followed a polar segment (a metal–ligand complex), repeated many times over.

In the solid state, the polymer chains underwent phase separation — they folded in such a way as to form some domains that were rich in hydrocarbon segments and others that were rich in metal–ligand complexes. The combination of long-chain polymers and phase separation gave rise to a physically crosslinked network, a molecular architecture that makes the material tough.

The molecular characteristics of Burnworth and colleagues' polymers were ideally set for localized healing driven by ultraviolet radiation. First, the polymers undergo heat-induced depolymerization, presumably because the equilibrium between polymerized and non-polymerized material favours the latter at higher temperatures. Second, the metal–ligand complexes absorb and are excited by ultraviolet light, with the energy involved being efficiently converted to heat as the excited complexes return to their ground states. So, when the authors shone ultraviolet light at damaged films of the polymers, photothermal healing occurred because the light was converted into heat, which then caused the materials to depolymerize, liquefy and seal up cuts in the film (Fig.1).

Although supramolecular approaches to intrinsic healing hold great promise, the synthesis of a strong, stiff polymer with autonomous healing properties remains a key research challenge. In current state-of-the-art supramolecular polymers, healing does not occur automatically, and energy in the form of light or heat must be supplied while the metal–ligand bonds are still able to re-form. Burnworth and colleagues' work does not specifically address these problems, but it does provide exciting new opportunities. Because different metal–ligand complexes absorb light at different wavelengths, it should be possible to tune the wavelength at which materials heal simply by changing the complexes. This in turn offers the prospect of smart, force-sensitive polymers that change colour when damaged, with the colour being matched to the wavelength of light that triggers healing; irradiation with that light would thus cause localized healing only at the damaged spots. ■

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EVOLUTIONARY BIOLOGY

Light sense

Evidence that a larval brachiopod has ciliary photoreceptors that are directionally selective, and therefore may function as eyes, bears on an enduring puzzle about photoreceptor evolution in animals.

DANIEL OSORIO

Brachiopods are bivalved marine animals that superficially resemble molluscs. They are an ancient lineage, and the genus *Lingula,* which appeared 400 million years ago, still thrives. It is a pleasure of modern biology that the understanding of cellular processes built on a few model organisms is now extending to groups such as brachiopods that hitherto were scarcely known in the laboratory. Often, the richer view of evolutionary variation that emerges yields insight into how physiological mechanisms are adapted to biological needs.

An intriguing example now comes in a paper by Passamaneck *et al.* in *EvoDevo*[1], describing studies of the planktonic larva of a brachiopod named *Terebratalia* (Fig. 1). They find that the larva violates a distinction between the type of visual photoreceptor that is used by chordates (including vertebrates such as ourselves) and that used by protostomes (such as arthropods, annelids, molluscs — and brachiopods)[2,3].

Animals have two kinds of photoreceptor cells that use rhodopsin photopigments: rhabdomeric and ciliary. In each case, light activates rhodopsin, but the subsequent stages of phototransduction are quite different. One consequence is that in rhabdomeric receptors light causes cation channels to open in the photoreceptor cell membrane, thereby depolarizing the cell, whereas in ciliary receptors light hyperpolarizes the cell by closing these channels.

The common ancestor of extant bilaterally symmetrical animals had both ciliary and rhabdomeric photoreceptors, and they continue to coexist in living phyla, including chordates, molluscs and annelids[2]. Is the evolutionary persistence of two photoreceptor types indicative of their being adapted to different roles, or simply of developmental conservatism[3]? A particular puzzle is that visual photoreceptors — those present in eyes — are ciliary rods and cones in vertebrates, but rhabdomeric in protostomes. Conversely, vertebrate rhabdomeric receptors have non-visual roles such as regulating circadian rhythms, whereas protostome ciliary receptors have, until now, been thought to be non-visual[2,3].

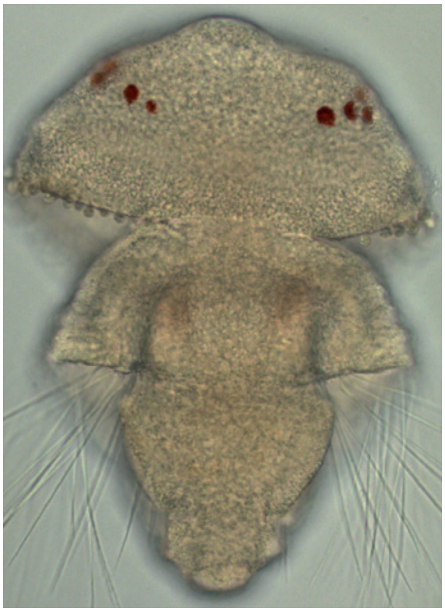

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Figure 1 | The *Terebratalia* larva. The eyespots (red) contain photoreceptors that have cilia and ciliary rhodopsin. On the evidence of Passamaneck and colleagues' anatomical and genetic studies[1], these photoreceptors function as eyes rather than as ambient-light detectors. The larva is about 200 micrometres long.

Brachiopods belong to the superphylum Lophotrochozoa, which includes annelids and molluscs, and so were expected to have rhabdomeric visual photoreceptors[2]. However Passamaneck and co-workers[1] find that the *Terebratalia* larva, although barely 200 micrometres long, has photoreceptors containing cilia and ciliary rhodopsin. There is no sign of a rhabdomeric rhodopsin gene.

The interest here rests on these photoreceptors acting as eyes, rather than as ambient-light detectors. Each of the larva's three to eight pairs of eyespots consists of two photoreceptor cells, one of which also contains screening pigment and the other a lens-like intracellular body.

