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Nature’s palette

How animals, including humans, produce colours

Colour is an important means of identification for both animals and humans [1, 2]. Its use influences the way they communicate amongst themselves and adapt to their surroundings. Colours can be used to be seen or to camouflage, to mimic, shock or frighten. The use of colour is an important survival strategy in the animal world and plays a major role in the avoidance of being eaten.

What is colour? Perceived colour is dependent on the wavelength of the light that hits an object and which wavelengths are reflected. It is not understood exactly how humans or animals see colour, but it is known to be dependent on the structure of the eye and the brain. Humans and apes have three different cones in the retina, which is a thin layer of cells in the back of the eye. The cones are each sensitive to a different colour; red, green or blue (trichromates). The colour white is generated if all three cones are activated. The cones contain rhodopsin which is a photosensitive pigment absorbing photons and transferring their energy to electrical signals. These signals activate nerve cells and create an image in the vision centre of the brain.

Not all animals have the ability to see all of the colours that humans can. Most mammals are dichromates and do not have the ability to see red. This also includes the bull, in spite of the fact that the bullfighter often waves a red cape. It has recently been found that some animals can also detect ultraviolet light. Our common goldfish is an example of a tetrachromate which can see ultraviolet, red, green and blue. Most squid and deep-sea fishes can, on the other hand, only detect blue light and are therefore called monochromates.

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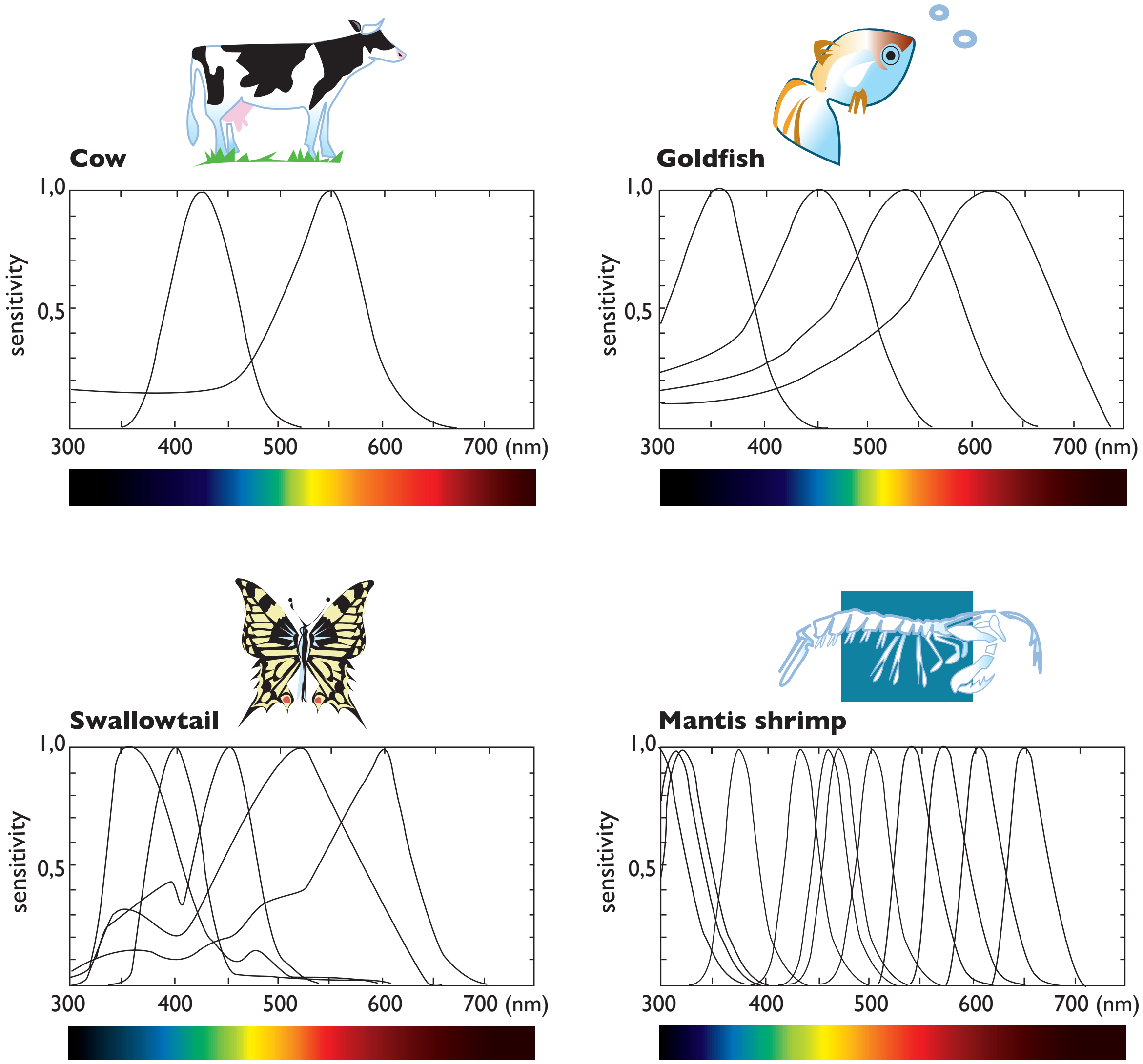
Figure 1 shows that the cow has two types of cones, the goldfish two, the swallowtail five and mantis shrimps, at least twelve. Ultraviolet light is not able to pass the lens and the cornea in humans and many mammals. It is even more complicated in birds and also in certain reptiles. They have red, orange, yellow or transparent oil droplets in the retina, changing the wavelength of the light that strikes the different cones thereby affecting the colour vision. Cones require a lot of light and do not function in low lighting. Another type of light-sensitive cells, rods, are very sensitive to light and are used to see in dim light or during the night. The colour vision is lost since the rhodopsin of the rods has only one bluegreen adsorptionpeak at 598 nm.

