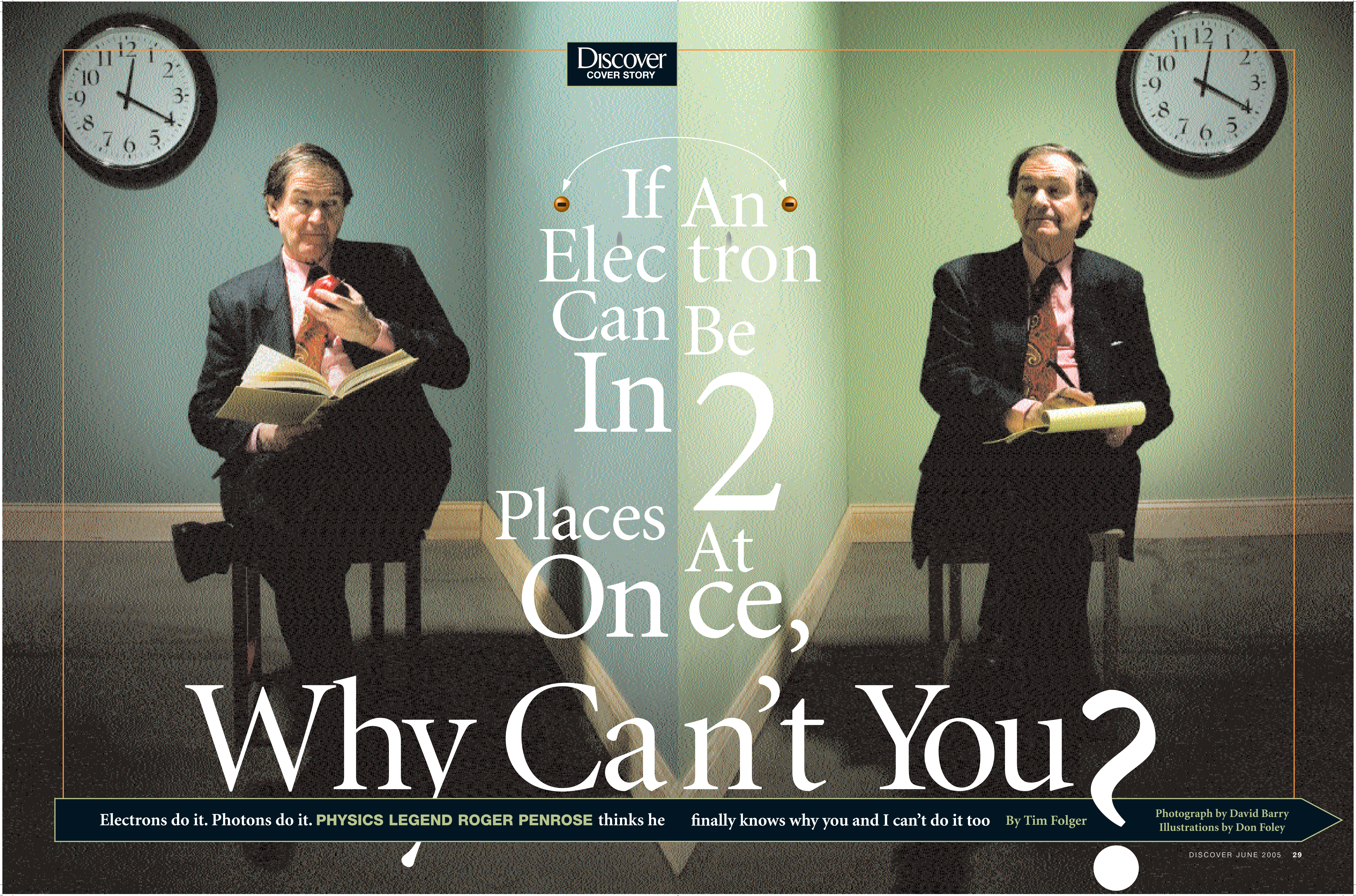


If An Electron Can Be In 2 Places At Once, Why Can't You?

