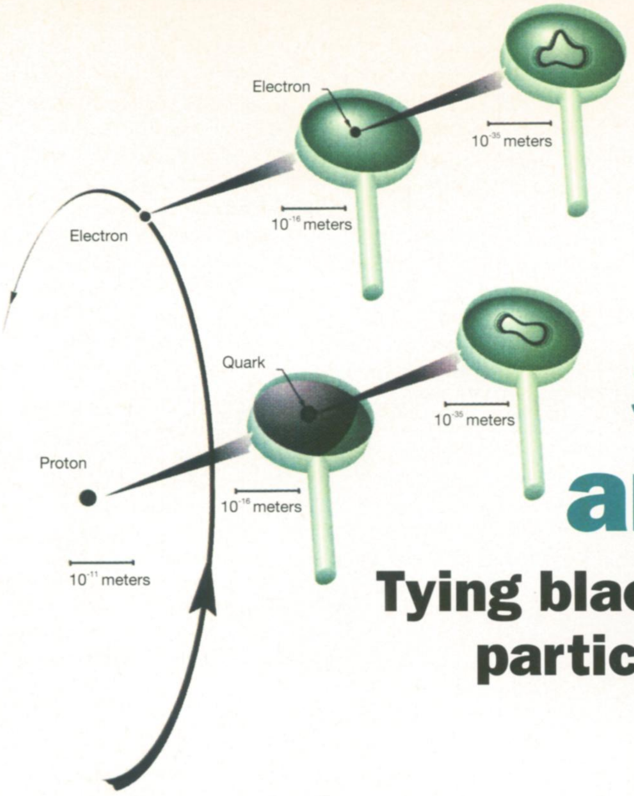

According to string theory, electrons and quarks can be viewed as extremely small vibrating loops.

Summer 1994 Beam Line/Stanford Linear Accelerator Center

Strings and Webs

Tying black holes to elementary particles in string theory

By IVARS PETERSON

To build a universe like the one we inhabit and observe requires the right sorts of energy and matter interacting in appropriate ways.

The standard model of particle physics includes such basic ingredients as quarks, gluons, electrons, and neutrinos. Rooted in the notion of quantum fields, the equations of this theory describe the forces acting between subatomic particles such as quarks and electrons (SN: 7/1/95, p.10).

But there's no place in this framework for gravity. A separate theory and different equations present this fundamental force as a consequence of the curvature of space and time (SN: 12/3/94, p.376).

Albert Einstein's general theory of relativity describes gravity in terms of geometry. Objects travel along the "straightest" possible paths through a dimpled spacetime distorted by the presence of mass and energy. Heavier bodies simply create larger dimples and greater curvature.

General relativity also posits the existence of black holes. These objects represent accumulations of mass so dense they throw up an impenetrable spacetime shield—an event horizon—from within which no light or other signal can emerge.

Theorists have long sought to unite gravity with quantum field theory to create a "theory of everything." For the past decade or so, the leading candidate for achieving such a unification has been string theory (SN: 2/27/93, p.136).

This theory has just one type of fundamental object. It replaces the many different pointlike particles of the standard model, quantum mechanics, and general relativity with minuscule entities called strings, which can be pictured as closed loops. Though finite in size, these strings of matter and energy are so tiny they look and act like point particles when probed at even the highest energies accessible to particle accelerators.

The equations of string theory have proved extremely difficult to solve and interpret. No one has yet used the theory to make predictions that can be tested experimentally.

In recent months, however, researchers have overcome a major mathematical obstacle to using string theory to make predictions that can be verified experimentally. They have found a way to integrate black holes into the theory, a feat that may simplify the task of identifying the physical meaning of the mathematics underlying the theory.

First, physicist Andrew Strominger of the University of California, Santa Barbara found a correspondence between strings and certain kinds of black holes. Then, working with Strominger, physicist Brian R. Greene of Cornell University and mathematician David R. Morrison of Duke University in Durham, N.C., showed that, in the context of string theory, transformations between black holes and elementary particles of matter are really no stranger than phase transitions between solid and liquid.

Thus, at the quantum level, black holes and elementary particles represent simply two different aspects of the same physical objects.

"This work takes us forward in the overall program of trying to extract physical features of string theory that really characterize its most fundamental aspects," Greene says. "It's a very satisfying development."

The theorists presented their findings in June at a conference in Trieste, Italy, and they have submitted reports of their results to NUCLEAR PHYSICS B.

According to string theory, all matter boils down to infinitesimal strands of energy. Depending on how a particular one-dimensional wisp vibrates or rotates, it manifests itself as an electron, quark, or some other building block of matter.

Moreover, these strings can interact only by touching and joining, which automatically makes all forces related to each other.

Solutions to the differential equations of string theory indicate that these strings exist in a 10-dimensional environment. Four dimensions of this peculiar setting—height, width, depth, and time—correspond to the spacetime of relativity theory. The remaining six dimensions are somehow crumpled up so tightly that, in effect, they vanish from view.

Nonetheless, the geometric properties of these curled-up, compact, six-dimensional spaces are reflected in the physical laws that govern the way matter behaves in everyday four-dimensional spacetime.

The trouble is that mathematicians and physicists have discovered thousands of solutions to the equations, each one apparently describing a different six-dimensional structure or space. Such an abundance of solutions leads to an equally large number of possible descriptions of our own four-dimensional universe.

Which one matches the real universe?

Strominger didn't originally set out to settle this question. He was interested in getting rid of certain singularities that seemed to afflict string theory: In certain circumstances, the mathematics describing the forces between particles gives infinity as the unacceptable answer to the string theory equations.