This economical arrangement should confer directional sensitivity, which is a minimal requirement of vision[4]. Also, axons connect the photoreceptor cells to the nervous system. This direct evidence for eyes is supported by the fact that the eyespots are located where *Terebratalia*'s orthologues of two homeobox genes (*Pax6* and *Otx*), widely associated with eye development, are co-expressed. In behavioural tests carried out by Passamaneck *et al.*[1] the mature larvae did not respond to light, although it would be surprising if they are indeed blind. The authors report that gastrula embryos, an earlier stage of development at which the animals lack eyes but possess rhodopsin, move towards a light source. How this directionality might be achieved is unclear.

The existence of a ciliary visual photoreceptor in the Lophotrochozoa is not unprecedented. In addition to rhabdomeric eyes, some molluscs, including scallops, have ciliary detectors that initiate shell closure in response to shadows warning of potential predators[2,3]. Such instances of ciliary vision in a predominantly rhabdomeric lineage suggest that natural selection can vary the choice of photoreceptor according to need, and hence that each type has particular advantages.

Ciliary and rhabdomeric phototransduction mechanisms are well studied, and have fundamental differences. For example, the ciliary intracellular signalling pathway uses cyclic nucleotides, whereas the rhabdomeric receptor pathway is based on phospholipase C and calcium ions[2]. But the significance of those differences is not obvious[3]. Insects have rhabdomeric receptors and vertebrates have ciliary receptors, but both have excellent vision. Comparisons of vertebrate and invertebrate eyes usually emphasize physical limitations to light sensing, and imply that the performance of their phototransduction mechanisms is similar; for example, that at low light intensities photoreceptors are near-optimal photon counters.

In this context, the work by Passamaneck *et al.*[1] complements a review by Fain *et al.*[3] of differences in photoreceptor performance. The authors[3] argue that, in bright light, ciliary receptors are superior to rhabdomeric receptors because they consume less energy and suffer less from variation in response time-course — which reduces signal reliability. Also, a higher photopigment density in ciliary receptors enhances their sensitivity. Rhabdomeric receptors, however, function over the huge intensity range from starlight to bright sun, whereas the ciliary mechanism has to trade off response speed against the rate of spontaneous photopigment activation in the absence of light[5]. This spontaneous activation, or dark noise, is equivalent to a constant veiling light, which, in cone photoreceptors, overwhelms vision at low intensities but is insignificant in daylight.

To overcome this problem, vertebrates have a duplex retina of rods and cones. Low spontaneous activity allows rods to signal detection of a single photon, but they suffer from slow responses and take many minutes to recover from an effect known as bleaching, which leaves them blind in daylight. Vertebrate cones have fast responses, but dark noise makes them useless at night. Fain *et al.*[3] suggest that the ancestral chordate had a cone-like ciliary photoreceptor and was active in bright light. The acquisition of separate rods and cones, perhaps following a genome duplication, then allowed early vertebrates to see over as wide a range of light levels as the early protostomes that used the rhabdomeric system for vision.

Taking the work of Passamaneck *et al.*[1] further, one line of study will be to find out whether brachiopod photoreceptors are rod- or cone-like, or indeed have novel properties. Also, little is known about how the planktonic *Terebratalia* larvae live, beyond the facts that they cannot feed and have to find a site to settle. Interestingly, the sessile adults occupy a great range of depths, whereas the larvae's possession of ciliary receptors perhaps implies that they inhabit shallow, sunlit waters. ■

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ATOMIC PHYSICS

A route to quantum magnetism

The trend towards using ultracold atoms as simulators of condensed-matter and many-body phenomena is gaining momentum. These systems can now be used to simulate quantum magnetism. SEE ARTICLE P.307

IAN B. SPIELMAN

At nanokelvin temperatures — 100 billion times closer to absolute zero than room temperature — ultracold atoms are the coldest stuff in the known Universe. At such low temperatures, these quantum gases, each consisting of hundreds to hundreds of millions of atoms, are quintessential quantum many-body systems. Unlike their more conventional solid-state cousins, nearly every property of quantum gases can be controlled[1] in the laboratory with unprecedented flexibility and exquisite precision*.

On page 307 of this issue, Simon *et al.*[2] create one-dimensional chains of ultracold rubidium-87 atoms that behave as if strong magnetic interactions were present[3]. Their novel technique encodes the magnetic properties into the configuration, or geometry, of the atoms in each chain instead of the atoms' quantum mechanical spins as is usually the case in magnetic systems. This increases, by more than a factor of ten, the temperature at which magnetic ordering takes place (when the spatial pattern of spins becomes ordered rather than random), finally allowing quantum magnetism to be studied using ultracold atoms.

Understanding the properties of many-particle interacting systems is a crucial component of modern science. How do interactions between relatively simple components give rise to complex behaviour? How does consciousness emerge from a collection of neurons? How is the large-scale Universe organized? Why do electrons superconduct in some materials and give rise to magnetism in others? Each of these questions involves the emergence of macroscopic properties that are qualitatively distinct from the properties of the individual components.

In physics, we are interested in understanding and classifying the generic ways in which such macroscopic phenomena emerge, linking the microscopic properties of the components (including their environment) to the macroscale. This is usually the domain of condensed-matter physics, in which innumerable interacting electrons in materials give rise to complex phenomena such as superconductivity, the quantum Hall effect and magnetic ordering. Ultracold atoms provide a unique system in which to study many-body physics because the components and their environment are simple and can be nearly perfectly controlled. Indeed, many-body phenomena studied using ultracold atoms have been subjected to unprecedented quantitative comparison with many-body theories. Examples of this

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*This article and the paper under discussion[2] were published online on 13 April 2011.