Electrons do it. Photons do it. **PHYSICS LEGEND ROGER PENROSE** thinks he finally knows why you and I can't do it too

By Tim Folger

Photograph by David Barry
Illustrations by Don Foley

Sir Roger Penrose

—Knight of the Realm, Emeritus Rouse Ball Professor of Mathematics at Oxford University, controversial author, and polymath extraordinaire—is worried that his car might be towed. It is parked in a temporary space beside Oxford's Mathematical Institute, where we've arranged to have the first of our meetings. So before settling down to discuss his solution to one of the greatest mysteries in physics, he hustles out a couple of times to make sure the car is still there, displaying impressive bursts of speed for a 73-year-old.

I am sure that he would like to be in two places at once: here in an otherwise empty conference room with me and outside in the chill autumn rain, keeping an eye out for the bobbies. That's impossible, of course, and therein lies the mystery that consumes Penrose.

About 80 years ago, scientists discovered that it *is* possible to be in two locations at the same time—at least for an atom or a subatomic particle, such as an electron. For such tiny objects, the world is governed by a madhouse set of physical laws known as quantum mechanics. At that size range, every bit of matter and energy exists in a state of blurry flux, allowing it to occupy not just two locations but an infinite number of them simultaneously. The world we see follows a totally different set of rules, of course: There's just one Oxford University, just one car, just one Penrose. What nobody can explain is why the universe seems split into these two separate and irreconcilable realities. If everything in the universe is made of quantum things, why don't we see quantum effects in everyday life? Why can't Penrose, made of quantum particles, materialize here, there, and everywhere he chooses?

Many physicists find this issue so vexing that they ignore it entirely. Instead, they focus on what does work about their theories. The equations of quantum mechanics do a fantastic job describing the behavior of particles in an atom smasher, the nuclear reactions that make the sun shine, and the chemical processes that underlie biology. For Penrose, that is not nearly enough. "Quantum mechanics gives us wonderful predictions and experimental confirmations for small-scale scenarios, but it gives us nonsense at ordinary scales," he says, relaxed now that a receptionist has assured him of his car's safety. "If you just follow the equations, you get a mess. So you have to ask: What leads to this world?"

He has an answer, which, if correct, will lead to the first quantum theory that makes as much sense for people as for particles. Penrose believes he has identified the secret that keeps the quantum genie tightly bottled up in the atomic world, a secret that was right in front of us all along: gravity. In his novel view, the same force that keeps us pinned to the ground also keeps us locked in a reality in which everything is tidy, unitary, and—for better and for worse—rooted in one place only.

ASIDE FROM A FRUSTRATING INABILITY TO MANIFEST IN any number of places simultaneously, Penrose qualifies as something of a quantum phenomenon himself. There do indeed seem to be many Penroses; they just all happen to occupy the same body.

There is Sir Roger the physicist, knighted in 1994 for his contributions to science, among them pioneering efforts to reconcile Albert Einstein's general theory of relativity with quantum mechanics. There is Penrose the puzzle master, creator of geometric illusions that M. C. Escher incorporated into some of his most famous works. There is Penrose the neuroscientist, who developed a controversial theory linking consciousness to quantum processes in the brain. And there is Penrose the author, most recently of a 1,049-page tome called *The Road to Reality,* which is modestly subtitled *A Complete Guide to the Laws of the Universe.* It's an impressive résumé for someone who was demoted a grade in elementary school because he couldn't master arithmetic.

On our second meeting, all of those Penroses are slumped on a sofa in the living room of his spacious home a few miles outside Oxford. A coffee cup and a plate of cookies rest on his chest, which, since he is sunk so deeply into the sofa, is almost perfectly horizontal. Tall windows look out on a lush green yard, damp from the rain. In this pensive setting, he looks back on the events that convinced him that quantum theory has serious problems, a view that would be heresy for a young physicist entering academia today.

