Black holes—theoretical versions of them—have become crucibles for forging a theory joining the macroworld of gravity with the microworld of quantum mechanics

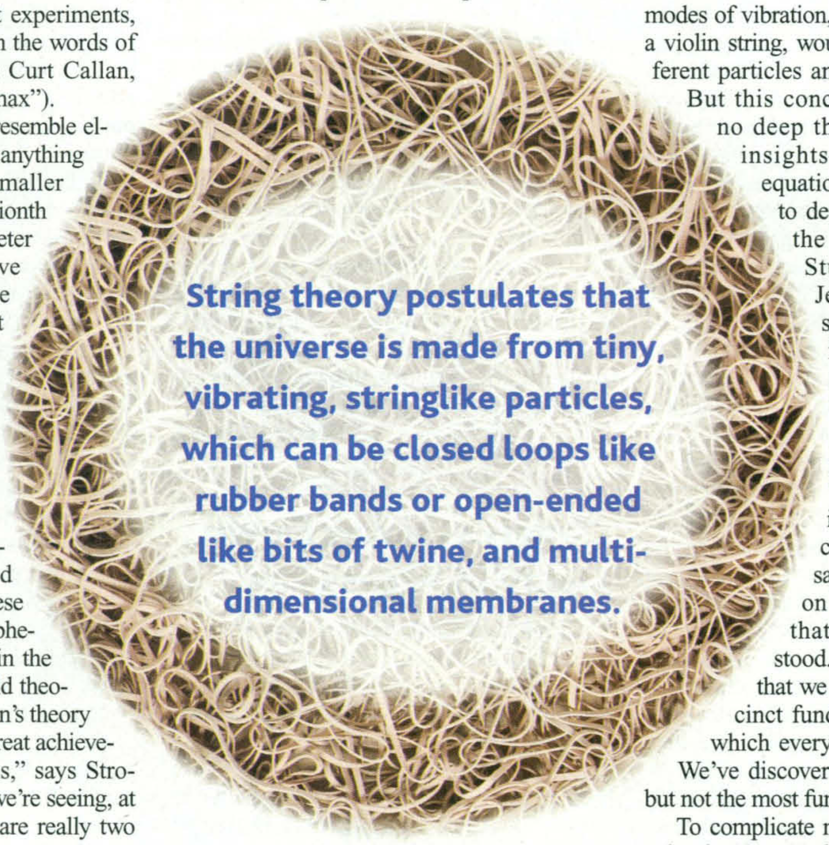
String Theorists Find a Rosetta Stone

There is a belief promulgated by Dante, Joseph Campbell, and the makers of major motion pictures that to get out of a bad situation you must pass through the depths of the abyss. Theoretical physicists have lately taken up this philosophy, although the hell through which they must travel is the guts of black holes—not the kind in the universe at large, but what physicists often refer to, pace Einstein and his thought experiments, as *gedanken* black holes (or, in the words of Princeton University theorist Curt Callan, "*gedanken* black holes to the max").

These hypothetical objects resemble elementary particles more than anything else, and, if real, would be smaller than a hundredth of a quadrillionth of a quadrillionth of a centimeter across. Nonetheless, they have lately taken on the leading role in string theory, physicists' most recent attempt to create a "theory of everything" that unites the forces operating on the microscopic scale of quantum mechanics with the large-scale force of gravity. *Gedanken* black holes have become, in effect, a Rosetta stone, says Andrew Strominger of Harvard University. In the physics of these hypothetical objects, the same phenomena can be found written in the languages of both quantum field theory and general relativity, Einstein's theory of gravity. "These are the two great achievements of 20th century physics," says Strominger, "and for the first time we're seeing, at least in some cases, that they are really two sides of the same coin."

If this latest string theory revolution turns out to describe the universe we live in—an enormous if—it will give physicists an unprecedented tool with which to finally develop a quantum theory of gravity. It will allow them to interpret the force of gravity not just according to the rules of general relativity—as the curvature of space-time caused by the presence of matter—but as the result of quantum mechanical fluctuations of the infinitesimal strings out of which, says the theory, all matter is composed. Whether or not the latest work leads to a working theory of everything, it is already responsible for a paradigm shift in how string theorists think about gravity, and it seems poised to provide solutions to some of the most perplexing paradoxes in the field.

