H21: Light, Materials and Colour

When we are viewing an object or a surface, it is the light reaching our eyes that conveys the appearance of the surface to us. The appearance is our interpretation of the characteristics of the light, characteristics that arise from the interactions of the light incident on the object with the material of the object.

The object may absorb, scatter or reflect the light. Some types of interaction are wavelength dependent, for example some wavelengths of light may be absorbed more strongly than other wavelengths. Other types of interaction may be occurring giving rise to effects such as interference or luminescence.
As an example of the many types of possible interaction, consider the light shining onto a glossy printed layer, as illustrated in Figure 1. The light will be partially reflected at the surface, partially absorbed and scattered by the pigments present in the ink layer, and may be either absorbed or reflected by the underlying substrate layer.

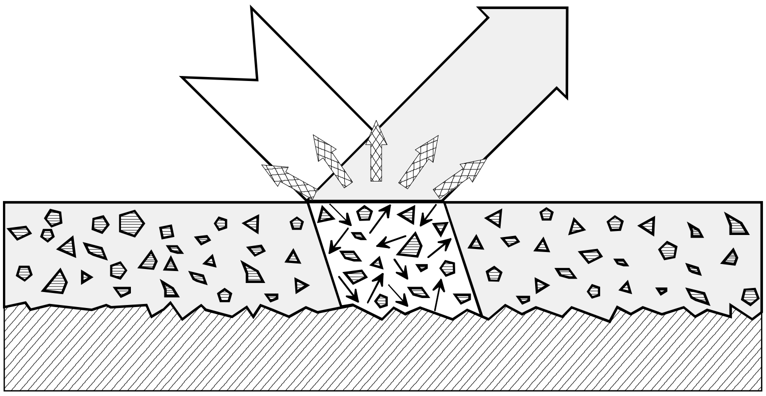


Figure 1: Interactions of a light beam with printed surface

In most cases, several effects will combine to give the overall colour appearance of the printed surface. The most common effects are reflection, refraction, diffraction, absorption, scattering, interference and luminescence; each of these effects will be discussed in the following sections.

Reflection and refraction

Reflection of light and refraction of light occur whenever the beam travels across a boundary between two materials that do not have the same refractive index. At such a boundary, the incident light is partially reflected (back from the boundary) and partially refracted (into the body of the material), due to the change in refractive index. The process is illustrated in Figure 2.

Boundary reflection

Reflection of light at a boundary or a surface does not of itself cause colour. However, in many materials it contributes towards the overall appearance through the impression of the gloss of the surface. The boundary reflected light has the spectral properties of the light source, as it has not entered the material at all. If the object is illuminated with white light, then the gloss or boundary reflection is also white light.

The colour of the print is arises from the light that has passed through the boundary layer and interacted with the pigments or dyes in the ink layer. When the print is viewed at an angle so that white gloss light from the boundary is mixed with the coloured light from the interior, the intensity of the colour is reduced, making the print appear lighter and weaker than at other viewing angles.

The proportion of light that is reflected by the boundary rather than refracted into the layer is determined by the difference in refractive indices between the two materials (Fresnel's law) and by the angle of incidence the light beam makes with the boundary. For example, a boundary between air and a high gloss print will reflect more than 4% of the incident light.

Gloss surface

Boundary reflection of light from a perfectly flat surface follows the well-known law that the angle of incidence is equal to the angle of reflection (Figure 2). When this mirror like law applies the reflected light is often known as the specular reflected light.

Imagine that a beam of light is shone at a particular angle onto a very smooth surface. The boundary reflected light would all be along a narrow set of directions, the surface would be judged as very glossy. An observer viewing such a surface will see, at certain viewing angles, reflected images of the surroundings. This gives rise to the visual impression of gloss, as illustrated by the right-hand-side vase of Figure 3.

