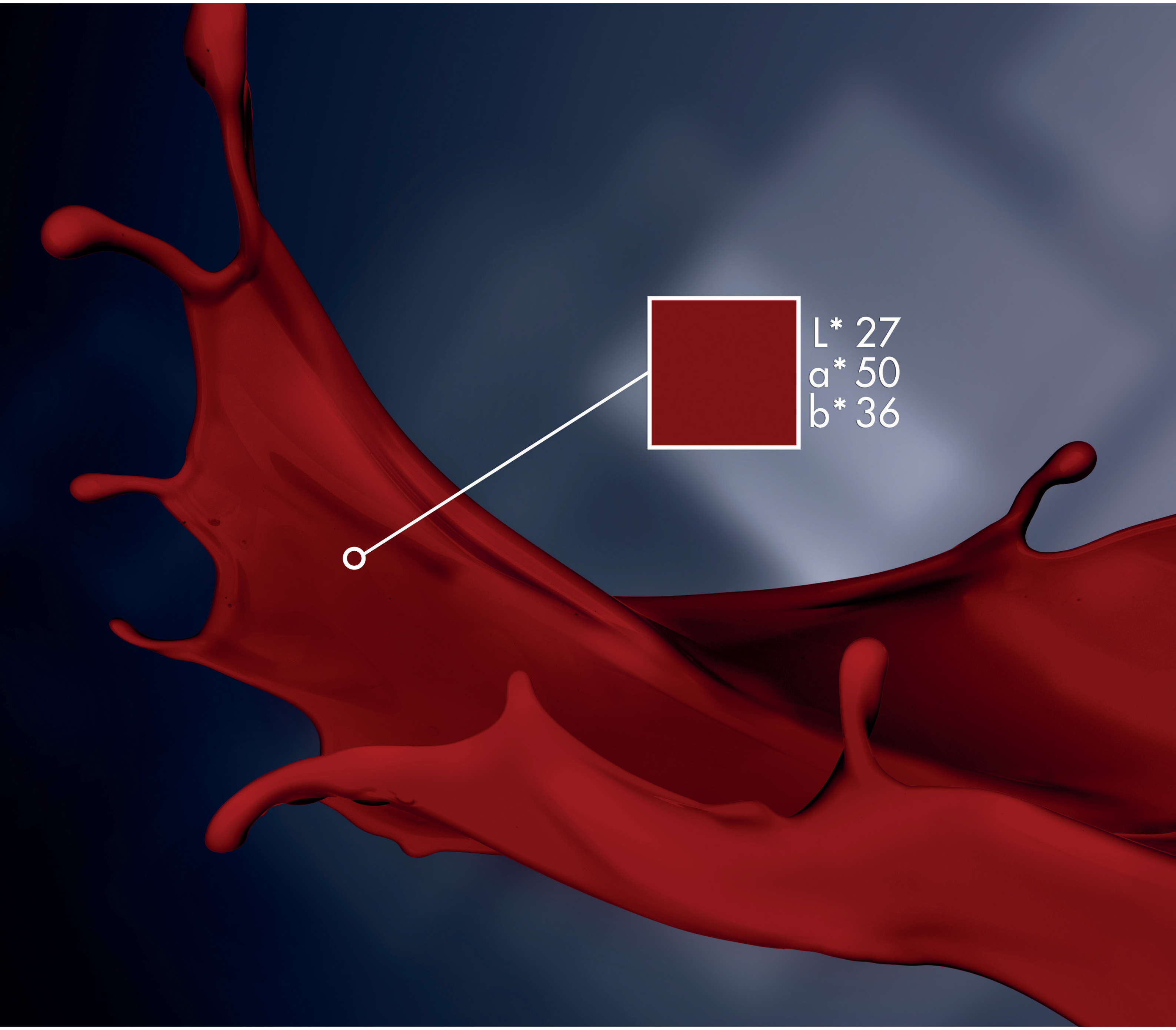
BOOK TWO OF COLOR MANAGEMENT



The triplet of color:
Light, object and observer

datacolor

[...what color is the object?
The triplet:
light source – object – observer

A light source, an object, two observers!
Interpretation means that each observer sees in his/her head and in his/her own way.

Chapter 5

The triplet

The elements of the triplet

We are surrounded by color. Wherever we look, we perceive colors of various shades and intensities.

But what, exactly, is color?

Color is not a physical attribute of objects. An object interacts with radiant energy and our eyes are wired to detect that interaction. This physical sensation is transmitted to our brain where it interpreted and we have an experience of color.

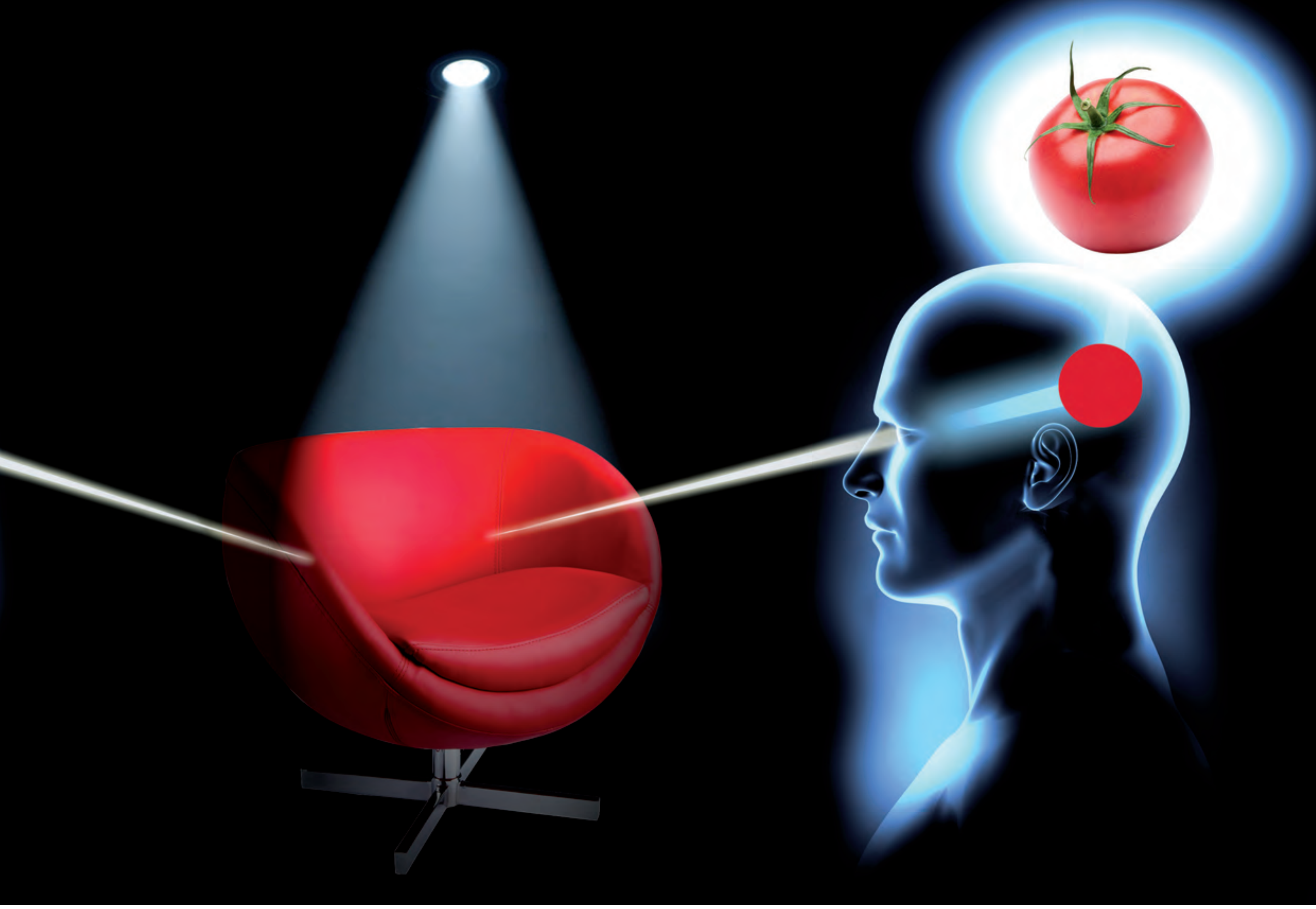
Sensations are subjective – each person perceives color differently. Physical, physiological, and psychological factors all influence perception. Therefore, a person can perceive one and the same color differently, due to different states of mind, for example. This raises the question – can a visual evaluation by a human observer be expressed in objective numerical values?

