A Theory of Everything Takes Shape

String theorists have broken an impasse and may be on their way to converting this mathematical structure—physicists' best hope for unifying gravity and quantum theory—into a single, coherent theory

ASPEN, COLORADO—In an ordinary year, the idyllic setting might be the only thing buoying the spirits of string theorists gathered here at the Aspen Center for Physics to discuss the state of their arcane field. But this summer, at a month-long workshop on string theory, a mood of uncharacteristic optimism and exhilaration prevailed. For more than a decade, these theorists have been struggling to make sense of a mathematical framework that may constitute a unified theory of particles and forces, of gravity and quantum physics—a.k.a., a theory of everything. But they have made little headway. Now, after a quick succession of breakthroughs, this collection of equations, which had seemed to describe many different universes, none clearly related to our own, is showing signs of turning into a coherent theory.

"This spirit has not been in string theory for 10 years," says Harvard University theorist Cumrun Vafa. "Many things we've been working on for the past 10 years, we now see them finally coming together. Sparks are connecting them, and we just have to write them down as they come." String theory may be overcoming its history, which Lenny Susskind, a theoretical physicist at Stanford University, calls "a very bizarre one, perhaps one of the most bizarre episodes in science."

String theory, he explains, has never been a complete theory at all. It is no more than a set of unsolvable equations originally written down in the mid-1960s to describe the collisions of protons in accelerator experiments. Only later did physicists notice that the equations could be viewed as describing a new kind of fundamental particle: infinitesimal, one-dimensional strings that, depending on their vibration and interactions, could account for all known forms of matter. Later still, they realized that those same equations actually require the existence of gravity to be consistent, which suddenly made string theory the sole viable candidate for a single theory uniting the large-scale realm of gravity and the microscopic realm governed by the other forces of nature.

But while all other successful theories of physics have been built on some brilliant revelation about the underlying physical behavior of the universe—the uncertainty principle in quantum mechanics, for instance—string theorists have had no such vision or understanding, only equations. Approximate solutions do look vaguely like the universe in which we live—"they have all of the right ingredients, roughly speaking," says Susskind, "the right size, the right shape to look pretty much like nature." But the cases that have been studied are either vastly too simple to represent our universe or vastly too complicated to be analyzed.

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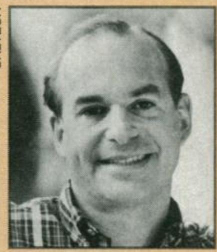

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—John Schwarz

To make matters worse, theorists have discovered five consistent but seemingly distinct formulations of the string equations, each describing a different type of fundamental string, which for a supposedly unified theory of everything can be considered moderately embarrassing. And all five of those formulations happen to describe 10-dimensional universes. String theorists do have a mathematical technique for disposing of the six apparently superfluous dimensions, leaving them with the three dimensions of space and one of time found in the real world. But the technique yields tens of thousands of these four-dimensional "compactifications," and the equations say nothing about how to choose one over any other. As a result, the field of string theory has been mired since the late 1980s in a world of seemingly obscure mathematics, drifting ever farther from the real world of physical phenomena.

But in the past year, the problems of string theory have stopped looking so unsolvable, triggering a frenzied revival. "The field exploded," says Susskind. "Off-scale things may be happening." At the core of this explosion is the recent realization that string theory is rife with what are known as dualities, which means, simplistically, that apparently different formulations of the theory are actually equivalent. String theorists have learned that their equations permit the existence of a whole new zoo of potentially fundamental objects—from strings and magnetic monopoles to minuscule black holes and even five-dimensional bubblelike membranes. At the same time, they have found that all these objects and all five different formulations of string equations appear to be simply different manifestations of the same underlying theory.

Historically, dualities have proven to be extraordinarily powerful tools in physics. Problems that couldn't be solved in one formulation of a theory would turn out to be eminently solvable in the dual formulation. Such may be the case now with string theory. "A year ago if someone had said there's going to be a paper appearing tomorrow that explains how you solve the hardest problems in string theory, no one would have believed it," says Jeff Harvey, a University of Chicago theorist. "Now it's not inconceivable that such a paper would appear and be taken seriously, and maybe even be right."

Imperturbable equations

To understand those problems requires a sense of how string theorists try to make progress and why they have been criticized as practicing something more akin to pure mathematics, or maybe religion, than physics. The sticking point is that the unification of quantum physics and gravity that string theory aims to describe can take place only at an energy scale known as the Planck scale—18 orders of magnitude higher than the energies achieved by the most powerful accelerators.

