Supersymmetry and Supergravity

A series on particle physics and cosmology concludes with supersymmetry, and the promise of a quantum theory of gravity

Cosmologists and particle physicists talk a lot these days about gravitinos, photinos, Winos, squarks, and a host of similar entities—all of them hypothetical, yet all of them tied together by a unifying principle known as supersymmetry.

The cosmologists' interest is largely practical. The universe has confronted them with a great deal of invisible, or "missing," mass that manifests itself only by its gravitational effects on the galaxies. Because this cosmic ectoplasm behaves very much like a haze of weakly interacting elementary particles, cosmologists are ready to entertain any candidate particles that the physicists might have to account for it.

The physicists, meanwhile, see gravitinos, photinos, and the like primarily in aesthetic terms, as manifestations of the supersymmetry principle. Originally just an exercise in abstract quantum field theory, supersymmetry now holds out the promise of a true quantum theory of gravity, and an explanation of the endless proliferation of quarks and leptons. Unfortunately, nearly 10 years after the discovery of supersymmetry there is still not a scintilla of empirical evidence for it. Pending some unexpected find at the accelerator laboratories, in fact, most theorists now believe that cosmology offers the only real way to test the idea. As physicist Heinz R. Pagels, executive director of the New York Academy of Sciences, says, "We have already entered the era of post-accelerator physics for which the entire history of the universe becomes the proving ground for fundamental physics."

This fascination with an untested abstraction is ironic, because it comes at a time when, for the first time in history, physicists have verifiable theories in place for all the forces of nature. Every phenomenon now accessible to experiment can in principle be understood. It is just that no one is satisfied.

On the one hand, there is general relativity, Einstein's theory of gravity. Here the concept of gravitational force is actually banished in favor of geometry: planets, apples, and people move through space and time as if they were traveling on a kind of four-dimensional surface; what appears to be a mutual attraction is only the deflection of paths by a curvature of that surface. The theory has a beguiling elegance and naturalness. It is one of the two great monuments of 20th-century physics. And yet it stands apart, defying theorists' every attempt to bridge the distance to the other great edifice, quantum field theory. Indeed, there is a widespread consensus among physicists that general relativity is incomplete, that it must be modified in some profound way before it can grapple with such singular conditions as the Big Bang, or the inside of a black hole.

On the other hand, there are the particle theories: the Weinberg-Salam model, which unifies the electromagnetic and weak interactions; and quantum chromodynamics (QCD), which deals with the behavior of colored quarks and gluons in the interior of such strongly interacting particles as protons and neutrons. These theories replace the concept of force with something that resembles a game of volleyball: particles toss "quanta" such as photons or gluons back and forth, and in the process exchange energy and momentum. The two theories are fully consistent with quantum mechanics and with each other. In fact, they can be combined into larger mathematical frameworks known as grand unified theories, which predict such new phenomena as proton decay and magnetic monopoles, and which have already offered plausible explanations for a number of cosmological mysteries (*Science*, 28 January, p. 375).

But for all of that, these quantum models still have an ugly, ad hoc air. The Weinberg-Salam model, QCD, and the grand unified theories are members of a class of mathematical constructs known, for historical reasons, as gauge theories. The problem is that there are an infinite number of such theories, and it remains an utter mystery why these particular gauge theories—or any gauge theories at all—should describe matter so well. In particular, there appears to be no constraint on the numbers and kinds of particles in the universe. Quarks and leptons (cousins of the electron and neutrino) can be added to the theory at will, which means that the theory does not really explain the particles at all. Without some new principle to constrain the possibilities, the gauge theories are little better than a sophisticated form of phenomenology.

Thus the appeal of supersymmetry: it promises the best of both approaches, combining a certain naturalness and economy with quantum mechanical consistency. Supersymmetry was first discussed in 1974 by Julian Wess of the University of Karlsruhe and Bruno Zumino of the University of California at Berkeley in the context of a very abstract (and unrealistic) model field theory (*1*). Their starting point was the quantum mechanical fact that all elementary particles fall into one of two classes: the fermions, whose intrinsic angular momentum, or spin, is equal to 1/2, 3/2, 5/2, and so forth, times Planck's constant; and the bosons, whose spin is equal to 0, 1, 2, and so forth, times Planck's constant. The essential idea was to postulate a one-to-one "super" symmetry between the classes: each fermion should have a bosonic partner of the same mass, and vice versa.