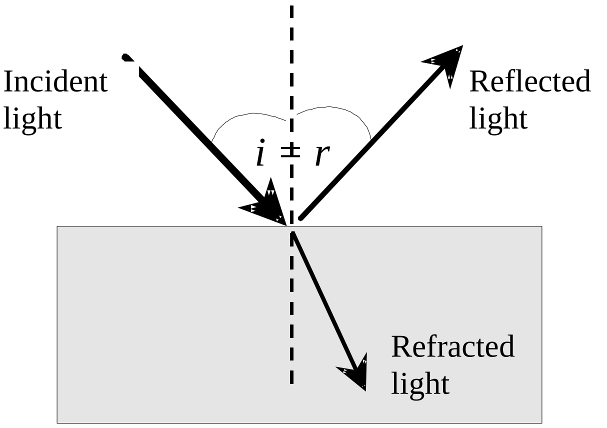


Figure 2 Surface reflection and refraction

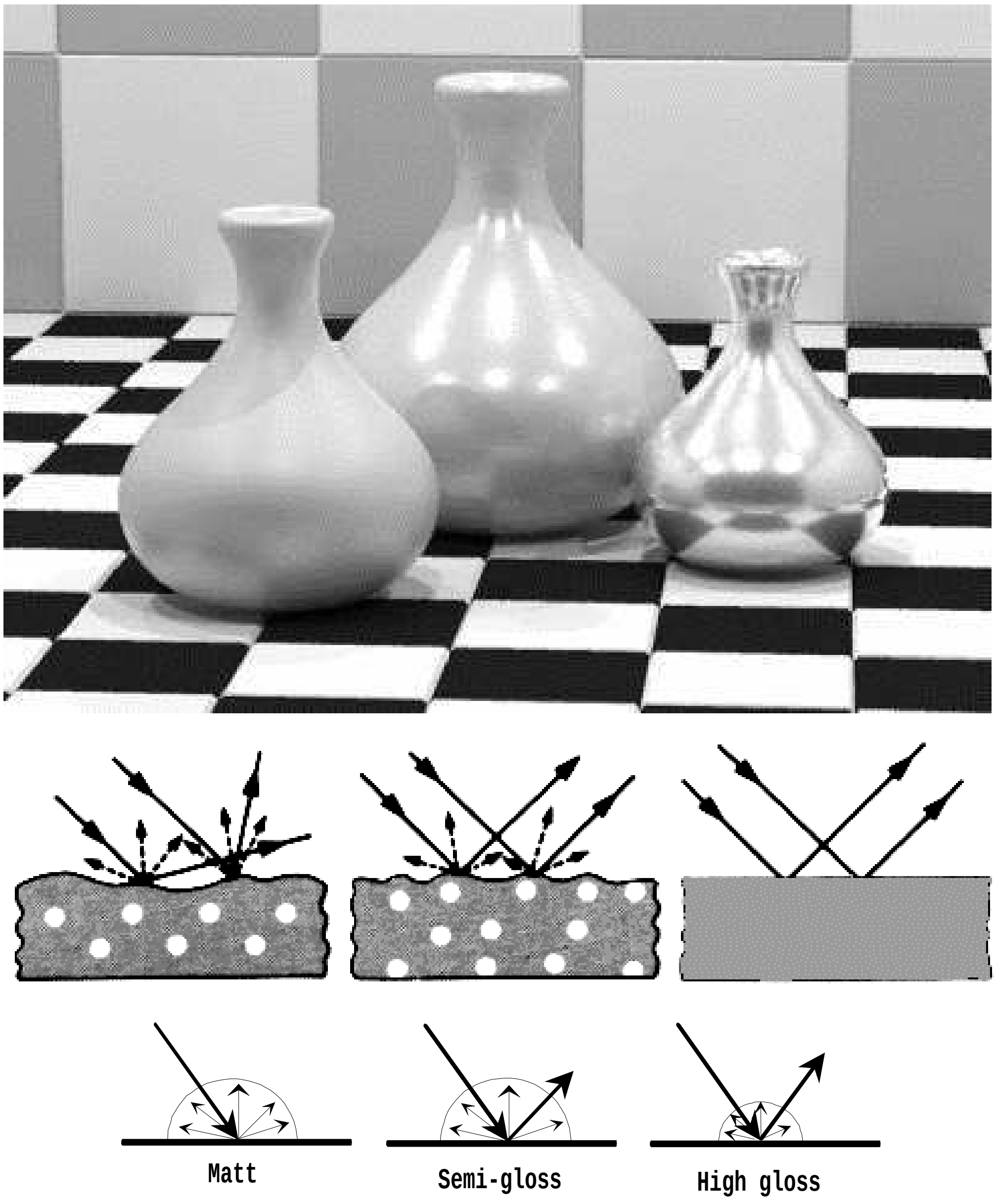


Figure 3: Reflection from different types of surface finish

Matt surface

The boundary of a very rough surface will tend to reflect light at many different angles, because the light meets the surface at many different angles. The boundary reflected light is so diffuse that the observer cannot make out images of the surroundings. The visual impression is that of a matt surface, as illustrated by the vase on the left-hand-side of Figure 3.

This type of appearance characterisation is best visualised as a polar distribution, as shown in the lower diagram of Figure 3.

Metallic effect coatings

A further example of the use of reflection in surface coatings is that of coatings containing metal flake pigments, such as the metallic effect paints used on cars. The pigments used in the coatings are generally aluminium flakes, which act as tiny mirrors within the coating and increase the amount of white light reflected.

The surfaces of the flakes are aligned parallel to the surface of the coating layer, and so enhance reflection at the specular reflection angle, as illustrated in Figure 4. However, reflection also occurs from the edges of flakes, and from flakes that are imperfectly aligned.

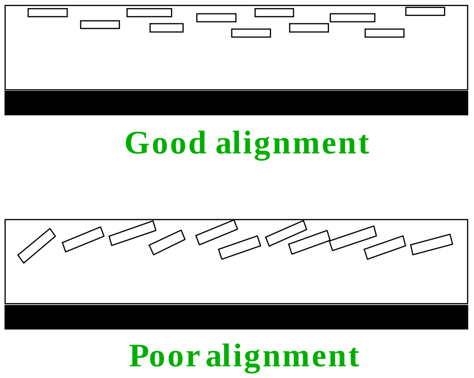


Figure 4: Flake alignment

The flake reflected light, although highly directional is “spread out” over a greater angle compared to that from the boundary reflectance of a highgloss conventional paint. This enhances the look of the coating, and in particular is thought to enhance the curves on a car and make it look more sleek and attractive. On closer inspection, it is also possible to see the individual flakes sparkling in the light that further increases the attractiveness of the coating.

Refraction

When a beam of light is shone onto a smooth, transparent surface, some of the incident light is reflected at the boundary and some is transmitted into the material. The direction of travel of the transmitted beam is changed from that of the incident beam, the angle made with the normal to the surface is called the angle of refraction, Figure 5.

Snell’s law gives the relationship between the directions of travel.

$$n_0 \cdot \sin(\theta_i) = n_1 \cdot \sin(\theta_r)$$

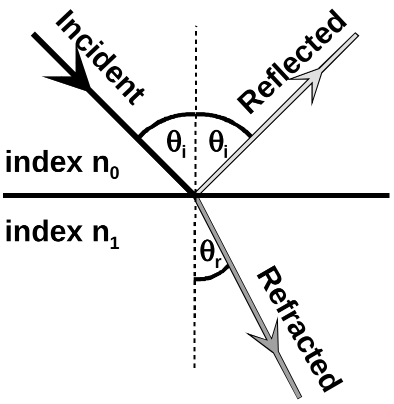


Figure 5: Reflection and refraction at a boundary

The splitting of white light into different colours by a prism and by certain gems arises from refraction. The refractive index of glass, and many other materials, changes with the frequency of the light. This means that blue light is refracted to a different angle compared to red light as it passes through a glass prism. The rainbow, colours produced by water droplets in the atmosphere, is also generated by different degrees of refraction of the various wavelengths of light as they pass in and out of the droplets.

Diffraction

Diffraction is a form of interaction that all types of waves have with objects. The effect if the interaction becomes very important when an object or a pattern has a size or spacing of few times the wavelength of light.