Color is a subjective experience and it is impossible to generate a numerical description of color that fully captures the experience. However, the science of colorimetry offers useful tools for measuring and identifying the physical components of color.

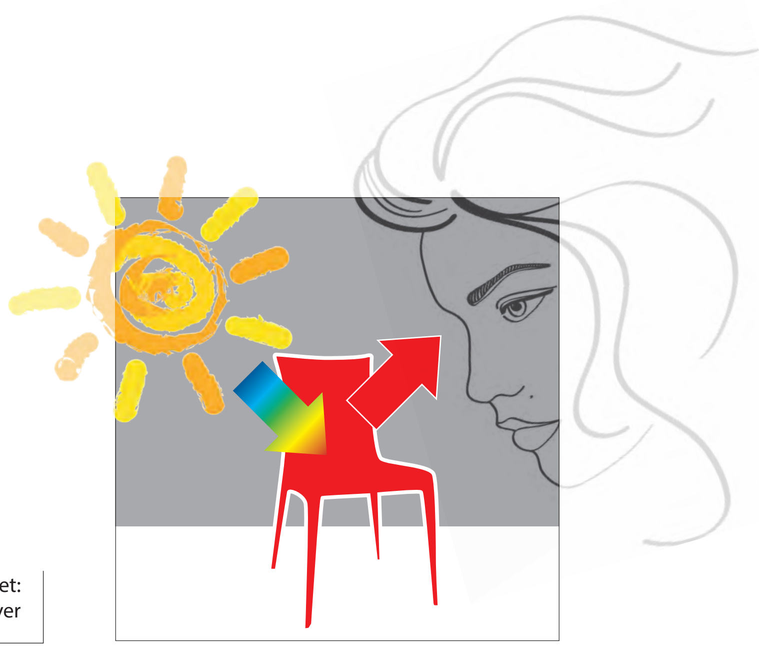
These Include:

- A light source
- An object
- An observer

If just one element of this set is missing, a color impression is impossible.



The science of colorimetry has developed methods for quantifying each of the three elements. We will now look closely at how we generate a numerical description of each component in the triplet.



The 3 elements of the triplet:
light source – object – observer

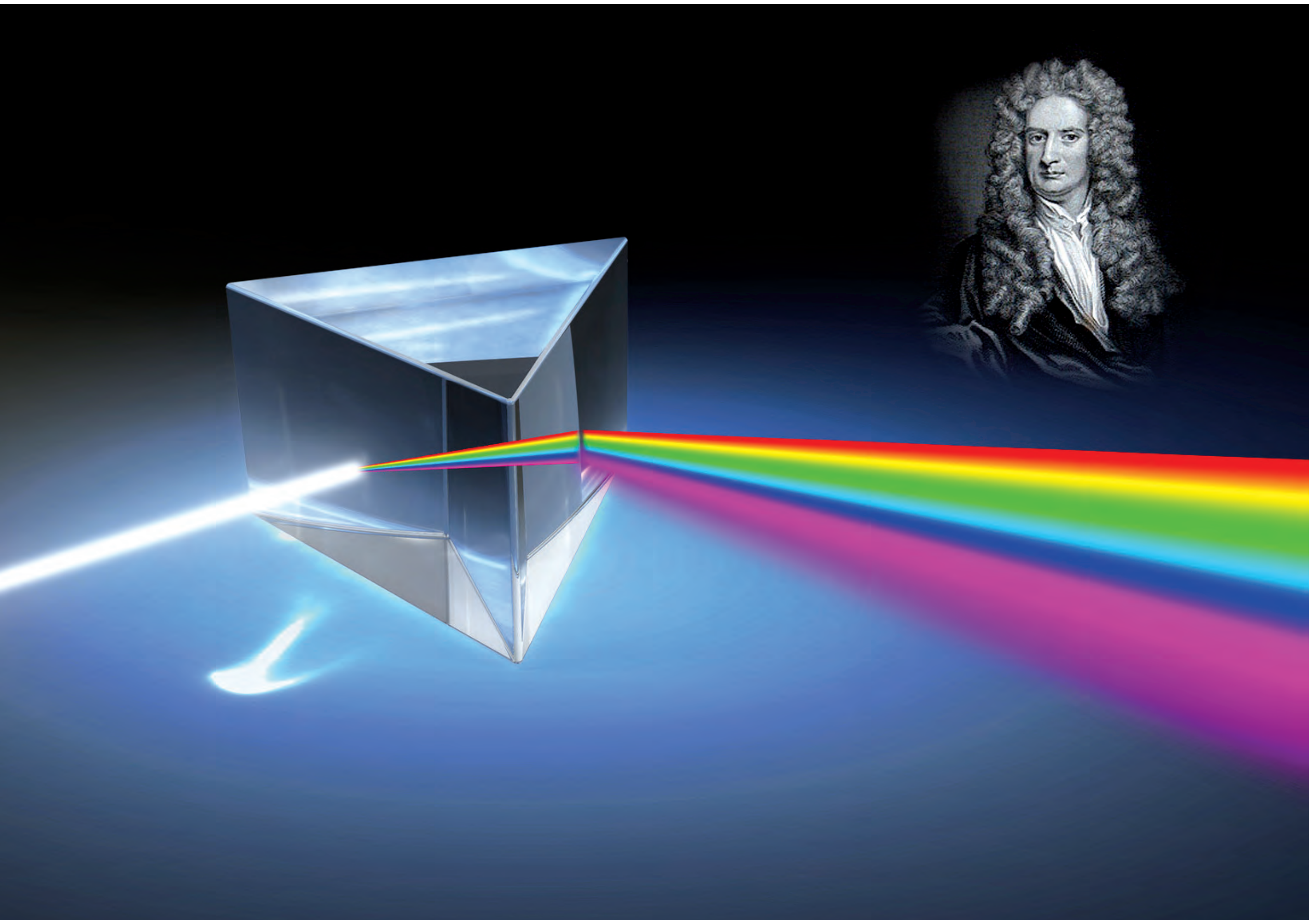
The light – the light sources

Referring to music, Isaac Newton distinguished seven fundamental shades of color.