Humans and other mammals are not especially brightly-coloured, but have many shades in a limited range. Why do humans have different coloured hair, and other mammals have stripes and speckles? Hair colour is determined by the presence of the light absorbing molecule melanin. Melanocytes are the cells that produce melanin in pigment granula called melanosomes. The melanocytes are found in the hair bulb where the melanosomes are transferred to the hair.

Fig. 1
The cow has two types of cones, the goldfish two, the swallowtail five and mantis shrimps, at least twelve.



The amount of melanin in the hair determines whether a person is going to become light- or dark-haired. Dark hair absorbs much more light than light hair. There are several different shades since we can produce two different kinds of melanin; eumelanin which is brown to black and pheomelanin which is red to yellow (Figure 2). Eumelanin dominates, so it is mainly the amount of melanin that determines how light or dark an individual hair becomes. The production of eumelanin is induced by activation of a receptor (melanocortin receptor) on the surface of the melanocytes.

Human hair has the same colour along the whole strand, but certain mammals can have hair strands that are *e.g.*, black at the top and the base while the middle part is yellow. Such a mixture of colours is caused by differences in the production of eumelanin and pheomelanin during the different growing phases of the hair.

Redheads have a melanocortin receptor that differs slightly in amino acid sequence from the ordinary receptor. Activation of their receptor causes production of pheomelanin instead of eumelanin (Figure 3).

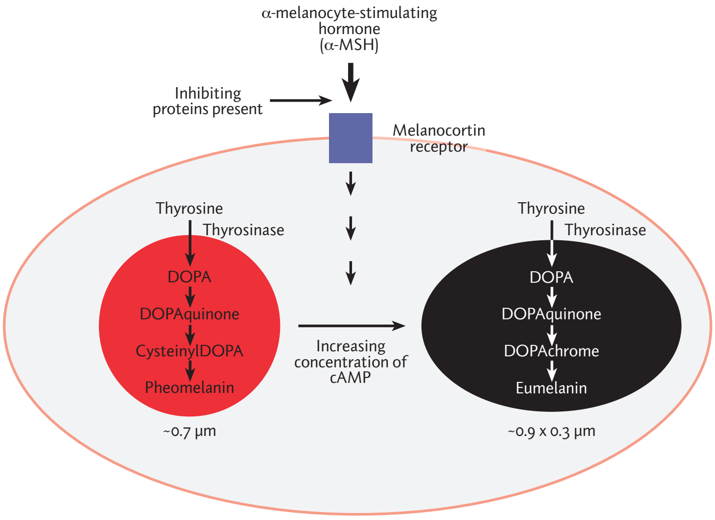


Fig. 2
Melanocytes can produce both red/yellow pheomelanin and brown/black eumelanin. The activation of melanocortin receptors leads to the production of dominant eumelanin.

