for the observations," the Super Kamiokande collaboration asserts.[1] And, after 18 months of abundant data, so are statistical fluctuations. "More important than another year's worth of data," says University of Delaware theorist Tom Gaisser, who made major contributions to the neutrino-flux calculations, "will be another year of working to understand possible systematic uncertainties in the measurements and the calculations, especially the normalization."

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Strings May Tie Quantum Gravity to Quantum Chromodynamics

> Might we learn more about the strong interactions by studying string theory? That's one possibility raised by recent work showing that string theories and gauge field theories are flip sides of the same coin.

Although string theorists explore bizarre multidimensional spaces filled with tiny loops and membrane-like objects, they are ultimately seeking a description of the real world. They may have come close with a recent hypothesis that links a ten-dimensional string theory to a gauge field theory in the four dimensions of our ordinary world. The theorists' great hope is that this connection extends to the specific gauge theory describing quantum chromodynamics (QCD), which governs the strong interactions.

String theorists have been quite excited about this hypothesis since about February—which is when they realized the import of a paper that Juan Maldacena of Harvard University had posted in November on the Los Alamos e-print archive server.[1] By the time of the international Strings '98 conference,[2] held in late June at the Institute for Theoretical Physics at the University of California, Santa Barbara, over a hundred papers had elaborated upon and extended the basic idea, and it became the focus of the meeting.

Maldacena identified a duality between a particular string theory, which inherently includes gravity, and a particular gauge theory, which does not. The duality says that the string theory on a particular curved spacetime background maps onto the gauge theory. The best part of the duality is that the two theories overlap when the coupling between fields in the gauge theory is strong. That's precisely where it is difficult to do calculations in the gauge theory and, fortuitously, just where it is easy to do calculations in the string theory. (For a background on superstrings and duality, see two articles by Edward Witten in PHYSICS TODAY: April 1996, page 24, and May 1997, page 28.)

Extensions and refinements

Since Maldacena's paper, others have suggested ways to translate between the two theories, relating observables in one to those in the other. In particular, Steve Gubser, Igor Klebanov and Alexander Polyakov (all at Princeton University)[3] and, independently, Witten (Institute for Advanced Study in Princeton)[4] have proposed a precise version of this correspondence, which relates quantities in the interior of a region (spacetime) to quantities in a gauge theory located at the boundary.

As originally formulated, Maldacena's duality was limited to gauge theories that are supersymmetric—that is, theories in which each of the known bosons (fermions) has a supersymmetric fermionic (bosonic) partner with identical properties except for the spin. The duality was also restricted to conformal, or scale-invariant, gauge theories, those having additional symmetries besides translation and rotation. Thanks to work by a number of other theorists, Maldacena's duality has by now been freed of these two restrictions.

Before Maldacena's work, many theorists had worked out specific cases of duality between gravity and two dimensional conformal theories. Their calculations lent some credibility to the proposal, and a host of other calculations since Maldacena put forth his thesis have provided additional supporting evidence for it. Some papers have offered formal proofs of the conjectured duality, albeit in specific rather than more general spacetime geometries.

Leonard Susskind (Stanford University) is among many who are ecstatic about the new developments in string theory. Not too many years ago, he recalls, people were discouraging others from going into quantum gravity because it was not expected to lead to anything. Maybe now, he speculates, everything will turn on its head, and quantum gravity can give insight into particle physics.

Polyakov is more cautious in his reaction: "If this idea works in the nonsupersymmetric case, it will provide the theory of quark confinement. If not, it will remain an unimportant curiosity. I hope the answer will not take too long, but it is too early now to celebrate."

The large N limit

Doing calculations in the strong-coupling limit of QCD has long been a dream of theorists. Unlike in quantum electrodynamics, one cannot do a perturbative expansion to calculate quantities in QCD: There is no small coupling constant in which to expand. One trick is to assume that quarks come in a large number (N) of colors instead of the three that have been observed. (Quarks also come in three families of flavors such as the up/down one.) Because the interactions between N colored quarks would be transmitted by $N^2 - 1$ different gluons, the large N limit would correspond to the strong-coupling limit.

