how nature dresses to impress

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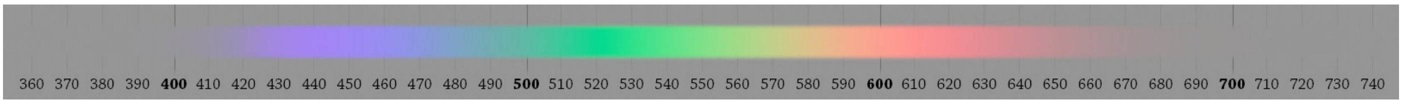
Physics of structural colour



Spectrum of visible light with corresponding wavelengths in nanometres (1 nm = 0.000 000 001 m). Colours of light which we can see are a part of electromagnetic radiation spectrum between infrared (IR) at low energy / high wavelength side, and ultraviolet (UV) at the opposite end. UV is invisible to humans, but for example bees can see it.

1. What is colour?

Human eyes register light coming from the surroundings. Light can behave like waves, and its wavelength is a very important parameter when discussing colour. You see various colours when light of a given wavelength, or a mixture of wavelengths, is detected by the eyes and processed by the brain. Some colours have specific wavelengths, for example: a 460 nm wavelength is a blue, range of 490 nm to 560 nm creates various shades of green, and 589 nm is a familiar orange light of sodium street lamps. Several other colours arise from mixtures of different wavelengths, like white which combines the whole visible spectrum of light. In the same way, there is no one wavelength for pink!

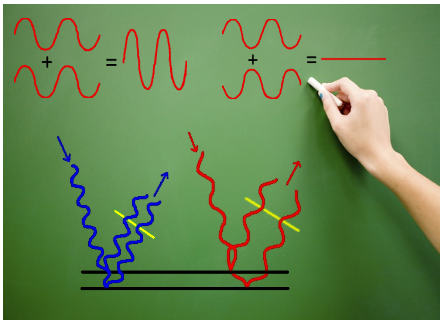
2. Ways to produce colour

Many colours in nature arise from pigments, dyes and metals, which act as a filter absorbing some wavelengths of light, and you see what is left to be reflected. This is so because the light interacts with electrons in those materials. Colour can be observed as a result of reflection or transmission of light falling onto an object, *e.g.* images on this page vs. tinted glass windows. Also, an object itself can emit light, which is generally called luminescence. There are several mechanisms for luminescence, and you may be familiar with its occurrence in fireflies (bioluminescence), glowsticks (chemiluminescence), or perhaps your watch's hands glow in the dark (phosphorescence).

Common examples of colourful objects: glowsticks, watercolours, a stained glass window and CDs. In each case a different mechanism produces colours.

Black body radiation is a mixture of a large number of wavelengths, with a tint depending on the temperature of the source: *e.g.* almost white for the Sun, red for steel heated in fire. Atomic and molecular transitions can produce monochromatic (single wavelength) light, like the sodium lamp. Finally, colours can arise from diffraction and interference of light on structures that can be made of completely transparent, colourless material. A soap bubble is colourful because light scatters on interfaces of this thin liquid film and interference occurs. Colours on a CD are caused by diffraction on periodically spaced data grooves on the surface, creating **structural colour**.

3. Colour from white light: diffraction and interference

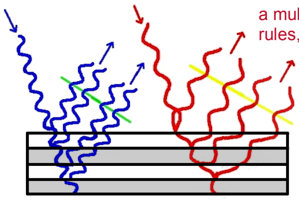


Basic rules of interference of light: constructive interference (top left), destructive interference (top right), diffraction and interference on a thin film interfaces for two wavelengths of light: blue and red (bottom).

Two waves will interfere constructively if they are in phase with one another (coinciding hills and valleys), creating amplified output signal. However, they will cancel one another if they are out of phase. This can be used to selectively amplify or extinguish light of certain wavelengths and thus to change colour by varying the geometry of the illuminated object. The colour of thin film marked with two black lines on the blackboard above is blue for this particular angle of light's incidence. Can you tell why?

4. Structural colour from nanostructures

Structural colour does not require pigments, and can produce striking coloured objects with orders of magnitude stronger brightness. Combining transparent materials with different refractive indices it is possible to obtain constructive interference condition for a given wavelength of light. This is optimised by creating periodic arrangements of those materials at nanoscale. For example, by staking layers of two different transparent materials with thicknesses of a quarter of the given wavelength it is possible to obtain constructive interference for that specific wavelength and consequently obtain a strongly predominant color. Such objects are called multilayers, and are a type of photonic crystals.



Interference of light on a multilayer — same rules, stronger colour enhancement

Moreover with growing number of layers in the stack, the number of light reflections at interfaces increases and the colour gets more and more intense. Similar structures are found in nature, for example in the *Selaginella willdenowii* leaves (shown below), in order to produce a strong blue coloration.

A young *Selaginella willenowii* plant and an transmission electron micrograph of its leaf with indicated multilayer. Black scale bar is 500 nm.

Multilayers are also widely use to create mirrors for application in laser industry.

