Learning Optics in Nature's School

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Introduction

For as long as there has been science, inspiration has been drawn from natural phenomena and structures. However, as branches of science mature, they develop an increasingly rich store of ideas, techniques and technology, and the tendency to search the realm of nature for inspiration diminishes. Optics is certainly one of the oldest branches of science, and many of its practitioners perhaps imagine that most of what could be learnt from nature was learned in the epochs of Newton, Grimaldi, Young and Fresnel. However, with increasing maturity come new tools with which we may look more closely at some of nature's more subtle structures, and discover new things hidden from previous explorers. The emerging field of *optical biomimetics* seeks to examine structures in living systems, to understand how they deliver optical effects, and perhaps, to discover new designs arrived at by evolution which may be applied in technology.

This article aims to present some examples of optical systems in nature from which we may learn new tricks, or present, as interesting examples of old tricks, to students. We believe all practitioners of optics should be interested in optical biomimetics as an emerging subfield which builds bridges to the world of living systems and which illustrates that you don't have to craft in glass.

Mirror, Mirror, Not on the Wall

We all should know the story of Archimedes of Syracuse, called in to use his science to help his city fend off the invasion of a fleet from Rome. He had artisans manufacture great mirrors of metal, with which he set fire to the sails and rigging of the Roman ships, foiling for a time their inevitable conquest.

Much less well known is the South American mirror fish. This ingenious fish is a rather thin, flat sided animal, which engages in optical warfare *a la* Archimedes during its territorial battles. It curves its flank in an attempt to focus ambient light in the eyes of rival fish. The more successful design will deliver a flux capable of stunning the nervous system, and the defeated fish will fall limply out of the lists, leaving Mr. Parabolic in possession of the terrain.

Our collaborator, David McKenzie of the University of Sydney, was one day lunching with colleagues at the Sydney Fish Markets when they noticed, in the display, a local fish with a shiny underbelly and a dull back. From this, there started a discussion of why the fish sought its high reflectance on one side, and also how it achieved it. The why is easily answered: the fish lives at mid-depths, and seeks to be mistaken by predators below it as being part of the reflecting surface of the water which terminates their world above. The predators above it see, with difficulty, only the dull back of the fish.

To answer the how, our colleagues bought a fish, and conducted an electron microscopic examination of the skin on its shiny belly. They discovered that the skin contained a structure consisting of layers of flat guanine crystals with random spacing (McKenzie *et al*, 1995). The guanine provides a higher refractive index than surrounding material, and the layers of crystal each operate like partially reflecting mirrors. If there is a sufficient number of such layers, they will generate a high reflectance. The random spacing means that the high reflectance will not be delivered in a narrow wavelength band, but will be wideband. Further, as the fish grows and the spacing alters, the high reflectance will be preserved.

David McKenzie and colleagues have also taken up a subject initiated by Robert Hooke, who in his book *Micrographia* reported on the lustre of the common silverfish. He observed "the appearance of so many several shells or shields that cover the whole body, every one of these shells are covered or tiled over with a multitude of transparent scales, which, from the multiplicity of their reflecting surfaces, make the whole animal a perfect pearl colour". An electron microscopic examination of silverfish samples (Large *et al*, 2001) in fact showed the scales had a ribbed structure with spacings in the range 1–3 μm, while below the scales there was a complicated multilayer structure, composed of high index layers of chitin (with index around 1.53–1.56) interspersed with low index (around 1.4) layers. The reflectance of the silverfish rises from around 15 percent near 0.4 μm, to just over 20 percent at the end of the visible, reaching a peak over 60 percent at around 1.3 μm. Most of this reflectance is due to the multilayer stack that Hooke didn't see, rather than the scales that he thought were the reason for it. Other multilayer stacks are found in some beetles having a metallic reflectance, but the beetle multilayers have a less complicated chirping than the silverfish layers.

Colour by Chemistry or Physics

Many animals rely on colour to attract mates, to attract lunch, or to signify that they are not a particularly desirable item for a predator's menu. There are two main methods for achieving colour: by chemistry, through the use of pigments, or by physics, through the use of interference or diffractive structures. Animals tend to use pigments where there is plenty of light and energy: pigments tend to photobleach, and so will have to be replaced, which burns up energy. The pigments deliver colour by selective absorptance rather than selective reflectance, and so are not as good in low light environments, where photons have to be handled with somewhat greater care.

The colours arising through interference and diffraction are called structural colours, and are coded into a physical structure within the living system. They have been detected in a range of animals, fish and insects, and those occurring in butterflies have received much recent attention in Exeter (Vukusic et al, 1999) and Sydney (Quantum, April, 2001).

Butterflies use both pigments and structural mechanisms to obtain colour effects. One interesting way to distinguish one from the other is to look at old specimens, such as those in the collection of the Australian Museum. The pigment colours bleach and fade with time, leading to dull specimens, while those relying on structure are not subject to colour loss, and are as bright today as when they were collected. This is an interesting advantage, which may be sufficient to ensure commercial success for those who find a way to generate at low cost patterns of structural, rather than pigmental, colour.

One remarkable fact is that we can look at the fossil record, and in exceptionally well-preserved specimens, such as those from the Burgess Shale in British Columbia, we can see examples of structural colours arising even in long extinct animals. We can also follow, if we are lucky, the evolution of an optical design towards increasing complexity and better functionality in a sequence of fossils. Those who wish to read more of this should consult Andrew Parker's beautiful review article (Parker, 2000), 515 Million Years of Structural Colour.

