An introduction to biomimetic photonic design

■ S.M. Luke and P. Vukusic - DOI: 10.1051/epn/2011302
■ College of Engineering, Mathematics and Physical Sciences, University of Exeter, Stocker Road, Exeter EX4 4QL, UK.

Nature uses a large number of optical phenomena to create a vast array of coloured appearances. The brightest colours and most dazzling optical effects are often those which are created through the use of intricate microstructures that manipulate light. Bio-inspired designs are increasingly leading to improvements in diverse arrays of products for which manipulation of light and appearance is important.

The natural world exhibits many examples of efficient design and specialised functionality. Scientists have long sought inspiration from the natural world; biomimetic design is responsible for many everyday products, for example Velcro. Inspired by the minute hooks on the seeds of the burdock plant, Swiss engineer George de Mestral produced a synthetic mimic which has since found a multitude of applications. Optical biomimetics is a research discipline inspired by optical systems found in nature and by the bright appearances that often result from such systems. Colour in nature can be attributed either to wavelength-selective absorption by chemical pigments, to colour from wavelength-selective reflection from micro-scale structure, or a combination of both. Structural colour can offer ultra-brightness and saturation, as well as offering other interesting properties such as iridescence and polarisation-dependant reflection.

Highly saturated colours, such as those found on the blue wings of many *Morpho* butterflies, often result from coherent scattering [1]. This arises when light is scattered from periodically-arranged discrete changes in refractive index. A strongly scattered reflection maximum arises at a given wavelength and therefore with a distinctive colour. The colour depends on the periodicity, the refractive indices of the materials and the angles of illumination and observation.

Multilayer structures that offer such periodicity are common in nature. They are often found in brightly coloured beetle species such as the buprestid *Chrysochroa raja* (shown in figure 1) [2]. In this species a 1.5 μm layer on the wing casing surface contains alternating layers of two materials, each with a thickness of approximately 100 nm. The characteristic reflection from this structure is the bright green colour seen at normal incidence. The reflected colour shifts towards blue at higher incident angles, a feature of the iridescent effect (notice in figure 1 where the outer edges of the wing casings appear blue).

The bright blue of many *Morpho* butterfly wings is the result of a discrete multilayer structure [1]. Each wing is imbricated with a layer of scales which feature prominent structural ridges. A series of lamellae protrude from each ridge giving it 'Christmas tree'-like profile in cross-section (see figure 1). The periodicity of the discrete multilayer and the large number of lamellae result in an intense blue reflection (up to 80%) that can be seen 'from a quarter mile off' [1]. Long-range signalling is the likely function of such colouration.

