Darwin at the edge of the visible universe

Simon Conway Morris

"Sans teeth, sans eyes, sans taste, sans everything", observes Shakespeare's Jaques bitterly in *As You Like It*. Today, we might bristle with prosthetics that keep our senses ticking along, but unless your job as a fighter pilot or tea specialist depends on 20/20 vision or subtle taste, then for the most part lack of acuity in our senses passes largely unremarked. It was not always so. For much of human history, defects in seeing, hearing or smelling the sabre-tooth tiger had irreversible consequences. One does not have to subscribe to the Rousseauian notion of the 'noble savage' to appreciate the example of the native Tierra del Fuegians Jemmy Button and York Minster—returning to their homeland on the *Beagle*—delighting in pointing out distant ships that none of the English crew could see until a telescope was hoisted to their less acute eyes.

Charles Darwin, of course, opened the door to understanding the evolution of sensory systems, but perhaps there is one aspect of this particular Darwinian mantra that deserves a re-examination. By definition, sensory systems are functional: photons demand eyes, wafting molecules olfactory surfaces, and pressure waves ears. Equally fascinating are those sensory modalities that are entirely alien to human perception: echolocation, electro-communication, infrared sensation and even ultraviolet vision. Unsurprisingly, they have all independently evolved many times, reinforcing the Darwinian concept of adaptation. Yet each also represents a customized, jury-rigged contraption, using whatever happens to be at hand. Think of the multiple co-option of crystallins in eyes; infrared detectors in insects are probably derived from cuticular mechanoreceptors and, more confidently, we can trace the lineage of the electric organs of fish from their musculature.

These sensory devices may be contraptions, but they have nevertheless evolved repeatedly to interpret the limits of the physical universe. As an example, consider the

epitome of Darwinian analysis: the camera-eye. Much has been made, rightly so, of the ease with which it has evolved; whether by co-opting proteins such as opsins and the crystallins, or the unremarkable transition from the simple spot eye in a flatworm to the cryptic intelligence with which the blue-whale views its world. Might there be a less-considered perspective? The shift in refractive indices across the lens corrects almost perfectly for its spherical aberration (Jagger & Sands, 1999), but the retina can also detect single photons. In comparison to the camera eye, the compound version is unavoidably deficient, but this does not prevent some insects flying by starlight. In the re-tellings of the story of how eyes evolve, perhaps we have lost sight of Darwin's somewhat mischievous rumination on the perfection of the eye. His straw-man conceals the fact that not only do eyes evolve, but they might be as near to perfect as they ever will be.

And what about the other senses? The olfactory systems of insects and mammals are startlingly similar, and the former can detect a single molecule. In audition, the sensitivity of the male mosquito antenna is such that it is triggered by an infinitesimal deflection, equivalent to the top of the Eiffel Tower moving less than 1 mm (Göpfert & Robert, 1999). For vertebrates, the sensitivity of the transduction process in the inner ear is close to that of thermal noise (Denk & Webb, 1989). This represents an absolute barrier not only for biology, but also for the eye and nose; a photon or a molecule are the irreducible limits of detection.

This is not to say that all sensory systems are equally acute; the echolocation skills of bats or the sensitivity of snakes to infrared radiation clearly show the extent of sensory capacities and sensitivities. However, in horseshoe bats, the exceptional tuning of the ear to specific frequencies—notably with an acoustic fovea in the cochlea and specific neural organization in the auditory cortex (Neuweiler 1990)—suggests that the

limits of perception are close, or have perhaps been reached in existing lifeforms. Such extraordinarily fine-tuned sensitivities are also found in the infrared apparatus of crotalid snakes, which have facial pits that behave similarly to pinhole camera-eyes, and can detect minute temperature differences (Bakken & Krochmal, 2007).

There is a further insight. Whilst infrared detectors have evolved in many snakes, insects and mammals, the system in the crotalids—and also that found independently in the beetle *Acanthocnemus* (Kreis *et al*, 2005)—is a bolometer: a thin sheet of highly vascularized tissue, suspended in an insulated cavity. Astronomers, as well as others, use analogous systems. Such convergence between evolution and technology is not surprising, and is further exemplified by the similarities between the fibre-optic systems of some siliceous sponge spicules and telecommunications technologies (Aizenberg *et al*, 2004). Biology has reached the edges of the physical universe, but scientific instruments allow us to see deeper, not least into the mysterious world of quantum physics. Without such instruments we would be blind, but we should remember that the way that cognitive processes allow us to understand a universe that is largely beyond our Darwinian senses, remains deeply enigmatic.

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Simon Conway Morris is a professor in the Department of Earth Sciences, University of Cambridge, UK.

E-mail: sc113@cam.ac.uk

EMBO reports (2010) **11**, 898. doi:10.1038/embor.2010.176