The pursuit of a theory of everything and a viable quantum theory of gravity is predicated on a simple fact: Extrapolations from



experimental data imply that at a scale of energy known as the Planck scale—some 18 orders of magnitude beyond what even the most powerful particle accelerators can generate—the gravitational force of the universe at large and the two forces of the microscopic universe, known as the electroweak and the strong force, would be equally strong and potentially indistinguishable. A theory that describes this unification, casting gravity in the same terms as the electroweak and strong forces, "is what we really need for a complete description of nature," Strominger says.

Reasons to discount string theory as a candidate have always been easy to come by. The theory postulates that the universe is made from tiny, vibrating, stringlike particles, which can be closed loops like rubber bands or open-ended like bits of twine, and multidimensional membranes. Their different modes of vibration, akin to the harmonics on a violin string, would correspond to the different particles and forces in the universe. But this conception is supported by no deep theoretical or geometric insights—it's simply what the equations of the theory happen to describe. Edward Witten of the Institute for Advanced Study in Princeton, New Jersey, the field's impresario, calls the lack of any fundamental principles underlying string theory "the big mystery." Nevertheless, he is sure such principles must exist. "Just as general relativity is based on Einstein's concepts of geometry," he says, "string theory is based on deeper geometric ideas that we haven't yet understood. One facet of this fact is that we can't write down the succinct fundamental equations from which everything else should follow. We've discovered all kinds of equations but not the most fundamental ones."

To complicate matters further, the theory exists in 10 or 11 dimensions, six or seven of which are compactified, as physicists call it, in the universe we live in. They are curled up tightly in such infinitesimal spaces that they go unnoticed, leaving four dimensions—three space, one time. All this counterintuitive weirdness aside, the biggest barrier to the acceptance of string theory as a theory of everything is that it so far provides no compelling predictions that can be tested by experiment. The problem is those 18 orders of magnitude to the Planck scale unification: "The physics is still extremely remote," says

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Lenny Susskind of Stanford University.

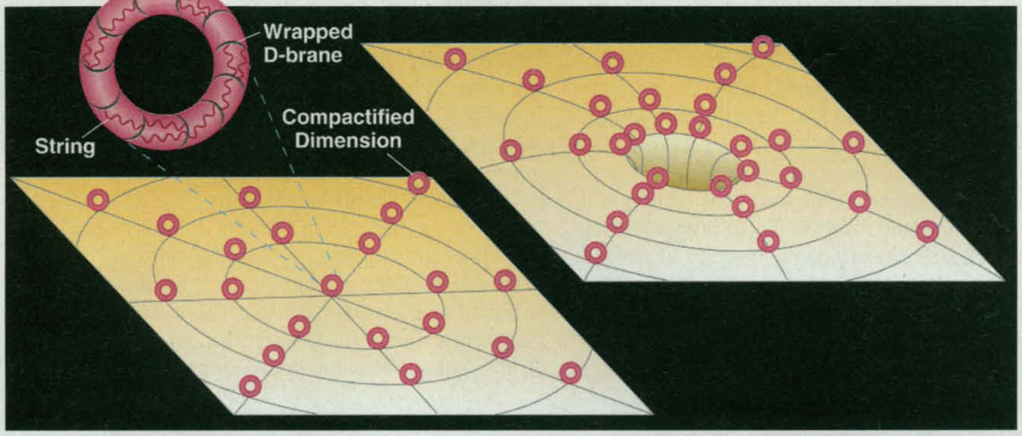
Despite all its drawbacks, however, string theory has been the subject of thousands of papers since 1984, when it emerged as a potential theory of everything, and over 400 physicists have registered for the latest meeting in Potsdam, Germany, this month. Universities, once hesitant to hire string theorists, have been competing vigorously to get them on campus. Harvard, for example, lured Strominger away from the University of California (UC), Santa Barbara, while Stanford snatched Steve Shenker from Rutgers University, and Princeton snagged Eric and Hermann Verlinde, twins who had been tenured at separate institutions in the Netherlands.

