The Quantum Wave Function of the Universe

Stephen Hawking is trying to create a theory of quantum cosmology; if he is right, then the universe is very weird indeed

SLUMPED IN HIS MOTORIZED WHEELCHAIR, immobilized by a slow degeneration of the motor neurons known as amyotrophic lateral sclerosis, or "Lou Gehrig's disease," a thin, bespectacled figure stares intently at a computer screen. And in the quiet of his dimly lit office one hears the soft and oddly compelling sound of clicking. Cambridge University's Lucasian Professor of Mathematics, the current occupant of a post once held by Sir Isaac Newton, is communicating in the only way he is able: by using a hand-held pressure sensor to pick out words from an on-screen menu.

"The field of baby universes is in its infancy," types Stephen W. Hawking. And then he gives his leprechaun grin: "But growing fast."

Well, yes. So it is. As the author of *A Brief History of Time*, perhaps the most challenging book ever to spend half a year on the *New York Times* best seller list, Hawking has already introduced hundreds of thousands of lay readers to Big Bang cosmology, quantum field theory, "hot" black holes, the arrow of time, the quantum wave function of the universe, and even the hypothetical Theory of Everything, all in just 200 equation-free pages. And in the process, he has doubtless convinced them that his vision of reality is exceedingly strange.

But *A Brief History of Time* covers Hawking's work only up to about 1985, when the original draft was completed. Since then, as he has pushed on to consider baby universes, "wormholes," and other such exotica, Hawking has been led into an even stranger vision—one that involves not just a single quantum universe, but an infinity of interconnected and self-reproducing universes. Furthermore—and this is what has other physicists particularly intrigued—Hawking's recent ideas have inspired a new approach for understanding and perhaps for calculating such fundamental quantities as mass and charge. And they may even point the way toward one of the holiest of the Holy Grails in physics: a satisfactory quantum theory of gravity.

"Hawking has dominated the development of quantum gravity as much as Niels Bohr dominated the development of the old quantum theory," says Harvard University's Sidney Coleman, who is highly regarded in the community as having a discerning eye for new ideas. "But until recently, he was the king of an isolated kingdom. Quantum gravity was not part of the mainstream." Yet if these recent ideas do work out, he says, "then Hawking's influence *will* make itself felt in the larger community."

To get a sense of Hawking's approach to quantum gravity and quantum cosmology, it helps to start with conventional, nonquantum cosmology. And to understand that, in turn, it helps to start the way Hawking himself so often does: with a picture.

As Fig. 1 suggests, our universe can be thought of as a kind of huge, rapidly inflating balloon. The stars and galaxies would then be like particles moving around on the surface of the balloon. In conventional cosmology, the dynamics of our cosmic balloon are described by one of the two great achievements of 20th-century physics: general relativity, Einstein's theory of gravity. Roughly speaking, Einstein's theory says that the presence of matter and energy causes the surface of the balloon to form puckers and dimples; in fact, the curvature of the surface at every point is determined by the density of matter and energy at that point. In cosmic terms this means that the overall structure and overall history of the universe is inescapably bound up with its overall content. Too much matter, for example, and the universe will ultimately recollapse into a "Big Crunch"; too little, and it will continue expanding forever.

Unfortunately for the physicists, however, the same theory of general relativity that has proved so successful at explaining the large-scale workings of gravity and cosmology has also proved to be at odds with the other great achievement of 20th-century physics, quantum theory. First formulated in the 1920s, quantum theory is the mathematical expression of a strange and disturbing insight: namely, that what we are pleased to think of as reality is in fact resting on a foundation of chaos. Consider an elementary particle such as an electron. Quantum theory asserts (and experiments confirm) that each electron is subject to a certain fuzziness, a lack of definition that finds formal expression in the Heisenberg uncertainty principle. In pictorial terms, however, it is not too far wrong to think of each particle as undergoing a kind of random, microscopic vibration. Step back and the vibrations become invisible; the particle seems to be a paragon of predictability. Look more closely, however, and its random dance becomes very visible indeed. The smaller the scale, in fact, the more violent the vibrations will seem. In the end there is no way to express the particle's behavior except as an array of probabilities: it has such and such a probability to be *here*, or it has such and such a probability to be moving *that* way.

The effort to apply the quantum theory to gravity began almost as soon as it was invented. After all, if quantum theory describes the dynamics of everything else in the universe, how could it *not* describe gravity? How could quantum effects give an uncertainty to the particles themselves without also creating an uncertainty in the cosmic balloon they live in?