Penrose's faith began to waver while he was a graduate student at Cambridge. The crucial moment came during a lecture by Paul Dirac, one of the legendary early thinkers in quantum mechanics. "He was talking about the superposition principle, whereby objects could be in two places at the same time. To illustrate, he broke a piece of chalk in two and then tried to explain why you never saw superpositions in real life. My mind may have wandered briefly, because I never heard his explanation!" Penrose says, laughing. "But when I think about it, I'm not sure it did wander, because it's not possible to explain why you don't see objects in two places at once on the basis of present-day quantum mechanics. It's a big problem. It's what I've worried about ever since."

The maddening part of that problem is that the ability of particles to exist in two places at once is not a mere theoretical abstraction. It is a very real aspect of how the subatomic world works, and it has been experimentally confirmed many times over. One of the clearest demonstrations comes from a classic physics setup called the double-slit experiment.

In this test, a beam of light is projected through two parallel slits cut in an opaque barrier and then onto a white screen. When light hits the screen, it does not produce just two overlapping regions of brightness. Instead, something strange appears: a series of alternating light and dark stripes, called an interference pattern. The 19th-century explanation for this was that light is a wave and that light waves overlap after passing through the slits. The light waves seem to behave much like water waves on the surface of a pond: Where two crests meet, the wave gets higher, creating a bright stripe; where a crest meets a trough, the two cancel out, and the wave vanishes, yielding a dark zone.

With the development of quantum theory in the early 20th century, the explanation became far weirder. Physicists realized that light is not a wave exactly but rather a wavelike particle called a photon. That discovery suggested a new experiment. In principle, it would be possible to send light through the slits one photon at a time and collect them on photographic film. Common sense says there should be no interference pattern in this case: There is only one photon in the apparatus at any given moment, so there is nothing for the light to interfere with.

Then in 1909 a young British physicist named Geoffrey Ingram Taylor actually ran the experiment and witnessed the bizarre result. As the photons accumulate on the film, the same old interference pattern of alternating bright and dark stripes gradually appears, defying common sense. In this case, there is only one thing each photon can interact with—itself. The only way this pattern could form is if each photon passes through both slits at once and then interferes with its alternate self. It is as if a moviegoer exited a theater and found that his location on the sidewalk was determined by another version of himself that had left through a different exit and shoved him on the way out.

Since then, other researchers have repeated the experiment with electrons, atoms, even with relatively bulky molecules containing as many as 70 carbon atoms. The results never vary. Individual atoms and molecules go through both slits at once. Yet for some reason the laws of physics take away that ability for large objects like paper clips, people, and planets. "Something has got to go wrong with quantum mechanics

Other Penrose Questions #1

How do black holes work? Penrose and physicist Stephen Hawking developed a detailed mathematical description of the gravitational collapse that produces black holes. Penrose developed the idea of cosmic censorship, which holds that information about processes happening within black holes remains forever hidden from outside observers.

Fast File — ROGER PENROSE

BORN: August 8, 1931, in Colchester, England.

PARENTS: Margaret Leathes Penrose, a physician, and Lionel Penrose, a medical geneticist.

UNDERGRADUATE MAJOR: Mathematics. Penrose graduated with first-class honors from University College London in 1952.

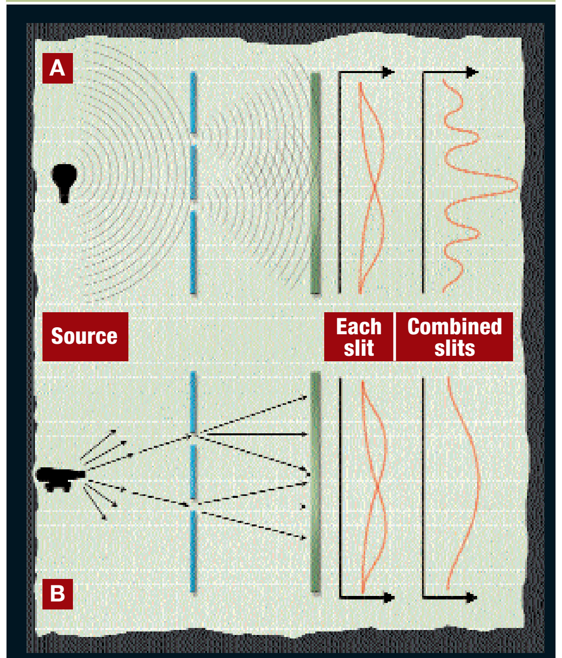
Ph.D. THESIS TITLE: *Tensor Methods in Algebraic Geometry* at St. John's College, Cambridge.