"It is astounding and probably unprecedented that there would be that level of activity for that long in an area which so far has absolutely no tie to experiment," says University of Chicago theorist Jeff Harvey. "The reason we keep on with it is that it seems to lead to new physical insights and beautiful things, wonderful structures. While that may not be proof, it's sufficiently convincing that there's either something to it, or it's got all the best minds in particle theory completely hornswoggled."

Without experiment to guide them, string theory practitioners engage in the theoretical equivalent, testing what happens to their equations when they push the relevant parameters to their limits—when they make the forces between strings extremely strong, for instance, or when they add more or less symmetry to their equations. The more symmetry they add, the more constraints they put on the problems, making them easier to solve, if less realistic. String theorists talk about tweaking these parameters as though they're playing with the dials on a stereo to see what happens to the music. "Much of the progress we make," says UC Santa Barbara theorist Joe Polchinski, "just comes from taking things we know and trying to push them further, or by looking for puzzles where we can't understand what the physics does when we vary parameters. In that sense it is almost like experimental physics: We don't really know what the theory is. We know a lot of things about it, and we're accumulating facts and trying to put them together into a theory."

The work then proceeds in a manner unique to science. Because practitioners publish their work electronically, through the e-print archives at the Los Alamos National Laboratory in New Mexico, the entire community can read a paper hours after its authors finish typing the last footnote. As a result, no one theorist or even a collaboration does definitive work. Instead, the field progresses like a jazz performance: A few theorists develop a theme, which others quickly take up and elaborate. By the time it's fully developed, a few dozen physicists, working anywhere from Princeton to Bombay to the beaches of Santa Barbara, may have played important parts.

Since 1996, the quantum mechanical properties of black holes have been the dominant theme in this performance, and the field has been playing it with a passion. "Everybody is working on it in one way or another," says Strominger—evidence of either the power of the approach or what Princeton theorist Igor Klebanov calls "a certain amount of herd mentality in the field."



Two views of a black hole. In Einstein's description, a black hole is a region of space-time curved so sharply that nothing can escape from it (top). In string theory, which posits extra, "compactified" dimensions (donuts), a black hole is a mass of strings and stringlike D-branes wrapped around the compactified dimensions (bottom).

SOURCE: A. STROMINGER

The second revolution continues

The latest series of breakthroughs, assuming they pan out, constitutes the second half of the second revolution in string theory. The first revolution came in 1984, when theorists realized that the theory could conceivably account for all the particles and forces in the universe. The second began a decade later and led directly to the latest progress. Until 1995, string theorists could study the behavior of their equations only in the simplest possible cases, consisting of a few elementary strings with very weak interactions between them. That wasn't adequate for testing the behavior of strings when they interact strongly, under conditions like those in the atomic nucleus or the innards of a black hole. "With strong interactions, where everything is pulling strongly on everything else, you can't use such a simple approximation," says Polchinski. "We had no good tools for understanding what's happening."

In 1995, however, string theorists discovered a wealth of what they call "dualities." These were pairs of equations that allowed them to understand what happens when strings interact strongly, by working instead on "dual" formulations of the relevant equations at weak interactions (*Science*, 15 September 1995, p. 1511). "With these dualities," says Polchinski, "we had a whole new, remarkable set of tools to map out how physics changes when interactions become strong. To make an analogy to water, it was like prior to 1995, we knew about steam but nothing else. Now we know about steam and water and ice, and how they change when you change the parameters. It was that kind of conceptual leap."