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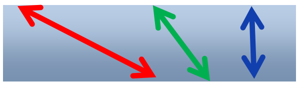
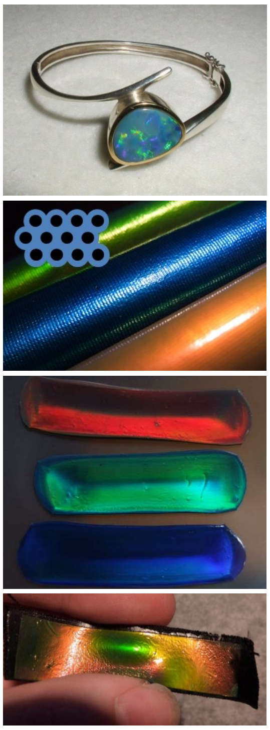
5. Iridescence

The iridescence effect is a direct consequence of structural colour. An object is iridescent when it changes its colour depending on the direction in which we are looking at it, like the case of the CD or natural opals. This can intuitively understood considering that the distance that the light covers inside the layer of optical material changes as a function of the light incidence angle, affecting the constructive interference condition and thus also the colour. For a fixed thickness of the illuminated object, for example a layer schematically shown below:



the light constructively interfering in the direction perpendicular to the surface will have a shorter wavelength than light interfering constructively at another incidence angle.



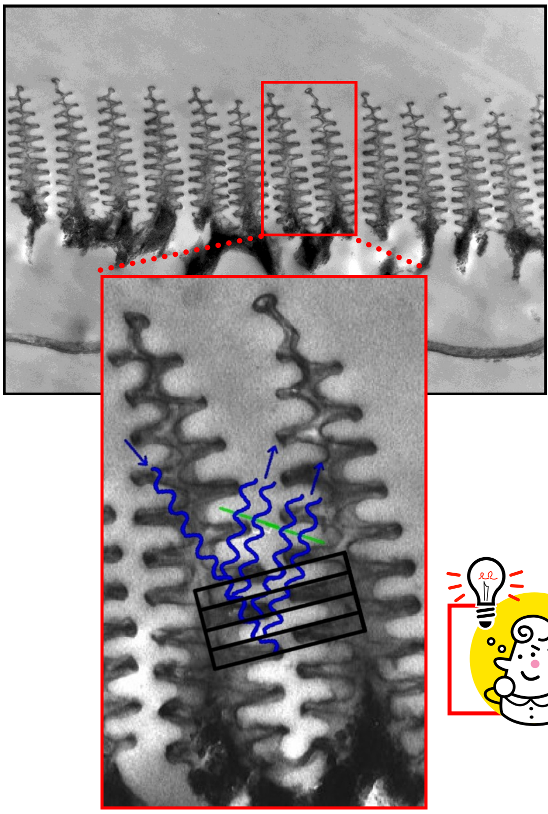
6. Polymer opals

Scientists use their knowledge about structural colour generation in nature to create synthetic materials with striking optical properties. Polymer opals are made by assembly of spheres only a few hundreds of nanometers across, each with a hard core and a soft shell. In a ready material spheres are ordered and produce a periodic spatial distribution of regions with different refractive indices, a photonic crystal. This causes selective light reflection and striking colour, just like in multilayers, although the geometry is a bit more complex in this case. It is possible to obtain different colour opals by changing the dimensions of the spheres or by changing spacing between them, *e.g.* by stretching the sample.

Left from top to bottom: natural opals often feature in jewellery because of their striking colour; synthetic polymer opals (on fabric) made from nanoscale spheres with hard core and soft shell; varying the sphere size leads to different colours; polymer opals can change colour when stretched.

7. Putting it all together: the science of butterfly wings

Morpho butterflies are a very famous example of striking structural colour found in nature. Their iridescent blue colour, told to be visible form half a mile away, is resulting from light interactions with very complex surface nanostructures. On a closer examination these tree-like stacks resemble a multilayer with a few extra gaps, leading to same interference phenomena as discussed above. Here, the two materials with different refractive indices are the solid "tree" material itself, and the air entering between the "branches". The difference between these refractive indices defines how much the light will bend on each interface, and this in turn fixes the constructive interference condition. Can you guess what would happen to the *Morpho* wing colour if the butterfly fell into a river and the air was replaced by water, which has a higher refractive index?



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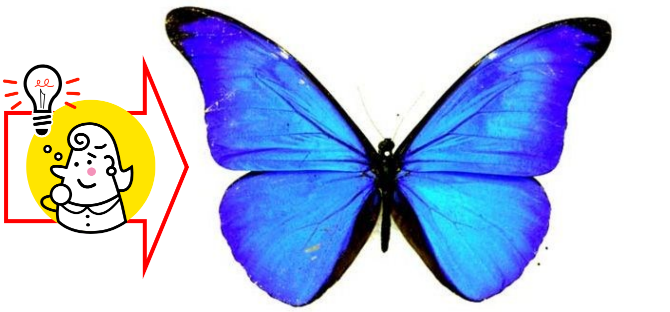
http://www.np.phy.cam.ac.uk
http://newton.ex.ac.uk/research/emag/butterflies/

Nanoscale structures on *Morpho* butterfly wings (shown on a Transmission Electron Microscope image on the left) interact with light falling onto the surface of the wing. As you can see, the structure resembles a multilayer stack, where thickness and spacing of layers defines interference conditions for various wavelengths of light. In this case blue light wavelengths "fit" to the structure while for example red interferes destructively and does not get reflected. Also, this structure reacts differently to light falling at different angles producing iridescence effect. That is why *Morpho* butterflies have such a striking blue colour!



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