Strominger found a potential avenue toward solving the problem in recent work by Edward Witten of the Institute for Advanced Study in Princeton, N.J., and Nathan Seiberg of Rutgers University in New Brunswick, N.J.

Witten and Seiberg found a way to eliminate certain singularities in a four-dimensional quantum field theory known as supersymmetry—an extension of the standard model of particle physics that attempts to incorporate all the forces of nature except gravity. They did it by introducing to the theory a hypothetical particle called a magnetic monopole.

By gradually changing a particular parameter in the equations describing supersymmetry, the theorists could show that this monopole becomes massless right when the equations, in the absence of monopoles, point to infinity as the answer. This approach makes it possible to circumvent troubling singularities and obtain reasonable solutions to the equations.

Strominger asked himself whether miniature black holes carrying an electric charge might play a similar role in string theory. These curious objects are closely related to the black holes of relativity theory and astronomical speculation.

"Ordinary" astronomical black holes are generally characterized by their mass, electric charge, and angular momentum, or spin. In string theory, researchers deal with "extremal" black holes—tiny bodies with mass and charge comparable to those of elementary particles.

Strominger looked at what happens to such a black hole when one varies parameters determining the shapes of the curled-up, six-dimensional spaces that arise in string theory. He discovered that as the shape changes, the mass of a charged black hole dwindles to zero precisely when the singularities he was worried about would arise.

At first glance, the notion of a massless black hole may seem contradictory, but it arises naturally out of the mechanics of string theory. In some situations, a black hole's mass is proportional to its area. Making this area smaller and smaller eventually leads to a black hole with zero mass.

"It's a very special kind of black hole," Greene says. "But it's still sensible to think of it as being a black hole, because it evolved from a massive black hole."

The transformations studied by Strominger also revealed a direct correspondence between extremal black holes and strings. He could avoid the singularities normally encountered in the particular formulation of string theory he was using by treating black holes as strings and strings as black holes.

When Greene and Morrison heard about Strominger's work, they quickly realized there was no barrier to continuing a shape transformation beyond the massless black hole stage. In fact, this stage appeared to mark a transition not unlike that occurring when a solid melts or a liquid freezes.

In the case of water, for example, lowering the temperature turns the liquid to ice. Raising the temperature reverses the process. Although ice and liquid water look and behave differently, they merely represent two phases of the same molecular substance.

Something similar happens as the geometry of the six-dimensional components of string theory gradually changes. At a certain critical value of a shape parameter, one gets a phase transition in which tiny, charged black holes are transformed into strings in specific vibrational states. The vibrating strings, in turn, correspond to various elementary particles.

"When you follow the transition in detail, what appear to be black holes in the first phase—analogous to water—evolve into fundamental particles in the second phase—analogous to ice," Greene says. "That is, black holes reappear as more conventional elementary particles, such as electrons or quarks."

"What wasn't clear, but becomes obvious with this work, is that black holes and elementary particles are really one and the same thing as they smoothly change from one to another," he adds.

The researchers also noted that, at the same moment black holes transmute into elementary particle states, the topology, or basic geometric shape, of the accompanying six-dimensional space changes markedly. Such topological transformations can be as radical as changing a beach ball into a doughnut-shaped ring by ripping a hole in the plastic before reshaping the material into its new form.

In contrast, general relativity allows spacetime to stretch or shrink but not to tear. String theory apparently offers much more startling possibilities for the evolution of space and time.

"This work allows for far more drastic changes in the basic structure of spacetime than any of us really thought possible," Greene remarks.

String theory's spacetime phase transitions also serve as bridges between what theorists previously thought were separate, compact, six-dimensional spaces. One choice for the curled-up component of the universe can smoothly turn into another choice for this component.

By allowing the theory to undergo these phase transitions sequentially, it's possible to link together essentially all the known choices for the curled-up component of spacetime, Morrison says.

"We have this giant web of [compact spaces], all connected by spacetime phase transitions," Greene notes.

"What we have accomplished in our recent work," Morrison adds, "is to show that the physical theories—possible universes—represented by these different curled-up spaces can actually be seen as different aspects of a common underlying theory, smoothly linked by the variation of certain parameters."

This accomplishment doesn't solve the problem of making a definitive choice for the compact space leading to the appropriate description of our universe. "But it does set up a framework for such a solution," Morrison says.

There are complications. Strominger, Morrison, and Greene were working with only one of the varieties of string theory that have been proposed over the years. Other versions have as many as 26 dimensions. Some include strings not only in the form of closed loops, but also as segments with free ends.

One important step is to see whether the kind of unification found by the theorists for one type of string theory applies to other formulations. The researchers are also interested in exploring what more can be learned about the behavior and characteristics of black holes in the context of string theory.

Greene and Morrison are taking a closer look at the basic phase transition, this time going from elementary particles and strings to black holes. "We would like to see exactly how to cross the bridge in the reverse direction, which we know is definitely possible," Greene says. "But the detailed description of it is a bit involved, and we're trying to work that out."

Overall, these new accomplishments offer a modicum of hope that the string theory equations may, in the end, produce only a few candidate solutions that theorists must sort through and strive to understand and link with the observable universe.

"We don't know what the number of solutions is or what they will look like," Morrison says. "But this is a major advance, giving us hope that there are only a handful of solutions that we can ultimately test to find out which one is the model for the universe we're living in."

Given the complexity of the string theory paraphernalia, theorists are still far from making testable predictions. But despite the daunting barriers, many see string theory as the only viable option currently available for unifying quantum mechanics and gravity. ☐