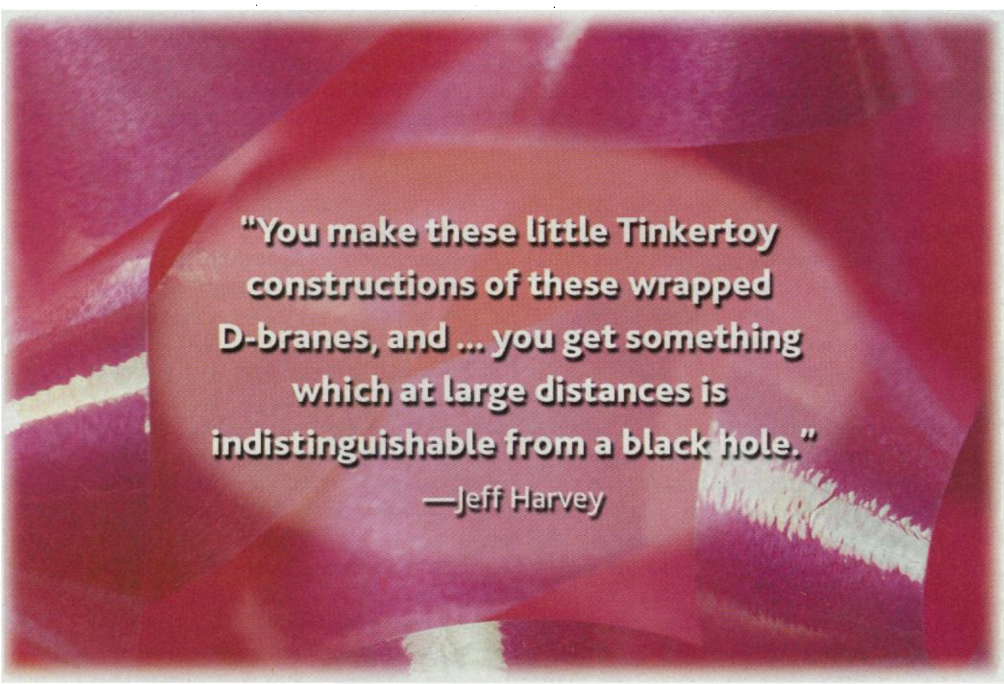
With their new understanding, the string theorists also found that their equations seemed to describe a slew of potentially fundamental particles—"not just strings," says Harvey, "but membranes or blobs or higher dimensional widgets." It would take another year to figure out what role these objects played in the theory. In September 1995, Polchinski settled the issue, providing the springboard for the latest progress. Klebanov calls it "the lightning bolt" and says, "all we've been doing since then is milking various applications of his idea."

Polchinski realized that the astonishing new multidimensional objects were all variations on D-branes—objects that he and two students, Jin Dai and Rob Leigh, had identified in 1989 without recognizing their full importance. Some D-branes are stringlike and one-dimensional, while others are surfaces in two, three, or more dimensions. Polchinski, Dai, and Leigh defined them simply as the surfaces on which open strings could end, just as a table leg ends at a table.

Polchinski used dualities to reexamine his D-branes and came up with a comprehensive set of rules for calculating the quantum dynamics of these new objects and understanding their role in the string theory universe. Among the more remarkable properties of Polchinski's D-branes was that their electromagnetic repulsion and their gravitational attraction canceled each other out. As a result—at least on paper and in the imaginations of theorists—they could be stacked on top of each other to create massive objects: objects, as Callan says, "that can be as heavy as you like." For instance, you could wrap one-dimensional stringlike D-branes around one of the tiny compactified dimensions of the string theory universe, or you could wrap multidimensional D-branes around multidimensional compactified spaces, then add more D-branes, inexorably piling on mass. "You make these little Tinkertoy constructions of these wrapped D-branes," says Harvey, "and if you do it in the right way, you get something which at large distances is indistinguishable from a black hole."

In fact, such a Tinkertoy construction, if it existed, would manifest all the properties of a black hole as defined by the rules of general relativity, even though it was constructed purely from the stuff of string theory. It would be so massive as to trap light within its gravitational field; it would have an event horizon, beyond which no light or anything else can escape. And, most critical to what would follow, it would also have a temperature and an entropy, which is a thermodynamic concept that can be thought of as the amount of disorder or randomness in a system. Entropy can also be thought of as the number of different ways you can generate the energy of a system from the combined energy of all its microscopic constituents (atoms, for instance, or molecules—or strings, or even D-branes). Entropy is usually lowest when the temperature of the system is precisely absolute zero. As the temperature rises, the number of different possible states of the system that can generate the energy increases, as does the entropy.