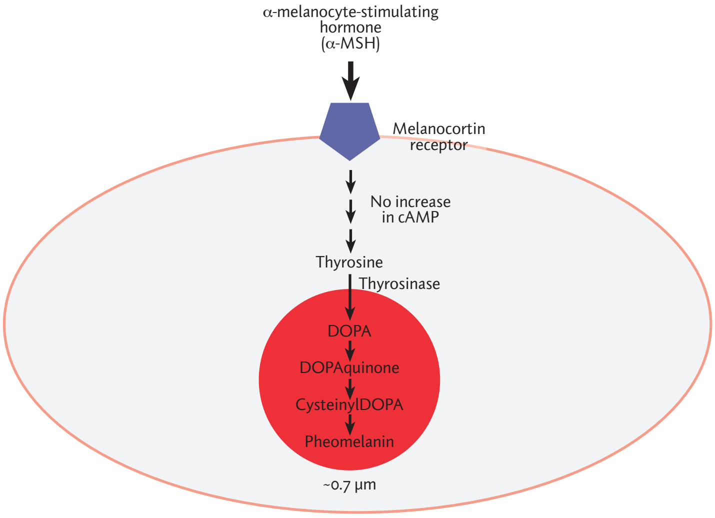


Fig. 3
The melanocortin receptor is somewhat different in red-haired people and for example, in red cows, resulting in the production of only pheomelanin.

This difference is not unique to humans, but is well-known in other animal *e.g.*, where different receptors are found in red and black cows. The gene or genes causing white have not all been discovered yet. It is believed that the cows have the gene for the melanocortin receptor causing red colour, but that white cows do not show any red because of the effects of other genes. For more information and figures see http://www.cbc.umn.edu/tad).

There are many proteins which are important for the production of melanin, and further research will reveal how they interact.

Fig. 4
Three common colours of cows.

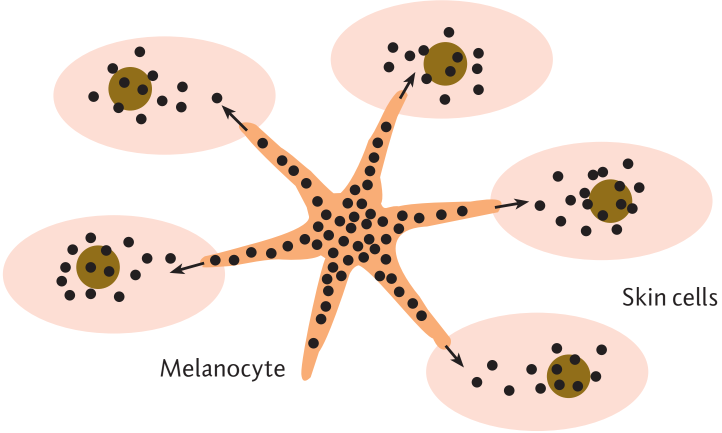
Sooner or later, humans become grey-haired. The melanin production in the melanocytes ceases and the hair colour fades. It is however, a myth that one can turn white overnight, because to turn white the hair must grow out without addition of melanin — a process that takes considerably more time than one night. Stress, however, or a traumatic situation can cause hair to fall out. Grey hair is more firmly bound to the skull, and is not shed as easily as the coloured. The effect is therefore that we appear to become increasingly grey-haired. We get truly white hair when melanin production has ceased completely and when small air bubbles become included in the hair. Occasionally hair can turn green. This colour is not intrinsic to the hair, but caused by the binding of copper ions from *e.g.*, swimming pool water to the surface of the hair. The green colour is lost from the hair after a couple of washes.

