

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<sup>4</sup> — 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.*<sup>1</sup> and Da Rold and Pomarol<sup>2</sup> 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<sup>5</sup>.

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

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## 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.**

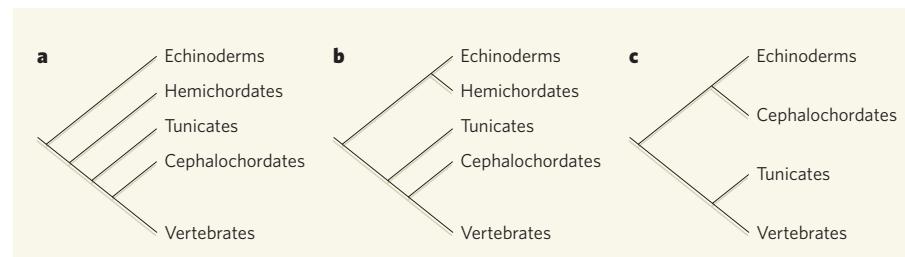
History is written by the victors. This is as true for our account of evolution as it is for purely human affairs. But as the paper by Delsuc *et al.* (page 965 of this issue<sup>1</sup>) makes plain, we the apparent victors still need to be prepared to rethink our own deep evolutionary history as time 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 squishy 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<sup>2</sup>, a proposal revived at first tentatively and then supported with increasing conviction by molecular evidence (Fig. 1b)<sup>3</sup>. 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<sup>4</sup>.

In their report, Delsuc *et al.*<sup>1</sup> 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.*<sup>1</sup>. 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.

vertebrates (Fig. 1c). Moreover, they argue that amphioxus is not a close relative of either vertebrates or tunicates, but is more akin to echinoderms. This conclusion is not nearly as robust as the tunicate–vertebrate link. It does, however, seem to be a persistent feature of the analysis, and is worth careful consideration. After all, the close hemichordate–echinoderm link seemed unorthodox when it was first revived, and few would have expected that the tunicate–vertebrate link would receive such strong support.

So, if lancelets really are close relatives of echinoderms, what are the implications for our picture of deuterostome evolution? The short answer is that the textbook scheme is turned on its head. Rather than the steady acquisition of progressively more chordate-like (and, by implication, human-like) features from an ancestor with nothing much to recommend it, the story becomes one of persistent loss. The last common ancestor of extant deuterostomes would have been a free-living, bilaterally symmetrical creature with a distinct throat region perforated by gill slits, segmented body-wall musculature and possibly a reasonably sophisticated brain and central nervous system. In a sentence, the ancestor would have looked like a cross between an amphioxus and a larger, brainier, tunicate tadpole larva. Crazy? Possibly. But possibly not.

Most modern tunicates seem to be immobile relatives of motile ancestors, but some, such as the appendicularian tunicate *Oikopleura*, do move about. So in this group the proposed ancestral deuterostome portrait has not so much been erased as extensively modified by changes in the evolution of tunicate development. Fossil evidence fills in more details, with the discovery of the strange Cambrian vetulicolians<sup>5</sup>, which look strikingly like the hypothetical ancestral deuterostome form — and, like the ‘somatico-visceral animal’, a model for a chordate ancestor described in one of the last and most prescient papers by the late great palaeontologist A. S. Romer<sup>6</sup>.

Echinoderms have lost all these features to the extent that the ancestral portrait cannot be recognized at all in modern forms. However, some members of a group of fossil echinoderms called stylophora may have had gill slits (an interpretation made more likely by the reaffirmed hemichordate–echinoderm link) and, according to R. P. S. Jefferies’ controversial calcichordate theory, an internal organization similar to that of tunicates<sup>7</sup>. Jefferies proposes that each kind of stylophoran should rather be assigned to the groups containing modern tunicates, vertebrates or cephalochordates, respectively, and that the characteristic echinoderm calcite skeleton has been lost in each case. However, a simpler alternative is that the calcite skeleton was acquired just once in the ancestry of echinoderms, when this creature still looked much like the proposed deuterostome ancestor. The irony is that even with this shift in perspective, many of Jefferies’ detailed anatomical

interpretations of stylophoran anatomy, particularly as regards the anatomy of the pharynx<sup>8</sup>, could still be correct (but see ref. 9).

Much remains to be found. As Delsuc *et al.*<sup>1</sup> acknowledge, adequate tests of these ideas require the sequenced genomes of hemichordates, of more echinoderms and — especially — of amphioxus. This last is particularly important: for generations, amphioxus has been viewed as a model organism, representing a picture of the first stirrings of vertebrate evolution. But if this radical and certainly controversial new view is supported by further evidence, amphioxus could occupy a far more significant and inclusive position — the

closest extant organism we yet have to the ancestor of all deuterostomes. ■

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## PLANETARY SCIENCE

# Pluto's expanding brood

Richard P. Binzel

**Pluto is no lone ranger in the farthest expanses of the Solar System — its travelling companions now number three. And if Pluto can have so many, why shouldn't other objects in the distant, icy Kuiper belt?**

Once thought to be a solitary denizen of the outer reaches of the Solar System, Pluto — which piqued our curiosity in 1978 with the discovery of its large satellite, Charon<sup>1</sup> — is becoming ever more intriguing. In fact, the relative sizes of Pluto and Charon (Charon’s diameter of around 1,200 kilometres is just over half that of Pluto’s) means they are a ‘double planet’, orbiting a mutual centre of gravity, or barycentre, outside the surface of Pluto. But the story does not stop there. On page 943 of this issue, Weaver *et al.*<sup>2</sup> present Hubble Space Telescope images showing that the Pluto system is at least quadruple. And as Stern *et al.* indicate in a companion paper<sup>3</sup> on page 946,

this complexity portends further discoveries: more small satellites may be lurking out there, and cratering impacts on them may have liberated rings or arcs of matter. Propitiously, NASA’s New Horizons mission<sup>4,5</sup> is now successfully launched (Fig. 1) and on its way to a flying visit to Pluto and its companions in 2015.

Following Clyde Tombaugh’s discovery of Pluto in 1930, searching for satellites was an obvious first task. But none was found until Pluto’s march towards its point of closest approach to the Sun, coupled with the exquisite optics of a ground-based telescope, finally allowed Charon to be pinpointed<sup>1</sup>. Since then, ground-based surveys<sup>6,7</sup> have yielded



NASA

**Figure 1 | Destination Pluto.** The New Horizons spacecraft took off from Cape Canaveral on 19 January 2006 aboard an Atlas V rocket, bound for the Pluto system. Speedy results are not to be expected: the half-tonne, piano-sized spacecraft must cover a distance of just under five billion kilometres, and will reach a point of closest approach some 10,000 kilometres from Pluto on 14 July 2015.