That's hopelessly removed from experiment, although string theory does have what its practitioners refer to as a "low-energy" side that might be testable. It is known as supersymmetry, a feature of nature that must exist for string theory to achieve its ultimate unification. Supersymmetry postulates a relation between the particles of matter, known as fermions, and the wavelike particles, called bosons, that mediate forces. In known physics, those two classes of particles seem distinct, but supersymmetry holds that for each existing fermion there must be a matching boson, and vice versa.

Regrettably, no existing particles seem to be the "superpartners" of any other existing particles, but as an anonymous wit of physics once put it, there's room for optimism: "Assume that we've already discovered half of the superpartners. That leaves the half we haven't." Physicists partial to supersymmetry, including all string theorists by definition, predict that the lighter superpartners will appear at the energies of the next generation of accelerators. If they do, string theory will gain a tremendous boost; if not, theorists will surely suggest that experiments at still higher energies are needed.

For now, string theorists can make progress only by mathematically analyzing their equations—studying their behavior under various conditions and sets of parameters in the hope of gleaning insight into the physics they might describe. In trying to do so, string theorists have faced an overwhelming obstacle: The theory has remained unamenable to the techniques that physicists studying quantum theories have traditionally used to calculate physical processes.

Because of the uncertainty inherent in the world of quantum physics, any theory attempting to describe the interaction of particles and forces has to take into account an infinite complex of possibilities, which makes the equations impossible to solve exactly. The only way to come up with solutions, says Texas A&M theorist Michael Duff, "has been to resort to some sort of approximation scheme, and the age-old way of doing that in physics is what's called a perturbation series or a perturbation expansion."

"The closer we get to the real world ... the fewer tools we have to analyze the theory."
—Andrew Strominger

Take the theory of electromagnetism, for example, known as quantum electrodynamics or QED. In QED, Susskind explains, physicists might want to compute what happens when two electrons approach each other. "The most likely thing that will happen," he says, "is nothing. The two electrons just move through the space and they don't see each other. The next most likely thing, which is already unlikely, is one electron will emit a photon and the other will absorb it and thereby scatter. Beyond that everything else is extremely improbable." So in QED, the outcome is the sum of these possible interactions, multiplied by ever-increasing powers of a number called the fine structure constant, which is a measure of the probability of interaction of two particles.

In QED, this "coupling constant" happens to be a very small number—1/137 to be precise. Because successive powers of 1/137 very quickly approach zero, just a few terms of a QED perturbation series result, says Duff, "in spectacular agreement with experiment, and everybody is very happy. QED is the most accurate theory man has been able to come up with."

If the coupling constant is larger than one, on the other hand, as it is with "strong" interactions—such as the strong force that holds quarks, protons, and neutrons together in the nucleus—"then you're out of luck," says Vafa. A perturbation expansion will grow with each successive term, never converging on an answer. That's the case in quantum chromodynamics, the existing theory of the strong force, forcing physicists to rely heavily on experimental measurements and computer simulations.

String theory, too, has to explain strong coupling scenarios such as nuclear binding, and it is far out of reach of experiment. Instead theorists resort to studying extremely simplified versions of their equations—"toy" theories not likely to bear much resemblance to reality. These are either 10-dimensional string theories or the four-dimensional supersymmetry theories that are an ingredient in string theory, and they contain not just one supersymmetric relationship between fermions and bosons, but lots of them. The relevant mathematics permits up to eight supersymmetries, and although theories with more than one (known as n = 2, n = 4, or n = 8 supersymmetry) are mathematically incapable of generating "real" physics, they are increasingly easy to study and solve.

"Those added symmetries are a very powerful tool enabling us to analyze the theory," says Andrew Strominger of the University of California, Santa Barbara. "But the closer we get to the real world, the fewer symmetries there are, and the fewer tools we have to analyze the theory." To make more headway, says Duff, "we needed a way to do nonperturbative string theory." The recent proliferation of dualities, say string theorists, promises a way to do just that.