NUMBER OF PUBLISHED PAPERS: 200 and counting.

MENTOR: Astronomer Dennis Sciama, a leading 1950s advocate of the steady-state theory, which held that the universe is eternal.

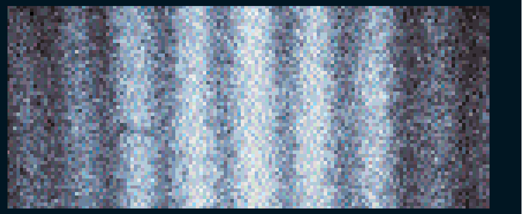
ALTERNATIVE CAREER: While at University College London, Penrose was forced to choose between biology and mathematics. "My parents were rather annoyed when I got home; my medical career had disappeared in one stroke."

Duplicity in the Quantum World



In the famous double-slit experiment (A), a light source shines on a solid barrier containing two small holes. On the other side of the barrier is a screen that registers where the light hits. (The curved lines at right represent the intensity of what hits the screen.) Light from each slit alone makes a smoothly distributed glow, but the combined result is a complex interference pattern: bright where the waves reinforce each other, dim where they cancel each other out. If the same experiment is done with large particles such as bullets (B) instead of light waves, the particles hit random spots spread out around each of the slits, so the combined distribution looks like a smooth curve.

When electrons or atoms run though the double-slit experiment, they create interference patterns. In other words, the particles act like waves, not like bullets. Weirder, the same pattern appears even if the particles pass through the experiment one at a time. Since there is no other "wave" to interfere with, the only way this can happen is if each particle passes through both slits, interfering with itself along the way! Clearly, electrons are discrete entities, since the detector screen shows them as dots each time one hits, yet the resulting interference pattern is undeniable (see below). Moreover, if one slit is closed off, the pattern disappears. Only in the absence of a measurement do the electrons sneak through both slits at once. This behavior sounds crazy, but it has been confirmed by countless experiments. ***—Corey S. Powell***



PHOTOGRAPH COURTESY OF HITACHI, LTD., RESEARCH & DEVELOPMENT GROUP.

Other Penrose Questions #2

What is gravity? For nearly 40 years, Penrose has worked on twistor theory, a radically original description of gravity, space, and time. Rather than treating space-time as an empty arena in which physical events unfold, Penrose postulates that objects called twistors build the fabric of space-time from the ground up.

somewhere," Penrose says. "I regard this as a major problem that is going to require another revolution. But rather few people seem to agree with this viewpoint."

When pressed, quantum theorists usually fall back on what is known as the Copenhagen interpretation. The idea was promoted in the 1920s by Danish physicist Niels Bohr and his protégé German physicist Werner Heisenberg. In their view, we do not see quantum effects in the everyday world because the act of observation changes everything, fixing the many possibilities allowed by quantum mechanics as one. As a result, when we look, we only see one version of events, with every object firmly anchored to one position at a time.

The flaw in the Copenhagen interpretation is that it has no basis in theory—it is more like a story that scientists tell to make sense of facts that otherwise would seem nonsensical. It also suggests that the universe does not become fully real until someone observes it. Einstein found this idea abhorrent. "I like to think that the moon is there even if I am not looking at it," he fumed in response to Bohr. Nevertheless, the Copenhagen interpretation was voted the preferred explanation of quantum weirdness by physicists at a conference in 1997.