The interplay between light and matter

In 1666, physicist Isaac Newton was experimenting with sunlight. On a sunny day, he directed a ray of light through a hole in the shutter of a window. This light passed through a glass prism and Newton projected the light onto a screen. He noted that the light was split into different colors, which were identical to those of the rainbow.

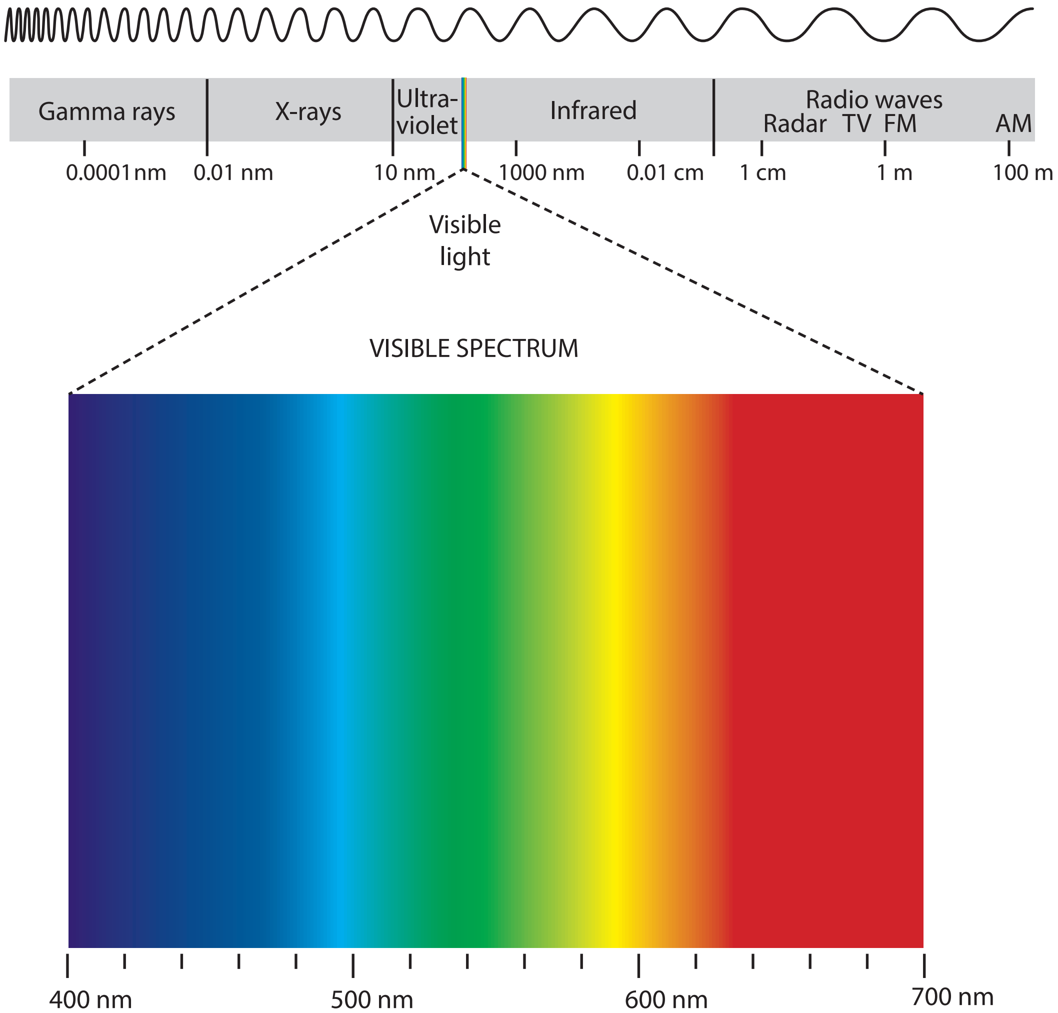
Light, in fact, is the raw material of color. Newton correctly theorized that the individual colors had to be components of daylight. After countless experiments, Newton went on to identify the fundamental color hues as violet, indigo, blue, green, yellow, orange and red.



In 1666, physicist Isaac Newton passed white sunlight through a prism. The ray of light was disassembled into its components, resulting in a color spectrum.

Building on Newton's work, modern physicists have established that light is made of electromagnetic waves. So are x-rays and radio waves. Scientists define light rays by their wavelength. The unit of wavelength measurement is a nanometer, or 1 billionth of a meter (10-9m).

The order in which the colors appear in the rainbow is based on wavelength. The visible spectrum is organized from shortest to longest wavelengths. Blue light is associated with shorter wavelengths, followed by green, yellow, orange and red.



Theory of electromagnetic oscillation. This includes all of the types of radiation in use in modern civilisation.

The spectrum of the light visible to the human eye in the range of 400-700 nm.

The light sources

The first element of the triplet is the light source.

Light can be generated in different ways – by heating an object until it glows (like the wire in a lightbulb) for example, by stimulating atoms or molecules using an arc, or via electric discharge in a gas (e.g. in a xenon flash lamp).

Each different light source has a different light color. This light color affects the color of the object that it illuminates. The measurement for the color impression of a light source is the color temperature, which is specified in kelvin (K). The "black body" (Planckian radiator) serves as a reference for the color temperature.

"Black bodies" do not exist in reality. It is a model concept in physics, serving as the basis for theoretical observations and as a reference for the practical research of electromagnetic radiation.

A black body has two very important characteristics:

- It completely absorbs the electromagnetic radiation of all wavelengths that falls on it, and
- In each spectral range, it emits more radiated power than any other body for the same temperature.

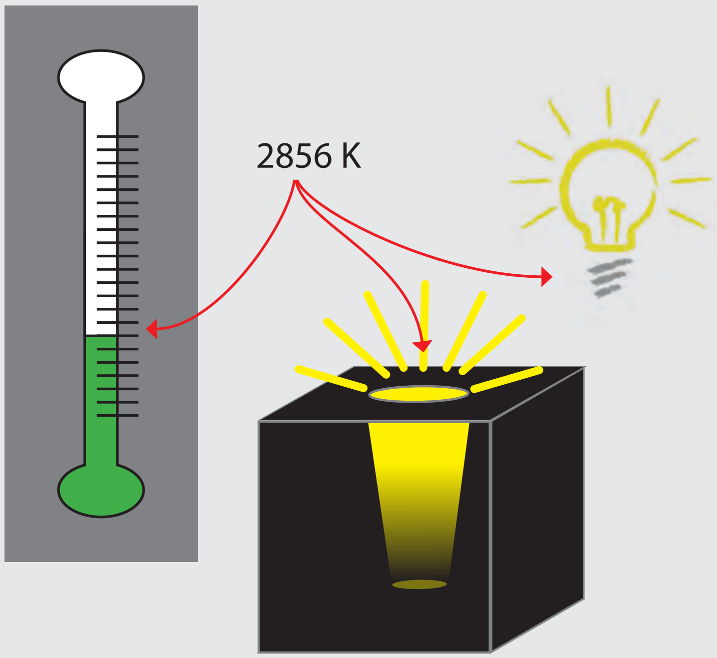
In order to identify the color temperature of a light source, a black body is heated until it emits a light of the same color as the actual light source.

The most important natural light source is the sun.

