Structural Colours in Biology: Scientific Basis and Bioinspired Technological Applications

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Abstract

Beetles whiter than white, insects with metallic colours and butterflies with coloured wings that seem to shine by themselves, even in low light conditions – structural colours are omnipresent in biology. As opposed to pigment colours, structural colours are caused by the interaction of light with micro- and nanoscopic structural features of the biological material: total reflection, spectral interference, scattering, and, to some extent, polychromatic diffraction, all familiar in reference to inanimate objects, are also encountered among tissues of living forms, most commonly in animals. The structure rather than the material are important for the generation of the colours.
The physical principles of the generation of structural colours will be reviewed, various examples from the animated world will be given and possible applications of biomimetic colours in man-made devices such as humidity sensors and allergy control fabrics (keyword smart colours) will be discussed.

Keywords: biomimetics, structural colours, bioinspiration, structures, nanotechnology

1. Introduction

There are two types of colours (Fig. 1): chemical colours and physical colours. In chemical colours, coloured pigments are the source of the colour. The material itself determines which colour we can see. Physical colours, on the other hand, are generated by the structure of the material. The structures interact with the light, and the colours are generated. For this to be effective, the structures have to be on the range of the wavelength of the light, which means that in the visible range, structures of several nanometers are needed.

The colours are generated via various physical phenomena such as interference or diffraction.

Already in 1704, Sir Isaak Newton, the English physicist, mathematician, astronomer, natural philosopher, alchemist, and theologian, connected in his work "Opticks" [1] iridescent colours (i.e., colours who change dependent on the angle of viewing) with optical interference:

'The finely colour'd feathers of some birds, and particularly those of the peacocks' tail, do in the very same part of the feather appear of several colours in several positions of the eye, after the very same manner that thin plates were found to do.'

(Isaac Newton, 1704, Optiks)

In 1920, the French chemical engineers Clyde W. Mason investigated bird feathers with the optical microscope and reported structural elements that are responsible for the colouration [2]. Today, we know about manifold colour generating structures in animals and plants.

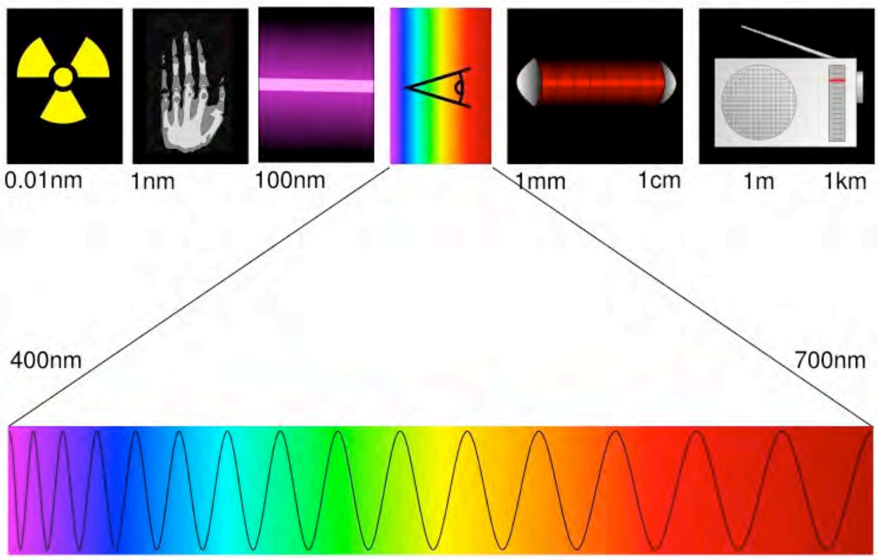

Fig. 1. The visible electromagnetic spectrum.
Source: http://electricalfun.net/visible_spectrum.jpg

One example for a system leading to structural colours is a thin film as we have it in soap bubbles (Fig. 2) and oil stains on the street. The nice colours are generated via positive interference of the light that is reflected on the surface of the layer and the light that is transmitted through the layer and reflected at the back of the layer. For positive interference, the thin layer has to be just a couple of hundreds of nanometers thin. The colours in soap bubbles change since the bubble gets less thick with time. Going through the whole spectrum of the rainbow, the thin soap films exhibits all kinds of colours, and when it is finally too thin for positive interference in the visible range, just before bursting, the soap bubble appears perfectly black. This is too short to be seen with the naked eye, but high-speed cameras can catch this “black moment” just before bursting.

