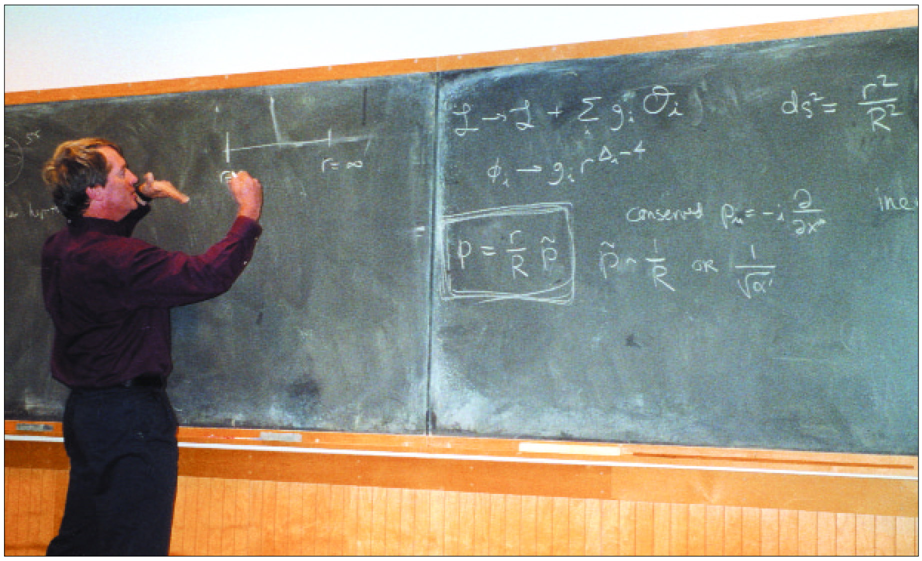
After spending 30 years as a possible theory of everything, string theory is returning to its roots to describe the interactions of quarks and gluons, with profound implications for theories of quantum gravity

String theory meets QCD

Nick Evans

STRING theory began life in the late 1960s as an attempt to understand the properties of nuclear matter such as protons and neutrons. Although it was not successful as a theory of quarks and gluons, it has since developed a life of its own as a possible theory of everything – with the potential to incorporate quantum gravity as well as the other forces of nature. However, in a remarkable about face in the last five years, it has now been discovered that string theory and the standard theory of nuclear matter – QCD – might in fact describe the same physics. These exciting developments were the topic of discussion at a major workshop in Seattle in February.



Strings and QCD on the brain – string theorist Joe Polchinski speaking at a recent workshop in Seattle that was organized to bring string and QCD physicists together.

We can now describe the physics of quarks and gluons by talking about black holes and the curvature of space–time. The concept also suggests a deep unification between the forces that are described by quantum mechanics and gravity, which until now have been seen as completely separate.

The story of string theory began with attempts to understand the strong nuclear force. The strong force is one of the four fundamental forces in nature – along with gravity, electromagnetism and the weak nuclear force. It is responsible for holding atomic nuclei together as it is strong enough to overcome the electromagnetic repulsion of the protons. Quantum chromodynamics (QCD) is the theory of the strong force that emerged in the 1970s. It is closely based on quantum electrodynamics (QED), which describes the interactions of electric charge and photons. QCD and QED are examples of a particular class of quantum field theories called gauge theories, which make up the highly successful Standard Model of particle physics.

Gauge theories are particularly good at describing the basic forces in nature. They treat all interactions between particles as being due to the exchange of gauge bosons: the photon for the electromagnetic force, W and Z bosons for the weak force, and gluons for the strong force. Gravity, however, does not seem to fit in this picture, and is instead described by Einstein's general theory of relativity. A theory of quantum gravity remains one of the great goals in physics as it could pave the way to the unification of all four forces of nature.

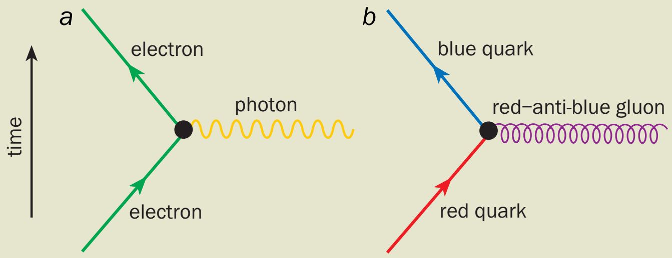
Strong strings

At first sight, QCD is very similar to QED. The only difference is that QCD has three different kinds of charge (called colours) compared with one in QED (electric charge).

