PHYSICS

# Strings Unknot Problems in Particle Theory, Black Holes

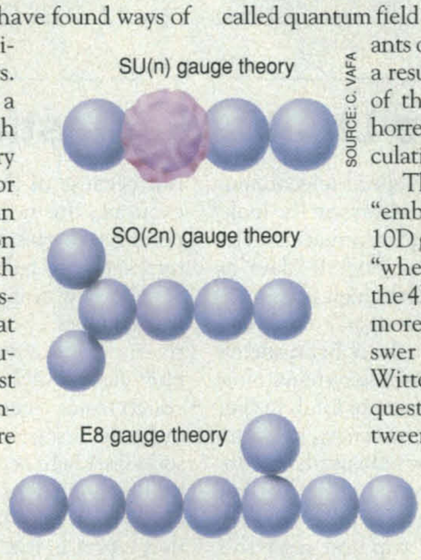
PHILADELPHIA—In a story by Guy de Maupassant, a little piece of string takes on an almost cosmic significance when its discovery changes a French peasant's life forever. For almost 30 years, a group of physicists have been trying to establish the cosmic significance of their own brand of string: 10-dimensional (10D) abstractions with vibrations and interactions that may describe the structure of our universe at its most fundamental level. The obscure mathematics of string theory has made it seem remote from the problems other physicists grapple with. But a recent meeting here showed that even though the theory's ultimate significance remains uncertain, some physicists are paying it a telling compliment: They are finding ways to apply it.

So far, says Cumrun Vafa of Harvard University, the problems solved by string theory are "still one little step removed from experiments." That may be an understatement. Like several others who spoke on the topic at the 5th International Conference on Supersymmetries in Physics, held at the University of Pennsylvania from 27 to 31 May, Vafa used the string formalism to solve abstract problems in particle physics and relativity. Still, the work is turning some heads. "There was an enormous number of skeptics in the particle-physics community about the whole enterprise," says Thomas Banks, a string theorist at Rutgers University in Piscataway, New Jersey. "I think some of these new results have changed [that]."

Physicists are discovering that string theory sometimes opens the way to solving seemingly intractable problems in other realms of theory by simple geometrical reasoning. As theorists explained at the meeting, entire field theories—equations describing arrays of particles and their interactions—correspond to sets of shapes in the high-dimensional space occupied by strings. Intersections between the shapes can then reveal how particles behave within those field theories. String theorists have also made progress in calculating a seemingly abstruse quantity: the entropy, or information content, of black holes, and what happens to the information when a black hole "evaporates."

These glimmerings of practical application are a return to string theory's basic mission. For all its abstraction, the theory aims to resolve fairly concrete problems in the theory underpinning the Standard Model—particle physicists' current picture of the fundamental structure of matter. Among them is the Standard Model's tendency to explode with "infinities." The strange rules of quantum mechanics are to blame: They allow any given particle to spend part of its life as another particle—which can, in turn, sometimes exist as still other particles, ad infinitum. The resulting "loop corrections" add up to divergent values for the particle's total mass. "It's very uncomfortable," says Mirjam Cvetič, who organized the conference along with her Penn colleague Paul Langacker.

Mainstream theorists have found ways of manipulating those infinities to get sensible answers. But some are finding a more satisfying approach in a largely untested theory called supersymmetry, or SUSY, which is actually an offshoot of an early version of string theory. For each known particle, SUSY posits a massive partner that makes opposite contributions to the loops, almost canceling most of the infinities. Experimentalists are still searching for those partners, but meanwhile, theorists have looked for ways to nix the lingering infinities in SUSY.




**Geometric reasoning.** By wrapping so-called D-branes (purple) around intersecting spheres, string theorists devise geometric representations for theories of particles and forces. (The diagram omits eight dimensions.)

String theory, says Edward Witten of the Institute for Advanced Study in Princeton, New Jersey, "gets rid of the whole kit, cat, and caboodle of infinities." It does this by identifying particles with resonances—vibrational harmonics, in essence—of the 10D strings. The procedure introduces an infinite "tower" of particles of increasing mass that fix all the loop corrections, like a series of ever-tinier shims used to make a bookcase stand upright on an uneven floor. (The more massive a particle, the smaller its influence on the loop corrections of particles that are light enough to measure.) String theory achieves these cancellations "in an automatic way, without any arbitrary adjustment of anything," says Witten. It also gives rise to a particle called the graviton, which conveys the force of gravity, making string theory physicists' best hope for unifying gravity with other forces.

