attend to human speech, the authors speculate that speech may have evolved to match the properties of cochlear filters.

The efficient-coding hypothesis posits that the neural code should be adapted to the statistical properties of stimuli on all timescales. Where Smith and Lewicki were studying adaptation that had occurred over an evolutionary timescale, Sharpee and colleagues[3] looked for adaptation over seconds and minutes, the much faster timescale relevant to behaviour.

Sharpee and colleagues studied adaptation to natural scenes (images of a forest) of a particular subclass of neurons — the 'simple cells'— in the primary visual cortex of anaesthetized cats. Simple cells respond to oriented bars or edges, and it was already known that they could adapt to the most basic statistical properties of images — the luminance, mean and contrast (variance). So the authors probed these neurons with a control ensemble consisting of white-noise images (like the static on an untuned television monitor) whose mean and contrast were matched to those of the natural scenes. Consistent with the efficient-coding hypothesis they found that, after seconds or minutes of exposure to the natural ensemble, these neurons adapted their response properties so as to increase the information they transmitted.

The appeal of the efficient-coding hypothesis is that it predicts structure in a large and complex data set: the response properties of sensory neurons throughout the nervous system. As such, it is one of the great successes of theoretical neuroscience. But why should the nervous system encode sensory stimuli efficiently? One possible explanation is that neuronal connectivity requires space, and that therefore information must be transmitted using as few 'wires' (axons) as possible[4]. Alternatively, the limiting resource may be the energy associated with neuronal activity[5]; a sparser code using fewer spikes uses less energy.

Finally, the motivation might (as Barlow[1] supposed) be computational: sparse encoding requires uncovering as much of the underlying structure of the signals as possible. That the nervous system seems to be able to do this is impressive, because it is not an easy task. As anyone who has ever tried to write a *Nature* letter knows, writing succinctly requires a very clear idea of what one is trying to say. Or as Mark Twain put it, "I'm sorry this letter is so long, but I did not have time to make it shorter." ■

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1. Barlow, H. B. in *Information Processing in the Nervous System* (ed. Leibovic, K. N.) 209–230 (Springer, New York, 1969).
2. Smith, E. C. & Lewicki, M. S. *Nature* **439,** 978–982 (2006).
3. Sharpee, T. O. *et al. Nature* **439,** 936–942 (2006).
4. Chklovskii, D. B., Schikorski, T. & Stevens, C. F. *Neuron* **34,** 341–347 (2002).
5. Laughlin, S. B., de Ruyter van Steveninck, R. R. & Anderson, J. C. *Nature Neurosci.* **1,** 36–41 (1998).

PARTICLE PHYSICS

Quarks on a gravitational string

Nick Evans

Quantum chromodynamics, the theory of the strong nuclear force, is notoriously intractable. An alternative approach brings gravity to bear, and produces fairly accurate predictions of some physical quantities.

The strong nuclear force is the force that causes quarks to bind together to form composite particles, such as the proton. It is explained within the standard model of particle physics by a theory known as quantum chromodynamics (QCD) in terms of fields analogous to electric fields that arise between particles that possess 'colour' charge — the strong-force equivalent of electric charge. Unfortunately for the theorists, however, QCD has consistently eluded analytical solution. The best available calculations rely on huge supercomputer simulations, and the parameters that emerge must be fitted to experimental results.

That situation might change with a remarkable complementary description of the strong force. The new theory incorporates four spatial directions and a dynamic force of gravity that curves space-time in the spirit of the general theory of relativity. As Erlich *et al.*[1] writing in *Physical Review Letters* and Da Rold and Pomarol[2] writing in *Nuclear Physics B* report, it can already be used to produce reasonably accurate quantitative descriptions of light quark–antiquark pairings (mesons) such as the pion.

The genesis of the models is string theory, in which fundamental particles are not points in space, but have an intrinsic length. Seen from afar, the length of these one-dimensional 'strings' is too small to be discerned, but oscillations along this length determine the mass and spin of the particle the string represents. String theory has become a leading contender for a theory of everything, as it can accommodate both gravity and the other forces of nature: so-called open strings have free ends and look like the photon or gluon (the particles that mediate the electromagnetic and strong nuclear force as quanta of the respective fields), whereas closed loops of string have the properties of a graviton, the as yet undiscovered particle that would mediate gravity in a quantum version of general relativity. Problematically, however, string theory turns out to make sense only in a world with nine spatial dimensions, rather than the three that we see.