In the mid-1970s, Cambridge University physicists Stephen Hawking and Jacob Bekenstein, now of the Hebrew University of Jerusalem, had demonstrated that the familiar kind of black holes, described by general relativity, must have both a temperature and an entropy, and that they obey a set of laws equivalent to the laws of thermodynamics in gases. In gases, as Ludwig Boltzmann had shown in the 19th century, entropy could be derived by counting all the microscopic configurations that molecules in the gas could adopt, which physicists call the microstates of the system. So Hawking and Bekenstein's result implied that a black hole's entropy could be calculated not just by its description from general relativity, known as the Bekenstein-Hawking formula, but by counting microstates. And that, in turn, strongly implied that black holes had a microscopic description, making them a potential bridge between the macro- and the microworld.



Such a description was beyond any theories of the time. To be meaningful, it would have to satisfy three constraints, says Strominger. "One, it had to include quantum mechanics; two, obviously, it had to include gravity, because black holes are the quintessential gravitational objects. And, three, it had to be a theory in which we're able to do the difficult computations of strong interactions, because the forces inside black holes are large. String theory has these first two features: It includes quantum mechanics and gravity. But until 1995, the kinds of things we could calculate were pretty limited."

Polchinski's work on D-branes provided the tools to do the calculations. If a black hole consisted of D-branes stacked together, physicists might be able to convert its microscopic properties into its entropy. Strominger and Harvard theorist Cumrun Vafa looked for a theoretical black hole that they could build out of D-branes, then find its entropy by counting microstates. "There are all kinds of black holes with different numbers of dimensions and different charges and so on," Strominger says. "What we discovered was a black hole in five dimensions. We ended up with this one because it was the only one we could map to a problem we could solve."

To be precise, Strominger and Vafa took the 10 dimensions of the string theory universe and compactified them down to five. Then they wrapped five-dimensional and one-dimensional D-branes around the compactified dimensions, ending up with what Strominger calls a "rather complicated bound state of D-branes, contorted and twisted, wrapping around the internal dimensions." Because D-branes are defined as the surfaces on which strings end, strings were also stuck to the D-branes, and these strings, like the D-branes, had excitations running around them. Strominger and Vafa used statistical techniques to count all the possible quantum states of this tangle of strings and D-branes, giving them one measure of the entropy. Then they applied the Bekenstein-Hawking formula, based on general relativity, to find the other. The two agreed exactly.

Impressive as that agreement was, the work still generated skepticism. For all its twists and contortions, the black hole that Strominger and Vafa had constructed, called an extremal black hole, is the simplest of *gedanken* black holes, and its simplicity made it a questionable example. Black holes slowly evaporate through a process known as Hawking radiation. Unlike other black holes, however, extremal black holes carry an electromagnetic charge; as they evaporate, the electromagnetic force eventually cancels out the evaporation and halts the process. That makes extremal black holes relatively easy to work with, says Strominger, "because they're not changing. They're just sitting there."

Theorists worried that what works for tidy extremal black holes might not work for more complicated and more interesting black holes—the "gray bodies," for instance, that are still emitting Hawking radiation. In the 18 months that followed, says Strominger, various teams tried "to build a more precise dictionary relating these two descriptions of black holes." First, Callan and Juan Maldacena, who was then his graduate student, and independently, Strominger and Gary Horowitz of UC Santa Barbara, constructed and calculated the entropy for what Callan calls "the next more

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The Holographic Universe

Black holes have turned out to be fertile ground for extending string theory and demonstrating its connections to known physics (see main text). Along the way, string theorists may have solved a puzzle posed by black holes, which has troubled theorists for decades: the question of what happens to information that falls into a black hole. String theory, combined with earlier theoretical work, implies that the information swallowed up by the black hole is somehow expressed on its boundary, just as a three-dimensional object can be captured in the two dimensions of a hologram.

