



## THE DEMOCRACY OF MEASUREMENT

In the annals of demonology, Maxwell's imaginary critter, with the ability to keep track of the position of every molecule of gas in a chamber, has an even more venerable ancestor, a being we might call Laplace's demon. While we humans can identify with Maxwell's little imp, frantically gathering bits, scrutinizing the sequences for patterns, trying to squeeze what order it can from the deluge, Laplace's demon sits back calmly, studying the world with the all-seeing eye of God. In his celebration of a completely knowable Newtonian world, Laplace imagined, in the eighteenth century, an intelligence so powerful that, given the position and velocity of every particle in the universe, it could calculate the unfolding of history. Laplace's conclusion has been quoted many times. "For such an intellect," he wrote, "nothing could be uncertain; and the future, just like the past, would be present before its eyes."

These days it is tempting to think of the Laplacian demon as a great computer, an automated version of the Tesuque camel. If the universe were classical and we fed the demon the position and momentum of every particle at a certain instant, it would know all that could be

known. Everything would be implicit in the data stream, including the events that came together to form Laplace and the experiences that marbled his brain, leading ultimately to his proposition that the universe is Laplacian. For this ultimate intelligence, there would be no point in doing science: every experiment ever conducted—including who did it, when and where, how it came out—would be as trivial as the tickings of a clock.

To an all-seeing eye, nothing would ever really happen in this static, Tralfamadorean world. Only its inhabitants, these Maxwellian demons with their tiny brains and blindered senses, would find life interesting. The compensation for ignorance is surprise. Even the most diehard determinist—sure that history is encoded in advance, in the Book of Revelation or (as some Santa Feans would have it) in cosmic pictographs carved somewhere on the etheric plane—would be blessed with never knowing nearly enough to make life a bore.

Even before the emergence of quantum theory, the rise of mathematical chaos spelled the downfall of the Laplacian god. We have learned that even simple, deterministic systems can be ruled by strange attractors. The tiniest change in the initial conditions, the numbers we plug into these seemingly innocent equations, can cause huge, essentially unpredictable swings in the output. Our ignorance is amplified exponentially until within moments it overwhelms all. A tiny imprecision in the measurement of the position of a single particle—an 8 instead of a 9 in the millionth decimal place—would be rapidly compounded until the course of cosmic history was changed. In theory the behavior of such a system is completely determined—it is all there in the initial conditions—but only if they are known with infinite precision. We can still imagine a Laplacian demon, but we have to grant it infinite powers. By definition, an infinitely powerful being can do anything, so Laplace's powerful vision is reduced to a tautology. The universe is completely predictable, but only if you happen to be God.

It may be surprising to realize that for all the inherent unpredictability of quantum theory, the wave function itself is quite well behaved. It is linear with a vengeance. Left unmeasured, it is deterministic, and not in the strange sense of chaotic equations, which are predictable in theory but not in practice. Given the shape of a probability wave at one point in time, we can predict what it will look like later, or we can extrapolate backward and see how it must have looked in the past. The complex of possibilities, all in superposition, evolves in an orderly manner.

when a measurement is made that randomness enters into the picture, as the wave collapses unpredictably into one of the possible states.

The primordial mass of the big bang can be thought of as a particle, and so, the cosmologists tell us, nothing in quantum theory prevents us from imagining a wave equation for the whole universe, with every possible history superposed. Again, we are left with the vision of a world of perfect information, where there doesn't seem to be room for science. Every possible outcome of every experiment that could be done, including the circumstances in which it was conducted, would all be implicit in the quantum wave function of the universe—a universe that, from the outside, would be as tedious as Laplace's machine.

But again, to those of us on the inside, blessed with ignorance, such a world is not boring at all. In our modest attempts to illumine the darkness, to gather information, we shatter the beautifully symmetrical world of pure potentiality—where all unrealized possibilities somehow coexist—into our messy world of specific objects and specific events. By measuring, we break the symmetry, and the outcomes of these quantum experiments inevitably contain a residual bit of uncertainty. To the Laplacian demon, on the outside looking in, our measurements may simply be nodes in the ever-forking maze of Everett space, as our observations cause the universe to split again and again, once for each of the possible outcomes. Behold all the branches simultaneously and nothing appears to happen. In one universe the electron has an up spin, in another universe it has a down spin. But, stuck as we are on our own branch, sealed off from the rest, we see a universe of constant surprise. We look at our instrument and there is a fifty-fifty chance of seeing a down spin or an up spin. We cannot predict which it will be. From our blindered point of view, the quantum dice seem to fall at random.

When we contemplate the mystery of how this quantum limbo gives rise to a real world of measurers and measurements, we run into many of the same problems raised by thermodynamics. The supposedly magical effect of the observer—Maxwell's demon seemed to be able to generate perpetual motion simply by making measurements—was brought back to earth by taking a harder look at what happens when one gathers and processes bits. The key was to realize that there is nothing ethereal about intelligence, that information is physical, that as finite creatures we pay a price for its processing—the energy that it takes to erase our limited short-term memories and start over again. The hope of Wojciech Zurek, Murray Gell-Mann, and others drawn to northern New Mexico's

scientific frontier is that quantum theory and the role of the observer can be demystified in a similar way, by looking at them in terms of information. Working with others around the world, they are crafting a new interpretation of quantum theory and quantum cosmology. Both are built on a scaffold of information.