At its simplest, the effect of diffraction is seen in the shadows cast by small objects. Figure 6 illustrates the puzzle that the edge of the shadow is not sharp but fuzzy, and the smaller the object is, the fuzzier the edge becomes.

The effect is explained by considering how waves flow around and reflect from by the objects that they meet.

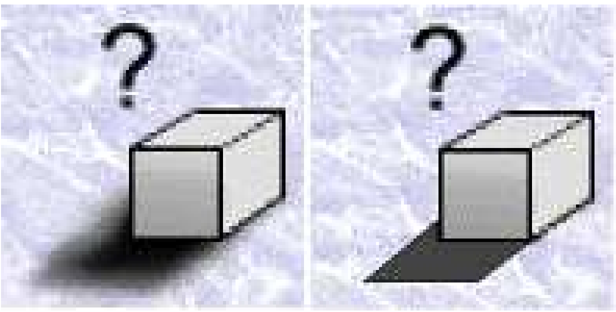


Figure 6: Diffraction causes the edges of shadows to be fuzzy instead of sharp

In Figure 7 a parallel beam of plane waves is shown advancing towards a small object. The incident beam interacts with each atom in the surface by inducing oscillations in the position of the electrons, the oscillation causes the atom to act as an emitter of radiation.

The emitted waves from each neighbouring atom have a definite phase relationship to each other and combine to produce a short segment of a “reflected” diffracted wavefront. This wavefront is not sharply bounded but is spread out; the smaller is the size of the particle then the more spread out the diffracted edge of the reflected beam becomes.

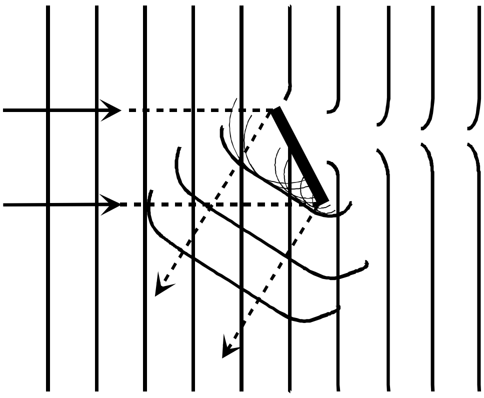


Figure 7: Reflection and diffraction of a wave around a small object

Notice also in Figure 7 that the edges of the transmitted beams are not sharply bounded. The spreading out of the transmitted beams into the shadow zone causes the edges of the shadow to be fuzzy.

A second type of diffraction effect can give rise to colour. If the single object in Figure 7 is replaced by a series of objects in a regular pattern, then the “reflected” diffracted beam can be intensely coloured. A regular spacing can cause the different wavelengths of light to be reflected into different angles. Many spectrophotometers and colour measuring instruments make use a device called a diffraction grating to analyse the incoming beam of light into a series of beams of different wavelength bands.

Another example of the creation of a colour effect by a regular spaced pattern is given by the surface of CD ROM computer disc. The reflected light displays an intense colour at certain illumination and viewing angles.

Absorption

The selective absorption of wavelengths from white light is probably the most common cause of the creation of colour; it occurs in almost all conventional dyes or pigments, from chlorophyll in plants to indigo in blue jeans. Examples of the use of light absorption in creating colour might be dyed fabrics, paint layers, pigmented plastics and printed card.

“Absorption” implies that the light absorbed is lost as visible light; it may be converted to heat, or other forms of energy. This conversion may be made in several ways; the most common involves absorption of light energy by molecules to excite electrons into a less stable (higher energy) arrangement within the molecule. The electrons quickly fall back to their original, stable arrangement, the molecule dissipating the extra energy as heat.

A system will only absorb light of particular wavelengths (the absorption band of that system), which correspond exactly to the amount of energy needed to promote the electrons involved. The absorption band may be wide, however, due to the constantly changing vibrational energy of the molecules involved changing the amount of energy needed for promotion.

Only those substances that absorb light, radiation in the visible region of the electromagnetic spectrum, (380 to 730 nm) appear to be coloured.

Transparent materials

A material is called transparent if it does not contain any particles or discontinuities that will scatter the light. Examples of coloured transparent materials are coloured solutions and the inks used in the four colour printing process.

The simplest case to consider is that of a transparent, coloured material as illustrated in Figure 8. There are many coloured, transparent liquids where the light absorbing material is in solution; lager beer is a good example. In the case of a printed layer, if no scattering is occurring within the ink, then the light is refracted on entering the coating layer and selectively absorbed by the coating material. The remaining light is then reflected by the substrate as in Figure 9. The emerging light beam has passed through the coating thickness twice and therefore has twice the chance to be absorbed.

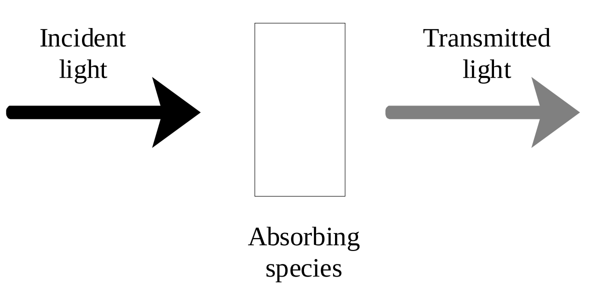


Figure 8: Selective absorption of light by a transparent, coloured material

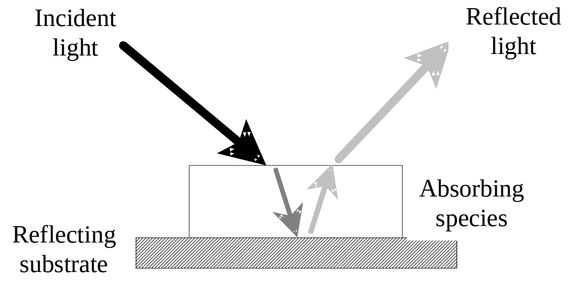


Figure 9: Passage of light energy through a transparent coating

In Figure 8 and Figure 9, the coloured material is absorbing some of the light incident on it, and transmitting the remainder. If we consider the spectral distribution of the intensity of the incident and transmitted light beams, that is, the light intensity at each wavelength through the visible spectrum, we might expect to see something similar to Figure 10.