THE DUALITIES MULTIPLY

Year	Theory	Duality
1931	Quantum Electrodynamics	Electric charges ⟷ Dirac monopoles
1979	Grand Unified Theory	Electric charges ⟷ Magnetic monopoles
1989	String Theory (10D)	Strings ⟷ Five-branes
1993	String Theory (4D)	Strings ⟷ Solitons
1994	String Theory (6D)	Strings ⟷ Strings
1994	String Theory (6D)	Heterotic Strings ⟷ Type II Strings
1995	String Theory (4D)	Strings ⟷ Black holes
1995	String Theory (10D)	Strings ⟷ Membranes

SOURCE: A. STROMINGER

Making connections

Its starting point was a venerable idea in physics: that the electron, the fundamental unit of electric charge, has a counterpart called the monopole, an elusive and so far undetected particle that carries an isolated magnetic charge. This "duality" between electric and magnetic charge was first proposed in the 1930s by the British theorist P.A.M. Dirac, who wrote it into the theory of electromagnetism to make the theory consistent with quantum mechanics. Dirac's monopole had several noteworthy characteristics. For one, if the electric charge was small, the magnetic charge of the monopole had to be large, and vice versa.

Dirac's monopoles played little role in physics for the next 40 years. In the early 1970s, however, Gerard t'Hooft of the University of Utrecht in the Netherlands and Alexander Polyakov, now of Princeton, showed that monopoles arose naturally as solutions of grand unified theories (GUTs), which attempt to unify all the forces of nature except gravity. Their work led Claus Montonen of the University of Helsinki in Finland and David Olive at the University of Wales in the United Kingdom to suggest in 1979 that certain GUTs might have a duality between electric and magnetic charges, similar to the one Dirac had proposed.

If the duality really existed, they added, the inverse relation between the monopole's charge and the electric charge implied that exchanging monopoles for electrically charged bosons would also flip-flop a theory from strong coupling—which was not amenable to perturbation expansion—to weak coupling, which was. In other words, if a theorist came across an unsolvable strong coupling scenario in one GUT formulation, he could look at its inverse in the weakly coupled formulation and solve the equations that way—"a really neat idea," as Duff puts it. On the other hand, Montonen and Olive managed to produce little evidence that GUTs really had this electric-magnetic duality, and for the next 10 years or so, says Duff, "everybody forgot about it."

But in 1989, electric-magnetic duality began attracting new interest from string theorists, who by then were at an impasse. Harvey and Atish Dabolkhar of Caltech, for instance, suggested that somehow electrically charged strings could be dual to solitons—hypothetical particlelike objects that include magnetic monopoles. That same year Strominger proposed an even more bizarre duality: between strings and objects called five-branes. A five-brane is a five-dimensional analog to a string (five-brane is short for "five-dimensional supermembrane"), and Strominger found that this five-dimensional object is a solution to the equations of string theory and could be a fundamental object just like a string. The equations also suggested that in some way these five-branes were dual to one-dimensional strings in the same way that electric charges and magnetic charges were dual in Montonen and Olive's conjecture.

The dualities proliferated when Duff made an excursion away from the usual 10 dimensions to a six-dimensional realm. (String theorists work in whatever number of dimensions is most convenient and then try to work their way back to the real world, like Dorothy trying to get home from Oz.) Duff suggested that if a five-brane were wrapped around a four-dimensional space known as a manifold in a six-dimensional universe, what would be left would be a one-dimensional object—a string, one of the five varieties described in string theory's various formulations. If, as Strominger had suggested, another species of string was dual to these five-branes-turned-strings, there might be a duality between two different types of strings, albeit one that only existed in a six-dimensional universe.

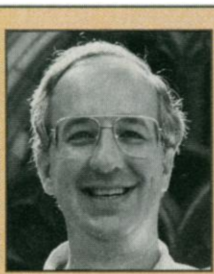
The pieces continued to fall together. First Ashoke Sen of the Tata Institute in Bombay, India, provided what Harvey calls "dramatic new evidence" that the electric-magnetic dualities Montonen and Olive had proposed for GUTs really exist in a four-dimensional supersymmetry theory. Then Nathan Seiberg of Rutgers University, in collaboration with Ed Witten of the Institute for Advanced Study in Princeton, showed that these dualities could open the way to analyzing a supersymmetric theory plagued by strong couplings.

Finally, last November, Chris Hull of Queen Mary College in London and Paul Townsend of Cambridge University conjectured that the electric-magnetic dualities not only exist in a six-dimensional string theory, but are much more powerful than ever before imagined. In this case, however, the dualities link not electrons and monopoles but two of the five different kinds of strings that theorists have envisioned, known as heterotic and type II strings.

