(seventeenth to nineteenth centuries) or the Medieval Warm Period (eleventh to fourteenth centuries). Nor do they seem to tie in with reconstructions of volcanic and solar behaviour that might drive climate change. The authors conclude, quite reasonably, that much of the variability seen in ENSO strength over the past millennium was probably not driven by external factors.

So, where does this leave us in attempting to predict future ENSO activity? Cobb *et al.* show that, as ENSO varies significantly on its own — that is, even without greenhouse warming — we might expect changes beyond those experienced in the twentieth century. Looking to other periods in the past there is increasing evidence that the ENSO cycle may have been weak, or even absent, between about 14,000 and 5,000 years ago[5,6]. The most likely explanations involve the sensitivity of ENSO to changes in the length and timing of the seasons resulting from the precession cycle in the Earth's orbit[7]. ENSO may also have been generally weaker during the cooler conditions of the last glacial period (100,000–20,000 years ago)[6]. These data hint that the ENSO system is sensitive to background climate, and that it may well respond to future greenhouse warming. But it is not easy to tell what this response will be — there is no past equivalent of expected twenty-first-century climate.

Cobb *et al.* looked at ENSO during a period of relatively little global climate change. The future is almost certainly going to be radically different, with predictions of a 1.5–6.0 °C rise in global mean temperature within the next 100 years[8] — potentially almost as much change as that between the last glacial period and the present interglacial. The only realistic hope for predicting the response of ENSO to this warming lies in the use of coupled ocean–atmosphere climate models. Some of the best of these models now generate a realistic ENSO cycle but produce a wide range of predicted outcomes for ENSO in a warmer world, from a significant strengthening of the cycle, to no effect or even a weakening[9,10]. Equally important in terms of potential social and economic consequences are changes in 'average' conditions, for example towards a more El Niño-like background state with associated reduction in rainfall over much of southeast Asia and South America[11].

The use of proxy data about past conditions has been limited in evaluating global ocean–atmosphere climate models[12], partly because modellers find it difficult to deal with isolated, short and imprecisely dated records like those from fossil corals. But such tests are crucial. The study of Cobb *et al.* is a step towards the more complete multi-proxy[13] archives of climate that will be needed. ■

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1. Cobb, K. M., Charles, C. D., Cheng, H. & Edwards, R. L. *Nature* **424,** 271–276 (2003).
2. Philander, S. G. H. *El Niño, La Niña and the Southern Oscillation* (Academic, San Diego, 1990).
3. Glantz, M. H. *Currents of Change: El Nino's and La Nina's Impact on Climate and Society* (Cambridge Univ. Press, 2001).
4. Folland, C. K. *et al. IPCC Third Assessment Report* Ch. 1 (Cambridge Univ. Press, 2001).
5. Rodbell, D. T. *et al. Science* **283,** 516–520 (1999).
6. Tudhope, A. W. *et al. Science* **291,** 1511–1517 (2001).
7. Clement, A. C. *et al. Paleoceanography* **15,** 731–737 (2000).
8. Cubash, U. & Meehl, G. A. *IPCC Third Assessment Report* Ch. 9 (Cambridge Univ. Press, 2001).
9. Timmermann, A. *et al. Nature* **398,** 694–696 (1999).
10. Collins, M. *Geophys. Res. Lett.* **27,** 3509–3513 (2000).
11. Cox, P. M. *et al. Nature* **408,** 184–187 (2000).
12. Collins, M. *et al. J. Clim.* **15,** 1497–1515 (2002).
13. Mann, M. E. *et al. Nature* **392,** 779–787 (1998).

Quantum physics

Uncertain future

Miles Blencowe

The uncertainty principle limits the accuracy of measurement at the quantum level. A device sensitive to subatomic-scale displacement has come close to revealing that principle in action in the macroscopic world.

In 1927, Werner Heisenberg introduced his famous quantum principle[1], which states that the uncertainties in the position and the velocity of a particle are inversely proportional to each other: a particle's position or its velocity can be known precisely, but not both at once. This principle is one of the cornerstones of quantum mechanics, and is traditionally relevant to the domain of subatomic particles. But what about more familiar macroscopic objects, comprising many atoms, that we think of as possessing simultaneously well-defined positions and velocities of their centre-of-mass? If we could be sufficiently precise in our measurements on such objects, would we encounter the quantum uncertainty principle at work?