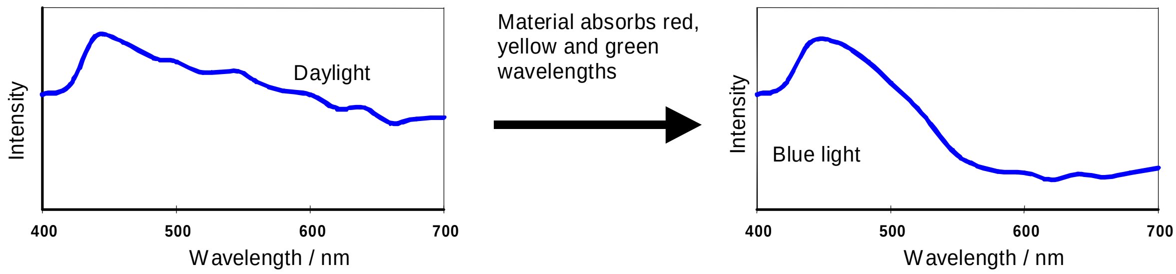
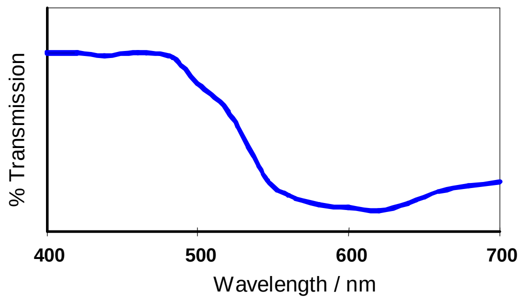


Figure 10: The effect of selective absorption on the spectral energy distribution

It is more usual to consider absorption in terms of the relative amounts that have been transmitted or absorbed, rather than the light intensities. In other words, we would plot the % ratio of the intensity of the transmitted (or absorbed) light to intensity of the incident light, as in Figure 11.



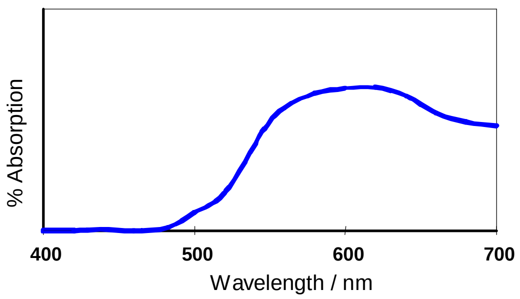


Figure 11: Typical plots of transmission and absorption

The hues of the transmitted colours due to absorption bands centred on particular wavelengths are given in Table 1. The colour will also depend on the width and profile of the absorption band. A wide absorption band may give duller colours as a wider range of wavelengths is being absorbed. For example, dull olive and brown shades require absorption almost throughout the visible spectrum. However, a very thin absorption band may result in rather pale colours, even if the extinction coefficient is high.

Table 1: Hues of the absorbed light and the transmitted light

Wavelengths absorbed	Hue of absorbed light	Hue of transmitted light
400 - 440 nm	Violet	Greenish yellow
400 - 500 nm	Blue	Yellow
460 - 500 nm	Greenish blue	Orange
400 - 620 nm	Bluish green	Red
480 - 520 nm	Green	Magenta
560 - 700 nm	Orange	Turquoise
600 - 700 nm	Red	Bluish green

If the profile of the absorption band is very steep and sharp, the colour is likely to be very pure as light of other wavelengths is transmitted easily. The absorption “baseline” often gives a good indication of the purity of the transmitted light.

Scattering of light

Scattering describes any process that changes the direction of the light and is usually associated with the interaction of light with small particles, as illustrated in Figure 12.

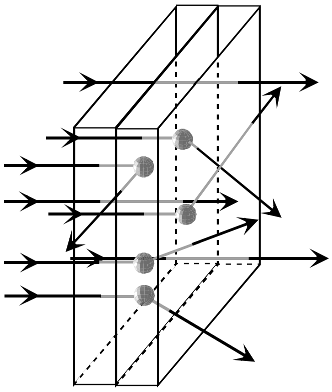


Figure 12: Change of direction by scattering

In fact, any change in the refractive index over a small region will cause scattering. Air bubbles within a liquid or a solid will also cause scattering and, in the case of beer, is the cause of the white appearance of the froth at the top of the glass, as shown in Figure 13.

The appearance of a material depends on the extent of scattering of the light and adjectives such as transparent, translucent, turbid and opaque are associated with the perceived degree of scattering.

Figure 13: Transparent (beer) and opaque (froth) forms of a liquid

For a colourless material, the degrees of scattering are approximately:

Transparent,	none of the transmitted light has been scattered
Translucent,	of order of 10% of the transmitted light has been scattered
Turbid,	of order of 50% of the transmitted light has been scattered
Opaque,	no light is transmitted through the material

The larger the difference between the refractive indices of the particles and the surrounding medium then the stronger is the scattering effect. For this reason, inorganic pigments, which often have high refractive indices, tend to scatter light much more effectively than organic pigments. Organic pigments often have refractive indices of about 1.5, similar to that of the medium in which they are used. Therefore, printing inks that contain organic pigments can be almost completely transparent.

Relatively large particles such as pigments, more than about 2.0 mm in dimensions, scatter light by the reflection and refraction of the light. Relatively small particles, less than about 0.3 mm in dimensions, scatter by diffraction of the light.

The scattering of light gives rise to one of the most common colours in the natural world - the blue of the sky. The sky is not “blue” in the sense that other wavelengths of light are absorbed. The sky is blue because blue light is scattered more effectively by very small particles than light of longer wavelengths.

During the daytime, when the sun is high in the sky, the blue light reaching our eyes (unless we look directly at the sun, which looks yellowish) has been scattered by interaction with tiny particles in the atmosphere. At sunrise and sunset, when the sun is low to the horizon, we see more of the non-scattered light and the sky appears red (Figure 14).