With both thermodynamics and quantum theory, there is a mismatch between the very small—or at least our conceptual picture of the very small—and what we actually experience. Rules on one level give rise to completely different rules on another level. Viewed individually, molecules conform approximately to the laws of classical mechanics, which are perfectly reversible: a particle can just as readily move from A to B as from B to A. But en masse the particles give rise to a breaking of the Newtonian symmetry: the one-way flow from order to entropy that seems to generate an irreversible arrow of time. If we see a film in which shards of hardened clay fly together to make an Anasazi pot, we can be sure that the projector is running backward.

To those of us in the macroscopic world, the entropy arrow points one way because information is dissipated into the bottomless pit of the environment. Breaking a pot is irreversible because we cannot keep track of the pieces and gather them together again. We have lost the information needed to reassemble the original object. Quantities like pressure and temperature also arise from this inherent ignorance: they are statistical averagings of the individual behavior of more gas molecules than our brains could ever hope to track.

Like the equations of classical physics, the quantum wave function is reversible; it contains no arrow of time. But once the wave function is measured and unpredictably assumes a specific value, we cannot reconstruct it from the way the data happen to break any more than we can confidently go from 4 to 2 + 2 rather than 2 + 1 + 1. Like breaking a pot, breaking a wave function is irreversible. Information is inevitably lost, as we go from a symmetrical world of pure potentiality to an asymmetrical one of actuality, creating randomness along the way. Whether we look through quantum or Newtonian eyeglasses, it is the finite nature of us, the observers, that gives rise to a macroscopic world where things happen, one after another, where the search for pattern inevitably creates randomness—where there is an arrow of time, so that our actions, like our measurements, can never be undone.

How far can we take these parallels? Could classicality itself have some rough equivalence to temperature and pressure within a quantum world?

rance of submicroscopic details? In a letter to Wolfgang Pauli, Heisenberg proposed that "time and space are really only statistical concepts, something like, for instance, temperature, pressure, and so on, in a gas. It's my opinion that temporal and spatial concepts are meaningless when speaking of a *single* particle, and that the more particles there are, the more meaning these concepts acquire. I often try to push this further, but so far with no success."

Part of the difficulty is the crucial difference between classical and quantum ignorance, between the probability of thermodynamics and the probability of the quantum wave. In thermodynamics we assume that all the gas molecules, whose vibrations give rise to what we call temperature, whose collisions give rise to what we call pressure, really have exact trajectories; we are just ignorant of them. The Copenhagen interpretation of quantum theory dictates that a subatomic particle doesn't have a trajectory until it is measured.

And so we are confronted again with this seeming difference between quantum information—qubits—and classical information. We usually think of information as being *about* something. An ordinary object like a marble has color, shape, weight, size—attributes that cling to some kind of underlying stuff. But what about the underlying stuff itself? Once we get to that level, there seems to be nothing but attributes. A marble has mass, color, size. But an electron *is* mass, spin, and charge. A particle is completely defined by its quantum numbers. It is all information. Spin  $\frac{1}{2}$  plus 1 unit of negative charge ( $1.6021892 \times 10^{-19}$  coulombs) plus a mass of  $9.1 \times 10^{-28}$  grams *is* an electron. These are not just labels or qualities exhibited by something underneath. There is nothing underneath. A marble can shrink or grow and still be a marble. Change the attributes of an electron and it is not an electron anymore. Two marbles with the same attributes are still different things; they have nicks and scratches, individual identities. If your daughter's cat is killed or even her goldfish, you cannot replace it with an identical one. With electrons there are no such subtleties. Two electrons are completely interchangeable, like all 3s or all C's.

In both the classical and quantum realms, we can talk about information that is static and information that can change. Leaving aside relativistic considerations, the mass of an accelerating object is fixed while its position and momentum vary. But, again, there is an important difference between quantum particles and what our nervous systems have come to recognize as things. We think of a marble's dynamic attrib-

utes—this extra information about position and momentum—as something that travels along with it; the data inhere in the marble somehow. But with quantum objects it is not so simple. We are told by the mathematics that an electron doesn't have a position or a momentum unless it is measured. Until then it is represented by the various mathematical constructs—Heisenberg's matrices, Schrödinger's waves—that give the probability that, if measured, it will assume a certain position or a certain momentum. It seems as though the dynamic attributes are not just in the electron but in the measurement as well. With the marble, any ignorance we have about its position or momentum comes because the information has not been registered by our brains. An electron is all information, so perhaps it should not be so surprising that it remains incorporeal until it is measured. Information unregistered is nothing at all.

In trying to make sense of quantum theory, some have been led to believe that consciousness, or at least the act of measurement, is necessary to bring about what we consider the real world. But many scientists are suspicious of what sometimes seems like a self-centered attempt to elevate humanity and the classical world we experience to a special, almost God-given role. As Gell-Mann likes to say, "When it comes to quantum theory even the most intelligent people can start talking nonsense."

