording. An impulse wave is either on or off, 1 or 0, and so they form the two letters in a binary alphabet. A digital compact disc recording of a symphony can be thought of as sine waves from the instruments—vibrating columns of air—refracted into impulse waves by the recording studio and turned back into sine waves as they emerge from the loudspeakers on your stereo.

Sound waves are made of stuff: vibrating strings, vibrating air, vibrating eardrums. In quantum theory, physicists apply the same rules to waves of probability: refract a wave function representing a particle through the proper mathematical prism and it becomes a sum—a superposition—of sine waves. Each sine wave represents the possibility that the particle will have a certain momentum. (Square the wave's amplitude—the measure of its "loudness"—and you get the probability.) Refract the wave function another way and you get impulse waves, which represent the particle's possible positions. And the Heisenberg uncertainty principle follows from the fact that sine waves and impulse waves are complementary. A sine wave representing a particle's momentum is a superposition of an infinite number of impulse waves, a haze of possible positions. Pinning down one value with perfect precision smears the other value all over the mathematical map.

We can see, then, what some theorists mean when they say that a quantum particle is pure potentiality, that it doesn't have coordinates until it is observed. Sine waves aren't *really* made of square waves, but we, as observers, are free to break them down that way. We could take our favorite aria and refract each tone into a superposition of square waves, but that doesn't mean that there really are square waves emanating from the soprano's mouth. Likewise, a wave function representing a particle isn't really made of sine waves or impulse waves; these stand-ins for momentum and position exhibit themselves only because we choose to refract the wave function a certain way. The position or the momentum is created by the measurement.

In this interpretation of quantum theory, every attribute of a particle can be thought of as a different prism through which we pass the wave function. Sine waves mean momentum, impulse waves mean position. Other waveforms stand for energy, time, spin, and so forth. But where do we draw the line? Mathematically, a wave can be refracted into a lim-

itless variety of shapes. There is nothing to stop us from breaking up the wave function into sawtooth waves, square waves, tulip-shaped waves, or a superposition of any waveform we randomly scribble. Implicit in the wave function is an infinity of attributes, most of which seem to have no counterpart in the way earthlings carve up the world. A few we have given names to—isospin, charm, strangeness—even though they have no clear physical interpretation. But the vast majority must remain nameless as well as unimaginable.

Why are position and momentum so fundamental to us? Can it be neurological, an accident of evolution? Or a happenstance of the way the universe itself evolved? If we had ended up on a different twig of the evolutionary tree, or in a different universe, perhaps position and momentum would be meaningless while qualities we can only think of as Xness and Yness were second nature. But it is easy to get carried away, taking our symbols for reality instead of as mere tools of description. When are we doing physics? When are we just conjuring with numbers? We build these systems to represent the world, then we are left to wonder what they mean. What is map, what is territory? Is there really any difference at all?

Niels Bohr believed the distinction was meaningless, that all we can hope for is good maps. The problem, he believed, is that the languages, both verbal and mathematical, that have evolved to aid our survival on earth are simply not equipped for navigation in the subatomic realm. "We must be clear that, when it comes to atoms, language can be used only as in poetry," he told Heisenberg one day as they trekked through the German woods. "The poet, too, is not nearly so concerned with describing facts as with creating images and establishing mental connections." Then, Heisenberg asked, "how can we ever hope to understand atoms?"

"I think we may yet be able to do so," Bohr replied. "But in the process we may have to learn what the word 'understanding' really means."

In building an interpretation of quantum theory, the reality behind the mathematics, we have to decide how to lay the foundation. We have two rough choices: either we can take our own world for granted and explain the quantum world in classical terms, or we can take quantum theory as fundamental and try to explain classicality in its terms.