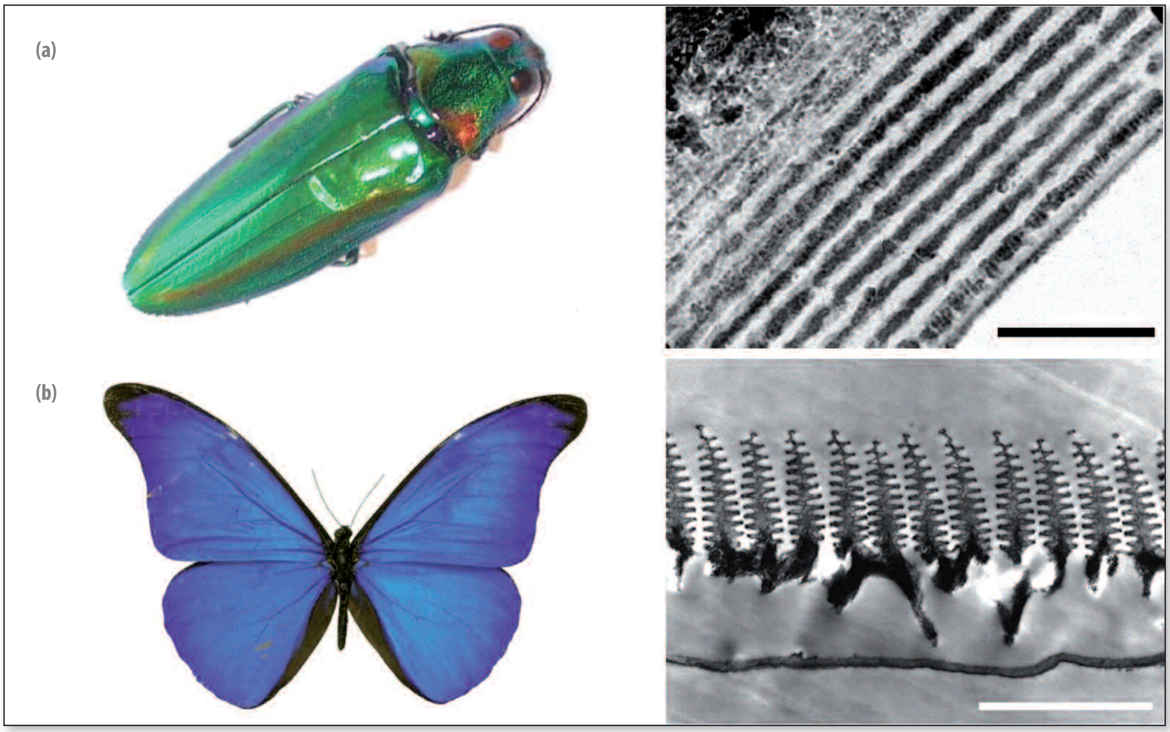
Photonic crystals in nature

The term 'photonic crystal' applies to any ordered sub-wavelength structure that affects the propagation of light, such as the 1D periodic systems described above. The term is more often applied, however, to 3D ordered crystals. The weevil *Eupholus magnificus* is one example of many 3D photonic crystal systems found in nature. *E. magnificus* exhibits a chitin matrix within its scales which is periodically perforated with air holes (figure 2). This 3D structure acts in a similar manner to a 1D structure, a coloured reflection results from coherent scattering from the periodically-arranged scattering centres that make up the crystal [3].

Each scale comprises discrete domains; these are regions where the orientation of the same 3D crystalline structure is changed. The characteristic reflectance from each domain is thus slightly different. As the domain size is below the resolution limit of the human eye, the macroscopically perceived colour is an additive mix of all of the domain colours. Rotation of the viewing angle, therefore, has little effect on the perceived colour; the domained structure creates angle-independent colour [3].

Bright whiteness of highly disordered systems

The highly periodic structures described so far are responsible for bright saturated colours. The converse of this is a highly disordered system which results in bright whiteness. Periodic structures produce relatively saturated colours. Aperiodic structures, however, produce white appearances since all wavelengths are scattered approximately equally. Such disordered systems have been identified both in butterflies (*Pieris rapae*) and in several species of beetle. Both *Cyphochilus* (figure 2) and *Lepidiota stigma* have a coating of white scales which contain a highly disordered filamentary structure [4]. Structural analysis confirms the absence of periodicity and indicates that the system is highly optimised for maximum optical scatter and thus whiteness and brightness. The whiteness of these scales, those of *Cyphochilus* in particular, compares favourably with those measured from many synthetic materials.



◄ **FIG. 1:** Both *Chrysochroa raja* (a) and many species of *Morpho* butterfly (b) derive their bright colours through constructive interference of light reflected from their periodic micro-structured surfaces (as seen in the accompanying structural images). Scale bars (a) 900 nm (b) 1.8 µm. (Beetle image in (a) courtesy of Dr. Joseph Noyes).

Mimicking nature's design - Structurally coloured fabric and cosmetics

Designing and developing applications for optical functions through bio-inspiration has gained momentum in the last decade. Lepidoptera, which display some of the brightest colours, have been at the forefront of this inspiration. The brilliant blue *Morpho* butterfly has provided inspiration for two diverse products. L'Oreal has pioneered bio-optical inspiration in the cosmetics industry. By mimicking the manner in which light interacts with *Morpho* scales, but using synthetic materials to form periodic nanostructures, L'Oreal has created a photonic cosmetic product which contains no chemical pigments (see figure 3).

Morpho species were also arguably the inspiration for a structurally coloured fabric known as *Morphotex* [5]. The fibre contains no dye but produces its colour through coherent scattering. 61 layers of polyester and nylon are laminated together into a multilayer structure. Altering the layer periodicity produces a fibre which is either red, blue, green or violet in colour. The fabric contains no dye, which has both economic and environmental benefits. The structural nature of the colour means that the fabric exhibits unlimited lightfastness. This makes it a desirable product for applications in the fashion industry (see figure 3) and automotive or domestic furnishing textiles.

A further bio-inspired fabric technology which is in development is an 'optical shield' coating, inspired by the *Cyphochilus* structure [6]. The beetle's disordered filamentary structure reflects visible and UV wavelength light with remarkable efficiency. The structure, therefore, acts as an extremely effective and efficient optical 'shield' for visible and UV wavelengths.

The technology for this comprises electro-spun plastic nanofiber webs [6]. Optimum whiteness is achieved with nanofibers that have an average diameter of 250 nm; this is similar to the filament diameters of *Cyphochilus*. In this application it is the optical shielding that the structure offers that is important. Polyurethane (PU) foam is widely used in the clothing industry but suffers from unsightly yellowing upon UV irradiation. These nanofiber web coating layers provide good UV protection and can be sprayed directly onto the PU foam product, thereby simplifying its manufacturing process.

Bio-inspired improvements in paper industry

The paper industry is another example where bio-inspiration is being implemented to improve a technology [7]. In this industry whiteness, brightness and opacity are the key factors when characterising a product. Brightness measurements indicate that the *Cyphochilus* structure is more efficient than conventional clay-based paper coatings. Ultra-high efficiency bio-inspired coatings could conceivably reduce coating material requirements with no detrimental optical effects.

