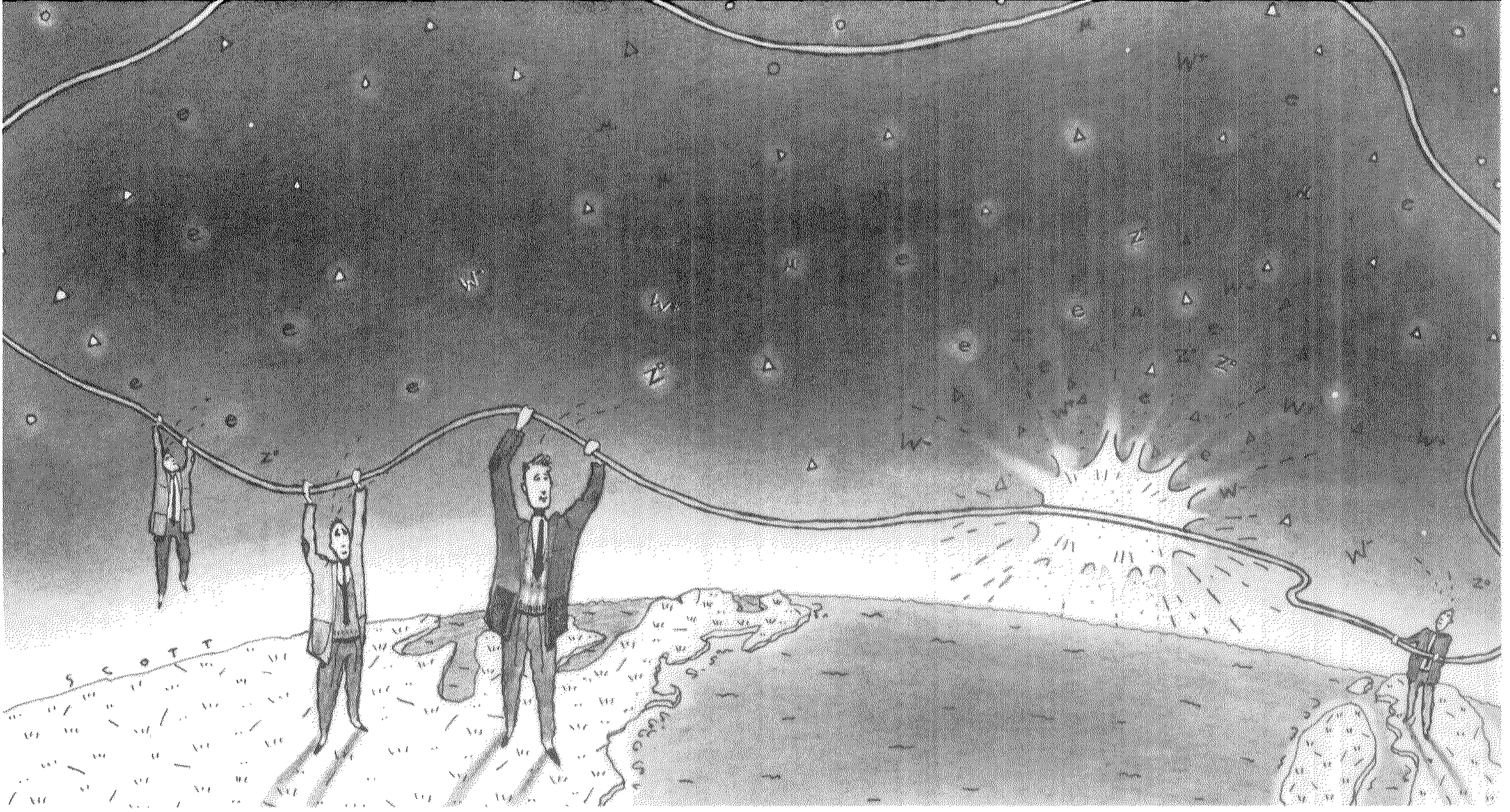


Superstrings

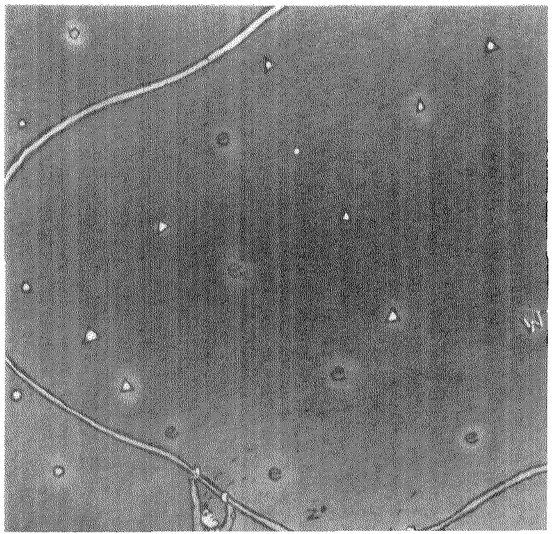
A YEAR AGO John Schwarz and Michael Green announced a discovery that pointed the way toward tying up a lot of loose ends in physics. With a mathematical breakthrough in their superstring theory, they suddenly found themselves with a very promising candidate for a unified field theory describing all four known fundamental forces of nature — electromagnetism, the weak and strong forces, and gravity. The search for a unified field theory has been the most compelling problem in modern physics, whose solution was Einstein's dream; it has eluded physicists ever since. Although electromagnetism and the weak force have been established as being related to each other, and progress has been made toward linking up the strong force, until a decade ago the inclusion of gravity appeared to most theoretical physicists a problem best avoided. Since then the search for a unified field theory has been an active subject of research, with today's theoretical physicists seeking a quantum mechanical field theory that would, at last, embed Einstein's general theory of relativity comfortably in quantum mechanics.

Not everyone has been looking for the solution in superstrings, a word coined by Schwarz. In fact, before August 1984 Schwarz, then senior research associate, and Green, visiting associate at Caltech (from Queen Mary College, University of London), may have been the only two people in the world working on superstring theory. Now hundreds have jumped on the bandwagon. Although not directly involved in the work, Murray Gell-Mann, Nobel laureate and the Robert Andrews Millikan Professor of

Theoretical Physics, has been providing encouragement along the way and considers the recent work of extraordinary importance. "If it's not *the* answer, it's an important step in moving toward the answer," he says. "If superstring theory works, it will prove to be the key to early cosmology as well as particle physics."

In superstring theory all elementary particles are, instead of points as previously assumed, strings, albeit very short ones (10^{-33} cm, — a Planck length), that exist in 10-dimensional space-time. They're not just mathematical fictions, insists Schwarz, but really do exist as one-dimensional curves with zero thickness. But they're so small that for most practical purposes they are well approximated by points. The string-like structure becomes important only at extremely high energies (or very small distances) and could be directly observed, says Schwarz, only in experiments at 10^{19} GeV. Current accelerators are capable of only 10^{3} GeV.