There is a great deal of interest in hair-care products from both young and older people. The blue-rinsed ladies of the past and punks with brightly-coloured hair may be just a memory, but there is a vast range of colour products today giving excellent results.

It is not just hair or fur that get its colour from melanocytes, but also the skin. Melanocytes are present together with skin cells in the area between the epidermis and dermis. These cells have many long processes that extend between surrounding skin cells. There is an especially large number of melanocytes in some regions such as freckles, moles, the genitalia, the nipples and the pigmented areas around the nipples. In other areas there are fewer, *e.g.*, lips, palms and the soles of the feet. Skin colour is dependent on how much melanin is produced and transferred to surrounding cells (Figure 5).

Fig. 5

Melanocytes produce melanosomes that move into the surrounding skin cells, giving the skin a darker colour.



The proportion of melanocytes does not differ between different ethnic groups, only the production and transfer of melanin. Tyrosinase is a key enzyme for pigment production. It has been shown that the activity of the enzyme can be affected of the pH of the melanosomes. Black people have a more neutral pH making its tyrosinase work maximally. The differences we can detect in white-skinned people are mainly dependent on the ratio of the production of eumelanin and pheomelanin. There seems to be a strong correlation between which variant(s) of the melanocortin receptor each person has, and the type of skin one gets. Although hair and skin melanocytes arise from the same embryonic source, the genes affecting colour can be independently expressed with combinations of dark hair and light skin or fair hair and more tanned skin. Variations can also depend on environment and age. Albinos have melanocytes, but do not produce any melanin because in most cases they do not have a functional tyrosinase.

A hypothesis has recently been put forward that melanin-producing cells are a part of the immune defence, particularly against bacteria and fungi. Melanosomes contain many enzymes that can take part in the destruction of infective microorganisms. Melanin can also act as a physical trap. Melanocytes are, furthermore, able to secrete a wide range of signal molecules of which some are known to be part of the immune system. The hypothesis explains why cells with melanosomes exist in the inner part of the body that could not be a part of a defence to UV-light. Many types of chemicals and drugs are known to bind permanently to melanin. Hair can therefore be used for detection of drug abuse because melanin is not broken down in the hair.

Fair-skinned people become tanned in sunlight. UV-rays increase the production of melanin in the melanocytes, making the cells darker. The dominating part in a suntan is however the transfer of melanosomes to surrounding skin cells. This process takes time that explains why it takes several days to achieve a dark suntan. Many of us feel healthier when we are tanned even if it is known that UV-light affects DNA, increasing the risks of skin cancer. It is therefore important to protect oneself against excessive sunlight. There are many products on the market that increase the reflectance of UV-light from the skin. However, even if we know that UV-light is harmful, many people want to get tanned and sometimes very quickly. Suntan oil is one product that promises to speed tanning. The oil reduces light-reflecting wrinkles on the skin and all cells therefore become more exposed. The same effect can be reached using ordinary cooking oil! No sun shield is given by 'sunless' tanning sprays and lotions, only an artificial suntan. These products contain dihydroxyacetone, that binds to amino acids on the outer layer of the epidermis, producing a brown colour.

While many white people want to become tanned, some Asian and dark people would like to become fairer. There are also certain diseases affecting skin colour. A long time ago one could buy mercury soap to decrease body colour, but there are most probably no buyers for such toxic products today. However, both pharmaceutical and cosmetics industries are trying to produce products that can change both hypo- and hyper-pigmentation.

Many animals such as fish and frogs have the ability to change colour, something which humans and mammals are unable to do. They have also pigment-producing cells, but they are called chromatophores. Colour change is often rapid in fish and controlled by nerve signals, even if hormones are also involved. The animal becomes aware of the colour of its surroundings by vision, and signals are sent via the brain to the chromatophores. Melatonin is a hormone that is produced mainly during the night. It induces lightening of the chromatophores and this is seen during the night. Colour change in frogs is slower and mainly influenced by hormones. Recently a special light-activated receptor has been found on the chromatophores.