If we follow the approach of some of the people at Santa Fe and Los Alamos and admit information as another fundamental, along with mass and energy, then quantum theory can be viewed in a subtly different light. All that is required to break the symmetry of the wave function is information processing. Not only are conscious observers superfluous—the theory does not even require artificial observers like photographic emulsions or photoelectric cells. The universe itself might process information just as it processes matter and energy. Seen in this light, our role as informational spiders, stringing and restringing our conceptual webs, is as natural as anything in the cosmos. We try to set ourselves apart from the universe and pretend to see it whole. But we are inevitably a part of what we are observing, and our observations may be but a single circuit in a great web of flowing bits.

At Los Alamos, Zurek and some of his colleagues have been examining the difference between classical and quantum measurements in an attempt to better understand how we come to know the world. The trick, they say, is to follow the information. Where does it go when we make

a quantum measurement? In addition to its static attributes—mass, spin, that which makes it an electron, a photon, or whatever—a quantum particle carries this huge complex of dynamic information: the wave function describing every possible state, and every possible combination of states, that it might assume. When it is measured and takes on one of these states, to the exclusion of all others, what happens to the extra information? Does it dissipate into the environment in an irreversible act of erasure?

One way to approach these questions is to reexamine Maxwell's demon from both the classical and quantum points of view. Recall Szilard's rendering of the thought experiment, in which a single gas molecule is trapped inside a cylinder. The demon inserts a movable barrier in the middle of the cylinder, then determines which side the molecule is on, A or B. Depending on the answer, the demon rigs a rope and pulley to one side of the barrier or the other, in just such a way that it acts as a piston: the molecule pushes against it and performs work. Szilard argued that the only way to ensure that the demon is not getting work for free is to propose that there is a minimum energy cost involved in processing information: recording which side of the barrier the molecule is on and (as is now believed) erasing the information so that another measurement can be made.

Suppose that, looking down upon the demon from a god's-eye view, we want to calculate how likely it is that the molecule is on *either* side A or side B of the partition. We would simply add probabilities: a 50 percent chance that it is on side A plus a 50 percent chance that it is on side B equals a 100 percent chance that it is on either side A or side B.

Szilard treated the single gas molecule as though it were a billiard ball. But the simplest gas molecule, hydrogen, is nothing more than a proton exchanging photons with an electron. It is better described by the rules of quantum theory. Until the demon makes the measurement, the molecule will not actually be on either side, A or B, but in a superposition of possible states. In the quantum version of the experiment, calculating the probability of where the molecule will be is no longer so straightforward. We must add A plus B plus a third term that expresses the fact that until it is measured the molecule is not on either side A or side B but on both sides at the same time. The two possibilities, side A and side B, stick together in superposition, interfering with each other. They "cohere." But once the demon makes a measurement, the possibilities come unstuck; they "decohere." The molecule assumes either position A or position B.

Suppose the demon and its apparatus are inside a black box and we are wondering what is going on inside. Before the measurement, our ignorance, like the demon's, is quantum and must be expressed by the three-term equation:  $A + B +$  the interference term. After the demon makes the measurement, we on the outside still don't know the answer. But simply knowing that a measurement has been made converts our ignorance from quantum to classical. We now can say that there is a 50 percent chance that the molecule is on side A or side B. Somehow in the act of measurement, the third term has disappeared. Now a particle can be said to have one position or another, not every possible position at once. The transition from quantum to classical seems to require this unsticking of possible outcomes, this phenomenon quantum theorists call *decoherence*.

In a more complex quantum system, we would have a longer equation with a term for every possible state of the particle, but always, tacked onto the end, will be the interference term, showing all the conceivable quantum juxtapositions that we never see in our world: particle in both positions A and B, in positions A, B, and C, in positions A and C, or B and C. Zurek wondered if the interference term could be thought of as information that is erased when we collapse the wave function. When we make a quantum measurement, these bits rapidly dissipate beyond our reach. Imagine the wave function as a sphere of glass. Hit it with a hammer and it shatters. The information in the interference term consists of the instructions for how to put the pieces back together again. Or, to stretch the metaphor, it is a kind of mathematical glue. In its absence, all the possibilities come unstuck and we are left with the familiar situation where something can be in only one state at a time.

Using this idea of decoherence—lost information—we can see the two-slit experiment, that paradigmatic example of quantum queerness, in a new light. First imagine the classical version, in which we are working with bullets. They shoot from a gun with a range of initial trajectories, some passing through slit A, some through slit B. The gun is not perfect, so if we open one hole, we get a probability distribution that might look like this:



BELL CURVE

What this bell curve tells us is that most of the bullets land in the center, many land near the center, but chance fluctuations cause a few to land farther away. Since we are dealing with classical particles, if we open both slits simultaneously the probability curve is simply  $A + B$ :



OVERLAPPING BELL CURVES

If we repeat the experiment with electrons, and open first one slit and then the other, we get the same two humps. But if we open both slits at once we get a quantum interference pattern:



INTERFERENCE PATTERN

Mathematically, this can be represented by the three-term equation  $A + B +$  the interference term—the information that causes the possible outcomes to stick together, allowing the electron to act like a wave and flow through both slits.

