DEVELOPMENTAL BIOLOGY

A brainy background

The vertebrate brain is so complex that tracing its origins among invertebrates is problematic. It must have evolutionary roots somewhere, but where? On page 289 of this issue, Pani *et al.* point the way with their finding that acorn worms have gene-expression signatures very similar to those that direct vertebrate brain development (A. M. Pani *et al. Nature* **483,** 289–294; 2012).

The closest relatives of vertebrates are the urochordates (tunicates, or sea squirts) and cephalochordates (the superficially fish-like lancelet). More distant on the evolutionary tree lie the hemichordates, which include acorn worms such as *Saccoglossus kowalevskii* (pictured), and the echinoderms (including starfish and sea urchins). Together, these groups comprise the deuterostomes, among which the elaborate structural and genomic innovations of vertebrates stand out rather like a cuckoo chick in a nest of willow warblers.

One such feature is the signalling centres — physical regions of a developing embryo in which a specific set of secreted proteins drives the formation of a particular body section. These centres are present in the vertebrate neuroectoderm, an embryonic tissue that gives rise to the brain and nervous system. They are modified or completely absent in tunicates and lancelets, suggesting that many aspects of brain development are unique to vertebrates and arose *de novo* in the vertebrate lineage.

Pani and colleagues' data contradict this theory. They show that a gene-expression program similar to that in three vertebrate neuroectodermal signalling centres is also present in *S. kowalevskii*. Although acorn worms do not have anything like a brain, Pani *et al.* show that these genetic programs are used to pattern (direct the development of) the ectoderm of the embryonic animal. The genes expressed are equivalent to those found in vertebrates, and they are deployed at similar times and places in vertebrate and acorn-worm embryos.

A. M. PANI

The researchers propose that these signalling centres were part of an ancient gene-regulation 'scaffold' that was present in the common ancestor of all deuterostomes, and that was retained in hemichordates and vertebrates but lost in the evolutionary branches that formed lancelets and urochordates. Such an idea implies that the common ancestor was unexpectedly complicated. This does not mean that it had a complex brain, but that the genetic programs that were eventually modified for use in patterning the vertebrate brain already existed in an ancestral creature that lived perhaps more than 600 million years ago. **Henry Gee**

HDDs provide the highest-capacity solutions, with an unbeatable cost per bit. But they are slow and prone to failure when shocked, causing the loss of documents, data or holiday pictures. Solid-state memories such as Flash, which are ubiquitous in memory sticks and memory cards for cameras, are faster and more robust than HDDs. However, they cannot match the cost per bit and maximum storage capacity of HDDs. But they are well suited to mobile electronic devices, and the consensus is that most future data-storage solutions will be based on solid-state memories.

The question is how to increase storage density and reduce the cost of solid-state memories while maintaining their good performance (fast data-access and write times, low power consumption and high endurance). Following the advice of physicist Richard Feynman, researchers have for decades exploited the "room at the bottom" — that is, they have tried to reduce the size of memory cells. Impressive progress in nanometre-scale lithography has allowed a marked reduction in the size of a memory cell. So today, the smallest commercial Flash memory cell[4] has a lateral size of about 80 nanometres.

To further reduce the size of memory cells, problems related to charge leakage, which causes undesired data erasure, and general reliability issues must be solved. This is proving more challenging than ever as cells reduce in size. One solution is to increase storage density not by using fine-pitch lithography but by piling up two-dimensional arrays of memory cells and creating three-dimensional structures, thereby exploiting the 'room at the top'. The practical implementation is, however, extremely difficult in terms of circuitry, which prevents the pile-up of more than a few layers.

In their study, Lee *et al.*[3] propose another method of data storage that exploits 'the room inside' the memory cell itself to store more than just one bit of information. Rather than Flash, the authors address ferroelectric random access memories (FERAMs), which, along with phase-change and magnetic memories, are an alternative type of non-volatile random-access-memory technology[5]. In a FERAM cell, a bit of information (a '1' or '0' logic state) is usually stored in the direction (up or down) of the polarization of a ferroelectric material — one that can retain a permanent electric dipole in the absence of an electric field (Fig. 1a). The polarization of a ferroelectric is the sum of the electric dipoles present in each unit cell of the material. Its direction can be switched by applying a voltage, just as the magnetization in a ferromagnet (a material that maintains a magnetic dipole in the absence of a magnetic field) can be reversed with a magnetic field.

Rather than just relying on the direction of the polarization to store information in a FERAM cell, Lee and colleagues make the best of the physical mechanism at the heart of a memory operation by taking advantage of the structure of domains of different polarization orientation in the ferroelectric material. When a voltage is applied to reverse a ferroelectric's polarization, it usually does not reverse all of the material's constituent electric dipoles homogeneously. Instead, small regions (the domains), each with their own polarization, nucleate and then progressively expand. Depending on the voltage value, or the time during which it is applied, configurations — in which up and down domains coexist — can be stabilized. The net polarization is the sum of the up and down domains, and thus intermediate states of net polarization may be used to store information. These intermediate states define a multilevel memory element.

However, owing to the stochastic nature of ferroelectric polarization switching, controlling the up- and down-domain fractions by this voltage-based procedure creates poorly defined final intermediate polarization states. Lee *et al.*[3] show that this poor definition can be greatly diminished by limiting the electrical current that appears in the ferroelectric when its polarization starts to be reversed by the applied voltage. Thus, complete polarization reversal is hampered, and the ferroelectric is left in a multidomain configuration. In this way, the authors were able to write eight well-defined logic states (000, 001, 010, 011, 100, 101, 110 and 111; Fig. 1b), converting a one-bit conventional FERAM memory element into a three-bit one. Although the main results were obtained on single-crystalline ferroelectric materials, they also show that the approach is applicable to polycrystalline films, which are typically used in commercial FERAMs.