The chromatophores differ from mammalian melanocytes in that these cells can rapidly transport their chromatosomes either towards the centre of the cell (aggregation) or disperse them throughout the cell (dispersion) — see Figure 6.

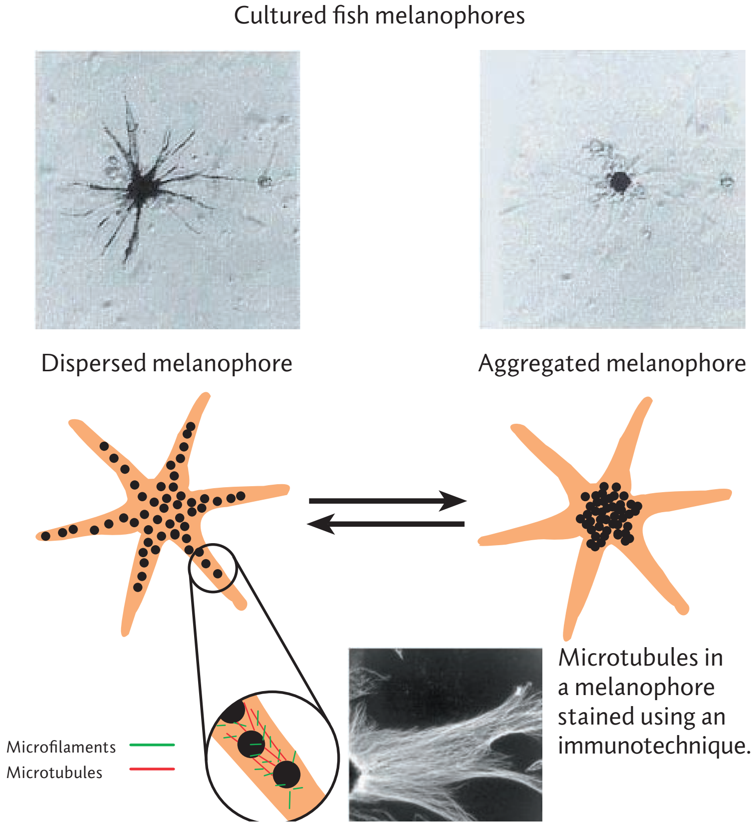


Fig. 6
Melanophores can be cultured in tissue cultures. When the melanosomes are spread throughout the cell it is dark. It becomes light upon addition of melatonin or the nerve signalsubstance noradrenaline which induce a transport of melanosomes to the centre of the cell. Melanosomes are transported along microtubules and microfilaments by motor proteins.

In Figure 7 the spotted triplefin (*Grahamino capito*) becomes dark on a dark background (a) and pale on a bright background (b). Chromatophores are present both on the skin and on scales. Figure 7c shows dispersed melanophores on a scale, and in (d) they are aggregated. The chromatosomes are transported along 'tracks' within the cells. These tracks are composed of protein subunits that assemble to form long thread-like structures, the cytoskeleton. Two different cytoskeletal components are involved; the microtubules and the microfilaments, along which long-distance and short-distance transport occur respectively. The latter is involved in the spreading of the chromatosomes throughout the cell, while the former is used for rapid transport to or from the cell centre.