Each quark comes in one of the three colours and it is this colour charge that is acted upon by the gluons (in the same way that the photon only acts on particles that have electric charge). A particle that has no colour charge will therefore not feel the strong force. Protons, neutrons and other hadrons, for example, are colour-neutral combinations of quarks, just as atoms are electrically neutral combinations of protons, neutrons and electrons.

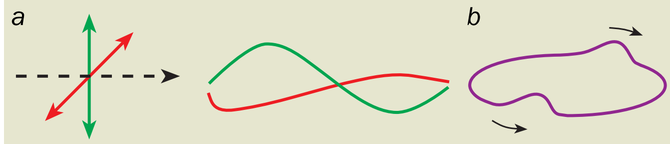
But there is one major difference between QCD and QED. Gluons carry colour charge, while the photon is electrically neutral. In fact, gluons carry the colour charges of a quark–antiquark pair and redistribute colour charge during quark interactions (figure 1). As a result, the strength of QCD interactions increases with distance, which leads to the strange property of quark confinement. This means that if you could reach into a hadron and pull two of its quarks apart then the further you tried to separate them the more they would be attracted to each other, which is the reason why free quarks do not exist. Conversely, the QCD interaction becomes very weak when two quarks are closer than a few tenths of a femtometre (10^{-15} m).

1 Gauge theories



In the gauge theories that make up the Standard Model the forces between fundamental particles are mediated by gauge bosons. (*a*) In quantum electrodynamics (QED) a negatively charged electron enters from the left, emits a neutral photon and then exits. (*b*) In quantum chromodynamics (QCD) this picture is complicated by the fact that gluons themselves carry colour. A red quark can therefore convert to a blue quark by emitting a red–anti-blue gluon, which carries away the difference in colour charge between the incoming and outgoing quarks. In both diagrams the electric and colour charge are conserved at the vertex (black circle).

2 Strings and spins



Strings can mimic the properties of fundamental particles. (*a*) The electric (red) and magnetic (green) fields of a photon share many of the same properties as the waves on an open string, which allows a string to mimic a spin-1 photon when viewed from afar. (*b*) A closed string can support waves that travel clockwise and anticlockwise and can therefore mimic a spin-2 graviton.

The strength with which a quark interacts with a gluon is measured by the QCD coupling constant. All gauge theories have coupling constants, and the peculiar property of a coupling constant that decreases as two particles are brought closer together is known as asymptotic freedom. This is one of the major successes of the theory of QCD. In particle accelerators we can collide protons together at enormous energies, which drives the quarks very close together in a way that is beautifully described by the theory. On the other hand, the properties of bound states of quarks such as the proton are difficult to predict from the fundamental QCD theory. This is because the quarks can sometimes separate as they orbit in the hadron, and unleash the more ferocious long-distance forces.

In retrospect we can see how a string-like description of hadrons might emerge from the quark model. As two quarks are moved apart it is as if they are connected by a rubber band of "colour field", which becomes increasingly difficult to stretch. Although appealing, this string picture could not capture the interactions of two quarks that are close together. Theorists dropped string theory and instead diverted their attentions to the gauge theory of QCD.

Strings move on and up

But string theory was not completely abandoned, and it soon became clear that it held surprises in an entirely different arena. By thinking in terms of fundamental strings, instead of fundamental particles, the theory provided tantalizing hints of a unified description of the basic forces of nature. At first, the concept of strings was used to describe how quarks were joined together. But strings have other properties such as excited modes, which are just like the notes on a guitar string. This means that from a distance the string will look like a particle, and different string oscillations will lead to different particle properties. The mass of the particle, for example, is given by the energy of the string oscillations.

It became clear that the simplest transverse oscillation of a string can fool us into thinking we are seeing the polarization of a quantum field. The electric and magnetic fields in a photon, for example, can oscillate in the directions that are perpendicular to the photon's motion. Similarly, a string can oscillate in two perpendicular directions (figure 2*a*). Strings can therefore describe the intrinsic spin of a particle. In a circularly polarized photon its direction of polarization rotates and this gives rise to angular momentum, or "spin". The photon is said to be a spin-1 (vector field) particle because it has an angular momentum of 1 in units of $\hbar$, where $\hbar$ is Planck's constant divided by 2π.