Good questions. What has made them so hard to answer is that the mathematics of quantum theory and Einsteinian gravity go together about as well as oil and water. The hypothetical theory that would combine them—quantum gravity—has so far been a chimera. No one even knows what a quantum theory of gravity ought to look like. And without it, cosmologists have no hope of answering some of their most fundamental questions—starting with "Where did the Big Bang come from?" The thinking is that a satisfactory theory of quantum gravity will have to wait until someone can devise a complete unified theory of all particles and forces, a hypothetical series of equations known half jokingly as the Theory of Everything.

Hawking has no more insight into the ultimate Theory of Everything than any other physicist. But instead of just waiting for a revelation, he has spent the past decade or so pursuing a strategy that says, in effect: "OK, let's try to use what we do understand to shed some light on the broad features of quantum cosmology, features that ought to be true no matter what the details of the Theory of Everything."

To accomplish this, Hawking revived an approach first explored in the 1960s, with the idea being to apply the Heisenberg uncertainty principle to the cosmic balloon itself. Imagine that we were somehow standing outside of space and time, looking at the surface of the balloon through a microscope. At low magnification, the surface would seem perfectly smooth. But just as with the electron mentioned earlier, higher magnification would begin to show that the surface was vibrating furiously (Fig. 2). And by the time the magnification was high enough to resolve the surface on scales of 10^{-33} centimeters or so, about 20 orders of magnitude smaller than a proton, we would find the vibration becoming incredibly violent and chaotic: there would be some probability for the surface to be doing *anything*.

In particular, says Hawking, there is a probability that our madly vibrating cosmic balloon will develop a bulge in its side, a kind of aneurism that will then billow out and expand indefinitely (Fig. 3). In other words, he says, it is possible that empty space can spontaneously give rise to a whole, new, baby universe.

Now, a skeptic might object that we would surely be able to observe such a spectacular event. But in fact, no, says Hawking. The most probable size for the umbilical cord that connects us to the baby universe—the wormhole—is only about 10^{-33} centimeters across, the same size as a typical quantum fluctuation in the surface. From our own macroscopic standpoint, the wormhole would look like a tiny black hole that flickered into existence and then evaporated again in only 10^{-43} seconds. It would be lost in the chaos of the quantum vibrations. We would never notice it.

However, this does not mean that the baby universe itself is trivial, says Hawking. Indeed, it can easily behave like a full-fledged universe like our own, eventually expanding into something billions of light-years in extent. Nor is it necessarily empty. Just as in the first instants of our own universe, the sudden inflation of the baby universe would produce a firestorm of particles. That is, the increasingly negative potential energy of gravity would be converted into the positive energy of matter. So it is entirely possible for this baby universe to have stars, galaxies, planets, and even life.

Indeed, says Hawking, it may be that whole new universes are constantly coming into existence all around us, utterly invisible to our everyday senses. It is even possible that *our* universe was formed in this way, emerging as a quantum fluctuation from some earlier cosmos, and then giving rise to myriads of others in its turn. As suggested in Fig. 4, in fact, it may well be that the full quantum wave function of the universe actually describes an infinite labyrinth of universes, splitting off and merging with one another in unending sequence.

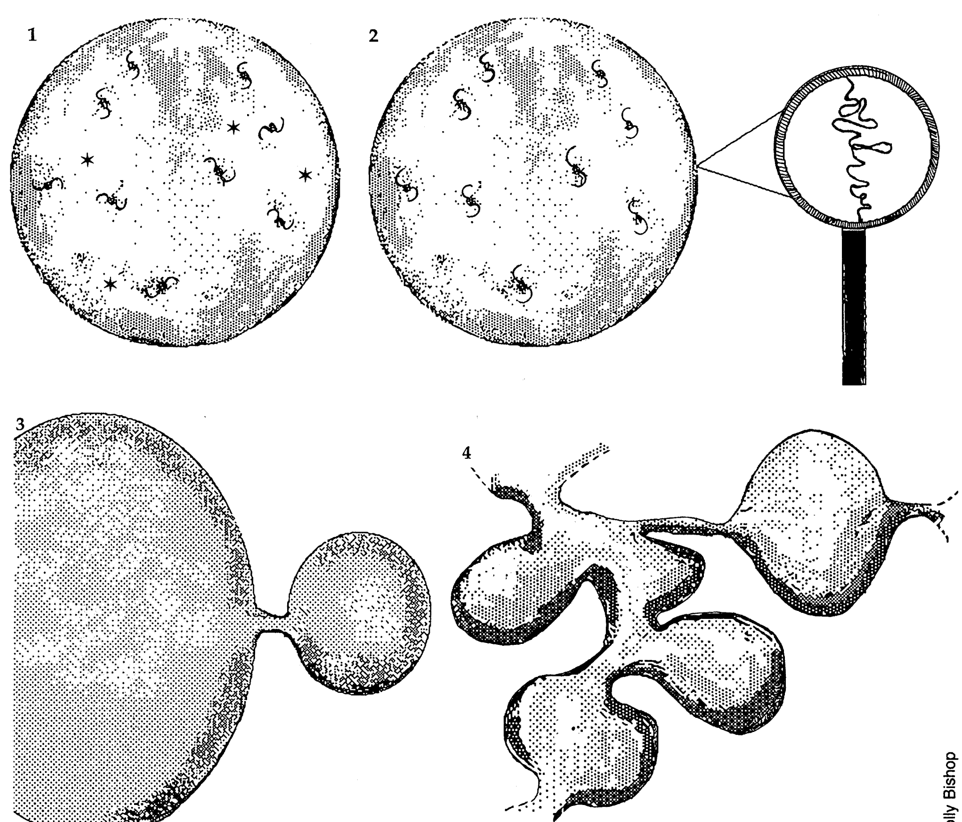
As awesome as this picture is, however, a skeptic would be fair in asking whether it is anything more than armchair speculation. Does it make any testable predictions?