On page 291 of this issue, Knobel and Cleland[2] address this question. They describe an exquisitely engineered device — a vibrating crystal beam, only a thousandth of a millimetre long, and an extremely sensitive motion detector — that is capable of detecting displacements as small as about one-thousandth of a nanometre, or one-hundredth of the size of a single atom. The beam may seem tiny by everyday standards, but its mass is equivalent to that of about ten billion atoms. A demonstration of the

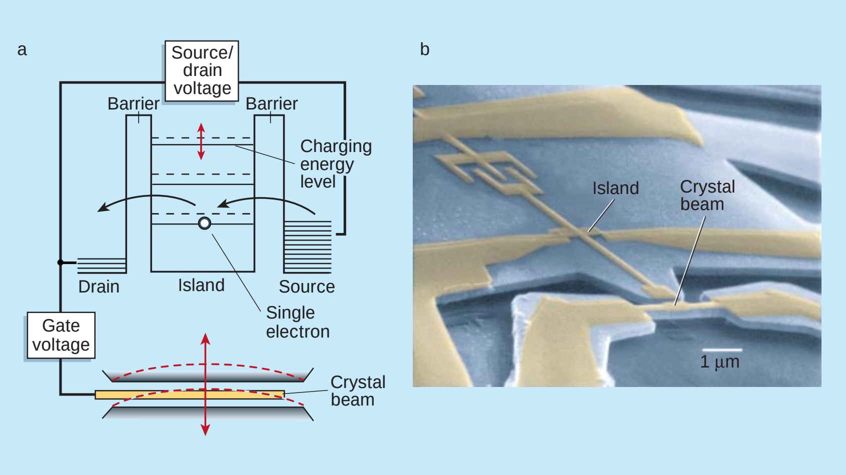

Figure 1 **Closer to the limit. Knobel and Cleland[2] have built a device, based on a single-electron transistor, to investigate the effect of Heisenberg's uncertainty principle on a macroscopic system.** a, **Electrons tunnel from the source to the island and then to the drain, constituting a flow of current. The voltage between source and drain is only strong enough to charge the island by one electron at a time (as indicated by the position of the source level relative to the island charging levels). If the gate voltage is varied, this causes the island charging levels to shift, changing the magnitude of the tunnelling current. Alternatively, fixing the gate voltage and allowing the crystal beam to bend also shifts the levels and modulates the tunnelling current.** b, **The device, shown here in an electron micrograph, is only micrometres in size, and although the quantum zero-point detection limit has not yet been reached, the experiment is the best demonstration so far of sensitivity to subatomic-scale displacements of a nanoscale beam.**

uncertainty principle for such a system would be a striking manifestation of quantum mechanics well outside its traditional, microscopic domain.

If you clamp one end of a wooden ruler to the edge of a table and then pluck the other, free end, it vibrates with decaying amplitude and eventually returns to apparent rest. But if you were to look at the free end of the ruler under a sufficiently powerful microscope, it would not be at rest at all, but jiggling up and down in a random fashion. This motion is a consequence of the air molecules striking the ruler, as well as of its countless, fluctuating internal defects, and is an example of thermal brownian motion.

There are other, quantum fluctuations in the ruler, though, that are completely masked by this classical thermal motion. These quantum 'zero-point' fluctuations have much smaller amplitude and arise from the necessary uncertainty in position and velocity stated in Heisenberg's principle. The situation is analogous to the hydrogen atom, which is stable because the attractive electrostatic force that would like to pull the electron into a tighter volume around the proton is balanced by the repulsive effect of the electron's fluctuating velocity. Similarly, for a macroscopic object such as a crystal beam or a ruler, the elastic restoring force on the bent beam balances the repulsive effect of its fluctuating centre-of-mass velocity.

Because the magnitudes of the zero-point fluctuations in position and velocity are so small, they can only be detected if the structure is cooled down to very low temperatures. As the temperature is lowered, the amplitude of thermal motion decreases. Eventually, there will be no thermal motion, only pure, temperature-independent zero-point fluctuations. At a temperature of about a hundredth of a kelvin (close to the temperature Knobel and Cleland achieve in their experiment[2]), zero-point fluctuations should dominate in a structure with a mechanical vibration frequency of about one billion cycles per second (1 gigahertz, or GHz). It is well known that the pitch of a plucked violin or guitar string increases with decreasing length, so it's easy to appreciate why such a structure must be extremely small. A tiny, 1-GHz, crystal beam was demonstrated recently[3]; Knobel and Cleland's beam vibrates at a frequency only about ten times lower, at the upper end of the FM radio band.