To get from this abstract, 10D world to our 4D universe, string theory holds that the remaining dimensions are shrunken, or "compactified," in the string theorists' argot. In our world, a string might be as small as $10^{-20}$ the size of an atomic nucleus. To bridge that huge gap in scale, physicists have been turning to even quirkier entities called D-branes, which were discovered by Joseph Polchinski of the Institute for Theoretical Physics in Santa Barbara, California.

A multidimensional counterpart to a 2D or 3D membrane, a D-brane is "a submanifold in space where strings can end," says Witten. Strings normally form loops, but a D-brane provides a kind of anchoring surface. This ability to sprout many strings means that a D-brane can represent a vast array of particles and their behavior, and configurations of D-branes can stand for entire classes of so-called quantum field theories—particular variants of SUSY, for instance. As a result, simple manipulations of the D-branes can replace horrendously complicated calculations within those theories.

The trick, says Witten, is to "embed" a calculation into a 10D geometric configuration, "where it's less obvious what the 4D physics question is, but more obvious what the answer is." At the conference, Witten showed how one such question—the couplings between particles in a version of SUSY—could be solved by manipulating what looked like a series of D-brane "ladders" embedded in 10D space. Because strings wind like vines within these ladders, they represent all the enormously complicated particles and interactions in that field theory. Vafa went further, coming up with basic principles of what he called "geometric engineering": translating a given field theory into a set of geometrical shapes wrapped in D-branes (see illustration). "We found the dictionary, basically," says Vafa.

Because D-branes can have mass, momentum, and a kind of charge, they can also be compactified to represent physical objects—"things" made of real particles rather than theories containing abstract particles. One target of this effort is black holes—objects whose gravity has caused them to collapse behind an "event horizon" from which nothing can escape. More than 2 decades ago, using techniques unrelated to string theory, Stephen Hawking of Cambridge University and others showed that black holes have a kind of entropy, or information content, and emit radiation. But Hawking's result posed two puzzles. The form for the entropy suggested that all the black hole's information was concentrated at its event horizon, rather than spread throughout its volume, as it is in ordinary objects. Moreover, black-hole radiation raised worrisome questions about information loss.

The radiation, said Hawking, stems from the pairs of virtual particles that, according to quantum mechanics, continually wink in and out of existence throughout space. Just outside the event horizon, the black hole's enormous gravity might convert one of these normally fleeting events into a single particle that flies off into space, leading to the radiation—and an effective mass loss for the black hole. Thus, the black hole shrinks, and its information content dwindles. But the laws of quantum mechanics imply that information is never destroyed, only dispersed or rearranged, so Hawking's picture could be viewed as a paradox.

Last year, Andrew Strominger of the University of California, Santa Barbara, and Vafa tested the theory by constructing black holes from scratch out of D-branes. They compactified massive, charged D-branes by wrapping them around 6D tori to create small, massive objects resembling black holes. The team then considered possible excitations of the D-branes—"ripples" along the compactified dimensions—which could encode information about the black hole's internal state. By counting up the number of possible vibrations for a given black hole, they found an entropy that agreed exactly with the value Hawking and others had calculated.

But they also found, says Vafa, that the information existed not just on the event horizon, but "hidden in those extra [six] dimensions." At Penn, Cvetič and Finn Larsen went further. Building on earlier work Cvetič did with Donam Youm of the Institute for Advanced Study, Larsen reported, they showed how the entropy is sometimes split between the usual horizon and a cloaked, "inner" horizon that forms a second point of no return: Light rays that pass inside it cannot even return to the outer horizon. "Our calculations would say that at least mathematically, the inner horizon plays at least as big a role as the outer horizon," explains Larsen.

Later work by Vafa and Strominger even suggested a way out of the information paradox Hawking had posed. Their D-brane–based analysis showed that the "hidden" information might not be lost as the black hole shrinks: It might be escaping along with the Hawking radiation. If string theory can plug a cosmic information leak, it may start getting more attention on Earth.