Aphrodite's Allure

We turn now to a humble sea creature with a splendid name, the sea mouse or *Aphrodita sp*. This lives on the sea bed, from depths of a few metres to a few thousand metres, and is a *Polychaeta* or bristle worm. It is seen in Fig. 1 to be generally dune coloured, to merge in with sandy or muddy bottoms. However, the lower edge of its body carries longer felt or hair, with a beautiful iridescence.

Fig. 1: A sea mouse or *Aphrodita* (note the iridescent felt on the edge of its body). From Sue Daly, *Marine Life of the Channel Islands,* 1998 (with permission).

This iridescence was known to fishermen, and was commented on by Linnaeus, who classified the species in 1758. It intrigued us as to how this animal was able to achieve such brilliant colouration with the limited index contrast of the materials available to it (about 1.54 for the chitin to 1.33, given it lives in water). We were given a spine or thicker bristle from a specimen collected by Andrew Parker at Palm Beach, which had a strong reddish colouration in white light, and subjected it to an electron microscopic examination.

The results in Fig. 2 show that the spine is annular, with a hollow core and a wall punctuated by an amazingly regular array of holes (white) in the biological material chitin (dark). One can view the spine structure as a sequence of interference layers, taking the hole region to have an effective index between that of chitin and sea water, with these equivalent low index layers being separated by chitin. In order to achieve strong colouration (with spectrophotometry revealing spine reflectance close to 100 percent in the red), the relatively weak reflectance resulting from low index differences must be compensated by a large number of layers adding their reflectance coherently. This is the case only if the spacing of the layers of holes is as regular as that shown in Fig.2, much as X-ray multilayer stacks must be of very high regularity.

Fig. 2 An electron microscopic image of a spine of a sea mouse. The wall of the spine contains 88 layers of holes, whose spacing is 0.51 micron.

We view the structure of Fig. 2 as being composed of a stack of diffraction gratings, and we use tools that we have developed (McPhedran *et al*, 1999; 2001, Botten *et al* 2000) to model the reflectance and transmittance of stacks of cylinder gratings of one index embedded in a matrix of another index. In this way we calculate the reflectance of the spine structure for a range of wavelengths, for a given incidence angle of plane waves. The result is shown in Fig. 3, for one of the two principal polarizations (denoted E and H depending on whether the incident wave has its electric or its magnetic field oriented along the holes). Note that, "normal" light is not polarized, so we always have a mixture of the two polarizations.

The optical properties of the sea mouse hairs are then in good accord with the results of rigorous calculations, using as data their measured geometry. Another way of looking at the sea mouse structure, developed to yield high reflectance in a narrow wavelength band, is to regard it as having exploited a photonic band gap.

In this way, it is connected with a currently "hot" area in electromagnetic optics, in which groups all over the world are attempting to create and exploit structures in which light is unable to propagate in certain wavelength ranges, for all angles of incidence and polarizations. These structures would then be the optical analogues of semiconductors, and could be doped by the introduction of appropriate irregularities in their optical properties.

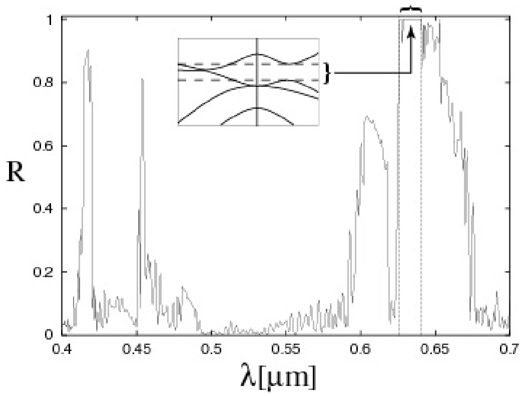

Fig.3 Reflectance of the 88 layer stack of gratings constituting the spine structure of Fig.2, for normally incident radiation, and E polarization. The vertical dashed lines correspond to the band gap in a segment of the photonic band diagram shown in the inset.

Normally, to achieve a bandgap in which propagation is impossible for all directions, the structure has to incorporate high index contrast (around 3 to 1). Nature does not have at its disposal such high index materials for living creatures, and so the sea mouse structure achieves only a partial band gap (shown in Fig. 3), inhibiting propagation for a range of wavelengths in the red, but only for a restricted range of directions and polarizations. Nevertheless, the result is adequate for its purposes: strong reflectance in a narrow band which shifts with angle of incidence, giving the creature its characteristic iridescence, which presumably warns predators it is not particularly good eating.

Conclusions

We have argued that Nature provides a good book for the education of opticists, and that many good design ideas have been arrived at by evolution rather than analysis and computer power. The main example we have cited, the sea mouse, is a spectacular example of nature's micro-engineering, and may well give rise to technological off-shoots, if we can find a way to mimic its tricks in molecular assembly that give rise to the regular structure of Fig. 2. If we could make such layer structures at reasonable cost over large flat areas, the result would be a new technology delivering brilliant, pure and unfading colours.

For those who wish to learn more about the sea mouse, references and colour images may be found at http://www.physics.usyd.edu.au/~nicolae/seamouse.html

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