String theory also contains objects of dimension larger than one: two-dimensional 'membranes', and extensions of still higher dimension known as branes (Fig. 1). These branes emerge in the theory as sub-spaces to which the motion of the open strings, those relevant to QCD, is restricted. Much entertainment has been derived from constructing theories with different matter fields and forces restricted to the volumes of branes of different dimensions — including three.

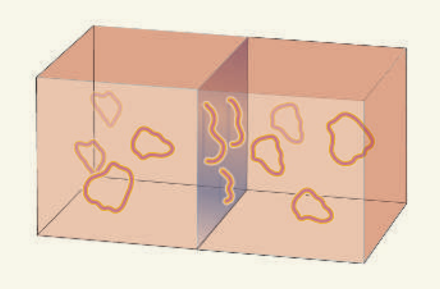

Figure 1 | Braney stuff. In the string theory construction of quantum chromodynamics (QCD), open strings, which describe quarks, are restricted to a membrane-like surface, known as a brane. Closed strings live in a higher-dimension space off the brane and generate an alternative description of QCD.

In brane theories, the closed strings that describe gravity continue to move in all nine spatial dimensions. Away from the branes' surfaces, the branes' energy generates curvature in space-time, as does gravity in general relativity. Naively, there are therefore two sectors to brane theories: off the brane, describing a theory with similarities to gravity, and on it, describing a theory such as QCD.

But what if these two sectors are actually two alternative descriptions of the same physics? This was originally conjectured[3] for an idealized version of QCD incorporating constraints on its solution to make the theory easier to handle mathematically. But subsequent work that has aimed to remove these devices seems also to support the supposition.

To appreciate how two different theories can describe the same physics, we must first understand that the behaviour of QCD is very different at different energy scales. Colour charge depends, for instance, on the energy exchanged between two quarks in an interaction. If the energy is large, the coupling is weak; if it is small, the coupling becomes very strong. So, the farther quarks move away from each other (and the less energy is exchanged between then), the stronger they bind. This 'quark confinement' is the reason why we never see a free quark, only those bound into composite particles.

In the gravitational, string-theory description of this phenomenon, the quark coupling is represented by a field that describes the distribution of strings in space. The role of energy scale is assumed by the direction radial from the brane in the extra dimensions of the purely gravitational theory. Variations in quark coupling turn up as a variation in a gravity field in this radial direction. Crucially, gravity fields are weakly coupled and therefore easy to compute — unlike the fields of QCD.

Another consequence of the strong coupling in QCD is that its vacuum is actually filled with quark–antiquark pairs, created by 'borrowing' energy for a short period of time, as permitted by the Heisenberg uncertainty principle. The quark and antiquark might be expected to annihilate almost instantaneously, but the strong force is so strong that the energy liberated by their attraction is greater than that borrowed by the vacuum to create them. The vacuum's debt can thus be paid off. In the gravitational string-theory approach, the vacuum quark density is, like quark coupling, described by a field in the higher-dimension space. The solution for this field switches on at values of the radius where the coupling is strong[4] — an important first step in showing that the approach indeed can reproduce the same behaviour as does QCD.

Quark–antiquark pairings such as pions are simply fluctuations in the number of quarks above vacuum level. In the gravitational description, the known mesons are wave excitations on top of the background field configuration just described. However, the mathematical tricks used to get to this stage mean that there are more stable wave excitations than there are mesons predicted by QCD, corresponding to there being extra heavy quarks present. Erlich *et al.*[1] and Da Rold and Pomarol[2] study the wave excitations appropriate to known QCD mesons. (Only particular waves thrown up by the gravitational theory, corresponding to discrete meson mass values, are stable in space-time.)

The gravitational theory has the same number of defining parameters as QCD. Fixing the parameter that determines the warping of space-time in the gravitational theory corresponds to fixing the QCD coupling to its experimentally measured value. The authors use the background value of a gravitational field to set the masses of the two lightest quarks, 'up' and 'down', through the mass of the various pions and the rho meson (each of which is a combination of an up and down quark and an up or down antiquark). They can use these masses to predict the masses of other bound particles and the strengths of interactions between these states. The values they come up with lie within 10–15% of the values found in nature.

The agreement suggests not only that the approach could provide a radical new description of QCD phenomena such as the mass spectrum of the particles found, but also that many of the consequences of strong-force interactions are common to a broad range of theories. The outstanding challenge is to find a way to remove all artefacts of the mathematics used to simplify string theory in a controlled fashion.

