obtained by genetic analyses for the origin of modern human variation[1] only heightens their importance. ■

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High-energy physics

Into the fifth dimension

Juan Maldacena

Particles such as the proton can be imagined as vibrating strings. We also know that protons contain smaller, point-like particles, going against the string theory. But in five dimensions, the contradiction disappears.

In fundamental physics, our description of nature involves four forces: gravitational, electromagnetic, weak and strong. The strong force is responsible for binding protons and neutrons inside the atomic nucleus. Two different theoretical approaches have been taken in describing the workings of the strong force and the structure of particles such as the proton and neutron. The theories are seemingly at odds with each other, but steps are gradually being taken to reconcile the two. Writing in the *Journal of High Energy Physics*, Polchinski and Strassler[1] now dispel worries over an apparent contradiction between the theories, by showing that it isn't necessarily a contradiction at all.

In the 1960s, experiments on high-energy collisions between protons revealed a plethora of other short-lived, strongly interacting particles. Shortly afterwards, a theory emerged that proposed that all of these different particles were particular excitation modes of a string: as a violin string can vibrate with different frequencies, these strings could oscillate in different ways, corresponding to the 'zoo' of particles that was observed. This 'string theory' proved useful in explaining some aspects of the masses and spins of the particles.

But further experiments carried out through the 1970s showed that protons are not fundamental particles. In the same way that, much earlier in the century, Rutherford had shown that the atomic nucleus was much smaller than an atom, experimenters showed that protons, and neutrons, have small point-like constituents. This didn't fit with the theory of protons as strings, which are extended objects. In fact, these experiments led to a new description of the strong interaction in terms of point-like quarks and gluons, through a theory called quantum chromodynamics (QCD).

As the electron carries an electric charge, quarks and gluons carry a new type of charge, called 'colour' (hence 'chromodynamics'). The gluons transmit the strong force between quarks in much the same way that the photon transmits the electromagnetic force between electrons and other charged particles. To describe the strong force we need three 'colours' — three different types of charges, usually designated 'red', 'green' and 'blue'. The validity of QCD has been spectacularly confirmed by experiments at high energies in particle colliders. But, despite this success, it is still remarkably hard to do theoretical calculations with QCD at low energies. And that's exactly where things should get interesting: at low energies, the colour flux lines form bundles of energy that should behave like a string — a tantalizing connection from QCD to string theory. These strings, made of gluons, bind the quarks together.

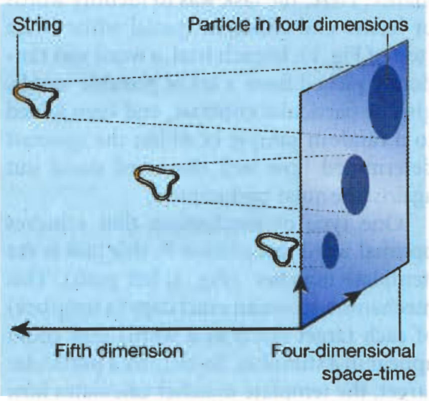

Figure 1 **Strings, particles and extra dimensions. Strings moving in the fifth dimension are represented in the everyday world by their projection onto the four-dimensional boundary of the five-dimensional space-time. The same string located at different positions along the fifth dimension corresponds to particles of different sizes in four dimensions: the further away the string, the larger the particle. The projection of a string that is very close to the boundary of the four-dimensional world can appear to be a point-like particle.**

In fact, in the 1970s, Gerard 't Hooft[2] showed that QCD becomes a theory of free (non-interacting) strings if the number of colours is infinite. This simplifies the theory considerably. Strings still exist in the three-colour version of QCD, but in this case the strings are interacting. No way has yet been found to simplify QCD into a free-string theory, but it could be the key to understanding many low-energy properties of particles that interact through the strong force, and in particular for deriving a curious property of QCD, called confinement. No one has ever observed a free quark, because colour-charge-bearing objects such as quarks and gluons are subject to confinement: in other words, as two quarks are gradually separated the attractive force between them due to their colour charges remains constant; this contrasts with the more familiar forces in electromagnetism and gravity that fall off with the square of increasing distance.

The way forward has been signalled by work on strings in 'QCD-like' theories[3–5]. A surprising and counterintuitive feature of these strings is that they move in more than the familiar four dimensions of everyday life — three spatial dimensions and one of time. Even though the gluons that make up the strings move in four dimensions, the string itself moves in five dimensions. Polchinski and Strassler[1] now show that this fact is a crucial element in reconciling the string picture and the point-like behaviour seen in high-energy collisions.

The strings move in a five-dimensional curved space-time with a boundary. The boundary corresponds to the usual four dimensions, and the fifth dimension describes the motion away from this boundary into the interior of the curved space-time. In this five-dimensional space-time, there is a strong gravitational field pulling objects away from the boundary, and as a result time flows more slowly far away from the boundary than close to it. This also implies that an object that has a fixed proper size in the interior can appear to have a different size when viewed from the boundary (Fig. 1). Strings existing in the five-dimensional space-time can even look point-like when they are close to the boundary. Polchinski and Strassler[1] show that when an energetic four-dimensional particle (such as an electron) is scattered from these strings (describing protons), the main contribution comes from a string that is close to the boundary and it is therefore seen as a point-like object. So a string-like interpretation of a proton is not at odds with the observation that there are point-like objects inside it.

Because the theory that describes the interior of the five-dimensional space-time includes gravity, there are other interesting consequences of this line of argument. One of the most striking is the following. In QCD, when the temperature reaches sufficiently high values (above 10^{12} K), a phase transition occurs and quarks and gluons are no longer confined — instead, a 'soup' of free particles is formed, called quark–gluon plasma. In the five-dimensional theory, this transition also corresponds to the formation of a black hole in the interior. Our knowledge of black holes can then tell us something about quark–gluon plasma. In addition, the QCD–string theory provides a simple explanation for an interesting feature of black holes — the Bekenstein–Hawking entropy. This entropy, a measure of the number of possible quantum microstates, arises from the thermodynamic properties of a black hole (which are also at the root of Hawking radiation). Counting these microstates to work out the entropy has proved a major challenge in theories of quantum gravity. But in the five-dimensional theory, the black-hole entropy becomes just the entropy of the plasma of quarks and gluons.

There is an intimate connection between the physics of strong interactions and both string theory and quantum gravity. Hopefully, in the next few years a string-theory description for real-world QCD will emerge, making it possible to perform computations in a relatively simple way. And perhaps, beyond that, we might even arrive at a QCD-like theory that can describe gravity. ■

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