Optimisation of the beetle structure's filling fraction, scattering centre size and spacing appears to underpin its exceptional whiteness. Optimisation of the paper coating layer in a similar manner would see an

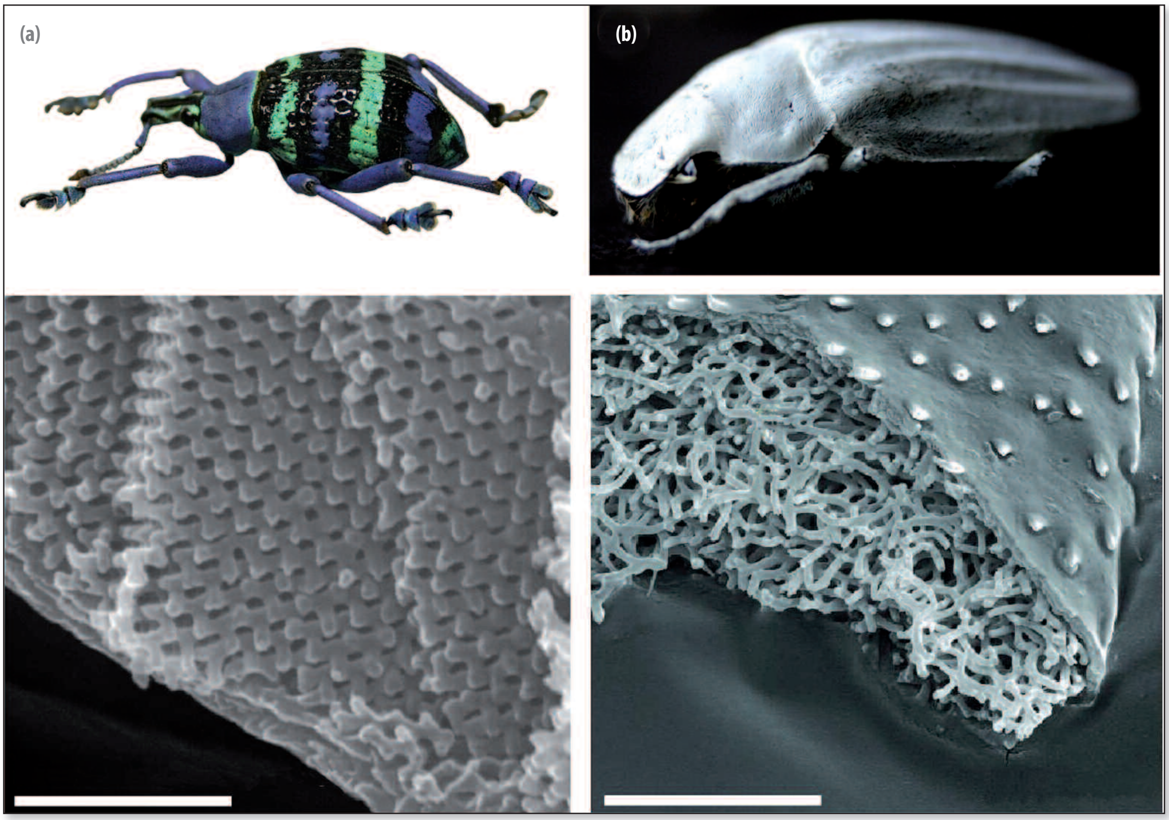


FIG. 2: (a) The bright green coloured stripes of *Eupholus magnificus* result from interference of light reflected from parallel planes in its 3D photonic crystal structure. (b) A highly disordered filamentary structure gives *Cyphochilus* a distinctive bright white appearance. Scale bars: (a) 2 µm (b) 3 µm.

improvement in its whiteness and brightness properties. The paper coating structure consists of air pores, which act as discrete scattering units, within a mineral particle matrix. The air-pore size is intrinsically linked to the mineral particle size and therefore concurrent optimisation of both the air-pore size and spatial density is not possible. A compromise is sought which avoids 'optical crowding', a phenomenon where adjacent scattering centres interact and act as a less efficient composite system. The *Cyphochilus* structure limits this effect by de-coupling the relationship between the fibril and air void sizes.

A multi-mineral blend with a mixture of particle sizes could conceivably achieve a similar de-coupling affect in a paper coating layer, thereby optimising its optical properties. Whilst current mineral coating technologies do not allow accurate replication of the *Cyphochilus* structure, understanding the design that underpins the beetle's optical performance allows mineral design parameters to be mapped in a systematic manner in order to enable optimisation of the coating layer [7].

The Future

Nature provides a wonderful database from which to borrow ideas, concepts and designs. Investigation of natural samples leads to the discovery of ideas and designs which have been optimised for distinct biological functions. Bio-inspired design has already led to innovations in several fields; we have presented here just a few examples of the applications which are under development. The success of products such as *Morphotex* and L'Oreal's photonic cosmetics are prime examples of successful bio-inspired design. We are likely to see many more bio-inspired optical products, devices and technologies in the near future. ■

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(a)

(b)

▶ **FIG. 3:** (a) L'Oreal has developed a range of bio-inspired photonic cosmetics which contain no chemical pigments. (Image courtesy of L'Oreal). (b) *Morphotex* fabric in use in the fashion industry, dress designed by Donna Sgro. (Image courtesy of Donna Sgro / Stephen Reinhardt).