–**James Glanz**

OPTICS

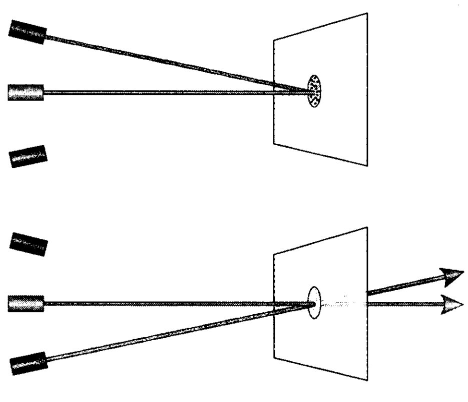
# Tripping the Light at Fantastic Speeds

In today's world of high-speed telecommunications, researchers are always on the lookout for faster ways to send information. The speediest schemes today encode data as pulses of laser light fired through glass optical fibers. But the comparatively slow electronic switches that pulse the light on and off limit the overall speed of these systems. Now researchers at the University of Utah in Salt Lake City and Osaka University in Japan have come up with a new polymer-based optical switch that has the potential to dramatically boost the data rate.

Beams of laser light trip and reset this speedy switch. One laser fills the polymer with evanescent charge pairs called excitons, which block an information-carrying infrared beam; a second laser can collapse the pairs and open the switch again in just a trillionth of a second. "It's something I find very interesting," says Joseph Perry, a chemist at the Jet Propulsion Laboratory and the California Institute of Technology, both in Pasadena, who has worked on designing other polymers for high-speed switching applications. Perry and others caution, however, that a series of technical hurdles—such as the polymer's tendency to break down when hit repeatedly with laser light—must be overcome before the new switches are ready for the market.

Present-day optical switches apply an electric field to an inorganic crystal to change its optical properties, turning light on and off. Such devices can generate light pulses at about 20 gigahertz, or 20 billion times per second. In recent years, Perry and others have been working to design polymers that can boost the switching speed of the same basic setup to more than 100 gigahertz. But because of the hair-trigger response of excitons, the new polymer switch has the potential to switch 10 times faster still, at 1 terahertz, or a trillion times a second.

The new switch relies on polymers that can conduct electricity and emit light, derivatives of a compound known as poly (p-phenylene vinylene), or PPV. Several research teams recently used these materials to make the first polymer-based laser, which absorbs laser light of one color and reemits it as a beam of a different color (*Science*, 27 September 1996, p. 1800). In their new work, which they report in the 2 June *Physical Review Letters*, Utah physicists Sergey Frolov and Valy Z. Vardeny and their colleagues exploit these light-handling talents to create their switch. Other high-speed exciton-based switches have been reported in the past, but they rely on different optical effects for their switching.



**Quick change.** A pulse of green laser light on a polymer film creates charge pairs (black dots), which block an infrared, data-carrying beam (taupe). Red laser light collapses the pairs, allowing the beam to pass through the film.

To make the conducting polymer opaque and turn the switch "off," the researchers hit it with a pulse of green laser light. The pulse excites electrons in the material to a higher energy state, leaving behind positively charged electron vacancies, or "holes." These newly created energetic electrons and holes stick close together to form excitons, which themselves absorb light at an infrared wavelength. The absorption essentially blocks the infrared data beam.

To turn the switch back "on" again, the researchers zap the polymer with a pulse from a red laser that is precisely tuned to stimulate the excitons' electrons and holes into recombining. That makes the polymer transparent again to the infrared data beam. In their initial demonstration, Vardeny and company only created 80 million pulses per second. Raising this to a trillion would of course also require the control lasers triggering the switches to be pulsing at the same speed. Conventional setups can accomplish that by splicing together separate, rapid-fire laser pulse trains, although such systems are difficult to set up.

For this and other reasons, even Vardeny admits that the scheme has a long way to go before it could become a real-world technology. One "particularly difficult" problem, says electrical engineer Mohammed Islam of the University of Michigan, Ann Arbor, is that conducting polymers tend to break apart quickly when triggered to give off photons of light. Another obstacle, he adds, is that the polymer films heat up when they absorb infrared light, which may cause further degradation. But if researchers can work out these problems, telecommunications could be in for a big switch.

–**Robert F. Service**