Maybe, says Hawking.

To begin with, forget about wormholes and baby universes for the moment and consider just our own cosmic balloon. In 1983, Hawking and James Hartle of the University of California, Santa Barbara, showed how to define the quantum mechanical probability for the balloon to have any particular size and shape. That definition, in turn, has allowed for a wide variety of calculations suggesting that Hawking's cosmology meets its first and most basic test: it predicts a universe very much like the one we actually live in.

More precisely, the calculations suggest that by far the most probable configuration for the quantum universe is to be a large, homogeneous cosmos expanding at just the observed rate, and with plenty of room for exactly the kind of stars and galaxies we see around us. Among other things, the calculations also predict that such a universe would have a well-defined "arrow of time," with its entropy increasing steadily; and that it would have started out with a brief, "inflationary" epoch of very rapid expansion, much like the kind of inflation often discussed in the context of nonquantum cosmology.

Now, wormholes. If we can imagine a wormhole appearing for an instant in one spot, says Hawking, then we can equally well imagine quadrillions of wormholes flickering in and out of existence at every spot in the universe. We would certainly never notice them ourselves. But from the point of view of an elementary particle such as an electron, "empty" space would look like a constantly shifting minefield. So what happens when an electron trying to move in a straight line actually hits one of these wormholes, he asks? In pictorial terms, it would fall into the wormhole and go flying off into an alternate universe somewhere, while an identical electron comes back the other way and pops into our universe to maintain the overall conservation of energy, momentum, and charge (Fig. 5). The net effect of a sequence of such encounters is that the electron would still appear to move



The quantum cosmos. (**1**) *Einstein's view: the cosmic balloon.* (**2**) *Hawking's view: quantum chaos.* (**3**) *Chaos up close: birth of a baby universe.* (**4**) *Chaos in the large: an infinite labyrinth of universes.*

in a straight line on the average. But its mass would appear to be increased.

By the same token, if either the infalling or emerging electron were to be accompanied by a photon, the process would look to the outside world like the absorption or emission of a photon—that is, like an electromagnetic interaction (Fig. 6). The net effect would be a shift in the electron's electric charge.

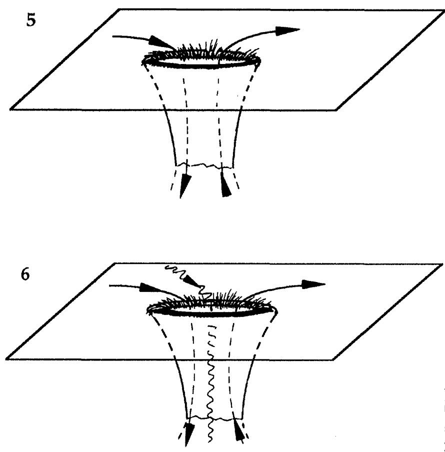
In fact, says Hawking, it is at least conceivable that this kind of wormhole scattering is responsible for *all* particle masses and *all* particle interactions. True, he is a bit skeptical himself. If nothing else, his original calculations of the wormhole effect suggested that it would make for enormous particle masses, roughly 20 orders of magnitude heavier that the true mass of the proton.

Just this year, however, a number of physicists—notably Coleman, Steven Giddings of Harvard, Andrew Strominger of the University of California, Santa Barbara, and Thomas Banks of the University of California, Santa Cruz—have sketched out a theory of how the wormhole effect could produce much more reasonable numbers for mass and charge. Paradoxically, their model also suggests that such numbers may not be calculable, even in principle. Instead, the fundamental constants of nature would be quantum variables, which would be fixed at random in each quantum universe at the moment of that universe's creation. On the other hand, this approach is still very new, and there are hints that these fundamental numbers can indeed be calculated.

