



Nick Lane

Darwin and the evolution of the eye

To celebrate the sesquicentennial of *The Origin of Species*, Nick Lane takes a look at what Charles Darwin did for the eye, and what he would love to know about eyes if he were still alive today

WHAT use is half an eye? No sentence is more closely linked with Darwin's doubters than that; and none is more likely to be trotted out by the genuinely perplexed, those who accept that the eye evolved but can't imagine how. And Richard Dawkins's truculent riposte – "half an eye is precisely one per cent better than 49 per cent of an eye" – doesn't help those who can't picture half an eye.

Ophthalmologists, of course, know all about half an eye – either the back half or the front. It has always amazed me how little cataract and refractive surgeons really need to talk to retinal specialists or vice versa, even if *EuroTimes* now caters for both. And anyone reading this who prefers to keep the old boundaries alive can take some comfort in evolution, which backs the old split.

There's no better illustration of how useful half an eye can be than the 'eyeless' rift shrimp *Rimicaris exoculata*. Swarming in hordes in the black depths of the ocean abyss, on ledges beneath the black smoker vents, the supposedly blind shrimp have a pair of naked retinas on their backs (See image above).

Discovered by Cindy Van Dover, who now heads the Duke Marine Laboratory, these naked retinas are packed with invertebrate rhodopsins (very similar to melanopsin, responsible for regulating circadian rhythms in human retinal ganglion cells). It soon transpired that other vent species, from shrimp to crabs, also sport naked retinas.

Many suspected that the naked retinas are some form of degenerate organ, not actually used for sight, until a succession of larvae were discovered, all of which turned out to have quite normal eyes. These disappear during development, to be replaced by naked retinas sensitive to green light at around 500 nm.

That was another mystery, as the hot vents glow faintly red, but not detectably green. NASA intervened with a probe called ALISS (Ambient Light Imaging and Spectral System), which did detect a small spectral peak of green light in the vent wonderland. It might be generated by bubbles or crystals crushed instantaneously by the huge pressure in the abyss, they say.

Whatever its cause, the faint green glow is enough to power photosynthesis in some bacteria; and although we can't see it with the naked eye, the distinguished neurobiologist Mike Land, at the University of Sussex, has calculated that the naked retinas of 'blind' shrimp are some seven million times more sensitive to photons than the shrimp's own larval eyes.

Presumably, detecting the faint glow of the vents falling on their backs makes the difference between life and death, whether by drifting away from the vents, or baking in them. Half an eye is better than a whole eye when sensitivity matters more than resolution to the nearest hemisphere. And because the

lens, cornea and all the other accoutrements of eyes just get in the way of photons, they're simply stripped away.

Mechanical contrivances

A naked retina is a sexier name for a light-sensitive spot, which was Darwin's own starting point for evolving the eye. He is often quoted deliberately out of context, even by scientists seeking to solve Darwin's 'mystery', as saying, "to suppose that the eye evolved by natural selection seems, I freely confess, absurd in the highest possible degree."

With the benefit of hindsight, that was an unfortunate rhetorical flourish. In the very next sentence he went on to say, "Though insuperable to our imagination, the difficulty can hardly be considered real."

Darwin argued that the eye could evolve, so long as the three conditions of natural selection are met. First, eyesight should vary between individuals. Second, these variations should be heritable. And third, they should make some difference to survival. Even in Darwin's day, it was plain that all three conditions are met in full. But that didn't make the actual succession of steps any more superable to the imagination.

Then about a decade ago Suzanne Pelger and Dan-Eric Nilsson, at Lund University, Sweden, modelled a realistic sequence of steps beginning with a light-sensitive spot and ending with a simple camera eye, complete with a lens. Each step was a conservative estimate – a recess in the sheet, a slight deepening into a pit, the first swelling of a lens and so on.

The surprise was that fewer than 400,000 tiny steps are needed to get from a light-sensitive spot to a fully functional eye, albeit one lacking in optional extras like accommodation.

If each step (limited to a one per cent change in an existing structure) were to take place in a single generation, and each generation lived for a year, then an eye could evolve in less than half a million years.

