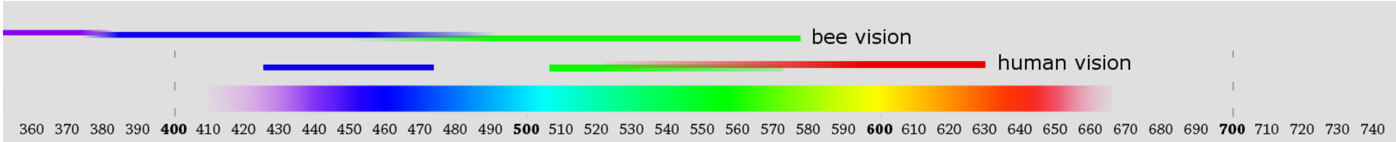
how nature dresses to impress

SELECTED 2011 THE ROYAL SOCIETY SUMMER SCIENCE EXHIBITION

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 see are a part of the electromagnetic radiation spectrum between infrared at long wavelengths 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 sense light which is a wave, with colour set by its wavelength, λ. When a mixture of wavelengths is detected by the eyes and processed by the brain, you see a combined colour. Some colours can be made from a single wavelength: λ=460nm looks blue, from 490-560nm creates shades of green, and 589nm is the familiar orange light of sodium street lights. Other colours arise from mixtures of different wavelengths, such as white which combines the whole visible spectrum of light. There is no one wavelength for pink !

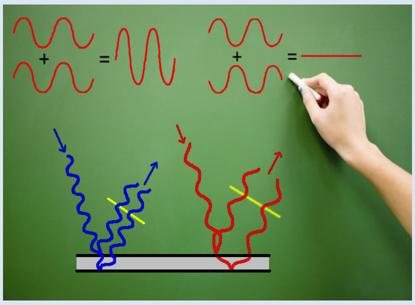
Glowsticks, watercolours, stained glass and CDs each produce colours by a different mechanism.

2. Making colour

Most colours in nature come from pigments or dyes. These absorb some wavelengths of light and reflect the rest into your eye. **Absorption** happens when light excites electrons. You see colours in reflection (reading this page) or transmission (through tinted windows). But objects can also emit light or '**luminesce**' including fireflies (bioluminescence), glowsticks (chemiluminescence), or the glowing hands of your watch (phosphorescence). Hot things also glow, emitting many wavelengths with hue depending on the temperature: from red-hot steel to white-hot Sun. Atoms and molecules instead emit single wavelengths, as from sodium lamps.

Colours can also arise from **diffraction** and **interference** of light, even from structures made of completely transparent colourless materials. A soap bubble is colourful because of interference between the light reflected from the front and back of the thin liquid film. Colours on a CD are caused by diffraction on regularly spaced data grooves on the surface, creating **structural colour**.

3. Colour from white light: diffraction and interference



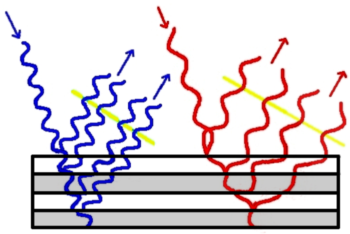
Rules of interference: constructive interference (top left), destructive interference (top right), interference from a thin film for two blue and red wavelengths.

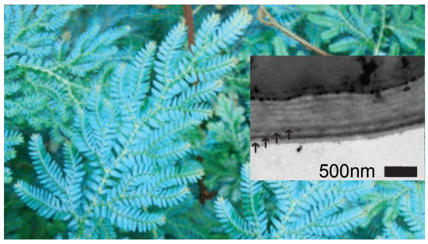
Two waves interfere constructively if they are 'in phase' with one another (coinciding hills and valleys), summing strongly. But they cancel out if they are 'out of phase'. This enhances or extinguishes light of different wavelengths, changing the colour of objects built differently. The colour of the thin film on the blackboard above is blue at this angle. Can you tell why?

4. Structural colour from nanostructures

Structural colour doesn't need pigments, and produces brightly-coloured objects. Combining transparent materials with different refractive index gives constructive interference for a given wavelength. It is even better if materials are regular arranged on the nano-scale. Stacking layers of two different materials each λ/4 thick, gives strong reflection at wavelength λ. Such multilayer objects are a type of 'photonic crystal'.

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





Selaginella willenowii plant. Image of leaf multilayer.

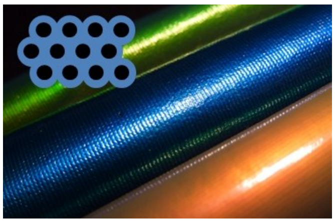
With more layers in the stack, more reflections add together, giving brighter colours. Multilayers found in nature include *Selaginella willdenowii* leaves (above) which are very blue. Multilayers are also used to make the shiniest mirrors for lasers.