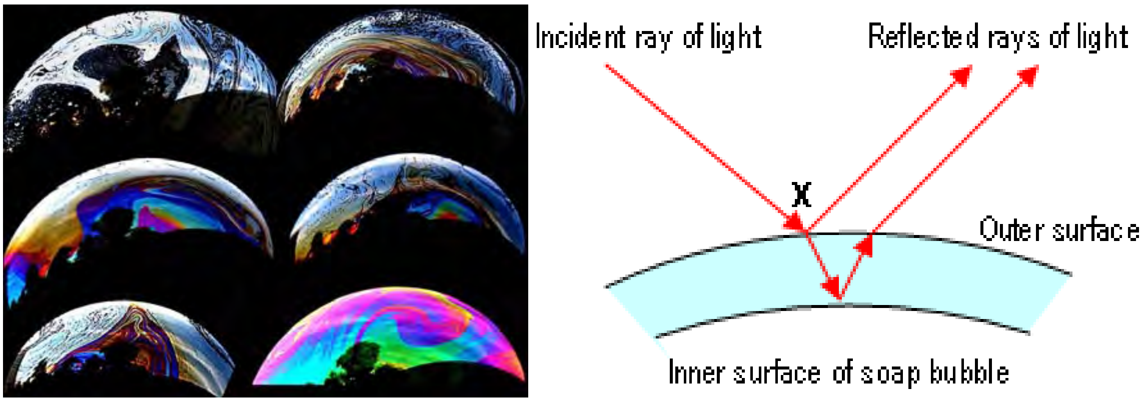

Fig. 2. Soap bubbles and the physics of their colours. Source: http://en.wikipedia.org/wiki/File:Soap_bubbles_2.jpg and http://en.wikipedia.org/wiki/File:Reflection_from_a_bubble1.png

In multilayer systems (Fig. 3) the wavelength (and therefore the colour) of the primary peak can be calculated from the indices of refraction of the two materials (n_1, n_2) and the respective thickness of the layers (d_1, d_2):