In 1974, Gerard 't Hooft (Utrecht University in The Netherlands) suggested that one could expand the equations for QCD in the variable $1/N$, taking N to be large. His suggestion led to some insights but fell short of solving the problems of interest in QCD. (See the article by Witten in PHYSICS TODAY, July 1980, page 38).

But 't Hooft also predicted that one should be able to find a string theory describing QCD, in which $1/N$ would play the role of some coupling constant. (Around the same time, Kenneth Wilson realized that, in the strong coupling limit of QCD, the Faraday flux lines behave as strings and confine quarks by tying them together.) In 1981, Polyakov (then at the L. D. Landau Institute in Moscow) realized that the appropriate string theory might be in five dimensions. But neither he nor many others who looked could find the string theory anticipated by 't Hooft.

Witten thinks that the string theory identified in the recent duality is substantially closer to what is needed for understanding the $1/N$ expansion than anything yet found. As evidence to support this claim, Witten notes that the duality has been used to give explanations of quark confinement and the hadronic mass gap—two of the main mysteries of QCD—that are roughly along the lines originally foreseen by 't Hooft.

Realization of the duality

Maldacena came to recognize the duality as a result of work that he and others had been doing on the entropy of black holes. The key to the duality is that black holes—or more generally, supergravity—can be described in terms of structures known as D-branes. One can also describe the low-energy dynamics of field theories in terms of D-branes. By thus formulating both string and gauge theories in terms of these strange structures, Maldacena was able to elucidate the connection between them. (See the accompanying box.)

Maldacena compared the supergravity and gauge theory solutions in the region where the parameter N is large. In gauge theory, large N (that is, many colors) corresponds to strong coupling. But how does this parameter relate to anything in supergravity? As discussed in the accompanying box, N turns out to be the number of D-branes in the formulation of the gauge theory and also of supergravity. In turn, the number of branes determines the radius of curvature of spacetime for the supergravity solution. Thus, taking the limit of large N carries the gauge theory into the strong-coupling limit and the supergravity theory into a region far from the (remote) boundary—a region where it can be trusted to give accurate results. More precisely, Maldacena demonstrated the validity of his conjecture for the case that g^2N is large, where g is the Yang–Mills coupling constant.

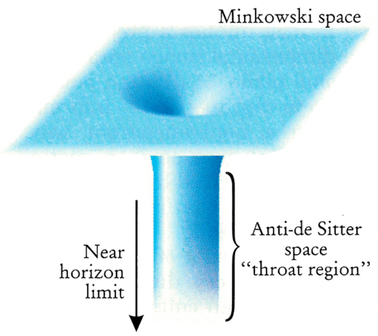
Maldacena was led in this direction by earlier work on black holes. Most notably, Andrew Strominger and Cumrun Vafa (both now at Harvard) used a description of black holes in terms of D-branes in their 1996 proof that the entropy for a certain type of black hole is related to its area in the predicted way. (See the news story in PHYSICS TODAY, March 1997, page 19.) Since that work, a number of researchers including Maldacena have been doing similar calculations for broader categories of black holes.

Klebanov and his colleagues had also studied the correspondence between supergravity and gauge theories, formulated on D-branes.[5] Specifically, they calculated the cross sections for entities such as gravitons to be absorbed by certain surfaces in the supergravity theory; these values agreed exactly with the corresponding calculations in the gauge field theory, where the values were related to two-point correlation functions. Thus, Klebanov and his group were exploiting some special cases of the duality be-

Duality Demonstrated on D-Branes

Juan Maldacena made clear the duality between two very different types of theories by formulating them both in terms of strange topological structures known as D-branes. D-branes are a subset of a larger class of objects known as p-branes (p is the object's spatial dimension), which are distortions of spacetime geometry, rather like dislocations in a crystal. If $p = 2$, the p-brane is an ordinary two-dimensional sheet, or membrane; if $p = 1$, it's a string and if $p = 0$, a point particle.

