Through the history of physics, unification has been a persistent theme as well as an ultimate goal. Isaac Newton took a number of what looked to his contemporaries like disparate phenomena and united them with the single theory of what is called the gravitational interaction.

The nineteenth century was the great age of unification of electricity and magnetism, starting with Hans Christian Oersted's demonstrations that there was an empirical connection between the two and ending with James Clerk Maxwell's derivation of a mathematical theory that formally united them. Einstein entered at this point. He wrought a revolution in electro-dynamic theory, followed that with a radical recension of gravitational theory and then set out to close the circle by uniting the two in a unified field theory. He spent more than 30 years at it but made little progress.

Meanwhile, developments in the investigation of quantum physics, the world of the atom, the atomic nucleus and subnuclear particles opened several new chapters that seemed to be leading to greater diversity rather than unity. Quantum physics discovered two new interactions or species of force called the strong and the weak, which operate over such extremely short ranges that they had escaped the notice of macroscopic investigations. (Gravity and electromagnetism extend throughout the universe, the strong and weak interactions to not much more than the diameter of an atomic nucleus.)

What was worse, quantum physics was a new kind of physics, statistical, acausal, indeterministic, dualistic. Things are both waves and particles; locations and momenta are mutually uncertain; the behavior of individuals cannot be predicted; only the statistics of what a large number will do can be found.

When it became certain that the acausality and indeterminism were fundamental to the domain of quantum physics, Einstein withdrew from participation in it because he simply could not deal with those things. Yet throughout his life he expressed a belief that someday a formulation would be found that would include quantum mechanics in a much more comprehensive theory, and that framework would explain the seeming inconsistencies, paradoxes and indeterminism.

It seems now that the route to that consummation may be opening. It goes through a newly developed principle called supersymmetry, which has a sub-

The mathematical symmetry groups that physicists have called upon to help them build theories have done a good deal here and there. But none has the ability to hold macrocosm and microcosm together. That's a job for supersymmetry.

SUPERGROUP

BY DIETRICK E. THOMSEN

category called supergravity. According to a number of prominent theorists including Bruno Zumino of CERN, Stephen S. Hawking of Cambridge University and Yuval Ne'eman of the University of Tel Aviv, it seems the way to go for those who seek further unification as well as those who would extend the legacy of Einstein. It seems fitting that work on it should be heating up in this year of Einstein's centennial.

However, the thing is likely to come about in a way that Einstein didn't envision. He probably would have liked to start with a big global theory, such as the unified gravitation and electromagnetism that he worked so hard on, and then work inward toward the short range local interactions of the microcosmic world. Lately the thrust toward unity has been coming from the field theories of the quantum world.

The global theories have the universe for their playground. The forces they deal with extend in principle to infinity, and space and time play an important role in them. One of Einstein's great achievements was to equate gravitational forces with curvature of space, but when he tried to extend this by equating electromagnetic forces with "gauge," a mathematical quality of space that is related to how distances are measured, he didn't do so well.

The quantum field theories of the subatomic world are less concerned with the far reaches of the universe and the detailed shape of space and time. Everything in them happens in such short bits of space-time that they don't need to be. They are local theories made for the corner of the laboratory not larger than a couple of atoms in which the things of interest to them happen to be taking place, and they usually disavow connections with the opposite corner of the lab where something else is going on. In them forces, fields, interactions are represented by so-called field quanta, particles actually, that other particles bounce back and forth among each other when they are exerting some influence on each other.

Supersymmetry intends to unify both kinds of fields. It can be quite simply stated: a symmetry between the class of particles called fermions and those called bosons. Bosons are particles that have integral amounts of spin (0,1,2). Fermions have half-integral spin ($1/2$, $3/2$, etc.) In their dynamics the two classes obey different statistical principles: Two fermions with exactly the same values of their proper characteristics (quantum numbers) cannot be in the same place at the same time; any number of bosons with the same quantum numbers can. This distinction is one of the most fundamental in mathematical physics. Among other things it means that protons, neutrons, atomic nuclei and atoms all have stable structure. Quarks, protons, neutrons and electrons are all fermions and so can maintain a structure without falling together in a blob.

Simply put, the theory postulates that for every fermion there is a boson and vice versa. In a more dynamic way, as Glennys R. Farrar of California Institute of Technology puts it, the supersymmetry operation "turns fermions into bosons." It can change spin, and it is something like a rotation. All of this is very spatial, and in fact this supersymmetric operation is called the only known generalization — that is, wider extension — of what mathematicians call the Poincaré group of operations. The Poincaré group includes translations (which are linear movements in space), rotations and Lorentz transformations (which are the special ways of moving from one frame of reference to another in special relativity). So, says Farrar, "Space-time may have a higher symmetry and we haven't found it." But she presents

Science Service, Inc. is collaborating with JSTOR to digitize, preserve, and extend access to *Science News*. www.jstor.org

an idea of where to look for it.

Farrar was telling assembled physicists at a recent meeting of the American Physical Society how one might find that symmetry by looking for the yet-unknown particles that would be consequences of its existence. At the same session Zumino, who pioneered the theory of supersymmetry, outlined the theoretical and philosophical goodies it might deliver, but he cautioned that they are dependent on "whether it has anything to do with physics."

The prospects are inviting. The Poincaré group includes the mathematical operations characteristic of relativity theory, and when it is generalized with things basic to particle physics, "such a symmetry is surely compatible with causality and general relativity," Zumino says. That would go far to remove Einstein's objections. In addition, it is a quantum field theory with the properties of locality and renormalizability (ways of getting rid of inconvenient infinities) that are dear to particle theorists.