The runner-up explanation is an even stranger view of reality. Called the many worlds interpretation, it was proposed in 1957 by Princeton University doctoral candidate Hugh Everett III. Its adherents take the laws of quantum theory at face value: Every possible quantum outcome really exists—but in worlds parallel to our own. In one universe, Penrose is talking with me in Oxford; in another, he is watching a monster-truck rally. From this perspective, people and particles behave much the same way. We just do not see them in many places at the same time because each potential location is tucked away in a different universe (see "Quantum Schmantum," *Discover,* September 2001, posted on our Web site, www.discover.com).

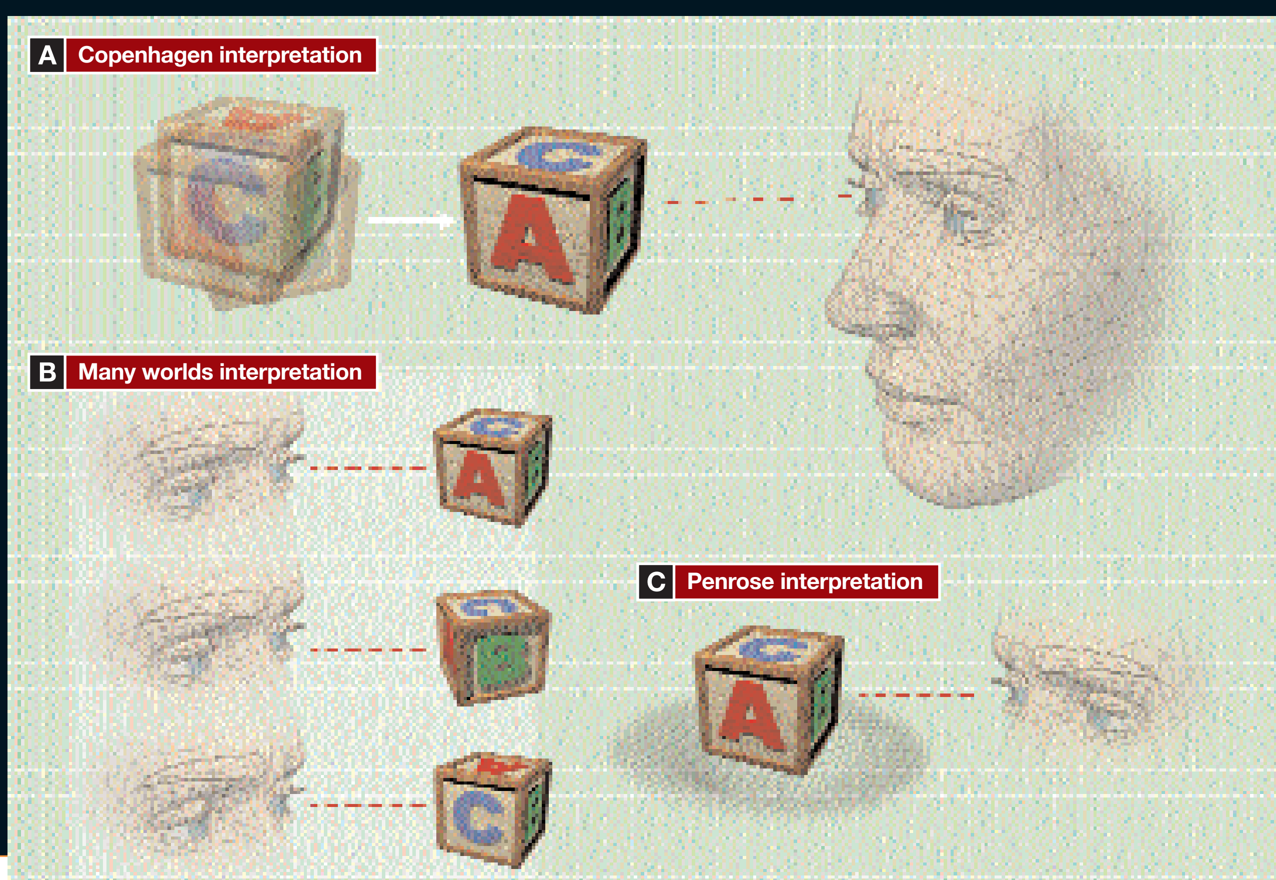
Penrose cannot believe anyone finds either the Copenhagen interpretation or the many worlds picture satisfactory. "If you take the equations of quantum