We generally see colors by daylight. Daylight consists of direct sunlight and light that is radiated by the atmosphere. The spectral range of sunlight goes from 200 to 4000 K. It can be compared with the radiation of a black body heated to 5800 K. However, the quality and energy of this light source varies and is not constant. Sunlight is influenced by location, time of year, weather conditions, atmospheric pollution, and the time of day, and changes accordingly. As a result, the color temperature of daylight varies between 4000 and 6500 K.

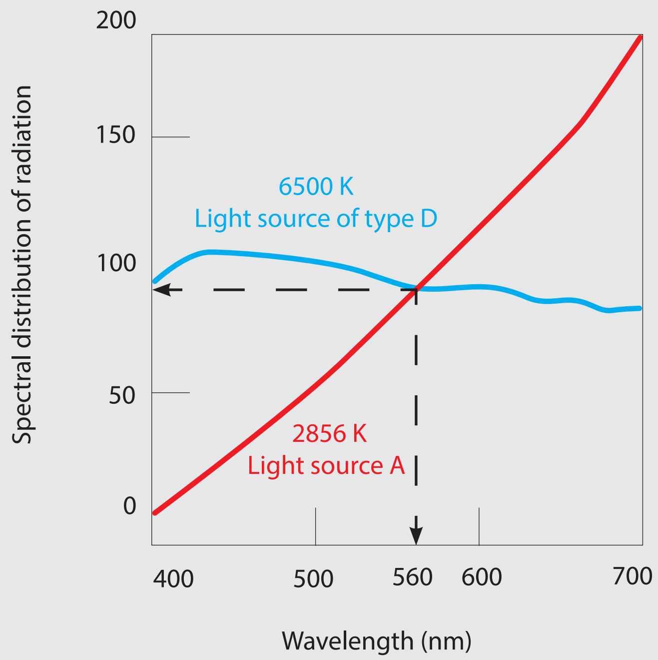
Such a light source is not suitable for colorimetric calculations. For color measurements, the light source referred to as daylight must be standardised so that it is reproducible and constant.

The black body



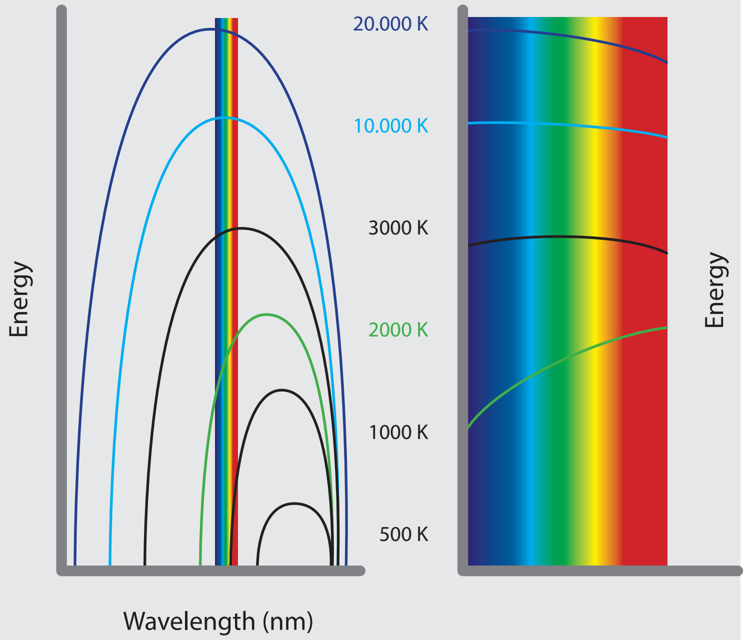
The Color temperature of illuminant type A (lightbulb) is equivalent to the light color of a Planckian radiator (black body) that is heated up to 2856 Kelvin (2856K).

Spectral radiation distribution of 2 light sources



[At 560 nm, the radiation energy is the same for both light sources. For standardisation, the radiation energy at 560 nm is defined as 100% or as identical.

The color temperature



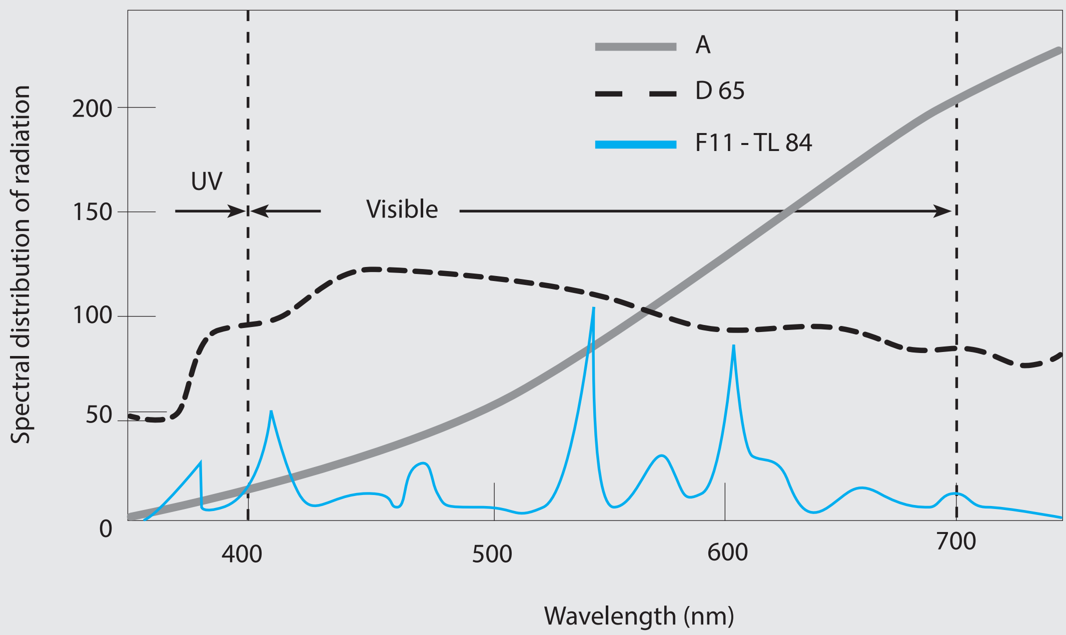
Illuminant types

The color impression of an object appears different with different light sources, so the illumination must always be defined.

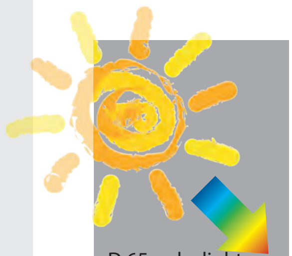
In order to be able to describe a light source in a way that is reproducible and constant, the CIE* International Commission on Illumination evaluated and characterised different light sources to create reliable industry standards. These defined light sources are called "standard illuminants". Standard illuminants are not physical light sources. They have been defined in such a way that their spectral distribution of radiation resembles that of the natural light sources. The most important of the illuminant types standardised by the CIE are D65 (daylight at 6504 K), A (Tungsten), and F11 (a fluorescent lamp).

(*) CIE: Commission Internationale de l'Éclairage/ International Commission on Illumination – founded in 1913 – the only international organisation for recommendation and standardisation with regard to illumination, color and color measurement.