$$\lambda = 2\,(n_1 d_1 + n_2 d_2) \qquad (1).$$

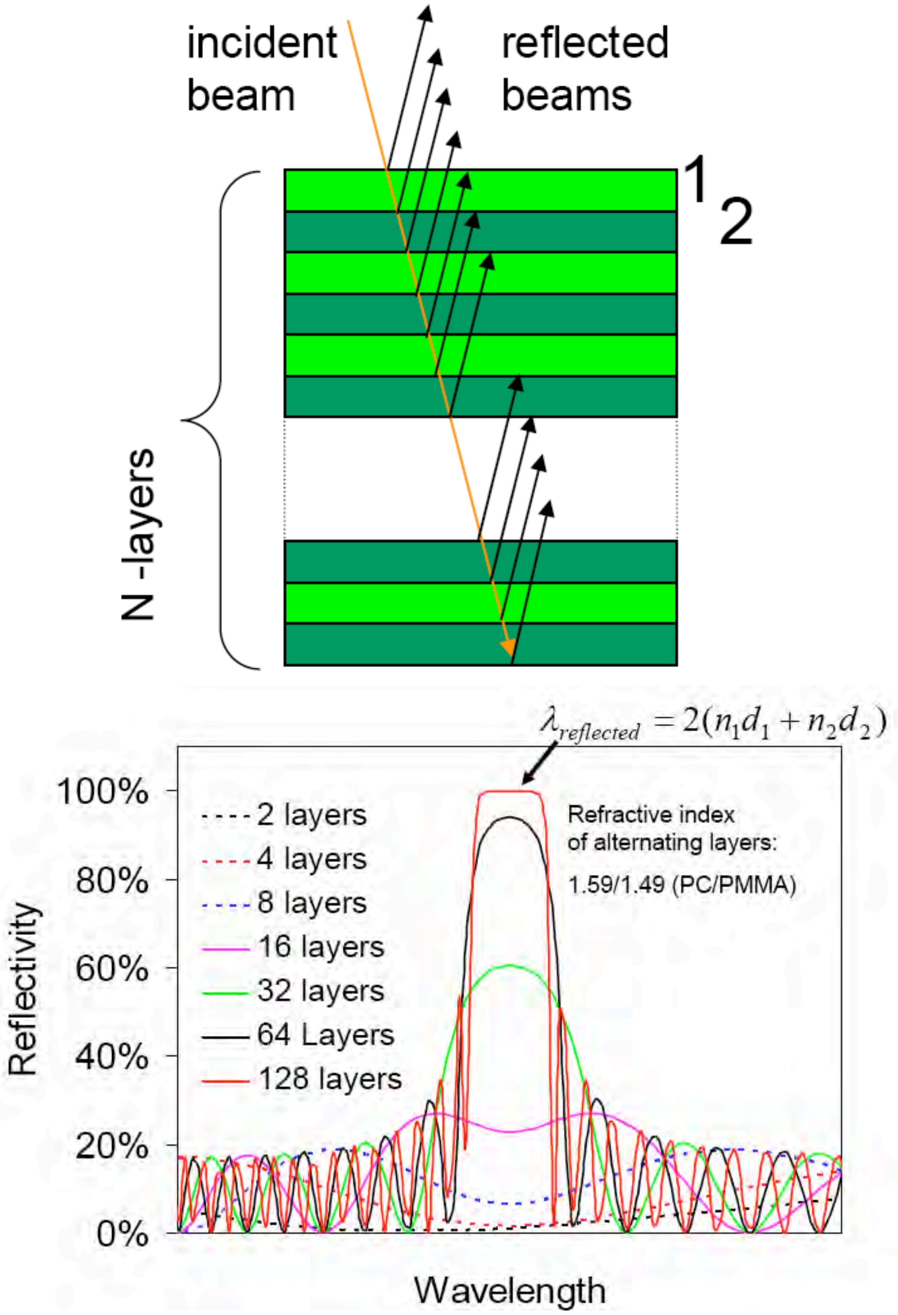

Fig. 3. Interference in a multilayer system. The coefficient of reflection for a given wavelength range increases with the number of layers.

The more layers the multilayer system has, the larger is the coefficient of reflexion and the more brilliant are the colours. An example from nature, where such a system is responsible for the generation of colours is the Hercules beetle *Dynastes hercules*. This beetle is named after Hercules, the mythical Greek demigod Heracles, son of Zeus and the mortal Alcmena, who is famous for his strength: it can carry 850 times its own weight! This beetle reversibly changes its colour between green and black. It lives in the rainforest, and is with its green colour well protected when the weather is fine. During the rain, when humidity is higher and it is darker, the colour of the beetle is black, and again, he is well protected. In March 2008 the New

Journal of Physics published an article that explains this colour change: with scanning electron microscopes and spectrometers the authors showed that at high humidity the layers of a thin layer system on the beetle surface swell, and therefore no interference phenomena occur anymore (too large layer thickness!) – the beetle appears black [3].

Besides interference phenomena, scattering phenomena (Fig. 4) are important physical reasons for the generation of colours. Coherent scattering on ordered structures of proper size yields colours. Incoherent scattering can cause a brilliant white (see below).

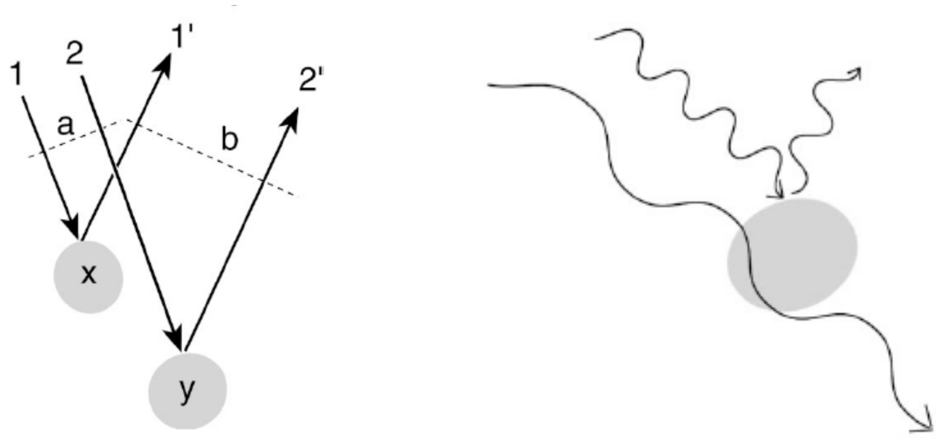

Fig. 4. Coherent (left) and incoherent (right) scattering.

In the inanimate nature we find colour generation at regular structures via coherent scattering for example in the precious opal. This gemstone is a natural photonic crystal, with a regular array of amorphous silicon dioxide spheres (Fig. 5).