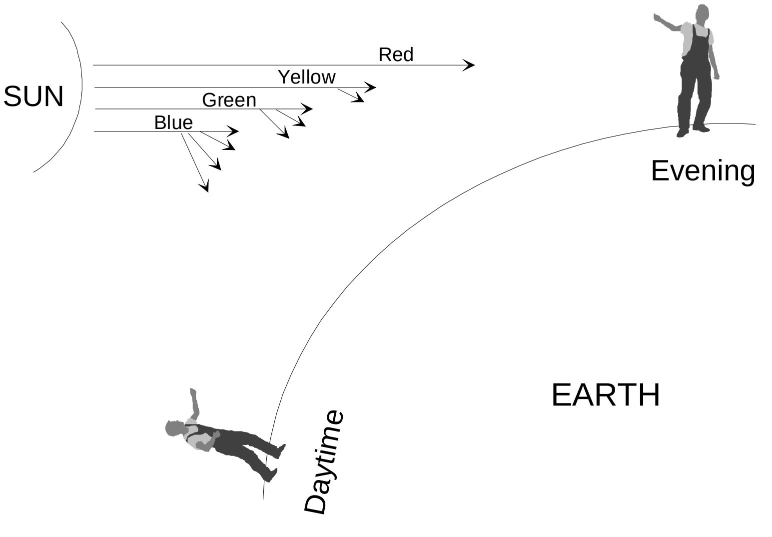


Figure 14: Blue sky and red sunset

Rayleigh scattering

Lord Rayleigh was the first to explain light scattering by very small particles. He determined that the intensity of scattering varies in three ways:

directly with the intensity of incident light

directly with the average volume of scattering particles

inversely with the fourth power of the wavelength of incident light.

It is the third relationship that gives rise to the different scattering power of particles to blue light compared to red light. Very small particles (less than about 300 nm in diameter) will scatter blue light (wavelength 400 nm) over ten times as more strongly than red light (700 nm).

An even more spectacular illustration of atmospheric scattering is a rainbow, caused by scattering, (by refraction) of sunlight by very fine water droplets. Each wavelength of light is scattered to a different extent and so the familiar spectrum of colours is seen.

Opaque materials

When a material contains a large amount of pigment, or a coating layer is thick enough, none of the incident light will penetrate through the material or the coating layer. The spectrum of the light reflected from an opaque layer is determined by the absorption and the scattering properties of the components in the material and does not change very much with the thickness of the material. Another property of an opaque material is that the addition of a transparent, colourless diluent to the material will not change its appearance.

For an opaque material, the fraction of the incident light reflected at each wavelength is determined by the ratio of the absorption coefficient to the scattering coefficient and not on their absolute values.

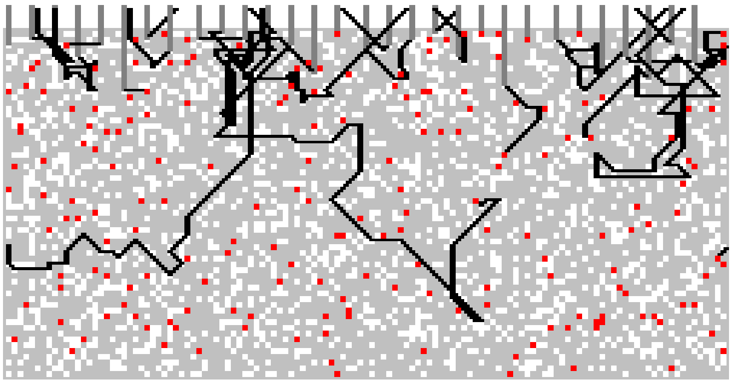


Figure 15: Simulated photon paths, opaque layer

Figure 15 illustrates the paths that photons might take in an opaque, pigmented material. The figure was obtained by using a computer program to simulates the interactions of an incident light beam with a layer composed of a clear medium, a white pigment and a coloured tinter pigment.

Photons were “fired” at the top surface of the layer and when the photon encounters a particle, a random number generator is used to decide whether the photon is absorbed or scattered by the particle. The figure shows the paths obtained when 30 photons were fired at the layer.

<u>Interference</u>

Interference effects are responsible for the iridescent colours seen in soap bubbles, in oil droplets and in the wings of many insects. The basis of this effect is the interaction between beams of light having the same wavelength and travelling in the same direction.

The oscillating electric fields can interact with each other, causing either constructive reinforcement or destructive cancellation (Figure 16).

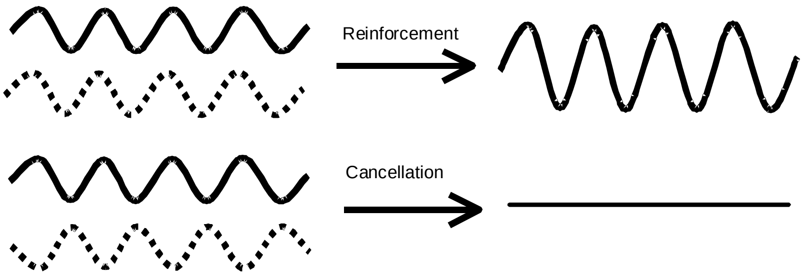


Figure 16: Constructive and destructive interference

In order for interference to occur, the oscillations of the electric fields involved must be exactly in phase with each other (reinforcement) or 90° out of phase (cancellation). Ordinary white light is fairly disordered with respect to phase, the phase of the wave jumps forwards and backwards every few cycles and this is known as non-coherent light. Because of this, interference rarely occurs for ordinary light, except under specific circumstances.

Thin film interference

A common situation when interference can occur is in thin films or layer structures, as illustrated by the colours shown in the reflections from the surface of soap bubbles, Figure 17.

The intensity of the incident light is split at the surface of the film, and part is reflected from the top boundary and part is refracted into the material. The refracted beam passes through the layer and is internally reflected at the lower boundary. The back reflected beam passes back through the upper surface boundary and then has the same direction as the top boundary reflected beam.