And that helps to make sense of the abrupt appearance of animals in the fossil record, around 550 million years ago – the so-called Cambrian explosion, whose speed had troubled Darwin himself. After aeons of emptiness, large animals like trilobites burst into the fossil record in a couple of million years, and the very first trilobites already had eyes, as did other animals in the early Cambrian period.

Oxford biologist Andrew Parker has argued that the fossil record did not lie – eyes really did evolve that fast. The sudden appearance of eyes, he says, transformed relationships between predator and prey. The ensuing arms race gave rise to the hard shells wielded by the strange Cambrian creatures, and that in turn made them more likely to fossilise.

Others are less convinced, and point to the difficulties involved in growing a functional lens from scratch. The trilobites are a case in point: their lenses were formed not from crystallin proteins but from crystals of calcite, clear rhombs with specific optical properties. The fact that trilobites fell extinct in the Permian extinction, 250 million years ago, makes it hard to know how they grew such crystals.

Until the discovery of crystal lenses in brittlestars, that is. In 2001, Joanna Aizenberg and her colleagues, then at Bell Labs, showed that the spiny calcite skeleton of brittlestar *Ophicoma wendtii* forms an array of calcite knobs on its arms resembling trilobite lenses. Each knob has light-sensitive neurons underlying it; and this optical system helps the brittlestar scuttle away at the first sign of danger.

Similar calcite lenses can be seeded *in vitro* by crystallisation of a calcium carbonate solution onto proteins with acidic side-chains, even those found in mollusc shells, which certainly play no role in sight. Each crystal is a perfect rhomb, with its optical 'c-axis' pointing directly up. No magic involved: just the spontaneous reaction of any acidic protein in a saturated mineral solution, pressed into service by natural selection.

This theme of opportunism is rife with lenses. Numerous other animals have evolved crystal lenses, typically composed of organic crystals like isoxanthopterin, cysteine or guanine (the latter more usually known as a base in DNA). Indeed guanine crystals are found in fish scales, giving them their silvery lustre and are added to cosmetics for the same reason (they also lend their name to guano, the dried excrement of birds and bats). Again, a naturally forming crystal was simply pressed into service.

Even bits of the cell have been enlisted in this way. My own favourite example is the tiny parasitic flatworm *Entobdella soleae*, which has a lens formed from mitochondria fused together. Other flatworms don't even bother to fuse their mitochondria – a cluster of quite ordinary cellular components apparently bends light well enough to serve some advantage.

But the best example of opportunism is surely the crystallins of the vertebrate lens. Over several decades Joram Piatigorsky, at the National Eye Institute, has shown that vertebrate crystallins arose by what he calls



Rimicaris exoculata (copyright P. Briand-Iffremer, France)

'gene sharing' and have no inherent optical properties.

"The diverse lens crystallins comprise a variety of unrelated multifunctional proteins serving refractive functions in the lens and nonoptical functions, often enzymatic or stress protective functions, in other tissues," he says.

The α -crystallins, for example, are stress-inducible small heat-shock proteins, discovered in *Drosophila* and since found in many human tissues.

The vertebrate crystallins are united not by common properties or descent, but by equivalent changes in their regulatory sequences, specifically the cis-control elements of their promoter and enhancer regions.

"A change in the molecular function of a protein by a change in the regulation of its gene means that gene duplication is not a prerequisite for functional innovation as was thought for many years," Piatigorsky notes.

A fine example of how the crystallins were first recruited is found in the brain of the larval sea squirt *Ciona intestinalis*. Literally a pillar of intestines, the adult sea squirt is famous for anchoring itself to a rock and then reabsorbing its own brain. But the larvae are tadpole-like creatures, betraying the squirt as an early chordate that branched away from the vertebrates before the origin of the lens.

In the last few years, Sebastian Shimeld and his colleagues at Oxford have shown that despite lacking a lens, *C. intestinalis* larvae have bona fide $\beta\gamma$ -crystallins tucked away in their brains (specifically the palps and otolith, pigmented cells in the light-sensing ocellus). What's more, the crystallin gene is under regulatory control of the same genes responsible for lens development in vertebrates, including Pax-6.