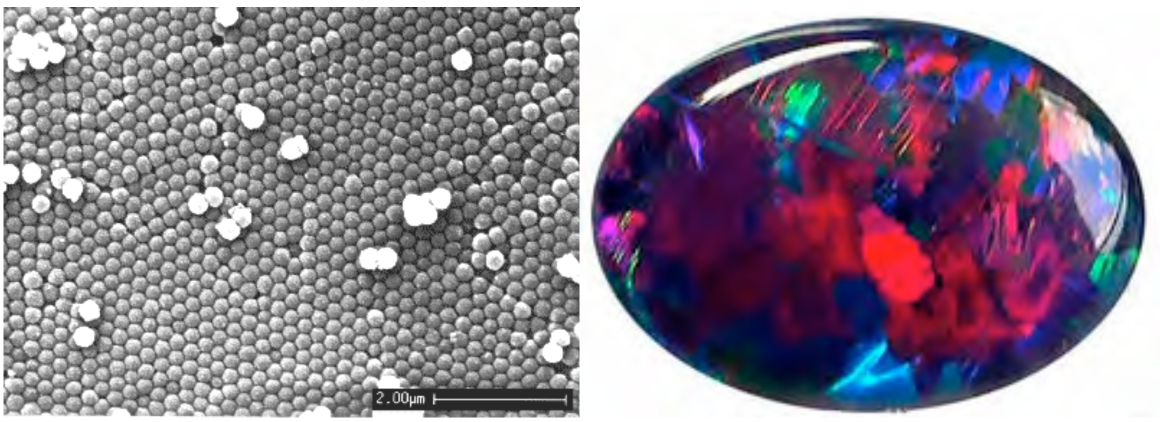

Fig. 5. Left: Scanning electron microscope image of an opal. Scale bar: 2 μm – this is equivalent to 1/50th of the diameter of a human hair! Right: Precious opal. Source: http://minerals.caltech.edu/Mineral_Pictures/Opal_gem.gif, http://www.carat-online.at/edelsteine/opale/images/opal_3.jpg.

2. Examples from Nature

2.1. Beetles whiter than white

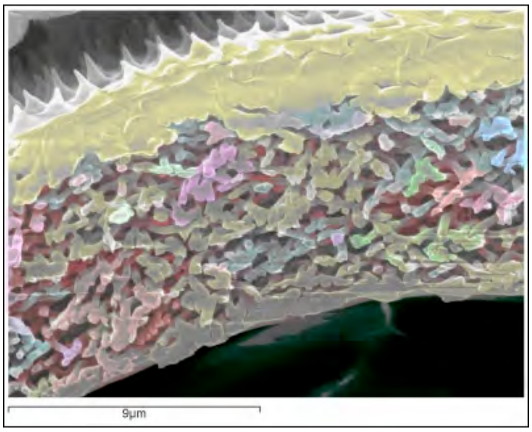

Fig. 6. Left: The tropical beetle *Cyphochilus* from South East Asia. Right: The random protein filament arrangement responsible for the brilliant white. Sources: http://ima.dada.net/image/medium/1480533.jpg, http://physicsworld.com/cws/article/news/26846

The South East Asian beetle *Cyphochilus* has scales with a thickness of about 5 micrometers. These scales contain a network of randomly oriented protein fibers with diameters of about 250 nm. Such fibers strongly scatter all visible wavelengths; this is the physical basis for the intense white (Fig. 6) of the beetle [4].

The scales of the beetle are about two orders of magnitude thinner than man-made materials of equivalent whiteness. Possible technological applications of such structures are with ultrathin reflectors, novel light sources, light emitting diodes, writing paper, teeth replacements and white paint.

2.2. Cabbage white

In Nature during evolution various structures have developed that produce white. The white colour of the cabbage white butterfly (Fig. 7) is generated by small structures that are ornamented with elongated beads (Fig. 7 right, Fig. 8). These elongated beads scatter the incident light in all possible directions, resulting in white appearance of the butterfly.

The lower part of the left trace in Figure 8 shows how the little black dot on the cabbage white wing gets its black: the base structure is the same, but the elongates beads are missing, and therefore light is not reflected or scattered, but absorbed – the little dot appears black (although it is made from the same material as the surrounding white).

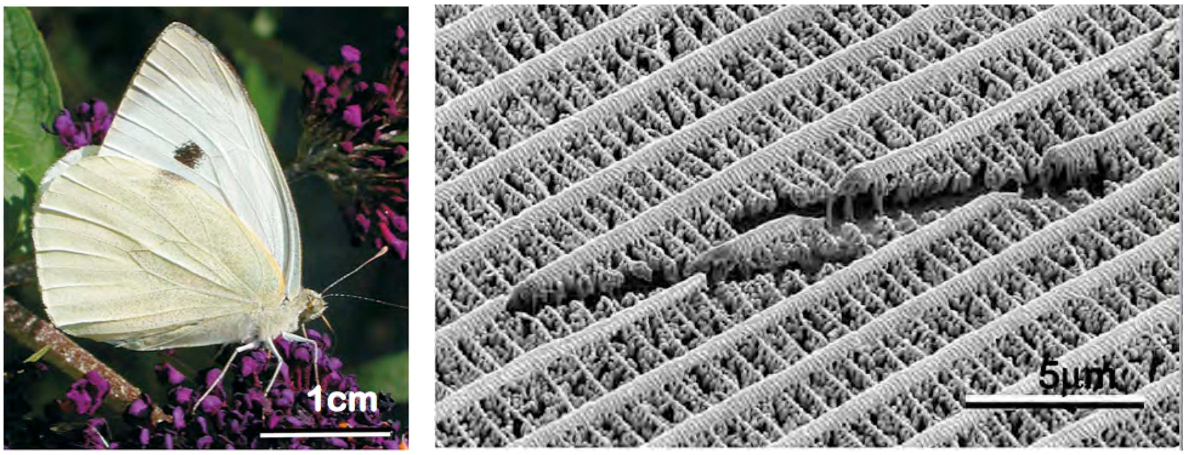

Fig. 7. Left: A cabbage white butterfly. Right: Microstructures from the cabbage white butterfly wing. On stripe-like structures arranged in parallel, with crossbars between them, numerous small, elongated beads are fixed [5]. These beads scatter the light in all directions and the wing appears white (see also Fig. 8). The scale bar on the right bottom has a length of 5 micrometers. 20 such bars next to each other would give the width of one human hair, 200 of these bars next to each other would be one millimetre in length.