Three Different Views of Quantum Weirdness (and What It Means)

A: According to the orthodox view of quantum mechanics, called the Copenhagen interpretation, a system (represented here by a child's block) does not occupy a definite state or location until it is measured. Before then it is just a blur of overlapping possibilities.

B: The many worlds interpretation insists that the system occupies all its possible states but that every one of them exists in its own alternate universe. Each universe sees one state only, which is why we never observe the block in two states at once.

C: In Penrose's interpretation, gravity holds our reality together. In each potential state, the block generates a separate gravitational field. Over time, the energy required to maintain these multiple fields causes the block to settle into one state only—the one that we observe.



mechanics up to the level where you can actually see things going on, you're driven to an absurd viewpoint. People are led into views of the world which are pretty fantastical. And rather than say, 'This is a bit wild, let's try to do something a bit more commonsense-ish,' they come up with theories that are completely wild."

After struggling for years to come up with a better explanation, he finally has a solution.

TURNING TO GRAVITY FOR A SOLUTION TO the quantum mystery is in many ways a natural strategy, at least from Penrose's perspective. There are four fundamental forces in the universe: electromagnetism; the strong force, which binds atomic nuclei together; the weak force, which is responsible for radioactive decay; and gravity. Gravity is the only one of the forces that physicists have been unable to explain in quantum terms. Albert Einstein spent more than 30 years in fruitless attempts to harmonize his theories of gravity with quantum mechanics, and his successors are still stumped.

To Penrose, the failures are a clue that physicists are on the wrong path. Most believe that quantum theory is fundamentally sound but that our understanding of gravity must change. Penrose says that rather than seeking to change Einstein's theory of gravity, we should study how gravity affects an object small enough to exist in the borderland between the quantum world of atoms and the human world of visible objects.

An object the size of a speck of dust would provide the perfect test. At this scale, an object is small enough to be strongly affected by the rules of quantum mechanics but large enough to observe directly. Current theory predicts that such an object could exist in more than one location and could remain in that split state almost indefinitely. If there were a way to observe the speck without disturbing it, we would see quantum strangeness laid bare: a macroscopic thing sitting in two places at the same time, confounding reality as we know it.

Penrose is convinced that conventional quantum theory seems absurd because it is incomplete. Specifically, it ignores the effects of gravity. On atomic or subatomic scales, gravity is so weak compared with the other forces that most physicists see no problem with leaving it out of the picture. But in Penrose's view, the only way to understand the quantum world is to consider all the forces that act on it. To do that, he is combining Einstein's relativity with quantum physics in a way nobody has considered before.

In Einstein's theory, any object that has mass causes a warp in the structure of space and time around it. This warping produces the effect we experience as gravity. Penrose points out that tiny objects—dust specks, atoms, electrons—produce space-time warps as well. Ignoring these warps is where most physicists go awry, he believes.

If a dust speck is in two locations at the same time, each one should create its own distortions in space-time, yielding two superposed gravitational fields. According to Penrose's theory, it takes energy to sustain these dual fields. The stability of a system depends on the amount of energy involved: The higher the energy required to sustain a system, the less stable it is. Over time, an unstable system tends to settle back to its simplest, lowest-energy state—in this case, one object in one location producing one gravitational field. If Penrose is right, gravity yanks objects back into a single location, without any need to invoke observers or parallel universes.