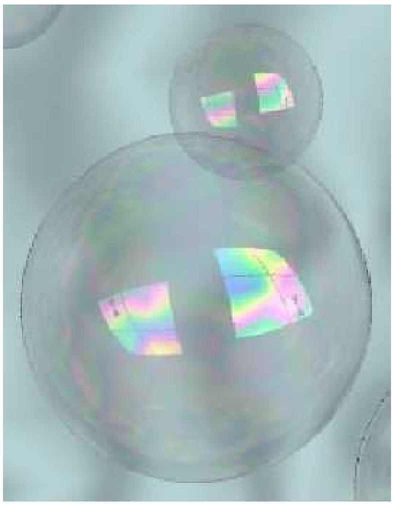


Figure 17: Interference creates colours in reflections from a soap bubble

This is illustrated in Figure 18. Thin-film interference colours can be seen even with non-coherent incident light so long as the film is very thin.

In Figure 18 it is clear that the lower boundary reflected beam has travelled further through the material than the top boundary reflected beam.

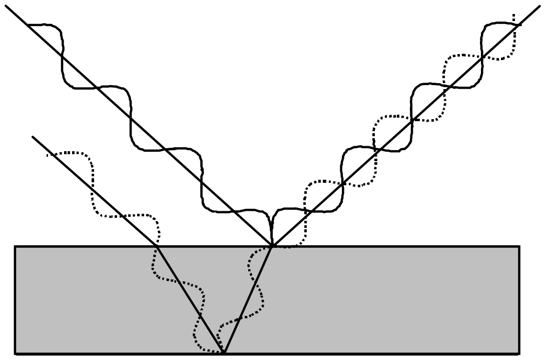


Figure 18: Interference due to reflection at top and lower boundaries of thin film of material

Thus, at a particular angle of viewing the two beams leaving the surface of the material will be out of phase with each other and interfere destructively, such that no light emerges. The light energy is not being lost, merely re-distributed to take part in constructive interference at another angle of viewing. For a particular wavelength of light, we can calculate the angles of viewing at which constructive interference will occur and a bright colour will be seen.

Interference pigments

Interference pigments make use of this effect to generate colour from white light. The pigments are generally composed of platelets of natural mica coated with a thin layer of a transparent metal oxide (such as titanium dioxide, chromium (III) oxide or iron (III) oxide), Figure 19.

When incorporated in a coating, the platelets are aligned such that they behave as a multiple layer system, Figure 20. The thickness of the metal oxide layer is closely controlled such that interference will occur when the coating is viewed at particular angles.

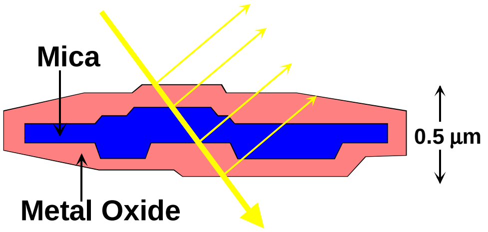


Figure 19: Cross section of a particle of a mica based interference pigment

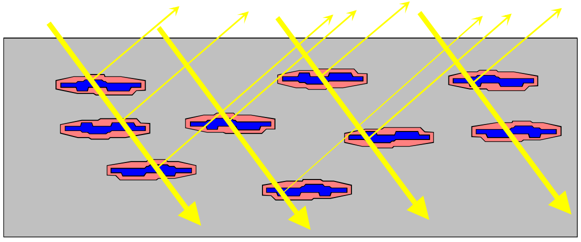


Figure 20: Mica platelets aligned in a coating layer

These coatings exhibit what is known as "colour flop", whereby the colour seen changes with the angle at which the surface is illuminated and viewed, as shown in Figure 21.

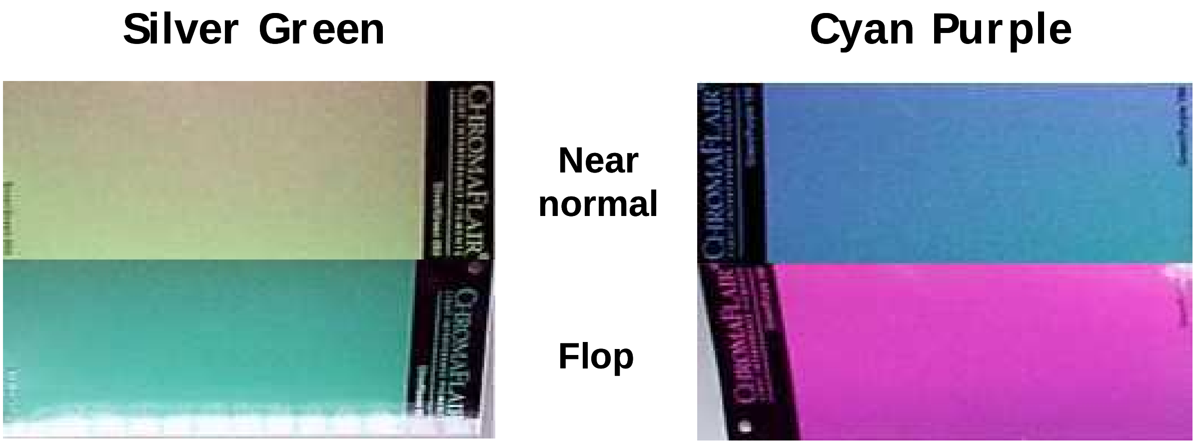


Figure 21: Near normal and Flop colours for coatings containing Chromaflair pigments

Luminescence

The term "luminescence" covers the generation of light by the conversion of other forms of energy. The stimulus energy may be supplied in many ways such as by heating (thermoluminescence), by the action of an electrical energy (electroluminescence) or by irradiation with visible or ultra-violet light (photoluminescence).

The most familiar type of luminescence is probably photoluminescence. Radiation of a relatively short wavelength (high energy) is absorbed by a material and after a short time; the energy is emitted as light of a longer wavelength (lower energy). The energy changes undergone by a molecule are illustrated in Figure 22. The residual energy is converted to heat.