As Shimeld put it, "The evolutionary origin of the lens was based on co-option of pre-existing regulatory circuits controlling the expression of a key structural gene in a primitive light-sensing system."

Grabbing proteins that already existed, in other words.

A surprising green ancestor

The riot of opportunism displayed in the evolution of the lens is curiously counterbalanced by the deep evolutionary conservation of the opsins, along with their regulatory framework.

All sighted vertebrates and invertebrates share similar opsins, which bind retinal and clearly derive from a common ancestor.

What came as a big surprise, back in the 1990s, was Walter Gehring's seminal discovery that the same master gene, Pax-6, controls eye development in both mice and *Drosophila*.

He proved it by expressing the mouse gene in *Drosophila*, which erupted with diminutive eyes on its legs, antennae and elsewhere.

Gehring argued that while rhodopsin is subject to structural constraints, which might force convergent evolution, the same is not true of the regulatory context, which is little more than a historical quirk. If the eye evolved repeatedly (and Ernst Mayr had totalled at least 40 occasions), that regulation

really ought to have been different each time. It wasn't.

Gehring's claim that the primordial eye evolved only once is challenged by the two different types of photosensor cell in vertebrates and invertebrates – the ciliary and rhabdomeric photoreceptors, which show distinct architecture and transduce the light signal by different transduction cascades.

In 2004, however, Detlev Arendt and his colleagues at EMBL in Heidelberg showed that the primitive ragworm *Platynereis*, barely changed since early Cambrian times, possesses both types of photoreceptor – rhabdomeric photoreceptors with r-type opsins in the eye, and ciliary receptors with c-type opsins in the brain (responsible for circadian rhythms).

The find was significant because a worm like *Platynereis* was the ancestor of all bilaterians, which is to say, both arthropods (insects etc) and vertebrates. *Platynereis* is a living fossil, an 'ur-bilaterian'.

The fact that *Platynereis* has both types of photoreceptor implies that arthropods branched in one direction, using rhabdomeric photoreceptors for vision and ciliary photoreceptors for circadian rhythms,

whereas the vertebrates used exactly the same regulatory framework, but switched around their photoreceptor cells.

An ancestor of *Platynereis* presumably possessed some sort of photosensitive neuron, as predicted by Darwin, and later duplicated that photoreceptor, and its opsin, giving rise to rhabdomeric and ciliary cells in the same organism.

The identity of this ancient common ancestor with a single opsin is as yet unclear, but gene sequences may hold the answer.

Unexpectedly, Peter Hegemann and his colleagues at Regensburg University have identified an opsin gene that is a mosaic of both the c-type and r-type opsins: not only do the retinal-binding sequences share similarities with both opsin types, but even the introns are conserved in equivalent positions. It looks very much like an ancestral opsin gene.

The surprise is that this ancestral opsin belongs to a luminously beautiful photosynthetic alga, *Volvox*, which uses it to calibrate light levels for photosynthesis. The algal rhodopsin controls the beating of its cilia, driving the alga towards brighter sunlight.

Hegemann notes that rhodopsins are quite common among algae and protists, and widespread among bacteria and archaea, where bacteriorhodopsins work as light-powered proton pumps in a rudimentary form of photosynthesis.

How on earth an algal rhodopsin ended up in the metazoan line is an unresolved question.

Endosymbiosis is one possible answer, proposed by Gehring. Certainly, some dinoflagellates possess amazing microscopic 'eyes', complete with retina, lens and cornea all packed in the same cell. These tiny eyes apparently derive from degenerate chloroplasts, following an endosymbiotic event.

But perhaps the link between light, sight and photosynthesis should not come as a surprise. It would have delighted Darwin, who could see 'no very great difficulty' in believing that natural selection had converted a cell 'coated with pigment' into a structure "even as perfect as the eye of an eagle."

Nick Lane's new book, *Life Ascending: The Ten Great Inventions of Evolution* (Profile/Norton, 2009) has a chapter on the evolution of the eye.

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