When we put detectors at the slits so we can measure which way the electrons go, we get the two-humped classical distribution again. The detectors apparently cause decoherence. As they measure the particle, collapsing the wave, they siphon off the excess information, the interference term. The possibilities split apart and the particle goes through either slit A or slit B. Where does the information go? It is dissipated into the environment.

As a final variation on the experiment, imagine that instead of shooting the electrons through a vacuum, we shoot them through a gas of photons dense enough to ensure a reasonable chance that the quantum bullets will interact with the medium. The interference is gone and we get the classical distribution pattern again. Apparently we don't need a measurer or even an inanimate detector to cause decoherence. It seems that the environment itself can absorb the excess information and cause the possible outcomes to come unglued.

And there lies the beauty of this interpretation: there is no reason to give special status to an observer or to sanctify the measurement act.

Anything that can absorb information can be thought of as making a measurement. The collapse of the wave function can be shifted from the observer and placed on the environment itself.

"The essence is that the environment 'knows'—it has a record," Zurek said. "It takes the burden of having to collapse the wave function. We can blame the collapse on the watchful eye of the environment." Or as Zurek put it in his manifesto on information physics: "It is as if the 'watchful eye' of the environment 'monitoring' the state of the quantum system forced it to behave in an effectively classical manner."

Like the inevitable fall from order to entropy, this loss of quantum coherence is irreversible. According to the second law of thermodynamics, the entropy arrow points one way because, as the disorder of the universe increases, information is dissipated beyond retrieval. If we knew the speed and direction in which each shard of the shattered pot was flying, we could theoretically reverse their many courses and cause them to reembrace. This lost information is out there somewhere: in the vibrations of air molecules disturbed by the moving pieces. But these air molecules disturb other air molecules and the information scatters.

Likewise, the quantum-to-classical transition cannot be undone, because the extra information in the wave function is irretrievably scattered throughout the environment. The air molecules in the atmosphere, photons streaming from the stars—even in deep, dark space, the cosmic background radiation is there, interacting with quantum particles, causing decoherence, spiriting away the excess information at the speed of light. And, as Zurek says, you can't catch up with a photon. The environment is monitoring everything all the time, collapsing wave functions, bringing hard-edged classicality out of quantum mushiness.

Like a city saturated with sounds, the universe is saturated with the information from these constant measurements. We simply eavesdrop on the conversation. Like a mechanic measuring the pressure of a tire, or an electrician the voltage of a wire, we bleed off a tiny amount of information.

We are used to thinking of the difference between quantum and classical as the difference between the very small and the very large. Zurek sees it instead as the difference between a system that is closed and a system that is open. A completely closed system—one that is interacting with nothing—is represented by the pristine symmetry of the wave function, with every possible state and every possible combination of states in superposition, interfering with one another. In its unmeasured state, a

quantum die would read six and one at the same time—and two and five, and three and four and five and six, and so on. But, in Zurek's view, these arbitrary superpositions are extremely unstable; they can survive only in a closed system. When we open up the system—forcing it to interact with the environment—they dissipate so rapidly that they cannot be retrieved. Only a small fraction of the possible outcomes that coexisted in the wave function are stable enough to endure on their own—the ones that behave classically, in which something can be in only one state at a time.

There are still many possible outcomes (six for the quantum die) left for us to contend with, but these are now probabilities that are knowable. So we go from quantum ignorance to classical ignorance, from inherent randomness to randomness rooted in what we don't yet know. The interaction with the environment acts like a sieve: it sifts the wave function, leaving a set of classical probabilities. Then we resolve our classical ignorance by measuring and gaining information.

The environment can be thought of as any system large enough to absorb the excess information and bring about decoherence. In this demoracy of measurement, we cannot really say which is the observer and which is the observed. The photon leaves an imprint on our retina; our retina leaves an imprint on the photon. Measurement is simply the correlation of two systems, which go away from the encounter with a record of each other.

The result of all this is what we might call the classical illusion. Once decoherence occurs, all the pieces of the wave—even the weird juxtapositions—are echoing through the environment somewhere. But all we experience is the classical outcomes, where something is in one place at a time. For it is only these classical states that are stable, long-lasting, and predictable. We can measure them without fundamentally disturbing them, recording the information in our brains. There is no reason for our senses to perceive the superposed states, which dissipate so rapidly. They carry no meaning for us, they are invisible to our information processing. "Our senses did not evolve for the purpose of verifying quantum mechanics," Zurek has written. "Rather, they developed through a process in which survival of the fittest played a central role. And when nothing can be gained from prediction, there is no evolutionary reason for perception."

It is only when we can make stable records—memories—of something that it can be said to exist. Two things must leave imprints on each

other to be mutually real—i.e., in the same universe. Decoherence makes possible information exchange, and it is only through information that we can know the world.