Now, as a model of the real world this supersymmetry principle seems patently absurd. The two tribes of particles differ in more than just spin; most crucially, bosons like to congregate in vast swarms—a laser beam is simply an army of bosonic photons marching in step—while fermions such as the electron or proton obey the exclusion principle, shunning each others' company so much that no two of them will occupy the same quantum state. Even worse, physicists know enough about the real particles and their interactions to say that no known fermion could possibly be the superpartner of any known boson.

But neither of these objections was fatal. First, Wess and Zumino found that the mathematical process of changing a boson into a fermion is quite simple. In fact it is closely related to the structure of space and time: reflect a boson in the mirror of supersymmetry once and get a fermion; reflect it twice and get the boson back again—displaced a bit to one side.

Next, the lack of any fermi-bose symmetry among the observed particles could be explained away by a phenomenon known as spontaneous symmetry breaking. (By 1974 this kind of symmetry breaking had already become an integral part of theoretical physics, not least because it had been crucial to the Weinberg-Salam model, which appeared in 1967.) In essence, the idea is that the true symmetries among the particles manifest themselves only when matter is at extraordinarily high temperatures, such as occurred during the Big Bang. The universe thus started out in a symmetric state, but as it expanded and cooled the symmetries underwent a kind of phase transition, in the same way that supercooled water vapor crystallizes into frost on a window pane.

The particles themselves did not stick together—the transition actually involved a shift in the internal structure of empty space—but the change did alter the particle masses and interactions. Presumably, supersymmetry was spontaneously broken in just the right way for the superpartners to acquire very large masses while the ordinary particles retained relatively small masses. Thus our current-generation particle accelerators are not able to produce superparticles, and it is not surprising that no one has ever seen them.

Physicists were well aware of all the "if's" involved in this argument, but nonetheless, it meant that supersymmetry could not be dismissed out of hand as a model of the real world. Moreover, as theorists began to work on the idea, it quickly became apparent that supersymmetry had some very appealing features that the standard models did not.

Supersymmetry has the kind of abstract beauty that leads people to believe it must be true.

First, supersymmetry—spontaneously broken or not—eliminates the arbitrary proliferation of particles. A given supersymmetric field theory may call for a very large number of particles (some versions have hundreds), but it is always a finite number. Moreover, the particles must always fall into precisely defined groups: a spin-0 boson and its spin-1/2 partner in the simplest model; a spin-1/2 fermion, two spin-1 bosons, and a spin-3/2 fermion in a somewhat more complex model, and so on.

Second, supersymmetry seems to ameliorate the infinities that have plagued quantum field theory since it was first invented in the 1930's. In quantum electrodynamics, for example, quantum fluctuations in the electromagnetic field cause a shift in the apparent mass and charge of the electron. When these shifts are calculated, however, they come out infinite; the answers are given by divergent integrals. The situation is no better in quantum chromodynamics or the grand unified theories. True, these divergent quantities can be papered over by replacing them with experimentally determined charges and masses (a process known as "renormalization"), but the infinities are nonetheless troubling. Renormalized quantum electrodynamics is the most accurate and successful physical theory ever devised, and yet beneath its precise surface there is something mysterious and violently out of control.

With supersymmetry, however, the infinities have a near-miraculous way of canceling out. A divergent integral describing the quantum fluctuation of each fermion field must be added to a similar contribution from its bosonic partner—but added with the opposite sign. In some supersymmetric field theories, in fact, the infinities cancel out perfectly, yielding answers that are completely finite.

Finally, supersymmetry holds out the hope of a true quantum theory of gravity. Conventional attempts to quantize general relativity have usually started by setting aside the geometrical picture of gravity in favor of an approach that more nearly resembles field theory. Bends and ripples in the four-dimensional surface of space-time—"gravity waves"—are reinterpreted as spin-2 "gravitons," quanta analogous to the spin-1 photons or gluons in unified field theories. To a first approximation this picture gives answers identical to Einstein's. But when quantum fluctuations are included, the theory is beset with infinities of the worst sort. Not only do the integrals diverge, but they do so in a way that cannot be swept under the rug. Conventional quantum gravity is not renormalizable, and in fact it is probably inconsistent.

Supersymmetry helps out in two ways. First, the fermi-bose symmetry requires that the graviton must be accompanied by a spin-3/2 "gravitino," which serves to cancel out many of the worst infinities. Although no one has yet been able to show that *all* the infinities cancel in supergravity, many physicists still hope that is indeed the case. At the least, they hope that supergravity is renormalizable—and thus manageable—in the same way that the more conventional field theories are. On the other hand, some physicists have expressed strong doubts; the question is still very much open.