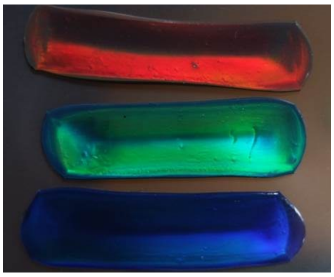
UNIVERSITY OF CAMBRIDGE
Computational Science Laboratory
Microsoft Research Cambridge
UNIVERSITY OF EXETER

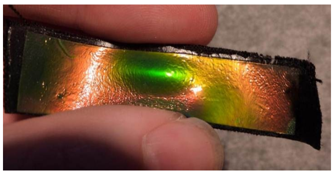
5. Iridescence

Iridescence is a direct consequence of structural colour. It describes an object whose colour depends on the direction in which you look at it, like CDs or natural opals. Because the distance light travels when reflecting from the top and bottom of a layer depends on the angle it hits at, the constructive interference condition (and thus the colour) changes. Bluer light reflects at higher angles.

Natural opal.







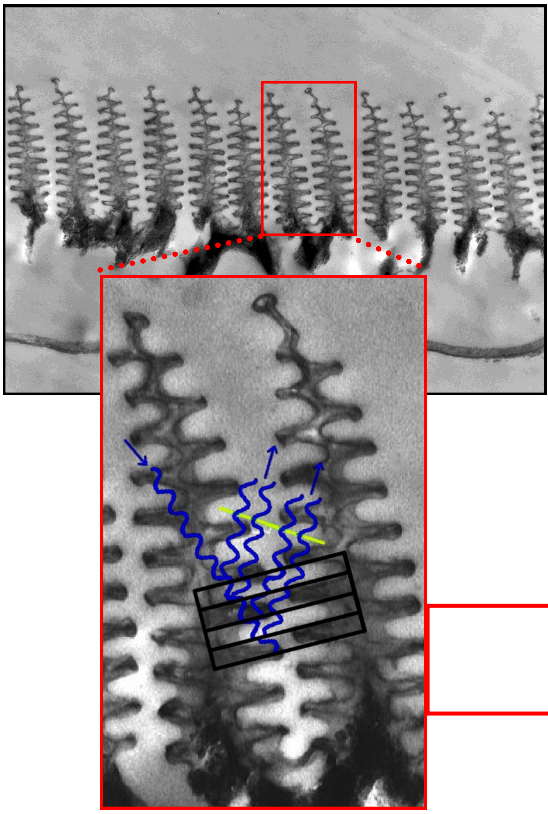
6. Polymer opals

Scientists use their knowledge of nature to create synthetic materials with striking structural colours. Polymer opals are made by assembling billions of spheres only a few hundred nanometers across, each with a hard core and a soft shell. Once the spheres are perfectly stacked they form a photonic crystal, giving colours similarly to multilayers. Different colour opals are made by changing the size of the spheres or changing their spacing by stretching them.

Synthetic opals of nanoscale spheres.
Varying the sphere size gives different colours.
Polymer opals change colour when stretched.

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

Morpho butterflies are a famous example of intense structural colour. Their iridescent blue, visible over half a mile away, comes from light interactions with complex surface nanostructures. Closer examination reveals tree-like stacks resembling multilayers. The extra gaps lead to interference phenomena as above. The two materials with different refractive indices are the solid 'tree' material and the air between the 'branches'. The difference between these refractive indices fixes the constructive interference condition. Can you guess what would happen to the *Morpho* colour if the butterfly fell into a river and the air was replaced by water, which has a higher refractive index?

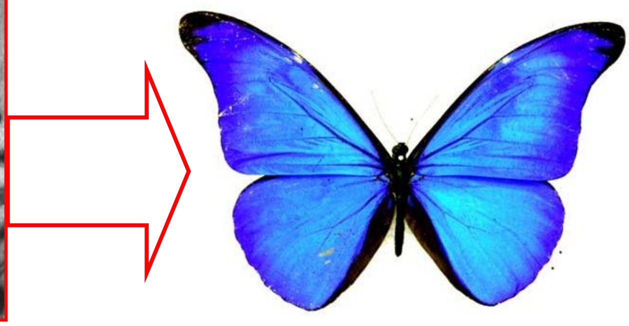


Want to know more?

http://www.colours.phy.cam.ac.uk

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

Nanoscale structure of *Morpho* butterfly wings. Blue wavelengths 'fit' in the structure while red interferes destructively and is not reflected. Colours at different angles interfere differently producing iridescence.



how nature dresses to impress

SELECTED 2011
THE ROYAL SOCIETY
SUMMER SCIENCE EXHIBITION

UNIVERSITY OF CAMBRIDGE

Computational Science Laboratory — Microsoft Research Cambridge

UNIVERSITY OF EXETER