All of this goes a long way toward painting a picture in which classical probabilities arise from quantum uncertainty, without the need for observers. We are dealt this hand of premeasured, "decohered" states, but why do we experience just one of them? In the terminology of Everett and the many worlds interpretation, we make a measurement and the universe splits into branches: one in which the molecule is on side A, one in which it is on side B; six branches for each role of the die. But nothing in Everett explains why we are stuck on just one of the branches.

Zurek believes decoherence may hint at an answer. We have to remember, he says, that in this democracy of information exchange, our brains are also being measured by the environment. As we observe the die, neurons are momentarily placed in superposition between all the possible juxtapositions. But our brains are not closed systems. Blood brings in nutrients, carries off wastes. Networks of neurons send signals to one another. And so the superposed brain states decohere long before we are aware of them. The nonclassical states—the die simultaneously showing two, five, and six—are instantly spirited away. The brain, just like the die, will still be left with a variety of premeasured classical states, i.e., Everett branches. But here is the crux of the argument: there will be only one branch in which the die says six and our brain says six. That is the one that we perceive as real.

"Decoherence is preventing our brain from getting into these funny superpositions," Zurek said. "There is only one option in which I see the cup here and it is here. So we are in one state of mind at any one time and that state of mind is correlated with one state of the universe."

"It is sort of the reverse of the observer creating reality. The universe through your senses adjusts the record in your brain."

While Zurek is trying to use decoherence to understand the quantum measurement problem, some physicists are trying to apply the notion to the most fundamental wave function of them all—the one said to have emanated from the big bang. Zurek's colleague and intellectual sparring partner Murray Gell-Mann considers Zurek's interpretation a huge improvement over those that sanctify consciousness or the measurement act. But he feels that decoherence needs to be reexamined.



exceedingly abstract realm of quantum cosmology. Working with James Hartle, a cosmologist associated with the University of California at Santa Barbara and the Santa Fe Institute, Gell-Mann has been attempting to understand that earliest instant when the universe was nothing but a primordial mass, no larger than a subatomic particle, emerging from the vacuum.

A world so tiny should by all rights obey the same laws as a photon or an electron. But how did the wave function of this ancestral "particle," with all its possible histories hovering in superposition, interfering with one another, give rise to our particular world? The old Copenhagen interpretation of quantum theory cannot begin to answer the question. "What was being measured when the universe was the size of an elementary particle?" Hartle asked. "You can't divide the system into observer and observed." It is fine to speak in terms of closed systems becoming open, interacting with their environment. But the universe, by definition, has no environment. There is nothing outside it. How do we think of decoherence in a system that remains forever closed?

Instead of talking about the environment, Gell-Mann prefers to cast quantum theory in terms of what he calls coarse-graining. One can always look at a system at different levels of abstraction. A very fine-grained description of a beach would include the position of every grain of sand. Viewed from a higher vantage point, the details become smeared together, the grains become a smooth expanse of brown. At this coarser level of description, different qualities emerge: the shape of the coastline, the height of the dunes. Could the qualities we call classical also emerge this way, a product of one's point of view?

A fine-grained description of the universe, the finest there could be, might include every possible position every particle could assume at every moment in time. (Or the description might include every particle's possible momentum—Heisenberg's uncertainty principle barring the possibility of knowing both.) In this most detailed of descriptions, all the information in the wave function would be accounted for, and all the possible histories would hover together in superposition. Like the possible histories in the two-slit experiment (particle through slit A, particle through slit B, particle through slits A and B), they interfere with one another, making it impossible to assign classical probabilities. In this state of pure potentiality, it is meaningless to say that a particle might be here or there. But if we look at the universe through a coarser mesh—folding only certain things and ignoring everything else—the details of

our description blur together like the grains of sand on the beach. If the description is coarse enough and done from just the right angle, the interference terms cancel one another out. The extra information is washed away. Now we can say that a particle is in one place or another and not in every possible place at once.

As Gell-Mann sees it, getting to the world of everyday existence requires still another level of coarse-graining. We live in a world where quantum effects are often negligible, where the motion of objects can be approximated to a remarkably accurate degree by classical Newtonian mechanics—a world he calls the *quasi-classical realm*, reminding us that nothing is purely Newtonian. The quality that allows for this stability is inertia: we must have objects that are large enough to resist tiny perturbations like those caused by photons bouncing against them. And so the description must be coarse enough that particles blur together into objects like billiard balls and planets.

Now this might still sound a little subjective. Who is devising these descriptions, these coarse-grainings? Physicists? God? But suppose, Gell-Mann asks, that there is a level of description coarse enough for all the possible histories to decohere, and coarse enough for inertia to emerge, but not the slightest bit coarser. This domain of "maximal" coarse-graining can be thought of as an objective feature of the universe, not dependent on the myopia of a particular observer. It is from this vantage point that physicists and astronomers behold creation.

Gell-Mann's interpretation is more general than Zurek's. The information that is ignored in coarse-graining can be thought of as the environment. Whichever way we think of decoherence, the essential point is that quantum information is lost somehow, banishing quantum interference and allowing a quasi-classical world to emerge.