Standard illuminants A, D65, F11 - TL 84




A = tungsten


D 65 = daylight


F11 - TL 84
= fluorescent lamp

The most important standard illuminant types: D65, A and F11

The object – the matter

The interaction between light and object

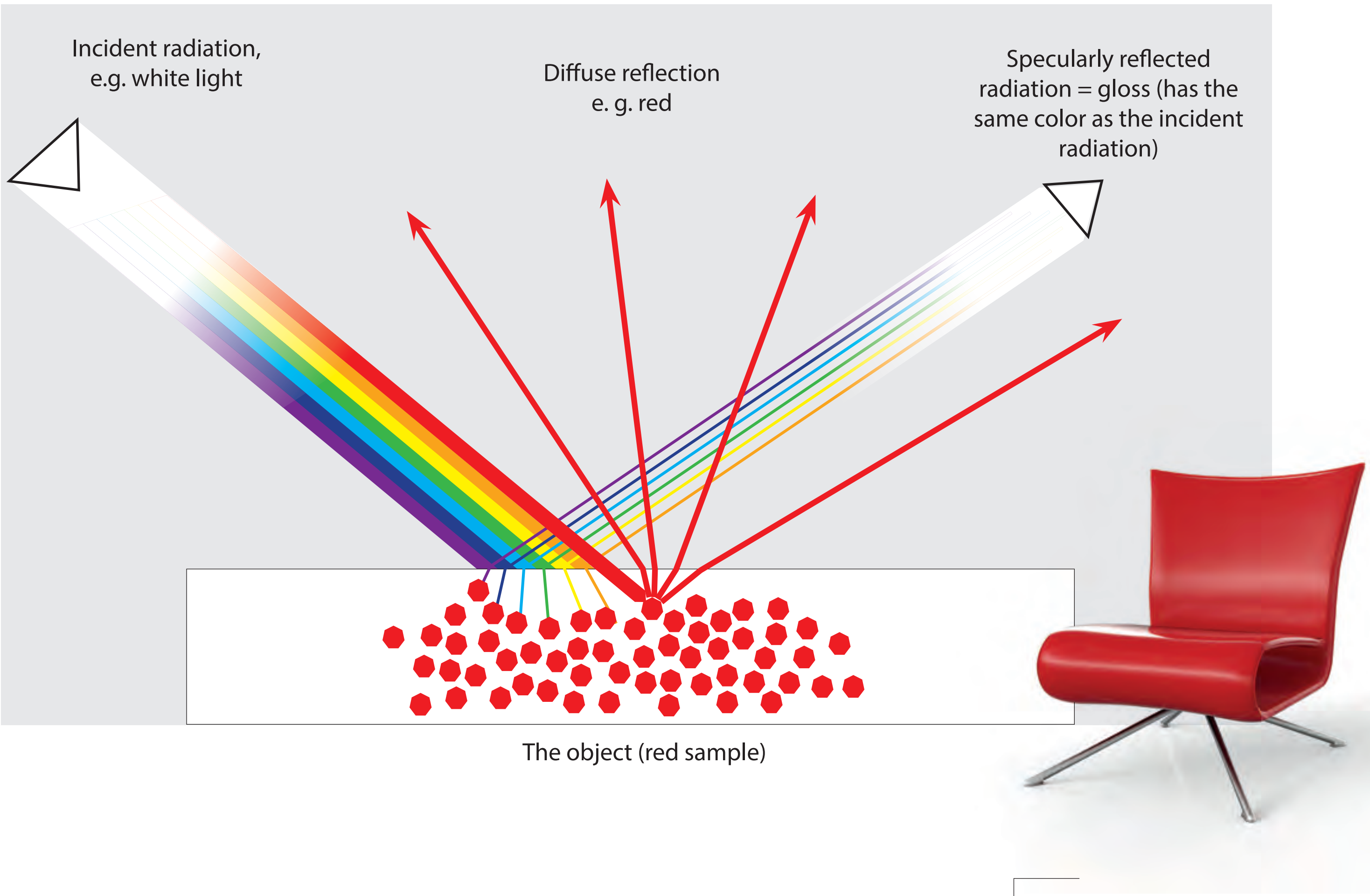
The second element of the triplet is the object.

An object must interact with light in order for the eye to see color. This interaction takes one of three forms:

Each object and each surface has specific individual characteristics, which affect the way in which irradiating light is reflected or absorbed. A distinction is made between

- Opaque or non-transparent objects: part of the light is absorbed and part is reflected
- Transparent objects: part of the light is reflected, part is absorbed, and part is allowed through without being scattered
- Translucent objects: part of the light is reflected, part is absorbed, and part is allowed through but is scattered

Objects have the characteristic of reflecting electromagnetic radiation to a greater or lesser extent
Visual impressions of the different materials are determined by various factors, including also the characteristics of the material itself. Therefore, the color of a glossy sample appears considerably more intensive and vibrant than the same color with a matte surface. With separate analysis of the color characteristics (color) and the geometric characteristics (gloss, form, texture), this problem can be simplified by separating the radiation emitted by the object (color) from the specularly reflected radiation (gloss). The separation of these two types of radiation makes it possible to determine each individual component. We will go into more detail on the measurement instruments used for this and the applicable analysis methods in chapter 12 (scientific measurement techniques in color measurement).



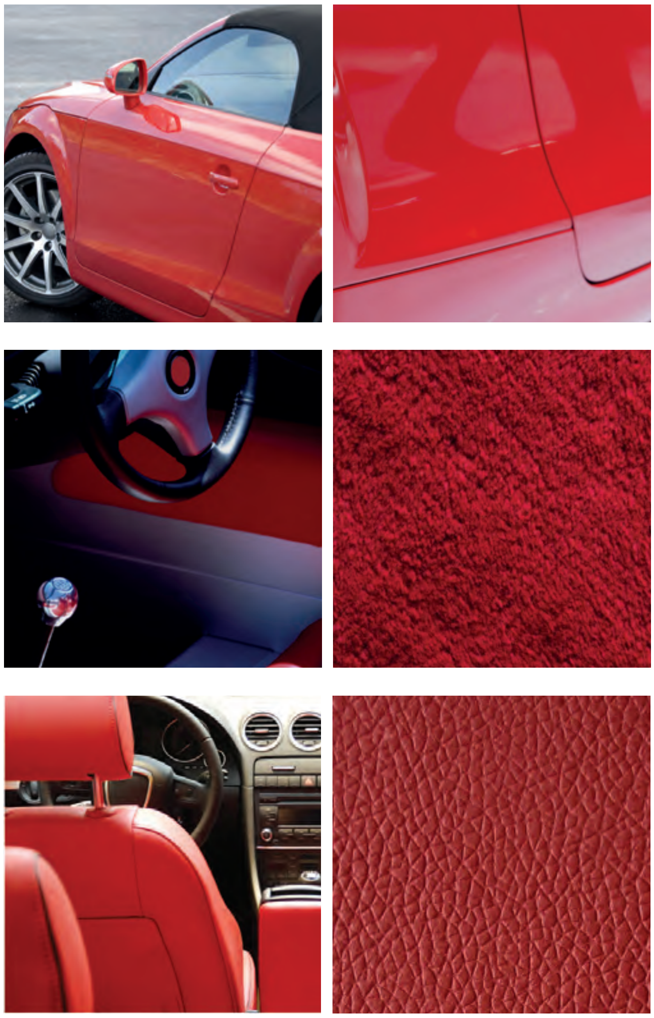
The interaction between light and object. E.g. a red sample

The reflection generated by the specular reflected radiation is responsible for whether the object appears glossy, semi-matte, or matte. Metals are generally characterised by more strongly reflecting rays than other products, and smooth surfaces generally look glossier than rough surfaces.