Basic principles of physics teach that information in the universe is preserved: If you had perfect knowledge of the present, you could, in theory at least, reconstruct the past and predict the future. (Such perfect knowledge is impossible in practice, of course.) Suppose you threw an encyclopedia into a fire, for example; if you had perfect knowledge of the radiation emitted and the ensuing motions of all the atoms and molecules, you could, with infinite attention to the details, reconstruct the knowledge inside the encyclopedia. Physicists refer to their equations as "unitary"—that is, they preserve information.

But once information falls through the horizon (or edge) of a black hole, it can never get back out. This would not be a problem if the information simply remained inside the black hole, but, as Stephen Hawking demonstrated in the 1970s, black holes evaporate through a process called Hawking radiation. Pairs of particles are created outside the hole, one with positive energy and one with negative energy. The negative one drops into the black hole, lowering its mass, while the positive one comes out as radiation that is independent of what was inside the black hole. "Hawking claims that when the black hole disappears, the information is irretrievably lost," explains Andrew Strominger of Harvard University. "This was a very shocking statement because it bears on our most fundamental, cherished beliefs about the laws of physics."

Although no one has found a flaw in Hawking's argument, few physicists believe that black holes should behave in a way contrary to everything else in the universe. Over the last 3 years, however, string theorists may have finally found a way around the problem, by providing support for a concept called holography, proposed in the mid-1990s by Lenny Susskind of Stanford University and Gerhard t'Hooft of the University of Utrecht in the Netherlands, with contributions from other theorists, such as Kip Thorne of the California Institute of Technology in Pasadena and Jacob Bekenstein of the Hebrew University of Jerusalem. Although the concept is surprisingly simple—it says that a theory within a region of space-time is equivalent to a theory on the boundary of that region—it "was considered absolutely off the wall by all general relativists and basically all string theorists," says Susskind.

Last year a thoroughly holographic conjecture by string theorist Juan Maldacena of Harvard University won over some of the skeptics. Maldacena's conjecture says that a string theory, describing both gravity and microscopic quantum interactions, in a given space is equivalent to an ordinary quantum system without gravity that lives on the boundary of that space. Applied to black holes, Maldacena's conjecture implies that the theory describing the nature of a black hole's interior is equivalent to a conventional quantum field theory describing the boundary of the black hole—the kind of unitary theory in which information is conserved. And because Hawking radiation is emitted from the boundary, the conjecture implies that it carries the information that would otherwise disappear as the black hole evaporates.

"This string theory episode has completely cut around the back of the barn," says Princeton University theorist Curt Callan. "It suffices to say that the thing at the bottom of the black hole is constructed out of strings, or D-branes," another fundamental object in string theory. "And you can use perfectly unitary rules for their interaction, to compute stuff that looks for all the world like Hawking radiation. So the combined system of what's outside and what's inside looks like a perfectly standard quantum mechanical system."

The implications of holography and Maldacena's conjecture could go well beyond the black hole paradox and lead to what Edward Witten of the Institute for Advanced Study in Princeton, New Jersey, calls "a real conceptual change in our thinking about gravity." They imply that what happens inside the black hole is somehow transferred a macroscopic distance to the surface, says Samir Mathur, a theorist at the Massachusetts Institute of Technology. "We have not been able to see how the conjecture or holography actually does that," he says. "That is the crucial point, because the moment we understand that, I think we will learn something very big about the nature of gravity." –G.T.

complicated" black hole. They imagined what would happen if their hypothetical tangle of D-branes and strings had vibrations traveling in opposite directions. These waves could collide, annihilate each other, and emit a suitably stringlike particle that would be free to escape the system, taking energy with it. "That coincides to a temperature" that can be calculated, Callan explains. "And then you can re-express it in terms of the properties of the general relativity black hole that this thing is modeling. And, son of a gun, it gives you exactly the Hawking formulas; you get the right Hawking temperature and the right Hawking radiation rate. These things match beautifully."