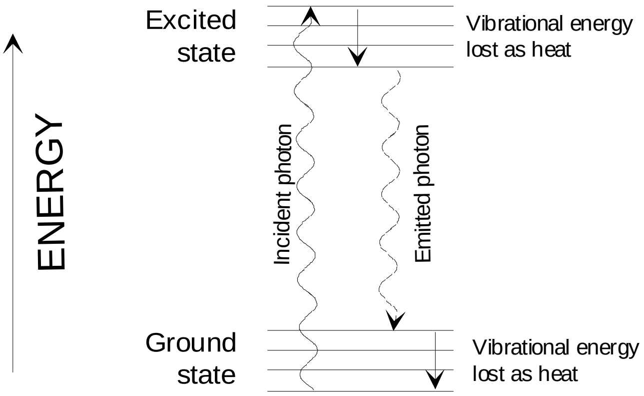


Figure 22: Loss of energy by photoluminescence>

For example, the optical whitening agents used in textiles and in detergents, absorb ultra-violet radiation and re-emit the energy as blue light (the "blue-whitener"). Luminous paints act in a similar way.

Photoluminescence may be split into *fluorescence* and *phosphorescence*. The distinction between these two is that emission by fluorescence occurs virtually immediately after the energy is absorbed. The light emission by phosphorescence is usually delayed and emission by excited molecules may persist for some time after the removal of the stimulus radiation.

Creation of Colour

It is clear from just looking around that most coloured objects can be classed as “reflective” or “surface colours”. They appear coloured because of the interaction of the white light shining onto their surfaces with the atoms and molecules within the surface. The majority of materials produced by the printing industry are surface colours and understanding the creation of surface colours is the topic of this section.

The majority of materials produced by the surface coatings industry and the printing industry create colour by the action of the dyes or pigments incorporated into the printing ink or the coating material.

The normal situation of viewing an object is illustrated in Figure 23. A “white” light source is used to illuminate the object. The colorants within the surface of the object interact with the incident light and a proportion of the light is reflected by the surface towards the eyes of the observer. The observer perceives the colour of the surface.

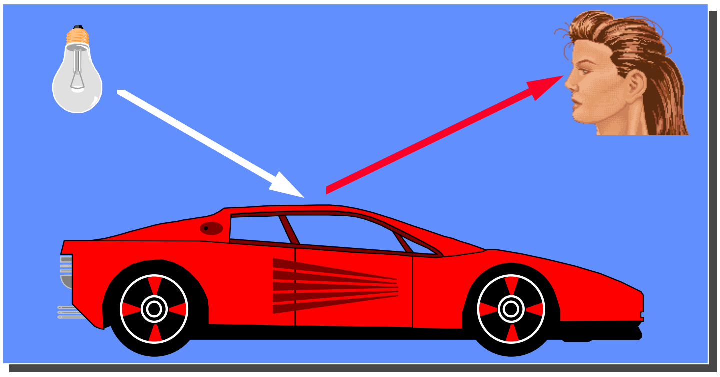


Figure 23: Creation of colour by the interaction of light with an object and an observer

Light absorption and reflection

When white light is shone onto a white piece of paper, the surface reflects some of the light towards the eye. The cone sensors in the eye produce a balanced set of three visual signals, from the long, medium and the short wavelength sensitive cones. The signal is transmitted to the brain of the observer where the brain interprets the balanced signal as “white”.

When white light is shone onto a print layer or a coating layer the pigments or dyes that are present absorb energy at some of the wavelengths in the incident light. The light at the remaining wavelengths is reflected back by the substrate or by any highly scattering “white” pigments that may be present. The process is illustrated in Figure 24.

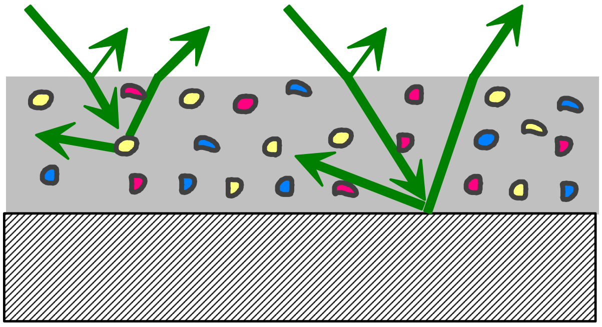


Figure 24: Absorption and scattering of light by a printed surface

The light reflected from the surface will enter the eye however, however some of the wavelengths are weakened or missing compared to "white" light, as a result the set of signals sent to the brain is no longer in balance. The brain interprets the unbalanced signal as a coloured surface.

Conventional pigments create colour by absorbing light within a band of wavelengths within the visible spectrum. The creation of various colours can be understood by considering the absorption and reflection of light within, a blue band (band 1), a green band (band 2) and a red band (band 3). The three bands of wavelengths shown in Figure 25

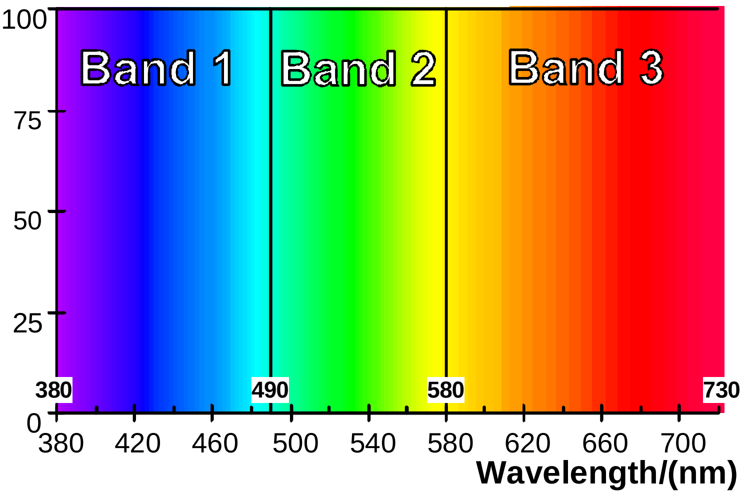


Figure 25: Blue, green and red wavelength bands>

To appear coloured, a material should mainly absorb light from wavelengths within one, or at most two of the bands shown in Figure 25. Table 2 illustrates the way in which the colour is created by selective absorption within the three wavelength bands. If the material absorbs in none of the bands then it will appear white. If it absorbs equally at wavelengths spread evenly through all three of the bands then it will appear grey or black.