Diffuse reflection is a characteristic of the object, its color and its composition.

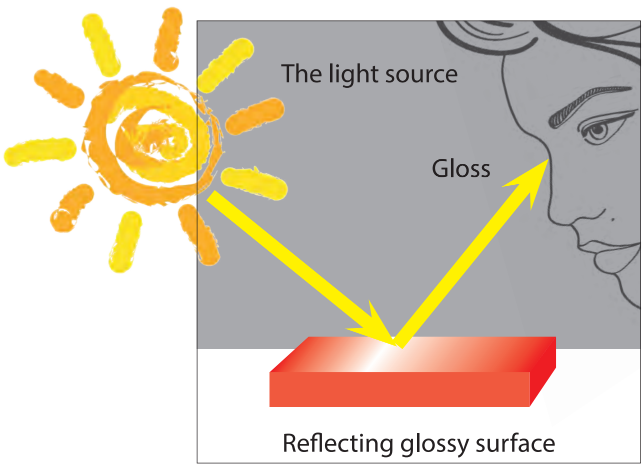
Color is generated when light strikes an object, a part of the light is reflected, and this part enters the human eye. The selective absorption of light therefore determines our perception of color. The more light that is absorbed, the less intensive are the resulting colors. If all of the light is absorbed, we perceive the color black. If all of the light is reflected (100%), we see the color white.

The reflection or absorption of light (specular reflected radiation, reflected diffuse radiation, normal radiation) is therefore responsible for the color and appearance of most objects. The components of this phenomenon can be physically analysed by means of spectrophotometric measurements (or goniophotometric also in some special cases). These spectrophotometric measurements result in diagrams showing the spectral distribution of radiation or spectral curves, which represent the light radiation reflected or allowed to pass through by an object for each wavelength. The spectral curves describe the color and appearance of an object.

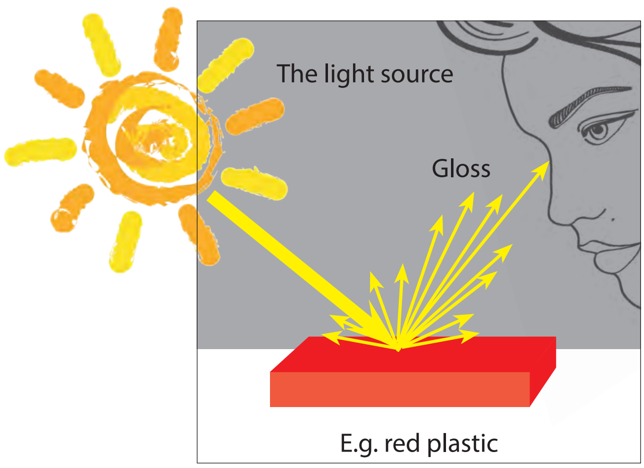


Absorption, scattering and gloss are responsible for the appearance of a product.

Gloss for a reflecting surface



Gloss for a textured surface



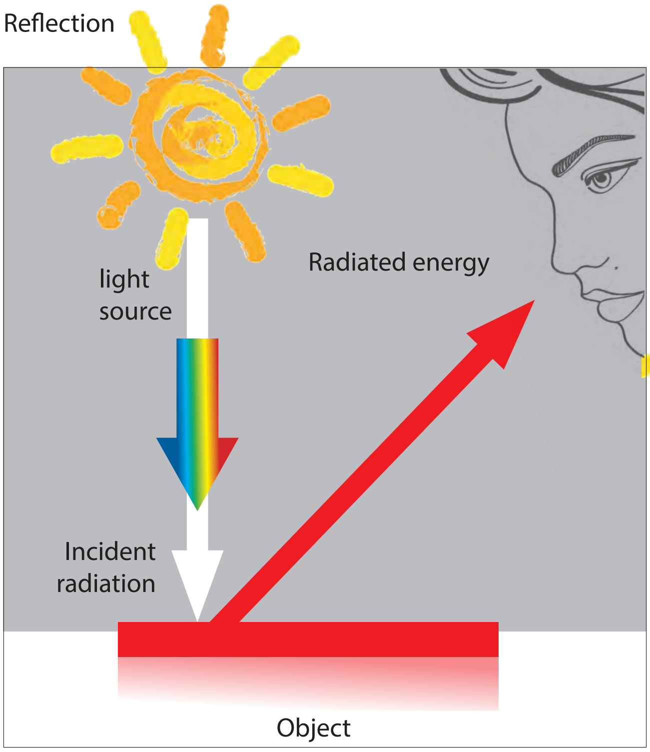
The color characteristics of objects – the physics of colors

As we already know, color is based on electromagnetic waves and on their distribution of radiation in the visible spectral range.

The wavelengths of the rays in the visible spectral range are between 400 and 700 nm. The color of an object results from light striking the object surface. Part of the radiation is absorbed, and part is reflected or allowed to pass through. The parts of the radiation that are reflected or allowed to pass through can be perceived by the eye and processed in the brain for the color impression.

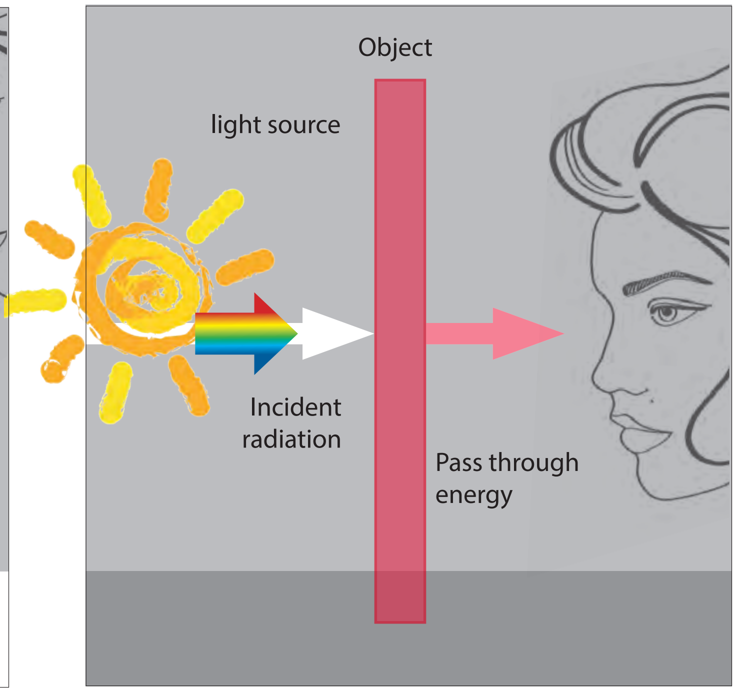
A yellow object absorbs light in the blue range. Red objects absorb light in the blue, green and yellow range. In physics, we refer to the spectrophotometric light distribution of an object, and it is due to this characteristic that the color of an object is determined and displayed. It is the representative graphical representation of the portion of incident light radiation that is reflected or allowed through as a function of the wavelength, for the visible spectral range of 400-700 nm.