The string can therefore mimic the properties of the QED photon, but what about the QCD gluon? QCD differs from QED only in the number and type of charges, and this can be accounted for by simply allowing the ends of the strings to carry the three colour charges. Strings that have open ends can therefore reproduce the types of forces we have in the Standard Model on length scales that are large enough that we do not notice the extent of the string.

We can also have closed loops of string, which has even greater implications. These strings can oscillate like open strings but they support two independent waves that travel clockwise and anticlockwise around them (figure 2*b*). When viewed from afar these closed strings look like spin-2 (tensor field) particles. And for a long time theorists have known exactly where spin-2 particles should appear – gravity. Gravitational waves are predicted by general relativity to have precisely this sort of polarization, or spin. Indeed, it is precisely this spin that makes it difficult to reconcile gravity with quantum mechanics. The successful techniques that were developed in QED and QCD cannot be applied to gravity because they are specific to spin-1 fields.

Strings in higher dimensions

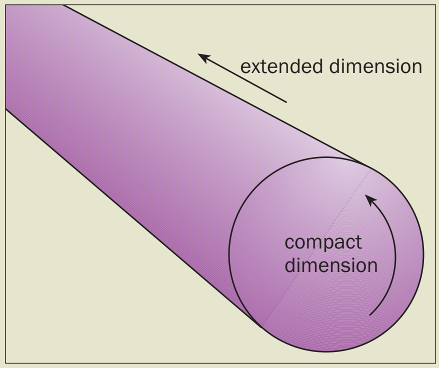
String theory is therefore a very exciting prospect because it can describe the fields of QED, QCD and quantum gravity in a single theoretical framework. On scales where we cannot detect their length, strings behave like photons, gluons or gravitons because they have the right spins. The smell of the ultimate unification of all four forces is in the air!

Understanding whether or not this is the big breakthrough, however, has been hard to confirm. String theory provides a theoretical structure for unification, but connecting this with the zoo of fundamental particles that we know from particle physics is a daunting task. There are many different particles with properties that we do not really understand from a theoretical perspective. And there are other particles, such as the Higgs boson, that we suspect exist but that have not yet been found experimentally.

A particularly good example of the separation between string theory and particle physics is the fact that string theory seems to live in 10 dimensions – nine space dimensions and one time dimension – as opposed to the four that we observe. This is not a total disaster because dimensions can be compactified at very short length scales (figure 3). But string theory fails to explain why six dimensions should be compact while four should not, and, furthermore, there is no experimental evidence to date for such compact dimensions.

In spite of this, string theory has much to offer. It allows us to investigate the behaviour of a quantum theory of gravity, albeit one that does not precisely match the world in which we live. The 1990s saw a lot of activity in this area. Joe Polchinski at the University of California in Santa Barbara discovered a remarkable new set of objects "living" inside string theory called branes. These are lower-dimensional slices of space that have different properties to the rest of the space. In the 10D space of string theory a variety of branes can exist with different dimensions. It is helpful to think about such objects in our 3D world whereby a 1D brane would exist in space like a piece of string or a 2D brane like a piece of paper.

3 Compact dimensions



We are only aware of three spatial dimensions, but higher compact dimensions are predicted to exist in string theory. The circumference of a compact dimension could be so small that we would be unaware of it in everyday life, or even in particle accelerators that probe distances down to 10^{-17} m.

It turns out that five of the nine spatial dimensions of the gravitational theory are compact, which means that they are not visible at long distance scales. This means that the gravitational theory has four extended spatial dimensions – one more than the supersymmetric QCD gauge theory on the brane. This extra dimension has a very nice interpretation in terms of the gauge theory. As we saw in real QCD, a gauge theory coupling between two charges depends on their separation and so it is not actually a constant. As we move in the fifth extended dimension of the gravitational theory, space–time is curved in such a way that the separation between the quarks changes. The variation in the gravitational field in that direction therefore describes the change in coupling strength between charges at different separations. The wonderful thing is that it is relatively easy to calculate the variation in the gravity theory when the charges are widely separated, but very difficult in gauge theories.

Branes are really sub-spaces on which the ends of open strings are tied such that they are unable to move elsewhere in the space. The closed loops in the theory, on the other hand, live throughout the entire 10D space. This means that the open strings that look like the QED and QCD fields of the Standard Model can live on a brane, while the closed loops of gravity can live in a higher-dimensional space (figure 4). Could our universe be a 3D brane in some multidimensional world? Recent theoretical work suggests that it could be, although there is no experimental evidence to suggest that it actually is. (See "The search for extra dimensions" by Steven Abel and John March-Russell *Physics World* November 2000 pp39–44.)