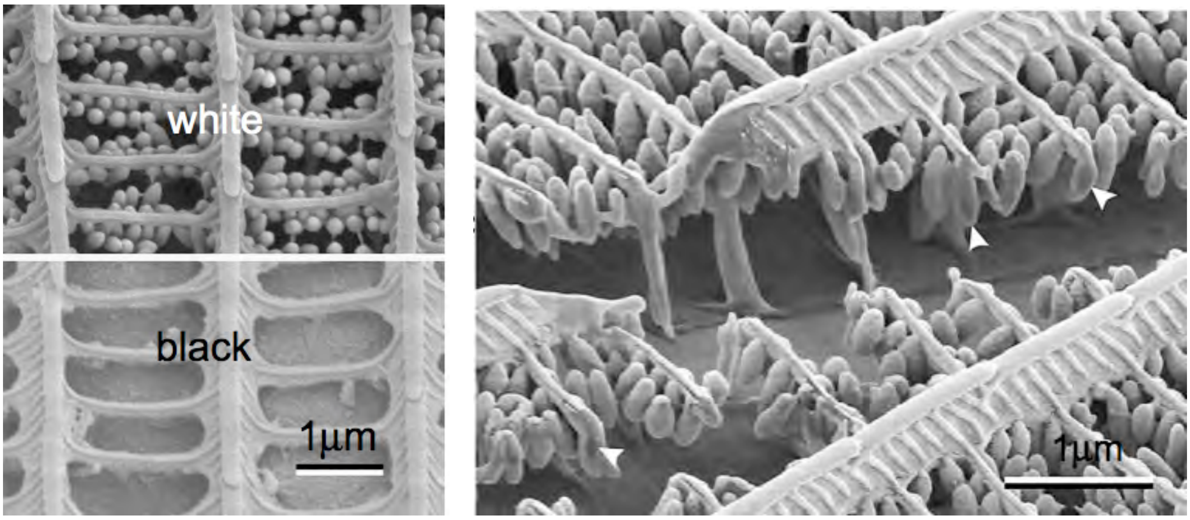

Fig. 8. Left: The structures on the cabbage white wing that are responsible for white (left top) and black (left bottom). Right: Magnification of Fig. 7 right. Scale bar 1µm. [5]

2.3. Peacock feathers

A Fabry-Perot type of interferometer is responsible for colour generation in peacock feathers (Fig. 9). Light is reflected on the front and backside of the structures in the peacock feather, whereby colour in a certain wavelength range is produced [6]. The colour generating structures in the peacock feather are made from melanin and have a photonic crystal like shape. The distance between the single melanin cylinders determines the main colour in the respective region of the peacock feather: in the blue area the distance is 140 nanometers, in the green area 150 nanometers (Fig. 9) and in the yellow area 165 nanometers. The melanin structures are embedded in larger spike-like structures. These spikes are made from keratin, which is the main material of skin, hair, fingernails, hoofs and horns. In the case of the peacock feather, as opposed to, e.g., fingernails, the keratin spikes include the melanin cylinders: in the green region about 10 rows, and in the yellow region about 6 rows.

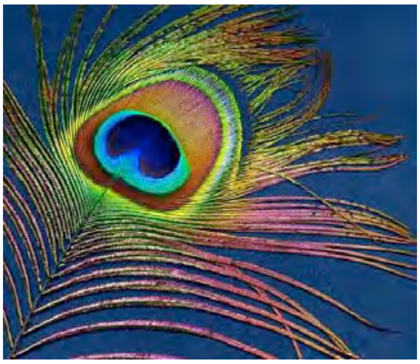
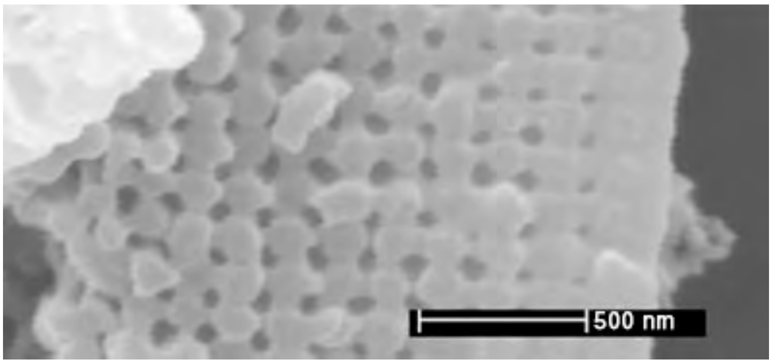