In what has come to be called the Copenhagen interpretation, Bohr and Heisenberg took the first course. The world of phenomena, that which we can observe, is the only reality we can know. Since trying to describe the quantum world in classical terms leads to contradictions and

absurdities, we can only conclude that beneath the surface we see, reality operates in ways that are inscrutable to us. Quantum theory is a kind of triangulation in which complementary pairs of imperfect concepts—wave/particle, position/momentum—are used to home in, as best we can, on phenomena beyond the pale of human nervous systems. The mathematics is not a picture of an underlying reality but simply a tool to describe the baffling interaction between the quantum and classical realms. An observer makes a measurement, the possibilities of the wave function collapse like an accordion, and we get a definite but unpredictable result. To Bohr and Heisenberg it was meaningless to speculate on whether the wave itself is somehow real. At the doorway into the atom, we have reached the limits of our powers. As Heisenberg put it: "What we learn about is not nature itself, but nature exposed to our methods of questioning."

Bohr was fond of saying that there is no deep reality. The confusion that arises when we contemplate the nature of the subatomic world is rooted in a conceptual mistake: our insistence that there is something behind the reflections in our experimental mirrors. All we have is our observations. There is no deeper realm. And even if there were, there is little reason to suppose that our brains would be tuned to understand it. With quantum theory we may have taken the mind as far as it can go.

But there is more than one way of looking at these things. The mathematician John Von Neumann found it arbitrary and anthropocentric to divide the universe into two separate realms, as Bohr and Heisenberg did, giving privileged status to our own. Einstein showed that within the neoclassical world of four-dimensional space-time there is no privileged observatory. Why should we abandon this democracy when we try to enter the subatomic realm? In building his interpretation of quantum theory, Von Neumann assumed it was the quantum world that was fundamental. Classicality was the mystery to explain. One could almost think of our classical world as an aberration, a snapshot taken when an observer makes a measurement and collapses the probability wave.

If quantum theory is indeed universal, then the macroscopic world, like the subatomic world, must be represented by wave functions. When we perform an experiment, the waves of the measuring device interact with the waves of what we are measuring. And the waves of the scientist interact with the waves of the measuring device. Somewhere along the way, possibility becomes actuality. But at what stage does the collapse occur, and what causes it?

a price. The good news is that we don't have to grant a special, God-given status to either measuring devices or consciousness. The bad news is that we have to accept the notion of what seems to be an infinity of parallel worlds.

Suppose we want to measure an electron's spin, determining whether it is "up" (counterclockwise) or "down" (clockwise). Like Von Neumann, Everett assumed that quantum theory was universal, that it applied with equal vigor to the classical realm. So when the wave function of our measuring instrument interacts with the wave function of the particle, the instrument will also be in a superposition of states, spin up and spin down. And when we interact with the instrument, then we will also be in superposition: in one component of the wave, we will discover that the instrument has registered an up spin; in the other component, we will discover that it has registered a down spin. And, for that matter, anything that interacts with us from then on will also be put into superposition, and so on, ad infinitum. The wave function never collapses; instead the quantum limbo radiates forever, giving rise to one universe in which the electron's spin is up and another universe in which it is down.

The big problem here, of course, is to explain why we perceive just one of these outcomes. The Copenhagen and Budapest interpretations cannot explain how we collapse the wave function; the Everett interpretation gets rid of the collapse, but how do we picture such a world? One interpretation, that of the physicist Bryce S. Dewitt, is to imagine that, invisible to us, there really is an identical observer who perceives the other outcome. One of us sees an up-spinning particle, the other a down-spinning particle. If we are measuring something, like position, that can take a range of values, then we split into a range of different observers, each in a different universe. So confident are some physicists of humanity's mathematical powers that they are willing to rely even this most counterintuitive of formalisms. If there are parallel states in the mathematics, then there must be parallel worlds.

But even many who find Everett's formalism the most attractive alternative resist its weirder implications. Zurek and his colleague Seth Lloyd, who frequently works at Los Alamos and the Santa Fe Institute, tried to persuade a cosmologist who subscribed to Everett's "many worlds" interpretation that he should be willing to play Russian roulette for a million dollars. Ultimately, where the pistol's cylinder stopped spinning could be traced to a quantum fluctuation. In one world the cos-

smologist would die, in five other worlds he would be alive and richer. The cosmologist finally conceded that he couldn't imagine taking such a risk. "I wouldn't want to cause my wife such suffering in any of the worlds," he said.