But not every imaginable universe would decohere. In the primordial wave function emanating from the big bang, all possible histories—these potential universes—are suspended in superposition. Only some can be coarse-grained in such a way that the interference terms cancel out. The others remain stuck in quantum limbo. Whether a universal waveform includes histories, like ours, that decohere depends on the initial conditions of the big bang, the way the knobs were set at the moment expansion began.

One of the main goals of quantum cosmology is a theory of the universe's initial conditions, a compelling logic for why the knobs had to be set a certain way. Whether we are trying to describe the universe's

arrow arcing parabolically against the sky or the orbit of the earth around the sun, our laws of physics are cast in a certain form. On one end, which we can think of as the input, are slots for the initial conditions, the way something is at a certain time. Suppose that given the position at time  $t$  we want to know the position five seconds later. We plug the numbers into the equation and switch on the mathematical circuitry. Out from the other end the answer emerges. Unless we know the initial conditions, the law is useless.

But where do the initial conditions come from? We measure them, of course, but what if we want an explanation of how they arose? If we use the equation to extrapolate backward, we can calculate the conditions at an earlier time. Moving farther backward, we can show that these depend on conditions earlier still. But eventually our regression must bottom out: in the case of the arrow, the farthest back we can go is to the conditions with which it left the bow. And how do we explain the origin of these parameters? Only by considering the details of the bow and the archer. Unless we are willing to take these as given, we are led into the vast web of contingencies that conspired to put a bow of this type in the hands of an archer with these characteristics at this point in space and time.

In the case of the earth, we could trace the initial conditions back to the swirl of the cosmic dust cloud from which the solar system is said to have congealed. And if we wanted to know why the cloud was moving in just such a manner, we would have to extrapolate back further, eventually reaching the big bang. We always have to stop somewhere and take the conditions as given. Otherwise every calculation would have to take into account the history of the universe.

It is not just the past of a particular object that is abbreviated by the initial conditions. No classical system is an island, and so every measurement of the earth in its orbit or an arrow falling through the air reflects the gravitational perturbations of the rest of the universe, the distant tug of the stars. The effects of this vast web of influence, which we can lump together and call the environment, are implicit in the initial conditions we plug into the equations. The initial conditions act as a stand-in for everything we are leaving out.

But how are we to think of the initial conditions of the universe, of the big bang itself? This is where the buck stops, where all regressions must end. By definition, the universe is everything. Nothing is left out. The initial conditions, then, must be part of the fundamental laws.

Astrophysicists since Sir Arthur Eddington, in the years before World War II, have marveled at the ways in which the universe seems too good to be true. Anyone who follows popular science writing has heard the litany: if its expansion rate were a little slower, the universe would have collapsed in on itself; if it were slightly faster, there wouldn't have been the leisure for structures like galaxies to form. If something called the "fine structure constant," the square of the charge of the electron divided by the speed of light multiplied by Planck's constant, were about 1 percent different from what it is, then the universe would be unrecognizable, perhaps uninhabitable by anything remotely like us. These are the kinds of cosmological coincidences that so impressed John Updike's character Dale Kohler, a young computer scientist, in the novel *Roger's Version*.

What was it about the initial conditions that led to a universe like the one we see today? A universe that, viewed through the coarse mesh of our telescopes, seems fairly homogeneous—whatever way we look things appear pretty much the same. A universe that seems approximately "flat," with just the right density of mass to keep it delicately poised between open (expanding forever) and closed, doomed to eventual collapse. A universe in which the possibilities bound together in the wave function decohere, giving rise to a classical domain.

How did the knobs get set in just such a way? Why should we be so lucky? Why, against all odds, are we here, seemingly equipped with the neurological and mathematical tools to make sense of it all (or at least to give ourselves that illusion)? These seeming coincidences have been a comfort to those who seek scientific evidence for the existence of an Almighty God, who made the universe just so. Those more taken with Sartre than with the Holy Bible revel in another interpretation: we are flukes of a random, unfeeling universe. If the initial conditions had been set another way, there would be no stars, no planets, no astronomers.

In recent years, science has been reversing this perspective, looking through the other end of the telescope. Instead of attempting to explain how the universe gave rise to life, they start with life as a given and work the other way. Given that we are here, the initial conditions must have been a certain way. This approach is called the weak anthropic principle to distinguish it from the stronger version. In the weaker rendition, it is not that observers create reality, or are part of a symbiotic circuit in which the universe gives rise to observers which give rise to the universe by collapsing the wave function. The claim is simply that the universe



observers puts some constraints on the initial conditions, narrows the search.

Even this weaker version of the anthropic principle seems maddeningly tautological to some: the initial conditions had to be a certain way because otherwise we wouldn't be here to wonder about it. Some find the concept more satisfying if they are willing to buy the argument that there is not just one universe but many, maybe an infinite number, each arising from a different set of initial conditions. Only a tiny fraction of them give rise to life. Then the fact that life arose in this universe is no more remarkable than the fact that cities tend to arise at the juncture of rivers. There are still vast deserts—uninhabitable universes—where nothing blooms.