Then Klebanov and Steven Gubser of Princeton, and Amanda Peet, now at UC Santa Barbara, tried to do a similar calculation with four-dimensional D-branes, rather than the tangle of five- and one-dimensional ones. After all, four dimensions—three spatial and one temporal—"is almost our world," says Klebanov. "We did it, and it seemed to almost work." Next, Samir Mathur of the Massachusetts Institute of Technology and Sumit Das of the Tata Institute of Fundamental Research in Bombay, India, calculated how quickly a black hole with some temperature would cool down to its ground state at absolute zero. This time, the two descriptions agreed perfectly.

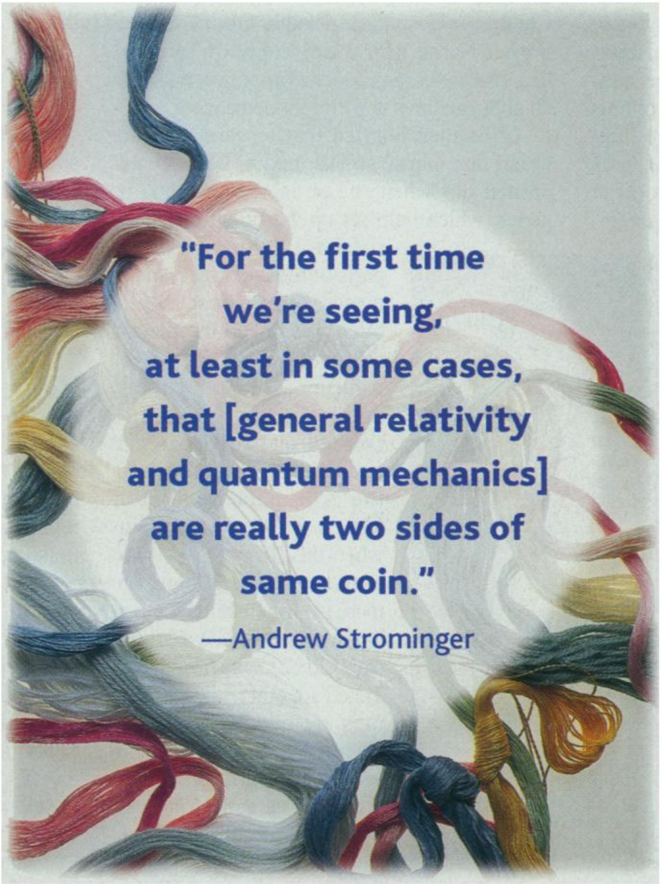
The next paper, says Callan, was "even more amazing." Strominger and Maldacena teamed up to calculate the dual descriptions of the total energy spectrum of the radiation emitted by a black hole, which is shaped by its gravity as well as temperature. When they calculated this spectrum from the equations of string theory, they got what Callan describes as "some crazy function"—which happened to agree exactly with the result given by general relativity. "Bingo," says Callan. "This is telling you something really uncanny is going on."

Maldacena's conjecture

By this time, Maldacena, who had moved to Harvard, had begun to put his finger on that uncanny something, the reason why these various descriptions of the black hole and its behavior agreed so well. The quantum theory that described the excitations on D-branes and strings, he speculated, was not only describing the quantum states inside the black hole, "but somehow also the geometry of the black hole close to its event horizon"—that is, close to the edge of the black hole. He formulated these thoughts into what string theorists now call Maldacena's conjecture, which states, for certain cases, that a quantum theory with gravity and strings in a given space is completely equivalent to an ordinary quantum system without gravity that lives on the boundary of that space. The conjecture represents the zenith—so far, at least—of revolution number two.

Maldacena took the two ways of looking at a black hole within string theory (one as the quantum mechanical tangle of D-branes and the other as the massive object described by general relativity) and studied what happens to them when the temperature of the black hole approaches absolute zero. On the D-brane side, as energy—and hence mass—dwindles at this low temperature limit, the gravitational force goes to zero, as do the interactions among the strings and the D-branes. What's left is a simple species of quantum field theory called a gauge theory, which is familiar to physicists because, among other reasons, it describes the electroweak and strong forces.