To Lloyd there are compelling reasons to consider only the branch we live in to be real. Samuel Johnson is said to have reacted to Bishop Berkeley's contention that there is no real world, that reality is all in the mind, by kicking a rock: "I refute him thus!" To Johnson, something wasn't real unless we could get information about it. The parallel branches in the Everett formalism are sealed off from one another; no information can flow between them. They are, Lloyd says, the best examples he can imagine of what *isn't* real. They are better thought of not as parallel universes but as possible histories. We can pretend what it would be like if we were in another of these possible worlds. But that is no more metaphysical a problem than the one posed by the movie *It's a Wonderful Life*, where we are asked to imagine what the village of Bedford Falls would be like without George Bailey and the savings-and-loan.

Ever since Einstein said that he found it hard to believe that God plays dice with the universe, some physicists have tried to argue that quantum theory must be incomplete, that the randomness it finds cannot be inherent. Like thermodynamic randomness, it must be subjective, arising from ignorance.

When a photon "decides" whether to bounce off a piece of glass or go straight through, when an electron chooses one slit and not the other, when a nucleus suddenly decays, shooting out a neutron, is the event really indeterminate? Or could there be a hidden mechanism? It is our fate never to know whether a string is random or whether we just aren't clever enough to compress it. As with the numbers emerging from the bingo machine at Tesque, might there be hidden biases, departures from randomness, orders we aren't acute enough to see?

In fact, such a "hidden variable" interpretation of quantum theory is always an option. If cosmologists can posit transparent dark matter, why not posit that the particle in the two-slit experiment is indeed sending out feelers, judging whether one hole is open or two and adjusting its trajectory accordingly? The physicist David Bohm called these hypothetical feelers "pilot waves." With that time-honored method of proposing an

entity that is in principle unobservable, he recast quantum theory in a way we can almost picture in our heads. In this view, first proposed in 1925 by the French physicist Louis de Broglie, electrons, photons, and the like are indeed both particle and wave. Traveling along with the particle, an undetectable pilot wave scouts out the territory, sending back information. The catch to Bohm's interpretation is that it requires us to believe in superluminal communication between the pilot wave and the particle. Again we are faced with the problem that a photon is traveling, by definition, at the speed of light, so any quantum radar beam that it used to probe the environment would have to travel faster.

In fact, a celebrated finding known as Bell's theorem concludes that all hidden variable theories necessarily imply some kind of instantaneous, superluminal contact. Bell reached this conclusion after carefully examining the implications of the notorious Einstein-Podolsky-Rosen paradox. Einstein and his colleagues Nathan Rosen and Boris Podolsky tried to undermine quantum theory by imagining a particle decaying into two particles which, by the laws of physics, must be spinning in opposite directions. According to quantum theory, the pair of particles forms a single system which is in a superposition of possible states. After letting the particles fly apart for miles or even light-years, an observer measures one of them, collapsing its probability wave so that it randomly assumes either an up spin or a down spin. Thereupon, the celebrated punch line: Once we have made this measurement, the second particle will by definition have to be spinning in the opposite direction. Somehow the effect of the first measurement seems to propagate instantaneously across space (or, alternately, backward in time). Since this "spooky" action at a distance seems to violate special relativity, Einstein naturally concluded that it is quantum theory that must be wrong: like classical particles, the two quantum particles must have had definite spins all along, not just when one of them was measured. The uncertainty wasn't inherent; it was simply due to our ignorance.

Bell showed, however, that Einstein was succumbing to wishful thinking. His theorem (later supported by experiments at the University of Paris under Alain Aspect) showed that no purely deterministic theory can explain the behavior of subatomic particles, unless it invokes some kind of "nonlocal," instantaneous connection. And the only way to get rid of this obnoxious notion is to deny the existence of hidden variables. In choosing which way to carve up the quantum realm, we are backed into a corner where we must either accept inherent uncertainty or believe

that particles on the opposite side of the universe can be, in some unfathomable sense, intertwined, that locality is an illusion.

Even if we choose the latter interpretation, Bell's theorem shows that the superluminal connections cannot possibly be used as channels to transmit information instantaneously within the classical realm. It seems that quantum information and classical information are two very different things. Classical information can be read without disturbing it and copied as many times as we wish, but it cannot travel faster than the speed of light. Quantum information—consisting of qubits, as some call them—is capable of these strange EPR effects, but it cannot be read or copied without being fundamentally altered.