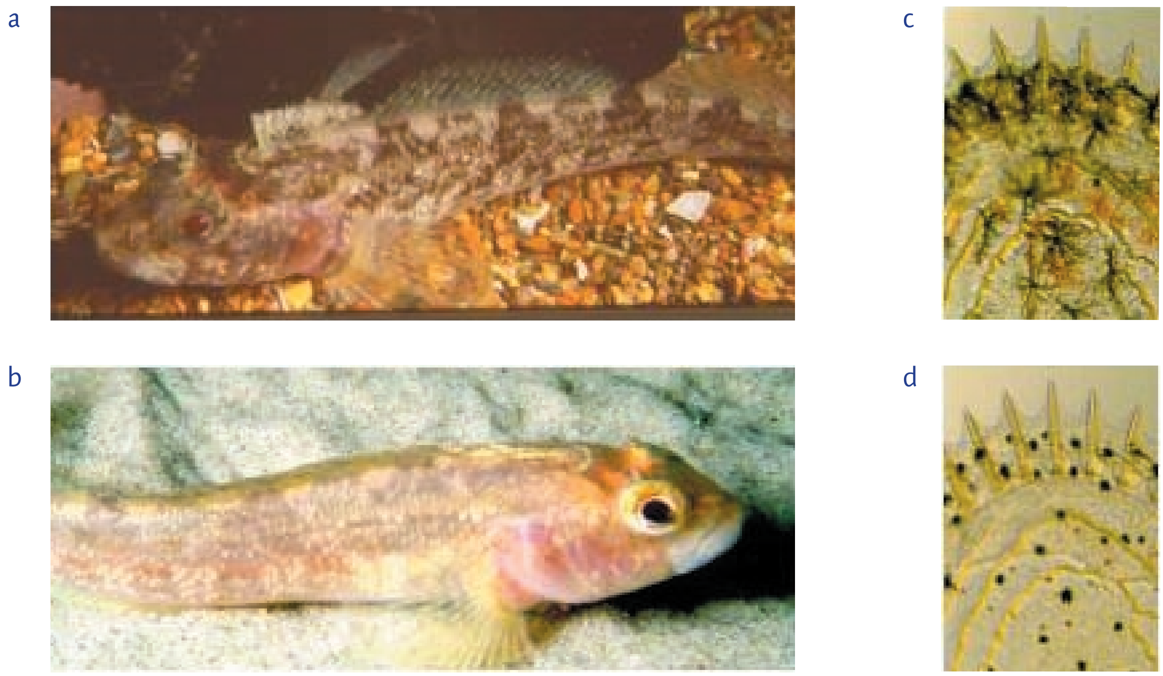
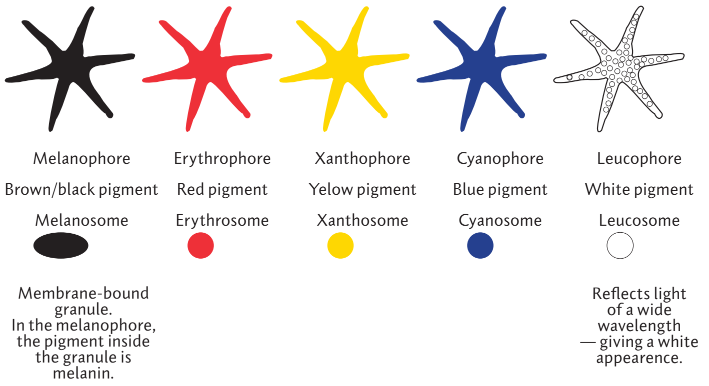


Fig. 7
Colour changes in the spotted triplefin, Grahamino capito. The fish adapts to a dark background by darkening its skin (a). If the fish moves to a light background, the skin becomes pale (b). The mechanism behind this reaction is rapid intracellular transport of pigmented organelles within chromatophores, like melanophores and erythrophores, in the skin and the scales.

If the pigment organelles are evenly-distributed throughout the cells (c), the fish appears dark. If the pigment organelles are aggregated at the cell centres (d), the fish looks pale.

Chromatophores come in many different colours, and only one colour is found per chromatophore. The chromatophores can contain black, red, yellow, blue and white chromatosomes (*e.g.*, melanophores, erythrophores, xantophores, cyanophores and leucophores, see Figure 8). Only a few animals are known that have chromatophores with green pigment. Metallic colours are created differently. The herring has a silvery colour and this is produced in iridophores that contain crystals of guanine. The crystals are present as parallel plates in the cell reflecting the light so that the fish looks silvery. Different types of iridophores exist and some fish can affect their colour by changing the distance between the plates (Figure 9). *Neontetra* has a beautiful colour on its lateral line that can change between blue and green. Some fish have melanophores below the iridophores in the skin and iridophores with very small crystals in the front. These iridophores reflect light in all directions creating a blue colour.

Fig. 8
Pigmented granules are formed from the Golgi apparatus and the smooth endoplasmic reticulum. Thereafter they produce and are filled with melanin and are dispersed into the cell.