Such a bizarre picture (although Schwarz maintains that it's really quite conservative) didn't suddenly appear out of nowhere last year. The basic idea of strings, including some mathematical machinery for them, has been around since the late 1960s, when it was proposed as a theory of hadrons — the numerous different subnuclear particles including the neutron and proton, which are held together by the strong force. But there were a few problems with the original string theory of hadrons. For one thing, it contained tachyons, massless particles that travel faster than the speed of light, whose existence was essentially impossible. And it did *not* contain any fermions. Fermions are particles that obey the Pauli exclusion principle, that is, no two of them can simultaneously occupy the same quantum state. The basic fermions are the leptons (which include the electron, the muon, the tau, and their neutrinos) and the quarks — building blocks of the hadrons. Besides the serious drawback of missing most of the particles, the theory also required a rather intimidating 26 dimensions of space-time.



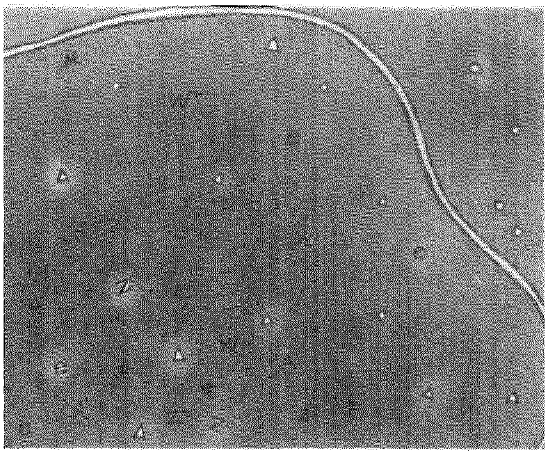
Fifteen years ago at Princeton, Schwarz and André Neveu, with a contribution from Pierre Ramond (who later also came to Caltech), set out to get rid of these difficulties. They came up with a version of the theory that incorporated fermions and that led to the elimination of the troublesome tachyons after the simple modification of consistently omitting certain parts of the theory. The number of dimensions of space-time was now 10 instead of 26. But although this new string theory was, according to Gell-Mann, "a beautifully consistent theory" and "very exciting," quantum chromodynamics emerged at about the same time (partly the result of Gell-Mann's own work and that of Harald Fritzsch, who was then also at Caltech) and was recognized as the correct theory of hadrons and the strong force. String theory was superseded as a theory of hadrons, and its popularity waned.