Theories on the brane

It is these developments that have paved the way for some revolutionary ideas that have recently connected string theory back to QCD. If the gauge theories of the Standard Model are restricted to a brane then they will only interact with the closed strings of the gravitational theory on the brane. Knowing nothing of the higher-dimension gravity theory, the gauge theory on the brane just interprets the values of the gravitational fields as fundamental constants of its world. The higher-dimension gravity theory therefore contains information about the coupling constants in the theory that lives on the brane. In other words, the gravity theory has the potential to be an alternative description of that theory.

In 1997 Juan Maldacena at the Institute for Advanced Study in Princeton put the flesh on the bones of this idea. He worked with a 3D brane on which a special "supersymmetric" version of QCD lived. This theory contained additional, massless superparticles – which do not exist in the real world – to make the mathematics of the theory far more constrained. Supersymmetry works by pairing up particles that have different spins such that two supersymmetric particles can be described by one mathematical expression. The constraints in Maldacena's theory are so strong that he was able to write down an exact 10D gravity theory that had the couplings of the lower-dimension supersymmetric QCD theory embedded within it.

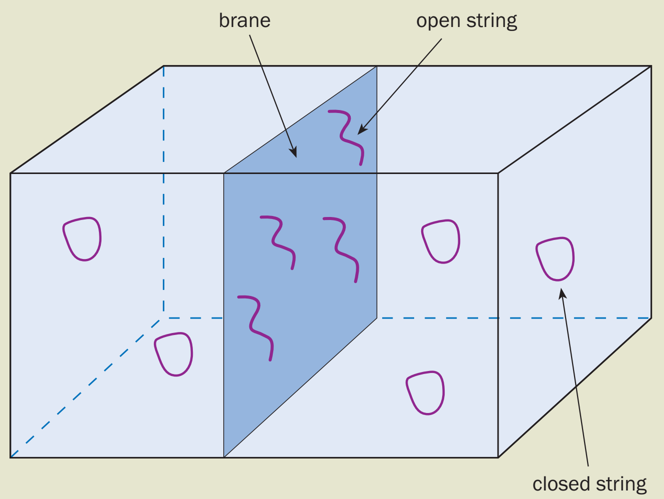
Strings and quarks reunited

The extra superparticles that were added to QCD to realize this "duality" between a gauge theory and gravity theory change the behaviour of the quarks and gluons quite radically, and to get closer to real QCD we have to make these extra particles very massive. We cannot completely remove them from the theory because the string description at low quark separation would collapse, just like it does in real QCD. The long-distance physics, however, should still look very much like real QCD.

The masses for the superparticles are just the values of some of the gravitational fields at the point where the closed strings meet the brane (figure 4). However, since these masses are zero in the supersymmetric QCD gauge theory, the gravitational fields play a passive role in Maldacena's dual theory because they will be zero everywhere. We now have to look for a more complicated gravitational theory in which the gravitational fields "switch on" and are not zero, which makes the superparticles massive. The mathematical technology that is needed to do this has been under development for a number of years, and recently the author and collaborators at Southampton University constructed the gravity dual of a particular theory of strong interactions that describes just gluons (see Babington *et al.* in further reading).

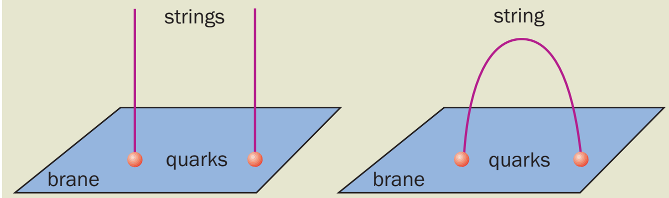
The gluon-only version of QCD, without quarks, is interesting in its own right. This is again because the QCD fields carry colour charge, which means that they interact with each other and can be confined into real colour-neutral particles called glueballs. The gravity dual describes this phenomenon precisely as being due to the propagation of gravitational waves in the higher-dimensional space of the gravity theory. The solutions for these waves change in the fifth spatial direction, and these changes tell us how the glueballs look at different length scales. The gravity dual makes predictions for the masses of the glueballs that match well with those from QCD, although the effect of the extra, massive superparticles sneaks in to make the numbers slightly different.