As a final consequence, the wormhole picture may offer a solution to one of cosmology's most nagging unsolved problems: the vanishing of the cosmological constant.

Mathematically, this constant is a straightforward extension of Einstein's equations. (In fact, it was first introduced by Einstein.) But if it really existed its effects would be almost metaphysical. It would be a kind of pressure acting inexorably at every point in the universe. This pressure would have nothing to do with atmospheric pressure, or the pressure of the earth against our feet, or any ordinary meaning of the word. Quite the opposite. The pressure of the cosmological constant would act everywhere uniformly, even in empty space far away from matter. It would be part of the fabric of empty space. And it would force our universe to expand far more rapidly that it actually does.

What makes this problem into something more than metaphysics is that the cosmological constant is observationally zero to a very high degree of accuracy. And yet, ordinary quantum field theory predicts that it ought to be enormous, about 120 orders of magnitude larger than the best observational limit.



Holly Bishop

The origin of interaction? (**5**) *Electron + wormhole = mass.* (**6**) *Electron + photon + wormhole = charge.*

Moreover, this prediction is almost inescapable because it is a straightforward application of the uncertainty principle, which in this case states that every quantum field contains a certain, irreducible amount of energy even in empty space. Electrons, photons, quarks—the quantum field of every particle contributes. And that energy is exactly equivalent to the kind of pressure described by a cosmological constant.

The cosmological constant has accordingly been an embarrassment and a frustration to every physicist who has ever grappled with it. But wormholes, says Hawking, offer a way out. Following up on a suggestion that Hawking himself made back in 1984, Coleman has recently shown that if the universe really is punctured by a multitude of wormholes at every point, then those wormholes would act to cancel out the cosmological constant produced by the particle fields. According to Coleman's calculations, in fact, the universes that have a net cosmological constant of zero would be overwhelmingly more probable than those with any other value. So we should not be surprised that it is zero in our own universe.

As Hawking is the first to admit, there is a lot more work to be done before any of this theorizing can be accepted as fact. But even as things stand, his ideas have revitalized the whole field of quantum cosmology. Perhaps the best measure of his impact is the way other researchers have started jumping in to dispute this assumption or that assumption, and to offer alternative models of their own.

However, there is still the larger question: what does all this theorizing really tell us about the true nature of reality, otherwise known as the Theory of Everything? After all, Hawking's whole program is ultimately founded on Einstein's general relativity, a model of the world that is at best a low-energy, large-scale approximation to the true theory. There is a widespread feeling in the physics community that this hypothetical Theory of Everything will almost certainly involve concepts that are strange even by Hawking's standards: extra dimensions, for example, supersymmetry, superstrings, or even some yet-to-be-determined set of variables that are somehow more fundamental than space and time themselves.

Nonetheless, says Hawking, "[The model] is fairly independent of the details of the final theory." The very fact that our observable world is well described by general relativity and quantum mechanics leads him to believe that, whatever the Theory of Everything may be doing at the submicroscopic scale, it will have to reduce to something very much like his theory when it is observed at larger scales.

And if Hawking is right, then his theory will have taught us something very important indeed: namely, that the laws of physics can apply everywhere, even at the creation of the universe. This is certainly not the case in conventional cosmology. Extrapolate Einstein's equations back to the Big Bang and the equations are guaranteed to break down into absurdities such as infinite density and infinite curvature. There is no way for physicists to talk about where the Big Bang came from because there is no way for the known laws of physics to apply.

But in Hawking's cosmology the equations never break down. Extrapolate them far enough back and the results are not so much absurd as meaningless. Asking what happens before the creation is like asking what lies south of the south pole. As Hawking writes in his book, "the universe would be completely self-contained, neither created nor destroyed—it would just be." Or, as he explained to *Science*, "[My proposal] is the statement that the universe is a closed system. We don't need to suppose there's something outside the universe which is not subject to its laws. It is the claim that the laws of science are sufficient to explain the universe."

Hawking is well aware that for many people this statement is arrogance personified—tantamount to asserting that a set of rules comprehensible by humans can encode the intentions of God. But then, he is also the first to admit that any set of equations, no matter how all-encompassing, are still nothing more than rules. Even if we had a Theory of Everything, he says, we would still be left with one final question: "What is it that breathes fire into the equations and makes a universe for them to describe?"

And does he have an answer?

"If I knew that," says Hawking, "then I would know everything important."

■ M. MITCHELL WALDROP