How long the process takes depends on the degree of instability. Electrons, atoms, and molecules are so small that their gravity, and hence the amount of energy needed to keep them in duplicate states, is negligible. According to Penrose, they can persist that way essentially forever, as standard quantum theory predicts. Large objects, on the other hand, create such significant gravitational fields that the duplicate states vanish almost at once. Penrose calculates that a person collapses to one location in a trillion-trillionth of a second. For a dust speck, the process takes nearly a second—long enough that it might be possible to measure.

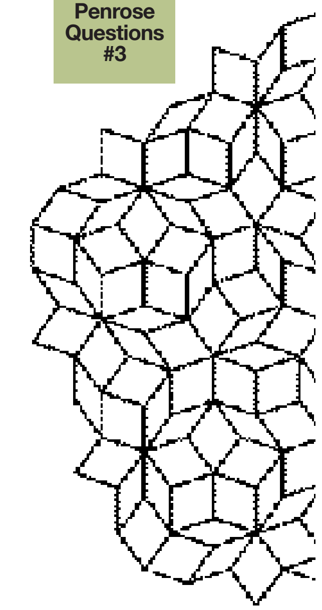
Growing excited, he hoists himself to a more upright position on his sofa. "Here is the scale where you should start to see differences between what quantum mechanics says and what reality does," he says. "The superposition that is part of quantum mechanics is unstable for large objects; an object will assume one or the other position on a timescale of about a second. Is this true? Well, we have to do an experiment."

A few years ago, Penrose figured out how to perform that experiment. Instead of a speck of dust he would use a tiny mirror, which would allow him to bounce radiation off it to see if it was in one or two places at the same time. If traditional quantum theory is right, the doubled state could remain stable for a long time. If Penrose is right, the mirror would maintain a dual existence for no more than a second before gravity chains it to a single location.

Penrose initially envisioned putting his theory to the test using an X-ray laser mounted on a platform in outer space. The laser would shoot photons toward a tiny target mirror tens of thousands of miles away. Here is where quantum weirdness comes into play. A half-reflective mirror, called a beam splitter, would separate each photon into two states so that it follows two paths (that is, it goes in two directions at the same time). On one path, the photon strikes the tiny mirror, moving it slightly; on the other, it is reflected away from the target mirror, so the mirror does not move.

In the prevailing view of physics, both events occur simultaneously: The mirror moves *and* remains in place at the same time because the mirror—like the photon—can remain in two states at once. On its return path, the duplicate photon that struck the tiny mirror hits the same mirror again, returning it to its initial position. The whole system then returns exactly to its initial state,

Other Penrose Questions #3



Can a pattern have no pattern? Using only a notebook and a pencil, Penrose devised a way to seamlessly cover a flat surface in a nonrepeating pattern with just two different shapes, now called Penrose tiles. This feat had been considered impossible. Researchers have since learned that certain chemicals naturally organize themselves into these patterns, some of which are now used to make nonstick coatings for pots and pans.

and there is fundamentally no way to tell which path the photon took. As a result, the two versions of the photon can interfere with each other and recombine into a single photon that is always reflected along a path back toward the laser. No X-ray photons can ever follow the path that leads them to a detector.

If gravity intervenes, as Penrose expects, it forces the mirror either to remain at rest or to move—but not both—and the outcome is totally different. Now the photon cannot follow both paths because gravity anchors the mirror to a single state. Consequently, each photon will follow one path only, so it cannot interfere with itself; half the time that path will lead it to the detector. Thus if an X-ray triggers the detector, the quantum duplicate of the mirror must have disappeared, and Penrose's view of reality must be correct.

THE EXPENSE AND TECHNICAL DIFFICULTIES of aiming X-ray lasers at targets thousands of miles away in outer space had seemed insurmountable, but Dirk Bouwmeester, a former postdoc under Penrose who is now a professor of physics at the University of California at Santa Barbara, saw a way to make it feasible. Along with colleagues William Marshall and Christoph Simon, he devised a way to bring Penrose's experiment literally down to Earth—to a tabletop in Bouwmeester's lab.