Next, supersymmetry allows one to unite the geometric picture of forces used in general relativity with the particle picture used in field theory. In its simplest form, supersymmetry can be expressed as a field theory in an eight-dimensional "superspace" having four ordinary dimensions—three for space, one for time—and four new dimensions. These latter four are somewhat bizarre, in that length and breadth along these new directions cannot be expressed as ordinary numbers. (They must obey a new multiplication law: $A \times B = -B \times A$; presumably this is why we never notice them.) Yet the mathematics is straightforward, and the payoff is that supergravity can now be expressed in terms of geometry in superspace. All the various particle fields simply measure how the space is bending and curving. Moreover, extended versions of supergravity can easily be accommodated by adding more new dimensions. (For technical reasons the dimensions must be added in multiples of four, up to a maximum of 32.)

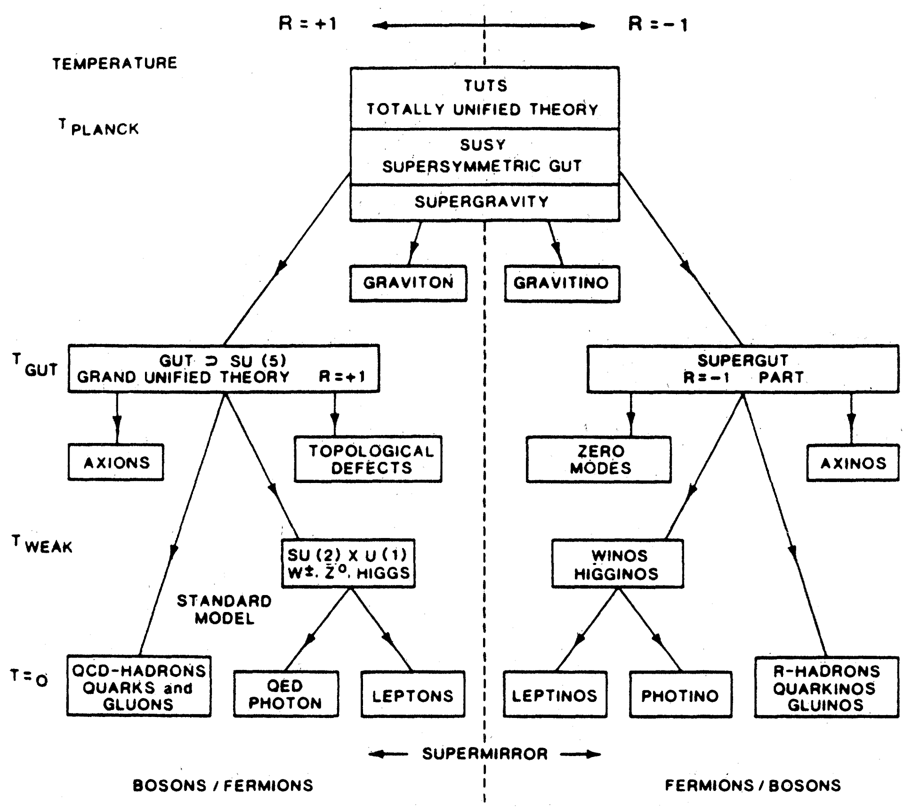
It is clear from all this that the details of supersymmetry are dauntingly complex. Yet, at its core the supersymmetry principle has the kind of compelling, abstract beauty that leads people to believe that somehow it must be true. As Pagels says, "People feel there is something right about this."

The problem, of course, lies in making the connection with reality. For all the hand-waving about spontaneously broken symmetry, the brutal fact is that the particle multiplets allowed in supersymmetry bear no resemblance whatsoever to the families of quarks, leptons, and vector bosons seen in the laboratory. Now, this may or may not be a problem; many physicists have speculated that the observed particles may be bound states of something else ("preons"), and in fact, Zumino and his co-workers (*2*) have recently shown that in certain supersymmetric models, bound states of the superpartners would indeed resemble the real particle families. But even so, no single theory has provided a perfect match to the real world.

The general consensus is that some crucial idea is missing. "I'm not pessimistic," says Edward Witten of Princeton University. "But I don't think that anyone has found the right approach. The breakthrough in applying supersymmetry to physics has not happened yet." History offers some reason to hope. Gauge theories were nothing more than a mathematical curiosity until Weinberg and Salam independently coupled them with spontaneous symmetry breaking and thus produced the first of the modern unified field theories. The geometric techniques developed in the 19th century by Georg Friedrich Bernhard Riemann remained a pure abstraction for nearly a century, until Albert Einstein used them in developing the geometric theory of general relativity.