We could think of each of these other universes as possibilities rather than actualities, as paths through Everett space. Or we could take them quite literally. The version of the big bang theory called the inflationary scenario suggests a way multiple universes might be made: an instant after the big bang, a tiny patch of space-time could undergo hyperinflation, ballooning into an entire universe. Thus an arbitrary collection of random initial conditions would be amplified into what we marvel at as natural laws and constants. There is no reason why this couldn't happen many times, leading to a population of universes, each sealed off from the others by the upper limit of the speed of light and each operating according to a different physics. Or those who believe we live in an oscillating universe, with big bang followed by big crunch followed by big bang again, might suppose that each time the cycle begins anew the dials are randomly reset. In this view, the multiple universes are spread out in time rather than space. Naturally we find ourselves living in an incarnation where the laws favor life. But these laws, which we take as sacrosanct, would be accidents. The masses of the particles, the fact that there are three families of quarks, four forces, even the fact that there are three spatial dimensions (of the ten proposed by the superstring fans), might all be frozen accidents, outcomes of dice that could easily have landed another way.

For those who find the notion of multiple universes too spooky or the anthropic principle dissatisfying, but who are unwilling to see life as a miracle or a fluke, there is another recourse. They can adopt the approach favored by Hartle, Gell-Mann, Stephen Hawking, and others and look for some deep principle, an internal logic that dictated that the initial conditions had to be a certain way. When we look at the universe

through our particular set of spectacles, we see laws and we see initial conditions. But why should this duality necessarily apply to the origin of the universe? If a way can be found to show that only certain settings of the knobs were possible, then the notion of laws and the notion of initial conditions would be one and the same. Cosmologists are still a long way from such a law, which would amount to no less than a precise description of the wave function describing the big bang. "The subject is in a rather primitive state," Hartle said. "It looks encouraging but there is a long way to go."

There is, for example, the problem of time. Wave functions evolve over time, but in the first instants of the universe the geometry of space-time is not fixed. It is subject to quantum fluctuations. "If you have two points you can't even tell if they are space-like separated or time-like separated," Hartle said. "So, in some sense, time as a fixed notion breaks down. That means you have to generalize the notion of quantum mechanics further so that it doesn't require a preferred time."

In collaboration with Stephen Hawking, Hartle has proposed a theory of the initial conditions—a wave function of the universe—in which, because of quantum effects, time and space are, in the beginning, indistinguishable. Most scenarios view the universe as a cone expanding from the singularity called the big bang. In this picture, time is represented by the vertical axis, the height of the cone, while the spatial dimensions of the universe are represented by the cone's circumference. Following along the cone's axis, the circle gets bigger and we have the notion of a universe expanding in time. But there is something arbitrary and inelegant about a universe that begins at a precise moment. Why then and not at some other time? And, as most cosmologists believe, if time, like space, began with the big bang, then what could it mean to say that the universe came into existence at a certain instant?

In the Hawking-Hartle picture, the base of the cone is not a singularity but a hemisphere. On this curved surface, time, the vertical direction, bends around, until it becomes indistinguishable from the horizontal, spatial dimensions. Time, like space, is simply a direction on the surface of a four-dimensional hemisphere. The universe could be said to unfold from any point on this surface. It makes no more sense to say that the universe began at a certain moment in time than it does to say that it began at a certain point in space. But begin it did, and as it unfolded, time gradually split off from space—the symmetry between them broke—leaving us with what Einstein called space-time. While the old calculation

universe seems to require something outside of it to "decide" when to press the creation button, Hartle and Hawking contend that their universe is mathematically self-contained. And, as Gell-Mann has argued, the Hartle-Hawking wave function can be derived from superstring theory, suggesting that particle physics and cosmology might be tied together with a single bow.

There are still unanswered or unanswerable questions. Though the theory avoids the need for an outside Creator, it presupposes the prior existence of quantum theory and mathematics. Again the notion of a platonic netherworld beyond time and space sneaks in the back door. The best argument for the model so far seems to be its aesthetic appeal to those in search of a self-consistent, all-embracing system. If we want a universe that does not arbitrarily begin at a certain instant, we may have to restrict our search to those primordial wave functions that behave like Hartle and Hawking's round-bottomed cone. And if we want a creation story that can explain why the world we inhabit is so different from the world generated by the equations of quantum theory, then we must also restrict the search to wave functions capable of spawning universes that decohere.

But a wave function alone is not enough to explain how our own world, with its extravagance of detail, came to be. With his Eightfold Way and later developments, Gell-Mann showed how to reduce the hundreds of subatomic particles to a handful of quarks: at the roots of complexity was simplicity—if you are willing to allow that six flavors of quarks, each available in three colors and dancing with eight kinds of gluons, qualify as a simple system. In more recent years he has been gazing in the other direction and contemplating how simplicity gives rise to complexity. This is the question that drove him to help found the Santa Fe Institute. How, as he puts it, do you go from the quark to the jaguar? How did the universe become such an interesting place to live? In developing a theory of complexity, physicists are assuming that, in the beginning, there was very little information, just a few simple settings of the celestial knobs. How did we get to a universe teeming with structure, with galaxies and galaxies of galaxies? This is the question that has plagued so many cosmologists, compelling them to come up with more and more dark matter. In quantum cosmology the question arises in another, more fundamental form.