Reflection



$$\text{Reflectance ratio R\%} = \frac{\text{Reflected light energy per wavelength}}{\text{Incident light energy per wavelength}} \times 100$$

Transmission



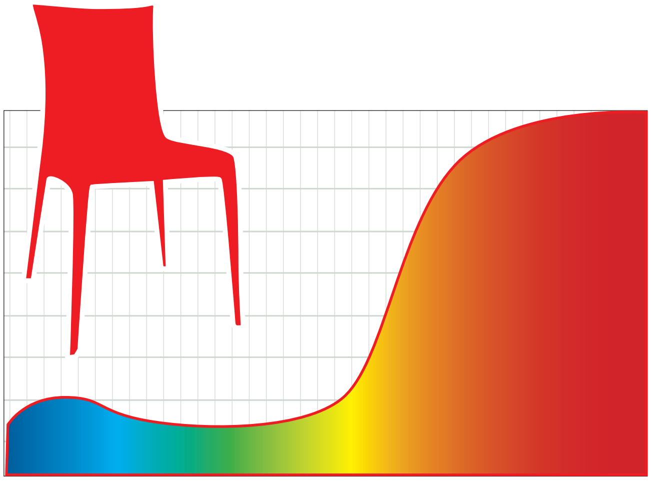
$$\text{Transmission ratio T\%} = \frac{\text{Pass through light energy per wavelength}}{\text{Incident light energy per wavelength}} \times 100$$

The R% reflectance values are the result of the ratio of incident light energy to reflected light energy per wavelength. This applies equally to the transmittance, where the incident radiation and outgoing radiation characterise the transmission curve. The reflection and transmission curves are material properties. They are independent of the light source used. It is prerequisite that the light source used emits energy in all ranges of visible light.

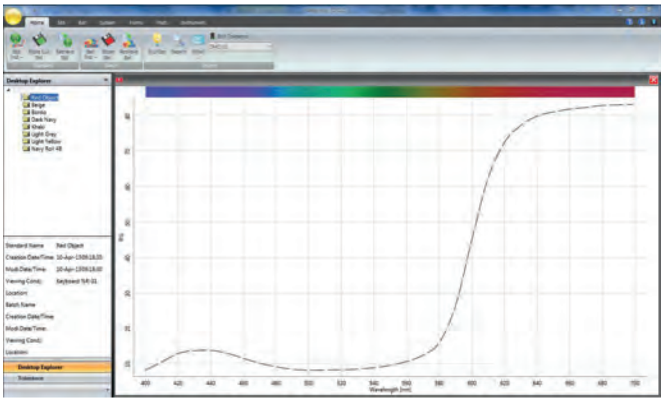
The following example shows the reflection curve for a red sample. This reflection curve describes the material and the color of the sample – it is the "fingerprint of this color".

Wavelength (in nm)	Reflection value (R in %)
400	8,17
410	10,47
420	12,87
430	13,67
440	13,76
450	12,92
460	11,46
470	10,11
480	9,10
490	8,40
500	8,12
510	8,14
520	8,25
530	8,45
540	8,84
550	9,50
560	10,63
570	12,36
580	15,97
590	26,40
600	45,11
610	62,43
620	72,43
630	77,21
640	79,64
650	81,01
660	81,81
670	82,30
680	82,64
690	83,01
700	83,19

Shiny red sample: measurement with a measurement geometry of d/8° with specularly reflected light (gloss)



Reflection curve for the red sample – the "imprint of this color"



The eye - the observer

Man as the observer – color vision

The third element of the triplet is the observer or the perceptual apparatus of the person (eye and cerebral cortex).

The light reflected by an object or directly radiated by a light source is absorbed by the eye and converted by the photoreceptors in the retina. Our cerebrum interprets this information and generates the color impression.

Depending on the wavelength, the eye exhibits different sensitivities to the lightness of the light in the visible spectral range (see chapter 9). We perceive light at different levels of lightness (light/dark vision), but also see the color characteristics (hue and chroma), and arrange the colors into a three-dimensional system.

Prerequisite for this three-dimensionality of color vision is the existence of three different types of receptors in the human eye. This has long been established in science. Understanding of the human color perception process began when Newton published his works on the splitting of white light with a glass prism in 1666. The most important findings and progress were not made, however, until it was possible to take measurements with regard to the sensitivity of the color receptors in the eye.

In 1801, English eye physician and physicist Thomas Young developed the three-component theory. This says that human color perception is based on only three different types of receptors (trichromatic perception of color stimulus). 50 years later, German scientist Hermann von Helmholtz helped establish the additive theory of color vision put forward by Thomas Young. He demonstrated that three primary colors (red, green and blue) are sufficient to generate all other colors.

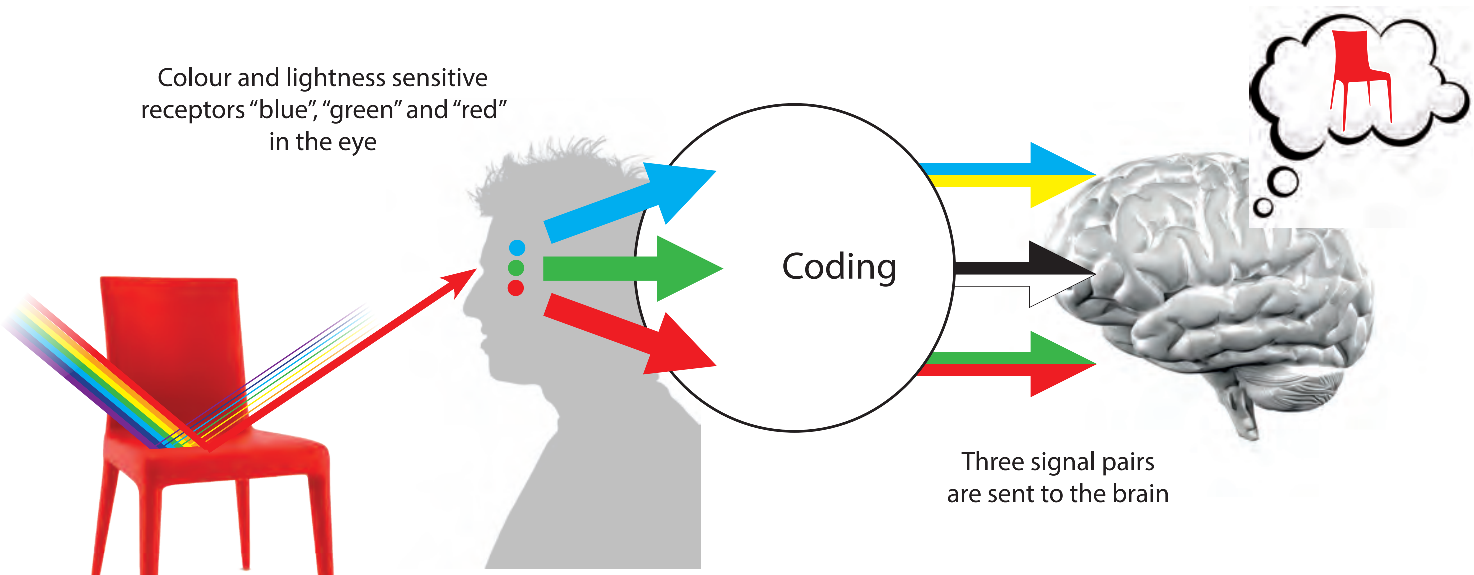
Thomas Young | Hermann von Helmholtz | Ewald Hering

In 1878, Ewald Hering published his opponent color theory as an alternative proposal to the three-component theory of Helmholtz and Young. Hering started out from the observation that color impressions such as "yellowish blue" or "reddish green" cannot be envisioned (mutual elimination of yellow and blue or green and red). Therefore, he assumed three separate chemical processes in the retina with two opponent colors each, each one trying to achieve equilibrium with an inhibiting and a stimulating part. The opponent color pairs are blue/yellow, red/green and black/white.

