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MANY COSMOLOGISTS NOW ACCEPT THE EXTRAORDINARY IDEA THAT what seems to be the entire universe may actually be only a tiny part of a much larger structure called the multiverse. In this picture, multiple universes exist, and the rules we once assumed were basic laws of nature take different forms in each; for example, the types and properties of elementary particles may differ from one universe to another.

The multiverse idea emerges from a theory that suggests the very early cosmos expanded exponentially. During this period of "inflation," some regions would have halted their rapid expansion sooner than others, forming what are called bubble universes, much like bubbles in boiling water. Our universe would be just one of these bubbles, and beyond it would lie infinitely more.

The idea that our entire universe is only a part of a much larger structure is, by itself, not as outlandish as it sounds. Throughout history scientists have learned many times over that the visible world is far from all there is. Yet the multiverse notion, with its unlimited number of bubble universes, does present a major theoretical problem: it seems to erase the ability of the theory to make predictions—a central requirement of any useful theory. In the words of Alan Guth of the Massachusetts Institute of Technology, one of the creators of inflation theory, "in an eternally inflating universe, anything that can happen will happen; in fact, it will happen an infinite number of times."

In a single universe where events occur a finite number of times, scientists can calculate the relative probability of one event occurring versus another by comparing the number of times these events happen. Yet in a multiverse where everything happens an infinite number of times, such counting is not possible, and nothing is more likely to occur than anything else. One can make any prediction one wants, and it is bound to come true in some universe, but that fact tells you nothing about what will go on in our specific world.

This apparent loss of predictive power has long troubled physicists. Some researchers, including me, have now realized that quantum theory—which, in contrast to the multiverse notion, is concerned with the very smallest particles in existence—may, ironically, point the way to a solution. Specifically, the cosmological picture of the eternally inflating multiverse may be mathematically equivalent to the "many worlds" interpretation of quantum mechanics, which attempts to explain how particles can seem to be in many places at once. As we will see, such a connection between the theories not only solves the prediction problem, it may also reveal surprising truths about space and time.

QUANTUM MANY WORLDS

I CAME TO THE IDEA of a correspondence between the two theories after I revisited the tenets of the many-worlds interpretation of quantum mechanics. This concept arose to make sense of some of the stranger aspects of quantum physics. In the quantum world—a nonintuitive place—cause and effect work differently than they do in the macro world, and the outcome of any process is always probabilistic. Whereas in our macroscopic experience, we can predict where a ball will land when it is thrown based on its starting point, speed and other factors, if that ball were a quantum particle, we could only ever say it has a certain chance of ending up here and another chance of ending up there. This probabilistic nature cannot be avoided by knowing more about the ball, the air currents or such details; it is an intrinsic property of the quantum realm. The same exact ball thrown under the same exact conditions will sometimes land at

IN BRIEF

The theory of cosmic inflation, which implies that the early cosmos expanded exponentially, suggests that we live not in a universe but a vast multiverse.

The problem with the multiverse idea, however, is that all events that can occur will occur infinitely many times, ruining the theory's predictive ability.

Physicists realized they can resolve the issue by viewing the multiverse as equivalent to a notion from quantum mechanics called the many-worlds interpretation, which suggests that our universe is one of many that coexist in "probability space" rather than in a single real space.

HUBBLE SPACE TELESCOPE'S Ultra Deep Field shows galaxies as far as 13 billion light-years away. Objects much farther out will forever be beyond reach because the expansion of space causes them to recede faster than the speed of light. This so-called cosmological horizon has important implications for the theory of the multiverse.

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point A and other times at point B. This conclusion may seem strange, but the laws of quantum mechanics have been confirmed by innumerable experiments and truly describe how nature works at the scale of subatomic particles and forces.

In the quantum world, we say that after the ball is thrown, but before we look for its landing spot, it is in a so-called superposition state of outcomes A and B—that is, it is neither at point A nor point B but located in a probabilistic haze of *both* points A and B (and many other locations as well). Once we look, however, and find the ball in a certain place—say, point A—then anyone else who examines the ball will also confirm that it sits at A. In other words, before any quantum system is measured, its outcome is uncertain, but afterward all subsequent measurements will find the same result as the first.

In the conventional understanding of quantum mechanics, called the Copenhagen interpretation, scientists explain this shift by saying that the first measurement changed the state of the system from a superposition state to the state A. But although the Copenhagen interpretation does predict the outcomes of laboratory experiments, it leads to serious difficulties at the conceptual level. What does the "measurement" really mean, and why does it change the state of the system from a superposition of possibilities to a single certainty? Does the change of state occur when a dog or even a fly observes the system? What about when a molecule in the air interacts with the system, which we expect to be occurring all the time yet which we do not usually treat as a measurement that can interfere with the outcome? Or is there some special physical significance in a human consciously learning the state of the system?

In 1957 Hugh Everett, then a graduate student at Princeton University, developed the many-worlds interpretation of quantum mechanics that beautifully addresses this issue—although at the time many received it with ridicule, and the idea is still less favored than the Copenhagen interpretation. Everett's key insight was that the state of a quantum system reflects the state of the *whole* universe around it, so that we must include the observer in a complete description of the measurement. In other words, we cannot consider the ball, the wind and the hand that throws it in isolation—we must also include in the fundamental description the person who comes along to inspect its landing spot, as well as everything else in the cosmos at that time. In this picture, the quantum state after the measurement is still a superposition—not just a superposition of two landing spots but of two entire worlds! In the first world, the observer finds that the state of the system has changed to A, and therefore any observer in this particular world will obtain result A in all subsequent measurements. But when the measurement was made, another universe split off from the first in which the observer finds, and keeps finding, that the ball landed at point B. This feature explains why the observer—let us say it is a man—thinks that his measurement changes the state of the system; what actually happens is that when he makes a measurement (interacts with the system), he himself divides into two different people who live in two different parallel worlds corresponding to two separate outcomes, A and B.

According to this picture, humans making measurements have no special significance. The state of the entire world continuously branches into many possible parallel worlds that co-