On the general relativity side of the equations, the result of lowering the temperature was even more surprising, says Strominger: "You start out with a universe with a black hole and strings in it, and then you lower the temperature. As you do that, the space-time of the universe literally gets frozen. Nothing can happen in it except for very, very near the event horizon of the black hole, where there will always be a region hot enough to allow strings to move around freely. The lower the temperature in the space-time, the closer to the horizon that region is forced to be." The space-time of the wider universe is a complex mixture of flat and curved regions, but in this sliver of a region close to the event horizon it becomes more uniform and symmetrical. The simpler geometry simplifies the string theory that lives in it. "At the end of the day, what's left is a quantum theory of gravity [that] is considerably simpler than the theory we started out with," says Strominger.



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This was, in effect, a first glimpse of the ultimate (so far) duality: The complicated D-brane gamische that made up the black hole had reduced to a simple field theory without even strings in it; the general relativity description of the black hole had reduced to a simple quantum theory of gravity. "Before this, it was thought that gravity theories are inherently different from field theories," says Maldacena. "Now we could say that the gravity theory is the same as the field theory."

Everybody in the field seems to interpret this duality a little differently, depending on their own mental images of the universe. Jeff Harvey, for instance, understands it to mean that instead of having two different ways to compute what's going on with the black hole, you now need only one—the microscopic string way. "Maldacena's conjecture says that all the things of ordinary gravity are somehow contained within what happens on these D-branes. It is almost as though gravity is some kind of residual field left over when you treat these other gauge theories in the right way." To Polchinski, the conjecture suggests that D-branes are somehow the atoms from which black holes are made, and gravity is just the combined effect of all these excited strings and D-branes furiously undergoing quantum fluctuations.

The conjecture also had potent implications extending well beyond black holes. (For one of them, known as holography, see sidebar on p. 515.) In particular, Maldacena's most precise formulation of the conjecture linked the simple string theory near the horizon of a black hole to a particular gauge theory known as a large N gauge theory, which had mystified physicists for 25 years. Gerhard t'Hooft of the University of Utrecht in the Netherlands had worked on these theories in the 1970s to understand the behavior of the strong force of the atomic nucleus, which theorists can only precisely calculate at very high energies or temperatures. (N stands for the number of colors in the theory; colors are one of the two strong-force equivalents of electromagnetic charge.) He also suggested that such large N gauge theories might in fact be string theories, because when physicists drew diagrams describing the interaction of elementary particles in these gauge theories, the diagrams looked a lot like the interactions of strings. t'Hooft did this work well before string theory emerged as a potential theory of everything. "The fantasy that gauge theory might really be a string theory has kicked around for a long time," says Stanford's Steve Shenker.

The catch was, no one had made much progress on the large N gauge theories, either. Now, through the circuitous route of black holes and string theory—"a minor miracle," says Klebanov—Maldacena's conjecture suggested a connection between this four-dimensional, large N gauge theory and a simple string theory that physicists knew how to solve. By making the large N theory tractable, the connection may even be a route to understanding the strong interactions.

Two papers followed Maldacena's, one by Witten and one by Princeton collaborators Klebanov, Gubser, and Alexander Polyakov, who had done crucial work on the four-dimensional gauge theories. These provided specific recipes for what theorists can and cannot calculate when they use a string theory to understand its dual gauge theory. The two papers, says Callan, "very specifically showed what's the rule, what's the recipe, how do you make this connection. And people have been elaborating on it ever since."

So although Maldacena's conjecture has yet to yield any further profound understanding of string theory, string theory is allowing physicists to make progress on theoretical questions that lie much closer to the real world. Whether Revolution Number Two will yield a theory of the universe we live in is still a wide-open question, however. As Strominger says, the work has produced everything a theoretical physicist could want, "except for an experimentally verifiable prediction. It gives us a very precise and explicit relationship between seemingly disparate fields of investigation, a relationship that we can use in some cases to solve problems we've wanted to solve for decades. And it has suggested new ideas that we've previously lacked the imagination to think about."

Once again, string theorists have made enormous progress, but if you ask them where that progress is leading them, they'll still admit that they have no idea. "Part of the goal," says Harvey, "is still to figure out what the hell it all has to do with reality."

–GARY TAUBES