Many experiments carried out subsequently, with 3 projectors of colored light (red, blue and green), showed that a wide range of colors can be generated by changing the light intensity of these 3 projectors. The results enabled the evaluation of the trichromatic perceptions of color stimulus and also the experiments carried out by W. D. Wright in 1928 and by J. D. Guild in 1931 on additive color mixing, among others.

Up to the beginning of the 20th century, various scientists carried out countless experiments to research our color perception system. The theories of Young/Helmholtz and Hering were competing up until the 1930s, when E. Müller finally confirmed the opponent color theory.

The Natural Color System (NCS) and the L*a*b* color model, for example, are based on the opponent color theory.

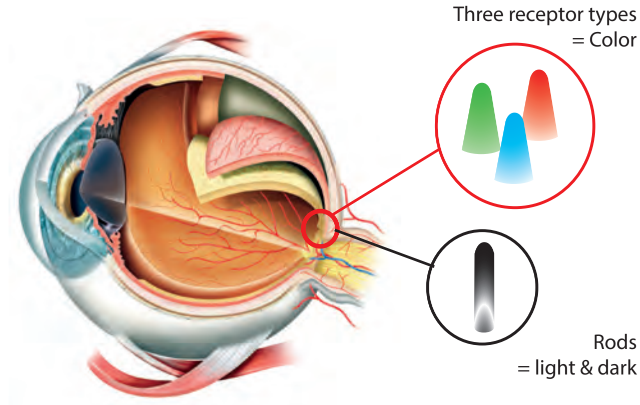


Neurophysiological theory of the complementary or opponent colors in color vision

Wilhelm von Bezold   Bezold-Farbtafel 1874   Ernst von Brücke

The human eye

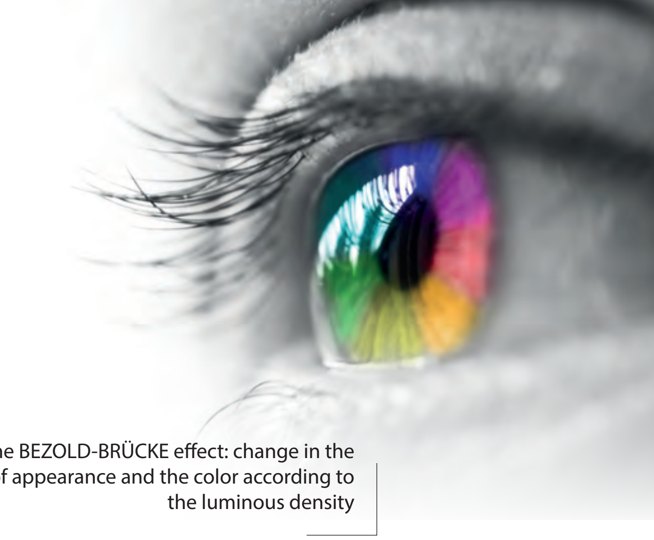
What we see as color is light waves of different lengths that arrive at the eye. The light reflected by an object triggers a stimulus in the photoreceptors of the retina. These photoreceptors consist of rods and cones. The rods are sensitive only to lightness/darkness and are responsible for scotopic vision, and thanks to them, we can see and distinguish shades of grey in weak light. colors cannot be distinguished when rods are responsible for our vision.



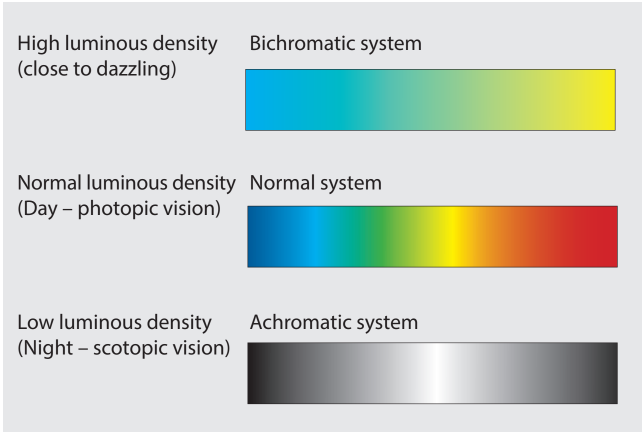
Under daylight conditions, the rods are completely saturated and incapable of processing data. In good lighting, e.g. in normal daylight, we see using only the cones (photopic vision), and it is precisely these that are responsible for distinguishing colors.

In the retina, there are approximately 7 million cones and 120 million rods. All photoreceptors are similarly sensitive but the cones are grouped around common exits, which makes them more sensitive for lateral vision. There are three types of color receptors in the eye (blue, red and green). They are predominantly found in the yellow spot in the middle of the retina. In the centre of the yellow spot, the fovea, are only cones. The average distribution for green : red : blue is 40 : 20 : 1. The sensitivity is a maximum of 477 nm for blue, a maximum of 540 nm for green, and a maximum of 577 nm for red. Blue cones are also called S cones (S for short wavelength), green cones are known as M cones (M for medium wavelength), and the red cones are also referred to as L cones (L for long wavelength).

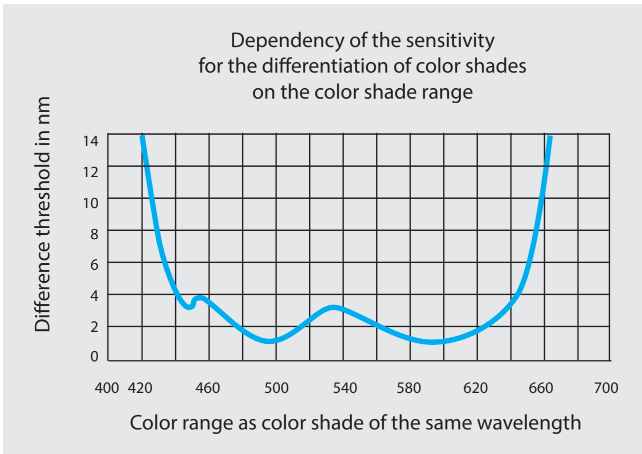
Color differentiation, or more precisely, the differentiation of color shades in the human eye is dependent on the luminous density. For a very low luminous density, a color stimulus between 400 nm and 480 nm results in a color specification of bluish violet, green is perceived between 480 nm and 570 nm, while red is perceived between 570 nm and the longwave visibility limit at 700 nm.



The BEZOLD-BRÜCKE effect: change in the form of appearance and the color according to the luminous density



This effect is called the Bezold-Brücke phenomenon (discovered in 1873, named after the German physicist Wilhelm von Bezold and the German-Austrian physiologist Ernst Wilhelm von Brücke). Differentiation improves with increasing luminous density, but worsens again at high density. Therefore, a sharp increase in illumination causes a change to the red and green shades in the direction of yellow, and to the violet and blue-green shades towards blue. In area of being dazzled, the human eye can perceive only a whitish yellow and a whitish blue-violet. A bichromatic system can therefore be achieved with virtually only 2 colors – yellow and blue. In visual and instrumental color measurement, it is ensured that the illumination conditions are normal (approx. 1500 lux), that is, they comply with the prerequisites for photopic vision.



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