"According to the microwave background, which is as close as we can get to a picture of the universe in the early stage, there's practically no

structure whatsoever," Hartle said. "What emerges is an early universe of remarkable simplicity. If there is a simple law of the initial conditions, it cannot contain much information, and therefore it certainly cannot describe the present complexity we see about us."

In fact, an explanation in which the information of the classical realm is implicit somehow in the wave function of the universe would constitute a hidden variable theory, which implies some kind of superluminal signaling. The implication is that the complexity of the universe was not encoded at the beginning but is injected along the way. "The present complexity we see about us arises mostly from the accidents of our particular history," Hartle said, "the particular rolls of the quantum-mechanical dice that have occurred since the beginning."

The rough features of our universe—cosmological flatness, the fact that it decoheres—may have been implicit in the initial conditions of the big bang. But the exact details—the order of the planets in the solar system, the shape of the Milky Way—are the accidents arising from a series of quantum splittings.

"In quantum cosmology we don't hope to predict from the wave function of the universe alone whether you sat in that chair or another chair or the number of planets in the solar system or the particular arrangement of galaxies in the sky," Hartle said. "Most things are not predictable from the initial conditions alone but only from the initial conditions *plus* the particular things that have happened in our particular history."

The history of trying to understand the world is replete with cherished fundamentals that were later abandoned as not so fundamental after all: the centrality of the earth was thrown out by Copernicus, the centrality of Euclidean geometry by Einstein's general theory of relativity, with its curved space-time; the wall between subject and object was breached by quantum theory; quantum cosmology may be on the verge of eliminating the distinction between initial conditions and laws. As Gell-Mann said in a speech at the Smithsonian Institution in 1987, important new ideas almost always are accompanied by "unnecessary intellectual baggage," prejudices that must be abandoned if we are to reach a deeper understanding.

We have seen how some cosmologists have concluded that we can't understand the universe unless we posit that as much as 99 percent of it is invisible. In a further attempt to squeeze creation into a simple set of

equations, we are asked to see the classical world as an aberration, a special case of that which is held paramount: the equations of quantum theory. What we take for granted seems less and less significant all the time.

Still, there is something comforting about another implication of this scenario: the notion that information-gathering beasts may have been implicit in the big bang, written into the initial conditions. Only certain primordial settings would give rise to universes in which decoherence is possible and thus to a world with a classical domain, where it is possible to make partitions, to engage in coarse-graining, to divide subject from object, to process information—a world orderly enough for information-gathering-and-utilizing systems, "Igueses," as Hartle and Gell-Mann call them, to arise.

So perhaps, in a very general sense, we are not flukes of the universe. The particular form we have assumed may be the outcome of a series of accidents, a branching chain of contingencies. But the fact that we live in a universe that allows for information processing may be a necessary (or at least highly probable) outcome of the initial conditions. We don't need the anthropic principle, weak or strong, to feel at home. Given a universe that allows for classicality—where things can be measured without setting them hopelessly askew—it is not surprising that Iguseses of some sort would arise to exploit the situation, beings that live off information.

If we rack up a set of billiard balls and send the cue ball racing toward them, balls bounce off balls and against the edges of the table. But the ricocheting soon stops. If we walked into the poolroom and saw the balls lying scattered across the felt, we couldn't work backward and calculate the initial condition: how and where they were arranged on the table. But though the balls stop, the bils keep flying. How fast the yellow ball was going when it struck the red one, where on the table the green ball bounced and at what angle—all this information is dissipated into the environment as heat. Though the signal gets weaker and weaker, its echoes remain; molecules in the environment have been rearranged, a recording has been made. We can imagine a beast whose perceptions are so acute that it could measure the changes caused by the thermal vibrations of the molecules, then use the data it collected to calculate backward and reconstruct the beginning of the game. Remember Maxwell's glass of water dumped into the sea. It is not really gone. We just lack the wherewithal to track all the molecules and retrieve them.

Nor does the information that dissipates during decoherence disappear. It is still in the universe somewhere, like the television shows that

radiate forever into space. A being who could follow every bit of information exported into the environment when a wave function unraveled would be like the quantum version of the Laplacian demon: it wouldn't see a classical world with objects in single locations moving at certain speeds. It would just see all the possibilities.

In fact, it would be impossible for such a being to exist. For one thing, much of the decoherent information is carried away by photons; it is impossible to follow because it escapes from us at the speed of light. Einstein's special relativity helps bring about the classical domain by setting an upper limit to the power of perception. But even more basic is this paradox: the demon's acuity would ensure that the possibilities in its own wave function never decohered. It too would be stuck in the limbo of potentiality.

If the quantum theorists are right, we and the classical world we live in exist because it is impossible to be so acute as the demon. Information-gathering-and-utilizing systems can arise because it is possible to ignore a huge amount of detail, to engage in coarse-graining. We partition the universe into an area of interest and an environment to which we can banish excess information. And so we can make rough predictions. Iguseses exist by virtue of this myopia, this inherent inability to keep track of every detail. If you know everything, you know nothing.