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Physics in Action

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Strings draw theorists together

Theorists are confident that they are closer than ever to finding a quantum theory that unites gravity with the three other fundamental forces in nature.

Many of the leading figures in the world of string theory met at the California Institute of Technology in January to discuss recent progress in the field and to reflect on the state of the theory. The enthusiastic mood of the gathering was based on the fact that string theory provides an elegant framework for a unified theory of all the forces and particles in nature, and also gives a consistent quantum-mechanical description of general relativity. (Most of the transparencies from the conference are now available on the Web at http://www.theory.caltech.edu/conf2000/program.html)

Many of the participants expressed the view that the current state of the subject is analogous to that of quantum theory between 1900 and 1925. The profusion of ideas, the confusion about the underlying structure of the theory, and the clear evidence that these developments have deep implications for physics parallel the position of quantum mechanics at the beginning of the last century.

String theory, and more precisely superstring theory, describes the assortment of elementary particles - such as quarks and leptons, and the gauge bosons responsible for mediating forces - in a unified manner as different modes of vibration of a single extended string. This version of the theory also embodies supersymmetry - a conjectured symmetry that unifies fermions (particles that have an intrinsic spin of $h/4\pi$, $3h/4\pi$ and so on, (where h is the Planck constant) and bosons (particles that have a spin of $h/2\pi$, h/

π etc). Furthermore, the fact that the string has a fundamental length scale - the "string length" - apparently cures the short-distance problems of uniting general relativity with quantum theory (see "Quantum gravity presents the ultimate challenge to theorists" *Physics World* December 1999 p21).

The main problem with the early formulations of superstring theory was that they emphasized the "perturbative" point of view, an approximation that describes string-like quantum-mechanical particles moving through classical (that is non quantum-mechanical) space-time. However, very general arguments require that any quantum theory of gravity should also describe space-time geometry in a quantum-mechanical manner. The classical geometry of space-time should then emerge as an approximate description at distance scales much larger than the so-called Planck scale of 10^{-33} m.

This requires an understanding of the theory beyond the perturbative approximation. It is the quest for this more fundamental description of string theory that has provided the main challenge for string theorists over the past decade. Much has been learned about the non-perturbative extension of string theory - now known as "M theory" - and this has shed light on many previously mysterious aspects of quantum field theory.

Theorists look to extra dimensions

The speakers at the Caltech meeting combined technical talks on current developments with retrospective views on the past century, and some speakers offered brave predictions for the future. The range of new and potentially important developments is indeed impressive.

One example is the accumulation of results on the role of "noncommutative geometry" in string theory. This novel branch of geometry is based on coordinates that do not commute - in other words, $x \times y$ is not equal to $y \times x$, where x and y denote positions in two different directions. It has long been suggested that noncommutative geometry should play a role in the quantum-mechanical description of space-time as related to quantum gravity. However, it is only with the most recent developments in string theory, prompted by among others Nathan Seiberg and Edward Witten of the Institute for Advanced Study in Princeton, that this idea has been confirmed.

Another major theme of the meeting was the new ideas on how string theory may describe observed physics, such as the forces and particles in nature and their properties. The recent work by Lisa Randall of Princeton University and Raman Sundrum of Boston University is a variant of the "brane world" idea that has come to the fore over the past couple of years. According to this idea, which was reviewed by Randall at the conference, our four-dimensional universe can be thought of as a membrane (known as a three-brane) that is embedded inside a higher-dimensional universe. The number of higher dimensions is predicted by the structure of string theory.

The possible consequences of this are striking. For example, in such a universe the fundamental energy scale of the theory may be much smaller than the Planck energy of 10^{19} GeV. Indeed, the scale could be so small that it will be accessible to direct experimental observation using the next generation of accelerators, such as the Large Hadron Collider that is currently under construction at CERN (see "Extra dimensions around the corner" *Physics World* June 1999 p21). This theme was further developed by Steven Hawking, who conjectured on how such a universe might have evolved from the initial quantum state that preceded the big bang.

Correspondence and confidence

One of the most exciting developments over the past few years has been in understanding how so-called Yang-Mills gauge theories - the bread and butter of the Standard Model of particle physics - are related to quantum gravity by string theory. Particularly important is the so-called "Maldacena correspondence", first developed by Juan Maldacena of Harvard University. This correspondence gives an explicit setting in which string theory in a space-time of dimension d is identical to Yang-Mills gauge theory in d - 1 dimensions. Maldacena and several others talked about recent developments in this area. It is one example of the remarkable "holographic principle", originally developed by Gerard 't Hooft of Utrecht University, who shared the Nobel Prize for Physics last year. Both he and Lenny Susskind of Stanford University, who introduced the holographic principle into string theory, spoke at the meeting.

According to this idea, a general feature of quantum gravity is that physical information inside any volume is encoded on the surface of that volume. 't Hooft believes that the holographic properties of quantum gravity can only be accommodated by making a radical change to the basic structure of quantum mechanics, which would imply that quantum mechanics has a classical origin (see "The new universe around the next corner" *Physics World* December 1999 pp79-84).

A number of other speakers gave fascinating glimpses into the way in which the structure of string theory should combine with the principles of quantum theory to produce a consistent description of physics under extreme conditions. For example, string theory could resolve long-standing paradoxes about quantum mechanics in the presence of black holes, which originated with the work of Hawking in the 1970s.

The confident mood of the meeting was based largely on the compelling theoretical ideas in string theory, but there was also an acute sense that experimental verification is crucial. The theory should obviously have many observational ramifications, most clearly in the realm of ultrahigh-energy physics or the physics of the early universe. There was also unanimous agreement that that the discovery of supersymmetry at Fermilab in the US or at the Large Hadron Collider at CERN would be a dramatic first step towards such verification.

About the author

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