There is indeed one arena of QCD where the gravitational description provides our current best theoretical tool. In collisions between heavy nuclei, the temperature and density are sufficient to compress nuclei into a soup of quarks. Properties of this strongly interacting fluid, such as its viscosity and thermal conductivity, are very hard to compute in QCD, but can be extracted with relative ease from the gravitational theory[5].

It seems we have a new tool in our kit for tackling the strong force and the complexities of quarks. ■

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1. Erlich, J., Katz, E., Son, D. T. & Stephanov, M. A. *Phys. Rev. Lett.* **95,** 261602 (2005).
2. Da Rold, R. & Pomarol, A. *Nucl. Phys. B* **721,** 79–97 (2005).
3. Maldacena, J. M. *Adv. Theor. Math. Phys.* **2,** 231–252 (1998).
4. Babington, J., Erdmenger, J., Evans, N. J., Guralnik, Z. & Kirsch, I. *Phys. Rev. D* **69,** 066007 (2004).
5. Son, D. T. & Starinets, A. O. preprint available at http://arxiv.org/abs/hep-th/0601157 (2006).

EVOLUTION

Careful with that amphioxus

Henry Gee

The textbook tale of vertebrate origins is brought into question by phylogenetic analyses of new genomic data. But the amphioxus, long viewed as a precursor to fish, remains a central character in events.

History is written by the victors. This is as true for our account of evolution as it is for purely human affairs. But as the paper by Delsuc *et al.* (page 965 of this issue[1]) makes plain, we the apparent victors still need to be prepared to rethink our own deep evolutionary history as time and technology advance.

The conventional picture of the evolution of the deuterostomes (our particular corner of organized life) has been one of steady and anthropocentric advancement (Fig. 1a). Starting with undistinguished squashy sea creatures, evolution produced the first signs of gill slits (in hemichordates, or acorn worms); a dorsal tubular nerve cord and a notochord (tunicates, or sea-squirts); and clear muscular segmentation (cephalochordates, or lancelets, represented by the fish-like amphioxus). The culmination was vertebrates (with all of the above characteristics, and heads), and finally ourselves. The echinoderms (starfishes, sea-urchins and so on), with their peculiar symmetry and strange calcitic skeletons, are seen as bizarre relatives to be locked in the attic, rather like the first Mrs Rochester in Charlotte Brontë's *Jane Eyre*.

Time and again, further work has exposed our prejudices for the parochial conceits that they are. As long ago as 1881, it was proposed that hemichordates and echinoderms formed a discrete group, the Ambulacraria[2], a proposal revived at first tentatively and then supported with increasing conviction by molecular evidence (Fig. 1b)[3]. And there have been persistent signs, from fragments of both morphological and molecular evidence, that the similarities between amphioxus and vertebrates conceal a wealth of difference — while the manifest oddities of tunicate morphology and development might be more attributable to recent innovation than to ancient heritage[4].

In their report, Delsuc *et al.*[1] apply a range of phylogenetic methods to a large genomic data set from an unrivalled range of taxa. They control for known problems such as 'long-branch attraction', and show that tunicates — not lancelets — are the closest extant relatives of

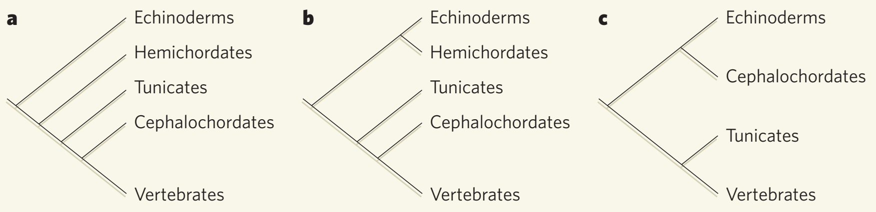

Figure 1 | Deuterostome relationships. **a,** The classic, textbook view, implying a smooth increase in complexity from a relatively simple and sedentary deuterostome ancestor to motile vertebrates. **b,** A more recent view informed by molecular evidence, in which hemichordates are allied with echinoderms, implying a more complex echinoderm history. **c,** The topology suggested by the results of Delsuc *et al.*[1]. This implies that the deuterostome ancestor would have been motile and relatively complex, and that the sessile habits of most echinoderms and tunicates evolved later. Hemichordates are notably absent.