D-branes can have any dimension, but it may be easiest to visualize them as sheets. They are distinguished from other p-branes by being, loosely speaking, surfaces where the ends of open strings get stuck. (The strings that end on D-branes must satisfy Dirichlet boundary conditions; hence the name of these sheets.) The open strings give rise to particles whose dynamics take place on the brane. Joseph Polchinski (University of California, Santa Barbara) discovered that each D-brane carries a charge and hence is associated with a gauge potential, much as an electric charge is. On a single D-brane, one can formulate a one-color gauge theory, represented by the symmetry group U(1): Stacking N such D-branes gives a U(N) Yang–Mills theory.



REGION OF SPACETIME similar to a black hole, formed by stacking a large number of three dimensional hypersurfaces known as D-branes. The flat portion of the surface resembles Minkowski space, and the cylindrical portion (the throat region) is an anti-deSitter space, described by five-dimensional spheres with negative curvature. According to a new duality, the ten-dimensional spacetime deep in the throat, near the horizon of the black hole, is related to a four-dimensional gauge theory, which can be thought of as existing on the very remote boundary of the throat region.

To get a gauge theory in four dimensions, one needs three-dimensional (D3) branes, which can be embedded in ten-dimensional spacetime. In general, the gauge fields on these branes will interact with the gravity field in the surrounding space, but for low enough energies, the gauge field on the D3 brane is decoupled from gravity. Thus, for the gauge field side of his duality, Maldacena took N D3 branes.

These same D-branes can be viewed as a spacetime gravity solution that is similar to certain types of charged black holes. For the supergravity side of the duality, Maldacena used the curved spacetime around N D3 branes—the same configuration used by Klebanov and company for their cross sectional calculations. The metric around this stack takes the form shown in the figure above. Much of the hypersurface is nearly flat, and resembles Minkowski space. But a portion descends into a throatlike region, which continues indefinitely. One can think of this throat as leading to the horizon of a black hole; particles descending into it steadily lose potential energy, as they would were they to fall into a black hole. In ten dimensions, the metric there is described—formidably—as the product of five-dimensional anti–de Sitter (AdS) space and a five-dimensional sphere. AdS space is analogous to a sphere with negative curvature, rather like a multidimensional hyperboloid. The product of AdS space with a five-sphere is considered maximally symmetric. (John Schwarz, who with Michael Green invented the type of superstring theory in which D-branes arise, pointed out in 1983 that it admits this type of solution.[9])

Maldacena's contribution was to look at the supergravity solution deep in the throat region, where the energy is low. It turns out that, in this AdS space, the radius of curvature is proportional to $N^{1/4}$. N is the number of D3 branes, but it is also the number of colors in the gauge theory. That's the amazing part. The supergravity solution can be trusted the most when N is very large, and that translates precisely to the strong-coupling limit for the gauge theory. Maldacena points out that for large N, the supergravity in the bulk region (toward the center of the throat) is not influenced by the remote boundary, just as the gauge theory on the brane is not affected by gravity in the space around it.

tween supergravity and strongly coupled gauge theory. He credits Maldacena with the insight to focus on that part of the supergravity solution that corresponds to being near the horizon of a black hole. There, the duality becomes more transparent. As a result, Klebanov says, Maldacena was able to make a general and efficient formulation of it.

The connection to holography

The supergravity–gauge theory duality is related to another intriguing concept: an idea that 't Hooft has dubbed "holography." In the context of string theory, holography is a relation between the information carried on a surface and that within the volume it encloses. Specifically, 't Hooft[6] and Susskind[7] proposed about six years ago that the degrees of freedom in the bulk of a region can be represented by the degrees of freedom on the surrounding surface, with an upper limit to the amount of information per unit area on the surface.