Fig. 9. Left: Peacock feather. Right: Melanin cylinders with a distance of 150 nanometers to each other from the green part of the peacock feather. [6]

2.4. Brittle stars

Just like many other organisms brittle stars control the growth of biominerals. The surface of the brittle star *Ophiocoma wendtii* consists of crystalline calcium carbonate ($CaCO_3$) that makes the whole surface of the animal to a perfect microlens array (Fig. 10). Even Carl Zeiss would have been more than amazed by the optical properties of these micro-lens arrays: the diameter of each of the calcium carbonate micro lenses is 20 to 40 micrometers. Each lens is oriented in a slightly different direction, thereby the brittle star obtains an image from the whole surrounding without having to turn. The complexity of this optical system is comparable to the complexity of an insect facet eye. Calcium carbonate is a double refractive material. The only crystal axis along which double refraction does not occur is the c-axis. The microlenses of the brittle star are exactly growing along the c-axis [7]! Furthermore the brittle star microlenses are corrected for the spherical aberration: the single lenses are not exactly spherical (Fig. 8). The brittle star also produces pigments that act as sunglasses. During the day the pigments shadow the photoreceptors, and during the night they are removed. The microlenses of the brittle star are also corrected for the chromatic aberration: the calcite crystals are doped with magnesium ions.

2.5. Butterfly wings

Various physical mechanisms contribute to the generation of structural colours in butterflies and moths: multilayer interference, diffraction, Bragg-scattering, Tyndall-scattering and Rayleigh-scattering [9].

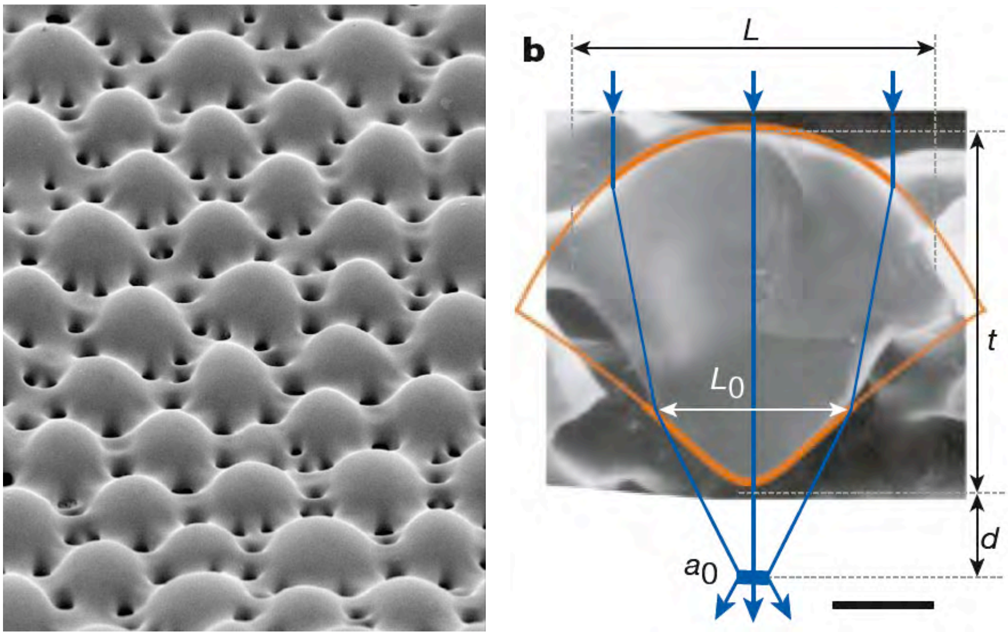

Fig. 10. Left: Calcite microlens array on the surface of the brittle star *Ophiocoma wendtii*. Right: Correction for the spherical aberration: the surface of each of the microlenses is not spherical [8]. Length of the scale bar: 10 micrometers.