Earlier, string theorists had written off type II strings as part of a theory of everything because these strings implied a universe without charged particles. To solve this problem, Hull and Townsend invoked yet another potential fundamental object—and the possibility of yet another duality. Their hypothetical charge-bearer is what's called an extremal black hole—the theoretical end of the line for charged black holes, which are believed to evaporate gradually, through a process called Hawking radiation. Hull and Townsend suggested, for good measure, that these black holes might be dual to strings, in the same way that magnetic monopoles are dual to electrons in the four-dimensional theory.

Web of dualities

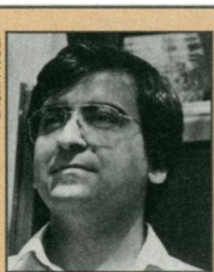
Even those string theorists who understood Hull and Townsend's ideas had trouble accepting this proliferation of dualities. "All of this was very confusing," says Harvey. "It wasn't clear which of these dualities were really going to work and which didn't work." That left it to Witten to play his accustomed role in string theory and clear the air, which he did in a paper and a lecture at a March conference on strings at the University of Southern California.


RANDY TUNNELL/UNIV. OF CHICAGO

"By pushing different buttons, you start to understand that [string dualities are] very powerful."
—Jeff Harvey

Says Harvey, "Witten sort of took all these ideas and in the way that he does with his kind of crystalline clarity, boiled it down to a set of dualities or conjectures that had the most forceful evidence, and he provided new evidence and codified how many of these things ought to work and discarded other things that probably didn't work. He also, of course, just gave it credibility in the community." Susskind puts it more bluntly: Witten "simply went over it like a steam roller."

By the time Witten was done, the string theory dualities seemed to have created a mathematical spider web touching every aspect of the field. On the one hand, the dualities seemed to have opened the way for the fundamental particles of string theory to be almost anything—any of the various string formulations, or monopoles, or five-branes, or even the extremal black holes. Indeed, much of the present excitement was generated when Strominger, together with David Morrison of Duke University and Brian Greene of Cornell University, showed that the black holes could turn into strings and vice versa (*Science*, 23 June, p. 1699). As Duff puts it, "The unique position that strings occupied has somehow vanished, because strings, black holes, and membranes—all these higher dimensional extended objects—have a part to play in the big picture, whatever that is."


LAURA WOLF

"For the first time, there's a hope that we can solve string theory in our lifetime."
—Cumrun Vafa

But that picture is starting to come into focus. For starters, says Witten, what once appeared to be five distinct string theories, "we now know are all equivalent to each other." Adds Caltech theorist John Schwarz, one of the originators of modern string theory: "It's now clear there is just one string theory, which is nice, because it's the only known theory consistent with gravity and quantum mechanics. We only need one. Now the claim is we only really have one."

At the Aspen workshop, the theorists excitedly discussed how they will exploit this proliferation of dualities. They now have the tools, they said, to explore versions of their theories with less supersymmetry and greater realism. "We're marching away from the highly symmetric configurations," says Strominger, "and marching toward situations in which there's less and less symmetry, and we're marching full steam, and we haven't run into a roadblock yet." Indeed, Witten and Vafa were hurrying to get a paper done for the workshop on a theory with $n = 1$ supersymmetry, and another half-dozen similar papers seemed to be in the works.

How far these theorists will get with their dualities—and how close to a coherent description of the physical world—is anyone's guess. "It's like a primitive society finding some advanced tool left behind by some other culture," says Harvey. "You push this button and it does one thing, and you push another button and it does something else. By pushing different combinations of buttons, you start to understand that it's very powerful and can do all sorts of interesting things."

No one is sanguine enough to predict that string theorists will have a theory of everything in the next few years, or even the next decade, but they all say they're suddenly much closer than they've ever been. "For the first time," says Vafa, on the optimistic side, "there's a hope that we can solve string theory in our lifetime." Schwarz is more pragmatic. "We got lucky now, and we're on a roll," he says, "and how far we're going to get before things slow down again, I don't know. There's no doubt in my mind that things will slow down again just like they did before, and we won't have solved everything, and there will be articles in newspapers claiming string theory is in the doldrums again. But when we do reach that point we'll know a hell of a lot more than we know today."

–Gary Taubes