In a collaboration with five other scientists, Charles Bennett has proposed that qubits and classical bits might be used for what he calls quantum teleportation. In this scheme, the sender (Alice, she is usually called) wants to transport a quantum particle to the receiver, Bob. Using two channels, one transmitting classical bits, the other qubits, she can send Bob two signals, which he can combine to create a perfect replica of the particle (the original is destroyed in the process).

First they create an EPR pair of quantum-correlated particles. Alice keeps one and Bob takes the other with him to another part of the world. Then Alice performs an experiment, allowing her EPR particle and the particle she wants to transport to come into contact. Since Alice's EPR particle is correlated with Bob's, the disturbance will be instantaneously transmitted to him as qubits. Then, using a classical form of communication—a telephone call, a radio broadcast, a classified newspaper ad—she tells Bob the outcome of the experiment. Then he can use this information to re-create the original particle's state in his EPR particle.

A few scientists, driven by a hunger for a deterministic universe, still hold out hope that the randomness of quantum theory will turn out to be an illusion, that there is a deeper order lingering underneath. At the end of a lecture sponsored by the Santa Fe Institute in 1992, Jim Crutchfield, who moved on from the Santa Cruz roulette collective to become a mathematical physicist at Berkeley, made an offhand remark about the problems arising from quantum theory. "What problems with quantum theory?" Murray Gell-Mann interrupted. "Well," Crutchfield replied, "I guess I am just a diehard determinist." Crutchfield was quick to admit that one can hardly quibble with the overwhelming success of quantum theory in explaining the outcome of particle experiments. But he hopes there is some way to show that the act of measurement *is* deterministic.

of chaotic effect. If that is true, then the random outcome of the collapse of the wave function might be governed by a strange attractor, the hallmark of deterministic chaos. Quantum randomness would be complexity too deep for us to fathom.

So far, though, no one seems to have made any progress in finding chaos beneath quantum randomness. A huge problem is Bell's theorem. Replacing quantum randomness with deterministic chaos would constitute a hidden variable theory, and so, once again, superluminal signaling would sneak in the back door. Some entertain the possibility that perhaps there is a hidden flaw lurking within Bell's network of beliefs and assumptions. Bell assumes, obviously, the ability of mathematics to accurately mirror the physical world. Some doubters have suggested that quantum randomness might somehow arise from the inherent randomness Chaitin found in arithmetic. But so far no one has begun to unravel what all agree is a beautifully knitted argument.

In fact Lloyd, Gell-Mann, Zurek, and others believe that those trying to attribute quantum randomness to chaos are looking through the wrong end of the telescope. Recall the calculation in which the position of an electron at the edge of the Milky Way is amplified by nonlinear interactions until it affects the outcome of a billiards game. From this perspective it appears that the randomness of chaos comes from quantum indeterminacy, not the other way around.

Of course, none of these interpretive contortions would be necessary if we were willing to accept that maps are not territory, that there are limits to our mental powers and our mathematics, that we are stuck with our classical conceptions because of our evolution, that the best we can do is talk about how our classical world and our language interact with the hidden subatomic world. Perhaps such a phenomenon as wave/particle duality simply shows that there can be two internally consistent but mutually exclusive models—human mental constructs—that let us make predictions about the world. We can use the one that works best under the circumstances.

But there is something about the human mind that rebels against limits the way an animal rebels against the bars of its cage. Instead of conceding that maybe our mathematics is not universal and omnipotent, that it is simply a fallible human invention, some prefer to accept its conclusion that causality doesn't exist outside our own domain. How foolish and parochial we were to think it would. With quantum theory, our brains and our mathematics seem strained to the breaking point, yet it is

part of human nature that we keep straining. Never really believing that it is impossible for us to know the ultimate, we seize on quantum theory not as a tool for interpreting experiments but as a statement about how the world really is. In a kind of mathematical transubstantiation, our numbers, like the Word, take on substance and become flesh.