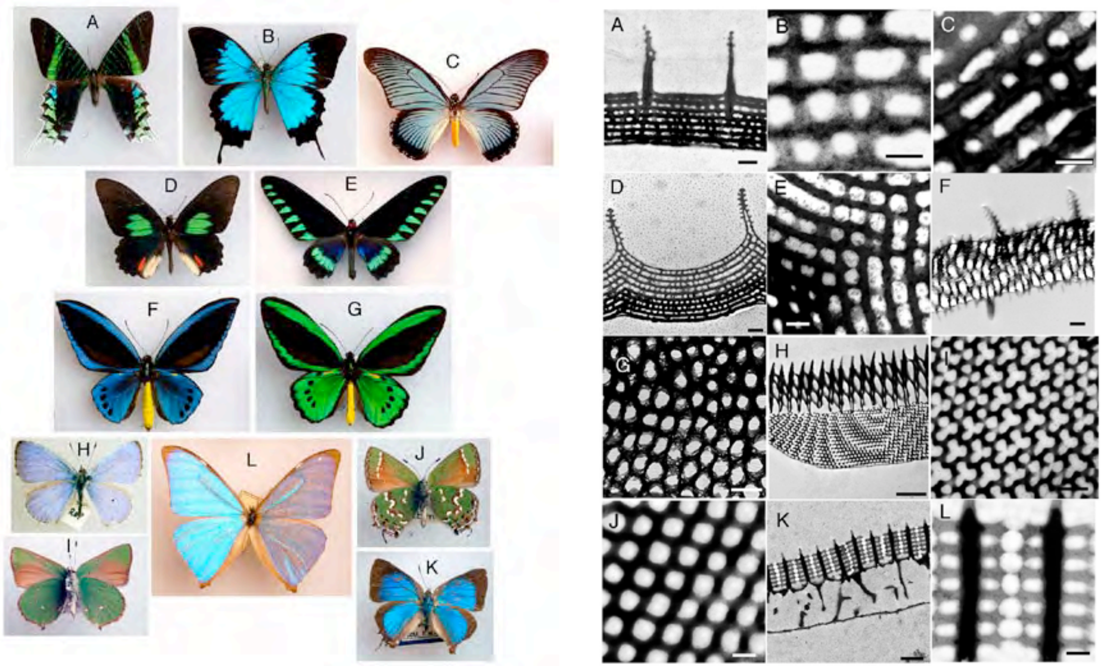

Fig. 11. Left: Structural colours in butterflies and moths. Right: The respective micro- and nanostructures that are responsible for the colours. Scale bars: 500nm (A, D, F, G), 200nm (B, C, E, J, L), 2μm (H) and 1μm (K). [10]

2.6. Iridescent plants

Blue iridescence is common in some extreme shade tropical plants such as the ferns *Selaginella willdenowii* (Fig. 12) and *S. uncinata* Spr. and *Begonia pavonina*, *Diplazium tomentosum* and *Phyllagathis rotundifolia* [11-13].

In both of these two *Selaginella* species blue iridescence develops on leaves in shade beneath foliage. The green leaves that develop in response to more direct sunlight do not become blue when subjected to this shade, but blue leaves gradually turn to green with age or exposure to more direct light (personal observation Prof. Lee).

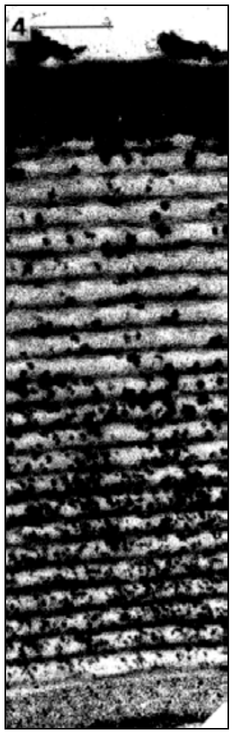

Fig. 12 Left: The "peacock" fern *Selaginella willdenowii*. Photo taken by Foozi Saad, IPGM, Malaysia, under the canopy in the darkness of the rainforest in the Bukit Wang Recreational Forest in Malaysia. Photo taken with very long exposure time, as to show the blue colour of the leaves. Seen with the naked eye, the fern is bluish and seems to glows in semi-darkness. Right: The multilayer system that is responsible for the generation of the blue colour in *Diplazium tomentosum* [13].

3. Technological Applications: Biomimetic optical materials

The colour generating structures of biological materials and organisms serve in various cases as inspiration in design and development of novel optical materials. Examples are man-made anti-reflectant surfaces inspired by moth eyes (Fig. 13), iridescent colours, inspired by butterflies (Fig. 14) or by the chiral thin films of the Rose chafers (*Cetoniidae*, Fig. 15).

The US company Reflexite developed in 2006 a moth-eye inspired nanostructured surface that reached in the wavelength range between 400 and 700 nanometers in its third developmental stage a reflexion coefficient of below 1% [14]! Biological inspiration for this development was a publication by Vukusic und Sambles that appeared 2003 in Nature [15].

A Japanese group was mimicking the iridescent colours of a blue butterfly by reproducing the structures on the wings with focused ion beam – chemical vapour deposition methods (FIB-CVD). The butterfly can make several square centimeters of these structures; whereas the technological method is time consuming and expensive and can just produce some square micrometers. In both structures the maximum of the reflected wavelength occurs at 440nm at a viewing angle of 30 degrees.