A well-known illustration of this proposition is the paradoxical relation between the maximal entropy S of a black hole and the area A of its surface. Over 20 years ago, work by Jacob Bekenstein (Hebrew University of Jerusalem) and Stephen Hawking (University of Cambridge) resulted in the relation $S = A/4G\hbar$, where G is Newton's gravitational constant. This relation has been confirmed by microscopic calculations based on string theory, at least for a certain class of black holes (see the accompanying box).

But this Bekenstein–Hawking relation raises a big question: A volume clearly contains many more degrees of freedom than its surface. If entropy depends only on surface area, does one lose information about the numerous initial states that could evolve into the same black hole state? Or are the surface degrees of freedom enough to contain all the relevant information about its interior?

Both 't Hooft and Susskind take the latter point of view. The term "holography", in fact, implies a projection of a three dimensional image onto a two dimensional plane. As Witten puts it, the hologram captures all the information but in a nontransparent way: Everything that goes on in a spatial region can be described by a full set of degrees of freedom that resides on the surface of that region.

With the advent of the supergravity–gauge theory duality, Witten and Susskind began cultivating a picture of holography in which all the information about supergravity theory (a theory in the bulk) is expressed—in quite a complicated way—by solutions to gauge theory at the boundary. In other words, the duality may be a realization of holography; it relates a gauge theory in four dimensions to a theory of gravity in five dimensions (five of the ten spacetime dimensions are irrelevant to this picture).

Witten and Susskind used the new duality to get an order of magnitude estimate of the degrees of freedom of a black hole.[8] In the process, they found that infrared (corresponding to long distance) effects in the bulk are related as ultraviolet (short distance) effects at the boundary. These ideas, along with many others aired at the Strings '98 conference, are still percolating.

The excitement over the new duality had the conference participants literally dancing in the aisles: At the conference banquet, Jeffrey Harvey of the University of Chicago led the crowd through the motions of the *macarena* while he and an improvised band and chorus sang the "Maldacena," with words written for the occasion.[2]

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Berlin–Heidelberg Group Reports Phase Transition in Glass at Millikelvins in Presence of Microtesla Field

Peter Strehlow of the Physikalisch-Technische Bundesanstadt (the German counterpart of the National Institute of Standards and Technology), and Christian Enss and Siegfried Hunklinger of the University of Heidelberg, have recently reported a phase transition in glass at very low temperature. The experiments were done at the PTB low-temperature lab in Berlin.

Why should a microtesla field raise the dielectric constant of a glass at millikelvin temperature?

In the 15 June issue of *Physical Review Letters*, the team reported that below 5.84 mK, small magnetic fields of about 10 microtesla caused surprising changes of ε, the dielectric constant.[1] The multicomponent glass that was used, $BaO\text{-}Al_2O_3\text{-}SiO_2$, is not expected to have paramagnetic behavior. Why should a field one-fifth the strength of Earth's magnetic field destroy a low-temperature phase in the glass and increase its dielectric constant? After all, says Strehlow, there is no known linear dependence between the magnetic field and the polarizability. The experimenters also found that if they varied the magnetic field with opposite sign, similar changes of dielectric constant occurred but the value of ε', the real part of ε was reduced. At this writing, the group was planning to report on high magnetic field measurements, at the Phonons '98 conference in Lancaster, England, at the end of July.

The group used as a sample a multicomponent glass capacitance sensor made of $BaO\text{-}Al_2O_3\text{-}SiO_2$, the kind of device that has been used in the past as a thermometer.[2] A coil was wrapped around the sample to vary the magnetic field. To avoid uncontrolled variations of the magnetic field from the stray field of the magnet in the nuclear demagnetization cryostat, the experimenters put the sample in a niobium cylinder, along with one of the temperature sensors. Although the team tried to screen Earth's magnetic field, a residual field, B_0, of about 20 μT remained. As the system's temperature was lowered below the transition temperature of niobium, the 20-μT field was frozen in.

The experimenters measured the capacitance of the thick-film sensor. They didn't use the sensor as a thermometer. Instead, they employed four other varieties of thermometer—^{3}He-melting curve, pulsed platinum NMR, resistance, and gold–erbium magnetization.

When the experimenters held the