But Schwarz stuck with string theory anyway, convinced that, in Gell-Mann's words, "somehow, sometime, somewhere, it would still be useful." Schwarz came to Caltech at Gell-Mann's invitation in 1972, and in 1974 he and Joël Scherk hit on the idea that the key particle — of mass 0 and spin 2 — which had been so troublesome for the hadron interpretation, might actually be a graviton, the hypothetical particle that carries the force of gravity. What was impossible for a theory of hadrons and the strong force was "just what one wants for a graviton," says Schwarz. (A graviton will not be observed directly in the near future because its interactions are so weak, but it definitely does exist, Schwarz says.) And Einstein's theory of gravitation appeared as an approximation to the theory.

With the revival of the string idea in a new context, their whole perspective changed. They abandoned the attempt to make it fit hadrons and began to consider string theory as a possible quantum theory of gravity — and all other phenomena as well. From this perspective the previously troublesome components of string theory settled quite neatly into place. Scherk and Schwarz reduced the hypothesized size of strings 20 orders of magnitude — from the size of the nucleus to 10^{-33} cm. They published papers in 1974 and 1975 reformulating Schwarz and Neveu's original string theory as a quantum theory of gravity. With the simple modification mentioned above, the reformulated string theory possessed supersymmetry and had supergravity (Einstein's theory of gravitation combined with supersymmetry) as an approximation.

A kind of supersymmetry arose out of Schwarz, Neveu, and Ramond's first string theory in 1971, when it was still being applied to hadrons. The more commonly discussed kind of supersymmetry was introduced for point particles at about the same time by a Russian group and later independently by Wess and Zumino in Europe. It involves a mathematical transformation that interchanges fermions and bosons (including the so-called gauge particles — photons, gluons, and gravitons, which shuttle between particles and transmit forces), so that each fermion has a boson partner and vice versa. These hypothesized particles have some fanciful names (Schwarz claims no responsibility for them); for example, the boson partners of quarks and leptons are squarks and sleptons, and the fermion partner of the photon is the photino. Observation of these predicted particles, which would confirm supersymmetry, may be possible with some of the powerful new colliders now on the drawing boards, or even with existing ones, Schwarz believes. The search has already begun.

One of the stumbling blocks of a quantum theory of gravity in which gravitons and other elementary particles are described as points is the occurrence of infinities. Supersymmetry turns out to play a crucial role in canceling out certain infinities. Calculations in quantum mechanical theories require contributions from all particles, the bosons in certain examples giving positive contributions and the fermions negative ones. When they are kept separate, you get the infinities that you don't want, but in superstring theory the fermion and boson contributions are combined, canceling each other out and producing finite results. This also happens to some extent in supergravity, although it is a point-particle theory, but not to an extent sufficient for meaningful finite results, according to Schwarz. In the late 1970s supergravity was itself a hot candidate for a unified field theory — so hot that Scherk and Schwarz's 1974 paper caused little stir. Very little was published on strings until Schwarz and Michael Green's first joint paper in 1981.



Green got involved with strings on meeting Schwarz at CERN, the particle physics laboratory in Geneva, in 1979, and thus began a fruitful collaboration that has continued during several months of each subsequent year, on one side of the ocean or the other. Since supergravity had captured the attention of most others, the two were left in peace. "It was nice, really," says Green. "We could work on a topic and be sure that no one else had already done it." And their results were interesting to enough people (Gell-Mann and Edward Witten of Princeton, in particular), that at least "no one treated us as if we were crazy."

The most popular version of supergravity postulates 11 dimensions of space-time, which Green says is impossible, since the correct theory must be chiral, that is, left-right asymmetric, or mirror asymmetric, as are the laws of physics. He believes that chiral theories can exist only in an even number of space-time dimensions, such as the 10 dimensions of superstring theory, which Schwarz had already suggested in 1972. And where are the other six, apart from the three of space and one of time that we know? Presumably they're too small to be observed and are described as curled up, collapsed, or compacted into a sort of six-dimensional ball. While the nine spatial dimensions could have been equivalent in the first moments of the Big Bang, symmetry could break in the rapidly cooling and expanding universe, leaving three dimensions very large and six very small.