The manuka beetle from New Zealand (*Pyronota festiva*) has thin chiral liquid crystal fims on its surface that generate the characteristic red-green iridescent colour. Biomimetic replicas were produced from titanium dioxide, in a size of about $2cm^2$. The colour of these replicas is dependent on the film thickness, and varied with the viewing angle. Furthermore, the circular polarization properties of beetle and replica match perfectly [18].

4. Conclusions and Outlook

Animated Nature offers a plenitude of examples for colour generating structures. We just started to produce such colours technologically. This guidance is made to make easier for the authors in writing full paper of this proceeding. Today available processes, structuring methods and technologies such as self-assembly, scanning probe microscopy, high resolution scanning electron microscopy, increasingly allow us to produce structural colours. Nature exhibits excellent combination of structure with function and can teach us how to do integration instead of additive construction; how to optimize instead of maximize single components and how multifunctionality combined with energy efficiency and development via trial-and-error can be applied instead of mono-funtionality [19].

Biomimetics has a great future, and bioinspired colours are a small, but important part of this new approach.

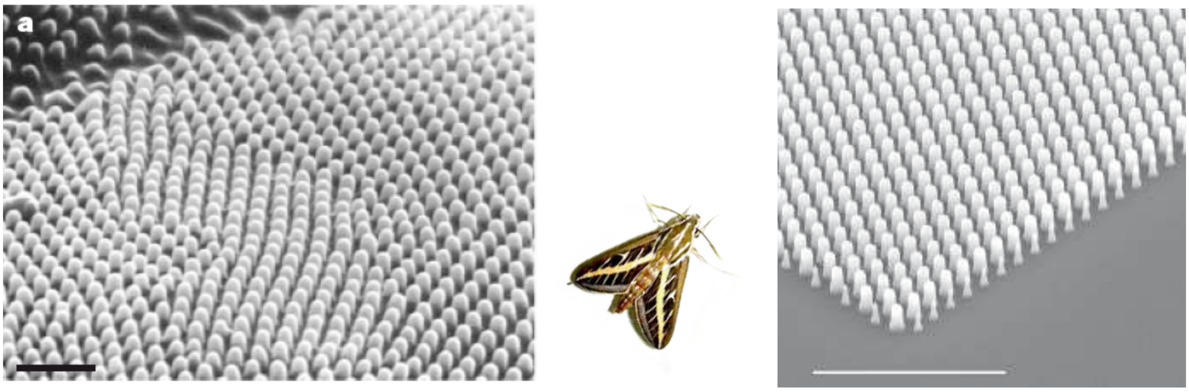

Fig. 13 Left: Scanning Electron Microscopy image of the surface of a moth eye [15]. Scale bar: 1µm. Middle: Moth. Right: Reflexite™, a material that yields in the wavelength range between 400 and 700 nm a reflexion coefficient of below 1% [14]. Scale bar 2µm.

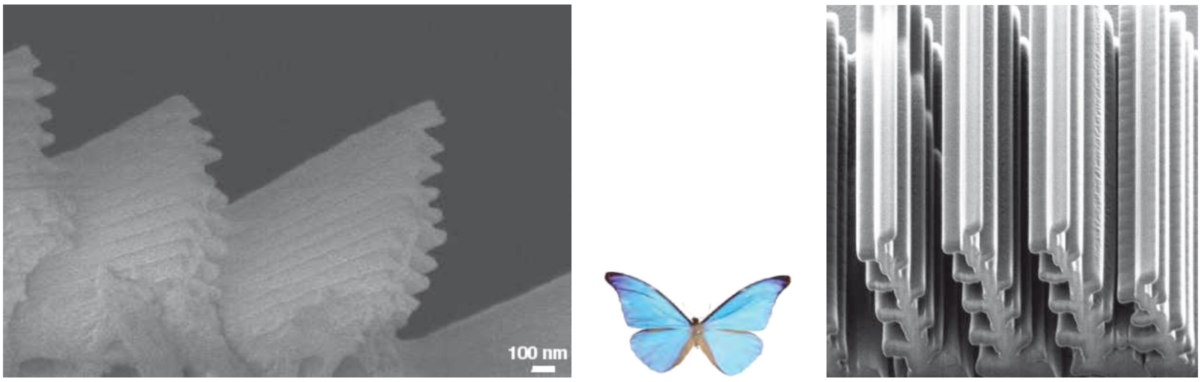

Fig. 14 Left: Colour generating structures in the morpho butterfly [16]. Scale bar 100 nm. Right: Man-made structure with comparable optical properties [17].

5. Acknowledgements

Living in the tropics and continuous exposure to high species diversity in the tropical rainforests is a highly inspirational way to continuously do biomimetics. Researchers have the current problems they are dealing with always at the back of their head, and an inspiring environment aids in having completely new ideas, approaches and concepts. The Vienna University of Technology, especially Profs. F. Aumayr, Störi and Badurek, are acknowledged for enabling ICG three years of research in the inspiring environment in Malaysia.

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