4 Duality in a multidimensional universe



String theory and QCD might actually describe the same physics. Strings with free ends that give rise to QCD can be restricted to a "brane", while closed loops of string that generate gravity live in a higher-dimension space. The two different theories only interact at the position of the brane. The QCD theory on the brane therefore interprets the values of the gravitational field that it sees as masses and coupling constants.

5 Strings and QCD



Two infinite strings that have one end attached to the brane represent quarks in the QCD theory on the brane. Depending on the shape of the space–time the quarks can lie independently of each other (left) or connect in order to minimize their energy (right). If the quarks are independent then they are screened in the gauge theory, while if they are connected the quarks are confined.

Work has begun on the next step – understanding how to include quarks in the theory. This requires more complicated brane structures or space–times. Although unphysical, the easiest thing to do mathematically is to put in quarks that have an infinite mass. Remember that the open strings that give rise to the gluons carry the colour charges of a quark and antiquark attached to their two ends. If we use an infinite amount of energy, we can rip one end of the string off the brane and extend it out into the fifth dimension of the gravitational theory (see figure 5). Since we have removed one of the colour charges from the brane, the particle that is left on the brane is just a quark or an antiquark.

If we have two such quarks then we can study their interactions in the presence of the gluons. In the gravitational description the strings try to lie in the curved space–time in such a way that minimizes their energy. It may be energetically favourable for each string to lie as it would if it was on its own and there was only one quark on the brane. This would mean that the two quarks do not interact and the gauge theory dynamics "screen" the charges from one another. On the other hand, the shape of the space may make it energetically favourable for the two strings to join and form a loop in the gravitational space (figure 5).

This is exactly what happens in Maldacena's theory. The quarks – the ends of the string – are connected, and separating them will cost energy because the string has to be stretched. This is a new version of the old idea that quarks can be thought of as tied together by a string. But the remarkable thing is that the string is in a higher-dimensional space than the QCD quark theory. Recently, Andreas Karch and collaborators from the University of Washington in Seattle reported progress in including light quarks that bind together, while the first studies of the properties of hadrons and their substructure are also under way (see Karch *et al.* in further reading).

Fascinating progress has also been made in understanding QCD phase transitions. In the very early universe it is thought that quarks and gluons were crushed together so tightly that they interacted very weakly due to asymptotic freedom. There is therefore a critical temperature at which protons and neutrons cease to exist and are replaced by free quarks and gluons. But how can this transition be understood in terms of a QCD–gravity dual? Ed Witten at the Institute for Advanced Study in Princeton has proposed that the phase transition corresponds to a transition in the shape of the gravitational space–time. He has shown that a previous computation by Stephen Hawking and Don Page at Cambridge University in the UK, which showed how a space can suddenly develop a black hole in its centre, is precisely the description that is needed to describe the QCD transition from confined to deconfined quarks. Several groups are currently investigating how to use this gravitational dual theory to calculate how waves propagate in such a quark–gluon plasma, which is crucial to understanding the very early universe.

The duality between gravity and QCD has the potential for a new basic understanding of the strong nuclear force. It also gives us a fresh perspective on gravity and string theory. QCD and related gauge theories have turned out to be an alternative way to define string theory, while QCD–gravity duals can provide powerful constraints on theories of quantum gravity. This has profound implications for the ultimate prize in modern physics: the construction of a unified theory of the fundamental forces of nature.

Further reading

O Aharony *et al*. 2000 Large *N* field theories, string theory and gravity *Phys. Rep.* **323** 183–386

J Babington, D Crooks and N Evans 2003 A stable supergravity dual of nonsymmetric glue *Phys. Rev.* D **67** 066007

B Greene 2000 *The Elegant Universe* (Vintage, London)

C Johnson 2003 *D-branes* (Cambridge University Press)

A Karch, E Katz and N Weiner 2003 Hadron masses and screening from anti-de Sitter space Wilson loops *Phys. Rev. Lett.* **90** 091601

J Maldacena 1998 The large *N* limit of superconformal field theories and supergravity *Adv. Theor. Math. Phys.* **2** 231–252

J Polchinski 1998 *String Theory I & II* (Cambridge University Press)

E Witten 1998 Anti-de Sitter space and holography *Adv. Theor. Math. Phys.* **2** 253–291

Link

Seattle conference: int.phys.washington.edu/PROGRAMS/03-28W.html

Nick Evans is in the Department of Physics, University of Southampton, Highfield, Southampton SO17 1BJ, UK, e-mail evans@phys.soton.ac.uk