The revised experiment relies on a relatively simple visible-light source rather than an X-ray laser. Still, everything about Bouwmeester's setup will push the boundaries of laboratory physics. To give the mirror the same kick a more energetic X-ray photon would produce, the light photons will have to reflect back and forth between two mirrors a million times. Until now, the largest objects ever studied in a state of quantum superposition were soccer-ball-shaped carbon molecules called buckyballs. Bouwmeester is trying to detect the same effect on a mirror that is a billion times bigger. "If we were able to observe that, it would be spectacular, a test of quantum mechanics in a completely new regime," he says.

The team at Santa Barbara is running the experiment right now, but with a significantly smaller mirror than needed to test Penrose's theory. If the current tests succeed, Bouwmeester will gradually increase the size of the mirror up to the necessary tenth-of-a-human-hair diameter. He and his colleagues are also working out ways to shield the experiment from the vibrations, stray photons, or temperature changes that would ruin the results. "It is not something that will happen overnight," he says. "We need to isolate the quantum world from our world and see what happens. If everything works well, I expect some results four years from now."

Penrose, who turns 74 in August, is hopeful that he will see the day when his ideas are vindicated. Not many physicists share this optimism. Tony Leggett, a Nobel laureate at the University of Illinois at Urbana-Champaign, suspects the experiment will fail to show that gravity has any effect on quantum systems. "I take the quantum paradox as seriously as Penrose does," Leggett says. "I'm personally convinced that somewhere between the level of the atom and human consciousness, something has to come in which changes the structure of quantum mechanics." The problem is that quantum theory has never yet failed to predict the outcome of any experiment. Without evidence of some such flaw in the theory, physicists are left groping in the dark for ways to improve it. "I think the odds of our being right are less than 5 percent," he says.

David Deutsch, a theoretical physicist at Oxford University's Centre for Quantum Computation, is a leading proponent of the many worlds theory. He turns the tables on Penrose, arguing that his quest is based more on aesthetics than science: "If something is wrong with a theory, or there is some experimental anomaly, those are motivations for changing a theory. When your motivation comes from a metaphysical reluctance for reality to be a certain way, then historically that kind of motivation has never produced the right answers."

Penrose responds that he is not changing quantum mechanics; he is merely putting it to a new, more rigorous test. "You can say we haven't seen any violation of quantum mechanics, but that's absolutely what you'd expect, because no experiment has ever been performed that comes remotely close to the level you'd need to see any violations. So unless you try to get to this level I'm aiming for, it's not at all surprising that we haven't been able to see any deviations," he says.

If Bouwmeester's experiment succeeds, it will show that the fantasy of being in two places at the same time really is impossible. As a kind of compensation, it will also show that the number of places science can go is far greater than we have come to believe. Most physicists today trying to unite Einstein's theory of gravity with quantum mechanics focus on microscopic realms beyond the reach of any conceivable experiment. Perhaps the solution that eluded Einstein is much closer at hand, in the strange territory where quantum mechanics just barely emerges into the human world.

The one Penrose rises from his one chair, preparing to pick up Max, his 4-year-old son, from school. He has no doubt that Max's generation will learn physics lessons different from the confusing, incomplete story that Penrose got from Dirac all those years ago.

"Is quantum mechanics the last word?" Penrose asks. "There is no reason to believe that." ☒

Other Penrose Questions #4

What is consciousness? Penrose argues that it is a by-product of quantum mechanical processes operating in the brain. Some intriguing recent research supports his contention that microtubules—tiny structures in brain cells—can allow quantum phenomena to influence how neurons behave.

Other Penrose Questions #5

Can a computer be intelligent? Penrose believes that the human brain performs feats that are beyond computational processes. He cites a famous proof by the logician Kurt Gödel on the limitations of all mathematical systems as an idea that no computer could ever devise.

DISCOVER MORE [also see Resources, page 85]

The Road to Reality: A Complete Guide to the Laws of the Universe. Roger Penrose. Alfred A. Knopf, 2005. Penrose's latest book contains some heavy math but delivers a sweeping overview of modern physics theories, along with some provocative speculations.