Knobel and Cleland estimate that their crystal beam has a zero-point displacement uncertainty of about 10^{-5} nanometres. To detect such small displacements, they use a device called a single-electron transistor[4], which consists essentially of a small island of metal, comparable in size to the crystal beam, separated by electrically insulating gaps from two wire leads that are connected to a voltage source (Fig. 1). The gaps are sufficiently narrow that electrons can tunnel across them, from one lead (the source) to the other (the drain), through the island. The voltage difference between the leads can be set so that only one electron at a time can tunnel onto the island: an electron on the island must tunnel off into the drain before another tunnels from the source to the island.

This single-electron current is extremely sensitive to charge fluctuations in the vicinity of the island, a property that Knobel and Cleland exploit to turn this single-electron transistor into a displacement detector. The metal island and the crystal beam in their device are separated by a vacuum gap of about 250 nanometres. The beam has a thin metal coating and a separate voltage applied to it (the gate voltage), coupling the beam electrostatically to the island. As the beam centre-of-mass position and hence the gap between the beam and island fluctuate, the charges on the island redistribute. This in turn causes a fluctuation in the tunnelling current that can be measured and related to the displacement of the beam.

Although Knobel and Cleland's device represents a milestone in fast and ultrasensitive displacement detection, it still doesn't quite take us to the quantum zero-point detection limit. To do so, the device's sensitivity to displacements must be improved by about a factor of a hundred, and the mechanical vibration frequency of the beam increased by about a factor of ten. Nevertheless, Knobel and Cleland's achievement throws out an exciting challenge — to close the gap of these remaining few orders of magnitude, and demonstrate Heisenberg's uncertainty principle at work in the macroscopic domain. ■

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1. Heisenberg, W. *Z. Phys.* **43,** 172–198 (1927); English translation in *Quantum Theory and Measurement* (eds Wheeler, J. A. & Zurek, W. H.) 62–84 (Princeton Univ. Press, 1983).
2. Knobel, R. G. & Cleland, A. N. *Nature* **424,** 291–293 (2003).
3. Huang, X. M. H. *et al. Nature* **421,** 496 (2003).
4. Devoret, M. H. & Schoelkopf, R. J. *Nature* **406,** 1039–1046 (2000).

Evolutionary biology

Body plans and simple brains

Thurston Lacalli

Genes expressed in the vertebrate brain and spinal cord show up in the surface nerve net of a closely related group of invertebrates. Could this mean that brains started out on the body surface?

As a vertebrate embryo grows, the development of its brain and spinal cord is controlled by complex and precisely regulated patterns of gene activity. Writing in *Cell*[1], Lowe *et al.* now report similar patterns from the embryos of hemichordates, which are invertebrates but are related to vertebrates and may resemble their ancient ancestors. This observation has implications for our understanding of how an internal brain and spinal cord first arose in vertebrates, and of other changes to their body plan that are controlled by the same genes.

The genes in question are responsible for patterning the body along its anteroposterior axis (that is, from front to back), notably Hox genes and the like. These genes are highly conserved in evolution, with similar expression patterns in animals as anatomically different as insects and vertebrates. Insects and vertebrates are advanced members, respectively, of the two major divisions of animals, protostomes and deuterostomes (Fig. 1, overleaf). Evolutionary biologists have long wanted to know what the last common ancestor of these two groups was really like. Was it segmented, as are both insects and vertebrates? Did it have a condensed, internal nervous system, as both do? Or was it much simpler, so that the similarities between its various descendants are due to evolutionary convergence? These are key questions relating to the nature of the genetic programme that underlies embryonic development and how it constrains evolution.

The enigmatic last common ancestor is now long extinct. But among modern deuterostomes there are surviving groups that are close to it — notably echinoderms, hemichordates and tunicates, the last being the most 'basal' chordates (the grouping to which vertebrates belong; Fig. 1). Enteropneust hemichordates — also known as acorn worms because of their bulbous proboscis — are of special interest. That's because, alone among the basal deuterostomes, they have a simple bilateral body plan (worm-like with a proper front and back end) and a comparatively active mode of life as burrowers in marine sediments. They thus provide a plausible model for the proximate ancestor of chordates. Among the other candidates, echinoderms and tunicates show varying tendencies to adopt a sedentary habit and a reduced or substantially modified (for instance, radial) body plan, which seriously complicates interpretation.

Hemichordates are obscure animals, but