Pending the arrival of that crucial idea, however, a number of physicists are pursuing a more phenomenological approach. Independent of any specific model, what does supersymmetry imply about particles and the way they behave? In particular, what does it imply about cosmology?

To begin with, if supersymmetry is true, then regardless of bound states, symmetry breaking, or any of the rest, bosons and fermions must still retain their fundamental partnership. The graviton has its gravitino, the photon its "photino," the W boson its "Wino," the quarks their superquarks, or "squarks," and so on. (The masses of the superpartners could be very different, of course, although no one can say what they might be—thus, any time an accelerator pushes into a higher energy range, physicists can hope that a superpartner or two will be found.)



One vision of how supersymmetry might unify particle physics is illustrated here by Heinz R. Pagels of the New York Academy of Sciences. In essence, he assumes that the universe started out at a ferociously high temperature, with symmetry between all the particles (TUTS). *Then, as the expanding universe cooled below 10^{32} K* (T_{Planck}), *a cascade of spontaneous symmetry breaking began. On the left are the conventional* (R = +1) *particles and the theories that describe them: the grand unified theories* (GUT), *the Weinberg-Salam model* [SU(2) × U(1)], *quantum chromodynamics* (QCD), *and quantum electrodynamics* (QED). *All have their counterparts on the right* (R = −1), *where the world has been reflected in a "supermirror." Presumably, these superparticles are too massive to be formed in current generation accelerators.*

Presumably, all of the superpartners were copiously produced in the Big Bang along with the conventional particles. The most massive ones decayed almost instantly, but the lightest were probably stable, in which case they should still be around today in rocks and in stars.

Two superparticles of particular interest to cosmologists are the gravitino and the photino. Assuming that they are light enough to survive until the present, they are ideal candidates for the missing mass: both are electrically neutral, and both interact very weakly with other forms of matter. Primordial swarms of them should still remain in intergalactic space, an invisible haze of matter that shows itself only through the effects of gravity.

In this sense, the hypothetical gravitino and photino closely resemble a family of very real particles, the neutrinos. A primordial haze of neutrinos does fill the universe. There are about 150 of them per cubic centimeter, which means that if neutrinos have even a tiny mass, as some (controversial) experiments have indicated, then they must be a major component of the cosmologists' missing mass (*Science*, 4 March, p. 1050). In addition, if the neutrino mass is assumed to be a plausible 10 electron volts or so, then shortly after the Big Bang the neutrino haze would have broken up into gravitationally bound clumps of about 10^{15} solar masses. Interestingly enough, this is just about equal to the masses of the giant superclusters of galaxies. The implication is that these neutrino clumps served as gravitational traps, gathering in protogalactic gas and dust until it was dense enough to form the galaxies themselves.

Something of the sort would have happened with gravitinos and photinos also, except that their interactions are such that the Big Bang would have produced fewer of them. The fundamental observational constraint is that the density of the primordial haze must not exceed the known limits on the total density of matter in the universe. This means, for example, that the gravitino mass must be about 1000 electron volts or less, which is an intriguing number in its own right: the primordial clumps formed by a 1000-electron-volt particle would contain about 10^{12} solar masses, or about the mass of a typical galaxy. It has always been a puzzle how the galaxies and the clusters of galaxies formed so quickly after the Big Bang. Now one has the elegant possibility that the largest structures in the universe were brought into being by hordes of the most infinitesimal objects in the universe, acting in concert.

What is one to make of all this? Certainly none of this cosmological speculation proves anything about supersymmetry. Proof, if it ever comes, will have to come from the accelerator laboratories, or perhaps some cosmic-ray experiment that finds a genuine superparticle. Yet even qualitative hints from cosmology should prove invaluable in guiding physicists' search for a better theory of nature.

"The common ground of high energy physicists and the relativistic cosmologists is the early universe," says Pagels. "[It is] a region of energy and momentum, time and space for which they have the least confidence that they know what is going on. Yet such circumstance is what creates the intellectual challenge."

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References

1. Supersymmetry has been reviewed by P. Fayet and S. Ferrara [*Phys. Rep.* **32C**, 249 (1977)].
2. J. Ellis, M. K. Gaillard, L. Maiani, B. Zumino, in *Unifications of Fundamental Particle Interactions*, S. Ferrara and P. Van Nieuwenhuizen, Eds. (Plenum, New York, 1980), p. 69.