Table 2: Surface colours and light absorbed

Colour of Surface	Band 1 Blue	Band 2 Green	Band 3 Red
White	REFLECTED	REFLECTED	REFLECTED
Black	absorbed	absorbed	absorbed
Yellow	absorbed	REFLECTED	REFLECTED
Magenta	REFLECTED	absorbed	REFLECTED
Cyan	REFLECTED	REFLECTED	absorbed
Blue	REFLECTED	absorbed	absorbed
Green	absorbed	REFLECTED	absorbed
Red	absorbed	absorbed	REFLECTED

Rectance spectra

Red surface

A red object appears red because the material absorbs most of the light with wavelengths in the blue band (1) and in the green band (2), only the wavelengths in the red band (3) are reflected into the eye. This is illustrated in Figure 26 for a red surface with the CIE specification L* = 60.0, a* = 50.0, b* = 15.0.

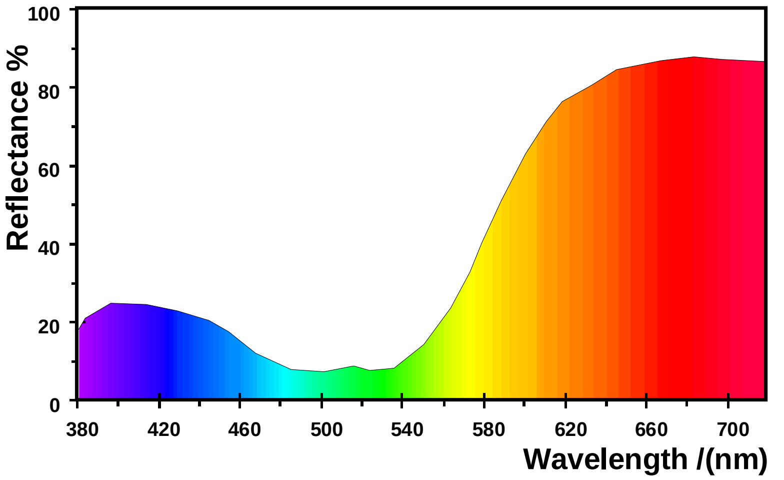


Figure 26: Reflectance spectrum of a red surface

Green surface

A green object appears green because the material absorbs the light with wavelengths in the blue band (1) and in the red band (3). Only the wavelengths in the green band (2) are reflected into the eye. This is illustrated Figure 27 for a green surface with the CIE specification L* = 70.0, a* = -50.0, b* = 10.0.

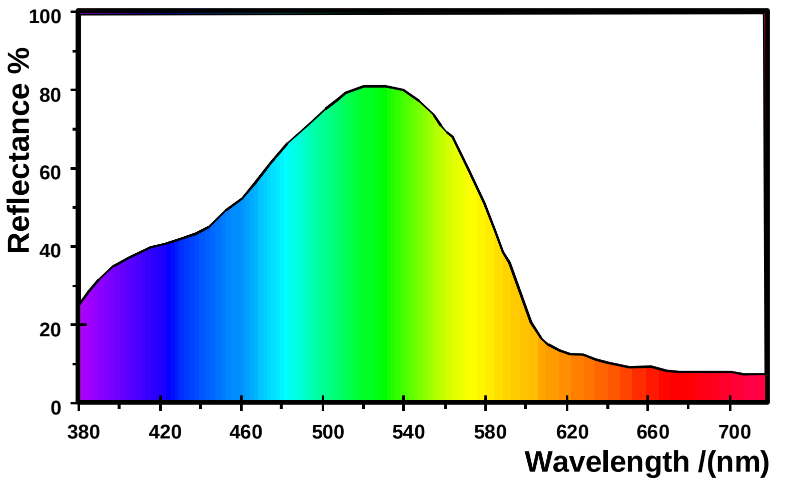


Figure 27: Reflectance spectrum of a green surface

Blue surface

A blue object appears blue because the light with wavelengths in the green band (2) and red band (3) are mostly absorbed by the material and only the wavelengths in the blue band (2) are reflected into the eye. This is illustrated in Figure 28 for a blue surface with the CIE specification L* = 70.0, a* = -10.0, b* = -35.0.

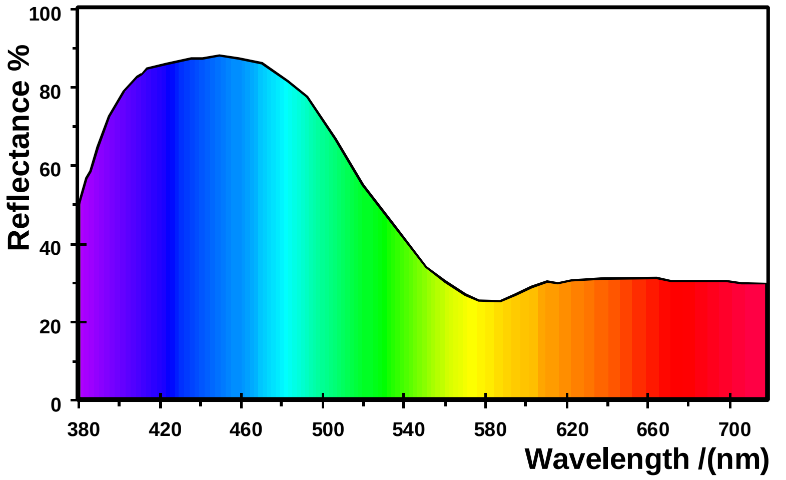


Figure 28: Reflectance spectrum for a blue surface

H21: Light, Materials and Colour