To a mathematical physicist symmetry includes the usual idea of spatial symmetry, of left hand versus right hand, of balanced patterns of tableware, candlesticks or functions in analytical geometry, but it extends to a more general notion of a kind of equalitarianism or interchangeability among items of the same sort. Just as dishes from the same set are interchangeable in a table setting, so atoms of a gas are interchangeable. It doesn't matter where a gas atom is. Each has the same relations to its neighbors, and, as classical physics taught us long ago, there is no way to tell them apart.

In a gas like this, one atom can be made to do the work of another, can be "turned into another" simply by moving it to another's place in space, an operation with the formal name of translation. Similarly, there may be a series of moves that will carry a dish around the table from position to position. (If there is a design on the dishes, a rotation as well as a translation may be necessary to accomplish a move.) The nature of the moves, their order and interrelation can tell much about the underlying structure of the pattern.

The symmetry groups that particle physicists have been dealing with, the gauge groups, have little to do with gross motions in space and time. They are concerned mainly with the "internal symmetries," the properties of the particles that give them their identity. "Gauge" here means mathematically pretty much what it did when Einstein was using it, but physically it translates to something associated with the identity of the particle as proton or pion or whatever.

The operations here alter the internal properties of the particles, as that of supersymmetry changes their spins. Enough such changes and the identity of the particle is altered, at least in the formal sense or in the imagination. The idea of studying such hypothetical operations is not to learn how to change particles into one another — nature does that easily and quickly enough without our help — but to learn about the underlying structure and interrelations of the particular collections of particles under consideration. The moves that can be made and their order and interrelations characterize mathematically a symmetry group, and such objects have been much studied by mathematicians in the last 200 years or so. Every time physicists decide to use one, a flock of mathematicians flies up to tell them all about it.

The classic example was the perception that the relationships among the hadrons (the class of particles that includes the protons, the neutrons and dozens of others), or a certain part of them, which were well manifested in physical terms, could be expressed mathematically by the group called SU_3 or the unitary symmetry group of rank three. (This is one of the Lie groups, which were extensively studied by the Norwegian mathematician Sophus Lie.) SU_3 has a pervasive tripartite structure. This translated physically into the three quarks, three subparticles out of which all these hadrons might be built. Nowadays there is abundant physical evidence for the existence of some such building blocks. Meanwhile, the quarks have brought in their train an extension of symmetry groups to all parts of particle physics, groups within groups.

The game is now to seek ever "higher" symmetry principles, symmetries that encompass more and more particles, more and more forces, more and more phenomena altogether. To do this one pays a price. Establishing an equalitarianism of sorts among more and more things means ignoring or doing away with the differences among them. Yet nature manifests such differences as we see the world.

So the breaking of symmetry enters as the serpent stalked the Garden of Eden. To give an example that is basic and frequently found — Farrar mentions it as a serious problem in supersymmetry — the symmetry principle will predict the existence of two or more particles that have complementary properties, say positive, neutral and negative electric charge, and the same mass. Experiment shows that the particles exist but have slightly different masses. If the symmetry is to hold, it must be slightly broken, and an asymmetrical term must be inserted into the mathematics to account for the mass differences.

Other differences come about through these partial symmetry breakings. The existence of various kinds of particles or forces depends on them. They are thus not an imperfection but a necessary part of the nature of things. One can establish a hierarchy of symmetries from higher to lower by way of these partial breakings, which gradually add in necessary aspects of actual physics. So the whole thing is a dialectic in which breaking is as necessary as symmetry. The breakings are often called spontaneous because they seem to be in the nature of things, a kind of acausality that Einstein might not have liked had he lived to see it.

In reaching for the ultimate symmetry principle that will cap this hierarchy, Zumino and others propose supergroup, supersymmetry. It deals with one of the most fundamental (mathematical) distinctions between particles: whether they club together (bosons) or act exclusive (fermions). It is based on spin, which is an internal property of particles that is strongly related to space and time. It contains both the local, internal gauge symmetries of particle physics and the global space-time symmetries of classical electrodynamics and gravity. And, Zumino points out, it removes the acausal aspects of quantum physics that Einstein so strongly disliked.

All of this will be at the cost of a lot of work and pain. The theory is not easy and it is less easy for those, like Ne'eman and others who choose to include supergravity. It has not been possible to develop a completely successful quantum theory of gravity, but what has been found indicates that gravity on the particle physics level will operate as an interaction carried by a particle called the graviton which would have two units of spin. That's high spin and very difficult to deal with. Some people would prefer to leave it out for the time being, but if you leave it in, the graviton gets a friend called the gravitino (in supersymmetry, every boson has a fermion "friend" and vice versa) that represents a parallel force field to the ordinary gravity with slightly different properties.

As supersymmetry goes down through particle physics everything else gets doubled like this. As Farrar points out, that raises a serious problem. Supersymmetry predicts a mass degeneracy between a boson and its fermion friend. From what we already know, there are no such coincidences except for the photon and the neutrino, which both have zero mass. So if known fermions are the friends of known bosons, then the mother of all symmetry breaking terms must be inserted into the theory to explain the mass differences. If not, why haven't the friends been found?

Even so, it seems that a number of particles crucially important to supersymmetry could be found in current experiments, slightly uncertain though their masses may be, if experimenters look correctly. There is not space here to detail how Farrar advised them to look, but some are sure to take the advice. □