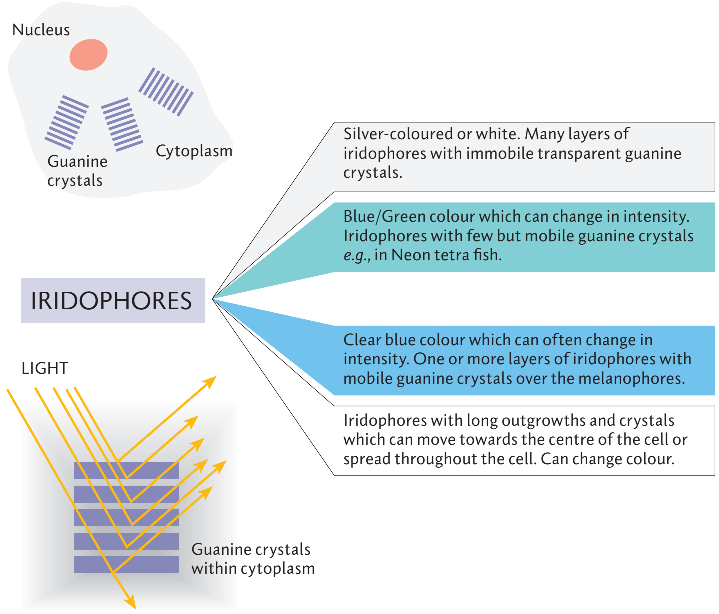
Chromatophores

These are cells in 'cold-blooded' animals which contain pigment granules. These granules can be moved into the middle of the cell or be distributed throughout the whole cell.

Melanocytes

These are cells in 'warm-blooded' animals which contain pigment granules.Pigment granules cannot be moved through the cell in the same way that chromatophores can.

Fig. 9
Light is reflected when it passes through many layers of guanine crystals and cytoplasm in the iridophores. The wavelength of the reflected light depends upon the refractive index of the guanine crystals and the cytoplasm, and the thickness of the different layers. There can be internal reflections in the crystals which strengthen or weaken different wavelengths.



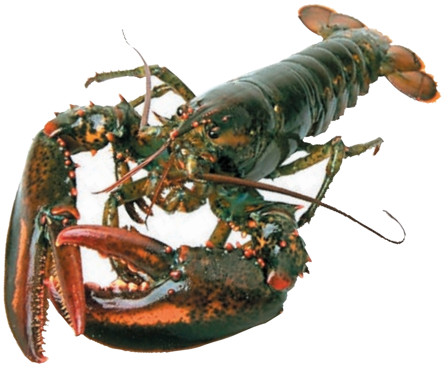
Many green animals exist, for example, the European chamaeleon (*Chamaeleo chamaeleon*, Figure 10), the tree frog (*Hyla arborea*, Figure 11) and many snakes and birds. Their colours are created in a complex way. Blue colour is produced by black melanophores in the back and iridophores in the front, just as described above for fish — but these animals also have chromatophores with yellow pigment on the surface. The overall effect is therefore a green colour. Different light-scattering also causes the blue colour of birds' feathers, in contrast to black and red/yellow colours from melanin and carotenes. The blue colour of the magpie is one example. Many examples exist where optical effects give a bluish colour, *e.g.*, beautiful butterflies with a blue colour like the swallowtail (*Papilio machaon*) (Figure 12). If the colour is an optical effect, then it will change depending on the angle of observation.

Fig. 10
The European chameleon, Chamaeleo chamaeleon.

Fig. 11
The tree frog, Hyla arborea.

Fig. 12
The Swallowtail butterfly,Papilio machaon.

Fig. 13
Lobsters are black when live, but turn red when they are cooked.
(Click on the black lobster to go to a Real Networks version of a film about them; click on the red lobster for a Windows Media version.)



Squid also have chromatophores, but colour change is controlled by contraction or relaxation of muscles surrounding the cells which changes the size of the chromatophore. Some squids produce ink that is composed of melanin which they eject into the water to be able to hide from predators. This is another use of melanin, but the squid 'ink' has nothing to do with ink in pens.