Although chirality is an essential feature of Schwarz and Green's theory, chiral fermions create what was thought to be an inescapable problem of anomalies (inconsistencies introduced by quantum effects). It was considered such a generic problem in higher dimension theories that theoretical physicists were stymied by it until the summer of 1984, when

Green and Schwarz showed that anomalies could cancel in superstring theories.

Their calculations showed that there were *no* anomalies for superstring theory in the case of two specific symmetry groups — the breakthough that suddenly attracted so much attention. In particle physics symmetry groups, of which there are an infinite number of possibilities, are used to define transformations that relate particles to one another and thereby relate the properties of those particles. Quantum field theories that describe the fundamental forces of nature other than gravitation (electromagnetism and the weak and strong forces) use specific symmetry groups to describe the interactions and the quanta that carry them. These established and accepted theories have not used theoretical criteria to select symmetry groups but have picked them because they are the groups that fit the experimental facts. For example, the electromagnetic force is characterized by a group of transformations called U(1). A symmetry group labeled SU(3) describes the strong force of quantum chromodynamics, and SU(2) the weak force. Glashow, Weinberg and Salam received the Nobel Prize in 1979 for mixing the SU(2) and U(1) symmetry groups (the electroweak forces). The theory that encompasses all three symmetry groups (SU(3) × SU(2) × U(1)) is called the Standard Model, and it describes all the known forces and particles — except gravity.

Ideally, however, the symmetry group should be uniquely determined by the theory itself without having to "dial knobs" in the equations, as Schwarz puts it. Schwarz and Green found, not by dialing any knobs but by using superstring theory, that mathematical consistency (that is, elimination of the anomalies) made two particular symmetry groups pop out — groups designated SO(32) and $E_8 \times E_8$. These are both very large symmetry groups (496 generators) easily able to encompass all known elementary particle symmetries. Schwarz and Green came up with a superstring theory with the SO(32) symmetry group that was free of anomalies and infinities, and just a few months later a group of researchers from Princeton, taking off from Schwarz and Green's work, presented a superstring theory for $E_8 \times E_8$. This particular symmetry group is especially exciting because it readily breaks down to the Standard Model. E_8 had long been a favorite of Gell-Mann (and others), who had been hoping someone would find a string theory for it. Suddenly a unified field theory looked to be within reach.

For Gell-Mann, one of the important answers superstring theory offers is to the question of the confusing and continuing proliferation of elementary particles. Why are there so many? Superstring theory suggests that there are actually an infinite number of particles, with only some of them lying in the low-mass states, that is, relatively low; in many cases the low-mass states are still high-mass states as far as experimental physicists are concerned. "But these infinitely many particles all obey a single very beautiful master equation," says Gell- Mann. He describes the theory as that of a field taken as a function of a one-dimensional path or string (which corresponds to an infinite number of functions of a point) in space-time. Just as the strings of a musical instrument can yield an infinite number of harmonics, so the theory's strings can vibrate in an infinite number of modes.

The second E_8 of the symmetry group brings with it a bizarre phenomenon of much interest to astrophysicists — shadow matter, that is, a whole other corresponding (although not exactly corresponding) type of matter that interacts with the matter we observe only through interactions of gravitational strength — that is, very weakly except in large aggregates. On the basis of observable behavior of galaxies, astrophysicists believe there must be a great deal of unseen "dark" matter exerting gravitational force — matter whose existence would determine whether the universe will forever expand or whether it will eventually collapse on itself. It is intriguing to consider that the E_8 shadow matter, hidden from our perception, may provide the answer.

The potential of superstring theory is exciting, and, according to Green, "it may soon be able to explain a great deal of experimental information." This potential for explaining observed phenomena has put a lot of physicists in gear, notably the group at Princeton working with Witten. Mathematicians are getting involved too, in particular attempting to describe the geometry of the six curled-up dimensions. One likely possibility is that they form what is called a Calabi-Yau space, which is a type of six-dimensional space of great importance in pure mathematics.

"We've formulated the basic equations," says Schwarz, who is now professor of physics. "Now all we have to do is solve them." □ — *JD*