Sometimes the colour of animals is confusing *e.g.*, the lobster is black when alive but becomes red when it is boiled (Figure 13). The black colour of the lobster is caused by the pigment alfa-chrustacyanine. The pigment is composed of two parts; one red carotene part which is called astaxanthine and one protein. When the lobster is boiled, the protein is denatured and the red colour remains. Many different carotenes exist and one well-known example is beta-carotene which gives an orange colour. Carotenes are lipid-soluble and stored in fat or fat cells in the skin. If one eats too many carrots the skin can even aquire a yellowish tone! Carotenes are only produced by plants and also by some algae. They are usually yellow or red, but can come in red, blue or black if they are bound to a protein.

Carotenes are also important for how attractive we find our food. For example, we are seldom fond of pale salmon or egg yolks. Wild salmon are red because they get a dose of pigment when they eat crustaceans. Astaxanthines are commonly added to food in commercial salmon fish farms, and to some poultry food for the production of especially yellow egg yolks (Figure 14). Another good reason to add carotenes is their role in protecting cells from free radicals. No wildlife park would like to have pale flamingos. This situation is avoided by feeding them with carotene-containing food. Carotenes are also an essential aid to vision since they split to vitamin A that is transformed to retinal and which makes up the photopigment rhodopsin together with opsin. Night-blindness is a typical sign of lack of vitamin A.

Fig. 14
We prefer not to buy pale salmon or eggs with pale yolks.

The 'golden rice' containing beta-carotene will most probably be the first example of genetically-modified plant that, perhaps, could change the negative attitudes towards GM food. It has been calculated that more than 800 million of people in the world, of which many are children, suffer from lack of vitamin A. This lack can lead to blindness and also mortality in infectious diseases. By eating the golden rice, that contains four co-operating genes for production of beta-carotene, such diseases and suffering will decrease or be eliminated.

Biotechnology is a growing area and recently the melanin of the eye has been suggested as our new identity card, creating a possibility of providing a means of secure trading *via* the Internet. It has been shown that the retina is as individual or even more so than fingerprints. All children are born blue-eyed. The blue colour is caused by the presence of a layer of melanocytes in the back of the retina. Light is reflected from this layer, and on its way out from the eye it is scattered so that a blue colour is created. Within a couple of months, or sometimes even up to 9–12 months, more melanocytes are formed in the iris. This is regulated genetically. The colour of the eye is dependent on how many melanocytes are present in the iris, and the colour therefore will be very individual. Albinos, however, do not produce any melanin. Their eyes are neither blue nor brown, but red because the blood vessels behind the eye are visible.

There exist many more substances which create colour than have been described in this article. One example is the red colour of blood, which is caused by the oxygen-carrying pigment haemoglobin. This is especially noticeable when we blush. The blood vessels in the face dilate and we become redder. Many synthetic colours are used in the cosmetics industry. Plantdyes are used to dye yarn and cloth. Colour will most probably always fascinate us. Genes for different colours will be identified with modern biotechnology and we could *e.g.*, produce flowers with beautiful colours. We are living in an exciting era.

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Web sites

http://www.astacarotene.se

A commercial website for production of astaxanthin. It includes useful information about astaxanthin.

http://www.cbc.umn.edu/tad

Albinism database. This Web site is a part of the HUGO mutation database initiative. It includes , for example, a table of pigment-associated genes, coat colour genes of cattle, and genetics of coat colour in dogs.

Photo credits

Figure 1

Anette Hedberg, AHForm, Sweden. Based on an illustration by E. Warrant and A. Kelber.

Figure 6

H. Nilsson, Kristineberg Marine Research Station, Sweden.

Figure 7

H. Nilsson, Kristineberg Marine Research Station, Sweden.

Figure 10

C. Andrén, Universeum and Göteborg University, Sweden.

Figure 11

C. Andrén, Universeum and Göteborg University, Sweden.

Figure 12

C. Andrén, Universeum and Göteborg University, Sweden.

Figure 13 (Web link)

Video recording from University Televison, Göteborg University, Sweden.